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Research Paper

Microclimatic conditions under different shade trees and their effect on tea leaf growth rate

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ABSTRACT

Micrometeorological variations within the tea canopy influence the tea yield to a considerable extent. An experiment was conducted at the Experimental Garden of Assam Agricultural University Jorhat, Assam during 2022 - 2024 to examine the effects of five shade tree species *viz.,* Sao koroi (*Albiziachinensis*), Xil koroi (*Albizia odoratissima*), Neem (*Azadirachta indica*), Amla (*Phyllanthus emblica*), and Areca nut (*Areca catechu*) on micrometeorological parameters such as air temperature (AT), canopy temperature (CT), relative humidity (RH), photosynthetically active radiation (PAR), soil moisture (SM), soil temperature (ST), and rainfall (RF) affecting leaf growth and yield. The highest green leaf growth rate (GLGR) occurred during the monsoon season (41.7 ± 12.1 kg ha^{-1}day^{-1}), with the highest GLGR (41.8 ± 13.1 kg ha^{-1}day^{-1}) achieved under Neem shade. GLGR has a significant positive correlation with most of the parameters except rainfall which showed no significant influence on GLGR. Regression analysis revealed that rainfall negatively impacted GLGR. This study highlights the role of shade trees in mitigating stress and optimizing growth conditions, providing insights into sustainable tea cultivation practices.

Keywords: Tea, Green leaf growth rate, PAR, Temperature, Soil moisture, Relative humidity

Tea is one of the major commercial crops in India and contributes 1.54% (USD 818 million) of total agricultural exports (USD 53.1 billion in 2022-23). In 2023, India occupied approximately 20% (6,19,000 ha) of the global tea cultivation area and shared 28% (13,70,000 MT) of the world production. Assam alone produces nearly 7,00,000 MT of tea annually, which is approximately half of India's total tea production (Anonymous, 2024). Tea is a shade-loving crop; hence, it is often adapted to the shade of undestroyed trees (Carr and Stephen, 1992). Shading not only limits the receipt of direct solar radiation but also provides unique microclimatic development. Tea, like all other crops, is highly dependent on weather. For optimal growth, tea needs a minimum temperature between 12°C and 13°C and an optimum temperature of 30°C, above which the growth of the tea plant decreases (Mallik and Ghosh, 2022). Wijeratne (1996) reported that temperatures up to 22°C positively affected the shoot extension rate of tea, but with increasing temperature, the shoot extension rate remarkably decreased. Ahmed *et al.,* (2024) reported the impact of frequent drought on tea quality. Despite providing important insights into the mechanisms through which tea production can be impacted by climatic variations, these studies failed to quantify the magnitude of weather impact on tea yield and quality. It has been reported that in the northeastern plains of India, the productivity of tea declines even to 50% of its potential level when it grows under open environmental conditions (Banerjee, 1993; Duncan *et al.,* 2016; Kukal and Irmark, 2020).

Micrometeorological parameters modified under different shades affect the quality and quantity of crop produce (Abror *et al.,* 2025; Meena *et al.,* 2022). Several researchers studied the variation of micrometeorological parameters within the tea canopy in the past (Mukherjee *et al.,* 2008(a, b); Dutta, 2014; Rwigi and Oteng'I, 2009; Bhowmik *et al.,* 2024). However, limitations in the study of microclimates often rest not only on the collection of data but also

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on the choice of appropriate forms of analysis, and it is important not only to quantify changes in microclimates but also to relate them to plant responses. Hence, the present study has been carried out to determine the relationships between tea leaf production and microclimatic parameters under different shade trees and their impact on overall tea yield.

MATERIALS ANDMETHODS

Study area

The present study was carried out at the Experimental Garden for Plantation Crops of Assam Agricultural University, Jorhat, Assam (Latitude: 26°45´N, Longitude: 94°12´E, altitude: 87m above mean sea level) from 2022-23 to 2023-24. Jorhat is located in a sub-tropical belt with hot and humid summers and cold and dry winters. The mean annual rainfall is 1900 mm, of which 62.6 % is received during the southwest monsoon from June to September. During post-monsoon (October - December), pre-monsoon (March-May), and winter seasons (January - February), the station receives 7.5, 26.2, and 3.7 % of annual rainfall, respectively. The monthly morning relative humidity of the station always remains above 85 percent, whereas the monthly evening relative humidity varies from 61 to 76 percent throughout the year. The monthly average maximum and minimum temperatures vary from 22.6 to 32.7°C and 9.7 to 25.2°C, respectively.

Soils

The soils of the experimental site belong to the major group of Inceptisol with high soil acidity. The soils are alluvium-derived, poorly drained, and nearly level to very gently sloping flood plains of the Brahmaputra valley. The soils are of light to heavy texture, showing a wide range of drainage behavior. The organic matter content and status of available nitrogen and potassium is medium; however, the available phosphorus content of the soil is low. High soil acidity, high phosphate fixation, excessive drainage, micronutrient deficiency, iron toxicity, periodic soil moisture stress during the winter season, etc. are some of the soil-related problems of this zone.

Experimental details

In this study, five shade tree species,*viz.,*(i) Sao koroi (*Albizia chinensis*), (ii) Xilkoroi (*Albizia odoratissima*), (iii) Neem (*Azadirachta indica*), (iv) Amla (*Phyllanthus emblica*), and (v) Areca nut *(Areca catechu*) were considered. The tea varieties were not pruned during the study period or the previous year. There are several shade trees present in the experimental garden, but only those five species are the predominant and most commonly used shade trees in the gardens of Assam and Northeast India; thus, only these five shade trees were considered for the study.

The green tea leaves were plucked periodically from March to December at7- 8-day intervals. Furthermore, the study period was segregated into three seasons, namely, the pre-monsoon (Mar-May), monsoon (Jun-Sep), and post-monsoon (Oct-Dec), to quantify the seasonal variation. Weekly plucked green leaf yield (kg ha^{-1}) was highly varied under each sector, along with the availability of labour and also their efficiency. Due to variations in labor availability and efficiency, the weekly green leaf yield (kg ha^{-1}) showed considerable fluctuations. To standardize the data for better comparison, the green leaf yield (kg ha^{-1}) was converted into a tea green leaf growth rate (GLGR) (kg $ha^{-1}day^{-1}$). This was done by dividing the weight of weekly green leaf plucked by the number of days taken from previous plucking, allowing for a more consistent measure of leaf growth across different periods.

Microclimatic observations

Relative humidity (RH, %), air temperature (AT, °C), photosynthetically active radiation (PAR, μmoles m^{-2} sec^{-1}), canopy temperature (°C), soil moisture (SM, %), soil temperature (ST, °C), and rainfall (RF, mm) were taken into consideration as weekly micrometeorological observations. Relative humidity, Air temperature, and soil temperature at three depths, *i.e.*, 5cm, 10cm, and 15cm, were recorded with the help of a mercury thermometer, Assmann psychrometer, and soil mercury thermometer, respectively. Photosynthetic active radiation (PAR) was measured as photon flux density (**μ** mol m^2s^{-1}) with the help of a line quantum sensor, once a week, at two-hour intervals from 8.00 IST to 16.00 IST. The periodic soil moisture contents at three depths, *i.e.,* 15cm, 30cm, and 60cm, were collected and measured by the gravimetric method. Daily rainfall was collected from the agrometeorological observatory situated at ICR Farm, AAU near the study site.

Statistical analysis

Five shade trees were taken into study during2022-2024 across the year to assess the tea green leaf yield. The study period was divided into three major 3 seasons: pre-monsoon, monsoon, and post-monsoon. Here, the season and shade tree were considered as treatments for analysis. Two-way ANOVA with no replication was performed following the procedures of Gomez and Gomez (1984) based on season and shade tree effect on tea yield. Further correlation (Pearson correlations with a significant level) and regression (stepwise both way multiple linear regression based on p-value) between the micrometeorological parameters and tea yield were done with the help of "GGally", "ggplot2" and "olsrr" package in R.

RESULTS AND DISCUSSIONS

Variation of green leaf yield under different shade tree

The average tea green leaf growth rate was found to be highest (41.7±12.1 kg $ha^{-1}day^{-1}$) during the monsoon season, followed by post-monsoon (32.8±9.53 kg $ha^{-1}day^{-1}$) and pre-monsoon season (24.7±7.25 kg $ha^{-1}day^{-1}$) as presented in Table 1. The seasonal variation in tea green leaf growth rate was found in the order of monsoon followed by post-monsoon, followed by pre-monsoon. From the shade tree-wise variation, it was found that the average tea green leaf growth rate was found to be highest (41.8±13.1 kg $ha^{-1}day^{-1}$) under Neem, followed by Xil koroi (37.3±12.1 kg $ha^{-1}day^{-1}$). The tea green leaf growth rate was almost similar in Amla(34.6±11.1 kg $ha^{-1}day^{-1}$) and Sao koroi (33.8±7.25 kg $ha^{-1}day^{-1}$), respectively. Under the Areca nut shade tree, the lowest average tea green leaf growth rate (19.6±6.19 kg $ha^{-1}day^{-1}$) was found. Shade coverage, type of leaf orientation and structure, branching type, and age of the shade trees, may be some important factors in influencing tea green leaf growth rate, where the shade tree-wise variation in green leaf growth was found.

The two-way ANOVA results presented in Table 2 shows

Table 1: Season and shade tree-wise variation of tea green leaf growth rate (GLGR)

Treatments	Average GLGR (kg ha^{-1}day^{-1})	Standard deviation
Season		
Monsoon	41.7	12.1
Post-monsoon	32.8	9.5
Pre-monsoon	24.7	7.3
Shade tree		
Sao koroi (*Albizia chinensis*)	33.8	7.3
Xil koroi *(Albizia odoratissima)*	37.3	12.1
Neem (*Azadirachta indica*)	41.8	13.1
Amla (*Phyllanthus emblica*)	34.6	11.1
Areca nut (*Areca catechu*)	19.6	6.2

Table 2: Two-way ANOVA of green leaf growth rate (GLGR) (kg ha^{-1}day^{-1}) under shade trees during three seasons and their interactions

Treatments	Df	Sum Sq	Mean Sq	F value	Pr(>F)	Sig. level
Seasons	2	10687	5343	147.41	< 2e-16	***
Shade trees	4	8833	2208	60.92	< 2e-16	***
Seasons× Shade tree	8	2959	370	10.2	1.35E-11	***
Residuals	170	6162	36			

(‘***’= 0.001, ‘**’=0.01,‘*’=0.05, ‘.’=0.1,‘’= 1)

a significant variation in green leaf growth rate among different seasons, shade trees, and the interaction of both at a 5% significance level. F values for the shade trees, season, and interaction of both are found as 60.92, 147.41, and 10.2, respectively.

The season-wise impact of each shade tree has been presented in Fig.1. The median tea yield under Neem was highest during monsoon and pre-monsoon, whereas tea yield under Amla shade was highest in the post-monsoon season. However, tea yield under Areca nut was found to be the lowest, irrespective of all seasons. After completing the annual regular pruning cycle in the winter season, new tea leaf emerges just after rain in the pre-monsoon season. So, vigorous growth of green leaf is not obtained in this season for tea grown under all five shade trees. The GLGR under a shade tree species is increasing gradually, and it reaches the highest value during the monsoon season; after that, the GLGR is decreasing gradually in the post-monsoon season. The effect of rainfall is manifested more by its influences on the moisture status of the soil and in inducing vegetative growth. Therefore, the distribution of rainfall is as important as the total annual rainfall. Ali *et al.,* (2014), in their study, found that tea leaf production and rainfall were moderately correlated and had a positive influence on each other. He also found that decreases in soil moisture occur because of increased temperatures, although this could be offset by simultaneously increased precipitation. Rainfall of less than 1300 mm per annum has a detrimental effect on tea growth. In his study, no significant relation between tea leaf production and temperature was observed.

Microclimatic variation under different shade trees

The shade tree-wise average of microclimatic parameters for different seasons is presented in Table 3. Higher relative humidity and soil moisture percentage were found in the monsoon season, followed by the post-monsoon and pre-monsoon seasons. However, monsoonal air temperature, canopy temperature, and soil temperature were found to be higher compared to pre-monsoonal and post-monsoonal seasons. This indicates that, irrespective of shade trees, tea plants are relatively under higher stress during the pre-monsoon season compared to the monsoon and post-monsoon season. Tea, being a shade-loving plant, is highly influenced by the modified microclimatic situation under different shade trees. Shade tree density and planting geometry substantially affect tea microclimate. Mallik and Ghosh, (2022) also reported that rainfall positively influenced tea productivity in dry months and negatively in wet months. Warm conditions during wet months and additional rainfall during dry seasons encourage tea productivity.

Correlation between GLGR of tea and microclimatic parameters

Pearson correlation coefficient between weather variables and green leaf growth rate was computed season-wise and presented an overall relationship in Table 4, in order to identify the crucial micrometeorological parameters affecting tea green leaf growth rate. Seasonal relational studies revealed that during the pre-monsoon season, only the incoming average photosynthetically active radiation positively affected the tea green leaf growth rate. During monsoon season similar significant positive correlation was found between photosynthetically active radiation (0.73***) and tea green leaf growth rate, however, soil moisture (%) at 60 cm depth and rainfall were found to significantly negatively affect the tea green leaf growth rate. This indicates that excess moisture condition leads to reduced growth in tea due to stress in the root; runoff of excess rainwater is a prerequisite in successful tea cultivation.

Interestingly, during the post-monsoon season, air temperature, photosynthetically active radiation, canopy temperature, and soil temperature at three depths, 5cm, 10cm, and

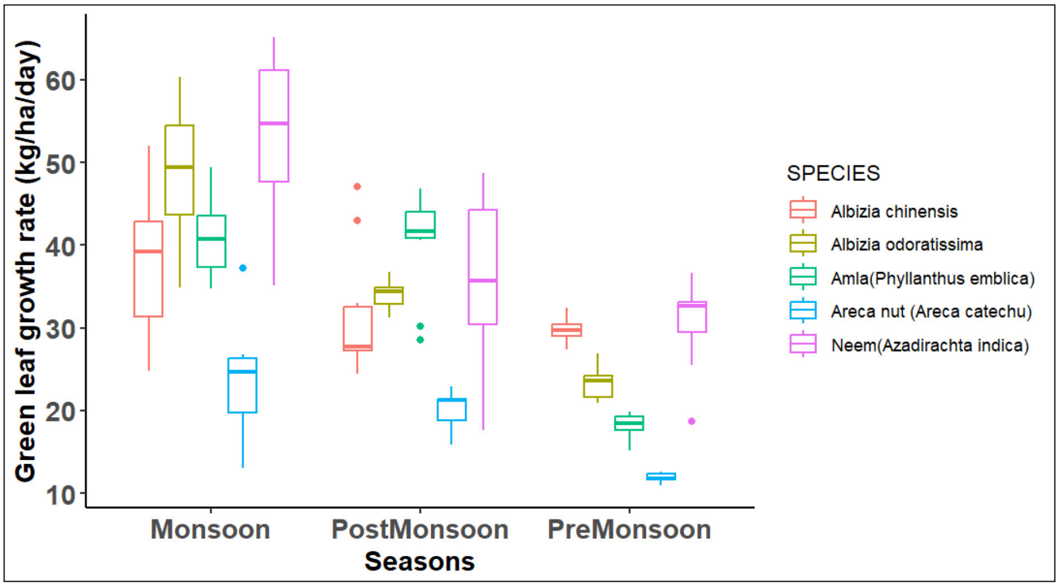

Fig. 1: Seasonal variation of green leaf growth rate (kgha^{-1}day^{-1}) of tea under different shade trees during three seasons

Table 3: Shade tree-wise average of microclimatic parameters for different seasons

Shade trees	RH	Air T	Avg. PAR	Canopy T	SM% (15cm)	SM% (30cm)	SM% (60cm)	T_{soil} (5cm)	T_{soil} (10cm)	T_{soil} (15cm)	RF (mm)
Pre-monsoon											
Sao koroi (*Albizia chinensis*)	77.0	24.7	635	28.0	16.4	18.0	20.2	29.4	28.4	28.2	290.3
Xil koroi *(Albizia odoratissima)*	76.6	24.1	563	27.0	15.9	18.4	19.5	27.6	27.2	26.9	212.7
Neem (*Azadirachta indica*)	78.7	25.1	585	27.9	17.1	18.3	19.1	28.3	27.8	27.7	453.7
Amla (*Phyllanthus emblica*)	78.2	26.1	531	29.4	17.2	17.8	19.1	29.6	29.0	28.6	295.0
Areca nut (*Areca catechu*)	76.3	25.8	574	29.0	15.7	17.8	19.1	29.3	28.7	28.4	230.0
Monsoon											
Sao koroi (*Albizia chinensis*)	81.1	29.3	787	32.5	21.2	21.9	22.3	32.4	32.2	32.3	1056.7
Xil koroi *(Albizia odoratissima)*	83.5	29.0	962	31.9	20.5	21.4	21.7	32.1	32.0	32.1	923.5
Neem (*Azadirachta indica*)	82.7	29.4	871	32.4	20.3	21.3	21.6	32.5	32.3	32.3	1006.8
Amla (*Phyllanthus emblica*)	83.0	29.6	806	32.8	20.8	21.7	22.0	32.8	32.6	32.6	1015.6
Areca nut (*Areca catechu*)	83.0	29.6	632	32.6	21.3	22.5	22.3	33.1	32.7	32.6	1067.4
Post-monsoon											
Sao koroi (*Albizia chinensis*)	78.7	24.0	646	26.9	19.4	20.2	21.6	27.0	26.9	26.9	192.3
Xil koroi *(Albizia odoratissima)*	80.9	23.0	662	26.1	18.6	20.0	18.0	25.8	25.9	26.1	186.2
Neem (*Azadirachta indica*)	79.8	24.2	570	27.2	19.2	19.9	19.6	27.5	27.5	27.7	229.2
Amla (*Phyllanthus emblica*)	80.4	23.3	692	26.2	19.2	20.1	18.6	26.0	26.0	26.1	246.6
Areca nut (*Areca catechu*)	78.8	23.4	573	26.7	18.8	19.7	20.0	25.8	25.8	26.2	213.0

RH :Average relative humidity (%), AIR T :Average air temperature (°C), Avg. PAR : Average Incident Photosynthetically Active Radiation (µmol m^{-2} sec^{-1}) over tea crop, Canopy T :Average tea canopy temperature (°C), SM%(15cm) :Average soil moisture percentage within 15 cm depth (%),SM% (30cm) : Average soil moisture percentage within 30 cm depth (%),SM% (60cm) :Average soil moisture percentage within 60 cm depth (%),T_{soil}(5cm) :Average soil temperature(°C) at 5 cm depth, T_{soil}(10cm) :Average soil temperature(°C) at 10 cm depth, T_{soil}(15cm) :Average soil temperature(°C) at 15 cm depth, RF(mm) : Total Rainfall (mm)

15cm found to be significantly positively affecting the tea green leaf growth rate. This indicates that with the advancement of the winter season, decreasing thermal regime and photosynthetically active radiation led to lower tea green leaf yield rate.

Overall, it was found that relative humidity, air temperature, canopy temperature, soil temperature at three depths; 5cm, 10cm, 15cm, soil moisture at three depths; 15cm, 30cm, 60cm and photosynthetically active radiation positively and significantly influenced green leaf growth rate, whereas no significant effect of rainfall was found. No significant effect of rainfall was also obtained by Dutta, 2014 during his study, but Nijamdeen *et al.,* (2018) found a positive and significant influence of rainfall and temperature on green leaf growth rate. Finally, stepwise, both-way multiple linear regression based on p-value was applied to identify the most influential weather variables on tea green leaf growth rate (Table 5). Using step-wise, both-way multiple linear regression based on p-value, a significant relationship was found between GLGR and PAR, soil moisture (%) at 30 cm depth, and relative humidity as follows.

Table 4: Correlation of average tea green leaf growth rate (kgha^{-1}day^{-1}) [average of all shade trees] with different micrometeorological parameters during three seasons and over the years, with observation number (n) for each variable

Parameters	Pre-Monsoon (n=49)	Monsoon (n=81)	Post-Monsoon (n=55)	Overall seasons (n=185)
Relative humidity	-0.071	0.070	0.127	0.238***
Air temperature	0.037	0.008	0.338	0.378***
Photosynthetically Active Radiation (PAR)	0.545***	0.726***	0.591***	0.782***
Canopy temperature	0.016	-0.025	0.318*	0.355***
Soil moisture at 15cm depth	-0.062	-0.138	0.134	0.419***
Soil moisture at 30cm depth	0173	-0.158	0.133	0.468***
Soil moisture at 60cm depth	0.078	-0.225*	0.052	0.292***
Soil temperature at 5cm depth	0.057	-0.069	0.334*	0.327***
Soil temperature at 10cm depth	0038	-0.041	0.333*	0.370***
Soil temperature at 15cm depth	0.069	-0.022	0.316*	0.400**
Rainfall	-0.083	-0.332**	0.071	0.100

(*** Correlation is significant at the 0.01 level; ** Correlation is significant at the 0.05 level; * Correlation is significant at the 0.1 level)

Table 5: Stepwise multiple linear regression

Model	Beta	Std. Error		t	Sig
(Intercept)	-40.419	9.337		-4.329	0
PAR	0.068	0.005		14.414	0
RAIN	-0.035	0.008		-4.34	0
SM_30	0.728	0.362		2.011	0.046
RH	0.194	0.099		1.956	0.052
	Sum of Squares	DF	Mean Square	F	Sig.
Regression	18676.719	4	4669.180	84.351	0.0000
Residual	9963.741	180	55.354		
Total	28640.461	184			

GLGR= Tea green leaf growth rate (kg ha^{-1}day^{-1})

GLGR = 0.068 × PAR – 0.035 × RAIN + 0.728 × SM_30 +0.194 × RH - 40.419

(R^2= 0.652; Adj. R^2= 0.644)

All the above weather variables positively and significantly affected the tea yield, whereas rainfall was found to be negatively affecting. It may be due to the very high rainfall in the study area. The R^2, Adjusted R^2, and RMSE values are found as 0.652, 0.644, and 7.44, respectively, indicating a significant and acceptable relationship between tea growth and micro-meteorological parameters. As the regression model was not tested with other years' datasets, this can be used for the identification of the crucial weather parameters for tea growth, irrespective of season and shade trees.

CONCLUSION

It can be concluded that the microclimatic variations induced by different shade tree species significantly influenced tea leaf production. If the season is considered, the highest tea green leaf growth rate (GLGR) was observed during the monsoon season. The Neem tree is found to be the most effective shade tree for enhancing tea yield, followed by Xil koroi *(Albizia odoratissima)*. The pre-monsoon season showed the highest environmental stress on tea plants due to elevated temperatures and reduced relative humidity and soil moisture (SM). Conversely, the monsoon season provided optimal growing conditions, marked by high RH, SM, and moderate temperatures. The distinct thermal regimes across seasons underscore the importance of adaptive management practices to mitigate stress during the pre-monsoon period. The shade tree species moderate microclimatic extremes, improving resource use efficiency and enhancing tea yield. The green leaf growth is positively correlated with relative humidity, ambient temperature, canopy temperature, soil temperature, and soil moisture.

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