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Report of the Working Group on Climate Change of the FAO Intergovernmental Group on Tea





Report of the Working Group on Climate Change of the FAO Intergovernmental Group on Tea

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Committee on Commodity Problems (CCP)

India:	R.M. Bhagat, K.Z. Ahmed, N. Gupta & R.D. Baruah
Sri Lanka:	M.A. Wijeratne
Kenya:	John K. Bore & Darl W. Nyabundi
China:	Wenyan Han, Xin Li, Peng Yan & G.J. Ahammed

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Foreword

Climate change is more than a buzz word. The world is getting warmer, and temperatures throughout the world have risen by approximately 0.8°C since the onset of the Industrial Revolution, increasing by 0.15-0.20°C per decade since 1975 (NASA Earth Observatory). The World Meteorology Organization ranked 2014 as the warmest year on record since the mid-1800s.

Scientific research and studies provide vast and robust evidence increasingly substantiating that human activities have prompted global warming which in turn has triggered a change in climate throughout the world and is increasingly threatening global agricultural systems. However, climate change does not only mean rising temperatures. Extreme weather events, such as drought, heavy, torrential rains and frosts, are becoming more and more frequent, and these phenomena are having negative impacts on agricultural systems in general and on tea in particular.

Contribution of agriculture to the economies in many countries in Asia and Africa are significant, and in some of these countries, tea is the major contributor to the livelihood of millions of rural smallholders. A review of the world tea economy indicates that the production value for tea was about USD 14 billion and world trade was USD 5.61 billion in 2014, contributing significantly to financing the food import bills of tea-exporting countries. For example, in Kenya and Sri Lanka export earnings, of USD 1.15 billion and USD 1.63 billion, respectively, financed more than 60 percent of Kenya's and 63.8 percent of Sri Lanka's food import bills in 2014. And although foreign exchange earnings from tea were relatively lower in other producing countries, these, too, evertheless remained significant.

Tea cultivation and production are facing climate-related challenges which need to be addressed. The problem is so severe and widespread that in January 2012, a Consultation on Climate Change and Its Implication on the World Tea Economy was held in Sri Lanka, where it was agreed to submit a proposal to create a Working Group on Climate Change to the 20th Session of the IGG/Tea, where it was endorsed.

The Working Group was mandated to:

- Review concepts and methods of climate change impact assessment and identify climate change databases and models, to support analysis related to the tea sub-sector and agree on collection and collation of available research data on climate change in member countries;
- Evaluate the analyses carried out on the impact of climate change on the tea sub-sector in selected countries and determine methodologies to measure the impact of climate change on the tea economy;

- Evaluate suitable technologies that could be adapted for mitigation and adaptation strategies for the tea economy; and

- Identify/suggest mitigation and adaptation strategies and develop appropriate long-term technologies for mitigation/adaptation.

At the intersessional meeting of the IGG/Tea which took place in Milan in October 2015, the Group agreed that the Working Group on Climate Change prepare a booklet on adaptation strategies common to all tea producing countries to be published and launched at the 22nd Session of the IGG/Tea, scheduled for 25-27 May 2016 in Naivasha, Kenya.

Major findings of the Working Group are contained in the booklet and highlights disturbing trends of declining yields and productivity due to climate driven stresses (biotic and abiotic) in recent years in tea growing countries of the Working Group. Tea production is controlled by three broad elements: genotype; environment; and management. Tea bushes remain in the field for several years, resulting in severe deterioration of the growing environment due to repeated interventions in the form of: regular plucking/ pruning; cultural practices; addition of external inputs; and resulting field traffic. Climate change impacting local weather conditions (prominently changing rainfall trends resulting in frequent flood and droughts besides increase in temperature, change in relative humidity and sunshine hours) further exacerbates the situation. The possible fallouts of the climate change are already witnessed in the loss of yields and increased management costs for developing coping strategies. Therefore, any spatial and/or temporal changes in the regional climate pattern will directly affect the regional economy and consequently the well being of the region. Most of the tea growing regions are typified by monsoonal climate or an alternate wet or dry season interspersed by temperature changes from mild to severe.

I sincerely hope that members of the Intergovernmental Group on Tea will find this booklet provides a solid foundation for the work on analysing the impact of climate change on tea and extremely useful in developing mitigation/adaptation strategies to deal with the spatio-temporal phenomenon.

I take this opportunity, on behalf of the FAO Secretariat of the Intergovernmental Group on Tea, to congratulate Dr. Rajiv Bhagat, Deputy Director/Chief Scientist, Tea Research Association of India, for ably chairing the Working Group along with his Co-Chairs Professor Wenyan Han (China); Dr. John Bore (Kenya); and Dr. M.A. Wijeratne (Sri Lanka).

Kaison Chang
Secretary
Intergovernmental Group on Tea

Food and Agriculture Organization of the United Nations

Preface

Tea is the most used beverage second to water in the world. Besides being a rejuvenating fluid, it has many health properties. Presently, the climate change triggered by global warming is posing a major threat to the resilience of agricultural systems including tea cultivation mainly because of increase in the frequency of extreme weather events. Increasing temperatures, changes to rainfall amount and distribution, coupled with major shifts in other meteorological parameters in comparison with long term observations have further complicated the production process. Agricultural production is mainly driven by the interaction of genotype, environment and management known as G x E x M. Although genotypic changes in tea are not very frequent, growing environment is becoming harsh and extreme; hence growers are compelled to modify management practices to sustain production, as per the advice of scientists and practitioners. In the last three decades, more extreme weather events have been witnessed compared to early and mid twentieth century, while the last decade has been reported as one of the harshest years of extreme weather events. Tea has still sustained mainly because of scientific inputs and appropriate decision making processes adopted at the garden level. Seedlings and vegetatively propagated tea cultivars have been developed suiting to local conditions and the cultural practices introduced considering the edaphic, climatic and socio-economic factors in a particular region or county. Hence, a universal approach for identification and recommendation of tea cultivation practices is not practical and acceptable. This implies that it is essential to develop country or regional specific adaptation measures for combating risks of climate change while sharing knowledge among tea growing nations.

Major tea producing countries in the world like China, India, Kenya and Sri Lanka have been working for decades on different tea cultivation practices under different geo-physical environments existing in the particular countries. However, all these countries, have witnessed a significant production upheavals in the recent past mainly owing to climate extremes causing significant impact on regional economies and livelihood of dependents. It is anticipated that this change will continue even with greater pace in the coming decades. Therefore, development and introduction of management strategies to cope with climate change is urgent in order to reduce the risks and ensure sustainable development of tea industries in the major tea growing countries of the world. Some trends in weather changes suggest that with rising temperatures due to global warming, tea growing areas may be extended to newer areas/ecosystems, and growing/flushing period can be lengthened in subtropical regions. Community involvement and technology extension are necessary to implement government policies and apply climate change mitigation and adaptation measures. Promotion of indigenous knowhow on this subject also needs to be integrated with new scientific mitigation and adaptation technologies.

This compilation of adaptation strategies for tea cultivation developed and practiced by major tea growing countries of the world, is the first step taken by the working group on climate change of the FAO-IGG on tea to minimize climate change impacts on tea plantations. It is a joint effort by the scientists of Tea Research Institute of India, Sri Lanka, Kenya and China supported by the FAO-IGG on tea in Rome. This documentation is mainly targeted at tea planting community, policy makers and other users such as researchers, national and international research institutes and multilateral organizations dealing with sustainable tea cultivation, development and livelihood security of dependents.

R.M. Bhagat

Co-ordinator for FAO IGG WG on
Climate Change & Deputy Director,
Tea Research Association,
Tocklai, India.

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The preparation of this booklet has been a joint effort of professionals from four Tea Research Institutes of the major tea growing countries in the world viz. China, India, Kenya and Si Lanka. The work was supported by the FAO Inter-governmental Group on Tea. We appreciate encouragement and great support of Mr. Kaison Chang, the Secretary of the FAO-IGG on Tea.

Tea Research Association India would like to thank the Chairman Mr. A. N. Singh, Vice Chairman Mr. P. K. Bezboruah, Secretary Mr. Joydeep Phukan and Director Dr. N. Muraleedharan for their support to make this publication a success.

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The guidance and support of the Chairman and members of the Tea Research Board of Sri Lanka and Dr. I. S. B. Abeysinghe, the Director, Tea Research Institute of Sri Lanka are gratefully acknowledged.

Authors

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Executive Summary

Climate change triggered by global warming is one of the major environmental problems, the world is currently facing. There are many countries in Asia and Africa that are agriculture based regional economies. Tea plantations in some countries of these two continents are the major livelihood option for millions of people. During the recent years' some of these tea growing countries have witnessed disturbing trends of decline in tea yield and its productivity basically due to climate driven biotic and abiotic stresses. Tea production is controlled by three broad elements, *viz*. genotype, environment and management. Tea crop remains in the field for many years, resulting in severe deterioration of the growing environment due to the repeated interventions in the form of regular plucking/pruning and other cultural operations, addition of external inputs and resulting field traffic. Climate change impacting local weather conditions (prominently changing rainfall trends resulting in frequent flood and droughts besides increase in temperature, change in relative humidity and sunshine hours) complicates the matter further. The possible fallouts of the climate change are already witnessed in the loss of yields and increased management costs for developing coping strategies. Therefore, any spatial and / or temporal changes in the regional climate pattern will directly affect the regional economy and consequently the well-being of the people in the region. Most of the tea growing regions are typified by a kind of monsoonal climate or an alternate wet or dry season interspersed by temperature changes from mild to severe.

Identification and mitigation/adaptation of the above mentioned problems require appropriate diagnostic tools which will enable better management of the plantations. As these changes are taking place in space and time, the concept of climate change is a spatio-temporal phenomenon. Statistical methods coupled with earth observation technologies can thus be used as an efficient tool for quantifying and monitoring tea plantation and to study tea yield and quality. For example, in North East India and specifically in humid subtropical Assam, there is wide variation in the soil and climatic conditions even in a small district and sometimes soil conditions are seen to be varying even at section of a tea field (unit) level. Such situations are also witnessed in other tea growing regions of the world.

Different tea clones/cultivars may respond differently to changing climate parameters. In different countries, downscaled regional climate models from global circulation models have been used to predict future climate scenarios. Various attempts have been made to predict the suitability/vulnerability of tea to climate change and its impact on spatial scale. In addition, studies have been initiated to check if there is a migration of tea to newer suitable areas in different countries, if the current areas become vulnerable or even unsuitable in future. Such information will be very useful to develop strategies and decision support systems for adaptation in future.

The adaptive strategies for combating change in climate triggered by global warming, have been developed in different countries. Many of these strategies may seem almost identical, but their implementation is country specific depending on local meteorological and geophysical conditions. It has been postulated that local edaphic factors also play a major role in developing management practices for a particular crop. Thus while combating climate change; the development of adaptive strategies (largely management at garden level) would require consideration of local edaphic factors in addition to meteorological conditions, which are again spatio-temporal in character.

This booklet reports the country specific growing conditions as well as climate trends, impact of climate change on production and the adaptive strategies. More emphasis has been laid on adaptive strategies country wise, since other countries can also think of using these strategies; however, some of the strategies may seem common across countries. As has been stated above, these common strategies may also have a different implication depending upon local bio-physical as well as socio-economic conditions. The objective of this work was to develop a scientific compilation of the adaptation strategies based on local conditions.

1. Impact of Climate Change on Tea and Adaptation Strategies (India)

India is the second largest tea producer in the world and over eighty per cent of the tea produced is consumed within India itself. India has acquired a prominent status on the global tea map due to Assam and Darjeeling tea. The Indian tea industry has grown to own many global tea brands and has evolved into one of the most technologically equipped tea industries in the world. In India, tea is grown in wide amplitude of climatic variables, at latitudes from 8° 12' N in Nagercoil in Tamil Nadu to 32° 13' in Kangra district of Himachal Pradesh and at altitudes ranging from near sea level in Assam to 2414 m (7920 feet) above mean sea level (a.m.s.l) in Korakundha in the Nilgiris in south India. Tea grows in a moderately hot and humid climate, preferred for better yield, crop distribution and quality. An ambient temperature within 13°C and 28-32°C is conducive for growth of tea. Temperature above 32°C is unfavourable for optimum photosynthesis and is synergically disastrous for the crop if it is accompanied by low humidity.

The anthropogenic impact on the environment and associated economic growth is believed to be a primary cause of global warming. Such warming has profound impact on living beings as well as plant species including tea. Rise of temperature, enrichment of ambient carbon dioxide, variation of total rainfall and change in its distribution pattern alongwith lowering of relative humidity have a profound impact on tea crop growth and yield. Productivity is also affected by pest behaviour and disease infestations which are also impacted by environmental changes. Moreover, studies have shown that changing environment can adversely affect tea quality. Climate change which has become more severe in recent years is already being witnessed in many tea growing countries of the world including India. Long time trend analyses (about 100 years) revealed that the rainfall in North East India has declined by more than 200 mm along with increase in minimum temperature in the region. Another important aspect is the increasing concentrations of atmospheric carbon dioxide from approximately 315 ppm in 1959 to a current atmospheric average of approximately 390 ppm plus. Impacts of climate change are reported from tea gardens of different region of the country. In such situation adaptation strategies need to be developed and implemented to sustain the crop which earns valuable foreign exchange for the country.

1.1. Origin of native Assam Tea

Tea was discovered in India by Scottish explorer Robert Bruce in 1823 in the Upper Brahmaputra Valley, Assam that used to be brewed by the local Singhpho tribe. The leaves were identified to be of the camellia family but different from the Chinese species *Camellia sinensis var. Sinensis* and were named as *Camellia sinesis var. Assamica* (Masters) *Kitamura*. The first tea produced in Assam (a consignment of 12 chests) was sent to England for public sale in 1838.The first private owned tea company, the Assam Tea Company, was formed in 1839 which was followed by other companies like George Williamson and Jorehaut Tea Company (Barua, 1989).

1.2. Present Status

India produces around 24% of the total world tea production (Table 1 – 1) and consumes about 21% of the total world consumption. Nearly 80% of the tea produced, is consumed within India.

Table 1-1 Worldwide production of tea in top 5 countries (Baruah, 2015)

Country	2010	2011	2012	2013	2014
	(in million kgs)				
China	1475.06 (34.44)	1623.21 (35.58)	1789.75 (38.13)	1924.46 (38.53)	1980.00 (39.39)
India	966.40 (22.56)	1115.72 (24.46)	1126.33 (23.99)	1200.41 (24.03)	1184.80 (23.57)
Kenya	399.01 (9.32)	377.91 (8.28)	369.56 (7.87)	432.45 (8.66)	445.11 (8.86)
Sri Lanka	331.43 (7.74)	328.63 (7.20)	328.40 (6.70)	340.03 (6.81)	338.03 (6.73)
Vietnam	175.00 (4.09)	178.00 (3.90)	174.03 (3.70)	180.33 (3.61)	170.00 (3.38)
Total World	4283.51	4561.68	4694.11	4995.31	5026.36

India is the second largest producer of tea in the world with 79.8% produced in North India and 20.2% produced in South India. Tea is mainly exported to CIS nations, UK, Iran and Pakistan. The CTC tea constitutes 89% of the total production while the rest is either orthodox or green tea.

India has around 563.98 thousand hectares of extent under tea cultivation, as per figures for December 2013. Tea production is led by Assam (304.40 thousand hectares), West Bengal (140.44 thousand hectares), Tamil Nadu (69.62 thousand hectares) and Kerala (35.01 thousand hectares) (Table 1-2). According to estimates, the tea industry is India's second largest employer. It employs over 3.5 million people.

Table 1-2 Area under tea cultivation (end-2013) & production in 2013-14 (Source: Tea Board of India)

State / Districts	Area under tea (in 1000 Hectares)	Production (Million Kgs)
Assam Valley	270.92	581.03
Cachar	33.48	48.02
Total Assam	304.40	629.05
Darjeeling	17.82	8.91
Dooars	72.92	177.85
Terai	49.70	125.34
Total West Bengal	140.44	312.10
Other North Indian States(includes Tripura, Uttarakhand, Bihar, Manipur,Sikkim, Arunachal Pradesh, Himachal Pradesh, Nagaland, Meghalaya, Mizoram and Orissa)	12.29	23.92
TOTAL NORTH INDIA	457.13	965.07
Tamil Nadu	69.62	174.71
Kerala	35.01	63.48
Karnataka	2.22	5.52
TOTAL SOUTH INDIA	106.85	243.71
ALL TOTAL	563.98	1208.78

Tea Board of India controls tea production, certification, exports and all other facets of the tea trade in India. Historically, India produced only black tea. In the recent years, however, there has been a growth of green, white, and even oolong Indian teas, although the vast majority of tea and styles of tea produced in India are still black teas.

1.3. Tea growing regions of India

In India, one of the best tea growing regions is located in the north eastern corner including the foothills of the Himalayas and areas near Nepal and Bangladesh border (Fig1-1). These regions include Darjeeling and Assam. Although similar climatic condition exist in the Himalayan foothills but tea is mainly found in some areas of Himachal Pradesh. On the other hand, in southern India tea is grown mainly in the Nilgiris and some parts of Kerala.

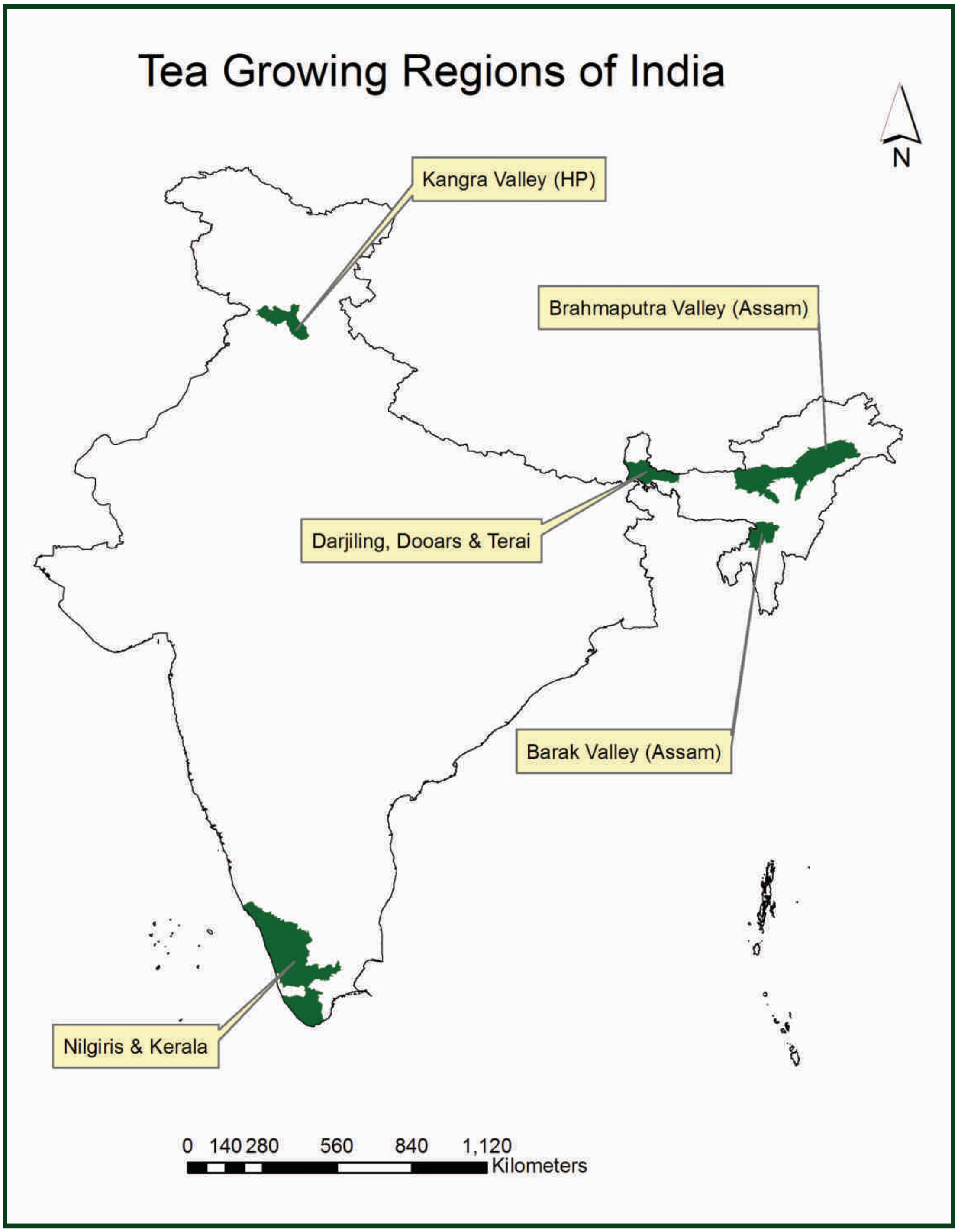

Figure 1-1 Major Tea Growing Regions of India

Assam: The major tea growing regions of Assam are Upper Assam, South Bank, North Bank and Cachar covering the districts of Dibrugarh, Tinsukia, Sibsagar, Jorhat, Golaghat, Sonitpur, N. Lakhimpur, Darrang, Nagaon, Morigaon, Cachar, Hailakandi and Karimganj. The state of Assam, which includes the northern Brahmaputra valley and the southern Barak valley (Fig 1-2) has growing season mainly between March and November with extremely humid summers and heavy rainfall. The elevation varies from 45-60 meters and rainfall varies from 2,500-3000 mm (Fig 1-3a). The *Assamica* cultivar normally grown in Assam has larger leaves, in contrast to the smaller-leafed Chinese cultivars grown in Darjeeling. Assam black tea has rich, full bodied, deep-amber liquor with a brisk, strong and malty taste. The distinctive second flush orthodox Assam teas have a rich taste, bright liquors and are considered to be one of the choicest teas in the world. The unique environmental conditions give these teas their special quality, reputation and character and help orthodox Assam Teas to qualify as a Geographical Indication (GI).

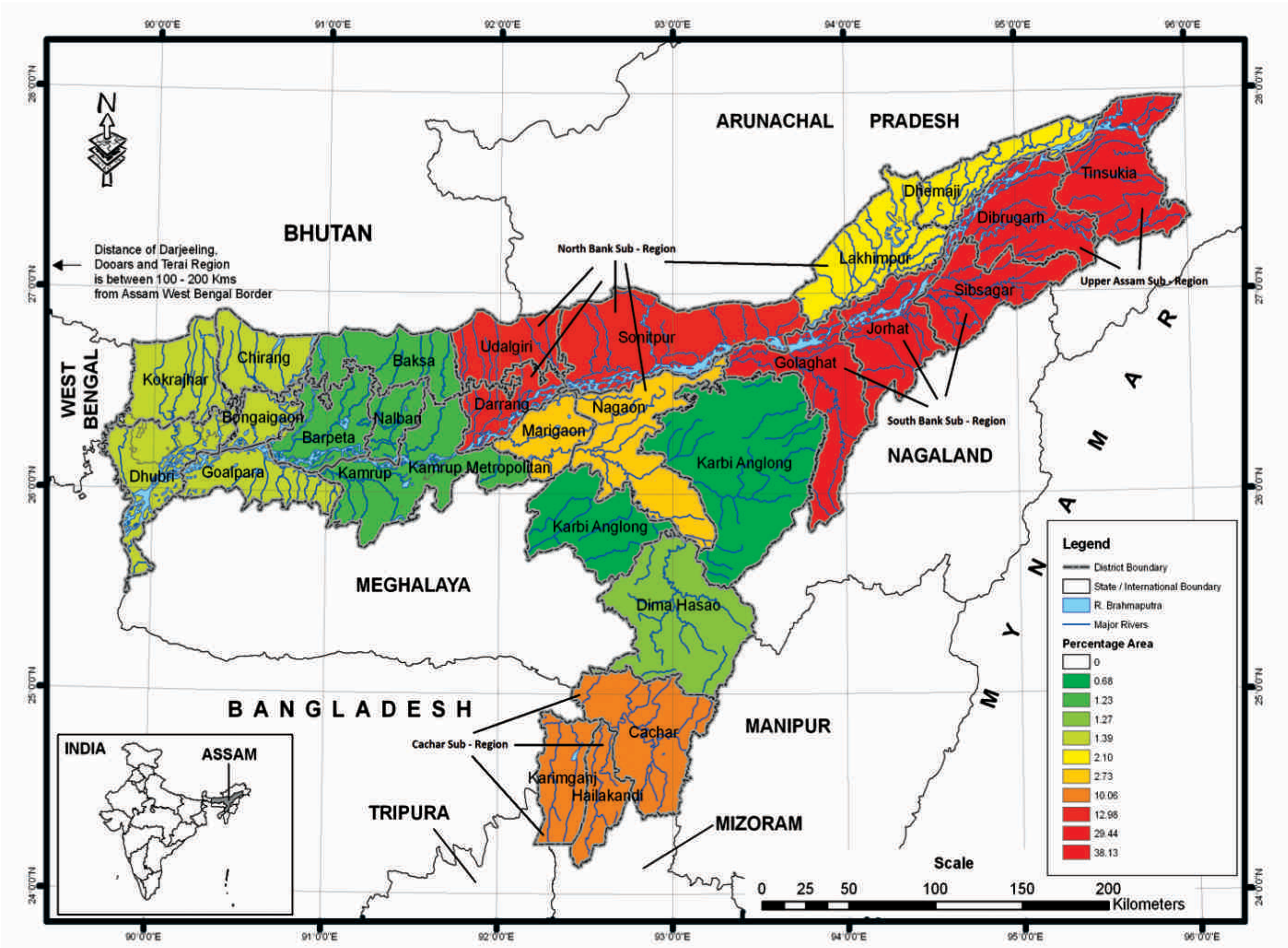

Figure 1-2 Percentage of area under tea in Assam, India

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Figure 1-3 (a) Tea garden of Assam (b) Tea garden of Darjeeling

West Bengal: In West Bengal, tea growing regions are Darjeeling, Terai and Dooars. Tea in this region grows at an elevation ranging from 600 to 2,000 meters with rainfall varying from 3,000 to 3,300 mm (Fig 1-3b). Darjeeling tea liquor is golden or amber in colour and has a unique, delicate flavour often described as "flowery," and "peachy”. The gardens are situated generally on steep slopes providing an ideal drainage system though susceptible to erosion and landslides. Darjeeling tea is also registered as a Geographical Indication in India and is protected internationally. In Terai and Dooars tea is grown at an elevation ranging from 90 m to 1750 m. Average rainfall in the area is about 3,500 mm. The first flush of the region has a fresh virgin flavour, good brightness and fragrance followed by a brisk flavoured second flush.

Himachal Pradesh: In Himachal Pradesh, tea is mainly grown in the Mandi and Kangra districts at elevations varying between 700-1,300 metres and rainfall from 2,300-2,500 mm. Tea grown in Himachal Pradesh is mainly organic.

In southern India tea is mainly grown in parts of Tamilnadu (Nilgiris), Kerala and Karnataka. Tea grows here mainly at elevations varying between 750 – 2600 meters and rainfall varying between 1000mm – 3800 mm. The Nilgiri teas are aromatic, yellow in colour and have a creamy taste.

1.4. Climate Trends

Climate trends of the historical data show as to how the climatic variables have behaved over time. This is, however, a very complex issue since many a times the trends are averaged out over long term time series. The impacts of these changes in climate have already started taking place and are visible at various locations across the agrarian state of Assam, including its tea growing regions. These impacts are changing tea crop productivity and directly affecting the livelihoods of millions of dependent communities in India. The graphical representation shown below gives a clear picture of climate change in the major tea growing regions of North East India.

Trend analysis of rainfall from North East India's tea growing regions shows a steady decline in the annual rainfall. Analysis of ninety six years of annual total rainfall data of South bank region at the TTRI, Assam (Fig 1-4) indicates that the rainfall in this region has declined by more than 200 mm. Similarly, for other tea growing regions, similar trend of decrease in rainfall has been observed.

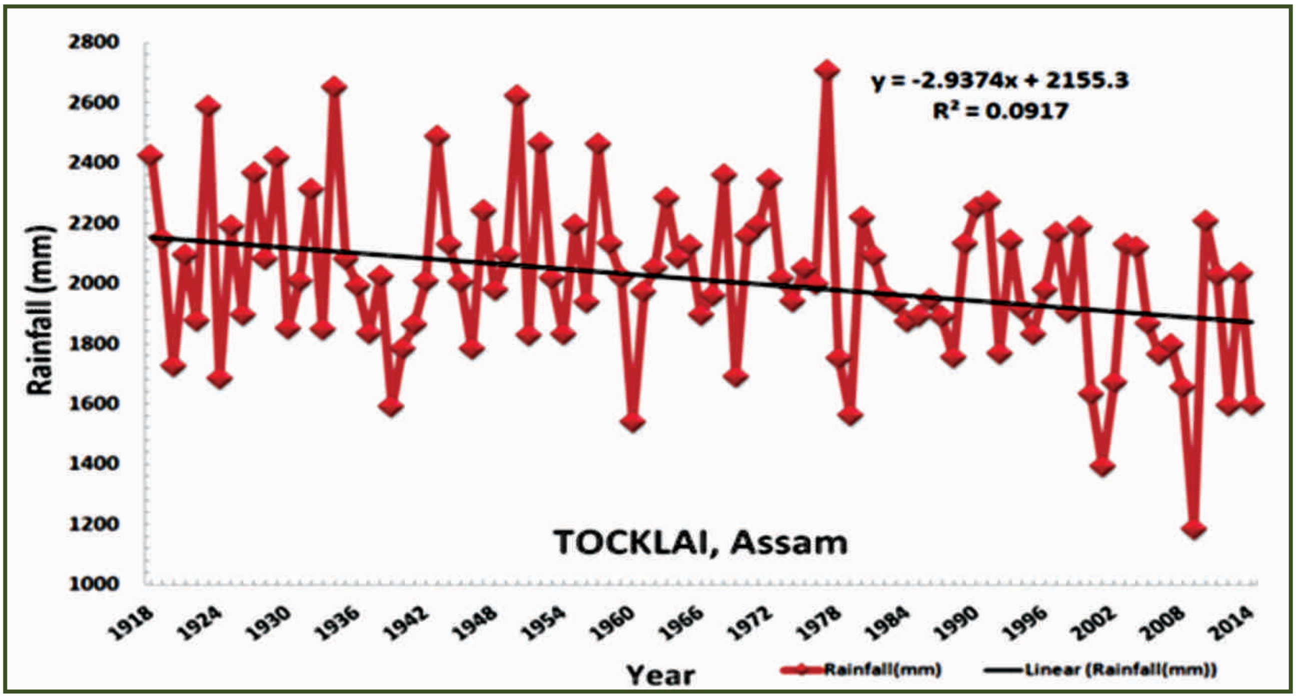

Figure 1-4 Annual total rainfall (1918-2014), Tocklai, Jorhat, Assam, India.

Along with rainfall, annual average temperatures have also shown a steady increase. It has been estimated that in the last about 100 years the average minimum temperature has increased by about 1.3 °C in North east India (Fig 1-5). Annual average maximum temperature has also shown similar trends.

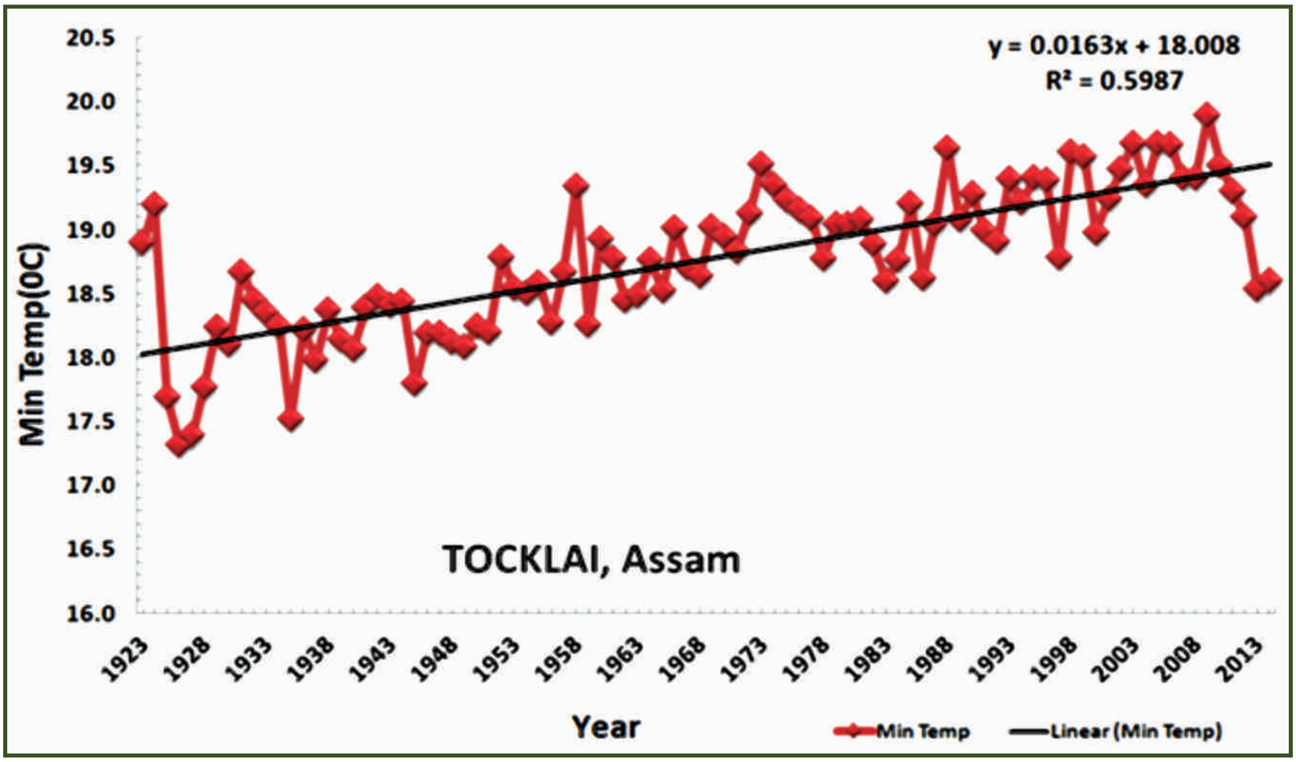

Figure 1-5 Annual average minimum temperature (1923-2014), Tocklai, Jorhat, Assam, India.

Analysis of last 30 years observation indicate that the number of days having temperature > 30°C or even >35°C (Fig 1-6a) is generally increasing along with the increase in average minimum temperature (Fig 1-6b).

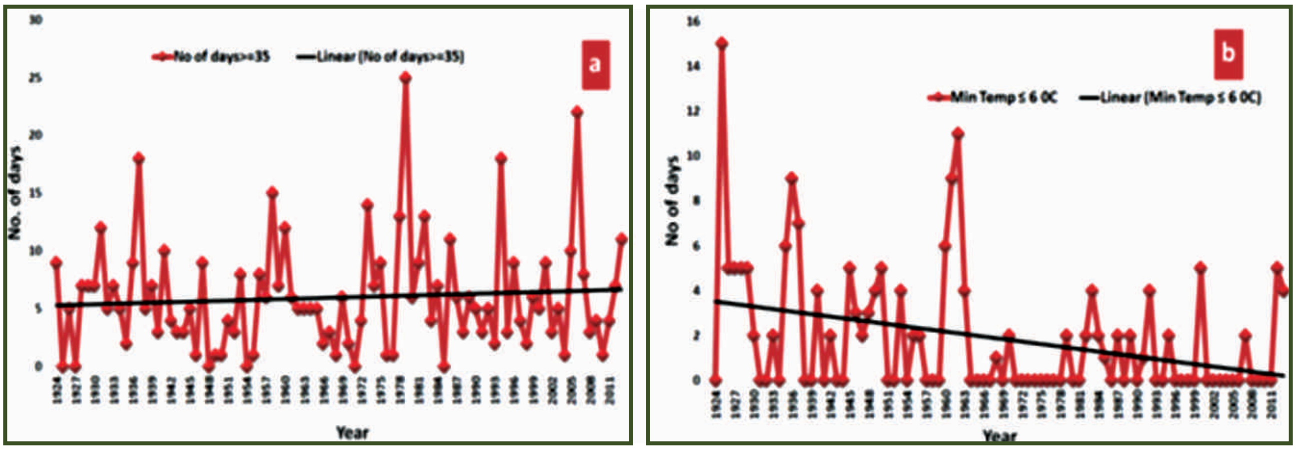

Figure 1-6(a) Total number of days having > 35°C temperature and (b) total number of days having ≤ 6°C temperature at Tocklai, Jorhat, Assam

The spatial analysis of total precipitation (annual as well as production season) in North East Indian state of Assam shows a wide range of variation during the period of analysis from 1993-2011 (Fig.1-7 a, b). Over all a decreasing trend was observed in precipitation. The declining trend of precipitation is more prominent during the recent years (post 2004). In several cases the total precipitation was found to be below normal, especially over the central and eastern Assam. This is a matter of concern as central and eastern Assam hold large areas under tea plantations and produces the highest quantity of tea in Assam.

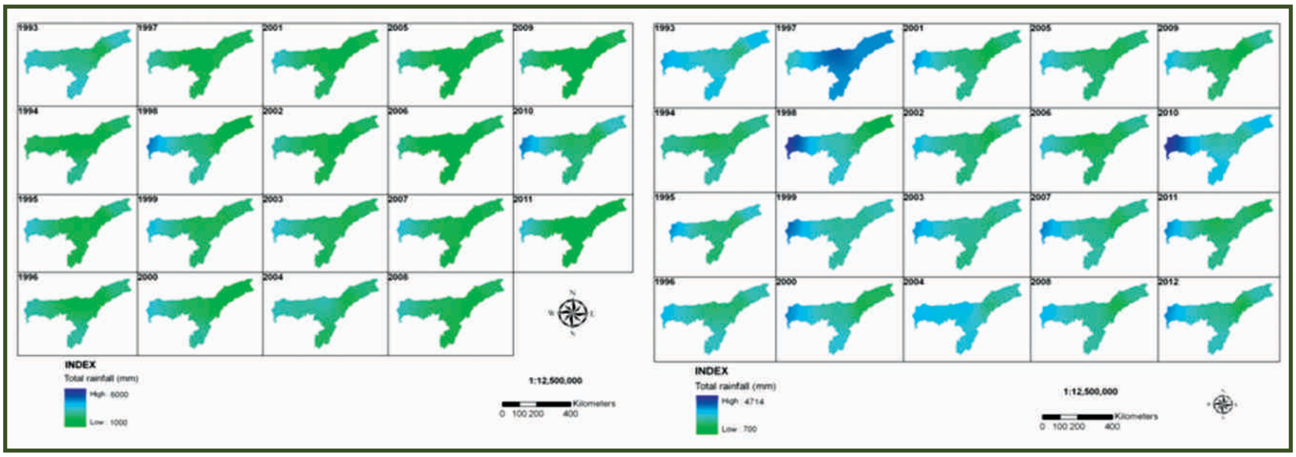

Figure 1-7 (a) Distribution of total annual precipitation (mm) in Assam (1993-2011) (b) Distribution of total production season (April – October) precipitation (mm) in Assam (1993-2012)

Similarly, temperature pattern studied in Assam for the time period of 1993-2012 both annually and for the growing season indicates that both the annual and seasonal maximum temperature remained above ideal in many instances, though no distinct trend in the maximum temperature was found. However, the minimum temperature shows a very clear increasing trend all over Assam which will have implication on the production levels.

1.5. Impact of climate change

Tea being a rain fed crop requires certain soil and air temperature as well as moisture condition for its growth. It is apprehended that increased temperature and decreased rainfall pattern observed in this region are undoubtedly going to affect the above conditions posing a threat to the sustainability of tea crop.

Tea cultivation though depends on the natural precipitation, are now-a-days being complemented by irrigation because of increased rainless periods leading to drought like situation (Fig 1-8e). Both excess and shortage of water affect growth of tea bushes. Tea bush need adequate and well distributed rainfall, but heavy and erratic rainfall is responsible for damage to tea plantation in terms of soil erosion (Fig 1-8d), lack of growth due to less sunshine hours and different types of diseases, besides flooding. Heavy rain washes away the top soil converting cultivable lands to barren or unproductive. Loss of soil fertility leads to reduction in water holding capacity of soil, exposure of root systems and reduction in microbial activities due to loss of organic matter. In undulating or hilly areas, particularly the Darjeeling hills, high soil erosion, landslides and depletion of inherent soil fertility is expected in coming years, if the present trends are continued.

Every year the river Brahmaputra inundates large area in its floodplain, which creates waterlogging condition in the productive tea growing areas in North East India (Fig 1-8a-c). Waterlogging is one of the major abiotic stresses which affect the growth and survival of plants. Every year about 15-20% crop is damaged due to surface waterlogging, localized water logging and profile water logging in tea plantation areas of north east India. Bank erosion (Fig 1-8f) is another major concern triggered by flood events. There are several tea gardens along the left bank of river Lohit and Brahmaputra from Hatikhuli to Rohmoria in Dibrugarh District of Assam, which are already found to be eroded by flood events.

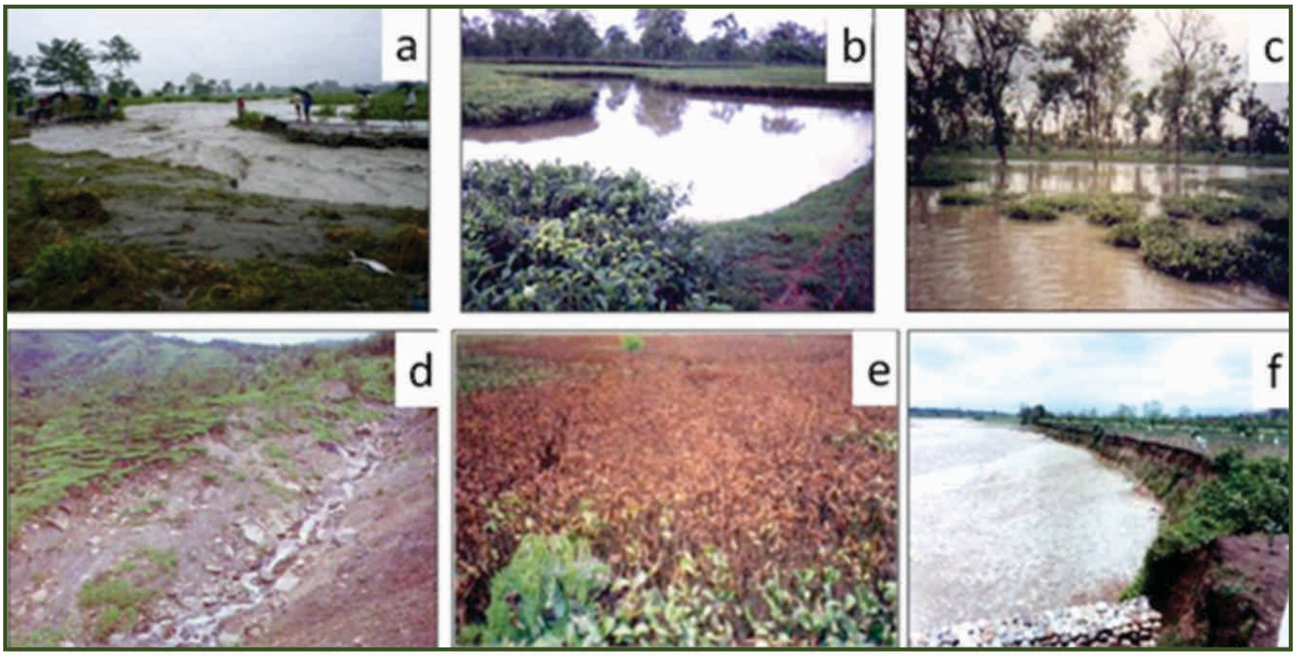

Figure 1-8 (a-c) Flood and waterlogged situation, (d) soil erosion, (e) drought condition and (f) bank erosion in the tea plantation areas in North Eastern India

The probability of pest infestation increases with the increase in temperature. The productivity also reduces as an after effect. Furthermore, as temperature rises the plants become stressed due to water deficit. The stressed plants are more susceptible to the attack of pests. Large areas in Assam and North Bengal under tea plantations are suffering severely from crop loss due to the outbreak of tea mosquito bug, looper caterpillar and red rust disease of tea leaf (Fig1-9a, b). The increase in pest infestation will lead to extensive use of agrochemicals which are hazardous and toxic.

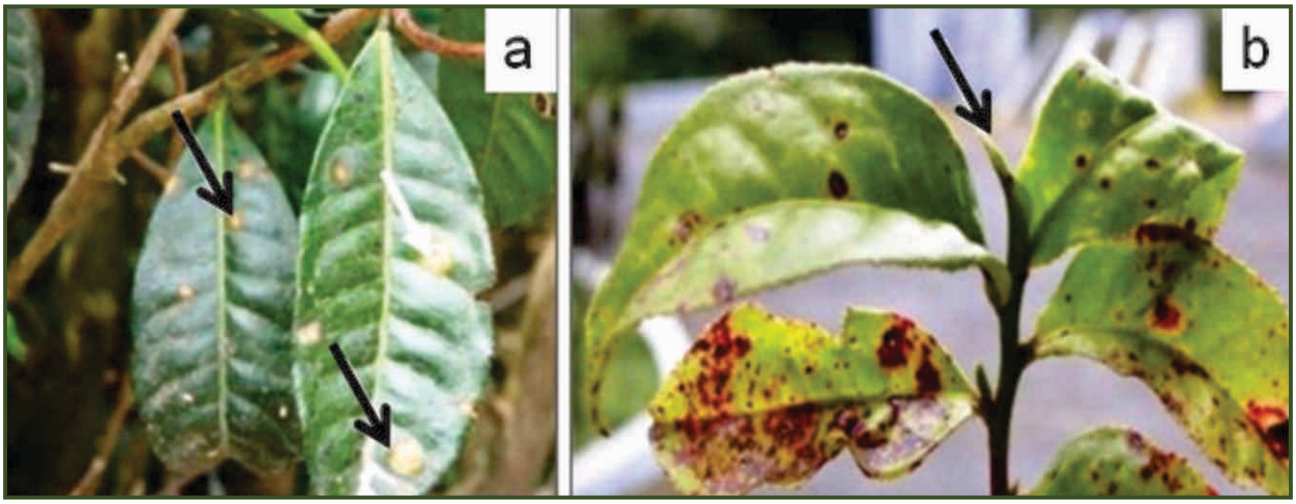

Figure 1-9 (a) Red rust infested tea leaves and (b) formation of *banji* bud due to severe disease infection

Over the time, these changes are expected to have implications on tea, resulting in some traditional tea growing areas becoming unsuitable for tea growth. Increased temperatures and decreasing rainfall patterns will influence both the quantity and quality of tea production, posing a threat especially to vulnerable smallholder tea farmers. The tea farmers might experience more frequent floods, droughts and pest infestations leading to reduction in productivity. The economical and sociological conditions are going to be severely hampered. Consequently, producers will have to make considerable changes to their existing practices in order to continue to meet global tea demand and quality requirements.

1.6. Vulnerable region

The future scenario for the climate parameters were studied for two periods namely immediate future and long term future. In both the cases future probabilities of precipitation and temperature scenario were developed using A2 scenarios described by the IPCC, where the population growth is assumed to converge very slowly resulting in consistent increase in global population. In this scenario the economic growth will be regionally oriented, fragmented and slower than other IPCC scenario.

Immediate future scenario for this region was extracted from the HadCM3 Global Circulation Model (GCM) outputs generated by the IPCC where mean monthly statistics of precipitation (mm/day) and temperature (maximum and minimum mean daily 1.5m Temperature in Kelvin) was modelled for 12 months for each year of 1980, 2020, 2050 and 2080. The spatial resolution is 150 km. The baseline data was referred as 1980 which represents the mean monthly values of precipitation

and temperature for the period of 1961 to 1990. For each of the year 2020, 2050 and 2080 the temperature and precipitation were expressed as mean monthly change in their values from the baseline (1980) data in the respective years. The seasonal precipitation and seasonal mean temperature at 1.5 m for the time slices 2011–2040 and 2041–2070 represent the climatic conditions during 2020s and 2050s, respectively. The absolute values of temperature and precipitation for 2020 and 2050 were then derived and mapped (Fig 1-10), which indicates precipitation to fall below the current levels and has a decreased rainfall. The real detailed picture will be available when the data are extracted for a high resolution.

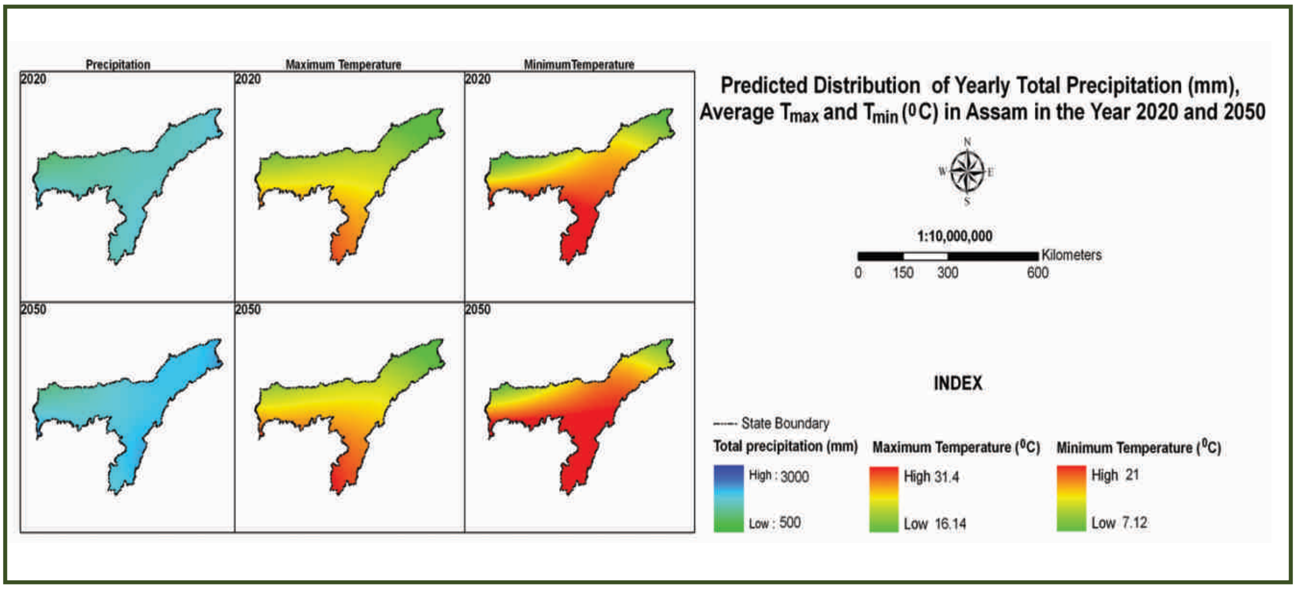

Figure 1-10 Predicted distribution of yearly total precipitation (mm) and temperature (T_{max} and T_{min} °C) in Assam for the year 2020 and 2050.

The long-term future scenario was developed from the Hadley Centre Regional Climate Models (HadRM2/HadRM3H/PRECIS). The Regional Climate Model (RCM) simulated for the Indian region on a grid size of 0.44 X 0.44 degrees and a spatial resolution of 50 kms. The future climate was developed for each year for the period of 2071 to 2100 under A2 scenario described by the IPCC. The long term scenarios mapped using spatial analysis showed that the annual total precipitation is likely to decrease in almost all over Assam except in some areas in the Cachar region where the annual total precipitation may increase (Fig 1-11).

The average annual maximum temperature does not show a specific trend; rather until 2080 it has a decreasing trend under A2 scenario. However, post 2080 sharp increasing trends are observed, particularly in southern, middle and parts of upper Assam area. The maximum average annual temperature is likely to increase most in the Cachar region of Assam, where it may reach up to 36°C. Unlike maximum temperature, the average annual minimum temperature shows a consistent increasing trend. The rate of increase is likely to be faster post 2080.

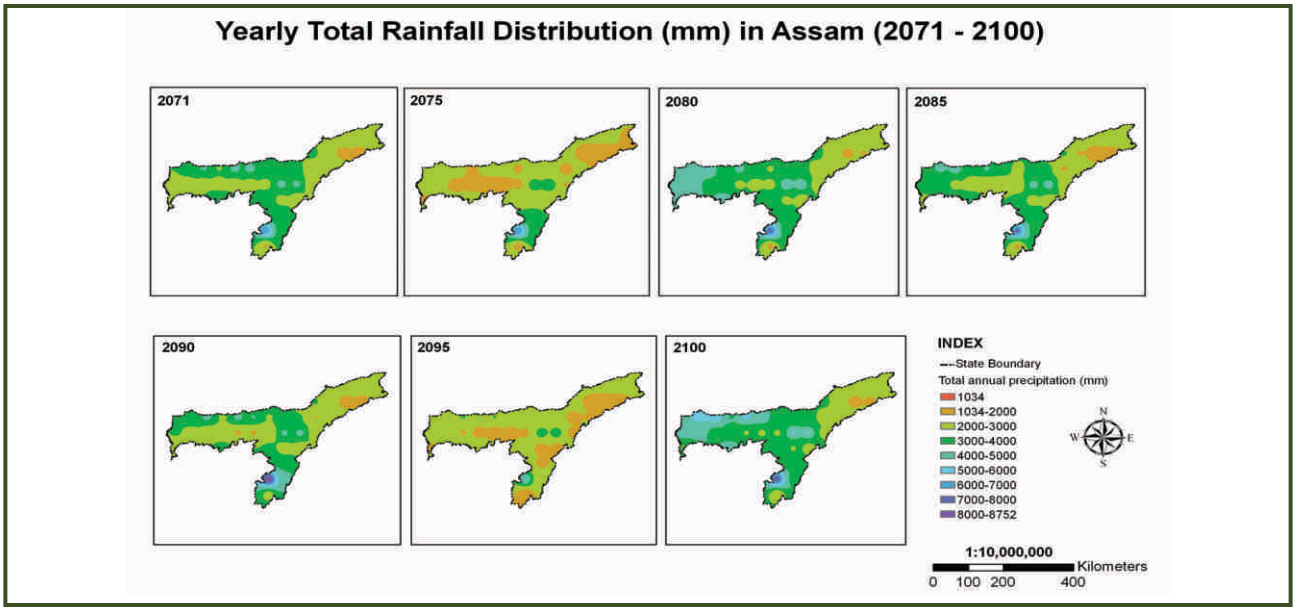

Figure 1-11 Distribution of total annual precipitation (mm) in Assam under IPCC A2 climate scenario for the time period of 2071-2100

Preliminary analysis has been done on a GIS platform to figure out the climatically suitable and vulnerable regions for tea growth based on the future scenarios for Assam (Fig 1-12). For the temperature 13-30^{0}C has been taken as the most suitable; 30-35^{0}C suitable; and >35^{0}C vulnerable and for precipitation: <2000mm is vulnerable to drought (drought situations may arise), 2000-4000 suitable: >4000 mm vulnerable to floods (floods may happen). However, it is assumed in the analysis that the precipitation is evenly distributed and there is an efficient drainage system in the garden (which is the ideal situation). The vulnerability analysis is being refined with more parameters. It has been observed that temperature wise Cachar will be most vulnerable while the rest of Assam will be moderately suitable while precipitation wise drought vulnerability will be more in south bank region and flood vulnerability in Cachar region. But monthly analysis using high resolution models are required for better understanding of the vulnerability of tea growing regions of NE India in future.

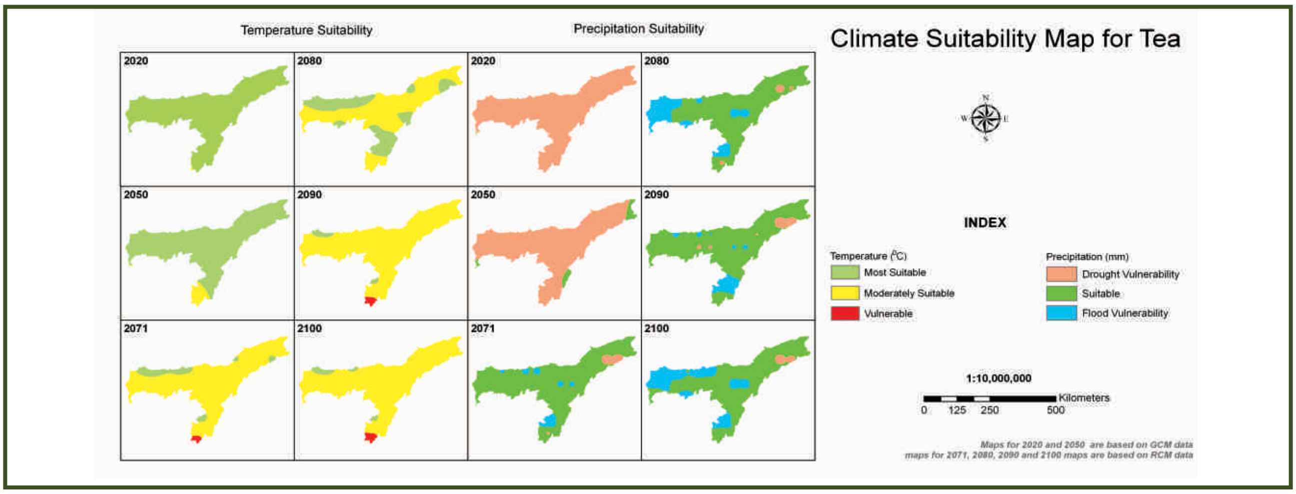

Figure 1-12 Future climatically vulnerable/suitable regions for growing tea in Assam

1.7. Climate Change Adaptation Strategies

Trend analyses of various meteorological data of North East India showed deviation of climate from the long term normal. Reports of tea planters of various tea gardens of Assam, West Bengal and South India also confirm the negative impact of climate on tea production. So it is an urgent need to critically identify and evaluate options for adaptation to climate change in future scenarios. The Intergovernmental Panel on Climate Change (IPCC) defines adaptation to climate change as '*adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities*'. The term adaptation strategy includes the actions of adjusting practices, processes to the threat of climate change. The purpose of undertaking agricultural adaptation is to effectively manage potential climate risks over the coming decades as climate changes.

Production of an area depends mostly on the genotype, environmental condition and management practices. So in tea cultivation more importance should be given on these factors to minimise the ill effect of climate change. Based on the Tocklai Tea Research Institute's recommendation the following strategies can be adopted to combat the impact of climate change.

1.7.1. Planting material

Drought tolerant cultivar: Planting of drought tolerant cultivar is an important adaptation measure. The Tocklai Tea Research Institute has developed 33 tea clones, more than 150 garden series clones and over a dozen Tocklai biclonal seed stocks. Tocklai vegetative clones were characterized on the basis of yield, quality, their preference for manufacture and response to drought. Some of them are tolerant, moderately tolerant, susceptible and highly susceptible to drought. Garden series clones were also characterized on the basis of yield, quality, their preference for manufacture and in some of them response to drought were also mentioned. Tocklai seed stocks were characterized on the basis of preference for manufacture and their drought response. It is believed that seed plants are more climate resilient than the clonal varieties. Planting materials suitable for unfavourable condition like marginal land, drought and poor drainage have been shortlisted by the TTRI. New/replanting of those stress tolerant cultivar in drought prone area can be considered as the major adaptation measure to combat the ill effect of climate change.

1.7.2. Improving farm management practices

Negative impact of climate change can be reduced by adopting proper management practices as follows.

Reduction of chemical load by integrated nutrient management: Chemical fertilizer, pesticide and weedicide are the major agro chemical inputs in tea plantation. They are vital for increasing crop production. But their overuse has been degrading the environment. In most cultivated lands, there is a depletion of organic matter which affects the water holding capacity of the soil. In such case Integrated Nutrient Management (INM) helps to overcome the problem. Integrated nutrient management is a practice where all sources of nutrients namely organic, inorganic and biofertilizer are combined and applied to the soils. It gives optimum crop nutrition, optimum functioning of the soil health and minimum nutrient losses or other adverse effect on the environment.

According to Kashyap (2009) different components of INM are Chemical fertilizer, Organic manures like FYM, Compost, and Vermicompost, Farm waste, Industrial waste, Inclusion of legume crops in cropping system, Bio fertilizers like Azolla, Blue green algae, Rhizobium, Crop residue and Green manuring. As per the TTRI recommendation some of the procedures of INM are already suggested. The INM practices improve both physical and chemical fertility of soils, thus making production system more resilient to climate change.

Organic agriculture practices in tea: Organic agriculture is highly adaptable to climate change when compared with the conventional agriculture. Organic agriculture preserves inherent soil fertility and maintains organic matter in soils which can sustain productivity in the event of drought, irregular rainfall with floods, and rising temperatures. Soils under organic management retain significantly more rainwater due to the 'sponge properties' of organic matter. It was reported that soil structure stability was 20-40% higher in organically managed soils than in the conventional soils (Mader *et al.*, 2002). It was found that water capture in organic plots was twice as high as in the conventional plots during torrential rains (Lotter *et al.*, 2003). This significantly reduced the risk of floods. Organic agriculture in general requires less fossil fuel per hectare. It has considerable potential for reducing emissions of greenhouse gases. It aims at improving soil fertility and nitrogen supply by using farm yard manure, leguminous crops, crop residues and cover crops. The enhanced soil fertility leads to stabilization of soil organic matter and in many cases leads to sequestration of carbon dioxide into the soils. This also increases the soil's water retention capacity due to improved soil structure, thus contributing to better adaptation of organic agriculture under unfavourable climatic conditions with higher temperatures and uncertain precipitation levels.

Organic matter is a source of cementing substance required for soil aggregate formation and thus protects the soil from erosion. Organic matter increases the water holding and cat-ion exchange capacities of soil and creates favourable conditions for adequate aeration and water movement. It also serves as food for microorganisms in soil and hence increases their activities and there by influencing the biochemical processes involved in maintaining the fertility of the soil. The benefits of using organic manure are as follows

- Organic manure provides all the nutrients that are required by plants but in limited quantities.
- It helps in maintaining C: N ratio in the soil and also increases the fertility and productivity of the soil.
- It improves the physical, chemical and biological properties of the soil.
- It improves both the structure and texture of the soils.
- It increases the water holding capacity of the soil.
- Due to increase in the biological activity, the nutrients that are in the lower depths are made available to the plants.
- It acts as mulch, thereby minimizing the evaporation losses of moisture from the soil.

Applications of cattle manure/decomposed oil cake: Cattle manure should be applied at a rate of 3-5 tonnes/ ha/ year; alternatively, decomposed oil cake may be applied at a rate of 2-3 tonnes/ ha/ year depending on the soil texture.

Mulching with succulent vegetative matter: In tea, mulching should be done at the time of new plantations, in young tea and in mature tea. Mulching should be done immediately after rainy season so that it can conserve the soil moisture during the dry spell that follows till March and April. A 10 cm thick mulch of porous matter is adequate. Black polyethylene sheets have also been used as mulches in young teas to conserve moisture during rainless periods and are found effective in combating drought like situations particularly in winter. These have been reported to favourably moderate hydro-thermal regime of soils. Mulching conserves soil moisture by reducing evaporation losses, reduces the impact of falling raindrops, surface run-off and soil erosion, as a result more water can infiltrate into the soil. Mulching lowers the soil temperature in summers. The most preferred mulching material is Guatemala (Fig 1-13a), Napier grass or any cut jungle vegetation such as Eupatorium, Ageratum and Water hyacinth (Fig 1-13b).


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Figure 1-13 (a) Guatemala grass (b) Water hyacinth

Retaining pruning litter and shade tree droppings: Retaining pruning litter is one of the easiest means of recycling crop residues. Hence, care should be taken that pruning litters are retained in the field. By chopping into small pieces either manually or with the help of mechanical choppers and returning the same to the tea soil, a great amount of nutrient is added to the soil. Along with pruning litter considerable amount of organic matter is also added through leaf fall and pod droppings from shade trees.

Application of decomposed tea waste: Tea waste compost can be used at a rate of 1-2 tonnes/ha/year.

Green Manure and Cover crop: Green manuring is the growth of a crop, not for the purpose of yielding a harvest, but in order to increase the fertility of land on which other productive crops are also grown. Usage of green leaf manure is advantageous both for crops and soil. The advantages are:

- They decompose rapidly and retain the organic matter in the soil.
- Green manures improve both physical and chemical properties of the soil.
- They provide energy to microbes.
- They provide nutrients to the standing crop and also to the next crop.
- Addition of green manure crops to the soil acts as mulch and prevents soil erosion.
- Leaching of nutrients in light soils can be prevented by addition of green manure.
- Cultivating green manure crops can control weeds.
- Majority of green manure crops being legumes, use of nitrogenous fertilizers can be minimized.

In young tea, adequate ground cover is to be provided by providing green manure crop to cover the ground besides improving the microclimate required to support growth of young tea. In undulating topography this also reduces top soil loss and helps in conserving moisture for young tea. Therefore, in sloppy topography green crop should be planted before planting tea, whereas in plains it should be grown at the time of planting (Fig 1-14). Green crops recommended by TTRI are *Crotolaria anagyroides, Pyrotripis cytisoides, Sesbania rostata.*

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Figure 1-14 Green crop along with young tea in a tea Estate in Cachar Region of Assam

Compost: Organic residues are piled up, moistened, turned occasionally to aerate and allowed adequate time to decompose partially and bring down the carbon nitrogen ratio to about 30. This process is called composting. In terms of climate change adaptation, composting provides numerous benefits. Adding compost to soil improves soil structure and aeration, which means better moisture-holding capacity, nutrient retention and ultimately, reduced vulnerability to water and wind erosion. It is estimated that 1kg of humus (relatively stable component of compost) can hold up to 6 litres of water. During rains, the addition of compost helps water to infiltrate into the soil rather than running off the surface. The addition of compost also protects against wind erosion as the humus in the compost helps to bind the soil particles together. Organic matter in the compost provides food for microorganisms, which keeps the soil in a healthy and balanced condition.

In tea, compost can be prepared from cut jungles, weeds and grasses. The compost so generated in the estate is more reliable and cost effective than out sourced one. All green crops recommended by TTRI such as *Crotolaria anagyroides* (Fig 1-15a), *Pyrotripis cytisoides*, *Sesbania rostata* can be used for composting. *Glyricidia sepium* and, *Ipomea carnea* (Fig 1-15b) can be used to obtain large amount of biomass. All these plants should be grown in vacant spaces, along road side and marginal lands for composting. The three standard methods of composting are composting in pits, composting in heaps and continuous composting.

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Figure 1-15 (a) *Crotolaria anagyroides* (b) *Ipomea carnea*

Vermicompost: Composting of biodegradable organic waste by earthworms is called vermicomposting. It is an efficient and eco-friendly way to convert biodegradable waste into value added manure within a relatively shorter period. Vermicompost should be used in tea garden because of the following purposes, which in the long run helps in reducing the ill effects of climate induced stresses.

- Vermicomposting can convert garden wastes of plant and animal origin to a valuable product
- It is rich in plant nutrients, provides all essential nutrient elements.
- Improves soil structure, aeration, water holding capacity and chemical composition of soil
- Reduces crusting of soil surfaces
- In compacted soil it improves water transmission capacity
- Vermicompost application improves water retention characters of sandy soils
- Increases cat-ion exchange capacity of soil
- It enhances the soil microbial activity

The TTRI developed vermicomposting procedure with four strains of earthworms, *viz. Eisenia foetida, Perionyx excavatus, Eudrilus eugeniae and Amyanthas diffringens. Eisenia foetida* is although mostly used, other strains are also equally good. The different materials that should be used as biowaste are dried weeds (mixed grass), shade tree loppings, Guatemala, Banana plant, Water hyacinth, Azolla, Mikania, Mango leaf etc. Fig 1-16 shows a vercomposting unit in a tea garden.

Figure 1-16 Vermicomposting unit in a garden

Integrated Pest Management: To avoid environmental pollution and residue in the made tea, emphasis has been laid on Integrated Pest Management. It is a sustainable approach for managing pests by combining biological, cultural, physical and chemical tools in a way that minimizes economic, health and environmental risks.

Shade: Shade trees afford some measure of protection to the tea bushes from hail and wind, besides reducing temperature. In North East India red spider mite causes maximum loss of the tea crop and the damage due to red spider is more severe in tea without shade. It was reported that shade tree can preserve the soil fertility, reduce temperature & evapotranspiration losses and moderate the impact of rain water on soil. Well managed shade can improve the microclimate of a tea estate (Fig 1-17). Shade tree roots are likely to help in improving soil aeration. There are several beneficial effects of shade for minimizing climate change induced abiotic stresses:

- Optimum population of shade trees helps to conserve soil moisture during the dry season and maintains microclimate.
- Lowering the temperature of tea leaves.
- Shade trees adds organic matter to the tea fields through dropping leaves, twigs and pods, thus increasing organic matter.
- The rate of development and proliferation of feeder roots of tea is high under shade trees.
- Shade trees absorb/redirect over 70% of infra-red radiation from the solar spectrum thus protecting the tea bushes from Sun scorch damage.
- Optimum shade density reduces transpiration loss of water and enhances photosynthetic efficiency and helps in the mobilization of nutrients.

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Figure 1-17 Well managed shade in a tea Estate in South Bank Region

The TTRI recommended permanent shade trees (Fig 1-18a) are *Albizzia odoratissima, Albizzia chinensis, Anadenanthera peregrine, Acacia lenticularis* and *Derris robusta*. Temporary shades are *Indigo feratesmanii, Melia azadarach, Albizzia lebbek, Leucaena leucocephala* and *Albizzia procera*.

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Figure 1-18 (a) Shade management in a T.E. (b) Shelter belt management in in Upper Assam tea growing region.

Shelter Belt: Trees are important for a number of reasons and support farmers in both mitigating and adapting to climate change. Tree cover assists in protecting land from periods of extreme rainfall as these act as soil stabilisers. These also provide shade to the soil reducing evapotranspiration. Shelter belt management (Fig 1-18b) is also a part of integrated pest management. Hence, crop grown along periphery with greater tree canopies and surrounding forests are able to minimise many ill effects of climate change. Alongwith Shelter belt, agroforestry is another most widely

adopted adaptation strategy to combat climate change. To create an ideal microclimate in and around the estate it is essential to plant suitable trees. The vacant marginal, sub marginal lands, roadsides, periphery of the estates should be grown with fast growing plants. According to TTRI recommendation, to minimize the ill effects of wind and hail, fast growing plants like Bamboo, *Albizzia moluccana, Cassia siamia, Leuceana leucocephala, Casurina equisetifolia* and *Melia azadirach* may be grown. However, care should be taken that trees should be conserved, possibly by regulating fuel wood consumption.

Drainage: Although the water requirements of tea are high, it is equally important for tea that about top 3 feet of the soil should not remain in a water-logged condition for a prolonged period. Excessive rainfall creates drainage issues. Drainage is required to remove surplus water from the land and the reduction of excess moisture in the soil beyond the needs of the tea. It has already been stated that the drainage status of even adjoining pieces of land may differ, depending upon the soil profile characteristics and topography. Each location may pose a different problem and it should rightly be tackled on its own merits. The following benefits are associated with proper drainage

- Improved aeration
- Improved nitrogen economy in the soil
- Increased benefit from mulching
- Improved "*tilth*" and soil structure, giving better soil workability.
- Increased depth of rooting.
- Increased water storage capacity and infiltration rates in the soil. This will also help in reducing soil erosion.
- Increased availability of soil moisture during the dry season, because of deeper root penetration. This will increase resistance to drought of tea bushes on drained soils.
- Decreased danger of tea bush diseases triggered by waterlogging

Water logging is a serious problem during the rainy season in North East Indian tea plantation (Fig 1-19a). Effective drainage can only solve the problem in such situations. It has been estimated that ideal drainage can increase yield as high as 40-50%.

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Figure 1-19 (a) Water logging condition (b) A view of irrigation in tea plantation

Irrigation: In certain tea districts of North East India the rainfall during the cold weather (winter dormant season) and spring, is either not sufficient or is not reliable, which results in droughts or drought like situations. It is in these tea districts that irrigation of tea is likely to be an economical proposition (Fig 1-19b). Irrigation in tea can be attempted with one of two objectives, or with both, it can be used to keep the tea bushes alive, or to produce early growth when this is prevented by drought. Irrigation permits the exploitation of unpruned and light skiffed tea in the production of early crop, where spread of crop is desirable. It is very difficult to establish young tea in droughty areas which can be overcome by irrigation. It is reported that irrigation increases yield of mature tea. In the absence of natural rain, irrigation at the appropriate time will enable one to maintain optimum yield by preventing loss in crop which would otherwise have resulted through lack of soil moisture. Irrigation will, however, accelerate the time when young tea comes into production, reduce mortality in a drought and is also known to reduce the incidence of Red Rust and Red Spider. Irrigation is more successful when the area has well managed shade.

Rain Water Harvesting: Rain water harvesting is an important criterion to meet the irrigation requirement and to maintain humidity in tea plantation during the period of moisture stress. This can lower down the vapour pressure deficit gradient from leaf surface to atmosphere and can cut down evapotranspirational loss of water. Water can be stored during heavy precipitation in monsoon by using water harvesting structures in valley areas where tea is grown in an undulating topography (Fig 1-20). Rain water harvesting should be planned in a scientific way because large amount of water is required to irrigate one hectare area and thus losses should be prevented from reservoirs or the water harvesting structures (Fig 1-21).

Figure 1-20 Rainwater harvesting in an undulating topography in Cachar region

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Figure 1-21 Rain water harvesting in Dooars

Crop Diversification: To get more return from the area of tea plantation, introducing other crops with economic benefits can be done. In some tea plantation crop diversification are done by planting spices such as black pepper (Fig 1-22). The basic aim remains that if one crop fails, still some returns can come from the other crop or as additional returns (Fig 1-23).

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Figure 1-22 Crop diversification (black pepper) in South bank region of Assam

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Figure 1-23 Pisciculture tank in a tea estate in South Bank region

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2. Impact of Climate Change on Tea and Adaptation Strategies (Sri Lanka)

2.1. Introduction

Tea (*Camellia sinensis* (L) O. Kuntze) was first introduced to Sri Lanka in1839 when a batch of tea seeds was planted at the Royal Botanic Gardens at Peradeniya. The first commercial tea plantation was undertaken by James Taylor in 1867 on nineteen acres of land on Loolecondera estate, Hewaheta (Nathaniel, 1986). The commonly growing tea cultivars of Sri Lanka were derived from two original varieties of *Camellia sinensis* (China type) and *Camellia assamica* (Assam type), respectively. In addition, some populations of tea have been derived from other variety known as *Camellia assamica* sub species *lasiocalyx* (Anandappa, 1986). In commercial plantation tea plants are generally trained as a flat-topped bush of about 60-90 cm in height. Although under humid tropical condition the production of tea shoots is more or less continuous throughout the year, shoot growth and harvesting is seasonal under temperate climatic conditions.

Increasing ambient temperatures and CO_2 concentration under climate change (global warming) are the two of the main driving forces affecting crop growth and yield. In addition, temperature changes influence wind direction and rainfall pattern influencing the crop environment. The changes to the total rainfall and its distribution pattern will no doubt have varying consequences on growth and yield of non-irrigated plantation crops such as tea. In addition to the direct effect of climatic changes on crop production, pest behaviour and disease infestations impacted by environmental changes can largely influence land productivity. The chemical composition of leafy materials and inherent quality of the end-product of agricultural crops such as tea are closely related to the prevailing environmental conditions. Therefore, climate change impact assessments have caught greater attention of scientists. Such assessments pave way for identification of most appropriate adaptation measures to minimize adverse impacts of climate change on agriculture.

2.2. Present Status of Tea Industry in Sri Lanka

Presently, there are approximately, 205,000 ha of tea in 14 administrative Districts in Sri Lanka. Around 75% of the total tea area is planted with VP tea cultivars (Fig. 2-1) and the balance occupies old seedling tea (Fig. 2-2). Of the total extent, about 58% isin the hand of smallholders who own less than 20 ha each and the balance is managed by the Regional Plantation Companies. Green leaf collectors, manufacturers (tea factories), value added tea producers, brokers, traders/ marketers and service providers & input suppliers are the other stakeholders of the tea industry in Sri Lanka. There are nearly 400,000 smallholders engaged in tea cultivation and about 75% of them are growing tea in the low country Districts such as Ratnapura, Galle, Matara and Kalutara. Tea has become the major source of income of the majority of these smallholders. Large number of estate workers and their families are resident in large tea estates (Corporate sector) and their livelihood is the earnings from field and factory work (Fig 2-3). Approximately, the tea industry supports a population of over 2million, which is about one tenth of the total population in Sri Lanka.

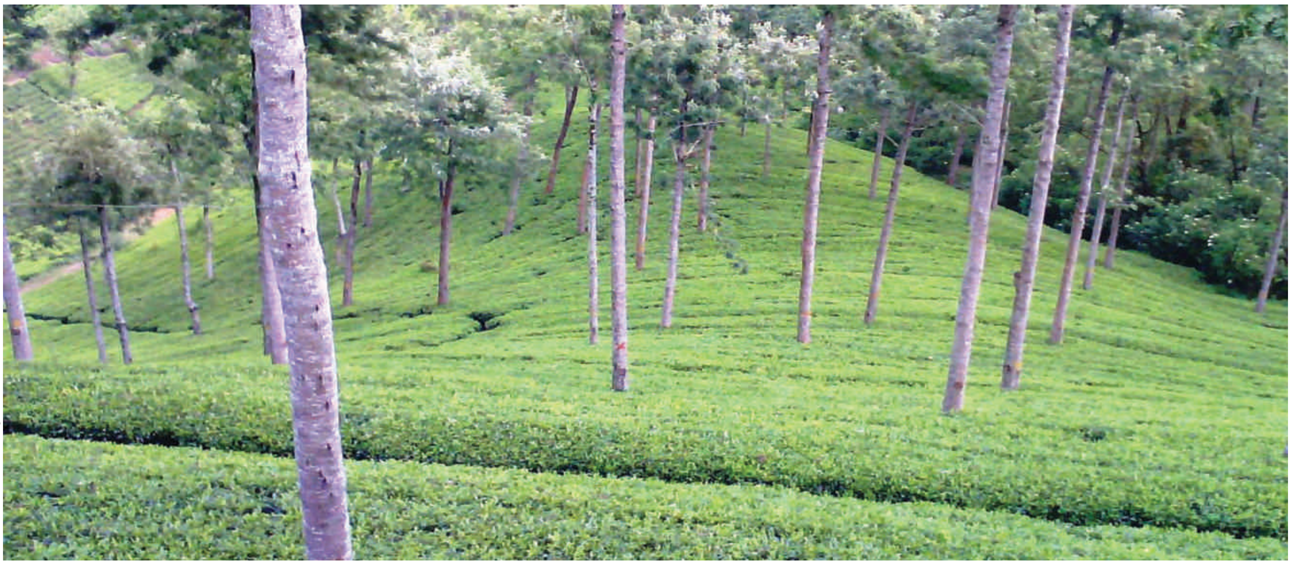

Figure 2-1 VP (Vegetatively Propagated) tea field in Sri Lanka

Figure 2-2 Old seedling tea field in Sri Lanka

The tea industry immensely contributes to the national development in Sri Lanka. Sri Lanka produced 338 million kg in 2014 (Central Bank, 2014), recording an average yield of about 1650 kg/ha/yr. The contribution of tea smallholdings sector with a higher land productivity (2000 kg/ha/yr) than the corporate sector is about 73%. There has been a significant increase in tea production at low elevation due to expansion of tea smallholdings sector in the last few decades (Fig 2-4). Presently, Sri Lanka is the fourth largest tea producer in the world contributing to about 7% of the world tea production. Around 93% of tea produced in Sri Lanka comprises of Orthodox Black Tea and the balance is CTC (6%) and Green tea (1%). More than 90% of tea produced in Sri Lanka is exported and 60% of them are in the value added form. Presently, it is the second largest tea exporting country covering about 17% of the world tea exports. Tea exports to more than 140 countries earned about 1.6 billion USD in 2014 as foreign exchange. Majority of tea exports from Sri Lanka (68%) goes to Middle East and CIS countries.

The profitability and sustainability of the tea industry is largely determined by the level of productivity in each of the above sectors and tea prices. In this context, land and labour productivity takes high priority as tea cultivation is known to be highly labour intensive. Sustainability of the industry is vital not only due to its socio-economic importance, but also in the environmental aspects as majority of tea lands in Sri Lanka are found on steep terrains and in watersheds feeding river system of the country that are vulnerable to erosion and degradation of soil in the event of poor management and abandonment of tea lands.

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Figure 2-3 Corporate sector tea estate in Sri Lanka

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Figure 2-4 Tea smallholding in Sri Lanka

2.3. Tea Growing Regions in Sri Lanka and Climatic Condition

There are three main climatic zones in Sri Lanka *viz*. Wet zone (W), Intermediate zone (I) and Dry zone (D), demarcated on the basis of annual rainfall quantity. They have been further sub-divided based on elevation with clear temperature variations. Accordingly, regions below 300 m above mean sea level (*amsl*) fall into the low country (L). Those between 300-900 m *amsl* are identified as the mid country (M) and those above 900 m *amsl* belong to the up-country (U). Finally, they are categorized into 46 Agro-Ecological Regions (AER), with approximately homogeneous climatic and soil conditions (soil series and landform). However, historically, tea industry in Sri Lanka uses a different system of categorization (tea elevations) *viz*. below 600 m *amsl* as Low-grown tea (Low country), 600-1200 m *amsl* as Mid-grown tea (Mid country) and above 1200 m *amsl* as High-grown tea (Up country) (Fig 2-5). When water requirement and soil conditions are considered, the Wet zone, and a considerable portion of the Intermediate zone are basically suitable for tea cultivation (Watson, 1986). Accordingly, around 25 out of 46 AER have varying extents of tea lands (Fig 2-6).

2.4. Climatic conditions in tea growing Agro-Ecological Regions (AER)

2.4.1.Up country wet zone

There are four AERs growing tea in the Up country wet zone *viz*. WU_1, WU_{2a}, WU_{2b} and WU_3. These AERs are differentiated primarily on the basis of differences in the amount and distribution pattern of the 75 percent expectancy (75 pe) of monthly rainfall. The WU_1 is the wettest AER with a 75 pe of >3,100 mm annual rainfall followed, in decreasing order, by WU_2 with a 75 pe value of >2,200 mm, and WU_3 with a 75 pe value of >1,800 mm. In these AERs, January-March has rainfall expectancy of less than 100 mm each (Panabokke, 1996).

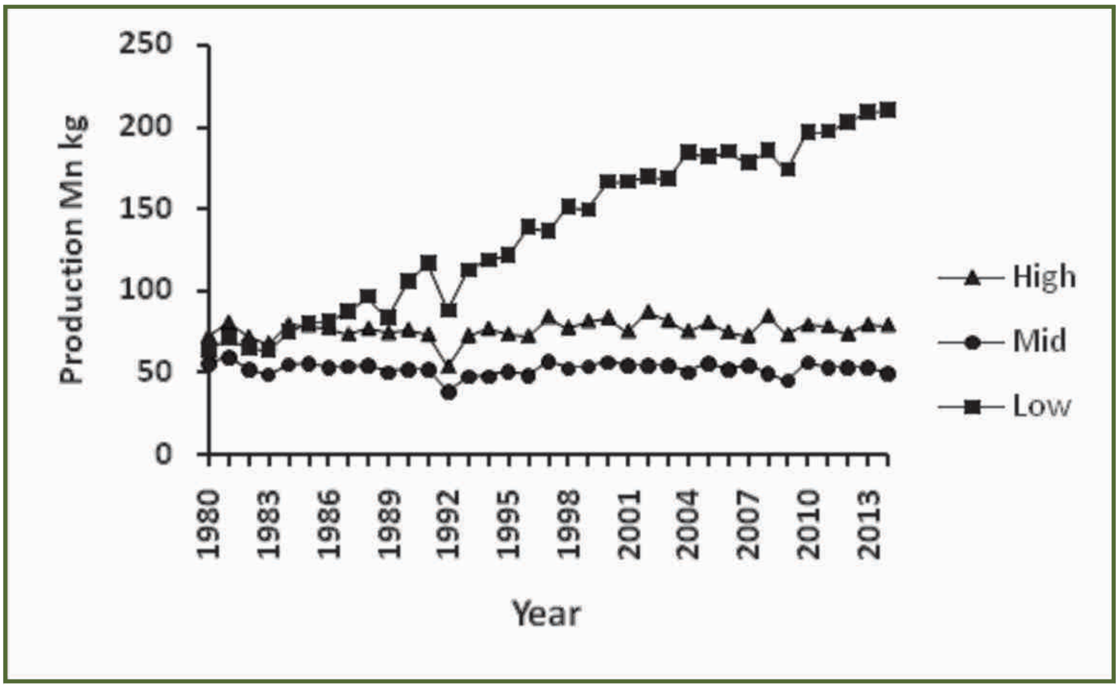

Figure 2-5 Tea production at different elevations in Sri Lanka (High>1200m amsl; Mid-600-1200m amsl and Low<600m amsl)

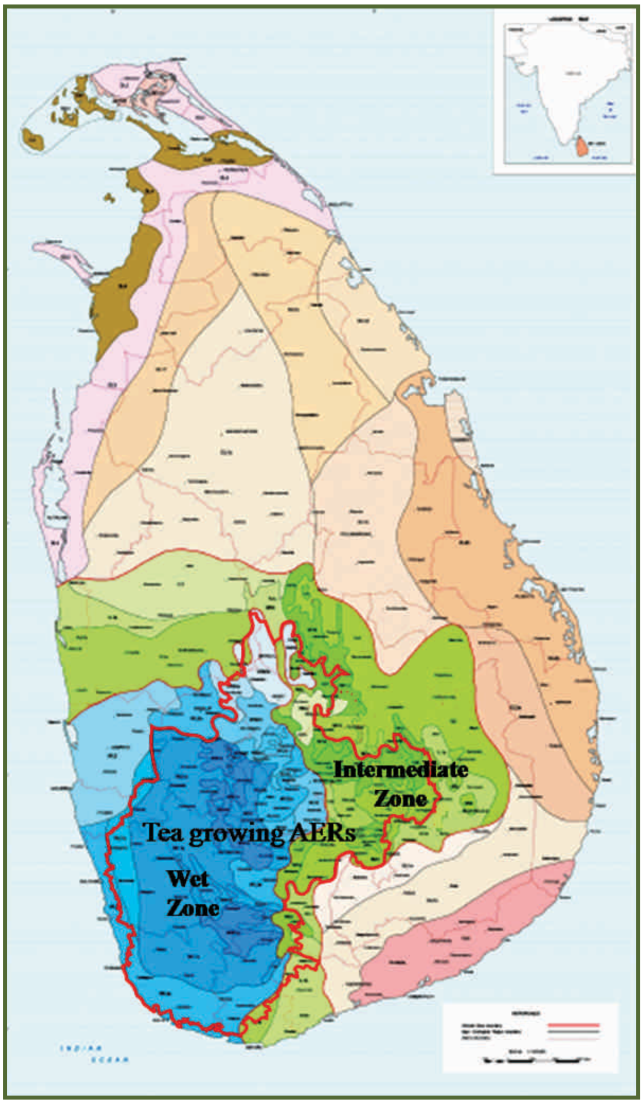

Figure 2-6 Tea growing Agro-ecological regions in Sri Lanka (Source: Department of Agriculture, 2003)

The WU_3 region covers the highest tea elevations in Sri Lanka with a mean temperature around 15.9°C. The mean minimum and maximum temperatures are around11.8°C and 20.1°C) respectively (Table 2-1).

2.4.2. Mid country wet zone

There are six AERs in the mid country wet zone with tea cultivations i.e. WM_{1a}, WM_{1b}, Wm_{2a}, WM_{2b}, WM_{3a} and WM_{3b},. The WM_1 regions have a 75 pe of >2900 mm annual rainfall followed in decreasing order by WM_2 regions with a 75 pe value of >1,800 mm and WM_3 with a 75 pe value of >1400 mm. January-March of WM_2 regions are dry months with less than 100mm rainfall expectancy. In the WM_{3b} region, January-September months receive very less rainfall (Panabokke, 1996).

The ambient temperatures in this elevation are few degrees higher than that of the up country. For instance, WM_{3b} region has recorded a minimum and maximum temperature of 20.3°C and 29.1°C respectively with a mean of 24.7°C (Table 2-1).

2.4.3. Low country wet zone

The AERs cultivating tea in the Low country wet zone are Wl_{1a} Wl_{1b} and $WL_{2a..}$ The AER of WL_{1a} is the wettest regions with a 75 pe of >3,200 mm annual rainfall followed in decreasing order, by WL_2 regions with a 75 pe of >2,200 mm. In the case of WL_1, two months *i.e.* January & February have rainfall expectancy of less than 100mm/month while in the other regions of the low country wet zone this dry period extends up to March. Low grown tea is very susceptible to drought damage during this short dry season due to shallower soils (Panabokke, 1996).

The Low country tea experiences the highest ambient temperatures in Sri Lanka. The mean minimum and maximum temperatures in WL_{1a} over a period of 50 years have been 22.9°C and 31.9°C with a mean of 27.4°C (Table 2-1).

2.4.4. Up country intermediate zone

The tea growing AERs in the up country intermediate zone, well known as the *Uva* region are IU_1, IU_2, IU_{3a}, IU_{3b-e}. The 75 pe of annual rainfall for IU_1 is >2,400 mm, followed by IU_2 with >2,100 mm, and IU_3 with >1,300 mm. The IU_{3d} and IU_{3e} AERs have very low rainfalls. Since the up country intermediate zone is located on the windward side of the northeast monsoon, it experiences the maximum rainfall during the period from October to January. May- September is a dry spell characterized with strong winds and less than 100mm rainfall expectancy.

2.4.5. Mid country intermediate zone

The mid country intermediate zone has 5 AERs with tea cultivations. They are IM_{1a}, IM_{2a-b} and IM_{3a} and IM_{3c}. The 75 pe of annual rainfall for IM_{1a} region is >2200mm. The IM_2 regions receive >1600mm rainfall expectancy while IM_3 region is characterized with very low rainfall expectancy. The IM regions also experience very low rainfall during May-September and in addition, IM_2 and IM_3 regions receive less rainfall during February-March.

Table 2-1Temperature of some AERs representing tea growing regions during 1961-2010

AER	Elevation m amsl	Minimum Temp. °C	Maximum Temp. °C	Mean Temp. °C
WU 3	1893	11.8	20.1	15.9
WU 2a	1382	13.4	23.8	18.6
IU 3c	1225	16.0	24.9	20.4
IM 1a	669	18.6	29.0	23.8
WM 3b	417	20.3	29.1	24.7
WL 1a	34	22.9	31.9	27.4

2.5. Ecological Requirements of Tea

With humid tropical climatic condition in Sri Lanka, tea crop is harvested throughout the year. Tender apical shoots are harvested to manufacture marketable product known as made tea. The yield of tea is determined by the density of shoot population and weight of the shoot at harvest. The size/weight of the shoot at harvest is largely governed by the rate of growth and harvesting (plucking) policies. The sizes of these yield components are influenced by both cultural and ecological (soil and climatic) factors, in addition to genetic potential (inherent factors) of cultivars. Rainfall, temperature and solar radiation are the most important climatic factors governing tea yield in Sri Lanka (Devanathan, 1975; Kandiah and Thevadasan, 1980).

2.5.1.Soil conditions

Root growth of tea is greatly influenced by physical properties of soil such as soil texture and structure that influence water holding capacity and porosity (aeration), and chemical properties such as soil pH and nutrient availability. The critical soil moisture deficit reducing tea yield has been found to vary from 30-50 mm at Low elevation in Sri Lanka (Wijeratne and Fordham, 1996). Tea prefers acidic soils with a pH of about 4.5-5.5. Soils should be deep, permeable and well-drained (Watson, 1986). Additionally, lack of soil organic carbon also limits productivity of tea. Most of the soil characteristics favourable for tea are found in Red Yellow Podzolic soils in Sri Lanka. Moreover, the Reddish Brown Latosolic soils are also categorized as moderately suitable for tea cultivation. These major soil groups in Sri Lanka have recently been further sub-divided into soil series (Table 2-2). Accordingly, there are more than 20 soil series in tea growing regions. Some physical and chemical properties of the soil series are given in the Table 2-3.

The soil organic matter is a source of plant nutrients and has a very important role in formation of soil structure, plant and water relationships, base exchange and soil pH. Heavy rainfall has a direct impact on the unprotected soil disturbing its structure and leading to loss of organic matter through soil erosion. High soil temperature causes fast decomposition of organic matter. The soil organic carbon content increases with increasing elevation in the tea growing regions (Anandacoomaraswamy, 1996).

2.5.2. Rainfall

Rainfall is one of the most important climatic factors limiting the growth and yield of tea. As reported by Watson (1986), an even distribution of annual rainfall of 2500-3000 mm is considered optimal while that of 1200 mm (100mm/month) is considered as the minimum for growth of tea in Sri Lanka. However, Kulasegaram (1972) reported that tea crop suffers when the mean monthly precipitation falls below 50 mm for several months. Moreover, a study conducted by Chenery (1966) showed that the growth of tea could be adversely affected if the precipitation is less than 50 mm over a period of one month. Recent studies have shown that optimum rainfall requirement varies from 223-417 mm/month among different Agro-ecological regions in Sri Lanka (Wijeratne, *et al.*, 2007). Not only dry weather, high intensity of rainfall also causes damages to tea lands mainly due to soil erosion. Absence of proper conservation measures and adoption of ecologically unbalanced agricultural practices pave way for varying degrees of soil erosion.

Table 2-2 Soil series found in different tea growing AERs (Source: Gunaratne, G.P., Tea Research Institute of Sri Lanka)

AER	Soil Series
WL 1a	Pallegoda, Dodangoda, Agalawatte, Boralu, Malaboda, Weddagala
WL1b	Pallegoda, Dodangoda, Agalawatte
WL2a	Boralu, Dodangoda, Pallegoda, Malaboda
WM1a	Malaboda, Weddagala, Pallegoda, Galigamuwa, Homagama, Kandy
WM1b	Malaboda, Weddagala, Pallegoda
WM2a	Kandy, Galigamuwa
WM2b	Mawanella, Kandy
WM3a	Kandy, Matale
WM3b	Kandy, Galigamuwa, Akurana, Matale, Ukuwela
WU1	Maskeliya, Mattakelle
WU2a	Mattekelle
WU2b	Maskeliya, Mattakelle
WU3	Nuwara Eliya
IM1a	Badulla, Mahawalatenne
IM2a	Malaboda, Weddagala, Pallegoda
IM2b	Mahawalatenne, Hunusgiriya, Weligepola
IM3a	Rikillagaskada
IM3c	Bandarawela
IU1	Hunusgiriya
IU2	Ragala
IU3a & b	Bandarawela
IU3c	Bandarawela, Badulla, Mahawalatenne
IU3d	Bandarawela
IU3e	Bandarawela

2.5.3. Temperature

The annual variation of temperature within a tea growing region of Sri Lanka is very narrow. But this is exceeded by the diurnal variation of temperature. The highest diurnal range of the temperature is recorded during the months of February to March. In general, the diurnal range of temperature varies between 8°C in the coastal areas to 14°C in the highlands. The decrease in temperature with the rise in altitude is greater on the western slopes than the eastern slopes of the highlands. In general, the warmest period throughout the island is from April to May and the coolest period is from December-January.

The optimum ambient temperature required for growth of tea is considered to be 18-25°C, and an air temperature below 13°C and above 30°C are found to reduce growth (Carr, 1972; Carr and Stephens, 1992; Watson, 1986; Wijeratne *et al.*, 2007). Although the base temperature for shoot growth of tea is generally considered as 12°-13°C (Carr and Stephens, 1992), it can vary from 7°C (Obaga *et al.*, 1988) to 14°-15°C (Stephens and Carr, 1990). The rate of shoot extension reduces with the rise in altitude.

Table 2-3 Some soil properties of tea lands in main tea growing AERs (Source: Amarathunga, M K S L D 2000)

Soil properties	WL	WM	WU	IM	IU
Depth-cm	79.5	83.5	95.0	80.8	84.0
Gravel %	39.5	40.5	13.5	35.4	28.2
Sand %	51.3	62.6	40.0	53.6	48.6
Bulk Density	1.2	1.2	1.08	1.18	0.86
OC %	1.37	2.30	4.40	2.17	2.60

2.5.4. Day length and solar radiation

Tea is a shade loving plant. Very low as well as very high solar radiation can limit tea production (Mohotti & Lawlor, 2002). Its importance becomes comparatively less than the other factors such as temperature and moisture, under the tropical weather conditions characterized by long day length and high intensity of solar radiation. The annual solar radiation in tea growing regions of Sri Lanka ranges from 5000-6000 MJ m^{-2}. The daily variation is between 4-28 MJ m^{-2}. The maximum solar radiation is received by canopy surface at high altitude could exceed 1000 Wm^{-2}. Of this amount, only 60% are utilised by the tea canopy. A single leaf becomes light saturated at around 350 Wm^{-2} and the whole canopy is saturated at around 800 Wm^{-2} (Anandacumaraswamy, 1996).

In Sri Lanka, the western and southern lowlands have recorded around 2,500 sunshine hours per year. The highlands receive still less sunshine annually, *i.e.* around 1,600 sunshine hours per year. The western slopes of the central highland record a lesser amount of sunshine than the eastern slopes because of the low duration of sunshine during the south-west monsoon period. The highest number of sunshine hours per day was recorded during February and March by almost all the recording station in the island (Panabokke, 1996).

2.5.5. Carbon dioxide

Rising ambient CO_2 concentration increases the CO_2 gradient leading to increase in CO_2 uptake by leaves. The process is known as "CO_2 fertilization effect". This is reported to have a positive effect on leaf and canopy photosynthesis. Field experiments on high CO_2 (600 ppm) conducted over a period of one year in Sri Lanka have shown a significant increase (20%) in net photosynthesis rate of tea leaves. Increase in ambient CO_2 concentration from 370 ppm to 600 ppm was found to enhance tea yield in Sri Lanka by around 33-37% (Wijeratne *et al.*, 2007).

2.5.6. Drought effects

Irrigation is hardly practiced in tea lands in Sri Lanka. Hence, dry weather conditions inflict irreparable losses to tea plantations (Fig 2-7). For instance, tea production in 1992 declined by about 26% in comparison with that of 1991 due to dry weather (Central Bank, 1992). The financial loss due to dry weather in 1992 in dollar-term was estimated to be about USD 70 million. The drought effects have been more pronounced in the warmer regions with poor soil conditions *i.e.* in low and mid country tea growing regions in Sri Lanka.

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Figure 2-7 Tea field affected by dry weather conditions in Sri Lanka

2.6. Vulnerability of Tea Plantations in Sri Lanka to Climate Change

Assessments on climate change impacts on tea carried out during 2002-2004 have shown that the majority of tea plantations in Sri Lanka, except those at high elevations (>1200m), are likely to be adversely affected due to climate change. Mid elevations seem to show mixed/neutral impacts (Table 2-4). The adverse impacts are attributed to higher temperatures and dry weather conditions that overweigh the beneficial impacts of increasing CO_2. The ambient temperatures (maximum and minimum) of most of the tea growing regions except maximum temperature in Nuwara Eliya, WU_3 (highest elevation) have increased over the last 50 years. Of the tea growing regions, the highest temperature rise (0.04°C/yr) have been recorded in Badulla (IM). The rising temperatures are found to be beneficial only at higher elevations where the present ambient temperatures are lower than that of the optimum for tea (around 22°C). In addition, poor soil conditions and ageing of tea bushes in tea lands make them more vulnerable to such adverse impacts (Wijeratne *et al.*, 2007).

A recent study conducted in Sri Lanka has classified all tea growing AERs into three vulnerability classes (Highly vulnerable, Vulnerable and Less/Not vulnerable). Weather data (rainfall and temperature) over a period of 1961-2010 and some important soil characteristics of tea growing regions were considered in this analysis (Wijeratne and Chandrapala, 2013). According to the results, tea lands in WL1a, WL1b, WL2a, WM2a, WM2b, WM3a, IM2b, IM3a and IM3c Agro-ecological regions are reported to be highly vulnerable while those in WM1a, WM1b, WM3b, IM1a, IM2a, IU3a, IU3d and IU3e are vulnerable to climate change impacts (Fig 2-8). This analysis shows that poor soil conditions also contribute to heighten the vulnerability of tea lands to climate change (Table 2-5).

Table 2-4 Projected tea yields for 2050 at different elevations in Sri Lanka (Wijeratne *et al.*, 2007)

Model	Yield (kg/ha/yr)		
	Low elevation *(Ratnapura)*	Mid elevation *(Kandy)*	High elevation *(Nuwara Eliya)*
Baseline	2489	2217	2454
CGCM-A1F1	2314	2217	3108
CGCM-B1	2380	2228	3072
HadCM3-A1F1	2348	2174	3130
HadCM3-B1	2419	2189	3115
CSIRO-A1F1	2401	2246	3167
CSIRO-B1	2472	2245	3137

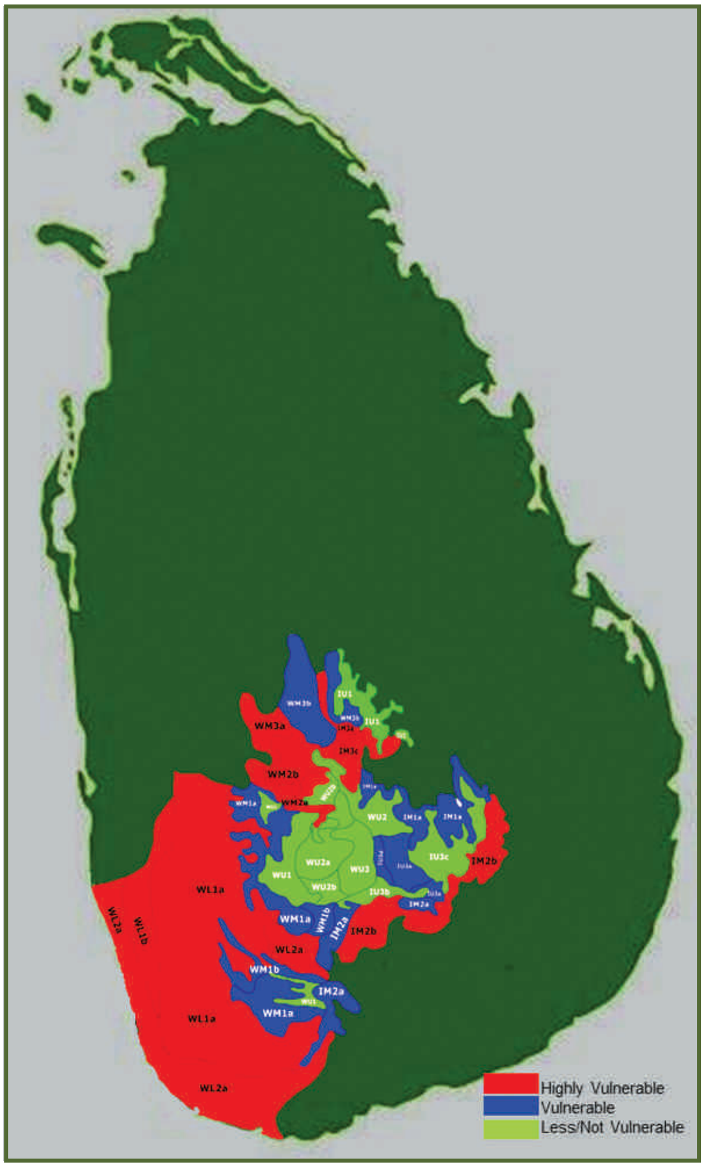

Figure 2-8 Vulnerability of tea growing regions to climate change in Sri Lanka

2.7.Adaptation Measures for Tea Plantations

2.7.1.Options for adaptation to climate change impacts on tea

Assessments of climate change impacts on tea in Sri Lanka have shown that except those at higher elevations (Up country), tea plantations in the other regions will likely to be adversely affected. Adverse impacts are due mainly to high temperatures and dry weather conditions those that overweigh the beneficial impacts of rising CO_2 in those regions. The beneficial effects at higher elevations are due to prevalence of lower temperatures than that of optimum for tea (around 22°C) at present. However, the potential benefits of rising CO_2 at high elevations could be reduced by dry weather conditions and possible changes in pest and disease incidences. Hence, adaptation measures proposed below will benefit all the regions and can be considered as *"No Regret Strategies"*.

Table 2-5 Overall index of vulnerability of tea growing regions to climate change (Wijeratne & Chandrapala, 2013)

Region	Rainfall changes	Temperature rise	Soil factors	Points (No of *)	Overall Index
WU 1					
WU 2a					
WU 2b	*			1	
WU 3	**			2	
WM 1a		*	**	3	*
WM 1b		*	**	3	*
WM 2a	*	*	**	4	**
WM 2b	*	*	**	4	**
WM 3a	*	*	**	4	**
WM 3b		*	**	3	*
WL 1a		**	**	4	**
WL 1b		**	**	4	**
WL 2a		**	**	4	**
IU 1	*		*	2	
IU 2			-		
IU 3a	**		*	3	*
IU 3b			-		
IU 3c			-		
IU 3d	**		*	3	*
IU 3e	**		*	3	*
IM 1a		*	**	3	*
IM 2a		*	**	3	*
IM 2b	*	*	**	4	**
IM 3a	**	*	**	5	**
IM 3c	*	*	**	4	**

As the cost of replanting/new-planting is very expensive and the pay-back period is comparatively long, it is prudent that the most suitable regions and lands for tea cultivation are identified for future planning. In this strategy, land suitability classification and mapping should be undertaken, on national, regional and plantation level. After identifying suitable lands for tea, less productive lands with marginal soil conditions can be diversified into other uses such as mixed-cropping and fuel wood or timber plantations. Marginal tea lands can also be converted to thatch banks (planting of rehabilitation grasses) in order to obtain green manure for composting and improvement of soil fertility in productive tea lands.

The cost of adaptation measures could inflate the total cost of production of tea. Further, they require labour which is a scarce input at present. Therefore, tea growers should be assisted with a reliable weather/rainfall forecast in order to help them to prepare tea lands for facing adverse weather conditions better.

Suitable adaptation measures need to be carefully identified so that the adverse impacts of extreme temperatures and moisture stress are minimized and beneficial effects of CO_2 enrichment is properly exploited. The most appropriate adaptation to climate change in the long run, is crop improvement *i.e.* developing varieties and graft combination etc that are tolerant to heat (high temperature) and moisture stress and well adapted to varying soil conditions (Fig. 2-9). However, such efforts require more time and funds. Therefore, adaptation measures aimed at minimizing drought effects, changing micro-climate around tea bushes to cushion the effect of rising temperatures and improving soil conditions should be immediately put into practice in tea lands while continuing with research and development activities on crop breeding and selection for climate resilient cultivars.

Considering the changes to rainfall pattern and increase in the dryness of the environment under global warming, rainwater harvesting and collection within large plantations and re-use them for irrigation would also minimize drought effects.

2.7.2. Adaptation measures for Low country region

Low country tea growing regions experience the highest temperature regimes in Sri Lanka. As already discussed, low country region is very important for the tea economy in Sri Lanka mainly because it contributes to around 62% of the national tea production (2014) and the majority of smallholders are clustered in this region. Further, Low grown tea often fetches a higher (average) price in the world market than those produced in the other regions. Vulnerability of tea lands at low elevations is mainly due to high temperature regimes and poor soil conditions. The low country tea growing soils have less organic carbon content and the rate of burning of organic matter is also high. As the present ambient temperatures at low elevations are above the optimum for tea, further increase in temperature will make the situation worst. Increasing temperatures not only have direct impacts on growth physiology of tea, but it can also increase evaporational losses of soil moisture and accelerate burning of organic matter from soils.

In this strategy, adaptations should target the improvement of soil conditions to retain more moisture and reducing ambient temperature around tea bushes (improving micro-climatic conditions).In this context, soil and soil moisture conservation measures by establishment and maintenance of drain system and stone terraces, mulching and envelope forking or burying of prunings in tea lands take priority (Fig 2-10). Application of compost and green manure help sustain organic matter status of tea soils. Additionally, such practices will improve fertilizer use efficiency and moisture retention capacity of soils thus sustaining productivity (Amarathunga & Wijeratne, 2001). Drip or sprinkler irrigation systems (Fig. 2-11) can also be used to mitigate drought effects and improve tea yield. Investigations in Sri Lanka have shown that the tea yield can be doubled by irrigation of tea bushes during dry months (Anon 2001 & 2002). A good stand of shade trees in tea reduces ambient temperature around tea bushes, increases RH, adds organic matter to soil and reduces drought effects (Sivapalan, 1993; Navaratne, 1992; Yatawatte, 1992). Therefore, establishment and management of shade trees in tea lands at low elevations are very important (Fig 2-12).

Figure 2-9 Differential cultivar response to dry weather (Sri Lanka)

Figure 2-10 Burying of pruned branches (prunings) (Sri Lanka)

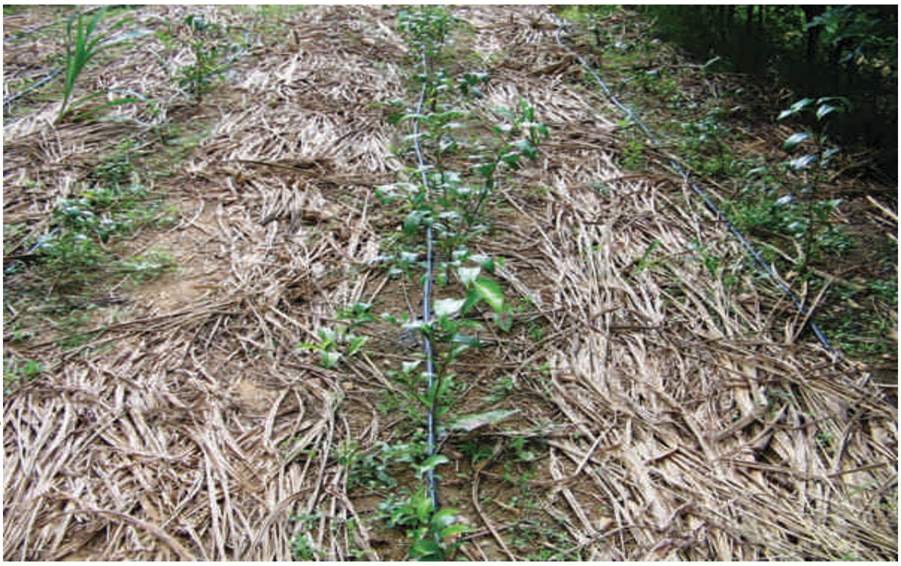

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Figure 2-11 Drip irrigation and Mulching in young tea (Sri Lanka)

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Figure 2-12 High and medium shade trees in tea (Sri Lanka)

2.7.3. Adaptation measures for Mid country region

About 15% of the total tea production in Sri Lanka (2014) comprises of mid grown tea. Present temperatures in the mid elevation are in the optimum range for tea. However, further increase in temperatures could make them less productive. Soil conditions in this region are often not very conducive for tea cultivation. Trends of rainfall variations show possible increase in dryness of the environment. Considering those limitations, same adaptation measures proposed for low elevations are applicable for the mid elevations too. Of those cultural practices, priority should be given for soil and soil moisture conservation and soil improvements in the mid country AERs of the wet zone. Additionally, shade is equally important for tea in the mid country Intermediate zone where the environment is comparatively dry.

2.7.4. Adaptation measures for up country (Intermediate zone) AERs

Of the tea growing AERs, those that are at high elevation are reported to be comparatively less affected by climate change due to prevalence of low temperatures and better soil conditions. However, some up country AERs in the Intermediate zone, such as IU3a, IU3d and IU3e are ranked vulnerable for climate change. Those AERs known as "Uva region" is of prime importance to the tea industry in Sri Lanka due to production of unique seasonal quality teas that fetch premium prices. The Uvaregion with about 70% of old seedling tea contributes to about 8% of the total production. Considering these factors, soil and soil moisture conservation and soil improvements discussed above are important to reduce adverse impacts of climate change. However, irrigation during dry months may not be advisable in some of the Intermediate zone AERs famous for seasonal quality teas as it could deteriorate the development of flavor compounds.

The adaptation measures described above are given in a summary form below.

2.7.5. Use of drought and heat tolerant tea cultivars

- Planting of tea cultivars, grafted plants and improved seedlings that can withstand adverse (dry) weather conditions, heat and poor soil conditions.
- As the pest behaviour and disease infestations can vary with climatic changes, use of a basket of cultivar including those with pest and disease tolerance is important.
- New recommendations on tea cultivars should be done based soil and climatic conditions of Agro-ecological regions

2.7.6. Crop diversification

- Select only good lands with better soil conditions for re-planting of tea and other lands that are characterized with greater soil degradation should be diversified into other economic uses.
- Lands that is not very suitable for re-planting of tea can be used for intercropping/ mixed-cropping with other perennial tree crops such as rubber, coconut, fruit and spices when soil and environmental conditions favour cultivation of those crops.
- Similarly, low yielding tea lands with marginal soil conditions can be diversified into fuel wood (energy plantations) or timber plantations.
- Converting unproductive tea lands into *"thatch banks" i.e.* planting of rehabilitation grasses such as Mana or Guatemala is another alternative which contributes to production of green manure/compost.

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2.7.7. Soil improvements and irrigation

- Adoption of soil conservation measures (drains, terraces, bunds etc)
- In *situ* generation of compost by planting of green manure crops in vacant patches & along the fences, etc.,
- Planting of green manure crops as SALT (Sloping Agriculture Land Technology) hedge rows
- Burying of *prunings* and envelop forking
- Mulching in young tea lands
- Irrigation of tea during dry weather

2.7.8. Establishment and management of shade trees

- Establishment and management of high and medium shade trees to reduce temperature and modify micro-climate.

2.7.9. Seasonal Weather forecasting

- Seasonal weather forecasting helps tea growers to prepare tea lands for facing adverse weather conditions better.

2.8. Implication and Barriers for Adaptation to Climate Change

The level of implementation of adaptation measures depends on the profitabilityof tea cultivations and or capacity of tea growers to pay (affordability) for such practices and availability of other resources such as labour. Additionally, lack of awareness on the climate change and its impacts has also been responsible for poor response to climate change mitigation and adaptation. Considering the economic and social importance of the tea industry, raising the awareness on climate change impacts and provision of financial assistance to tea growers will no doubt increase the rate of adoption of those well-known Good Agricultural Practices that are often reported to be *"No-Regret Strategies"* consequently minimizing adverse effects of climate change on tea.

3. Impact of Climate Change on Tea and Adaptation Strategies (Kenya)

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3.1. Background Information of the Kenyan Tea Industry

3.1.1. Importance of Tea Industry to Kenyan Economy

The tea industry plays an important role in the social-economic development of the country. In 2014, the industry generated Ksh. 120 billion from export and domestic sales. It is the leading single commodity foreign exchange earner for the country and a source of regular income to over 600,000 small scale tea growers. The small scale growers contribute about 65% of Kenya's tea production while the large Estates accounts for 35%. In addition, the industry has encouraged rural wealth distribution and directly and indirectly created employment for over 6 million people, 10% of the population of Kenya, along the value-chain. Establishment of tea factories has also resulted in industrialization and infrastructure development in rural areas. There are several enterprises along the tea value chain.

As a rural based enterprise, tea contributes to rural poverty alleviation since it directly contributes to 4% of the country's GDP and it is also an environmental conservation measure through its actions on carbon sequestration and erosion prevention by binding of soil by the roots of the tea plants.

3.2. Countrywide Tea Suitability Map

Currently, tea in Kenya is grown in 18 counties and the green outlines in Fig 3-1 below show the national tea growing areas across the country. Tea growing has traditionally been confined to Zone I, which is humid. But due to demand and perception that it is a better and stable cash crop (may also be due to problems in other sectors for example coffee); there has been a push to have tea in Zone II, which is sub-humid. The restriction of tea growing to this zone has mostly been through the 'Brown line' which is a demarcated lowest altitudinal boundary for tea growing in Kenya in 1965 and recently reviewed in 2012. Reference to this line has not changed over the years, despite perceived changes in climate and weather variability.

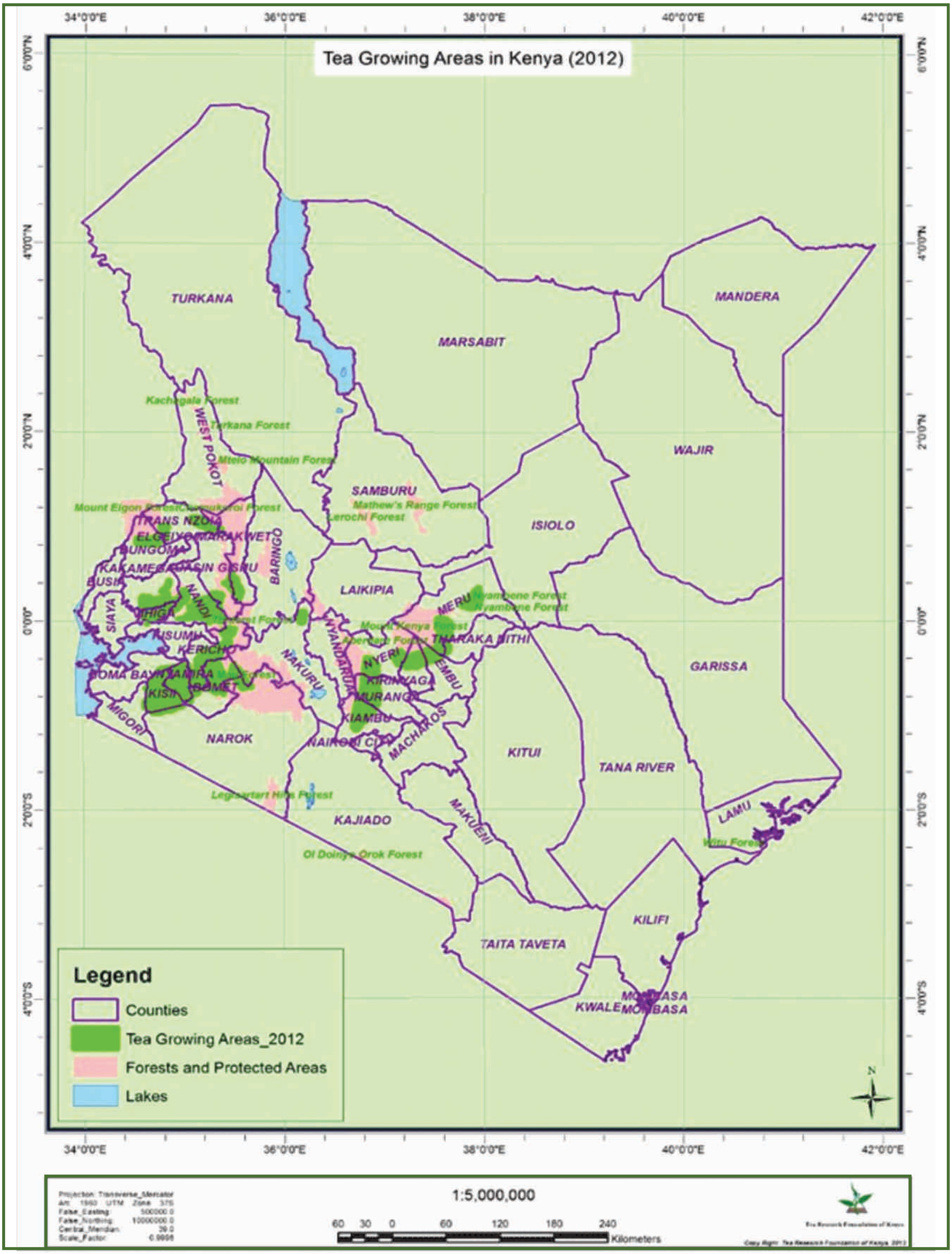

Figure 3-1 Tea Growing Areas as on 2012

3.3. Climate Change evidence in Kenya

Climate change signals already evidenced in Kenya include; temperature rise, unpredictable rainfall trends and increasing frequency of extreme weather events e.g. hail storms, drought and frost. Some of these changes have been recorded in tea growing areas. In Kericho an annual rainfall decrease of 2.84 mm over a period of 54 years (153 mm decrease) and annual temperature rise of 0.002°C over period of 54 years (0.1°C increase) have been recorded. Findings from a recent study (Bore *et al.,* 2013; Cheserek *et al.,* 2015;) conducted in Timbilil Tea Estate, Kericho, Magura Tea Estate, Sotik and Kangaita Tea farm, Kirinyaga, showed that all Estates have experienced increasing temperature trends with an annual rise of 0.02°C at Timbilil, 0.22°C in Sotik-Magura and 0.01°C in Kangaita, respectively.

3.4. Evidence of climate change in the tea growing areas

Evidence of climate change in the tea growing areas of Kenya is characterized by the rising trend of hail (Fig. 3-2), increasing incidences of frost, variability in rainfall trend and temperature rise, leading to decline in yields of tea. There has also been noted decadal increase in the magnitude of soil water deficits (SWD) from 1964 to 2014, indicating that the soil was becoming drier over the investigated period. The apparent SWD decrease between 2004 and 2014 was occasioned by heavy rains in most months of 2014.

3.4.1. Hail

Hail is common in most tropical countries especially in mountainous stations and generally above 1200 m amsl and its damage is well-known and documented in areas where hail falls frequently. In the western part of Kenya, hail is an important climatic variable causing huge damage and losses to the tea industry in most years in the recent past. In areas like Kericho, Sotik and Nandi Hills of Kenya, net loss of tea green leaf due to hail is estimated at over 2 million kilograms per year based on documented reports from Kericho, Nandi and Sotik areas. However, this loss is deemed to be higher because the hail reports received and documented at the Tea Research Institute are from large scale company owned farms, while a small proportion of small scale farmers do not submit reports comprising around 64% of tea farmers in Kenya.

Figure 3-2 Hail damage on tea tender pluckable shoots

Hailstorms occur at an average of 80 days within a year. The highest incidences occur between May and August causing heavy damage on tea plants resulting in significant tea yield losses. In 1961, the loss attributed to hail was estimated to exceed 907,185 kgs of made tea in Kericho alone. To counter such huge yield losses, Taylor (1961) suggested that explosive rockets be fired into hail bearing clouds with the aim of dispersing them. Between 1967 and 1975, Atmospheric Incorporated Limited of the United States of America in conjunction with the Kenya Tea Growers Association conducted a hail suppression programme in Kericho and Nandi areas by radar identification of potential hail producing cloud cells followed by seeding the cells with silver iodine (McGrigor, 1963; 1969). However, the pilot scheme was not effective and did not produce the desired results in suppressing hail and was discontinued (Henderson, 1966; Othieno, 1972). Consequently, the damage on tea due to hail still continues to pose a major challenge to the tea industry.

A hail reporting scheme was started in the tea industry in May 1973 to monitor occurrences of hail incidences and document the amount of crop loss due to this weather phenomenon. Since then, the Estate tea growers in Western Kenya have continued with this regular hail reporting scheme which provides basic information on hailstorm timing, physical characteristics of hail stones, accompanying wind direction and speed, amount of rainfall on the day, area of tea hit, state of the tea bushes at the time of damage and finally, an estimate of crop loss based on mean of yields from previous three plucking rounds prior to the storm (Mwebesa, 1978). These recordings indicate that there is no month of the year without hail damage to tea and the peaks are around August-September and troughs around November-December (Mwakha, 1983).

A close review of hail reports has shown that hailstorms occur as early as 11.00 am and as late as 10.00 pm, or even later as some night storms were not timed. More than 90% of hailstorms occur between 1.00 pm and 5.00 pm. These are normally windy and 88% of the accompanying winds are reported to blow from North-East, South-East or East (Othieno, 1972). The complexity of hail formation is probably exemplified by the physical characteristics of hailstones. These have been observed to vary in size from 0.05 mm to 10mm diameter. The shape is round, oval or irregular and the surface is smooth or rough (serrated). The colours of the stones are opaque, milky, pale white or clear and the texture either solid or soft. Hailstones precede normal raindrops or are accompanied by raindrops in the early part of a shower (Burt, 2007; Mwakha, 1983). Currently, the estimated loss of green leaf tea yields is 2.7 million kilograms per year, based on reports from Kericho, Nandi and Sotik areas (Bore, 2010) and the magnitude of the loss could be even higher in the months of September which has a higher probability of hail occurrence (Bore *et al.*, 2011). The findings also confirmed that the small sized hailstones caused more serious damage on tea compared to medium to large sized ones.

3.4.2. Rainfall

Tea cultivation in Kenya depends on rainfall for the maintenance of adequate soil moisture levels. Annual rainfall of 1200 mm is considered essential. However, the most important factor is the distribution. Inadequate rain imparts critical soil moisture stress on plants. During drought, it is estimated that about 20% of tea crop is lost. Apart from drought, frost and hail damage is also occasionally experienced. The rainfall trends show that rainfall is becoming more unpredictable

and poorly distributed throughout the year. Some months receive heavy rainfall over a short period of time followed by prolonged dry periods. This has resulted into less water in the soil to support the crop as shown in the graph below (Fig 3-3).

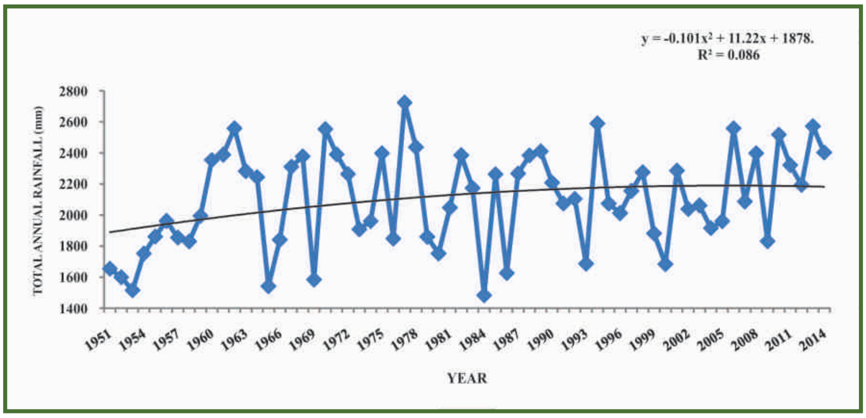

Figure 3-3 Dwindling rainfall trend from 1951 to 2014

Currently, due to climate change, there are more droughts occurrences that greatly reduce tea yields. The major effects arise from deviation outside the favorable conditions such as elevated temperatures and declining soil moisture levels leading to osmotic stress that induces numerous biochemical and physiological responses in tea (Duan, 1992). Tea plant can respond to water stress at morphological, anatomical and cellular levels with modifications that allow the plant to avoid stress or to increase tolerance (Hilton *et al.*, 1973).

3.4.3. Soil water deficits

The soil water deficits (SWD) as determined by the Hess (1994) model showed that the deficits are equally on the rise (Fig 3-4). Generally, high SWD have been prevalent in the period, January to March, a period associated with tea plant water stress and low tea crop season. During this period, due to low crop, some of the tea factories operate under capacity. Occasionally, the SWD be as high as 400 mm, but the critical levels that can cause extreme water stress characterized by temporary tea growth is about 120 mm. Soil water deficit with a linear decrease of -57 mm for every ten-year period average has been observed.

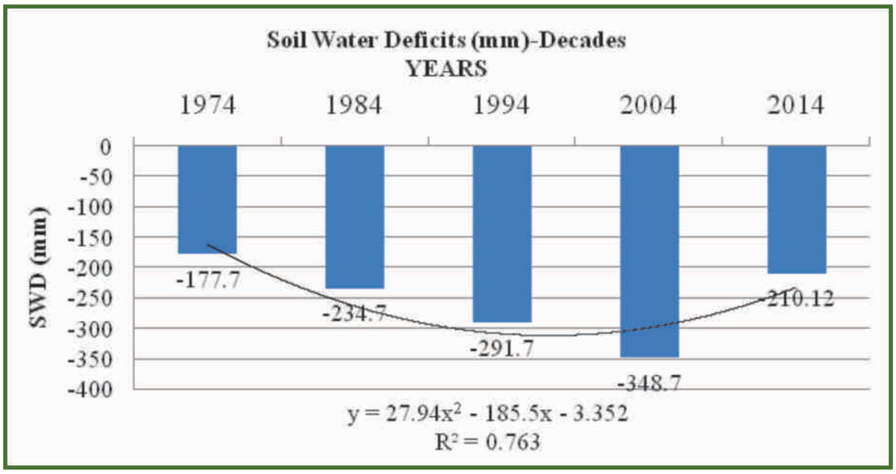

Figure 3-4 Decadal Soil Water Deficit trend at Timbilil Agro-met station

Inadequate rain imparts critical soil moisture stress on plants. Research on tea and its water requirements in Kericho concluded that the critical Soil Water Deficit is about 30mm above which there is a linear decrease in yield of about 1.1 kg ha^{-1} $week^{-1}$. Generally, during drought, severity of annual yield losses varies from as low as 12-20% depending on the clonal material planted and the length of the drought period.

3.4.4. Temperature

Temperature trends from data collected at the Tea Research Institute's Timbilil meteorological station indicates rising temperature over time as shown in Fig 3-5. The rise in temperature over time is a crucial indicator of global warming. However, the temperatures are still within the limits for tea production, which requires temperatures of between 14 and 30°C below or above which tea production is adversely affected.

Based on the indicators described above, a suitability projection was conducted to model the regions that would still be suitable for economic production of tea by the year 2075. This would help farmers in decision making and institute early precautionary measures in order to grow tea only within the suitable zones or find a suitable cropping enterprise as a precautionary measure in crop diversification. The unsuitable zones or the less suitable zones should be avoided and diversification to other annual crops such as cereals or perennial crops should be embraced as an alternative to tea.

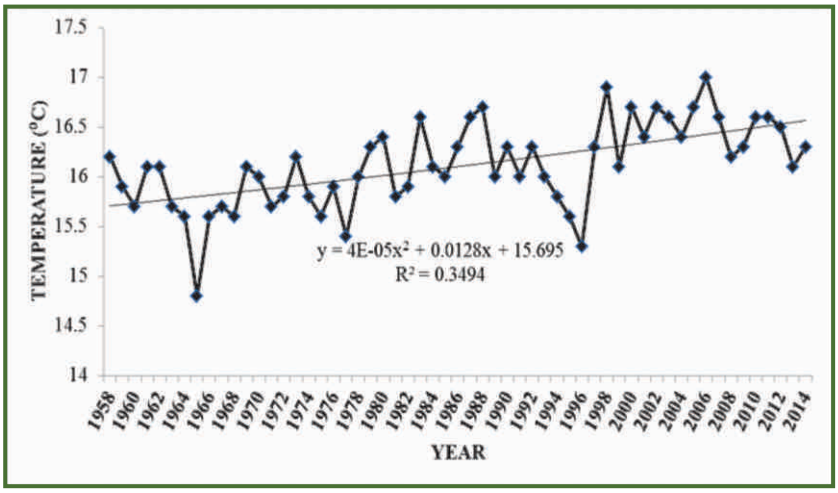

Figure 3-5 Rising temperature trend within the Tea Research Institute

3.4.5. Future scenario

The overall climate will have less seasonal variations throughout the year. The mean air temperature in East Africa is predicted to increase by about 2.5°C by 2025 and 3.4°C by 2075 while rainfall is predicted to increase by about 2% by 2025 and 11% by 2075. The implication is that the distribution of suitability of tea growing within the current tea-growing areas in Kenya will decrease. This is attributed to rainfall distribution and not amounts of rain received. The rise in mean air temperatures beyond the threshold of 23.5°C is likely to occur. The GIS analysis indicated that suitability of tea growing areas is expected to decline by 22.5% by the year 2075 while a suitability increase of 8% is expected by 2025.

Fig 3-6, 3-7 and 3-8 below represents the areas suitable for tea production in Kenya in the next 60 years. The maps were developed in a GIS environment using climate data from Kenya Meteorological Service.

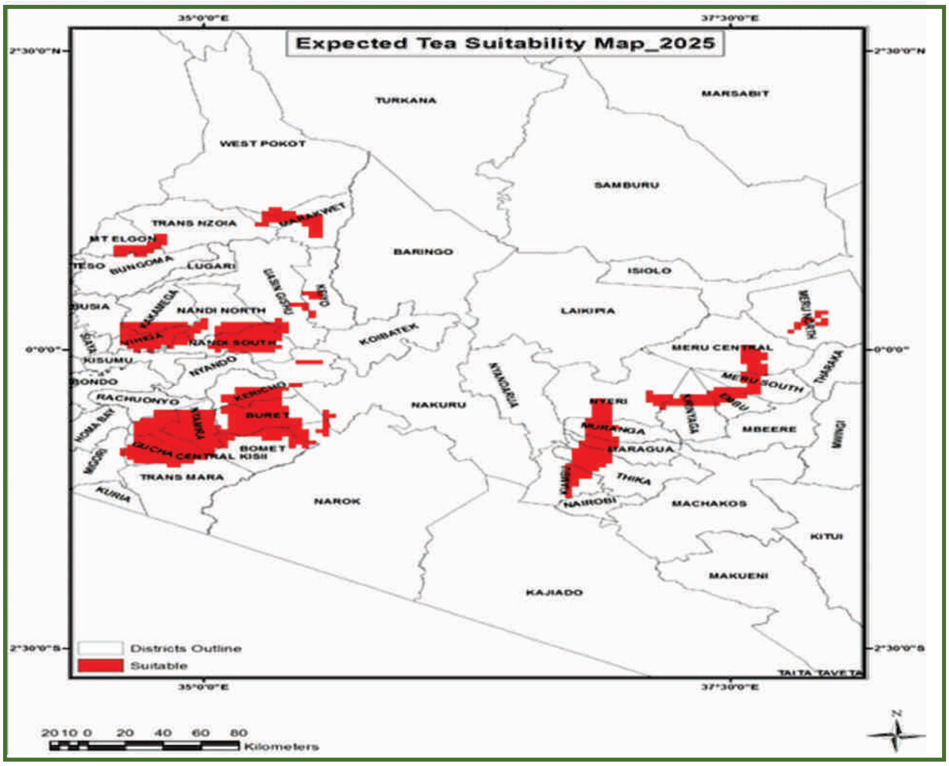

Figure 3-6 Projected suitable areas for tea growing in Kenya for 2025

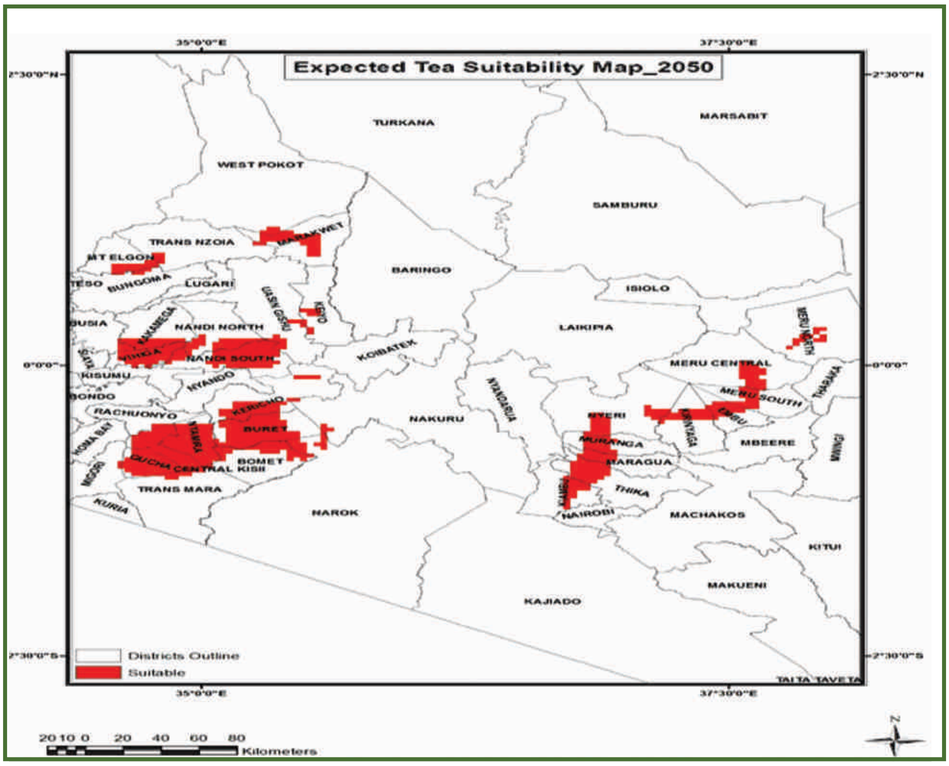

Figure 3-7 Projected suitable areas for tea growing in Kenya for 2050

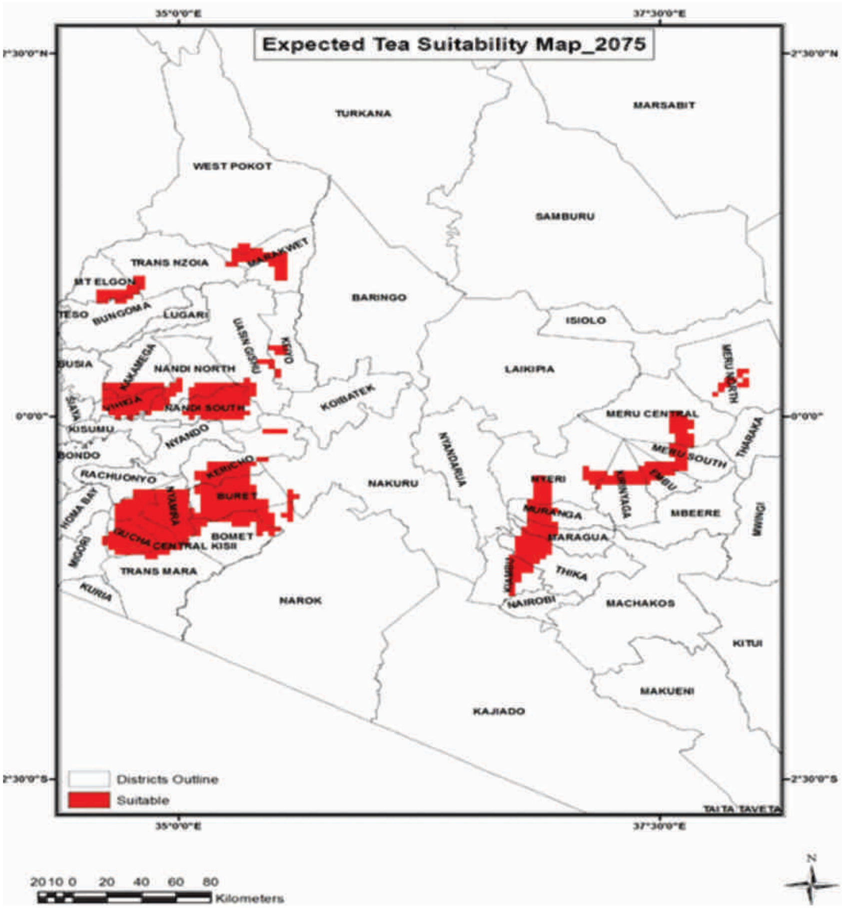

Figure 3-8 Projected suitable areas for tea growing in Kenya for 2075

3.4.6. Frost

Frost on the other hand is in a much lesser occurrence (Fig 3-9a), but when it does strike, there are huge losses incurred (e.g. in the year 2000 in the West of Kenya). It has received less attention, but there are indications that incidences could be increasing.

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Figure 3-9(a) Frost effect on tea field, (b) shade trees help in reducing magnitude of damage

One of the major impacts of climate change is the occurrence of severe weather conditions either in the form of hails, frost or drought. In the western tea producing counties of Kenya, for example; Kericho, Bomet (Sotik) and Nandi, net loss of tea green leaf due to hail is estimated at over 2 million kilograms per year depending on severity of hail occurrence in these areas. The reported cases are mainly from the large estates while few of the small scale- farmers report incidences.

Generally, frost occurrence is on valley bottoms and low lying areas. Analysis of long-term data suggests that the frost incidences are on the rise. Early January, 2012, frost hit all the tea growing areas across most tea producing counties causing up to a maximum of 30% yield losses. The crops could not be harvested until after 3 months from the time frost occurred.

3.4.7. Use of GIS technologies

Among the technologies that have been embraced is the ongoing calibration of the MODIS data to help in prediction of frost occurrence. The system consists of a Wireless Sensor Network that is capable of capturing and sending the weather variables to a receiving concentrator. In case of frost occurrence it would be possible to know the weather parameters of the day and future predictions be done in time to avoid crop losses. The project is conducted in collaboration with Regional Centre for Mapping of Resources for Development (RCMRD). One of the systems is shown in Fig 3-10.

Figure 3-10 Wireless Sensor Network (WSN) located in field 12

A tea producer survey was done to assess vulnerability at the producer level, production techniques and risk coping option. The results indicated that the farmers are more vulnerable to climate change scenarios. To cope with these changes, farmers should adopt use of drought tolerant clone and other Good Agricultural Practices. The other aspect is that the farmers have inadequate income from tea during the drought period. This makes farmers more food insecure considering the fact that many farmers have planted all their available land to tea.

3.5. Adaptation and Mitigation Measures for climate change

Tea Research Institute has developed several strategies of adapting to the changing climate related problems and ways of mitigating the magnitude of damage in case of an adverse occurrence. The proposed adaptation measures include; adopting the newly released clones that are bred for drought tolerance and can perform optimally in harsh environmental conditions, soil and water conservation methods, field management activities to reduce impact of droughts and frost incidences.

3.5.1. Fertilizers

Due to the frequent removal of two leaves and a bud for processing, tea soils need constant replenishment of nutrients. The main nutrients removed through harvesting are Nitrogen (N), Phosphorus (P) and Potassium (K). According to Kamau (2008), N is the most important nutrient and its removal through plucking ranges from 40 to 160 kg/ha depending on tea yields of about 1 to 4 t/ha. Replenishment of this nutrient has led to the fertilizer recommendations in the range of 100 to a maximum of 200kg N/ha/yr depending on the yield potential of a clone. The application of this fertilizer should also be regulated since excess application has been shown to reduce the soil moisture with increase in soil depth as shown in Fig 3-11. Excess fertilizer application has also been confirmed to cause high plant mortality during drought periods.

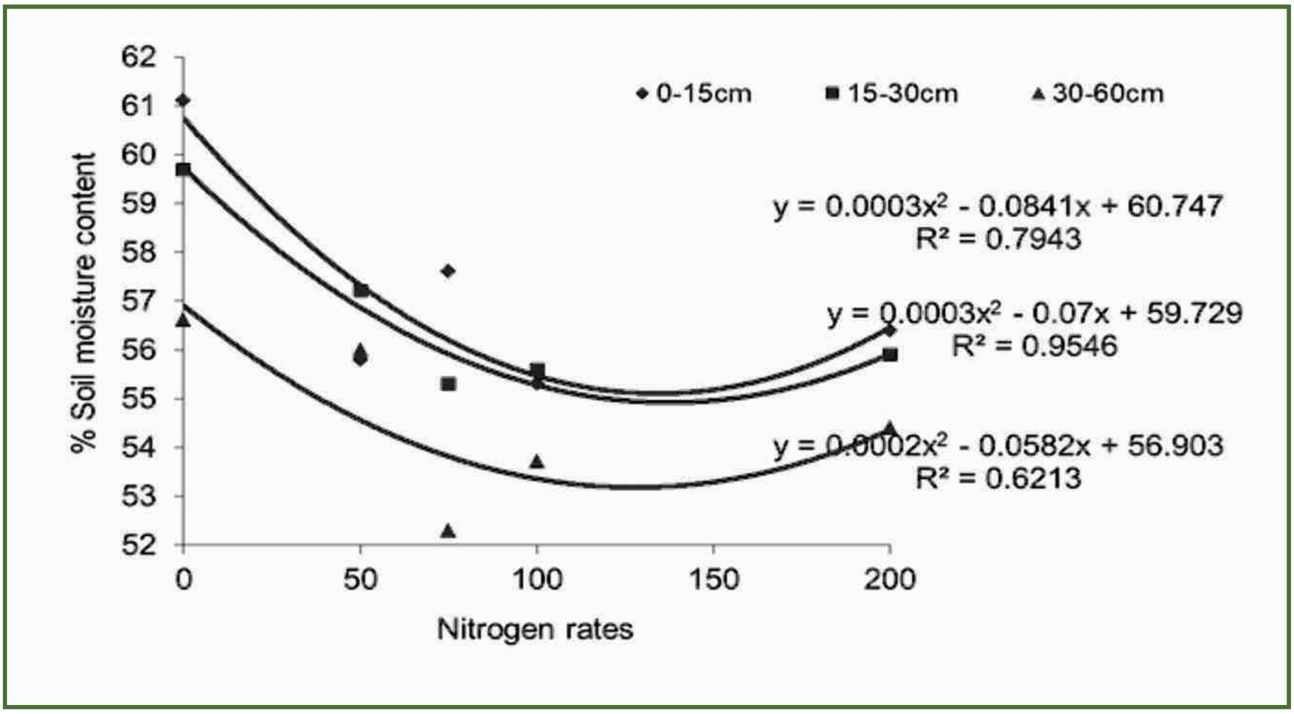

Figure 3-11 Effects of fertilizer on soil moisture content

3.5.2. Shade trees

Planting of shade trees has been shown to reduce the chances of frost occurrence and hence mitigates the frost damage in tea farms (Fig 3-9b). However, only tea friendly trees like *Grevillea robusta* (Silver Oak), tea trees, *Hakea Saligna* (Willow Hakea), *Millettia dura*, and *Sesbania sesbans* (Egyptian pea) are recommended as they offer negligible competition with tea for resources. Shade trees provides protection to the tea leaf because during drought, shade trees help to reduce evapotranspiration from the soil and tea bushes thus reducing the risk of the tea bush drying out and subsequent death. Also, shade trees protect soil and crops from the drying effects of wind by acting as a wind breaker. The use of shade trees have been found beneficial during incidents of frost by their ability to create a micro-climate which reduces the ability for frost to form on the tea leaves. It is recommended that shade trees should be planted in rows throughout the tea plantation. Spacing between rows should be approximately ten times the standard height of the tree that is being used. For example, if the tree height is 10 m at its maximum size, then the rows should be planted at 100 m intervals. However, advice may be sought from the Tea Research Institute on the most appropriate intervals for the shade tree. Use of unfriendly trees to tea may result in bringing in pests or cause severe moisture competition resulting disastrous damage as shown in Fig 3-12.

Figure 3-12 Tea plant death due to competition from eucalyptus trees

Figure 3-13 Tea friendly trees can result into better performance of the crop

Planting of recommended trees in an agro forestry system with tea, gives better tea growth (Fig 3-13). Shade trees are known to regulate climatic conditions. They reduce the negative impacts of high temperatures, reduce evapotranspiration, and help to reduce the impacts of frost. They also can improve soil fertility, particularly if leguminous varieties are grown and also protect tea bushes from drying and dying.

3.5.3. Tolerant clones

The institute has developed clones that are drought and cold tolerant and identified susceptible clones, which include AHP S15/10, TRFK 6/8 and TRFK 54/40. One key method of ensuring that tea can be grown in a changing environment is to ensure that a series of new tea clones/varieties are planted for evaluation, only clones that perform well under the changing climatic conditions are released for commercialization by farmers. New clones developed by the Tea Research Institute for improved performance under drought and frost conditions have also been selected for resistance to pests and disease to take care of future uncertainties where pests and diseases may occur as a result of climate change.

New clones include the following:

TRFK 301/4 and TRFK 301/5: These clones are 'tolerant' to drought and both clones have been observed to tolerate moderate to harsh adverse abiotic and biotic stress factors. TRFK 301/5 is a high yielding tea clone and thus is good for infilling.

TRFK 430/90 and TRFK 371/3: These two clones are both considered to be drought 'tolerant'. They have high yields too, out yielding TRFK 31/8 (TRFK's baseline clone), by more than 68%. The quality is good and comparable to TRFK 6/8 and the clones have resistance to mites and root-knot nematodes. The two clones also recover relatively fast from pruning and drought effects. Clone TRFK 430/90 has the added advantage of being suitable for mechanical harvesting/plucking.

TRFK 306/1: This is TRFK's new purple tea. The tea from this bush has higher medicinal properties than green and black tea varieties. It is also drought and frost resistant, pest and disease resistant, high yielding and grows in similar weather conditions to green tea verities. Purple tea contains high levels of Anthocyanin, a substance that is widely marketed for its health enhancing properties compared to standard black teas.

3.5.4. Soil erosion control

The effects of Climate change are likely to cause reduction in soil fertility. High temperatures, floods, droughts, winds and increased evapotranspiration can all cause a reduction in soil fertility. It is therefore important to address these issues by ensuring that soils are protected to remain healthy and sustainable. This will in turn help to reduce the impact of climate change in the agriculture sector. The fertility of soil is defined by its capacity to hold water and nutrients and supply adequately to plants. Thus a highly fertile soil is able to hold enough water and nutrients for successful and productive plant growth. To check soil erosion on the steep slopes and areas prone to heavy rainfall torrents, it is recommended to have cut off drains and soil filtering banks planted with Guatemala grass, which has good fibrous rooting system and is good in land rehabilitation. Fig 3-14 illustrates soil erosion control. Fertile soil is vital for sustaining agriculture and livelihoods. Thus, maintaining and improving soil fertility is an important way in which farmers can increase their resilience to climate change.


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Figure 3-14 Soil erosion control

3.5.5. Water harvesting

Water harvesting helps in adapting to climate change through the reduction of river water abstraction. The Institute has recommended and demonstrated this technique by installing a number of rainwater collecting tanks (Fig 3-15). The tank helps in supply of water during prolonged drought as a result of the changing climate.

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Figure 3-15 Rainwater harvesting within TRI

3.5.6. Tree planting (Afforestation and Reforestation)

Trees are beneficial in conserving the soil and binding of the soil particles. Trees also act as carbon sinks by sequestrating carbon. Several species of indigenous trees are propagated within the tree nursery in the TRI, in an effort to avail tree planting materials to tea growers and other stakeholders. Tree planting is recommended for depleted forest areas and open unutilized areas (Fig 3-16).

Figure 3-16 Planting indigenous trees

3.5.7. Farm forestry

Farm forestry (Fig 3-17) involves planting of trees within the farm and homestead. A wide selection of trees can be planted, for a variety of purposes, such as firewood, fruits, fodder and shade among others.

Figure 3-17 Farm forestry

3.5.8. Waste management

Careless disposal of wastes can result into gross pollution of the environment. The TRI recommends proper waste disposal and it has demonstrated commitment to proper waste disposal by implementing a waste disposal system whereby wastes generated within the institute are segregated prior to disposal (Fig 3-18). Hazardous wastes from the laboratories are incinerated at an approved facility in Kericho.

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Figure 3-18 Waste management

3.5.9. Nature Conservation and ecotourism

Communities are encouraged to appreciate nature, change their perception and conserve it. The Institute has demonstrated this by creating a nature trail (Fig 3-19) as an example to the local community. The trail leads through the indigenous forest of the institute and is characterized with such trees as bamboo, podo among many indigenous species. It is projected that the path will also lead to an arboretum which will host rare and endangered species for scientific investigations, medicinal use and boosting of the aesthetic value of the environment.

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Figure 3-19 Nature trail in the TRI leading to the indigenous forest in the background


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4. Impact of Climate Change on Tea and Adaptation Strategies (China)

4.1. Introduction

Physical and biological systems on all continents and in most oceans are already being affected by recent climate changes, particularly regional temperature increases (IPCC, 2007a). Agriculture is highly sensitive to climate change. Carbon dioxide (CO_2) is the most important greenhouse gas (GHG) emitted from anthropogenic sources both in terms of amount and effects on climate. Despite some efforts aimed at limiting anthropogenic CO_2 release, the annual growth rate in CO_2 concentration was still increasing, from average1.4 ppm yr^{-1} in 1960-2005 to 1.9 ppm yr^{-1} in 1995-2005 (IPCC, 2007b). Two other major GHGs methane (CH_4) and nitrous oxide (N_2O) are also increasing at rates of 0.4 and 0.25% yr^{-1}, respectively (IPCC, 2007b). As a result, global warming would be sped up and cause serious problems in agriculture.

Tea is one of the most important cash crops worldwide. It plays a significant role in rural development, poverty reduction and food security in developing countries. Tea is planted in 58 countries of all 5 continents with the majority in Asia and Africa. The total land under tea cultivation is 4.37 million ha with the annual production of 5.17 million ton in 2014 (ITC, 2015).

China is the largest country to produce tea. The total land under tea cultivation was 2.65 million ha with the production 2.10 million ton in 2014 (ITC, 2015), which account for 60.6% and 40.6% of world's total tea area and production, respectively. Most of the tea land in China is located in low hills and mountainous areas. It was estimated that 80 million people are involved in tea industry, who depend on tea as one of their income sources. Tea plays a key role in income and employment generation for small holders, especially in the tea growing mountainous regions.

Being mainly as a rainfed monocropping system, tea depends greatly on weather conditions for optimal growth. Therefore, the climate change has great impacts on tea growth and production. However, how the climate change affect tea economy and which mitigation and adaptation measures should be taken are not well understood. The purposes of this study were to (1) evaluate the climate change in tea growing areas and its impact on tea economy in China, and (2) suggest mitigation and adaptation strategies to cope with climate change for sustainable development in tea industry.

4.2. Climate change and variations in the last 60 years

To understand climate change in the last 60 years, 4 typical cities from south to north in different climate conditions in China were selected. The detailed information is listed in Table 4-1. Haikou is an island city in Hainan province of south China, producing black tea. Kunming is a plateau, producing Puer and black tea in southwest China. Hangzhou is located in subtropical zone, eastern China, producing green tea. And Jinan is in north China, the city is not producing tea as it is too cold in winter, but green tea is produced nearby its coastal areas.

The main climate parameters including monthly mean, lowest, highest, extreme lowest and extreme highest temperatures, monthly precipitation, daily highest precipitation, number of rainy days, mean air relative humidity, sunshine duration and percentage of sunshine in each month were downloaded from China meteorological data sharing service system (http://cdc.cma.gov.cn) for these cities dated from January1951 to December 2010. The climate change trend in the last 60 years was examined using linear regression analysis.

Table 4-1 Geographical location and major weather information of the selected four cities in China

City	Location	Altitude (m)	Mean annual temperature (℃)	Extreme lowest temperature (℃)	Mean annual precipitation (mm)
Haikou	110°20′ E 20°02′ N	14	24.1(9.3-36.1)	2.8	1688
Kunming	102°42′ E 25°04′ N	189015.0	(2.3-25.6)	-7.8	992
Hangzhou	120°10′ E 30°16′ N	40	16.5 (9.0-33.9)	-9.6	1417
Jinan	117°00′ E 36°40′ N	100	14.5 (-4.8-32.7)	-19.2	689

4.2.1. Temperature

Annual mean temperature was significantly and steadily increased in the last 60 years (Fig 4-1A). Linear regression equations were developed according to the temperature change in all 4 cities (Table 4-2). The temperature increase was different between the cities. Haikou, the tropical city and Jinan, the temperate city increased by 1.0 and 1.1℃, respectively in annual mean temperature in the last 50 years, less than subtropical city Hangzhou (1.6℃) and plateau city Kunming (1.6℃) (Table 4-2).

Further analysis showed that the highest temperature including monthly and extreme highest temperature was not much different. They were stable or slightly increased in most of the cities. For Hangzhou, the number of days ≥ 35℃ was significantly increased. But for Jinan, the highest temperature was even slightly decreased. However, the lowest temperature including the monthly lowest and extreme lowest was remarkably increased in all the cities studied. The extreme lowest temperature was increased by 2.3, 3.0, 2.1 and 3.8℃ in the last 50 years in Haikou,Kunming, Hangzhou and Jinan, respectively (Fig 4-1B). The seasonal difference indicates winter is becoming warmer.

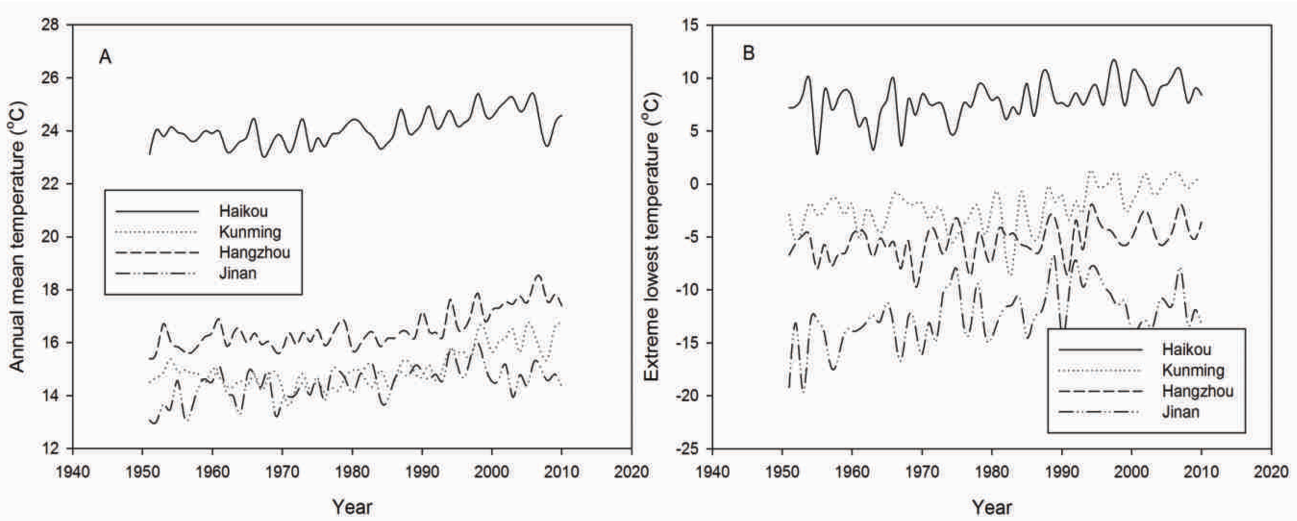

Figure 4-1 Changes in annual mean (A) and extreme lowest (B) temperature in 4 cities during the last 60 years

Table 4-2 Linear regression equations fitted with the change in annual mean temperature in the last 60 years

City	Linear regression equation (Y: annual mean temperature, X: year)	R^2 (Sig.)	Annual mean temperature increase in last 50 years (℃)
Haikou	Y=0.021X-16.721	0.378 (p<0.001)	1.0
Kunming	Y=0.030X-43.380	0.480 (p<0.001)	1.5
Hangzhou	Y=0.032X-46.149	0.591 (p<0.001)	1.6
Jinan	Y=0.021X-27.401	0.323 (p<0.001)	1.1

4.2.2. Precipitation and relative humidity

The annual precipitation (Fig 4-2A) did not change significantly in selected 4 cities in the last the 60 years, in spite of the prediction by China NDRC (2007) that mean precipitation tends to increase in China. However, the number of rainy days (≥0.1mm) was reduced (Fig 4-2B), while the change is not as significant as the mean temperature. The rainy days were reduced by 13.1, 13.2, 12.0 and 6.7 d in Haikou, Kunming, Hangzhou and Jinan, respectively in the last 50 years. The city in south is more remarkable than that in the north. In Kunming, the monsoon approaches later. For instance, in 2011, monsoon appeared some 22 days later than in 1980. Most of tea lands are rainfed and subjected to suffer from more seasonal drought or unpredicted highly intensive precipitation.

Over last 60 years, the atmospheric relative humidity reduced significantly. The annual mean relative humidity was significantly and negatively correlated with the year in all 4 cities (Fig 4-3). According to the linear regression equations, the relative humidity decreased by 3.3-9.4% in the last 50 years, with the lowest in Jinan and highest in Hangzhou (Table 4-3). The annual mean relative humidity in Hangzhou was 83.6% in 1950, but it declined to 72.4% in 2010. If the same trend continues, it will further reduce to 64.8% in 2050, which will seriously affect tea growth and development.

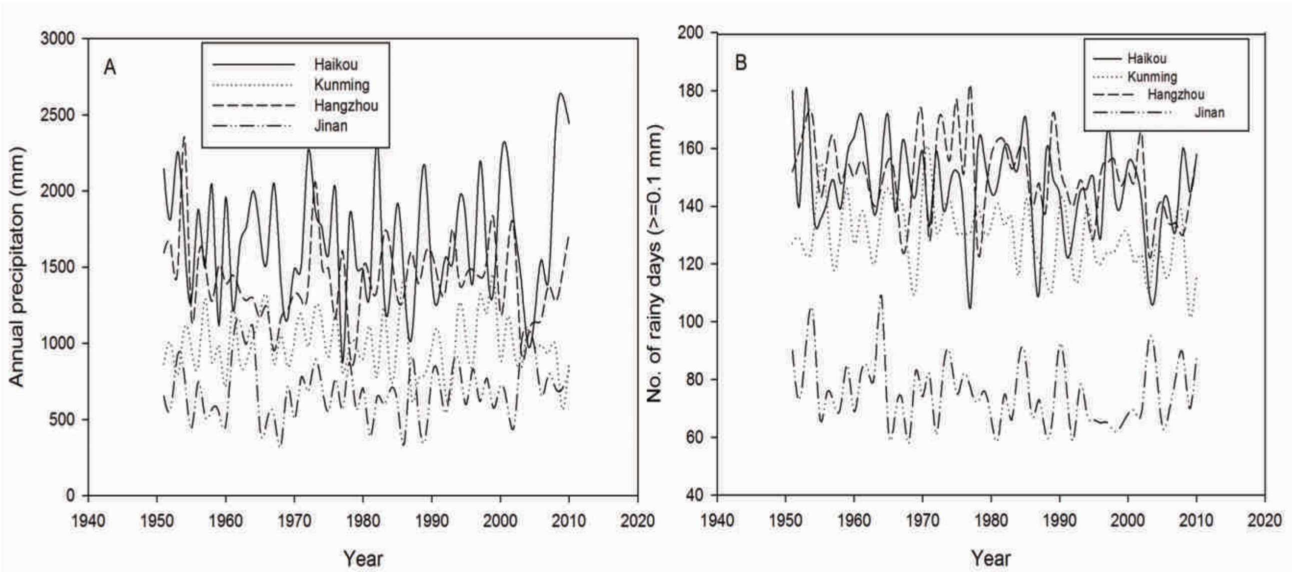

Figure 4-2 Changes in annual precipitation (A) and number of rainy days (≥0.1mm) (B) in 4 cities during the last 60 years.

Table 4-3 Linear regression equations fitted with the change of annual mean relative humidity in the last 60 years.

City	Linear regression equation (Y: annual mean relative humidity, X: year)	R^2 (Sig.)	Annual mean relative humidity increase in last 50 years (%)
Haikou	Y= -0.085X + 251.09	0.432 (p<0.001)	-4.2
Kunming	Y= -0.095X + 259.52	0.318 (p<0.001)	-4.7
Hangzhou	Y= -0.187X + 449.09	0.728 (p<0.001)	-9.4
Jinan	Y= -0.066X + 188.59	0.086 (p<0.05)	-3.3

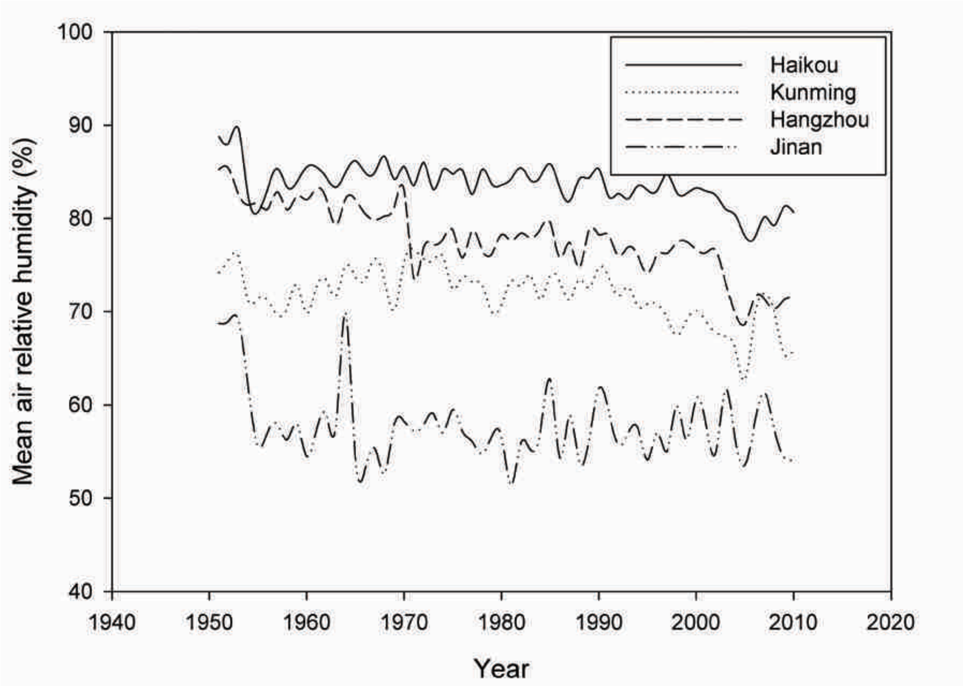

Figure 4-3 Change in annual mean relative humidity in 4 cities in the last 60 years.

4.2.3. Sunshine time

Annual sunshine time in all the 4 cities significantly reduced in the last 60 years (Fig. 4-4). Very significant and negative linear regressions were found (Table 4-4). The annual mean sunshine time was reduced from 207.1 h in 1950 to 158.0 h in 2010 in the 4 cities. Accordingly, the percentage of sunshine time was reduced from average of 56.3% in 1950 to 42.9% in 2010. If the same trend continues, the mean sunshine time and percentage of sunshine time will be decreased to 153.0 h and 43%, respectively in 2050, which will tremendously affect tea production.

Table 4-4 Linear regression equations fitted with the change in annual sunshine time in the last 60 years

City	Linear regression equation (Y: annual sunshine time, X: year)	R^2 (Sig.)	Annual sunshine time increase in last 50 years (h)
Haikou	Y= -0.747X + 1652.98	0.417 (p<0.001)	-37.3
Kunming	Y= -0.854X + 1883.77	0.629 (p<0.001)	-42.7
Hangzhou	Y= -0.538X + 1215.78	0.329 (p<0.001)	-26.9
Jinan	Y= -1.134X + 2457.81	0.681 (p<0.001)	-56.7

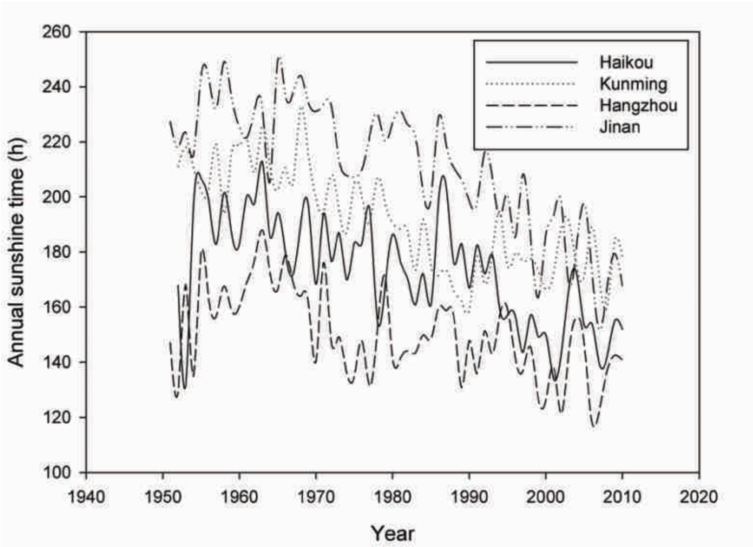

Figure 4-4 Annual sunshine time change in 4 cities in the last 60 years.

4.2.4. Climate extremes and variations

Compared to the smooth change in annual mean temperature, number of rainy days, air relative humidity and annual sunshine time in the last 60 years, the climate extremes and variations have happened more frequently especially in the last few years.

In Kunming city, the mean annual precipitation was 992 mm in the last 60 years. However, it was only 565.8 mm in 2009, the most severe drought since the city established meteorological record. It was estimated that tea yield decreased by 20% compared to the year with normal climate. Some tea plants (3300 ha) even totally died off due to the prolonged drought. In Haikou, same phenomenon was recorded in 2004, when the precipitation was 984 mm accounting for only 58% of the annual mean precipitation. However, the largest daily precipitation was 327.9 mm, accounting for 23.3% of the annual precipitation in Haikou in 1996. In Hangzhou, tea producers suffered late spring coldness almost every year since 2003. About 49% of the tea gardens in Zhejiang province were affected that caused direct economic loss accounting for ￥988 million Yuan in 2008. Some early sprouting cultivars such as Wuniuzao were plucked nothing in spring tea, resulting in a loss of￥1.69 billion Yuan by the late spring coldness in Zhejiang province alone in 2010 (Lou, 2010). In 2013 Hangzhou had experienced the hottest and driest summer since 1950, there was no any rain during 1st July to 15th Aug with the daily highest temperature above 39℃.

4.3. Impact of climate change on tea production and quality

Tea originated in southwestern China, at the center of Yunnan and Guizhou plateau, a junction of tropical and subtropical areas. This area is characterized by a warm and humid climate all year around, with warm weather, abundant precipitation, high humidity and sufficient diffused light. Under such conditions, tea plants have gradually evolved special characteristics of inclining for warm, moist weather, diffused light and acid soils. The normal ecological requirement for tea growth and development is listed in Table 4-5 (Yang, 2005). The climate change not only change temperature, precipitation, relative humidity, rainy days, and annual

sunshine time as stated above, it will also affect the other basic elements of tea growth and development, such as soil pH, moisture content, soil organic matter and nutrient availability, pest and disease management, and ecological system around tea gardens, and eventually the production and economy of tea.

Table 4-5 Normal ecological requirement for tea growth and development

Climate parameter	Extreme lowest	Normal range	Optimum
Temperature (℃)	-20 (var.*sinensis*), -8 (var. *assamica*)	13-26	18-23
Annual accumulated temperature (≥10℃)	3000	4000-8000	6000-7000
Annual precipitation (mm)	500	800-2500	1500-2000
Annual relative humidity (%)	60	70-90	80-85
Soil moisture (% of water holding capacity)	50	60-95	70-90
Soil pH (in water suspension)	3.0	3.5-6.5	4.5-5.5

4.3.1. Tea growing area and season

With the increasing temperature, especially increase in the lowest temperature, the tea growing area would be extended to higher latitudes and higher altitude ecosystems. The current northward line of tea production areas in China is Qing Ridge and Wai River. However, due to the area in north of the line has limited precipitation, and higher soil pH, the extension of production area would be limited.

The tea growing season can be extended in subtropical areas with distinct seasons, especially the tea budding time will be advanced. It would increase tea yield, but probably pose more extreme weather events, such as later spring coldness.

4.3.2. Spring tea production

The temperature increase in spring time means tea shoots grow faster, indicating that (1) premium spring tea composed of one bud one leaf or one bud two leaves, the most profitable green tea production will be declined due to the limited plucking time; (2) the "flood peak" of spring tea will be strengthened, resulting in labour shortage and processing machines overloaded, consequently reducing spring tea quality.

Premium tea plays a key role in tea production in terms of tea quality and tea profit in China. The amount of premium tea (majority produced in spring season) accounts for about 40% of the total production, its production value accounts for 80% of the total production value, and its profit percentage will be much higher since more than 50% of tea fields only produce spring tea. Therefore, if spring tea production, the foundation of tea industry in China, is adversely affected, tea economy would be damaged.

4.3.3. Tea yield

The climate change brings both advantages and disadvantages for tea growth and development, and will finally make great impact on tea production. The beneficial changes include increase in temperature and CO_2. The adverse impacts include decrease in rainy days, relative humidity, and increase in incidence of pests and diseases and degradation of soil quality. The reduction of sunshine time could be of uncertainty according to the degree of its change and where it is located.

Tea growing period and plucking season will be extended with the increase of temperature. It is reported that the number of days with ≥10℃, which is regarded as starting temperature for tea sprouting, can increase by 15 d if the annual mean temperature increases by 1℃ (Yang, 2006). As for an example, if 8d is allocated in the spring time, tea production period can be extended from 193 d to 201 d in Hangzhou. The tea yield can be increased by 4%. However, research also shows that the mean and high temperatures are not the main factors to decide the crop yield, but extreme temperature has a negative effect on crop yield (Challinor *et al.*, 2007). And also in higher mean temperature regimes (>25-26℃), tea yield tends to decline with increasing temperature (Wijeratne, 1996).

The increase in CO_2 concentration could improve photosynthesis of tea plants. If CO_2 levels are at 550 and 750 μmol/mol, net photosynthesis of tea shoots can increase by 17.9 and 25.8%, respectively, compared to the ambient air CO_2 concentration, and midday depression abated or disappeared (Jiang *et al.*, 2005). Our own research showed that plant height, fresh shoots and roots weight of tea seedling were 63.2 cm, 9.6 g and 9.9 g at 800μmol/mol CO_2 level, which were increased by13.5%, 24.7% and 67.8%, respectively, compared to that under the ambient CO_2 concentration of 380 μmolmol^{-1} (Table 4-6). The CO_2 enrichment also promotes photosynthesis and respiration in tea plants. However, the photosynthesis would acclimatize with high CO_2 concentration, so that the yield increase would not be as sound as it is expected since CO_2 concentration is gradually increasing with long-term climatic change.

Table 4-6 Effect of CO_2 enrichment on the growth of tea plant

Treatment	Height (cm)	Fresh Shoot Weight (g)	Fresh Root Weigh (g)	Root/Shoot ratio
Ambient CO_2	55.7±3.73 b	7.7±0.98 b	5.9±0.74 b	0.47±0.031 a
Elevated CO_2	63.2±4.65 a	9.6±1.47 a	9.9±1.32 a	0.60±0.064 b

Different letters in the same column denoted significant statistical difference ($P<0.05$)

The reduction in annual rainy days (even with same precipitation) and relative humidity, which are closely correlated, will adversely affect tea production. For example in Jinan, the mean annual rainy days, precipitation and relative humidity was only 689 mm, 75 d and 58% respectively in the last 60 years, further reduction in rainy days and relative humidity will certainly reduce tea growth and production. Furthermore, the increase of temperature will strengthen soil evaporation and plant transpiration, causing water shortage or seasonal drought in areas with low precipitation. We constructed a yield response model to estimate the effect of specific weather factors on tea

yield by using historical weather and production data in main tea producing provinces from 1980 to 2011. Data showed that tea yield was more sensitive to precipitation than temperature, and the monsoon retrieval date and rainfall occurring during the monsoon period were negatively associated with tea yields (Boehm *et al.*, 2016).

Incidence and proliferation of pests, diseases and weeds will increase with the climate change (Lal, 2005). The warmer weather helps insects and pathogens to survive in winter, which is a critical time to reduce the number of overwintering pests and pathogens, and thus it helps to extend damaging period by increasing number of annual generations and reproduction rates for some pests. For example, the annual generations of tea geometrid (*Ectropis oblique*) is 6 in Hangzhou in normal weather conditions. However, it will increase to 7 if the mean temperature goes above 20°C in October (Wang and Jin, 2010). The number of overwintering tea green leafhopper and its reproductive rate is very significantly correlated with the number of days with daily mean temperature above °C in Hangzhou district (Yang, 2005). The higher temperature together with lower relative humidity also favors some pests. The incidence of diseases is positively correlated to the temperature, and negatively correlated to the sunshine time (Li *et al.*, 2010). Recent investigation showed that tea blister blight, which normally occurred in tropical Yunnan and Hainan Provinces, has become a problem in Songyang County of Zhejiang Province, the typical subtropical zone.

Our research also showed that the incidence of anthracnose disease(*Colletotrichumgloeosporioides*) significantly increased under the elevated CO_2 concentrations (Li *et al.*, 2016). And pest activities, tea plant and pest interactions could be changed due to the altered plant physiology and/or morphology under increased CO_2 (Chakraborty *et al.*, 2000). Due to increasing incidence and activities of pests and diseases, the average yield could be lost by up to 40% if no proper measures being taken (Oerke *et al.*, 1994). In China, the gross agricultural output value is estimated to be lost by 20-25% due to the damage of pests and diseases (Wang *et al.*, 2006).

The depletion of soil organic matter by microbes will be sped up, while time to release nutrients from chemical fertilizers and nutrient availability will be shortened due to increase in temperature. Intensive daily precipitation could cause severe flooding, even landslide, which remove most fertile top soils. The enrichment of CO_2 and other air pollutants such as SO_2 and NO_2 will cause strong acid precipitation that will further increase tea soils acidity. It is to be noted that tea soils in China are already too acidic as one third of tea soils is below pH 4.5 (Han *et al.*, 2002) and thus further acidification will consequently degrade soil quality and tea production.

The reduction in sunshine time with decreased rainy days that were resulted from an increase in cloudy days and diffused light, would benefit tea growth and development, if the region belongs to the tropical or subtropical areas receiving intensive solar radiation. However, it would be harmful for tea cultivation in high mountains or ecosystems with low sun radiation.

Climate extremes and variations, such as drought, flood, extremely cold and hot weather will cause serious problems for tea production and sustainable development. Because of their unpredicted nature, they would be the most significant factors influencing year to year tea production. Our study showed that the previous year's weather factors had a significant impact on tea yields (Boehm *et al.*, 2016), and that heat stress caused obvious alterations in the leaf phenotype, and significantly declined net photosynthetic rate and tea yield (Li *et al.*, 2015).

4.3.4. Tea quality

The most commonly used tea quality parameters include free amino acids, polyphenols or catechins, caffeine and water extracted substances. With a certain polyphenols concentration, the higher the free amino acids, the better green tea quality. Polyphenols orcatechins are substrates of theaflavins and thearubigins in black tea processing, so the higher polyphenols to some extent, the better of black tea quality. The amino acids and polyphenols in tea shoots are mainly resulted from nitrogen (N) and carbon (C) metabolisms and their balance in tea plants, which are significantly affected by climate change.

Relatively low temperature is beneficial to N metabolism, especially the biosynthesis of amino acids. The high temperature has positive impact on C metabolism and biosynthesis of polyphenols (Fig. 4-5). The mean temperature at a specific time point such as 15 d before tea plucking is negatively and significantly correlated with amino acids, but positively correlated with polyphenols (Hu, 1985). The high temperature also results in biolysis of amino acids.

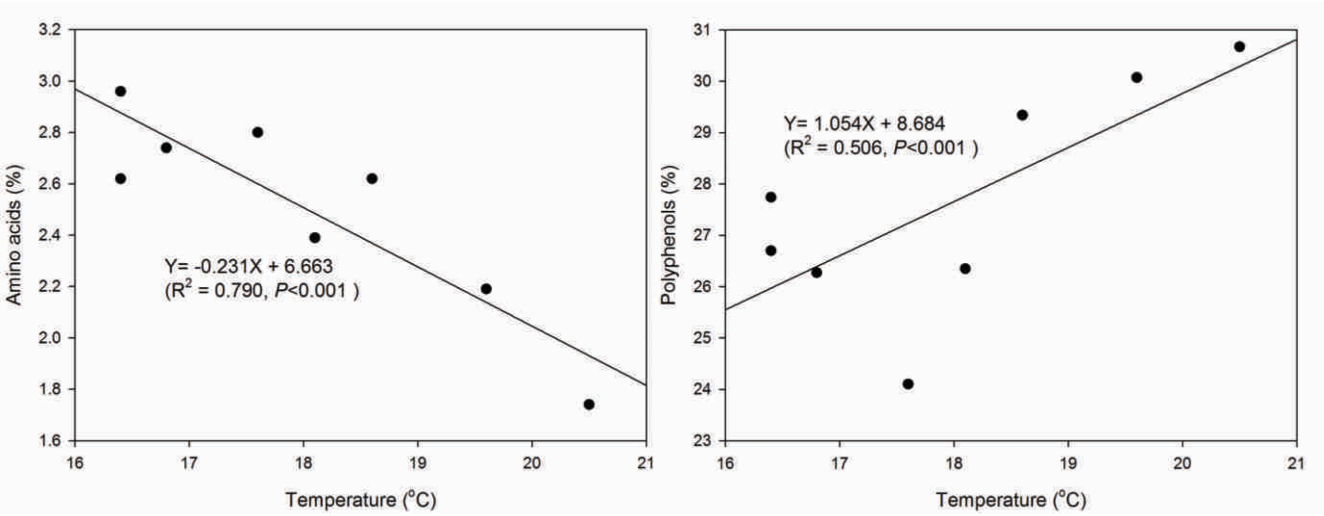

Figure 4-5 Relationship between temperature and amino acids and polyphenols in tea shoots

Relative humidity in tea garden is decided by water availability and temperature. The sunshine time is related with the intensity of solar radiation and it affects temperature. Amino acids concentration in tea shoots is positively correlated with relative humidity and negatively correlated with sunshine time. However, tea polyphenols show just opposite trends, which are negatively correlated with relative humidity and positively correlated with sunshine time (Hu, 1985; Wei *et al.*, 2011).

Majority of the famous Chinese green teas are produced in two typical places. First one is on the mountains with altitudes between 300 and 1000 m, and characterized by higher precipitation and higher relative humidity, more diffused lights, lower temperature and higher diurnal temperature variation compared to low lands (Wang and Jin, 2010). These weather conditions are favorable for tea plants to synthesize and accumulate amino acids and other N containing quality components. Our research also showed that with the increasing cultivation altitude, amino acids increased and polyphenols decreased, resulting in lower ratio of tea polyphenols to amino acids (Table 4-7) (Han *et al.*, 2016). The other kind of places where teas are grown in

China are near lake or river, characterized by higher relative humidity, more cloudy days and diffused light, and relatively stable temperature. Such weather conditions help in N metabolism and amino acids biosynthesis.

Table 4-7 Tea polyphenols, free amino acids contents and their ratios in green tea as influenced by changes in cultivation altitude

Sampling site	Elevation (m)	Total polyphenols (TP, mg/g)	Free Amino acids (AA, mg/g)	TP/AA ratio
Cumaling	212	245.2±4.7 a	26.1±2.7 d	9.5±1.2 a
Mazu temple	420	242.0±7.2 a	29.2±2.0 cd	8.3±0.8 a
Songshuling	574	200.8±4.8 b	35.2±2.0 b	5.7±0.4 b
Xiaotianchi	828	199.0±5.2 b	33.3±3.1 bc	6.0±0.7 b
Jingzuo station	1020	167.3±18.4 c	43.1±2.3 a	3.9±0.3 c

Mean denoted by different letters in the same column are significantly different ($P<0.05$)

Elevated CO_2 level exerts significant impacts on tea quality. Simulated research shows that elevated CO_2 at 500 and 700 μmolmol^{-1} decrease tea amino acids by 1.7-4.5% and 6.7-12.2%, respectively, compared to the current ambient air CO_2 concentration. At the same time, the caffeine contents also reduced by 3.1-4.6% and 5.1-10.7%, respectively. However, the polyphenols concentrations increased by 3.8-6.0% and 6.9-11.3%, respectively. The soluble saccharide contents increased by 8.4-14.4% and 18.1-28.2%, respectively (Jiang *et al.*, 2006).

From above evaluation, it is well perceived that global warming probably reduces green tea quality, but increases black tea quality to some extent. Of course, an inappropriate ratio of polyphenols to amino acids in shoots will also deteriorate black tea quality.

Other climate variations and extremes, such as late spring coldness, frost and hail, flooding and drought will not only damage the growth and development of tea plants, but deteriorate tea quality as well.

4.3.5. Tea product safety

There are two aspects of climate change indirectly affecting tea product safety. One is the increasing use of pesticides resulting in more pesticide residue in tea product. The other is atmospheric micro particles, which will increase with the increased atmospheric humidity and reduced precipitation. Due to increased air pollution, the toxic micro particles such as heavy metal and polycyclic aromatic hydrocarbons (PAHs) will be accumulated in tea leaf, and thus posing serious threat to human health.

4.4. Tea economy affected by climate change

The cost of tea production as affected by climate change includes lower yield, increasing cost of pests, diseases and soil management, decrease of labour efficiency, higher infrastructure cost to deal with erratic rainfall and drought and other cost of adaptations.

4.4.1. Tea production value or profit

From the discussion, we can see that the majority of tea fields located in subtropical zone in China will be benefited from the increase in mean temperature and CO_2 concentration. However, the spring premium tea production will be adversely affected. The reduction in rainy days, relative humidity and sunshine time will also cause yield decline. The erratic rainfall, proliferation of certain pests and diseases and other climate extremes and variations will definitely reduce tea yield. There are no specific models to predict the accurate yield change. However, integrated aspects show that, yield reduction is possible. According to the Chinese experience, especially in the domestic market, the moderate reduction in yield could be offset by increase in production price. Therefore, the total production value or profit/loss would be minimal when calculated as a whole in the country or a region in short term. Of course, tea production value or profit will be affected in the long run, and for individuals, the loss by extreme weather events could be 100% sometimes.

4.4.2. Cost of pest and disease management

As analyzed above, the incidence and proliferation of pests, diseases and weeds are enhanced by increase in temperature. The cost of pesticides will increase by 20% and even double (Wang *et al.*, 2011). The average cost of pesticides is about ￥1200 Yuan/ ha, if 80% of tea gardens in China suffer from increased pest and disease incidence, it will increase expense of￥509 million Yuan. If the subsequent yield reduction due to increased pest and diseases and labour cost of pesticide application are taken into account, the total cost will be more than double. What's more, the increased use of pesticides will cause food safety problem due to increased pesticide residue in tea products, and damaging tea ecosystems through reducing biodiversity, which has great impact on tea economy in the long run.

4.4.3. Cost of soil management

With the increase in temperature, the depletion of soil organic matter, increase in N volatilization, denitrification and leaching, enrichment of CO_2 and other air pollutants such as SO_2 and NO_2 will bring more acid precipitation that will further acidify tea soils, finally affecting soil nutrient balance, N use efficiency and soil quality. Though the fertilization effect of CO_2 augmentation can offset these changes to some extent, the increased use of fertilizer and soil amendment would be indispensible especially under harsh weather conditions, such as drought and heavy precipitation. If fertilizers use is increased by 10%, the cost will be increased by at least ￥600 Yuan/ha or ￥1.6 billion Yuan in China.

4.4.4. Cost of rehabilitation or new planting

Yong tea plants are very vulnerable to climate variability and extreme weather events, especially drought, cold and frost. The survival rate of newly planted clonal tea was very low ranging from 20 to 90% in the recent years due to seasonal drought and coldness. About 0.3 million ha of fields with tea stand at an age of more than 50 years and should be rehabilitated in China. The mean cost of rehabilitation is about ￥45,000 Yuan/ha. The high mortality rate of young plants not only causes enormous economic loss, but also delays harvesting time.

4.4.5. Labour cost increment

The increasing in temperature, climate variability and extreme weather events would decrease labour efficiency, especially field workers in plucking, pruning, soil and pest management in summer. Improvement of working conditions such as air conditioning facility in work place for processing workers will be needed. For example, due to improved microclimate in peach-tea ecosystem and comfortable working environment, labour productivity is increased by 23-30% compared to the mono tea garden management (Huang *et al.*, 2001). The labour cost accounts for 40-80% of the total production cost in China. The decline in labour efficiency would significantly increase total production cost and decrease profit margin.

4.4.6. Cost of infrastructure construction and improvement

To deal with the climate change, infrastructure construction and improvement will be the largest cost in tea production. It includes construction of drainage system in fields to remove downpour water to minimize soil erosion, irrigation system to prevent from drought, road improvement for transportation, planting trees along field roads in subtropical areas or inside tea gardens in tropical areas to improve field microclimate and biodiversity, electric fan to prevent late spring coldness and insecticidal lamps (light trap) to control pests. This will be a tremendous and unpredictable cost. For example, the cost of sprinkler or drip irrigation system alone will be at least￥22,500 Yuan ha^{-1}.

From foregoing analysis, we could conclude that production cost increased by climate change and variations is inevitable. The cost increase by 10% would be possible. The current mean cost of production is about ￥36,750 Yuan/ha, accounting for 70% of the production value in China. The total annual economic loss would be ￥9.74 billion Yuan if no appropriate mitigation and adaptation measures are taken.

4.5. Adaptation and mitigation strategies

An appropriate planning with climate change adaptation and mitigation initiatives is essential not only to deal with the negative impacts of forecasted climate change, but also to offer opportunities for cost-effective adaptation and mitigation options with additional benefits for sustainable development of tea industry. The adaptation and mitigation strategies should have at least three levels: government policy, technology and technique development, community involvement for extension of adaptation and mitigation measures, which should be integrated to achieve better outcomes.

4.5.1. Government policies and strategies

Climate change is often referred to as a global problem, which requires top-down international and national strategies to achieve substantial climate change adaptation and mitigation. For example, individuals are unlikely to take responsibility for global accumulation of atmospheric GHGs. Therefore, an integrated and coordinated government policies or strategies is required that will be cost effective and consistent in implementation.

(1) Establishing international and national networks on climate change

International and national networks can be initiated based on coordinated policies or/and strategies at international and national levels to advance research collaboration on impact assessment of climate change involving international and interdisciplinary research and communication units. Such network will help to set up policies through integration of natural, social and cultural aspects of climate change. The “Climate Change” working group in the FAO Intergovernmental Group on Tea should be strengthened to collect and collate available research data on climate change, to determine the impact of climate change on tea economy, to identify/ suggest mitigation and adaptation strategies, to develop appropriate long-term technologies for mitigation and adaptation. Collaborative research networks with a focus on climate change should be established at the international and national levels. For example, to deal with the extreme climate change variability, a national legal framework that can manage water resources in accordance with anticipated climate change impacts on water resources should be built for adjusting water allocations and improving water use efficiency. Extension networks to implement mitigation and adaptation measures at different governmental levels should be initiated.

(2) Strengthening R&D for new technologies and their extension

To cope with climate change, research and development on predication of climate change, mitigation of GHGs, adaptation strategies and measures should be strengthened with support from different levels of government. Recently developed new technologies and techniques should be extended and implemented systematically under the government support.

(3) Strengthening investment on field infrastructure

Infrastructure construction and improvement, such as drainage system, irrigation system, road construction, ecosystem diversity and rebalance should be strengthened. Infrastructure is considered as a very good investment from a cost-benefit analysis point-of-view, even in absence of climate change. Taking into account the high cost and normally across board of individual's tea gardens, government should play a key role in this regard.

(4) Promoting organic and GAP tea production

Organic farming is regarded as a farming system that could contribute to climate mitigation and sustainable agriculture. Recent research shows that organic tea production can enhance soil C sequestration (Han *et al.*, 2013) through increasing soil organic matter (carbon) levels. This would translate into better plant nutrient content, increased water retention capacity and better soil

structure, eventually leading to higher yields and greater soil resilience(FAO, 2009). Organic tea has 20 to 50% higher price compared to the conventional tea. Therefore, promoting organic tea production, could be not only beneficial to increase farmers' income, but as one of the solutions to climate change that offer significant scope for climate change adaptation.

GAP (Good Agricultural Practices) and/or green farming is a collection of principles with taking into account economic, social and environmental sustainability to apply for on-farm production and post-production processes for safe and healthy food and non-food agricultural products. It applies integrated pest management, integrated plant nutrient management and conservation agriculture, which could mitigate and adapt climate change.

4.5.2. R&D priorities for new and improved technologies

Traditional coping mechanisms often will not be sufficient for dealing with expected medium and long term impact of climate change. Innovative agricultural technologies and practices can play a significant role in mitigation and adaptation of climate change, especially in developing countries where agricultural productivity remains low; poverty, vulnerability and food insecurity remain high. Therefore, shaping research priorities, developing and disseminating innovative technologies are central to deal with climate change that can reduce negative environmental impacts and improve tea sustainability.

(1) Reducing greenhouse gases emission

Reducing GHGs in tea gardens to mitigate climate change is the first priority while not compromising tea production. Among the major GHGs, N_2O is a key GHG produced in tea soils. Tea, as a leaf harvest crop, is fed with large amount of fertilizer, especially N fertilizer. The annual N application rates ranged from 0 to 2600 kg/ha with an average of 553 kg/ha in typical tea fields in China (Han and Li, 2002). When 300, 600 and 900 kg N/ha are applied for tea fields, N_2O-N emissions account for 1.43, 1.96 and 3.44% of the N applied, respectively (Han *et al.*, 2013). Reducing N application, using slow-release N fertilizers and balancedfertilization can significantly increase N use efficiency (Han *et al.*, 2008). Further technologies and practices should be developed to increase N use efficiency and reduce N_2O emission.

(2) Enhancing C sequestration

Increasing soil organic matter not only strengthen C sequestration, but also improve water retention capacity, soil structure and biodiversity that would lead to higher tea yield and greater soil resilience from flooding, erosion, drought and heavy rainfall. Moreover, increasing soil organic matter would improve N use efficiency. In case of China, the average organic C in 0-40 cm topsoil is only 1.08% (Han *et al.*, 2002), if it would be increased by 0.1%, the tea soil could increase C sequestration by 5.2 ton/ha, or 13.78 million ton C, equivalent to 50.52 million ton of CO_2 in Chinese tea sector. Hence, a great potential exists in C sequestration. New technologies should be developed to increase soil organic matter along with organic farming or low tillage and mulching.

(3) Developing new resistant cultivars

To deal with increasing climate change and variability, it is urgent to develop new tea cultivars with strong tolerance to heat, cold and drought stress, new cultivars with high resistance to pests and diseases, new cultivars with high N/nutrient use efficiency and new cultivars with high net photosynthesis, especially high response to the elevated CO_2 concentration.

(4) Improving soil and water conservation capacity

Climate change negatively affects the basic elements of food production, such as soil, water and biodiversity. Most of tea fields are located in rain-fed sloping land of mountainous areas, in which tea yields depend not only on rainfall amount but also its utilization. With increasing temperature, high evaporation and transpiration, drought will probably be a normal phenomenon in the coming years. Therefore, to develop soil and water conservation measures, increasing soil water holding capacity, will be very important to reduce the impact of drought while maintaining tea production. Besides establishing contour terraces, mulching, cover crops and contour staggered trenches in tea gardens, ecosystem diversity and water conservation agent should be considered for further research and development.

(5) Improving integrated tea production ecosystem

Tea is a mono and perennial crop. The ecosystem is relatively simple and unstable. With climate change and its variation, more complex and integrated ecosystem should be considered to maximize use of natural resources such as hot weather, water and enriched CO_2, while to minimize stress conditions. Proper shade management and multicropping systems, such as “pig raising – biogas slurry - tea” and “tea – green manure - animal husbandry – biogas slurry – tea” should be further promoted. Conservation agriculture, precision agriculture, organic agriculture and other sustainable farming systems should be integrated to adapt to the climate change.

(6) Meteorological disaster predication and its impact assessment

The climate change predication and its impact magnitude assessment on tea industry, meteorological disasters monitoring and forecasting system, identification of the most vulnerable areas, counteraction measures and recovery technologies are very important. These services to tea producers should be systematically established or improved to reduce the risks of climate change.

4.5.3. Community involvement and technology extension

Majority of tea is produced by small holders in China, who are the most vulnerable group to the impacts of climate change and variations. Therefore, awareness creation, public education, information exchange, indigenous and community based adaptation strategies and new technology extension and crop insurance should be promoted to deal with climate change and extremes.

(1) Awareness creation of climate change and its impact

Public awareness of climate change and its impact on tea industry in community level is one of the key strategies not only to implement effective participatory adaptation in large scale, but practice low C excises in their daily life. Therefore, the public access to information of climate change and its effect, especially the localized specific climate events, educational and public awareness programs should be made available to the local community.

(2) Implementing mitigation and adaptation measures

The climate change mitigation and adaptation measures should be implemented immediately, especially in the most vulnerable areas, and the key tea producing areas. Indigenous and community-based mitigation and adaptation measures should be encouraged. New and integrated adaptation measures should be tested or evaluated locally before extension on a large scale. Community and individual participation in national or regional adaptation planning processes should be encouraged. Technical and financial support, scientific and managerial personnel training, and other capacity-building programs should be strengthened in local communities.

(3) Developing crop insurance to minimize the risks of meteorological disasters

Tea producers' especially small holders and low-income farmers should be encouraged to purchase meteorological disaster insurance to reduce the risks of climate impacts. Currently, insurance for late spring coldness is in practice by the leading insurance companies in China and supported by local government in Zhejiang Province. Due to the increasingly extreme weather events, such as drought, more insurance schemes should be developed and promoted.


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Recommendations to the industry

Strategies for tea growers

- Planting of tea cultivars, improved seedlings and grafted plants tolerant to adversities of weather (drought, water logging, warm/cold weather conditions)
- Soil and soil moisture conservation and rain water harvesting
- Improvement of soil organic matter content in tea lands
- Applications of compost, tea waste, cattle manure, decomposed oil cake etc
- Mulching with succulent vegetative matter
- Retaining of pruning litter and shade tree droppings/loppings and burying of pruning
- Green Manure and Cover crop
- Envelope forking
- Reduction of chemical Load by integrated nutrient management, proper waste management and preserve environment
- Integrated pest and disease management to improve bush vigour
- Establishment and management of shade trees and shelter belts to modify micro-climate and provide organic matter
- Improvement of drainage to remove excess moisture from the root zone
- Irrigation during dry spells
- Crop diversification to reduce risk of mono-cropping
- Afforestation, reforestation and establishment of watershed in tea plantations
- Selection of lands with suitable growing (ecological) conditions for new tea cultivation
- Nature Conservation and ecotourism

Strategies for local/regional institutes

- Breeding and selection of drought/heat/frost/pest and disease tolerant cultivars
- Development of more cost effective and less labour intensive strategies for tea cultivation
- Introduce integrated tea production ecosystem

- Seasonal Weather forecasting and Meteorological disaster predication
- Conduct impact assessments on climate change
- Conduct awareness programmes on climate change and its impacts

Strategies for national /international policy makers

- Strengthening R&D institutes generating new technologies on tea with special reference to climate change adaptation and mitigation and their extension arms
- Provide guidance and financial assistance for adopting climate change adaptation and mitigation (reduce GHG emissions and increase C sequestration) strategies
- Development of policies encouraging nature conservation and eco-tourism
- Establishment of national and international network on climate change to share knowledge and technologies
- Investments on development of field infrastructure, drainage system, irrigation system, road network and ecosystem diversity to improve level of adaptability of tea growers to climate change.
- Introduce crop insurance schemes to minimize the impacts on tea growers and other stakeholders

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