

Review on Impacts of Climate Change on Tea Yield, Yield Components and Quality

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Abstract: The tea plant grows in a variety of climates and it is difficult to specify an ideal climate. The monsoonal climate of Northeast India with alternate wet and dry seasons and the high elevation of subtropical mountains in China, India, and Sri Lanka provide optimal conditions for tea production. Climate change is expected to decrease not only the quality of tea, but also the quantity of tea production: as a consequence of increased soil erosion, pests, and diseases that are becoming more resistant. In addition to this; changing climate conditions impact the concentration of secondary metabolites, which are most important for the quality of tea. The dilution of phytochemicals as a consequence of more frequent extreme rains seems to explain the changes of the tea taste that tea farmers in Yunnan (South China) are experiencing. As tea is thought to have originated as an understory plant in the tropical rainforests, it is likely that its photosynthetic apparatus is adapted to function with maximum capacity under shade. Generally, tea grows well within a T_a range of about 18-25°C. Air temperatures below 13°C and above 30°C have been found to reduce shoot growth. The rate of shoot initiation in tea increases linearly with rise in temperature from the base (threshold) temperature (T_b) to an optimum temperature (T_o) and thereafter decreases linearly with further increases in temperature up to the maximum or ceiling temperature (T_{ce}). Reduction of shoot extension, leaf area expansion, stem diameter, internode elongation and number of lateral branches of woody plants including tea, have been reported to be associated with SWD.

Keywords: Impacts; Climate; Tea; Yield; Yield component; Quality

1. INTRODUCTION

The scientific community has contributed extensively with various data, discussions, and projections on the future climate, as well as on the effects and risks of the expected climatic change (IPCC, 2014; Werner *et al.*, 2017). Anthropogenic climate change due to CO₂ and other human-generated greenhouse gases is anticipated to affect agriculture all over the world, having both positive and negative effects (e.g., impacts on food production and food security). Tea [*Camellia sinensis* (L) O. Kuntze], is one of the most popular and lowest cost beverages in the world, and consumed by a wide range of age groups in all levels of society with more than three billion cups daily worldwide (Hick, 2009; Zakir, 2017). The tea plant grows in a variety of climates and it is difficult to specify an ideal climate. The monsoonal climate of Northeast India with alternate wet and dry seasons and the high elevation of subtropical mountains in China, India, and Sri Lanka provide optimal conditions for tea production. Despite of the variety of climates, tea production relies on suitable temperatures and well distributed rainfall. The specific climatic niche makes the growing of tea bushes vulnerable to climate change. Thus, global warming is expected to have a significant impact on tea production and presumably will influence both the quantity and quality of tea (Dutta, 2014; Duncan, 2016 and Kaye, 2017). The impacts of climate change on tea production are the following: drying of the soils causing reduced water content in the tea, decreasing yields and negative impacts on quality; appearance of new pests and diseases; changes in the suitability of existing tea growing areas (in extreme cases, as temperatures become too high for tea cultivation), new suitable land areas need to be found; reduced biodiversity and ecosystem function as the result of habitat conversion, high-energy consumption (logged timber); sun scorch damage decreasing yields and lowering tea quality; reduced resilience of tea crops; uncertainty with application of fertilizers, high application of pesticides in some countries; increase in extreme weather events such as droughts, hail storms, floods, frosts, extreme rainfall and landslides (MCCTS, 2014; Maina *et al.*, 2015 and Zakir, 2017).

Changing climate conditions impact the concentration of secondary metabolites, which are most important for the quality of tea (Werner *et al.*, 2017). The dilution of phytochemicals as a consequence of more frequent extreme rains seems to explain the changes of the tea taste that tea farmers in Yunnan (South China) are experiencing (Larson, 2015; Ahmed, 2017). According to recent findings in the Jiangxi Province (Eastern China), rising temperatures may deteriorate tea quality (Han *et al.*, 2017). Climate change is expected to decrease not only the quality of tea, but also the quantity of tea production: as a consequence of increased soil erosion, pests, and diseases that are becoming more resistant (Wijeratne, 1996). Generally, a moderate increase in temperature increases the tea yield (Werner *et al.*, 2017). However, above an optimal temperature a further temperature increase seems to reduce the productivity of tea plantations (Dutta, 2014, Wijeratne *et al.*, 2007, Gunathilaka *et al.*, 2017). Given the importance of the tea crop to the main production regions, this may result in negative economic and social consequences, particularly for tea farmers, workers on tea estates, and tea traders. Tea farmers are faced with the need of climate change adaptation strategies for their future tea production (Werner *et al.*, 2017).

2. LITERATURE REVIEW

2.1. General Overview of the Climatic Change Effect on Tea

Wijeratne (1996) analyzed the relationship between climatic factors and tea yield, in particular the effect of temperature on the shoot extension rate. He found that the shoot extension rate increases with increasing temperatures only up to 22 °C, but further increases in temperatures result in a decline. Wijeratne expects the adverse effects of climate change to be greater in the low elevation tea growing regions, where the majority of tea production enters the market. This paper also discusses the consequences of the predicted recurrent warm seasons, droughts, and heavy rains for the tea production in Sri Lanka: in particular the vulnerability to soil erosion and outbreaks of pests. To mitigate economic problems, Wijeratne suggests an adaptation strategy to minimize the adverse effects of global warming on the tea industry in Sri Lanka. In a follow-up (Wijeratne *et al.*, 2007) assessed the impact of climate change on the productivity of tea plantations in Sri Lanka. The authors concluded that (1) increasing temperatures are likely to reduce tea yields at low elevations and (2) low and mid elevations are more vulnerable to the adverse impact of climate change (Werner *et al.*, 2017). According to (Archer *et al.*, 2008) the implications of climate change for small-scale rooibos tea (*Aspalathus linearis*) farmers in western South Africa and discuss the ways in which farmers are adapting to current climate variability.

2.2. Impact Climate Change on Photosynthesis of Tea

Tea exhibits the C3 mechanism of photosynthesis (Roberts and Keys, 1978). Under normal ambient atmospheric conditions, rate of photorespiration in tea was around 19% of net photosynthesis. Tea leaves are the major plant organs where photosynthesis occurs, although the stems also contribute to CO₂ assimilation (Sivapalan, 1975). However, the efficiency of CO₂ fixation by mature brown stems is very low compared to that of leaves, and on a pruned stem, the newly emerging shoots draw this assimilated starch. Net photosynthetic rate (P_n) of fully-expanded mature leaves of tea shows the typical asymptotic response to increasing light intensity. There is considerable variation in the reported saturating light intensities, ranging from 600-800 μmol (PAR) m⁻² s⁻¹ (Sakai, 1975; Squire, 1977; Gee *et al.*, 1982; Mohotti, 2004) through 1000 μmol m⁻² s⁻¹ of PAR (Sakai, 1987; Smith *et al.*, 1993a, 1994) up to 1200-1500 μmol m⁻² s⁻¹ (Okano *et al.*, 1995). This indicates probable genotype x environment interaction effects. Similarly, the light-saturated maximum rate of photosynthesis (P_{max}) varies with genotype and environmental conditions under which tea is grown (Table 1).

Table 1. Response of light-saturated net photosynthetic rate (to fertigation of different genotypes of tea

Genotype	P _{max}		Q _E		R _d	
	Fertigation	Control	Fertigation	Control	Fertigation	Control
TRI3072	10.8 a	9.5 b	0.046a	0.049 a	1.51 a	1.14 b
DN	7.6 a	7.5 a	0.036a	0.064 b	0.21 a	1.34 b
DT1	4.7 a	3.3 b	0.031a	0.029 a	0.33 a	0.52 b

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*P*_{max} ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$); initial quantum efficiency (QE, $\mu\text{mol}^{-1} \text{ CO}_2 \mu\text{mol}^{-1} \text{ PAR}$) and dark respiration rate (R_d, $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). Fertigation = drip irrigation with water and dissolved fertilizer; Control = rain fed with fertilizer broadcasted. Within each genotype and variable, means with different letters indicate significant ($P < 0.05$) response to fertigation.

Source: Mohotti, 1998 and DE COSTA *et al.*, 2007

2.2.1. Photo Inhibition and Shade Adaptation of Tea

As tea is thought to have originated as an understory plant in the tropical rainforests, it is likely that its photosynthetic apparatus is adapted to function with maximum capacity under shade. Investigations of photosynthetic partial processes (i.e. light capture, electron transport, photochemical- and non-photochemical energy quenching and carboxylation) by Mohotti *et al.* (2000) and Mohotti and Lawlor (2002) have shown that the entire photosynthetic apparatus of tea is shade-adapted. The rate of P_n, stomatal conductance (g_s) and apparent quantum yield (i.e. P_n per unit of PAR absorbed) of 5-Month old seedlings of tea grown in cabinets were consistently higher under shade (i.e. 150 $\mu\text{mol PAR m}^{-2} \text{ s}^{-1}$) as compared to unshaded (i.e. 650 $\mu\text{mol PAR m}^{-2} \text{ s}^{-1}$) conditions (Mohotti *et al.*, 2000). Accordingly, several studies have shown that P_n of tea decreases due to photo-inhibition when the light intensity increases beyond 1400-1500 $\mu\text{mol m}^{-2} \text{ s}^{-1}$ (Smith *et al.*, 1993a; Mohotti and Lawlor, 2002). Decreased g_s in response to increasing irradiance, leaf temperature (TL) and air vapour pressure deficit (VPD) played a key role in inducing photoinhibition of tea. In a field study on mature tea, Mohotti and Lawlor (2002) observed that increasing irradiance, TL and VPD with the progress of the day towards midday do decrease g_s and sub-stomatal CO₂ concentration (C_i), thus leading to reduced RuBP carboxylation and P_n. By following the diurnal variation patterns of the relevant variables, Mohotti and Lawlor (2002) showed that P_n did not recover from photo-inhibition during late afternoon, despite g_s and C_i increasing substantially due to lower irradiance, TL and VPD. All these impose a source-limitation on tea yield. Studies with young tea plants under controlled environmental conditions showed that shade increased P_n by increasing the efficiency of PSII and the rate of linear electron transport (Mohotti *et al.*, 2000). Furthermore, shade reduced photoinhibition by increasing g_s (thus allowing greater CO₂ influx) and thereby channeling a greater proportion of excitation energy towards carboxylation (i.e. increased photochemical quenching). Similar results have been also obtained in field studies on mature tea (Mohotti and Lawlor, 2000; Karunaratne *et al.*, 2003).

2.2.2. Air and Leaf Temperatures

Maximum P_n of tea leaves occurs at 30-35°C in North East India (Hadfield, 1975). Photosynthesis rapidly fell beyond 37°C and there was no net photosynthesis at 42°C. Under natural conditions, when fully exposed to sun, TL is 2-12°C higher than T_a. Leaf temperature in tea is influenced by size, structure and pose of the leaf, wind velocity, relative humidity and rate of transpiration (Rahman, 1988). Mohotti and Lawlor (2002) reported that the capacity for CO₂ assimilation in tea was decreased by increased temperature brought about by high irradiance as the day progressed from morning to early afternoon. The high rates of P_n were 37% higher in the morning with cooler temperatures around 20°C, than at 30°C in the afternoon. In this experiment, P_n decreased with increasing T_a in the range between 20°C and 30°C. Responses of photosynthesis to T_a are cultivar dependent, as shown under South Indian conditions (Joshi and Palni, 1998 ; DE COSTA *et al.*, 2007). In four out of six cultivars tested, the optimum T_a for maximum P_n was shown to be 25°C. Beyond this temperature, P_n dropped drastically. For the other two cultivars, the optimum was 30°C and, interestingly, P_n did not drop as drastically as in the other cultivars. Furthermore, the two cultivars having a higher temperature optimum had higher g_s and water-use efficiency than the others at all T_a tested, indicating heat tolerance (DE COSTA *et al.*, 2007). Smith *et al.* (1993a, 1994) investigated the interplay between P_n, g_s and TL through a combination of irrigation and nitrogen fertilizer treatments.

In well-irrigated tea, maximum Pn was at an optimum range of 20-30oC, beyond which Pn decreased at a rate of 0.053 $\mu\text{mol m}^{-2} \text{s}^{-1} \text{oC}^{-1}$. In poorly- irrigated tea, optimum TL was around 20-24oC and rate of reduction of Pn was greater (i.e. 0.093 $\mu\text{mol m}^{-2} \text{s}^{-1} \text{oC}^{-1}$) (DE COSTA *et al.*, 2007).

2.2.3. CO2 Concentration

Response of Pn to variation of the atmospheric CO2 concentration (Ca) is important not only to determine spatial and temporal variations of leaf Pn, but also to determine how the productivity of tea would respond to long-term climate change with increasing Ca (DE COSTA *et al.*, 2007). Smith *et al.* (1993a) observed a positive, linear correlation between instantaneous Pn and CO2 concentration of their measurement chamber (which varied between 351 to 490 $\mu\text{mol mol}^{-1}$). The rate of increase of Pn per 1 $\mu\text{mol CO}_2 \text{mol}^{-1}$ was $8.16 \times 10^{-3} \mu\text{mol m}^{-2} \text{s}^{-1}$. Anandacoomaraswamy *et al.* (1996) showed that Pmax of tea can be raised temporarily up to 40-60 $\mu\text{mol m}^{-2} \text{s}^{-1}$ by artificial CO2 enrichment of the measurement chamber up to 1500 $\mu\text{mol mol}^{-1}$. Maximum Pn around 30 $\mu\text{mol m}^{-2} \text{s}^{-1}$ was reached around 1000-1200 $\mu\text{mol mol}^{-1}$ Ci in mature, field-grown tea (Mohotti, 1998). The corresponding values for young, container-grown tea were 7-10 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and 500-600 $\mu\text{mol Ci mol}^{-1}$. Parameters of the CO2 response curves of field-grown, mature tea varied with different shade and N levels (Table 2).

Table.2. Mean photosynthetic parameters of light and CO2 response curves of field-grown mature tea in Sri Lanka.

Treatment	QE	Pmax	Rd	dA/dCi	Vcmax	RS
No shade, HN	0.0256	9.70	-1.555	0.0615	47.3	26.7
No shade, MN	0.0284	11.19	-1.429	0.0662	47.3	26.5
No shade, NN	0.0248	7.09	-1.376	0.0331	38.0	18.0
35% shaded, HN	0.0434	6.73	-1.420	0.0916	45.4	38.2
35% shaded, MN	0.0300	10.26	-1.184	0.0535	38.6	35.5
35% shaded, NN	0.0423	7.40	-1.183	0.0664	66.9	40.8
70% shaded, HN	0.0282	10.19	-1.165	0.0514	13.7	34.3
70% shaded, MN	0.0303	10.96	-1.040	0.0605	46.9	29.8
70% shaded, NN	0.0293	9.88	-1.153	0.0605	48.0	23.5

QE, quantum efficiency, $\mu\text{mol}^{-1} \text{CO}_2 \mu\text{mol}^{-1} \text{PAR}$; Pmax, maximum light-saturated photosynthetic rate, $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$; Rd, dark respiration rate, $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$; dA/dCi; initial slope of the Pn-Ci curve; Vcmax, maximum rate of carboxylation of Rubisco, $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$; and RSL, relative stomatal limitation to photosynthesis, %HN = high-N application (720 kg ha⁻¹ yr⁻¹); MN = medium-N application (360 kg ha⁻¹ yr⁻¹); NN = no-N application.

Source: Mohotti, 1998 and DE COSTA *et al.*, 2007

2.3. Climate Change Impact on Temperature for Tea Production and Quality

Generally, tea grows well within a Ta range of about 18-25oC. Air temperatures below 13oC and above 30oC have been found to reduce shoot growth (Carr, 1972; Watson, 1986b; Carr and Stephens, 1992). The rate of shoot initiation in tea increases linearly with rise in temperature from the base (threshold) temperature (Tb) to an optimum temperature (To) and thereafter decreases linearly with further increases in temperature up to the maximum or ceiling temperature (Tce) (Squire, 1990; Roberts *et al.*, 1997). The Tb for tea shoot extension has been found to vary from 7oC (Obaga *et al.*, 1988) to about 15oC (Stephens and Carr, 1990), with 12.5oC being the average (Carr and Stephens, 1992). Stephens and Carr (1993) showed that Tb for shoot extension (i.e. 10oC) of tea growing with adequate water and nutrients was 2-3oC higher than that for shoot development (i.e. initiation). In contrast, Squire *et al.* (1993) observed similar Tb for both these processes in tea growing in the Kenyan highlands. However, the work of Squire *et al.* (1993) covered a temperature range of only 2oC while Stephens and Carr (1993) covered a range of 5oC. Moreover, Stephens and Carr (1990) observed a greater Tb for shoot extension during a warming phase (i.e. 15oC) than during a cooling phase (13oC). Although To for shoot growth of tea has not been clearly defined, Carr (1972) reported the To for growth of tea to be in the range between 18-30oC and Tce to be in the range 35-40oC. However, Tanton (1992) implied that the upper temperature limit for shoot growth could be as high as 36oC in the absence of other stress factors limiting shoot growth. Wijeratne and Fordham (1996) reported that shoot extension rate and weight per shoot decreased when Ta rose above 26oC. Shoot population density also decreased linearly above a Ta range of 25.5-29oC. A growing tea bud needs to

accumulate about 150°Cdays above a T_b of 12.5°C to unfurl a leaf and 450-500°Cdays to produce a harvestable tea shoot (Squire, 1990). Carr (2000) also reported that small differences in T_b can have relatively large effects on rate of shoot development and extension at high altitudes where T_a is low. Further, Wijeratne (2001) reported that the thermal duration requirement of the cultivar TRI2025 for producing a harvestable tea shoot (three leaves and a bud) in Sri Lanka varied from 330-370°C-days at high elevation to 500-600°C-days at low elevation. The thermal duration for initiation of one leaf (i.e. phyllochron) was estimated to be 30-40°C-days and 60-70°C-days at the same two elevations respectively. In addition to the phyllochron, the plastochron of tea (i.e. the duration for initiation of one leaf primordium) is also influenced by temperature. Moreover, the minimum temperature accumulation for producing a tea shoot of harvestable size in Kenya has been estimated to be 108-212°C-days. These findings cast doubt about the possibility of using a universal T_b in estimating the thermal time requirement. Therefore, such variations need to be carefully considered and necessary corrections included in the temperature response model before any the predictions are made (Wijeratne, 1994). An important parameter that illustrates the influence of T_a on shoot initiation and extension is the ‘shoot replacement cycle (SRC)’, which is the time required for an axillary bud released from apical dominance (when a shoot is plucked) to develop three leaves and a terminal bud. Stephens and Carr (1993) showed that SRC of fully irrigated and well-fertilized tea increased from 65 d during the warm wet season in Tanzania to 95 d during the cool dry season. The temperature difference between these two seasons represented a 5°C range. The unirrigated and unfertilized tea also showed an extension of SRC from 75 to 180 d. Because of the decline of T_a with rising altitude, there is an apparent variation in the rate of shoot growth of tea depending on the altitude where it is grown (Squire, 1990; Squire et al., 1993; Balasooriya, 1996). Squire et al. (1993) showed that the duration of the shoot growth cycle increased, but the SER decreased with increasing altitude (and decreasing T_a) in Kenya. Furthermore, there was a cultivar difference in the magnitudes of the above responses indicating cultivar variation in temperature sensitivity (DE COSTA *et al.*, 2007). Interestingly, the temperature-insensitive cultivar did not show a significant linear regression between SER and T_a , while the temperature-sensitive cultivar did. Although Wsh showed a significant cultivar variation, it was stable across altitudes within each cultivar. The yield of a temperature-sensitive cultivar decreased significantly with increasing altitude while that of the other temperature-insensitive cultivar remained stable until an altitude of 2120 m was exceeded. Smith et al. (1993b) also showed large cultivar differences in the response of exponential relative shoot extension rate to T_a within the range of 18-23°C. In addition, some tea growing regions experience both cooler and warmer climates at a given altitude. Under such conditions, during cooler periods with little – or no active shoot growth, carbohydrates are mostly partitioned to roots. During subsequent warmer periods, these carbohydrates are retranslocated to the developing shoots (Fordham, 1972; Rahman and Dutta, 1988; Squire, 1977). Hence, temperature modifies the balance between shoot and root growth by influencing the physiology of shoot growth. In addition to T_a , soil temperature (T_s) also influences the growth of the tea plant (Carr, 1970, 1972; Carr and Stephens, 1992), especially in situations where growth of tea is limited by low T_s . Magambo and Othieno (1983) reported that high T_s during the day time combined with low T_s during the night induced early flowering of tea and reduced its vegetative growth. Othieno (1982) showed that the diurnal variation of T_s in a young tea field with incomplete canopy cover (i.e. < 60%) differed under different types of mulches depending on their heat absorptivity. However, these variations disappeared when the canopy cover of tea increased above 60%. Othieno and Ahn (1980) and Tanton (1992) also reported a close relationship between T_s and yields of young tea. The mulches that allowed higher T_s levels showed higher tea yields (Othieno, 1982).

2.4. Water Stress

Shoot growth of tea is influenced by water deficits in both the soil (soil water deficits, SWD) and the aerial environment (air VPD). Reduction of shoot extension, leaf area expansion, stem diameter, internode elongation and number of lateral branches of woody plants including tea, have been reported to be associated with SWD (Fordham, 1969; Carr, 2000). Stephens and Carr (1993) showed that the length of a pluckable shoot with three leaves and a bud during the dry season of Tanzania was reduced from 130 mm in fully-irrigated and well fertilized tea to 15 mm in unirrigated and unfertilized tea (DE COSTA *et al.*, 2007). Due to slow growth of shoots under soil water stress tea yields are greatly reduced. This slow growth under environmental stress is a result of low shoot ψ_w that affects cellular turgor (Carr and Stephens, 1992; Squire, 1977). However, Carr (2000) reported

that although water stress reduces shoot length at harvest and decreases dry matter content it has little effect on Nsh. In many tea growing regions, seasonal fluctuation in tea yield has been related to the soil moisture level (DE COSTA *et al.*, 2007). Water stress delays or stops bud break leading to accumulation of dormant buds in the tea bush. These buds start growing simultaneously (synchronized bud break) with rain, thus forming a peak in the crop (rush crop) known as “Fordham peak” (DE COSTA *et al.*, 2007). When all the fast growing vigorous shoots are harvested within the peak cropping period, a subsequent trough in production occurs due to the absence of pluckable shoots (Fordham, 1970; Fordham and Palmer-Jones, 1977). In addition to the SWD, high ambient VPD also reduces shoot growth of tea even when the soil is irrigated. The critical VPD affecting growth of tea shoots has been reported to be about 2-2.3 kPa (Hoshina *et al.*, 1983; Squire, 1979; Carr and Stephens, 1992; Tanton, 1992). However, in the warmer low altitudes (< 600 m) of Sri Lanka, shoot growth has been affected at lower VPD of less than 1.2 kPa (Wijeratne and Fordham, 1996). Usually shoot extension is less sensitive to dry weather than leaf expansion (DE COSTA *et al.*, 2007).

2.5. Photoperiod Impact on Tea

Investigations have shown that the growth of tea shoots is depressed when the photoperiod is less than about 11 h especially when combined with warm (20°C) nights (Fordham 1970; Herd and Squire, 1976; Tanton 1982a). In addition, Barua (1969) found that there is a greater tendency for tea shoots to become dormant when the photoperiod is less than 11.16 h. Because of this influence of photoperiod on the onset and release of bud dormancy (and therefore the number of actively growing shoots at any given time), Matthews and Stephens (1998b) predicted that tea yields could be sensitive to the critical photoperiods (Roberts *et al.*, 1997) for controlling bud dormancy and shoot development. However, such influences may not have a significant impact on shoot growth or yield under tropical weather conditions where the photoperiod is usually greater than the critical value (DeCOSTA *et al.*, 2007)

2.6. Transpiration

Water use of tea and its controlling factors have been studied extensively (Carr, 1974; Stephens and Carr, 1991b; Anandacoomaraswamy *et al.*, 2000; Kigalu, 2007). However, water use (or evapotranspiration) include both transpiration from the foliage canopy and soil evaporation. A well-maintained tea canopy covers the ground almost completely allowing very little solar radiation to penetrate down to the soil surface. In such situations, evapotranspiration is almost equal to transpiration (DE COSTA *et al.*, 2007). There are only a few studies where direct measurements of transpiration have been done in tea over prolonged periods. In one such study, Anandacoomaraswamy *et al.* (2000) showed that both hourly and daily transpiration rates were highly sensitive to soil water availability. Daily transpiration rate was maintained at a maximum of 1.6 L plant⁻¹ d⁻¹ when the soil water content (SWC) decreased from field capacity (44% v/v) down to 33%. Within this range of SWC, maximum hourly transpiration rates of 0.53-0.93 L plant⁻¹ h⁻¹ were maintained during the period between 1000 and 1500 h. When the SWC decreased below 33%, daily and hourly transpiration rates declined rapidly down to 0.71 L plant⁻¹ d⁻¹ and 0.27-0.53 L plant⁻¹ h⁻¹ respectively near permanent wilting point (15%). In this instance, the reduction of transpiration rate with decreasing SWC was probably caused by gradual stomatal closure and consequent reduction of *g_s* (DE COSTA *et al.*, 2007).

2.6.1. Control of Transpiration by *G_s* and Shoot Ψ_w

Tea has highly sensitive stomata, which show partial closure during midday even when the plants are growing on a wet soil (Williams, 1971; Carr, 1977a). Stomatal closure was slightly preceded by reduced shoot xylem ψ_w , indicating that stomatal closure occurred as a response to an internal water deficit in the shoot. This indicates that the rate of root water absorption and its subsequent transfer through the xylem is not very efficient in tea even under conditions of moderate atmospheric demand (i.e. > 5 mm d⁻¹). This could be due to specific characteristics in the absorbing region of the root system and/or the xylem vessels (DE COSTA *et al.*, 2007). This stomatal reopening was probably a response to decreasing VPD in the surrounding air in late afternoon under cloudy conditions. Stomatal movement is one of several important physiological processes, which respond to VPD. In fact, Carr (1977a) showed that both *g_s* (measured indirectly as liquid infiltration score) and shoot ψ_w were negatively correlated with VPD, *T_a* and incident solar radiation intensity. Interestingly, Carr (1977a)

found that shoot ψW (and thereby g_s) of tea was more sensitive to T_a and VPD when the soil was wet than when it was dry. This was probably because higher T_a and VPD caused greater transpiration rates, which in turn, would have lowered shoot ψW even when tea is grown on a wet soil (DE COSTA *et al.*, 2007). In contrast, on a dry soil, early stomatal closure would have prevented transpiration from responding to higher T_a and VPD, making shoot xylem ψW less sensitive to atmospheric water stress. Squire (1978) also observed that g_s of tea growing in Malawi was principally determined by irradiance, except during the dry months. During the wet period, g_s was independent of shoot ψW , VPD and P_n . In contrast, during the dry season, g_s remained unaffected by ψW and VPD, but was more closely related to P_n . The observation that shoot ψW and g_s of tea is less sensitive to T_a and VPD in a dry soil provides indirect evidence that stomatal opening of tea may be controlled by hormonal signals originating from roots (Zhang *et al.*, 1987; Davies and Zhang, 1991). Callander and Woodhead (1981) observed that the canopy conductance per unit leaf area of tea was little affected by soil water deficits as large as 370 mm. This was attributed to the deep root system of tea. The wet season canopy conductance was 12% higher than for a dry season canopy, receiving the same net irradiance and VPD. This observation also indicates greater stomatal opening when the soil is wet and provides further evidence for hormonal signals from roots controlling the stomata of tea (DE COSTA *et al.*, 2007).

2.6.2. Effects of Water Deficits on Tea Yield and Yield Components

Most of the tea growing in different regions of the world experiences SWD of varying magnitudes and durations. Periods of SWD often coincide with higher VPD and higher T_a . The effects of water deficits on tea yield can be predicted by examining the effects on the two principal yield components, Nsh and Wsh. Carr *et al.* (1987) observed that the rate of shoot production, which primarily determines Nsh, decreased when the average midday shoot ψW fell below -0.6 to -0.7 MPa. Squire and Callander (1981) observed this limiting shoot ψW to be -0.8 MPa. Shoot ψW could fall below the limiting value due to an increase of SWD during prolonged rainless periods. Interestingly, the limiting shoot ψW could be reached even when tea is growing on a wet soil, if the VPD increases beyond a threshold (Williams, 1971). Carr *et al.* (1987) identified this threshold VPD to be around 2 kPa. Wijeratne and Fordham (1996) found that shoot ψW of tea decreased linearly with rising SWD above 30-40 mm at low altitudes in Sri Lanka.

2.6.3. Influence of Vapour Pressure Deficit on Tea Yield and Yield Components

Tea is one of the plant species which has been shown to be highly sensitive to atmospheric VPD of the growing environment. During the dry periods of many tea growing regions of the world, VPD could rise to levels which would influence g_s , shoot ψW and the rates of shoot initiation and extension (Squire and Callander, 1981). In addition, VPD influences these key processes of yield formation of tea even during periods when the soil is wet. Furthermore, the linear relationship between shoot extension rate and temperature breaks down at higher VPD (Squire and Callander, 1981). During wet periods with frequent rain, shoot ψW of tea has an inverse, linear relationship with VPD (Williams, 1971; Squire, 1976, 1979). This probably operates through the influence of VPD on transpiration, which increases with increasing VPD causing a decrease in shoot ψW . During these wet periods, VPD did not exceed 2 kPa and shoot ψW did not fall below -1 MPa. Furthermore, during wet periods, this relationship did not show hysteresis. However, it broke down during dry periods, with shoot ψW quickly falling to around -1.5 to -2.0 MPa during the early part of the day around 0900 h and then remaining at this minimum level while the VPD continued to increase up to 4.0 kPa. Moreover, even if the VPD decreased during the latter part of the day, shoot ψW remained at its minimum until the end of the day. Even when shoot ψW began to rise again during late afternoon, it showed hysteresis and lagged behind the decrease of VPD (DE COSTA *et al.*, 2007). Irrigated tea bushes during the dry period showed a similar diurnal pattern but their minimum shoot ψW was about 0.8 MPa higher. Interestingly, when the soil was re-wetted by rains at the end of the dry season, the linear relationship between short ψW and VPD was re-established and shoot ψW quickly returned to its higher values (i.e. > -1 MPa). This indicated that the roots in the top soil (0-15 cm) had remained alive during the dry period. Despite the absence of a clear relationship between shoot ψW and VPD during dry periods on a diurnal basis, Squire (1979) found a close inverse relationship between the weekly rate of shoot extension and mean VPD measured at 1400 h during the dry season in Malawi.

2.7. Productivity and Yield Components of Tea

The productivity of tea is quantified in terms of the weight of 'made tea' per unit land area per year. 'Made tea' refers to the form of tea obtained after the harvested (or 'plucked') shoot has gone through the manufacturing process (i.e. withering, fermenting and drying). Weight of made tea is directly related to the fresh weight of plucked shoot (2-3 leaves and a bud) by a factor of 0.2. Therefore, yield components of tea are the number of plucked shoots per unit land area (Nsh) and the mean weight per shoot (Wsh). Out of these two yield components, it is the variation of Nsh that has the stronger correlation with yield variation. The number of plucked shoots per unit land area is determined by the rate of shoot initiation whereas Wsh is determined by the rate of shoot expansion. Although Nsh has been identified as being the main factor responsible for the observed variation in tea yields between different genotypes, variation in the rate of shoot growth is the main parameter that causes season-to-season yield variation in a given genotype (Squire and Callander, 1981). The harvested leaf yield of tea (i.e. made tea) can generally reach 4-5 t ha⁻¹ yr⁻¹ under favourable climatic and soil conditions with proper management. There are occasions where yields up to 6.5 t ha⁻¹ yr⁻¹ have been reported (Carr and Stephens, 1992). Even at these upper limits, tea yields are much lower than the 10-20 t ha⁻¹ yr⁻¹ range of yields for crops in which a vegetative part is harvested. Reasons for this lower yield potential of tea were discussed earlier in this section. In the absence of soil constraints, tea yields under proper management are higher at lower elevations than at higher elevations. Both climatic and soil constraints would reduce tea yields from their upper limits under optimum conditions. Out of the two yield components of tea (i.e. Nsh and Wsh), it is the variation of Nsh that has the stronger correlation with yield variation (DE COSTA *et al.*, 2007).

2.8. Response of Tea to Climate Change

Long-term gradual climate change involves increasing C_a and the consequent warming of the atmosphere. The rising T_a triggers a variety of changes in the atmosphere leading to modified rainfall patterns, evapotranspiration rates and VPD. Because of the close relationships between tea yield and these atmospheric variables, long-term climate change is likely to cause significant impacts on the key physiological and developmental processes that determine the yield and yield components of tea (Wijeratne, 1996). Responses to different aspects of climate change can be both positive and negative. A clear positive effect is the response to increased C_a through increased photosynthetic rates (Anandacoomaraswamy *et al.*, 1996) and yields. However, there can be substantial genotypic variation in the response to increased C_a . For example, Anandacoomaraswamy *et al.* (unpublished results) showed that while the total dry weights and root dry weights of sand-cultured, nine-month-old tea seedlings of one genotype (TRI 3019) increased significantly at elevated C_a over a three-month period of CO₂ enrichment at high altitude, those of another genotype (TRI 3072) did not show a significant response under the same conditions (DE COSTA *et al.*, 2007). Such genotypic variation in the response to elevated C_a has been shown for other crops (De Costa *et al.*, 2007 for rice) and natural plant species (Poorter and Navas, 2003) as well. In two CO₂ fertilization field experiments carried out over a period of 18 months at low (60 m a.s.l.) and high (1380 m a.s.l.) elevations in Sri Lanka, Wijeratne *et al.* (2007b) showed that an increase of C_a from the present ambient level of 370 $\mu\text{mol mol}^{-1}$ to 600 $\mu\text{mol mol}^{-1}$ (which is predicted to occur during the middle of this century) increased tea yields in Sri Lanka by 33 and 37% at high and low elevations, respectively (DE COSTA *et al.*, 2007). The long-term averages of maximum/minimum temperatures at the high and low elevations were 20.5o/ 11.5oC and 32.0o/22.9oC, respectively. Increases in both Nsh and Wsh contributed to these yield increases. Tea at elevated C_a also showed higher P_n and transpiration rates than at ambient C_a (Wijeratne *et al.*, 2007a). The study of Wijeratne *et al.* (2007b) also identified several climate change-induced variables which would have negative impacts on tea yields and thereby reduce the potential yield gains due to increasing C_a . Particularly, a quadratic relationship, with the optimum around 22oC, was found between monthly tea yield and monthly mean T_a during 'wet' periods. Similarly, a quadratic relationship was found between monthly tea yield and rainfall of the previous month. These data were used in a simulation model to predict the impacts of increasing C_a , increasing T_a and varying rainfall on tea yields at different altitudes. Results of the simulations showed that the yield increases due to increasing C_a were augmented by increasing T_a at high altitudes (Table3). However, at low altitudes, yield gains of higher C_a were pulled back because the rising T_a pushed the already high T_a in to the supra-optimal range for most of the key physiological processes that determine yield. Predicted tea yields by the year 2050 under the climate change scenarios specified by different Global

Circulation Models also showed increased yields at higher altitudes, but reduced yields at lower altitudes (Table 3).

Table 3. Projected tea yields at four locations in Sri Lanka under different scenarios of climate change (increase in temperature by 1 and 2oC, increase in rainfall by 10%, decrease in rainfall by 10% and increase in ambient CO₂ concentration up to 435 μmol mol⁻¹) for the year 2050

CO ₂ (μmol)	Rainfall change (%)	Temperature change (oC)	Yield (kg ha ⁻¹ yr ⁻¹)			
			Ratnapura	Kandy	N ^o Eliya	Passara
370	0	0	2489	2207	2454	2651
370	0	1	2282	2177	2651	2569
370	0	2	2070	2117	2760	2469
370	-10	0	2456	2161	2418	2591
370	10	0	2482	2305	2480	2749
435	0	0	2710	2695	3035	3080
435	0	1	2502	2567	3035	2998

Location characteristics: altitude (m a.s.l.), maximum/minimum temperature, and annual rainfall: Ratnapura = 60 m, 32.0/22.9oC, 3617 mm; Kandy = 472 m, 29.0/20.2oC, 1863 mm; Nuwara Eliya = 2013 m, 20.5/11.5oC, 907 mm; Passara = 1028 m, 28.7/18.5 oC, 1777 mm.

Source: Wijeratne et al., 2007b

3. SUMMARY

Tea [*Camellia sinensis* (L) O. Kuntze], is one of the most popular and lowest cost beverages in the world, and consumed by a wide range of age groups in all levels of society with more than three billion cups daily worldwide. The tea plant grows in a variety of climates and it is difficult to specify an ideal climate. The monsoonal climate of Northeast India with alternate wet and dry seasons and the high elevation of subtropical mountains in China, India, and Sri Lanka provide optimal conditions for tea production. Despite of the variety of climates, tea production relies on suitable temperatures and well distributed rainfall. The impacts of climate change on tea production are the following: drying of the soils causing reduced water content in the tea, decreasing yields and negative impacts on quality; appearance of new pests and diseases; changes in the suitability of existing tea growing areas (in extreme cases, as temperatures become too high for tea cultivation), new suitable land areas need to be found; reduced biodiversity and ecosystem function as the result of habitat conversion, high-energy consumption (logged timber); sun scorch damage decreasing yields and lowering tea quality; reduced resilience of tea crops; uncertainty with application of fertilizers, high application of pesticides in some countries; increase in extreme weather events such as droughts, hail storms, floods, frosts, extreme rainfall and landslides. Changing climate conditions impact the concentration of secondary metabolites, which are most important for the quality of tea. Tea exhibits the C₃ mechanism of photosynthesis and under normal ambient atmospheric conditions, rate of photorespiration in tea was around 19% of net photosynthesis. Because of the close relationships between tea yield and these atmospheric variables, long-term climate change is likely to cause significant impacts on the key physiological and developmental processes that determine the yield and yield components of tea; while responses to different aspects of climate change can be both positive and negative and a clear positive effect is the response to increased Ca through increased photosynthetic rates and yields.

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