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Review on Research Carried Out by the Tea Research Institute of Sri Lanka on Climate Change Impacts and the Need of Implementing Good Agricultural Practices

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ABSTRACT

Recent placement of Sri Lanka at the 2nd place in the global climate risk index 2018 indicates the possibility of occurrence of frequent extreme weather events. Being a rain-fed plantation crop grown in different regions, vulnerability of tea plantations for impacts of climate change would be significant. Taking timely precautions on adaptation and mitigation measures for the reduction of adverse impacts of climate change, is therefore important. This paper will present a review of climate change research conducted on tea by the Tea Research Institute of Sri Lanka to update the knowledge and to identify the gaps. Additionally, the paper will present information on carbon sequestration potential and provisional carbon budget for tea plantations in view of assuring sustainability of the industry. It was re-confirmed that tea plantations are carbon negative or climate positive. Proper establishment and management of both high and medium shade trees in the plantations will not only enhance physiology of the tea plants resulting higher yield, but also contribute significantly for maintaining negative carbon balance or environmentally positiveness.

Keywords: Adaptation, carbon budget, climate change, mitigation, tea

INTRODUCTION

Global Climate Risk Index is an important index which is calculated annually based on the most reliable data sets of the direct impacts of extreme weather events such as storms, floods, drought and heat waves *etc*., and data on their associated socio-economic impacts. Sri Lanka was ranked in the second place accordingly as per the calculation for the year 2018 (Eckstein *et al*., 2018). This implies that Sri Lanka will experience more and more extreme events and heading towards frequent natural disasters in time to come. Therefore, it is necessary to take timely actions to identify the possible effects of climate change and to take precautions to minimize their adverse impacts.

Increase of atmospheric concentration of CO_2 is considered to be the main cause of climate change which results increase of global temperature via the greenhouse effects. Identifying the importance of regulating the atmospheric CO_2 by the expert scientists well in advance, the concentration of atmospheric CO_2 has been measured continuously since 1950s at the Mouna Loa in Hawai islands. This was initiated by Charles David Keeling of the Scripps Institution of Oceanography in March of 1958 at a facility of the National Oceanic and Atmospheric Administration (NOAA). It was clearly observed that the atmospheric CO_2 spiked in every April/May which overlaps the initiation and subsequent photosynthesis of leaves followed by the continuous decomposition of litter during autumn and winter of the northern hemisphere. The atmospheric CO_2 recorded its peak 415 ppm in May 2019 (Anon, 2019). Further, the increase of atmospheric CO_2 during the past years in different time durations clearly showed that the rate of increase is having an increasing trend (Table 1).

Table 1. Average rate of increase of global atmospheric CO_2 during the past

Period	Average increase of Atmospheric CO_2 per year
Early 1960s	0.6 ± 0.1 ppm
Last 10 years	2.3 ± 0.6 ppm
2015 – 2016	3.5 ± 0.1 ppm

(Adapted from Anon, 2019)

Along with the atmospheric CO_2 it was observed that the global temperature also increases exponentially during the past few years. Accordingly, the highest temperature was experienced in Sri Lanka during April 2019. Further, several landslides and extreme rainfall events were reported in some parts of Sri Lanka such as Ginigathhena while some parts were experiencing severe droughts resulting crops and livestock failure during June/July period of 2019. Added to these extreme events, the water bodies around the hydropower plants were also reported their lowest water levels in July 2019. Therefore, it is obvious that the Sri Lanka is experiencing the consequences of the climate change.

Tea, being a rain-fed plantation crop grown in different elevations and terrains is highly vulnerable to climate change (Wijeratne *et al*., 2019). The magnitude and the effects of climate change are different depending on the tea growing region. Soil quality/fertility is further deteriorated under climate change due to increased soil erosion and burning of soil carbon creating other environmental problems such as eutrophication. As climate change may affect the quality of tea as well as it may attract new pests and diseases, the Sri Lankan tea industry is at a greater risk. Therefore, it is worthwhile to review the climate change research done by the Tea Research Institute of Sri Lanka to identify the gaps and suggest the way forward to remain tea as a profitable industry in future too.

Impact of climate change on tea

Wijeratne *et al*. (2007) and Ratnasiri *et al*. (2008) have determined the optimum rainfall and the crop loss for 100 mm deficit of rainfall for different tea growing regions in Sri Lanka (Table 2).

Table 2. Optimum rainfall and the quantified crop loss per 100 mm deficit of rainfall in different tea growing regions in Sri Lanka

Agro Ecological Region	Optimum Rainfall (mm $month^{-1}$)	Loss of tea yield per 100 mm deficit of rainfall (kg ha^{-1} $month^{-1}$)
Low-Country wet zone (WL)	350 ± 20	29 ± 03
Mid-Country wet zone (WM)	417 ± 49	36 ± 06
Up-Country wet zone (WU)	223 ± 38	55 ± 07
Mid-Country intermediate zone (IM)	227 ± 10	81 ± 11
Up-Country intermediate zone (IU)	303 ± 34	39 ± 03

(Adapted from Wijeratne *et al*., 2007; Ratnasiri *et al*., 2008)

Accordingly, the optimum rainfall varied from 223 – 417 mm $month^{-1}$ depending on the different tea growing region. Further, the quantified crop loss for every 100 mm deficit of rainfall also varied from 29 – 81 kg ha^{-1} $month^{-1}$. As it is important to have an idea about the behaviour of future tea yields with the expected climate change, many scientists attempted to project the future tea yields using different techniques. Initially, correlation analysis between the weather parameters and tea crop yield was used to make predictions on the effects of climate change on crop production (Wijeratne and Fordham, 1996; Wijeratne *et al*., 2007; Ratnasiri *et al*., 2008). The projections for the year 2050 based on linear regression analysis according to different global circulation models (GCM) are given in Table 3.

Table 3. Yield projections for tea yields in different tea growing regions for the 2050

Baseline & General Circulation Model	Projected yield for the year 2050 (kg ha^{-1} yr^{-1})		
	Low Grown	Mid Grown	High Grown
	Ratnapura (WL)	Kandy (WM)	Nuwara Eliya (WU)
Baseline	2489	2217	2454
HadCM3-A1F1	2348	2174	3130
HadCM-B1	2419	2189	3115
CGCM-A1F1	2314	2217	3108
CGCM-B1	2380	2228	3072
CSIRO-A1F1	2401	2246	3167
CSIRO-B1	2472	2245	3137

(Adapted from Wijeratne *et al*., 2007)

Accordingly, the low grown tea yields showed a declining trend, high grown showed an increasing trend, while the mid grown were negligibly affected compared to the baseline in all global circulation models tested. However, it was said that only the rising temperatures and diminishing rainfall were taken in to account, but the variations of atmospheric CO_2 concentrations were not considered in these analysis (Wijeratne *et al*., 2007).

Climate change is a complex, multi factorial phenomenon. Therefore, when predicting the tea yield trends in response to climate change, it would be important to use process based crop simulation models instead of simple linear regression models which accounts more than one factor at a time and also consider about the plant physiological conditions and the associated environmental factors. As a result, Sheffield Dynamic Global Vegetation Model (SDGVM) was adjusted, calibrated and validated for making projections for tea plantations in Sri Lanka (Wijeratne *et al*., 2011). SDGVM was also tested for the HadCM3 under the A1F1 scenario and the behaviour of yields for low, mid and high grown tea were projected for a period of 100 years, *i.e*. until the year 2100 under variable atmospheric CO_2 conditions as well as constant atmospheric CO_2 conditions in the 1st and 2nd simulations (Figures 1a, b and c) respectively. These two simulations were done to facilitate the comparison of previous model projections. Ratnapura, Kandy and Nuwara Eliya were taken as the representative areas for the low, mid and high grown areas respectively (Wijeratne *et al*., 2011).

Accordingly, the tea yields in all three tea growing elevations were having an increasing trend under the 1st simulation highlighting the CO_2 fertilization effect of tea plants. This is in agreement with the findings of Wijeratne *et al*. (2007) and Ratnasiri *et al*. (2008), where it was observed that the tea yields at both low and high elevations showed enhancement in a study conducted under CO_2 enriched environments of 550 $\pm$ 50 ppm using open top chambers. However, under the 2nd simulation, *i.e*. under the constant atmospheric CO_2, with variations of rainfall and temperature, only the tea yields in high grown region showed the increasing trend, while the mid grown showed negligible responses and the low grown showed a declining trend agreeing with the findings of Wijeratne *et al* (2007). These results were further elaborated by Wijeratne (2015), considering the current ambient temperatures of these three teas growing regions in comparison with the optimum temperatures of 18 – 25 ^{o}C as indicated in FAO (2016). The current mean ambient temperature in the high grown region is around 19.2 ^{o}C which is within the optimum temperature for the growth of tea plants and thereby increase of temperature due to climate change can possibly increase the tea yields further. Similarly, in the mid grown region the current ambient temperature is 23.8 ^{o}C which is near the upper margin of the optimum temperature for tea and thereby further increase of the temperature would cause marginal or negligible increase of tea yields. However, in the low grown region the current mean ambient temperature is around 27.8 ^{o}C which is already exceeded the optimum temperature and thereby further increase of temperature would cause negative impacts (Wijeratne, 2015). Further, it was noticed that the 1st simulation predictions were more prominent compared to that of the 2nd simulation predictions (Wijeratne *et al*., 2011) having R^2 of 62%, 59 % and 63 % for low grown, mid grown and high grown tea respectively.

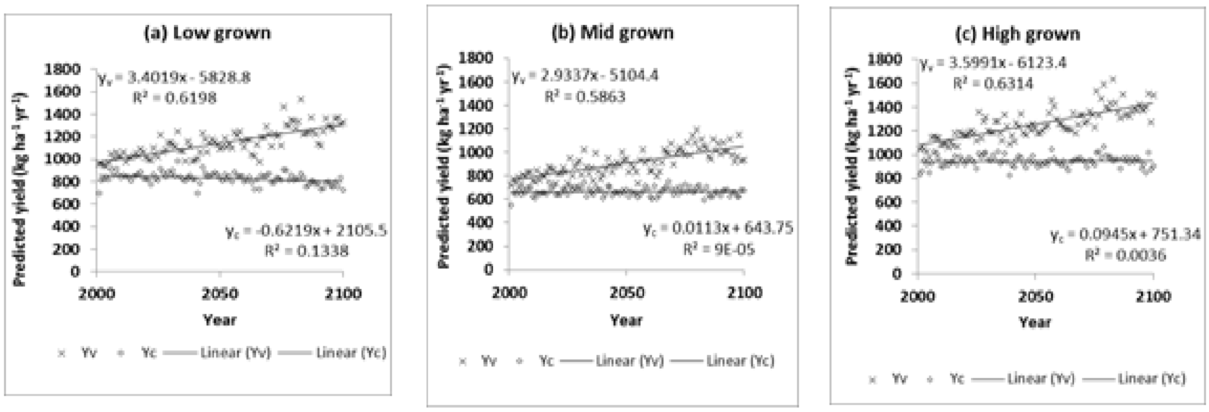

Figure 1. Variation of projected tea yields under variable atmospheric CO_2 (Y_v) and constant atmospheric CO_2 (Y_c) according to the Sheffield Dynamic Global Vegetation Model for (a) low grown, (b) mid grown and (c) high grown elevations (Adapted from Wijeratne *et al.*, 2011 and Wijeratne, 2015)

Wijeratne and Chandrapala (2013 and 2014) have developed the climate change vulnerability map for tea plants grown in Sri Lanka using the vulnerability indices developed with the long-term rainfall and temperature data along with some soil properties. Trend analysis showed that the variability and quantity of rainfall have significantly changed in some of the tea growing regions and the temperature increase over the 50-year period was estimated to be about 0.5°C-2°C. The variability of North East monsoon rainfall (NEM; from December - February) was found to be higher than that of the other monsoons. Vulnerability analysis was performed using rainfall variations, temperature increase and soil conditions. Accordingly WL1a, WL1b, WL2a, WM2a, WM2b, WM3a, IM2b, IM3a and IM3c regions were identified as highly vulnerable and WM1a, WM1b, WM3b, IM1a, IM2a, IU3a, IU3d and IU3e regions were identified as vulnerable for climate change. Resultantly, the tea industry of Sri Lanka will have to face a lot of challenges due to climate change in future as the highest contribution for national tea production in Sri Lanka which accounts for 63.2 % is given by the low grown region. In recent past it was decreased by 2.7 % and the total tea production decreased by 1 % to 303.8 million kg in 2018 from 307.1 million kg in 2017 due to the bad weather (Central Bank, 2018). Therefore, it is necessary to take all the precautions to minimize the adverse impacts of climate change timely and effectively if Sri Lanka tea industry is to remain profitable in the highly competitive world tea market.

How to overcome the challenges of Climate Change

In order to overcome the challenges of climate change, it is absolutely necessary to follow all the good agricultural practices (GAPs) which were already recommended by the Tea Research Institute of Sri Lanka. These GAPs are discussed under adaptation and mitigation measures and given in brief for easy reference.

Adaptation measures

1. Proper land selection and utilization

GAPs to be started from the very beginning of tea plantations, *i.e.* from the land selections itself. In order to minimize the negative impacts of climate change, the future tea plantations should be established only in the most suitable lands which have to be identified in national level, regional level as well as at estate level because not all the areas are suitable for the proper growth and development of tea plants.

It is utmost important to follow all the GAPs in already developed tea plantations and avoid establishment of new tea plantations in these highly vulnerable and vulnerable regions as far as possible. Further, intercropping and mixed cropping can be practiced to get the optimal productivity per unit land area with least risk from the bad weather. As tea is a shade loving plant, intercropping and/or mixed cropping can be easily practised. The marginal tea lands can be diversified to timber, energy or fuel wood plantations or they can be maintained as thatch banks (Ekanayake, 2003).

2. Proper selection of cultivars

Most suitable cultivars need to be selected for different agro climatic regions to avoid the risk of losing crop due to natural climatic variations. Further, due to the increased climate risk, it has become necessary to select drought, heat, flood, pest and disease tolerant cultivars in new tea plantations. Recently introduced bi and poly clonal tea plants can be planted in drought prone areas. Also, different graft combinations have been developed for drought prone areas by combining high yielding scions with better developing root stocks. Identified successful graft combinations of cultivar-cultivar as scion and stock were TRI 2023 on CY 9, TRI 2026 on DN, TRI 4046 on DN and TRI 4052 on DN respectively (Anon, 2017). Further, TRI 4053 on Sapumalkanda seedlings were also promising for drought prone regions. Development of new tea cultivars through controlled hybridization for biotic and abiotic stress tolerance is also in progress (Anon, 2017).

3. Management options

Until the recent past, lack of soil moisture was the main concern which attracted the scientists to find solutions for problems associated with the climate change impacts on tea plantations (Wijeratne *et al*., 2019). Therefore, most of the management interventions were discovered to avoid and reduce the drought impact on tea. Anandacoomaraswamy (1997) introduced a drought management package which is still useful to reduce the negative impacts of drought on tea. There it was suggested to clear the weeds, thatching, spraying of 2 % K_2SO_4 and sub soil irrigation *etc*. Further, it was necessary to identify/select drought tolerant cultivars at early stages in cultivar screening programmes of the Tea Research Institute. As a result, using physiological parameters such as net photosynthetic rate and relative water content, a Drought Susceptibility Index (DSI) was tested (Damayanthi *et al*., 2010) and being used to identify new cultivars tolerant to drought at early stages of growth in cultivar screening programmes (Damayanthi *et al*., 2017). Further, research is in progress to identify climate resilient cultivars using the DSI rating as well as carbon and nitrogen stocks in plant biomass. Resultantly, the accession 199 and cultivar TRI 2025 were identified as climate resilient for Uva region (Wijeratne *et al*., 2018).

Improvement of aerial environment through proper establishment and management of shade trees is highly effective in improving the microclimate surrounding the tea bushes (Premathilake, 2014; FAO, 2016 and Wijeratne, 2018). Shade trees enhance the physiology of tea plants and thereby improves the crop yields (Mohotti and Lowlor, 2002; Mohotti, 2004; Wijeratne *et al*., 2008). It is the only viable solution for minimizing the adverse impacts of increased atmospheric temperature in a perennial plantation like tea which covers a vast extent.

Use of both sprinkler and drip irrigation where ever possible also would be beneficial to prevent the moisture stress on tea plants. It has been found that the drip irrigated tea had annual yield increase of 21 % compared to rain-fed tea in the low elevations of Sri Lanka (Bandara, 2011). Further, it is necessary to use mulching materials to avoid excess evapotranspiration loses of water and minimize the moisture stress on tea plants. Cover crops or green manure crops can be planted in the vacancies, lopped time to time and used to cover the soil to prevent the direct exposure. Mulching also helps to reduce the soil loss through surface runoff. A bare clean weeded plot and a mulched plot had 18 and 0.03 tons of soil loss per acre respectively (Manipura *et al*., 1969). Artificial mulch materials can also be used to retain soil moisture in dry periods (Bandara *et al*., 2016). Harvesting of rain water and their use during dry spell also help to reduce the abiotic stress of the tea plants supporting their survival (Premathilake, 2014).

Improvement of soil is another important aspect in addressing the climate change impacts. Addition and incorporation of organic matter into the soil will support soil moisture conservation as well as increase in the soil fertility (Wijeratne, 2018). Construction of proper drains systems consisting of leader drains and contour drains will help removing the excess rainwater effectively during extreme rainfall events. Construction of terraces in hilly terrains and cutting of lateral drains with 'lock and spill' type provided with silt pits/reverse slopes will help retaining more water and arrest soil erosion (Premathilake, 2014). Burying of pruned litter, application and incorporation of green manure and compost into the soil will increase soil fertility while conserving soil moisture as well.

Use of site-specific fertilizer mixtures and the slow release fertilizer will minimize the excess use of synthetic fertilizers in the tea plantations. Site specific fertilizer replenishes the soils with only the depleted nutrients, thereby reducing fertilizer wastage which would ultimately reduce eutrophication and algal bloom (Wijeratne, 2018). Similarly, slow-release fertilizers release nutrients according to the requirements of the plants. Therefore, both these fertilizers help reducing the subsequent fertilizer production and associated greenhouse gas emissions. Use of bio filmed bio fertilizers (BFBF) in tea nurseries has proven that it helps reducing the use of synthetic fertilizers by 50 % (De Silva *et al*., 2014). Further, use of beneficial microbial inoculants reduces the use of synthetic fertilizer in tea plantations by one-third (Tennakoon *et al*., 2016).

Mitigation measures

Carbon sequestration and carbon balance can be considered under mitigation measures. Carbon sequestration is long term storage of atmospheric CO2 in plant biomass, soil *etc* without being entered into the atmosphere (Anon, 2009). According to the preliminary study results, tea industry is having a negative carbon balance (De Costa *et al*., 2008). However, these calculations were based on several assumptions. The calculated values of carbon absorptions and emissions for different tea growing regions are given in the Table 4.

Table 4. Carbon balance of tea grown in different regions in Sri Lanka

Region	C absorption (million Mg yr^{-1})	C emission (million Mg yr^{-1})	C balance (million Mg yr^{-1})
Low grown	1.426	0.677	- 0.750
Mid grown	1.278	0.334	- 0.944
High grown	0.874	0.430	- 0.444

(Adapted from De Costa *et al*., 2015)

These preliminary results led to a detailed investigation on carbon sequestration and emission studies in the Tea Research Institute of Sri Lanka. Climate change mitigation options in tea plantations can be considered under different levels such as populations, communities as well as ecosystems. If only the tea plants are considered, it becomes the population, where as if the shade trees are also considered, it becomes the community and when the soil is also considered it becomes the ecosystem. Detailed investigation of carbon sequestration potential of tea plantations were considered at the community level considering the tea plants, high shade trees and medium shade trees in different tea growing regions at different compliance levels to the TRI recommendations namely 100 %, 50 % and 0 % by quantifying the biomass carbon stocks (Wijeratne *et al*., 2014 a; Wijeratne *et al*., 2014 b and Wijeratne, 2015) (Figure 2).

Accordingly, it clearly showed that when the compliance to the TRI recommendations increases, *i.e*. incorporation of high shade trees and medium shade trees according to the recommendation, the carbon sequestration potential of tea plantations in all tea growing regions also increased tremendously. Further, the carbon sequestration of the community of the tea plantations are the highest in the low grown region (2.81 Mg yr^{-1}) followed by the mid grown region (1.03 Mg yr^{-1}) and it was lowest in the high grown region (0.37 Mg yr^{-1}). Therefore, the contribution of tea plantations to reduce the atmospheric CO_2 concentration is considerable (Wijeratne *et al*., 2014b).

It was also noted that the per plant carbon sequestration potential of the seedling tea was higher than that of VP tea in all tea growing regions as well (Wijeratne *et al*., 2014b).

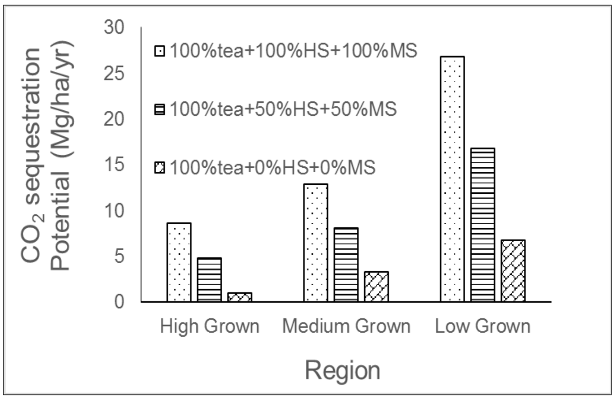

Figure 2. Variation of carbon sequestration potential of tea plantations in different tea growing regions according to the different levels of compliance to the recommendations of the Tea Research Institute of Sri Lanka (HS-high shade, MS-medium shade) (Adapted from Wijeratne *et al*., 2014b)

Similarly, Wijeratne *et al.* (2019) conducted a study to estimate the CO_2 emissions from tea lands in all tea growing major soil series covering high, mid and low grown regions with the objective of developing the carbon budgets for tea plantations. Maskeliya, Mattakelle and Nuwara Eliya soil series were selected to represent the high grown region, while Kandy and Ukuwella soil series were selected to represent mid grown region and Weddagala, Pallegoda and Dodangoda soil series were selected to represent the low grown region with the assistance of the Soils and Plant Nutrition Division of the TRI. It was expected to develop the greenhouse gas (GHG) inventory for the crop land remaining crop land category under the Agriculture, Forest and Other Land Use (AFOLU) sector through this experiment. These GHG inventories are important in assessing the contribution of different countries to the global warming and thereby to get the assistance from the developed countries to adapt low emission strategies for their developmental activities.

Early findings showed that the soil CO_2 emission, *i.e.* soil respiration is higher in the low grown region, followed by mid grown region and it was the lowest in the high grown region (Wijeratne *et al*., 2019). Along with these data and the data on carbon sequestration taken from Wijeratne *et al*., 2014a and 2014b, a provisional carbon budget was developed for the main tea growing elevations in Sri Lanka for the ecosystem level. As the carbon sequestration potentials were calculated in the tea plantations established at Pallegoda, Kandy and Mattakelle soil series, the soil respiration data on the same soil series were taken for the development of the provisional carbon budget and it was calculated according to the equation given below.

Carbon budget = CO_2 emissions – CO_2 absorption

The soil carbon stocks and sequestration potential were purposely omitted in this study and only the respiration of plant roots and the microbes were considered as the CO_2 emissions. Carbon budget was also developed as per the different compliance levels to the recommendations as in the calculations of carbon sequestration potentials without considering the soil carbon sequestration (Wijeratne *et al*., 2019) (Figure 3).

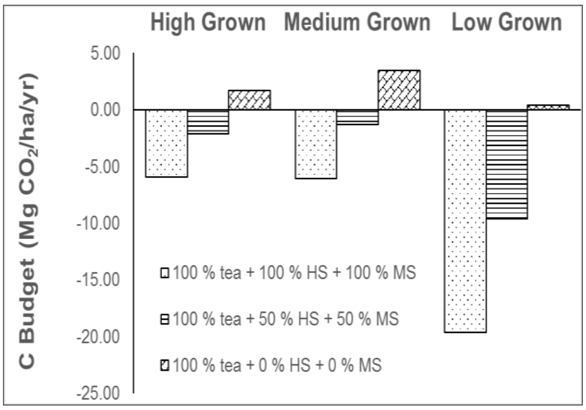

Figure 3. Provisional carbon budget (excluding the soil carbon sequestration potential) developed for different tea growing regions according to the different levels of compliance to the recommendations of the Tea Research Institute of Sri Lanka (Adapted from Wijeratne *et al*., 019).

Accordingly, the carbon budget was more negative in the low grown region, followed by the mid grown and it was less negative in the high grown region (Wijeratne *et al*., 2019). Further, the carbon budget becomes more and more negative with the increase of compliance to the recommendations of the TRI, *i.e*. incorporation of high and medium shade trees into the tea plantations as per the recommended densities. This further confirmed that the proper establishment and management of both high and medium shade trees in tea plantations will provide several benefits for the sustainability of the tea plantations.

SUMMARY

Tea plantations are highly vulnerable to the negative effects of climate change. The impacts of climate change may be more and more severe in future. Therefore, it is necessary to follow good agricultural practices and take timely precautions to overcome these emerging challenges of negative impacts of climate change. New tea plantations are to be established only in the most suitable lands following proper adaptation practices in future. Proper establishment and management of shade trees in tea plantations is a must, not only to improve the vigour of the tea plants and the associated yield improvements, but also to protect the environment by reducing the negative impacts of climate change by enhancing more carbon to be sequestered at community and ecosystem level. The policy makers should be influenced to explore potentials to tackle new markets such as "Payments for Environmental Services" for the sustainability of the tea industry.

REFERENCES

Anandacoomaraswamy A 1997 Drought management. TRI Update 2(1): 1.

Anon 2009 Available online http://alternativefuels.about.com/od/glossary/g/carbon sequestra.htm. Visited on 27th July 2009

Anon 2017 Synopsis of the contributions of tea research towards the sustainable development of the tea industry in Sri Lanka. Tea Research Institute of Sri Lanka. Talawakelle, Sri Lanka. 21st January 2017.

Anon 2019 Climate Change: Atmospheric Carbon Dioxide. NOAA Climate.gov. Available online https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide. Visited 24th June 2019.

Bandara S N 2011 Agronomy of irrigated tea in low elevation growing areas of Sri Lanka. PhD Thesis. School of Agriculture, Food and Wine, University of Adelaide.

Bandara N P S N, Vithana D W, Prematunga E W T P, Liyanage M G S and Madhubashini T G P 2016 Use of artificial thatching material in tea. *In:* Proceedings of the 232nd Experiments and Extension forum of Tea Research Institute of Sri Lanka. Colombo, Sri Lanka. 13th February 2015.

Central Bank 2018 The annual report for the year 2018. Central Bank of Sri Lanka, Colombo, Sri Lanka.

Damayanthi M M N, Mohotti A J and Nissanka S P 2010. Comparison of tolerant ability of mature, field grown tea (*Camellia sinensis* L.) cultivars exposed to a drought Stress in Passara area, Tropical Agricultural Research, Volume 22 (1):66-75

Damayanthi M M N, Ranaweera K K, Kottawa Arachchi J D and Ranatunga M A B 2017 Screening of new tea (*Camellia sinensis* L.) accessions for drought tolerance in Uva region of Sri Lanka. *In:* the Proceedings of the 1st International Symposium in Agriculture 2017 (ISA 2017) held in Faculty of Agriculture, Eastern University of Sri Lanka on 5th October 2017:1-10

De Costa W A J M, Wijeratne M A, Herath D R K B K and Gamage, A J 2008 Carbon trading and its relevance to the tea industry of Sri Lanka. *In:* Proceedings of the 217th Experimental & Extension forum, TRI, Talawakelle, Sri Lanka. July 2008, 6-24.

De Costa W A J M, Wijeratne M A and Herath D R K B K 2015 Carbon trading and its application to the tea industry of Sri Lanka, S. L. J. Tea Sci., 80 (1/2):19-39.

De Silva M S D L, Jayasekera A P D A, Seneviratne G, Abeysekera U P, Premathunge

E W T P and Wijesekera S N 2014 Soil fertility improvement through Biofilmed Biofertilizers: Potential for field application in tea cultivation. *In:* A. P. Keerthipala (Ed.) Proceedings of the fifth symposium on Plantation Crop Research – 'Towards a Green Plantation Economy'. Sugarcane Research Institute, UdaWalawe, 70190, Sri Lanka, pp. 229–36.

Eckstein D, Hutfils M and Winges M 2018 Global Climate Risk Index 2019. D. Baum, J. Chapman-Rose, R. Hannes & G. Kier (Eds). Germanwatch e. V. Bonn.

Ekanayake P B 2003 Crop diversification and intercropping in tea lands. Tropical Agric. Res. and Extension, Int. J. Fac. Agric. 6: 66-70.

FAO 2016 Report of the working group on climate change of the FAO intergovernmental group on tea. Contribution from R M Bhagat, K Z Ahmed, N Gupta and R D Baruah (India), M A Wijeratne (Sri Lanka), John K Bore and Darl W Nyabundi (Kenya) and Wenyan Han, Xin Li, Peng Yan and G J Ahammed (China). Food and Agriculture Organization of the United Nations, Rome.

Manipura W B, Somaratna A and Jayasooriya S G 1969 Some effects of mulching on growth of young tea. Tea Quarterly, 40(4): 153-159.

Ratnasiri J, Anandacoomaraswamy A, Wijeratne M, Basnayake S, Jayakody A and Amaratunga L 2008 Vulnerability of Sri Lankan tea plantations to climate change. *In:* Leary N, C Conde, A Nyong and J Pulhin (eds). Vulnerability to Climate Change. Earthscan, London. 351-372.

Mohotti A J and Lawlor D W 2002 Diurnal variation of photosynthesis and photoinhibition in tea: Effects of irradiance and nitrogen supply during growth in the field. Journal of Experimental Botany. 53(367), 313-322.

Mohotti A J 2004 Shade in Tea: Is it beneficial?, S. L. J. Tea Sci., 69 (1 & 2): 27-39.

Premathilake K G 2014 Climate change adaptation strategies for tea plantations. *In:* Proceedings of the 228th Experiment and Extension forum of the Tea Research Institute of Sri Lanka, Colombo, Sri Lanka. 31st January 2014.

Tennakoon P L K, Rajapaksha R M C P and Hettiarachchi L S K 2016. Potentials of plant growth promoting rhizobacteria based microbial inoculants for nutrient management in tea (*Camellia sinensis* (L.) O. Kuntze). *In*: V R M Vidhanaarachchi, H M I K Herath, M K Meegahakumbura, A D N T Kumara and M K F Nadheesha (Eds) Proceedings of sixth symposium on Plantation Crop Research – 'Plantation Agriculture towards National Prosperity', Coconut Research Institute, Lunuwila, Sri Lanka, 1, pp. 149–61.

Wijeratne M A and Fordham R 1996 Effect of environmental factors on growth and yield of tea (*Camellia sinensis* L.) in the Low-Country wet zone of Sri Lanka, S. L. J. Tea Sci., 46: 21-34.

Wijeratne M A, Anandacoomaraswamy A, Amarathunga M K S L D, Ratnasiri J Basnayake B R S B and Kalra N 2007. Assessments of impact of climate change on productivity of tea (*Camellia sinensis* L.) plantations in Sri Lanka. Journal of National Science Foundation Sri Lanka. 35 (2): 119-126.

Wijeratne T L, Mohotti A J and Nissanka S P 2008. Impact of long term shade on physiological, anatomical and biochemical changes in tea (*Camellia sinensis* (L.) O.

Kuntz). Tropical Agricultural Research (20): 376-387.

Wijeratne T L, De Costa W A J M, Woodward F I, Lomas M and Wijeratne M A 2011. Predicted impacts of climate change on the tea yields of different elevation zones of Sri Lanka during the 21st century. *In:* Proceedings of the international conference on the impact of climate change on agriculture, 20th December, 2011. (Eds.) M Wijeratne, N S B M Atapattu, W W D A Gunawardena, P W A Perera and N Y Hirimuthugoda. Faculty of Agriculture, University of Ruhuna, Sri Lanka: 292-301.

Wijeratne M A and Chandrapala L, 2013. Analysis of rainfall and temperature in tea growing Agro-ecological Regions and assessment of vulnerability of tea plantations in Sri Lanka to climate change, S. L. J. Tea Sci., 78 (1/2): 42-59

Mohotti A J and Lawlor D W 2002 Diurnal variation of photosynthesis and photoinhibition *in* tea: Effects of irradiance and nitrogen supply during growth in the field. Journal of Experimental Botany. 53(367), 313-322

Mohotti A J 2004 Shade in Tea: Is is beneficial?, S.L.J. Tea Sci.. 69 (1 & 2):27-39.

Wijeratne M A and Chandrapala L 2014. Climatic Variations in tea growing regions and vulnerability of tea plantations to climate change. Proceedings of the 228th Experiment and Extension forum of the Tea Research Institute of Sri Lanka, Colombo, Sri Lanka. 31st January 2014.

Wijeratne T L, De Costa W A J M and Wijeratne M A 2014a Carbon sequestration potential of tea plantations of Sri Lanka. Proceedings of the 228th Experiment and Extension forum of the Tea Research Institute of Sri Lanka, Colombo, Sri Lanka. 31st January 2014.

Wijeratne T L, De Costa W A J M and Wijeratne M A 2014b Carbon sequestration potential of tea plantations in Sri Lanka as an option for mitigating climate change; a step towards a greener economy. pp 205 - 212. *In:* A P Keerthipala (ed) Proceedings of the 5th symposium on plantation crop research - "towards a green plantation economy". Sugarcane Research Institute, Uda Walawe, 70190, Sri Lanka.

Wijeratne T L 2015 Estimation of carbon sequestration by Sri Lankan tea plantations and its variation with future climate change. PhD thesis. Postgraduate Institute of Agriculture, University of Peradeniya, Sri Lanka.

Wijeratne T L 2018 Assessing and reducing the environmental impact of tea cultivation. *In* V S Sharma and M T K Gunasekera (Eds.) Global Tea Science: Current Status and Future Needs. Swaston, Cambridge, Burleigh Dodds Science Publishing Limited, UK. ISBN - print 978-1-78676-160-6.

Wijeratne T L, Damayanthi M M N, Pathirana V P R P V, Sidhakaran V and Vinodhini T 2018 Selection of tea cultivars for a future tropical climate. In proceedings of the ICGEB Workshop "Plant responses to light and stress: emerging issues in climate change" held on 10th-12th October 2018 in New Delhi, India. pp.31

Wijeratne T L, Sugathapala A W L C, Pathirana V P R P V, Jayawardhene A D I U, Sivapriyadharshani A and Sidhakaran V 2019. Review on Climate change research and development of carbon budget for tea plantations. *In:* Proceedings of the 238th

Meeting of the Experiments and Extension Forum of the Tea Research Institute of Sri Lanka, Talawakelle, Sri Lanka. 26th July 2019.