# Spatial Assessment of Climate Change Effects on Crop Suitability and Yield for Tea Plantations in Sri Lanka

P.M.S. Jayathilaka[a], P. Soni[b]

[a] Department of national Planning, The Secretariat, Colombo 01, Sri Lanka

[b] Agricultural systems and Engineering field of study, School of Environment Resources and Development, Asian Institute of Technology, Pathumthani 12120, Thailand, E-mails: [a] jayatilake@gmail.com, [b] soni@ait.ac.th

**Keywords:** Climate change, Crop Suitability, Agro-ecological Zone, Plantation crop, GIS, Yield

**Abstract**

Global warming is a growing concern in this century. Particularly, it is imperative to identify the effects of climate change in agricultural areas. This study focuses on evaluation of climate change effect on tea (*Camellia sinensis*) as a major plantation crop in Sri Lanka. Geo-referenced maps of spatial and temporal changes in crop suitability and production potentials are generated and compared. Data pertaining to five agro ecological zones (AEZs) under the study area are analyzed for a period of 1980-2007. Crop suitability maps are generated amalgamating yield maps and climatic factors maps by using AHP in multi-criteria analysis under two time-frames of 1980-1992 and 1993-2007. Percent change in crop suitability and crop yield classes are calculated based on five crop suitability and five crop yield classes during two time-frames. Dynamics of climatic parameters and crop yield is recognized using geo-referenced maps. The suitability maps of the two time-frames are compared to identify the changes with tea crop in conjunction with changes in the prevailing climate and yield. Geographic shift of suitability, yield and climate classes are examined. High suitability tea crop cover shifted to 11.29 km from its original centroid. Net gain or loss in crop production is quantified. The highest average annual production loss of tea (219 kg/ha/yr) was recorded in Mid Country Wet Zone (MW) while Low Country Wet Zone (WL) (68 kg/ha/yr) and up country intermediate zone (IU) (162 kg/ha/yr) record loss during 1981-2007 period. Long term annual rainfall significantly decreased in mid country wet zone (WM); whereas, the mean temperature of the study area increased by 1.4 $^{o}$C.

## Introduction

Herath and Ratnayake (2004), after studying 60 rain gauges at tea estates in Central Mountains of Sri Lanka for 30 years, observed decrease in rainfall. Similarly, a significant downward trend of rainfall was noted in Central hills around Nuwara Eliya in Sri Lanka during 1900–2002 (Bandara and Wickramagamage, 2004). Tea crop in Sri Lanka are grown in an area of 0.23 million ha or 4% of the country's land which is shown in Figure 1. Tea crop contributes 10% to the agricultural share to the Sri Lankan GDP, and employs above 0.3 million people. It earns about 15% of the country's export earnings. Tea (*Camellia sinensis*) is the major plantation crop, with 1.2% contribution to GDP (Central Bank of Sri Lanka, 2008).

<u>Tea ecophysiology in Sri Lanka:</u>

Tea, a rainfed perennial crop of humid regions, grows at altitude between 0 to 2500 m above mean sea level in Sri Lanka. Annual rainfall between 2500–3000 mm year$^{-1}$ is considered as optimum, 1200 mm year$^{-1}$ as a minimum (Watson, 1986). The productivity of tea lands is known to be greatly influenced by rainfall and temperature. Similarly, its quality is significantly affected by the duration and intensity of rainfall (Herath and Ratnayake, 2004). Tea yield is so sensitive to the climate that it could be considered to be an indicator for representing the climate change stress (Anandacoomaraswamy et al., 2000). A 100 mm reduction in monthly rainfall could reduce the productivity by 30-80 kg of made-tea $ha^{-1}$ (Wijeratne, 2004; Wijeratne et al., 2007). In this study, the effects of climate change on tea crops in Sri Lanka are evaluated.

## Methodology

General approach

Based on Agro Ecological Zones (AEZs) secondary data (meteorological data, land use map, AEZs map and crop yield) were gathered from meteorological department, survey department, research institutes and estates. Primary data were collected using research survey. Climate and yield factors for each crop suitability classes were identified. The relative importance of these climate and yield factors were quantified by interviewing experts from tea plantations.

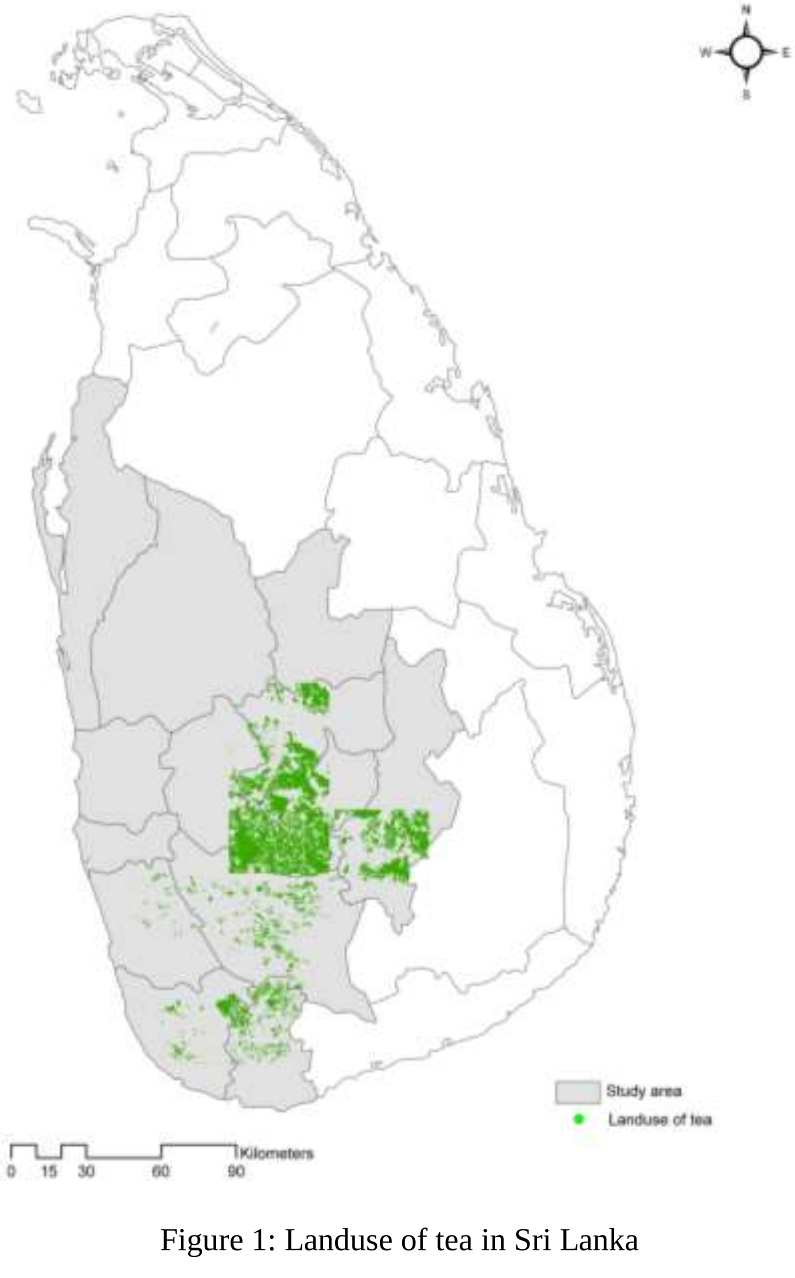


Figure 1: Landuse of tea in Sri Lanka

Analytic Hierarchy Process (AHP) was then used to determine the suitability level of tea crop accompanied with climatic factors (rainfall, relative humidity, temperature) and crop factors (evapotranspiration, crop yield). AHP, developed by Satty (1980), is a kind of multiple-criteria decision-making approach. The spatial data and their attributes were incorporated in GIS. Spatial maps of climatic parameters, actual yields and land use of tea were generated. These maps were later used for the identification of crop suitability for tea crop under climate change.

Data collection

Annual rainfall, average annual temperature and relative humidity data were collected from identified stations (Table 1) for 28 years (1980-2007).

Table 1: Sample sizes for meteorological observations within the study area

| Climate parameters | Total meteorological stations | Sample size | Error level* |
|---|---|---|---|
| Rainfall | 96 | 65 | 7% |
| Temperature | 25 | 22 | 7% |
| Relative humidity | 28 | 25 | 7% |

* calculated as per Yamane (1967)

Simple random sampling for plantation estates was carried out without replacement. Historical data of annual yield and extent were gathered from the selected tea estates confined in the study area. Location and distribution of these estates and meteorological stations in the study area are shown in Figure 2(a, b) and Table 2.

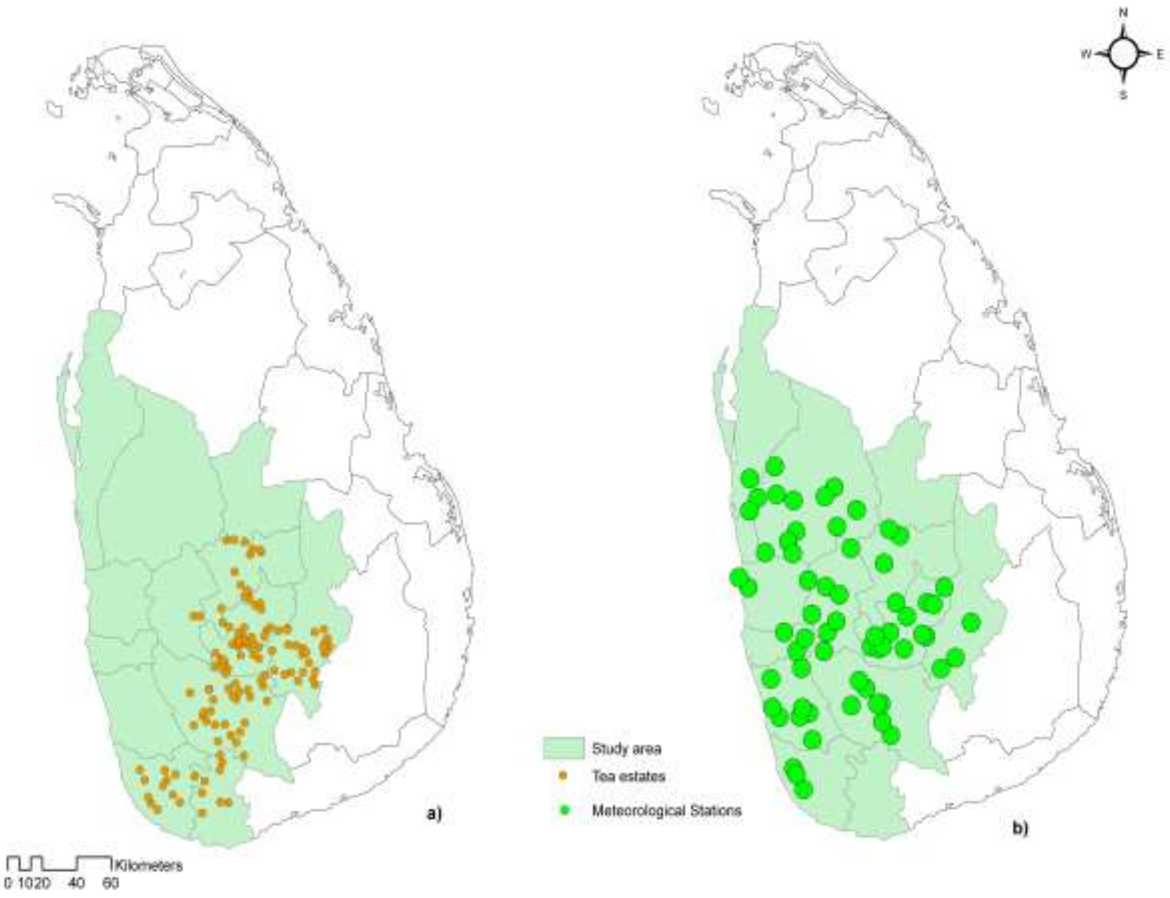


Figure 2: Location and distribution of a) tea estates; and b) meteorological stations (Source: Generated from the research survey)

Tea yield data were collected from vegetative propagated clones (aged between 4 to 20 years; plant spacing 1.2 m x 0.6 m; less than 0.5% of mortality; Nitrogen application 230-265 kg $ha^{-1}$ $yr^{-1}$) from each estate.

Table 2: AEZ-wise distribution of plantation estates for tea under study area

| Crop | AEZs | Total estates | Sample size* | Error level |
|---|---|---|---|---|
| Tea | Low country wet zone (WL) | 45 | 31 | 10% |
| | Mid country wet zone (WM) | 52 | 34 | 10% |
| | Up country wet zone (WU) | 37 | 29 | 10% |
| | Up country intermediate zone (IU) | 49 | 33 | 10% |

* calculated as per Yamane (1967)

<u>Spatial and temporal maps creation</u>

Spatial and temporal maps for crop suitability, spatial yield maps for tea crop and individual climatic factors maps were generated using ArcGIS 9.3 software. Tea crop suitability and yield dynamics were illustrated for 1980-1992 and 1993-2007 two time-frames. The geo-referenced data were transformed into spatial rainfall, relative humidity, temperature and evapotranspiration maps using the inverse distance weighing (IDW) interpolation, for 1980-1992 and 1993-2007 time-frames. Digital geo-referenced location maps for tea estates were created by using Geographical Positioning System (GPS). Actual yield data of tea estates were incorporated with attribute tables of each estate's location on the map. Spatial yield maps were created and variations in crop yield under two time-frames were analysed.

<u>Crop suitability maps</u>

Five factors including three climatic (RF, RH, T) and two crop factors (ET, CY) for crop suitability were ranked in the order of weighted average index (WAI) using Equation 1 (Miah, 1993).

$$\text{WAI} = [R_{I}\,(1.0) + R_{II}\,(0.5) + R_{III}\,(0.33) + R_{IV}\,(0.25) + R_{V}\,(0.20)] \,/ \sum i^{th} \text{ rank} \qquad (1)$$

Where,

$R_{i\,=\,I\text{-}V}$ : Frequency of $i^{th}$ relative importance factor of crop suitability

Pair-wise comparison matrix was constructed for climatic and yield factors to assess relative weight of those factors for their suitability to tea crop. This matrix was filled through research survey questionnaire, based on 1 to 9 point scale for pair-wise comparison. Consistency Index (CI), which denotes level of deviation from consistency, was computed using Equation 2 (Satty and Kearns, 1985).

$$CI = \frac{\lambda_{\max} - n}{n - 1} \qquad (2)$$

Where,

n : number of activities

$\lambda_{max}$ : maximum Eigen value

The ratio of CI to average Random inconsistency Index (RI) for the same order matrix is known as Consistency Ratio (CR). The relation of RI with n values is tabulated in Satty

(1980). By definition, the CR should be below 0.1 to obtain the acceptable consistency in the pair-wise comparison matrix.

Hopkins (1977) showed that the final suitability or impact is best deduced as a weighted sum of several factors, and suggested linear combination method. Crop suitability of tea crop, therefore, was expressed as a linear sum-product of suitability factors and weight assigned for its corresponding factor ($W_{i,\ i=1-5}$). The crop suitability was thus computed by the linear combination method (Equation 3) after calculating the weighing scores.

$$\text{Final suitability model} = (W_1 * RF) + (W_2 * RH) + (W_3 * T) + (W_4 * ET) + (W_5 * CY) \qquad (3)$$

Where,

| | |
|---|---|
| RF | : Rainfall |
| RH | : Relative humidity |
| T | : Temperature |
| ET | : Evapotranspiration |
| CY | : Crop yield |

Tea crop suitability map was generated overlaying climatic factors maps (RF, RH, T) and crop factor maps (ET, CY) in GIS environment by using Equation 3 under two time-frames. The suitability maps of both time-frames were compared to identify the temporal changes of tea crop under the climate change.

The geographic shifts of crop suitability classes and yield classes were also computed. For this purpose, raster maps of crop suitability were classified into five distinct suitability classes. After their conversion into vector format, spatial analyst tool operations were performed. Centroids of each polygon of similar suitability class were calculated; which in turn were used to locate the overall centroid of the group to represent the corresponding class as a point value. The centroids were calculated for all five crop suitability classes of 1980-1992 and 1993-2007 maps for tea crop. The geographic (distance and direction) shifts of centroids thus represented corresponding shifts of each suitability class. These geographic shifts were measured and compared for tea crop.

Statistical and economic analysis

The normal distribution of data was checked by normality test. The paired samples t-test and sign test were assigned to identify the magnitude of tea yield change between two time-frames of each AEZ. The descriptive statistics were done for the analysis of rainfall, temperature, relative humidity and evapotranspiration. Annual rainfall values in different AEZs were analyzed using linear regression to study the long term behavior.

Average annual yield change was calculated for 1993-2007 with respect to 1980-1992. The average annual yield change for tea was measured in kg $ha^{-1}$ $yr^{-1}$. Five yield classes were defined by the respective research institutes (Ministry of Plantation Industries, 2008). And five suitability classes were categorized using overlaid map of climatic and yield related factors viz. rainfall, relative humidity, temperature, evapotranspiration and yield. The total production loss or gain, during 28 years, was computed under two time-frames, considering mid value of the yield class and the area of its corresponding aerial extent.

## Results and discussion

Priority order of suitability factors, and crop suitability model

Perspectives of academicians and experts of tea crop, retrieved through first-hand interviews, were recorded. Levels of suitability factors (both climatic and crop yield) are presented with five crop suitability classes and five crop yield classes in Table 3.

For tea crop suitability factor, WAI values were calculated (Equation 1). Priority order of these factors, for tea crop, was determined based on WAI values (Table 4).

The consistency ratio (CR) in the pair-wise comparison of tea was 0.05. The crop suitability model was deduced by the linear combination method after weighting scores ($W_{i,\ i=1\text{-}5}$) were identified for tea crop (Equations 4).

$$\text{Tea suitability} = (0.45 * RF) + (0.05 * RH) + (0.11 * T) + (0.05 * ET) + (0.34 * CY) \quad (4)$$

Table 3: Levels of crop suitability classes and crop yield classes

| Suitability class | Rainfall (mm yr$^{-1}$) | Relative humidity (%) | Temperature ($^0$C) | Evapo-transpiration (mm day$^{-1}$) | Yield class *Tea* (kg ha$^{-1}$ yr$^{-1}$) |
|---|---|---|---|---|---|
| **Tea** | | | | | |
| Not suitable | 1000-1500 | 84-88 | 30.0-33.0 | >4.5 | < 900 |
| Marginally suitable | 1500-2000 | 80-84 | 26.5-30.0 | <2.5 | 900 - 1200 |
| Moderately suitable | 2000-2500 | 68-72 | 16.0-19.5 | 3.5-4.0 | 1200 - 1500 |
| Suitable | 3000-3500 | 72-76 | 23.0-26.5 | 3.0-3.5 | 1500 - 1800 |
| Highly suitable | 2500-3000 | 76-80 | 19.5-23.0 | 2.5-3.0 | > 1800 |

Table 4: Priority order of crop suitability factors for tea crops

| Crop suitability factor | Tea | |
|---|---|---|
| | WAI | Ranking in order of WAI |
| Rainfall | 0.90 | 1 |
| Relative humidity | 0.22 | 5 |
| Temperature | 0.41 | 3 |
| Evapotranspiration | 0.27 | 4 |
| Crop yield | 0.47 | 2 |

Changes in climatic factors

The climatic parameters were analyzed for the period of 1980-2007; descriptive statistics comparing the two time-frames for the study area is shown in Table 5. The mean temperature of the study area significantly increased by 1.4 $^oC$. Changes in rainfall and temperature during two time-frames are depicted in Figure 3 (a, b). Previous studies on regional climatic modelling (Benjamin et al., 2006) also estimated the temperature rise in the Asia and Pacific region of the order of 0.5-2 °C by 2030 and 1-7 °C by 2070.

Table 5: Changes in climatic factors in the study area during 1980-1992 and 1983-2007

| **Climatic factor** | **Time-frame** | **Mean** | **S.D.**[α] | **Minimum** | **Maximum** |
|---|---|---|---|---|---|
| Rainfall (mm) | 1980-1992 | 2574 | 282 | 2062 | 3057 |
| | 1993-2007 | 2522 | 355 | 1904 | 2989 |
| Relative humidity (%) | 1980-1992 | 80 | 2 | 77 | 83 |
| | 1993-2007 | 81 | 2 | 79 | 86 |
| Temperature ($^0$C) | 1980-1992 | 27.4 | 0.5 | 26.3 | 28.1 |
| | 1993-2007 | 28.8 | 0.3 | 26.7 | 31.9 |

[α] Number of observations, n=65 (RF); n=25 (RH); n=22 (T)

Long term mean annual rainfall values were compared at different AEZs, a total of 65 rain gauges were analyzed (Table 6). Mid country wet zone (WM) showed significant steep reduction in receiving annual rainfall. Although, WL, WU and IU indicated decreasing trends, yet not with statistical significance.

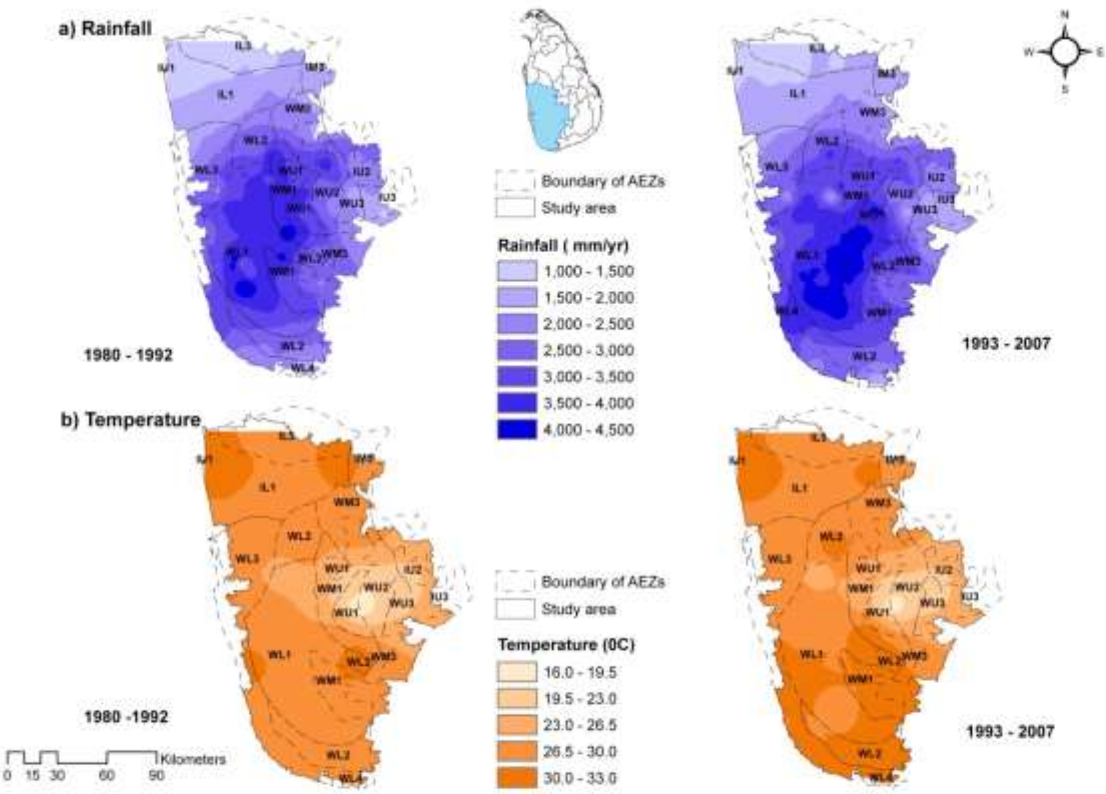


Figure 3: Change in a) rainfall: and b) temperature during the period of 1980 – 1992 and 1993 - 2007

Table 6: Results of linear regression analysis of mean annual rainfall values during 1980 - 2007 in different AEZs

| AEZ | Regression coefficient | t-value | Significance probability |
|---|---|---|---|
| WL | -1.65 | -0.21 | 0.832 |
| WM | -23.70 | -2.92 | 0.007* |
| WU | -23.55 | -1.69 | 0.103 |
| IU | -6.24 | -0.83 | 0.417 |

* Significant at p=0.05

Evaluation of changes in crop yield and crop suitability

Paired samples t-test and sign tests were conducted for paired yield data of two time-frames for tea crop to detect AEZ-wise crop yield change (Table 7). The tea yield was significantly affected in both WM and IU zones. Reduced tea yield in WM mainly corresponds to the declining rainfall (Table 6).

Table 7: Crops' average annual yield comparison under two time-frames

| Crop | AEZs (no. of observations) | Mean (SD) of yield | | p-value |
|---|---|---|---|---|
| | | 1980-1992 | 1993-2007 | |
| **Tea (made tea kg $ha^{-1}$ $yr^{-1}$)** | WL (n=31) | 1376.9 (586.9) | 1358.0 (470.3) | 0.845 |
| | WU (n=29) | 1805.6 (470.0) | 1641.3 (332.7) | 0.148 |
| | WM (n=34) | 2067.6 (355.6) | 1452.2 (369.0) | 0.000* |
| | IU (n=33) | 1551.0 (277.6) | 1799.0 (301.9) | 0.000* |

* Significant at p=0.05

The tea crop suitability maps were generated in GIS environment, and are shown in Figures 4. Changes in extent of different suitability classes for tea crop under two time-frames were analyzed. For tea crop, percent change in aerial extent according to five crop suitability classes (Table 8) and five yield classes (Table 9) during 1980-1992 and 1993-2007 were computed. There was no change in the total extent, as only those estates are considered for which data in both time-frames were available for comparison.

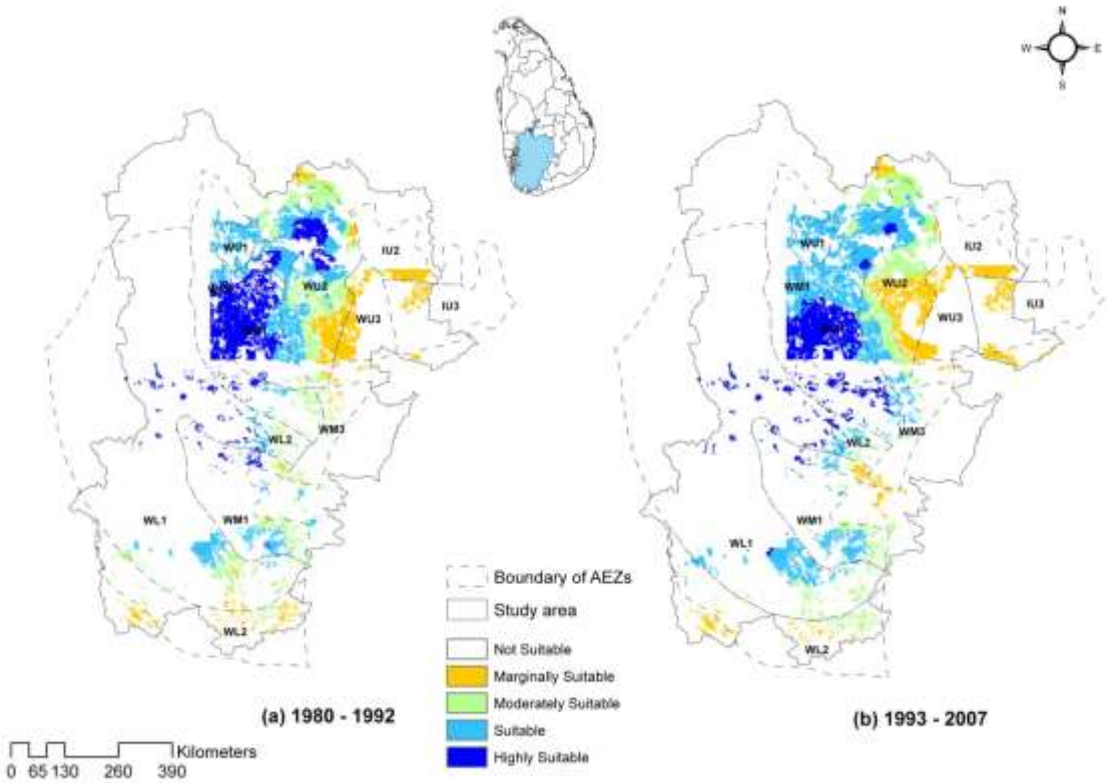


Figure 4: Crop suitability of tea during the period of a) 1980 – 1992; and b) 1993 – 2007

Table 8: Relative spatial shifts in aerial extent of crop suitability classes under two time-frames

| | **Crop suitability Class** | **Extent in 1980-1992 ($km^2$)** | **Extent in 1993-2007 ($km^2$)** | **% change w.r.t. first time-frame** | **% change w.r.t. total extent** |
|---|---|---|---|---|---|
| | Not suitable | 91.01 | 131.79 | 44.8 | 2.4 |
| | Marginally suitable | 293.48 | 318.4 | 8.5 | 1.4 |
| **Tea** | Moderately suitable | 390.59 | 337.24 | -13.7 | -3.1 |
| | Suitable | 508.74 | 637.29 | 25.3 | 7.4 |
| | Highly suitable | 442.51 | 301.61 | -31.8 | -8.2 |
| | Total extent ($km^2$) | 1726.33 | 1726.33 | | |

Threatening incidence was observed in tea sector, where *not suitable* and *marginally suitable* land increased by 2.4% and 1.4% respectively; and area under *highly suitable* class decreased by 8.2%. The WM and WU AEZs, where large estates are located, the prevailed declining trend of rainfall has badly affected tea yield. The extent of 1500-1800 kg $ha^{-1}$ $yr^{-1}$ and >1800 kg $ha^{-1}$ $yr^{-1}$ tea yield categories have declined by 4% and 1.3% respectively. The experts have ranked rainfall as their first priority for tea suitability (Table 4). The yield distribution of tea crop maps were generated in GIS environment, and are shown in Figures 5.

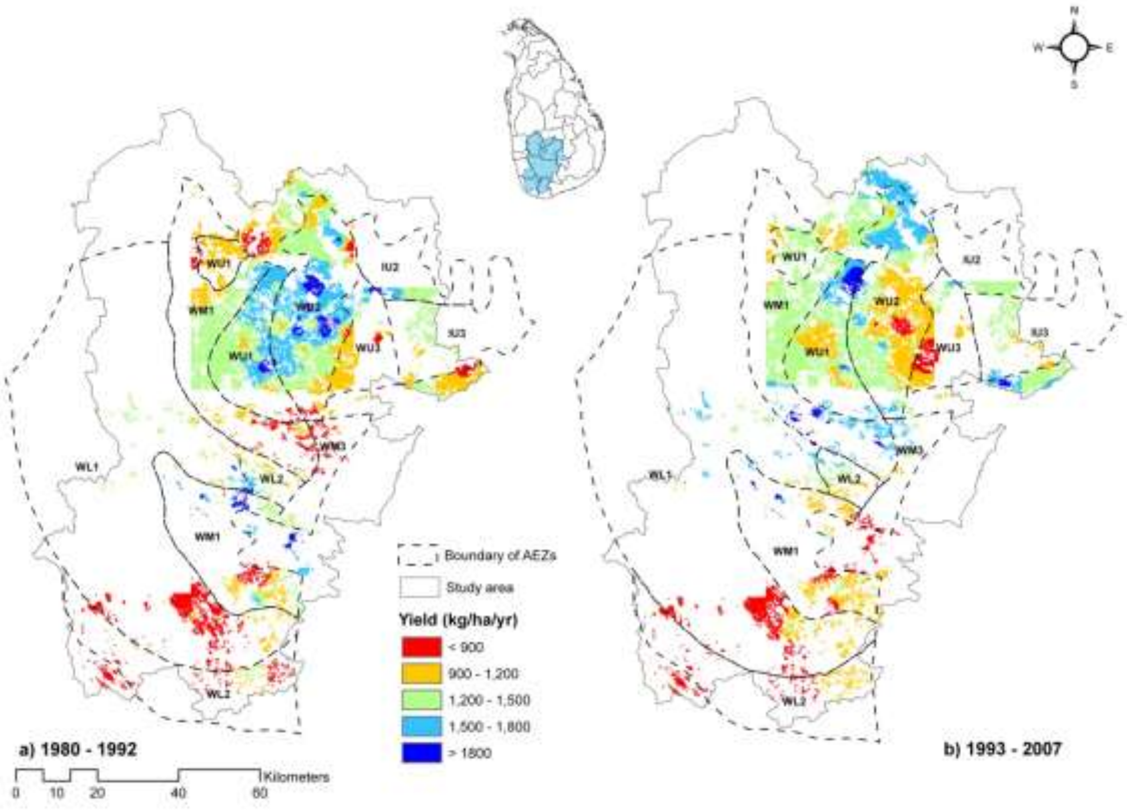


Figure 5: Yield distribution of tea during the period of a) 1980 – 1992; and b) 1993-2007

Table 9: Relative spatial shifts in aerial extent of crop yield classes under two time-frames

| | Yield class | Extent in 1980-1992 ($km^2$) | Extent in 1993-2007 ($km^2$) | % change w.r.t. first time-frame | % change w.r.t. total extent |
|---|---|---|---|---|---|
| **Tea(made tea kg $ha^{-1}$ $yr^{-1}$)** | < 900 | 253.71 | 194.02 | -23.5 | -3.5 |
| | 900 - 1200 | 412.27 | 480.82 | 16.6 | 4.0 |
| | 1200 - 1500 | 661.48 | 743.18 | 12.4 | 4.7 |
| | 1500 - 1800 | 332.75 | 264.21 | -20.6 | -4.0 |
| | > 1800 | 66.15 | 44.13 | -33.3 | -1.3 |
| | Total extent | 1726.36 | 1726.36 | | |

Loss/Gain of Tea Plantation Production

The total production of tea crop got altered during both time-frames, corresponding to changes in respective yields and aerial extents, which is shown in Table 10.

Table 10: Loss or gain in Tea production during the two time-frames

| Crop | Yield class Tea (kg $ha^{-1}$ $yr^{-1}$) | Total production during 1980-1992 Time-frame | Total production during 1993-2007 Time-frame | Change in total production during 1980-2007 |
|---|---|---|---|---|
| **Tea (made tea million kg)** | < 900 | 148.42 | 130.96 | -17.46 |
| | 900 - 1200 | 562.75 | 757.29 | 194.54 |
| | 1200 - 1500 | 1160.90 | 1504.94 | 344.04 |
| | 1500 - 1800 | 713.75 | 653.92 | -59.83 |
| | > 1800 | 154.79 | 119.15 | -35.64 |

The highest tea production gain of 344.04 million kg showed in 1200-1500 kg $ha^{-1}$ $yr^{-1}$ yield category, while the highest loss recorded in 1500-1800 kg $ha^{-1}$ $yr^{-1}$ category. Overall, net gain was noted for tea which is 425.65 million kg.

Geographic Shift of Suitability, Yield and Climatic Factors Classes

*Highly suitable* class of tea shrinks and shifts 11.29 km South-West from its earlier centroid (1980-1992 period) (Table 11). The geographic shifts of yield classes are illustrated in Table 12. The highest yield category of tea moved away 8.79 km North-West from hill country area with declining trend of rainfall (Table 6). The rainfall class of 3500-4000 mm $yr^{-1}$ moved 13.67 km South-West (Table 13), which is reflected in declining rainfall at WM zone.

Table 11: The geographic shift of crop suitability classes

| Crop | Suitability class | Geographic shift* | |
|---|---|---|---|
| | | Distance (km) | Direction |
| **Tea** | Not Suitable | 11.04 | NW |
| | Marginally Suitable | 6.18 | N |
| | Moderately Suitable | 6.43 | N |
| | Suitable | 2.87 | W |
| | Highly suitable | 11.29 | SW |

*Centroid of respective classes during two time-frames

Table 12: The geographic shift of crop yield classes

| Crop | Yield class | Geographic shift* | |
|---|---|---|---|
| | | Distance (km) | Direction |
| **Tea (made tea kg ha$^{-1}$ yr$^{-1}$)** | < 900 | 3.77 | SE |
| | 900 - 1200 | 10.18 | SW |
| | 1200 - 1500 | 4.78 | NE |
| | 1500 - 1800 | 1.48 | N |
| | > 1800 | 8.79 | NW |

*Centroid of respective classes during two time-frames

Table 13: The geographic shift of climatic factors

| Climatic factor | Categories | Geographic shift* | |
|---|---|---|---|
| | | Distance (km) | Direction |
| **Temperature ($^0$C)** | 16.0-19.5 | 2.01 | S |
| | 19.5-23.0 | 3.12 | E |
| | 23.0-26.5 | 9.50 | NE |
| | 26.5-30.0 | 30.44 | N |
| | 30.0-33.0 | 82.95 | SE |
| **Rainfall (mm yr$^{-1}$)** | 1000-1500 | 4.21 | NW |
| | 1500-2000 | 6.11 | NW |
| | 2000-2500 | 13.67 | N |
| | 2500-3000 | - | - |
| | 3000-3500 | 7.70 | NE |
| | 3500-4000 | 13.67 | SW |
| | 4000-4500 | 4.82 | E |

*Centroid of respective categories during two time-frames

## Conclusions

Analysis of meteorological data reveals significant declining trend of annual rainfall in mid country wet zone (WM) during last three decades. The mean temperature of the study area has shoot up by 1.4$^0$C during 1980-2007.

The study reveals that crop suitability classes have reshuffled clearly between the two time-frames of 1980-1992 and 1993-2007. The aerial extents of five yield classes of each crop have undergone substantial change, much in-line with corresponding change in prevailing climate. Areas under lower tea yield categories have expanded with shrunken extent of higher yield categories.

With respect to the base year 1980, the highest average annual production loss of tea (219 made tea kg ha$^{-1}$ yr$^{-1}$) was recorded in WM AEZ, while WL (68 made tea kg ha$^{-1}$ yr$^{-1}$) and IU (162 made tea kg ha$^{-1}$ yr$^{-1}$) AEZs recorded loss during 1981-2007. Considering changes in both yield and the aerial extent of yield classes, overall net gains were calculated for tea (425.65 million kg), during 1980-2007.

Tea crop growers may be made aware of these shifting trends of crop suitability and yield classes in concurrence with climate change. Results of this study could help planning appropriate land use change not only for new plantations and replanting, but also for formulating strategies to maximize the returns. More importantly, it is hoped that tea plantation managers will use this information to rationalize inputs by concentrating on areas that require costly agronomic practices.

## REFERENCES


Anandacoomaraswamy, A., De Costa, W.A.J.M., Shyamalie, H.W. and Campbell, G.S. (2000). Factors controlling transpiration of mature field grown tea and its relationship with yield. Agricultural and Forest Meteorology 103, pp.375 – 386.

Bandara, C.M.M. and Wickramagamage, P. (2004). Climate change and its impact on upper watershed of the hill country of Sri Lanka. Climate Change Secretariat Working Paper. Environmental Economics and Global Affairs Division, Ministry of Environment and Natural Resources, Battaramulla, Sri Lanka.

Benjamin, L.P., Ramasamy, S., Ian, M. and Janice, B. (2006). Climate change in the Asia/Pacific region. Climate change impacts and risk. CSIRO Marine and Atmospheric Research, Australia.

Central Bank of Sri Lanka, (2008). Annual Report, Colombo. Retrieved on 24th January 2010 from http://www.cbsl.gov.lk/

Herath, S. and Ratnayake, U. (2004). Monitoring rainfall trends to predict adverse impacts—a case study from Sri Lanka (1964–1993). Global Environmental Change14, pp. 71–79.

Hopkins, D. (1977). Method of Generating Land suitability Maps, A Comparative Evaluation. The American Institute of Planners, 43(4), 386-400.

Miah, A.Q. (1993). A course Handbook for human settlement planning. Division of human settlement development, Asian Institute of Technology. Bangkok, Thailand.

Ministry of Plantation Industries, (2008). Statistical pocket book plantation sector, Sri Lanka, Colombo.

Satty, T. L., (1980). The analytic hierarchy process, Mcgraw-Hill, New York, NY.

Satty, T. L., and Kearns, K. P. (1985). Analytical Planning, The Organization of Systems. Oxford, Pergamon

Watson, M., (1986). Soil and climatic requirements. In: Sivapalan,P., Kulasegaram, S., Kathiravetpillai, A. (Eds.), Handbook onTea. Tea Research Institute, Sri Lanka, pp. 3–5.

Wijeratne, M.A., Anandacoomaraswamy, A., Amaratunga, M.K.S.L.D., Janaka Ratnasiri., Basnayaka, B.R.S.B. and Kalra, N. (2007). Assessment of impact of climate change on productivity of tea plantations in Sri Lanka. Natural Science Foundation Sri Lanka.

Wijeratne, M.A., (2004). Impact of climate change on productivity of tea plantations in Sri Lanka. The experiments and extension forum report, TRI-Sri Lanka

Yamane, T. (1967). Statistics, An Introductory Analysis, 2nd Ed., Harper and Row. New York.