J.Natn.Sci.Foundation Sri Lanka 2024 52 (2): 183 - 190
DOI: http://dx.doi.org/10.4038/jnsfsr.v52i2.11762

RESEARCH ARTICLE

Agricultural Economics

Impact of climate on tea yield: an empirical investigation from Sri Lanka

JC Edirisinghe[1*], H Ranjan[1], HMLK Herath[1], UK Jayasinghe-Mudalige[1], M Wijeratne[2], V Kuruppu[1], C Jayathilake[3], W Wijesuriya[4], K Somarathna[1], S Karunaratne[5], S Jayawardana[6], D Gunathilaka[7] and D Balasooriya[4]

[1] *Department of Agribusiness Management, Faculty of Agriculture and Plantation Management, Wayamba University of Sri Lanka, Makandura, Gonawila (NWP), Sri Lanka.*
[2] *Tea Research Institute of Sri Lanka, Sri Lanka.*
[3] *Information and Communication Centre, Wayamba University of Sri Lanka, Sri Lanka.*
[4] *Rubber Research Institute of Sri Lanka, Sri Lanka.*
[5] *Commonwealth Scientific and Industrial Research Organization*
[6] *Department of Meteorology, Sri Lanka.*
[7] *Department of Export Agriculture, Uwa Wellassa University of Sri Lanka, Sri Lanka.*

Submitted: 16 July 2023; Revised: 11 November 2023; Accepted: 26 January 2024

Abstract: Agriculture is heavily climate dependent. Tea cultivation is of no exception. Tea is cultivated in many developing nations around the globe and the climate change impact is to be mostly felt by developing nations in comparison to the developed. In countries such as Sri Lanka, where the major portion of export earning from agriculture comes from the tea industry, the climate change impacts would harm its progress. Hence, understanding how climate has been linked with production would pave the way for development of a country specific policy. To this end, this research attempted to measure the long-run relationship of the climate with the yield per hectare, using monthly data from 2005 to 2019. A panel Autoregressive Distributed Lag model (ARDL) was used to obtain long-run cointegration between minimum and maximum temperatures and the amount of rainfall received. Data on production and input variables were obtained from records kept at 37 large-scale tea estates at monthly intervals. Monthly temperature and rainfall data were obtained from the Meteorological Department of Sri Lanka. Panel cointegration tests indicated that there is a coexisting long-run relationship between climate variables and the tea yield. Maximum temperature had a positive relationship with yield, but minimum temperature shows a long-run negative relationship. Rainfall is positively related. Production inputs show a long-run positive impact. Thus, the possible negative impacts of rising minimum temperature could be overcome if proper management practices are adopted in the long-run.

Keywords: Climate change, panel ARDL, rainfall, Sri Lanka, tea cultivation, temperature.

INTRODUCTION

Climate change is one of the greatest challenges faced in this century. Increasing global temperature and drought are altering agricultural production and productivity in the world (Appiah *et al*., 2018; Ahsan *et al*., 2020; Markou *et al*., 2020). Crop yields across Europe, Sub-Saharan Africa, and Australia have decreased because of climate change (Ray *et al*., 2019). The effects of climate change are unevenly distributed across the world. Adverse impacts of climate change on agriculture will have undesirable effects on food prices and therefore food security in the future. Predictions are that food prices will rise by 80% by 2050 due to climate change impacts on agriculture (Mbow *et al*., 2019). Agriculture is the backbone of many countries in the developing world, contributing in larger proportions to their gross domestic product (GDP), and in some cases are the main source of foreign exchange earnings. Therefore, the impacts of climate change need more attention than they

* Corresponding authors (jagathed07@gmail.com; https://orcid.org/0000-0003-4602-9266)

have received over the years, especially on agriculture in the developing world.

Sri Lanka is also an agriculturally based small island where a high proportion (27.1 %) of its population is involved in agricultural activities. Agriculture accounted for 6.9 % of the Sri Lanka's GDP in 2021 (Central Bank of Sri Lanka, 2021). Out of the agricultural products, tea is one of the main export earners of the country and Sri Lankan tea is a major player in the international tea market. At present, Sri Lanka is the third largest exporter of tea while being the fourth largest producer in the world (Sri Lanka Export Development Board, 2020). Sri Lanka has a 150-year history of tea cultivation with its origin in 1867. This industry has traditionally been the largest employment provider. According to estimates, the tea industry provides direct and indirect employment for about 1.5 million people, 11% of labour force of the country (Central Bank of Sri Lanka, 2018). Foreign exchange earnings from tea exports accounted for 11.3% of total exports earning in 2019 which is equivalent to US$ 1,346 million, the second-largest contributor to the total export earnings of Sri Lanka (Central Bank of Sri Lanka, 2019). Additionally, the tea industry accounts for 0.7% of the Gross Domestic Product (GDP) of Sri Lanka (Central Bank of Sri Lanka, 2020).

Around 4% of land area is covered by tea cultivation in Sri Lanka, which is close to 203,000 hectares (Sri Lanka Export Development Board, 2020). Tea is cultivated at three elevations: low (<600 m), medium (600 m – 1200 m) and high (>1200 m), by large scale tea estates as well as smallholders in lands less than 4 hectares. A temperature range of 20-30 degrees Celsius is desirable for shoot growth in tea (Jayasinghe *et al*., 2020). Tea needs a higher mean annual rainfall than most other perennial crops (TRI, 2002; Galmés *et al*., 2007) with an optimum around 2500 mm – 3000 mm (Jayasinghe *et al*., 2020). Data show that temperature in Sri Lanka is rising and the temperature change with respect to a baseline climatology is given in Figure 1. Hence, the impact of this on the main export crop in the nation needs attention.

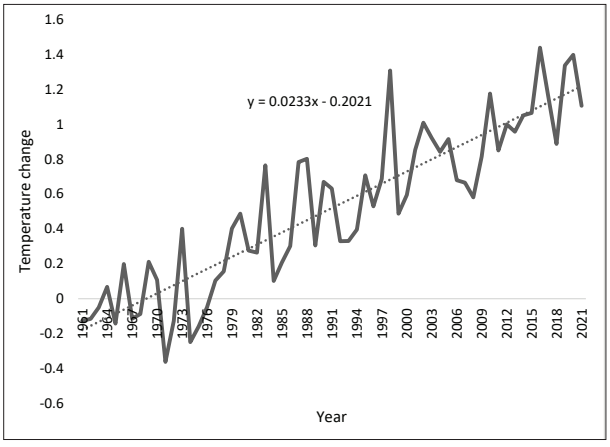

Figure 1: Annual change in temperature in Sri Lanka (Meteorological year). Source: FAO, 2022

MATERIALS AND METHODS

Data

Data were collected from 37 large-scale estates producing tea in three elevations: high, medium, and low. Data were in monthly intervals and related to the period 2005 – 2019. Monthly green leaf production and the extent of cultivation were obtained from each estate and the yield was calculated using those values. Other inputs into production, the labour, fertilizer, and chemicals were recorded as costs. Therefore, these were deflated by using the consumer price index (CPI). All input variables were converted to amounts per unit land area by dividing the relevant value by the cultivation extent. In addition to input and output variables, the GPS locations of all estates were recorded. These points were used to predict temperature and rainfall data obtained from the meteorological stations to exact GPS points of the estates by a Kriging procedure. All variables were converted to their natural logarithm values prior to estimation.

Model

The form of a panel ARDL model can be stated as.

$$YIELD_{it} = \sum_{j=1}^{p} \delta_i YIELD_{i,t-j} + \sum_{j=0}^{q} \beta_{ij}' \boldsymbol{X}_{i,t-j} + \varphi_i + \varepsilon_{it}$$

To obtain the short run and long-run relationships, the model is reparametrized as below:

$$\Delta YIELD_{it} = \boldsymbol{\theta}_i \left(YIELD_{i,t-j} - \boldsymbol{\lambda}_i' \boldsymbol{X}_{it} \right) + \sum_{j=1}^{p-1} \xi_{ij} \Delta YIELD_{i,t-j} + \sum_{j=0}^{q-1} \boldsymbol{\beta}_{ij}' \Delta \boldsymbol{X}_{i,t-j} + \varphi_i + \varepsilon_{it}$$

In this specification, λ_i is the vector of long-run relationships which includes the long-run relationships of all independent variables in the model. The group specific speed of adjustments is given by $\boldsymbol{\theta}_i = -(1 - \delta_i)$ which is expected to be less than zero. If $\boldsymbol{\theta}_i = 0$, then there is no long-run relationship. The term $\left(YIELD_{i,t-j} - \boldsymbol{\lambda}_i' \boldsymbol{X}_{it} \right)$

denotes the error correction while the $\xi_{ij}, \boldsymbol{\beta}'_{ij}$ are the short run dynamic coefficients. The $\boldsymbol{X}_{it}$, the $k \times 1$ vector is allowed to be purely I (0) or I (1) or cointegrated. This vector included three weather variables, the monthly averages of minimum and maximum temperatures and rainfall. There are many other input variables at play in explaining the variation of the yield. These are included as controls in the model. Thus, most common variables used in tea production, fertilizer and chemicals applied per unit area, and labour use per unit area were included. Because these inputs are recorded in estates as costs, they were deflated using the Consumer Price Index (CPI) to obtain constant values prior to the estimation.

There are several approaches for the estimation of this model. A fixed-effects (FE) estimation approach is suitable if one assumes that the time-series data for each group could be pooled and only the intercepts are permitted to vary across units. In the mean group (MG) estimator proposed by Pesaran & Smith (1995), the simple arithmetic average of coefficients is obtained after the model is fit separately for each group. Additionally, Pesaran *et al*. (1997) proposed a pooled mean group (PMG) estimator, where pooling and averaging carried out in the earlier two models are combined allowing intercept, short-run coefficients, and error variances to differ across the groups, while constraining the long-run coefficients to be equal across units (Blackburne & Frank 2007).

To examine the stationarity level and order of integration of the selected variables, a unit root test was carried out, the 'Im–Pesaran–Shin' (2003) unit root test, which uses mean of individual unit root test statistics to test unit roots of dynamic heterogeneous panels. Additionally, the 'Im–Pesaran–Shin test' reports a standardized t-bar test statistic grounded on the (augmented) Dickey-Fuller statistics averaged across the groups. Conducting such a test is important to ensure that no variable of order 2 is integrated. The optimum lag length of the panel ARDL model described above is selected by running ARDL models for each panel. Optimum lags were selected based on Akaike Information Criteria (AIC) and Bayesian Information Criteria (BIC). The most common lag for each variable was chosen to be used in the panel ARDL model. If cointegration exists, the panel ARDL model is said to have an error correction model interpretation. Therefore, there is better evidence that the long-run estimates are common across all estates under study. The cointegration test derived by Kao (1999) was applied to test cointegration, which assumes a cointegrating vector that is the same across all panels. Finally, the Hausman test was applied to select between MG and PMG estimators.

RESULTS AND DISCUSSION

Table 1 reports the descriptive statistics of the data used.

Table 1: Descriptive Statistics

Variable	Unit	Mean	Std. dev.
Yield	Kgs of green leaf per Ha per month	440.63	278.89
Extent	Hectares	193.22	110.72
Lab	LKR per Ha in constant LKR	17434.98	10722.61
Fert	LKR per Ha constant LKR	2427.43	2680.79
Chem	LKR per Ha constant LKR	498.23	844.94
Min T	Celsius	20.04	3.84
Max T	Celsius	27.80	3.51
RF	Millimeters per month	221.40	135.24

Lab: Labour, Fert: Fertilizer, Chem: Chemicals, Min T: Minimum temperature, Max T: Maximum temperature, RF: Rainfall

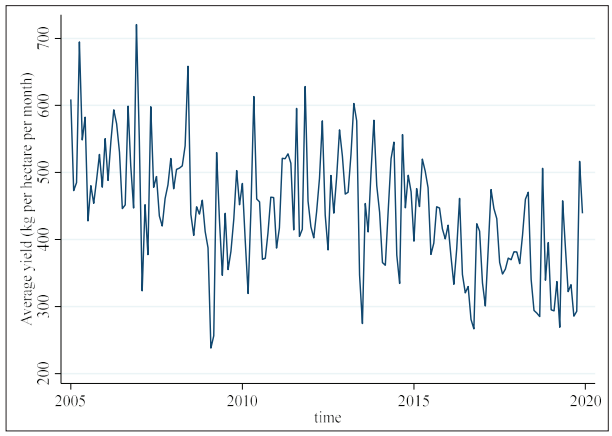

Figure 2: Average monthly estate yield (kg/ha/month) from 2005–2019

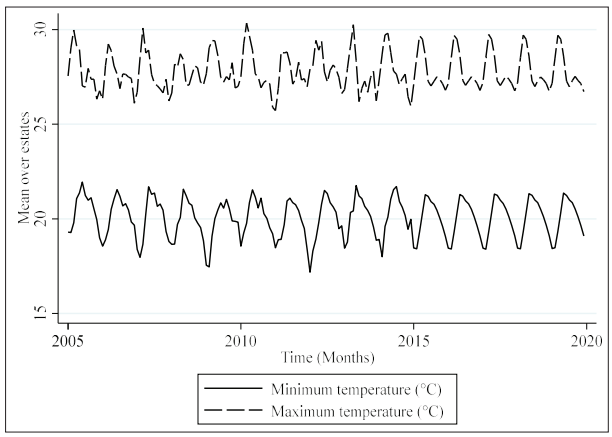

Figure 3: Variation of Minimum and maximum temperature (^{0}C) from 2005–2019 averaged over estates

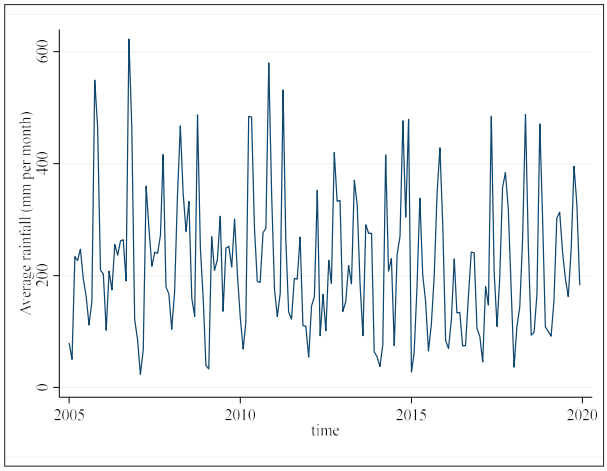

Figure 4: Variation in monthly rainfall 2005–2019 averaged over estates

According to the Figure 2, the estate level yield has declined over the years in the study period. The temperature shows a monthly variation but there is no marked overall trend from 2005-2019 (Figure 3). Rainfall, however, shows a greater variation (Figure 4).

Correlation analysis

The selected variables in the model were first subjected to correlation analysis. The results are presented in Table 2. Results suggested that labour, fertilizer, and chemical use are positively correlated to yield. Out of the climate variables, temperature (both maximum and minimum) shows a negative correlation with yield. However, rainfall show a positive correlation. Maximum and minimum temperatures show high correlation and may create multicollinearity in estimation. However, both variables were retained in the model estimation because of their importance in the model.

Table 2: Correlation analysis of variables in the model

	*ln*Yield	*ln*Lab	*ln*Fert	*ln*Chem	*ln*MinT	lnMaxT	*ln*RF
*ln*Yield	1.000						
*ln*Lab	0.617*	1.000					
*ln*Fert	0.468*	0.492*	1.000				
*ln*Chem	0.240*	0.179*	0.239*	1.000			
*ln*MinT	-0.304*	-0.407*	-0.139*	-0.199*	1.000		
*ln*MaxT	-0.352*	-0.481*	-0.262*	-0.251*	0.867*	1.000	
*ln*RF	0.192*	0.168*	0.264*	0.037*	0.127*	-0.033*	1.000

* Significant at 0.05

Lab: Labour, Fert: Fertilizer, Chem: Chemicals, Min T: Minimum temperature, Max T: Maximum temperature, RF: Rainfall

Table 3: Results of the Im-Pesaran-Shin test

Variable	IPS	IPS with trend
*ln*Yield	-31.725 (0.000)	-34.520 (0.000)
*ln*Lab	-29.066 (0.000)	-32.001 (0.000)
*ln*Fert	-32.774 (0.000)	-33.999 (0.000)
*ln*Chem	-29.202 (0.000)	-30.906 (0.000)
*ln*MinT	-29.599 (0.000)	-29.623 (0.000)
*ln*MaxT	-34.823 (0.000)	-34.833 (0.000)
*ln*RF	-42.894 (0.000)	-43.075 (0.000)

Note: Figures within parentheses are p values

Lab: Labour, Fert: Fertilizer, Chem: Chemicals, Min T: Minimum temperature, Max T: Maximum temperature, RF: Rainfall

Unit Root Test

Time series data are prone to unit roots and hence may be non-stationary. Use of such non-stationary series may create spurious regression outcomes. Therefore, all variables in the model were tested for unit roots. The results of the unit root tests are provided in Table 3. Specifically, the 'Im-Pesaran-Shin' (IPS) test proposed by Im *et al*. (2003) was used. The null hypothesis of IPS test is that all panels contain unit roots, hence a significant result of the test would indicate that data do not contain unit roots. The IPS with and without trend was used and the significance with respect to all variables show that unit roots are absent in them and thus, the data are stationary.

Optimum Lag Length Selection

Selection of optimum lag length is important as ARDL is sensitive to the lag lengths selected (Abbas, 2020). Since panel data were used, lag length selection was carried out for each panel using Akaike Information Criteria (AIC) values to select the lag lengths of each panel and then obtain the most common lag length of each variable selected. The results suggested a lag of one for dependent variable (yield). Of the independent variables, labour reported one lag while the other variables (fertilizer, chemical, minimum temperature, maximum temperature, and the rainfall) reported zero lags (Table 4). Hence, an ARDL (1,1,0,0,0,0,0) model was estimated.

Table 4: Lag lengths of each variable

Variable	Optimal lag length
*ln*Yield	1
*ln*Lab	1
*ln*Fert	0
*ln*Chem	0
*ln*MinT	0
*ln*MaxT	0
*ln*RF	0

Lab: Labour, Fert: Fertilizer, Chem: Chemicals, Min T: Minimum temperature, Max T: Maximum temperature, RF: Rainfall

Cointegration test

The cointegration test was done to see whether data are related in the long-run before the panel ARDL model was estimated. Here, the interest is to see whether there is a long-run relationship of labour, fertilizer, and chemical use, and especially the climate variables with estate level yield. Hence, the cointegration relationship was specified as.

$$lnYield_{it} = \gamma_i + \beta_1 lnLab_{it} + \beta_2 lnFert_{it} + \beta_3 lnChem_{it} + \beta_4 lnMinT_{it} + \beta_5 lnMaxT_{it} + \beta_6 lnRF_{it} + e_{it}$$

A model with panel-specific means without a time trend was used. The null hypothesis of this test is that no panels are cointegrated while the alternative hypothesis is that all panels are cointegrated. Table 5 reports 6 test statistics and their significance levels. The null hypothesis of no cointegration was rejected by all test statistics, favouring the alternative hypothesis that there exists a cointegration relationship between yield and the independent variables defined in the above model.

Table 5: Results of the Kao cointegration test

	Statistic	p-value
Modified Dickey–Fuller t	-20.687	0.0000
Dickey–Fuller t	-18.718	0.0000
Augmented Dickey–Fuller t	-10.415	0.0000
Unadjusted modified Dickey–Fuller t	-100.000	0.0000
Unadjusted Dickey–Fuller t	-35.411	0.0000

Model Checking – Hausman Test

This was carried out to test which estimator best fits the data at hand. Pooled mean group (PMG), mean group (MG), and dynamic fixed effects (DFE) models were estimated and compared using the Hausman test (Hausman, 1978). The results are reported in Table 6. The null hypothesis of these Hausman tests was that there is homogeneity. The probability value for PMG vs. MG is greater than 0.05 and hence, the null hypothesis is rejected; the PMG estimator is more efficient than the MG estimator. The second test compared PMG with DFE, and the resulting probability value is 0.9993. This indicates that best estimator to be used finally is the PMG estimator.

Table 6: Hausman test results of model selection

Model	Chi2	Prob>chi2
PMG Vs. MG	3.12	0.7936
PMG Vs. DFE	0.34	0.9993

The long-run relationship between climate variables and tea yield

The model consisted of three climate related variables: the minimum and maximum temperatures, and the rainfall. All these three variables are significant in at 5% error level. The average maximum temperature or the day temperature has a positive relationship with yield in the long-run. A one percent increase in the temperature would lead to an increase in yield by 1.352 % in the long-run. However, the average minimum temperature shows a negative long-run equilibrium relationship with the yield of tea. A one percent increase in the average minimum temperature would reduce tea yield by 0.81 % (Table 7). Impacts of temperature on tea yields as well as production has been studied in Sri Lanka as well as in other countries. Mallik & Ghosh (2022) reported that increases in summer and monsoon temperatures reduce tea yield in Dooars Region in India. Duncan *et al*. (2016) observed decreasing tea yields with increased monthly average temperatures in Assam, India. They

collect monthly data from 2004 – 2013 from 82 tea gardens and used a panel data regression to estimate the climate effects. However, they have used only average temperature and no distinction between minimum and maximum temperature has been made by them. Wijeratne (1996) also suggest that increase in temperature adversely affect growth and yield of tea. However, from the present dataset, the yield is negatively affected in the long-run (*i.e.*, the climate effect) only when the minimum or the night temperature increases, but not by the increase in day temperature. Maximum temperature has a positive effect. Yan *et al*. (2021) studied the effects of extreme weather events on tea production in China. They have reported that both heat and cold extremes negatively affect tea yields. However, they also predict positive net impacts of climate change on tea yield at both the 1.5 °C and 2.0 °C global warming levels. As tea is a C3 plant, increased CO_2 raises yield, and it can be further amplified by rising temperatures especially at high elevations, although it can be negatively affected in low elevations if increasing temperature reaches the ceiling temperature range. In the present dataset, the average maximum temperature in the study period is 27.8 ± 3.5 °C (Figure 3) and therefore, it does not reach the ceiling temperature range. Han *et al*. (2017) also found that in some regions, an increase in temperature would increase yield. Sitienei *et al*. (2017) found that climatic variables during some months in both the concurrent year and the previous year were positively correlated with the tea yield. Further, Sen *et al*. (1966) also reported that rise in mean temperature during the cold weather period increased tea yield in the Assam valley.

In Table 7, rainfall shows a positive and significant long-run association with the tea yield. A one percent increase in rainfall would increase tea yield by 0.135%. To have a good tea cultivation, a minimum annual rainfall between 1150 mm and 1400 mm is needed. The optimal annual rainfall is around 2500 mm – 3000 mm (Carr, 1999; Jayasinghe *et al*., 2020). The average annual rainfall in the present data set is 2657 ± 609 mm. The findings suggest that decreasing rainfall would reduce tea yield per hectare. Low moisture content in soil is known to reduce photosynthesis and hence growth of tea plants (Ahmed *et al*., 2014). Hence, prolonged dry periods would significantly hamper yields of tea. The positive effect of rainfall was also confirmed by Boehm *et al.* (2014), who studied the relationship between rainfall and tea productivity in India. Dutta *et al*. (2011) found that monthly rainfall has a positive effect on tea productivity in Northern India. They used a combined statistical and modelling approach to study the impact factors affecting tea productivity. Numerous studies revealed that uneven distribution of rainfall reduces the tea production in many tea-producing nations, including China (Boehm *et al*., 2016; Lou *et al*., 2021), India (Duncan *et al*., 2016; Biggs *et al*., 2018; Raj *et al*., 2019), and Sri Lanka (Wijeratne *et al*., 2007; Gunathilaka *et al*., 2017).

Long-run effects of input use in tea yield

In the discussion of climate's impact on tea yields, other key factors that affect the yield need to be controlled, and therefore they were included in the model as covariates. All descriptions of the effects of temperature and rainfall are, therefore, *'ceteris paribus'* explanations. However, as one would recognize, key inputs such as labour, fertilizer, etc. play a vital role in increasing yield. The production input variables used in the study are used per hectare, as the dependent variable is green leaf production per hectare. Results in the Table 7 show that labour, fertilizer, and chemical usage all have a long-term positive relationship with yield. Out of the three inputs, production elasticity with labour is the highest indicating a 0.235 % increase in yield for 1 % increase in labour use. The error correction term, ECT was –0.417 and significant. The ECT give the speed of adjustment from the short-run disequilibrium to the long-run equilibrium. This indicates that 42% of the disequilibrium in tea yield in the short-run is adjusted to equilibrium by the covariates in the model monthly.

Table 7: Results of the long-run analysis

Variable	Coefficient	Std. errs.	P>z
*ln*MinT	-0.816*	0.119	0.000
*ln*MaxT	1.352*	0.194	0.000
*ln*RF	0.135*	0.015	0.000
L(*ln*Lab)	0.235*	0.021	0.000
L(*ln*Fert)	0.033*	0.008	0.000
*ln*Chem	0.022*	0.009	0.019
ECT	-0.417*	0.039	0.000
Log-likelihood	855.739		
AIC	-1683.48		
BIC	-1596.22		

Lab: Labour, Fert: Fertilizer, Chem: Chemicals, Min T: Minimum temperature, Max T: Maximum temperature, RF: Rainfall

CONCLUSIONS

The research findings unveiled essential insights regarding the enduring relationship between climate variables and tea yields in Sri Lankan tea plantations from 2005 to 2019. Pairwise correlation analysis indicated a negative correlation between tea yield and both minimum and

maximum temperatures, whereas rainfall exhibited a positive correlation with yield.

The analysis derived from the study's models revealed intriguing results. Maximum temperature displayed a long-term positive cointegration relationship with tea yield, while minimum temperature exhibited a negative long-term cointegration relationship. This finding diverges from prior studies, highlighting that the long-term response of tea yield to temperature differs significantly between night time and daytime temperatures. Notably, rising night temperatures predominantly impact tea yield as opposed to daytime temperatures.

Furthermore, the research identified a sustained positive equilibrium relationship between rainfall and tea yield. Consequently, increased rainfall was associated with higher tea yields over the long term, while a decrease in rainfall predicted a reduction in future tea yields. The research also observed a declining trend in the yield of tea estates. However, it noted a long-term positive cointegration relationship between inputs used in tea cultivation and the yield.

Given the context of climate change, the research underscores the critical importance of proper tea land management practices such as timely fertilization, effective pest and disease control, and appropriate pruning. These measures are crucial in mitigating the expected yield losses due to the impact of climate change on tea cultivation.

Conflict of interest statement

There are no conflicts of interests

Acknowledgements

The authors acknowledge the financial support given by the National Science Foundation, Sri Lanka, under the grant No: NTRP/2017/CC&ND/TA-02/P-02/01.

REFERENCES

Abbas S. (2020) Climate change and cotton production: an empirical investigation of Pakistan. *Environmental Science and Pollution* **27**(23): 29580–29588. DOI: https://doi.org/10.1007/s11356-020-09222-0

Ahmed S., Stepp J.R., Orians C., Griffin T., Matyas C., Robbat A., Cash S., Xue D., Long C., Unachukwu U. & Buckley S. (2014). Effects of extreme climate events on tea (*Camellia sinensis*) functional quality validate indigenous farmer knowledge and sensory preferences in tropical China. *PloS ONE* **9**(10): e109126. DOI: https://doi.org/10.1371/journal.pone.0109126

Ahsan F., Chandio A.A. & Fang W. (2020). Climate change impacts on cereal crops production in Pakistan evidence from cointegration analysis. *International Journal of Climate Change Strategies and Management* **12**(2): 257–269. DOI: https://doi.org/10.1108/IJCCSM-04-2019-0020

Appiah K., Du J. & Poku J. (2018) Causal relationship between agricultural production and carbon dioxide emissions in selected emerging economies. *Environmental Science and Pollution Research* **25**(25): 24764–24777. DOI: https://doi.org/10.1007/s11356-018-2523-z

Biggs E.M., Gupta N., Saikia S.D. & Duncan J. M. (2018). The tea landscape of Assam: Multi-stakeholder insights into sustainable livelihoods under a changing climate. *Environmental Science & Policy* **82**: 9–18. DOI: https://doi.org/10.1016/j.envsci.2018.01.003

Blackburne III E.F. & Frank M.W. (2007) Estimation of nonstationary heterogeneous panels. *The Stata Journal* **7**(2): 197–208. DOI: https://doi.org/10.1177/1536867X0700700204

Boehm R., Cash S.B., Anderson B.T., Ahmed S., Griffin T.S., Robbat A., Stepp J.R., Han W., Hazel M. & Orians C.M. (2016). Association between empirically estimated monsoon dynamics and other weather factors and historical tea yields in China: results from a yield response model. *Climate* **4**(2): 20. DOI: https://doi.org/10.3390/cli4020020

Carr M.K.V. (1999). Evaluating the impact of research for development: tea in Tanzania. *Experimental Agriculture* **35**(3): 247–264. DOI: https://doi.org/10.1017/S0014479799003051

Central Bank of Sri Lanka (2018). *Annual Report 2018*. Available at *https://www.cbsl.gov.lk/en/publications/economic-and-financial-reports/annual-reports/annual-report-2018*. Accessed 14 November 2022.

Central Bank of Sri Lanka (2019). *Annual Report 2019*. Available at *https://www.cbsl.gov.lk/en/publications/economic-and-financial-reports/annual-reports/annual-report-2019*. Accessed 14 November 2022.

Central Bank of Sri Lanka (2020). *Annual Report 2020*. Available at *https://www.cbsl.gov.lk/en/publications/economic-and-financial-reports/annual-reports/annual-report-2020*. Accessed 14 November 2022.

Central Bank of Sri Lanka (2021). *Annual Report 2021*. Available at *https://www.cbsl.gov.lk/en/publications/economic-and-financial-reports/annual-reports/annual-report-2021*. Accessed 15 November 2022.

Dutta R., Smaling E.M.A., Bhagat R.M., Tolpekin V.A. & Stein A. (2012). Analysis of factors that determine tea productivity in North-eastern India: A combined statistical and modelling approach. *Experimental Agriculture* **48**(1): 64–84. DOI: https://doi.org/10.1017/S0014479711000834

Duncan J.M., Saikia S.D., Gupta N. & Biggs E.M. (2016). Observing climate impacts on tea yield in Assam, India. *Applied Geography* **77**: 64–71. DOI: https://doi.org/10.1016/j.apgeog.2016.10.004

Food and Agriculture Organization (FAO) (2022). FAOSTAT *Statistical Database*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Galmés J., Medrano H. & Flexas J. (2007). Photosynthetic limitations in response to water stress and recovery in Mediterranean plants with different growth forms. *New Phytologist* **175**: 81–93.
DOI: https://doi.org/10.1111/j.1469-8137.2007.02087.x

Gunathilaka R.D., Smart J.C. & Fleming C.M. (2017). The impact of changing climate on perennial crops: The case of tea production in Sri Lanka. *Climatic Change* **140**: 577–592.
DOI: https://doi.org/10.1007/s10584-016-1882-z

Han W.Y., Huang J.G., Li X., Li Z.X., Ahammed G.J., Yan P. & Stepp J.R. (2017). Altitudinal effects on the quality of green tea in east China: a climate change perspective. *European Food Research and Technology* **243**(2): 323–330.
DOI: https://doi.org/10.1007/s00217-016-2746-5

Hausman J.A. (1978). Specification tests in econometrics. *Econometrica* **46**(6): 1251–1271.

Im K.S., Pesaran M.H. & Shin Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of Econometrics* **115**(1): 53–74.
DOI: https://doi.org/10.1016/S0304-4076(03)00092-7

Jayasinghe S.L., Kumar L. & Hasan M.K. (2020). Relationship between environmental covariates and Ceylon tea cultivation in Sri Lanka. *Agronomy* **10**(4): 476.
DOI: https://doi.org/10.3390/agronomy10040476

Kao C. (1999). Spurious regression and residual-based tests for cointegration in panel data. *Journal of Econometrics* **90**(1): 1–44.
DOI: https://doi.org/10.1016/S0304-4076(98)00023-2

Labour Force by sector. *www.statistics.gov.lk*. Accessed 19 February 2021.

Lou W., Sun K., Zhao Y., Deng S. & Zhou Z. (2021). Impact of climate change on inter-annual variation in tea plant output in Zhejiang, China. *International Journal of Climatology* **41**: E479–E490.
DOI: https://doi.org/10.1002/joc.6700

Mallik P. & Ghosh T. (2022). Impact of climate on tea production: a study of the Dooars region in India. *Theoretical and Applied Climatology* **147**:559–573.
DOI: https://doi.org/10.1007/s00704-021-03848-x

Markou M., Moraiti C.A., Stylianou A. & Papadavid G. (2020). Addressing climate change impacts on agriculture: adaptation measures for six crops in Cyprus. *Atmosphere* **11**(5): 483.
DOI: https://doi.org/10.3390/atmos11050483

Mbow C. *et al*. (12 authors) (2019). Food Security. In: *Climate change, the monsoon, and Tea Yields in China* (eds. P.R. Shukla *et al*.). *Proceedings of the Agricultural and Applied Economics Association's Annual Meeting, Minneapolis, USA*, pp. 27–29.

Pesaran M.H. & Smith R. (1995). Estimating long-run relationships from dynamic heterogeneous panels. *Journal of Econometrics* **68**(1): 79–113.
DOI: https://doi.org/10.1016/0304-4076(94)01644-F

Pesaran M.H., Shin Y. & Smith R.P. (1997). Pooled estimating of long-run relationships in dynamic heterogeneous panels. *Cambridge Working Papers in Economics 9721*. Faculty of Economics, University of Cambridge, UK.

Raj E.E., Ramesh K.V. & Rajkumar R. (2019). Modelling the impact of agrometeorological variables on regional tea yield variability in South Indian tea-growing regions: 1981–2015. *Cogent Food & Agriculture* **5**(1): 1581457.
DOI: https://doi.org/10.1080/23311932.2019.1581457

Ray D.K., West P.C, Clark M., Gerber J.S., Prishchepov A.V. & Chatterjee S. (2019). Climate change has likely already affected global food production. *PLoS ONE* **14**(5): e0217148.
DOI: https://doi.org/10.1371/journal.pone.0217148

Sen A.R., Biswas A.K. & Sanyal D.K. (1966). The influence of climatic factors on the yield of tea in the Assam valley. *Journal of Applied Meteorology* (1962–1982) **5**(6): 789–800.
DOI: https://doi.org/10.1175/1520-0450(1966)005<0789:TIOCFO>2.0.CO;2

Sitienei B.J., Juma S.G. & Opere E. (2017). On the use of regression models to predict tea crop yield responses to climate change: A case of Nandi East, sub-county of Nandi County, Kenya. *Climate* **5**(3): 54.
DOI: https://doi.org/10.3390/cli5030054

Sri Lanka Export Development Board (2020). Pure Ceylon Tea: A Beverage, Legacy & Way of Life. Available at *https://www.srilankabusiness.com/tea/about-tea/*, Accessed 12 October 2022.

Tea Research Institute of Sri Lanka (2002). T.R.I. Advisory Circular. *Guidelines on Land Suitability Classification for Tea*, pp. 1–3. Tea Research Institute of Sri Lanka, Talawakelle.

Wijeratne M.A. (1996). Vulnerability of Sri Lanka tea production to global climate change. *Water, Air, and Soil Pollution* **92**(1): 87–94.
DOI: https://doi.org/10.1007/BF00175555

Wijeratne M.A., Anandacoomaraswamy A., Amarathunga M.K.S.L.D., Ratnasiri J., Basnayake B.R.S.B. & Kalra N. (2007). Assessment of impact of climate change on productivity of tea (*Camellia sinensis* L.) plantations in Sri Lanka. *Journal of the National Science Foundation of Sri Lanka* **35**(2): 119–126.
DOI: https://doi.org/10.4038/jnsfsr.v35i2.3676

Yan Y., Sujong J., Park C.-E., Mueller N.D., Shilong P., Hoonyoung P., Jaewon J., Chen X., Wang X. & Liu J. (2021). Effects of extreme temperature on China's tea production. *Environmental Research Letters* **16**(4): 044040.
DOI: https://doi.org/10.1088/1748-9326/abede6