

The impact of changing climate on perennial crops: the case of tea production in Sri Lanka

R. P. Dayani Gunathilaka^{1,2} · James C. R. Smart¹ ·
Christopher M. Fleming³

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Abstract The plantation crop sector, particularly tea, is a key contributor to the Sri Lankan economy in terms of foreign exchange earnings, employment, and food supply. However, changes in temperature, rainfall, and the occurrence of extreme weather events have adversely affected the sector. Many studies in the literature have focused on climate change impacts on major annual crops; however, to date, comprehensive assessments of the economic impacts of weather variations on perennial crops are rare. In this paper, we use monthly panel data from 40 different tea estates in Sri Lanka over a 15-year period to analyse weather effects on production from the tea plantation sector. Specifically, we use a two-stage panel data approach to explore how tea production in Sri Lanka is affected by both short-term weather variations and long-term climate change. Overall, our findings show that a hotter and wetter climate will have a detrimental effect on Sri Lankan tea production. In high, medium, and low emissions futures, our predictions show a negative proportional impact from increased rainfall and increased average temperature. Under a high emissions scenario, by mid-century, a decline of 12% in annual tea production is predicted. Other climate-susceptible perennial crops such as rubber, coconut, and oil palm play similarly major roles in the economies of other developing countries, suggesting that our approach could usefully be replicated elsewhere.

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✉ R. P. Dayani Gunathilaka
rpdayani.gunathilaka@griffithuni.edu.au; dayani@uwu.ac.lk; dayanigunathila@gmail.com

¹ School of Environment, Griffith University, Nathan, QLD 4111, Australia

² Department of Export Agriculture, Uva Wellasa University, Badulla 90000, Sri Lanka

³ Business School, Griffith University, South Bank, QLD 4101, Australia

1 Introduction

The plantation crop sector (tea, rubber, and coconut) is a key contributor to the Sri Lankan economy in terms of foreign exchange earnings, employment generation and food supply (Herath and Weersink 2009; Illukpitiya et al. 2004). Tea (*Camellia sinensis* L.) has become Sri Lanka's foremost agricultural export, contributing 15% to total foreign exchange earnings in 2014 (Central Bank of Sri Lanka 2013; Central Bank of Sri Lanka 2014; Ganewatta et al. 2005; Wijeratne 1996). In the same year, Sri Lanka produced 338 million kg of tea, about 9% of world tea production, and accounted for 18.3% of tea exports globally (Central Bank of Sri Lanka 2014); furthermore, the tea sector provides employment for 10% of the total Sri Lankan work force (FAO 2014; Ganewatta et al. 2005; Wijeratne 1996).

However, changes in temperature, rainfall, and the occurrence of extreme weather events such as droughts and high-intensity rainfall have adversely affected the sector. Yield and production of tea are greatly influenced by weather conditions, particularly drought (Costa et al. 2007; Wijeratne et al. 2007). Drought events in the region are primarily due to a weak south–west monsoon in the Indian sub-continent leading to a failure of wet season rainfall (Central Bank of Sri Lanka 1992; Central Bank of Sri Lanka 2009; De Costa 2010; Wijeratne 1996). Drought can affect both the quantity and quality (and hence value) of tea harvests, leading to considerable loss of export earnings. Production costs can also increase during drought due to the need for additional inputs (Upadhyaya and Panda 2004; Wijeratne 1996).

Report on Climate Change in Asia: Sri Lanka predicts a 10% extension of the dry and wet seasons in the main tea plantation area by 2070, together with increased frequency and severity of extreme weather events.¹ Temperature increases of 0.4 to 3 °C are also predicted, while rainfall is expected to increase with an uneven pattern of distribution. The Report also noted that tea production will be affected adversely by climate change (ADB 1994). The intensity of these climate impacts on tea production will likely vary across the major tea growing regions: low, up and mid country² (Wijeratne 1996; Wijeratne et al. 2007). Prior research has also identified the eight agro-ecological³ tea-growing areas which are most vulnerable to climate change (Wijeratne and Chandrapala 2014).

Many studies in the literature have focused on climate change impacts on major annual crops such as wheat, corn, maize, soy bean, and rice (Auffhammer et al. 2012; Deschenes and Greenstone 2007; Deschenes and Kolstad 2011; Schlenker and Lobell 2010; Welch et al. 2010). However, to date, comprehensive assessments of the economic impacts of weather variations on perennial crops are rare. In one example, Deschenes and Kolstad (2011) quantify the impact of weather and weather expectations for selected perennial fruit crops in California. Similarly, Ashenfelter and Storchmann (2010) use a hedonic approach to identify the effects of solar radiation and weather on revenues from viticulture in Germany. In the only previous study to address climate impacts on perennial crops in a developing country, Boehm et al. (2016) investigate the effects of monsoon variables on tea yield in China. However, in

¹ It is important to note the distinction between weather and climate. Throughout this paper, 'weather' refers to localized temperature and rainfall at a given time, whereas 'climate' refers to weather averaged over long periods of time (i.e. 15 years).

² Low-country tea plantations are located between sea level and 300 m elevation, mid-country plantations between 300–900 m, and up-country plantations at elevations above 900 m.

³ Agro-ecological regions (AER) are categorized based on rainfall, elevation and soil type. Sri Lanka comprises 46 AERs, of which 22 contain tea estates.

common with much of the remaining literature, Boehm et al. rely upon production data at relatively coarse spatial and temporal resolution.

This paper contributes to the literature by using monthly panel data from 40 tea estates in Sri Lanka over a 15-year period (2000–2014) to analyse climate impacts on tea production. Specifically, we use a two-stage panel data approach⁴ to explore how tea production is affected by both short-term weather variations and long-term climate change. The paper begins by summarising alternative approaches for estimating weather and climate effects on agricultural outputs. The methodological framework is given in Section 3, while study sites and the unique dataset collected for this study are described in Section 4. Regression analysis and an interpretation of regression results are provided in Section 5. The effects of long-term weather variation and climate change on tea production are discussed in Section 6, together with conclusions.

2 Background

Several approaches have been used to explore links between weather, climate and agricultural outputs: linear models,⁵ Ricardian methods,⁶ profit functions⁷ and production functions. The latter are frequently employed to predict the impact of climate on annual crop production in combination with climate change predictions from climate simulation models. For example, Hansen (1991) uses a Tobit model to estimate corn yield across 10 US states under both actual weather and predicted future climate. Hansen finds that short-term variations in weather have a stronger effect on corn yield than longer term changes in climate. Kaufmann and Snell (1997) use pooled annual cross sectional data at county level to quantify climate and social determinants (e.g., market conditions) of US corn yield. Lobell et al. (2007) use annual time series data on yield and climate for 12 different Californian crops, including some perennial fruits and nuts, over a 24-year period to assess the effects of changing climate on yield. Lobell's results indicate that models featuring a small number of climate variables have the ability to explain considerable observed variation in crop yield. More recent studies to employ the production function approach include Schlenker and Lobell (2010), who use a panel data model to examine the impact of climate change on four crops in sub-Saharan Africa. Guiteras (2009) who uses 40-year district level panel data on agricultural inputs and year-to-year weather variation across 200 districts in India, and Auffhammer et al. (2012) who employ a fixed effects model to quantify the impacts of monsoon characteristics and total rainfall on Indian rice production using 40 years of state-level production and climate data. All of these studies find that predicted climate changes are associated with reduced yield.

⁴ We acknowledge the suggestions generously provided by Prof. Jeffrey Vincent here.

⁵ Linear regression models were an early approach for exploring links between climate and agricultural outputs, but are now little used because of significant limitations associated with the assumption that yield responds linearly to climate.

⁶ Mendelsohn's Ricardian approach would not be appropriate for tea production in the plantation sector in Sri Lanka, because the Government retains ownership of the underlying land, so there is no competitive land market. Further, opportunities for crop switching on tea estates are extremely limited, given long term investments in perennial plantings.

⁷ Deschenes and Greenstone (2007), Deschenes and Kolstad (2011) and Kelly et al. (2005) use profit as the response variable in their climate-economy models; however, in common with the majority of the literature, profit is not the focus of the current paper.

Most recently, Boehm et al. (2016) estimate the effects of East Asian monsoon dynamics, monsoonal rainfall and solar radiation on aggregate tea yield in China. The authors employ a 32-year panel of annual yield data at province resolution, and rely on fixed effect terms to account for unobserved, time-invariant differences between provinces. Findings show that short-term weather variations in the current and previous years affect yield.

3 Methodology

3.1 Tea production, weather variations, and climate

As described above, the production function approach has been widely used for estimating the effects of climate on crop production, but has typically been applied to aggregated annual yield and production data. Lacking production-unit-specific data on variations in production output, annual aggregated data are unlikely to control adequately for time-invariant differences between production units. These differences could be confounded with climate factors. The production-unit-specific panel data on tea production and climate in our study enable a two-stage approach to be used to identify long-term climate effects on tea production with reduced risk of confoundment.

In a first-stage panel model (Eq. 1), we estimate a fixed effect, log-log form production function to analyse the short term effects of temperature and rainfall on tea production, alongside labour and fertiliser,^{8 9} as production inputs.

$$\ln(y_{it}) = \alpha_i + \delta_t + \gamma_{eg} + \sum_{j=1}^J \theta_j X_{jit} + \sum_{k=1}^K \beta_k W_{kit} + u_{it} \quad (1)$$

Indices i and t represent estate and year-month, respectively, and j and k index different production inputs (labour and fertiliser) and weather variables (monthly mean temperature, monthly total rainfall, and monthly total wet days), respectively. The dependent variable (y_{it}) is estate-specific monthly total tea production, expressed in green leaf kilograms. All variables in X_{jit} and W_{kit} are expressed as natural logarithms. An estate-specific fixed effect, α_i controls for time-invariant, estate-specific unobserved influences on production. Soil quality, slope, elevation, management expertise, and inter-estate differences in long-term weather could all contribute to these time-invariant fixed effects. The model also includes month indicators, δ_t , that control for monthly differences in tea production that are common across estates, possibly due to variations in inter-monthly long-term average weather (e.g., monsoonal rainfall, temperature, solar radiation, or cloud cover). The model also includes elevation-year fixed effects (γ_{eg}) to account for annual shocks common to all estates in a given elevation (e.g., unusually dry years).

The weather variables of interest in the first-stage model are the W_{kit} terms. We include monthly average temperature, total rainfall and number of wet days¹⁰ for each estate i in each

⁸ A lag period up to two months was used for fertiliser in accordance with advice from agronomists in Sri Lanka (Wijeratne: personnel communication—February 5, 2016).

⁹ We initially included agro-chemicals as an input variable, but it was not found to exert a significant impact on yield. This was subsequently confirmed by Sri Lankan tea agronomists.

¹⁰ Tea shoot growth depends on both intensity and distribution of rainfall. Approximately 6–7 days of rainfall per month are required for ideal growth.

year-month t . Current and lag periods for temperature, rainfall and wet days were used in accordance with findings from previous agronomic studies ¹¹ (Costa et al. 2007; Wijeratne et al. 2007).

X_{jit} is a vector of time varying, estate-specific non-weather variables which also affect tea production: area harvested, ¹² ratio of the area of vegetatively-propagated ¹³(VP) tea to the total area, fertiliser use ¹⁴ and number of field workers. Lastly, u_{it} denotes the statistical error term in the model.

We estimate a number of different model specifications, adding one weather parameter at a time and checking impact on model fit and parameter estimates. Diagnostic checks indicate the presence of heteroscedasticity and serial correlation in the error variance. We account for these issues using Arellano's method to obtain robust covariance matrix estimation (Arellano 1987). Results from the Hausman test confirmed that the fixed effect specification was appropriate (Hausman 1978).

Having obtained results from the first-stage panel model, we run a second-stage model with the estate-specific fixed effects from the first-stage ($\hat{\alpha}_i$) as the dependent variable (Eq. 2):

$$\hat{\alpha}_i = \varphi + \sum_{n=1}^N \rho_n \bar{W}_{ni} + \sum_{m=1}^M \tau_m Z_i + \mu_i \quad (2)$$

Indices i and n index estate and weather variables respectively, whilst m denotes other time-invariant control variables affecting long-term tea production. Estate-specific average temperature, mean rainfall, and mean number of wet days per month ¹⁵ over the 15-year period 2000–2014 (i.e., estate-specific long-term average weather) are denoted by \bar{W}_{ni} . Other time-invariant control variables Z_i included in the model were soil depth and two dummies for regions. φ is the constant term. From this model, we can quantify the effects of changes in climate on the estate-specific fixed effect and—since the fixed effects directly influence the log of production in Eq. 1—the effects of changes in climate on tea production.

3.2 Quantification of climate change impacts on tea production

Parameter estimates for the climate effects from the second-stage model were multiplied by the projected change in climate parameters derived from IPCC AR4 projections (Ahmed and Suphachalasai 2014). The inferred proportional impact on tea production, under a given climate change scenario and time horizon for an estate i , is given by Eq. 3.

$$\text{PREDICTED PROPORTIONAL IMPACT}_i = \sum_{n=1}^N \rho_n \Delta W_{ni} \quad (3)$$

¹¹ Phenological development of tea shoot usually takes 45–60 days, depending on elevation and other biophysical factors.

¹² Area harvested is largely fixed in the short-run because tea is a perennial crop; it can therefore be considered exogenous.

¹³ Planting materials obtained from asexual methods. Yield of vegetatively-propagated tea is higher than seedling tea.

¹⁴ Current, lag-1 and lag-2 variables in fertiliser were included to account for the time lag between application and effect.

¹⁵ We constructed different long-term weather variables to characterize monsoonal effects in the second-stage model, but unfortunately very high VIFs between weather variables from Sri Lanka's two monsoonal seasons prevented these variables from being used.

Where ΔW_{ni} is the predicted change in climate variable n for estate i and ρ_n is the relevant regression parameter from Eq. 2. The total production impact in relation to a specific predicted climate change scenario and time horizon is calculated by simply summing up the estate-specific proportional predicted impacts from changes in the separate elements of climate (temperature and rainfall). Findings are presented by grouping estates' impacts within the three tea-growing elevations.

4 Study sites and data

4.1 Study sites

A sample of 40 estates was selected from the 306 tea estates in the country. Sites for data collection were chosen to cover 20 of 21 AERs containing tea estates in Sri Lanka, and to encompass wide variations in rainfall, temperature and elevation. See Fig. 1 for a map of study sites.

Data detailing quantities of input factors and tea production were obtained directly from monthly accounts of tea estates over the period 2000–2014.¹⁶ Rainfall and elevation were obtained from estate records. Temperature data for nearby weather stations were obtained from the Sri Lanka Department of Meteorology. Soil depth data were drawn from Amarathunga and Wijeratne (2009).

Data were consistent across the sample. Major capital investments were excluded from the analysis, as these do not have an immediate effect on monthly production. Data were extracted at monthly resolution for the period 2000–2014.

4.2 Variables

The output variable in the first-stage regression is monthly total green leaf production. The non-weather input variables are total area harvested, the ratio of the area of VP tea to total area, labour input, and fertiliser applied. Weather variables are monthly average temperature, total monthly rainfall and total monthly number of wet days. Tea estates in Sri Lanka do not record daily temperature; we therefore, use average temperature from the nearest weather station.

4.3 Climate change predictions

The predicted impact of climate change on tea production is estimated using climate change predictions from the General Circulation Models (ECHAM5 = European Centre/Hamburg Model and MRI = Meteorological Research Institute), based on 3 scenarios: A2, A1B, and B1 from the Special Report on Emissions Scenarios of the fourth Intergovernmental Panel on Climate Change (IPCC) report (IPCC Special Report Emissions Scenarios: IPCC Fourth

¹⁶ Complete monthly records over the 15 years 2000–2014 (i.e., 180 data points per estate) were available for 28 estates, slightly shorter data sequences were obtained from some estates for which earlier records had been damaged or destroyed. Estate record keeping seems to be well organized and all expenditure items related to field and factory operations are neatly recorded in monthly accounts. The estate offices prepare this record monthly and send these to the head office of their plantation company for observation and verification. Annual external auditing of accounts is mandatory for all estates. These records are therefore believed to be accurate. We collected the data by digitally photographing estate record books and then transcribed relevant data manually.

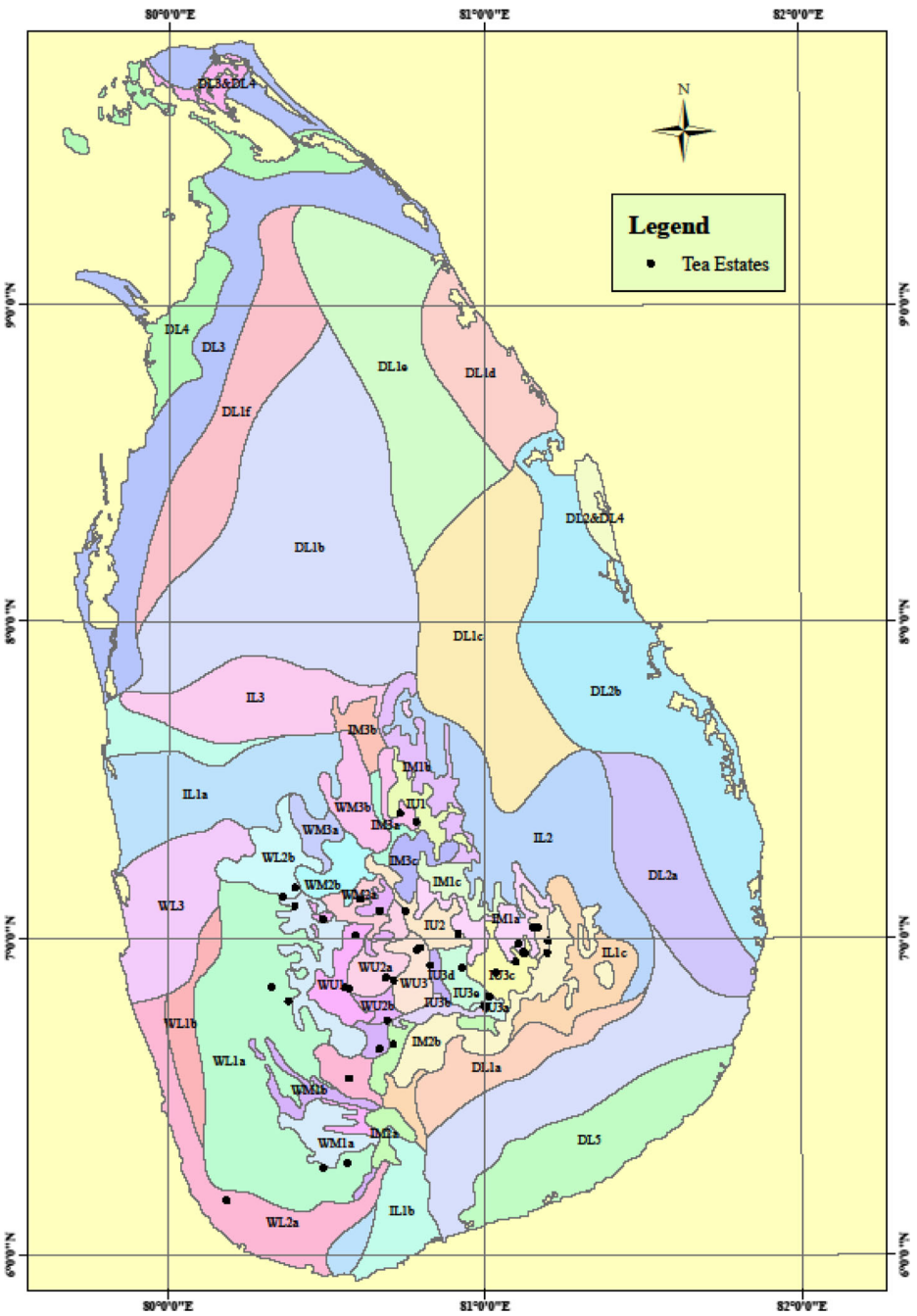


Fig. 1 Sample locations (displayed using dots) and agro-ecological regions (indicated by letters, using the designations of Punyawardena et al. 2003).

Assessment Report (AR4) 2007). The three scenarios: A2, A1B and B1 represent high, medium, and low emissions futures, respectively. See SM for further details.

Spatially downscaled climate predictions on a 30-km grid were obtained directly from the Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES) for three time windows: short-term (2026–2035), medium term (2046–2055) and long-term (2081–2090) from a baseline of (1990–2000) (Ahmed and Suphachalasai 2014). Inverse distance weighted averages were then calculated from 30-km grid points within a 40-km radius¹⁷ to assign predicted rainfall and temperature for estates and weather stations, respectively. These monthly predicted average temperatures and rainfalls are used as the drivers of tea production under climate change in the predictions from Eq. 3. Following the method described in Deschenes and Kolstad (2011), we account for possible model errors for each scenario for the three time windows using historical data predictions (1990–2000).

Table 1 shows summary statistics for the data used in the first-stage model.

5 Results

5.1 Short-term weather effects on tea production

Introducing weather variables sequentially, followed by production input variables, increases model fit for Eq. 1 as shown in Table 2. Our choice of model was guided by Wooldridge's approach for appropriate comparisons of fit between non-nested models (Wooldridge 2013). Including only temperature (Model 1), explains 30% of observed variation in tea production, adding rainfall (Model 2) increases explanatory power to 35%. Wet days are a significant predictor of production, but do not add further explanatory power (Model 3). Including production inputs together with the weather variables increases the model's explanatory power to 62% (Model 4).

A log-log specification was found to be more appropriate than linear and semi-log specifications.¹⁸ With log-log form, parameter estimates report elasticities (the percentage change in the explanatory variable which results from a unit percentage change in the relevant independent variable). Model 4 is our preferred model, and the remainder of the paper uses parameter estimates from that model.

Average temperature in the current month is found to have a significant positive effect on tea production, whereas average temperature from the previous month was not. In contrast, rainfall from the current month was significant and negative, whereas rainfall from previous months exerted highly significant positive effects. This is as expected because the current month's harvest comes from agronomical development of shoots over the previous 45–60 days.

Several non-weather variables are also significant. The ratio of VP area to total area was positive and significant. As expected, field labour was highly significant and strongly influential over yield; a 1% increase in field labour increases yield by 0.9%. Tea harvesting is highly labor intensive and completely manual in Sri Lanka. Fertiliser was expected to be an

¹⁷ Given the mountainous topography of tea growing areas in Sri Lanka, weather changes rapidly between locations. For interpolation, we therefore, chose climate grid points within a 40km radius of each estate and weather station.

¹⁸ We ran the different specifications with the same variables as Model 4 in Table 1. Following the method of Wooldridge (2013) pages 212–214, we found the adjusted R^2 for log-log and semi-log specifications to be 0.73 and 0.70, respectively, compared to 0.58 for the linear model. We also estimated a quadratic specification, but most of the parameters were not significant.

Table 1 Summary statistics on monthly weather parameters and production, grouped by elevation (up, mid and low country), over the period 2000–2014

Variable	Minimum			Maximum			Mean			Std. deviation		
	Up	Mid	Low	Up	Mid	Low	Up	Mid	Low	Up	Mid	Low
Average temperature (°C)	16.9	22.7	26	21.4	32.5	29.5	19.3	25.4	27.6	1.4	1	0.7
Rainfall (mm)	0	0	0	1568	1664	1145	219	261	272	188.8	207.1	186.4
Wet days	0	0	0	31	31	31	13	13	14	6.7	6.3	6.3
Tea production (kg green leaf)	7931	12,090	3042	537,700	627,500	108,700	165,200	159,100	48,070	92,543	71,937	24,772
Tea yield (kg green leaf/ha)	60	54	79	1908	1050	771	512	480	410	223	164	138
Area under mature tea (ha)	60	133	28	705	477	258	349	304	127	142	100	68
Labour (worker days)	929	1112	323	35070	24,320	11,050	12,640	10,010	3839	6040	4214	2171
Fertilizer (kg)	0	0	0	201,200	152,100	56,400	27,170	23,720	8675	23,944	17,415	7263

Table 2 Impacts of weather and production inputs on natural log of tea production, ln(kg)

Variables	Model 1: Average temperature only	Model 2: add rainfall	Model 3: add wet days	Model 4: add production input variables
Average temperature				
Current	1.132 (0.000)***	1.206 (0.000)***	1.290 (0.000)***	0.947 (0.004)***
Lag-1	-1.499 (0.000)***	-0.558 (0.071)*	-0.426 (0.143)	-0.059 (0.745)
Rainfall (total)				
Current		-0.027 (0.000)***	-0.033 (0.000)***	-0.018 (0.001)***
Lag-1		0.074 (0.000)***	0.043 (0.000)***	0.024 (0.001)***
Lag-2		0.050 (0.000)***	0.037 (0.000)***	0.017 (0.003)***
Wet days (total)				
Current			0.013 (0.384)	-0.009 (0.324)
Lag-1			0.067 (0.000)***	0.036 (0.000)***
Lag-2			0.029 (0.11)	0.009 (0.479)
Production inputs				
Area harvested				-0.119 (0.257)
VP:Total area ratio				0.180 (0.094)*
Fertilizer: current				0.005 (0.012)**
Fertilizer: Lag-1				0.010 (0.000)***
Fertilizer: Lag-2				0.006 (0.000)***
Labour: current				0.909 (0.000)***
Adjusted R^2	0.30	0.35	0.35	0.62
Observations	6862	6862	6862	6862
Number of estates	40	40	40	40

Notes. Table lists parameter estimates and relevant P -values (in parenthesis) for fixed effect panel models. Dependent variable (production) and all explanatory variables were in logarithmic form. Units for explanatory variables: °C for T_{average} , mm for rainfall, ha for area harvested, kg for fertilizer. All models included estate-specific fixed effects, month fixed effects and elevation/year fixed effects. Parameter estimates and P values are rounded to three decimal places. P values are derived from standard errors which are corrected for heteroscedasticity and serial correlation. Observations are from an unbalanced panel at monthly resolution from 40 estates across all agro-ecological regions of tea growing areas in Sri Lanka over the period 2000–2014

* $P < 0.1$, ** $P < 0.05$, *** $P < 0.01$

important production input, and all three variables relating to fertiliser were indeed positive and significant. However, fertiliser elasticities were unexpectedly low (a 1% increase in lag-1 fertiliser increases yield by 0.01%¹⁹). Area harvested is not, on its own, a significant driver of

¹⁹ Estimating the impact of fertiliser on production proved difficult because monthly data detailed expenditure on fertiliser rather than quantity applied.

Table 3 Regression coefficients on variables in the second-stage model

Variables	Parameter estimates	<i>P</i> values
Mean temperature (°C)	−0.0461	(0.0000)***
Rainfall (mm)	−0.0001	(0.0102)**
Wet days	0.0352	(0.0817)*
Soil depth (cm)	−0.0170	(0.0438)**
Mid country dummy	−0.0472	(0.5249)
Low country dummy	−0.5083	(0.000)***

Notes: Dependent variable is fixed effects. Parameter estimates and *P* values are rounded to four decimal places. Variables were selected by checking for the collinearity and VIF. Adjusted R^2 : 0.78, number of observations: 40
* $P < 0.1$, ** $P < 0.05$, *** $P < 0.01$

total production; other inputs (e.g., labour and fertiliser) would also have to be increased as estate area increased to deliver increased total production.

5.2 Long-term weather effects on tea production

Table 3 shows results from the second-stage model (Eq. 2), with the estate-specific fixed effects from Table 2, Model 4 as the dependent variable. The second-stage model is used to determine the impacts of long-term changes in weather on tea production. Since the first-stage models were in logarithmic form, the parameter estimates for long-term weather variables from the second-stage model express the proportional impact of a marginal change in the relevant aspect of long-term weather on tea production. Thus, the impact of long-term weather on tea production via the estate-specific fixed effect is interpreted as the relevant estimated climate coefficient (ρ_n), multiplied by estate-specific tea production.

For example, the impact of a 1 °C increase in long-term mean average temperature on tea production for a particular estate is around −0.046 times the production level (kg) for that particular estate (i.e., a 4.6% reduction) (Table 3). The corresponding estimate of the impact of long term mean rainfall indicates a 1% decrease in tea production for a 100 mm increase in mean annual rainfall.

Our results indicate that an additional wet day per month would increase tea production by 3.5%, given that total rainfall is held constant. This suggests that a more even distribution of rainfall is beneficial for tea production.

The coefficient estimate for soil depth is negative and significant, suggesting that an additional 1 cm of soil depth decreases estate-specific production by 2%. This may be a reflection of the fact that the less productive seedling tea is typically grown in deeper soil than the more productive VP tea.²⁰ The impact of regional variables is as expected; production from low-country estates is 50% lower than that from up-country and mid-country estates. This reflects both the smaller size and lower productivity of low-country estates (Table 1).

²⁰ Vegetative propagation (VP) technology was introduced to Sri Lanka in the 1950s and subsequent replantings have used this technology because it delivers higher yields. However, replanting with VP has proceeded less rapidly in the estate sector than the smallholding sector because of the high capital investment requirement. Currently, around 50% of the total tea area in the estate sector is VP tea while around 90% of the total smallholding area is VP. This is one of the key reasons for the high productivity of smallholder sector.

Table 4 Predicted proportional impact of climate change on tea production at elevation level, under GCM scenarios A2, A1B, and B1 for time horizons 2026–2035, 2046–2055, and 2081–2090

Elevation	Projected impact: 2026–2035			Projected impact: 2046–2055			Projected impact: 2081–2090		
	A2 (1)	A1B (2)	B1 (3)	A2 (4)	A1B (5)	B1 (6)	A2 (7)	A1B (8)	B1 (9)
(a) Average temperature (°C)									
Up country	-0.04921 (0.00054)	-0.05434 (0.00056)	-0.04569 (0.00062)	-0.08539 (0.00068)	-0.07537 (0.00074)	-0.06544 (0.00059)	-0.16971 (0.00102)	-0.16218 (0.00118)	-0.11119 (0.00088)
Mid country	-0.04930 (0.00107)	-0.05432 (0.00113)	-0.04567 (0.00129)	-0.08549 (0.00132)	-0.07517 (0.00134)	-0.06547 (0.00106)	-0.16964 (0.00192)	-0.16208 (0.00214)	-0.11122 (0.00152)
Low country	-0.04953 (0.00135)	-0.05444 (0.00128)	-0.04575 (0.00156)	-0.08580 (0.00156)	-0.07552 (0.00146)	-0.06594 (0.00116)	-0.17026 (0.00216)	-0.16294 (0.00233)	-0.11189 (0.00164)
(b) Total annual rainfall (mm)									
Up country	-0.01348 (0.00030)	-0.02219 (0.00041)	-0.00480 (0.00011)	-0.02778 (0.00035)	-0.03103 (0.00035)	-0.02201 (0.00009)	-0.06046 (0.00066)	-0.05574 (0.00069)	-0.05129 (0.00065)
Mid country	-0.01487 (0.00104)	-0.02338 (0.00137)	-0.00540 (0.00026)	-0.02931 (0.00138)	-0.03169 (0.00065)	-0.02218 (0.00025)	-0.06216 (0.00214)	-0.05771 (0.00224)	-0.05338 (0.00224)
Low country	-0.01569 (0.00098)	-0.02378 (0.00162)	-0.00630 (0.00014)	-0.03062 (0.00140)	-0.03147 (0.00076)	-0.02224 (0.00031)	-0.06263 (0.00253)	-0.05837 (0.00260)	-0.05441 (0.00258)
(c) Aggregate impact									
Up country	-0.06269 (0.00040)	-0.07653 (0.00040)	-0.05049 (0.00066)	-0.11317 (0.00064)	-0.10640 (0.00046)	-0.08745 (0.00051)	-0.23017 (0.00071)	-0.21792 (0.00084)	-0.16248 (0.00073)
Mid country	-0.06418 (0.00064)	-0.07770 (0.0008)	-0.05107 (0.0012)	-0.1148 (0.00096)	-0.10686 (0.00081)	-0.08766 (0.00086)	-0.23180 (0.00131)	-0.21979 (0.00145)	-0.16459 (0.00154)
Low country	-0.06521 (0.0005)	-0.07822 (0.00063)	-0.05205 (0.00146)	-0.11642 (0.00047)	-0.107 (0.00081)	-0.08818 (0.00086)	-0.23289 (0.00096)	-0.22132 (0.00094)	-0.16630 (0.00121)

Proportional impacts were calculated using the Eq. 3 for each scenario over each time horizon relative to the baseline 1990–2000. Standard errors of the mean per elevation proportional impacts are given in parenthesis. Number of observations for up country, mid country and low country are $N = 21, 13,$ and $6,$ respectively

5.3 Predicted proportional impact of climate changes on tea production

Having estimated the impact of changes in long term weather on tea production, we are now able to estimate the impact of predicted climate change. Table 4 shows the mean estimated proportional impact of predicted climate change under GCM model scenarios A2, A1B, and A2 for three different time horizons (2026–2035; 2046–2055; 2081–2090). The predicted changes are shown separately for up-, mid-, and low-country estates, for estate-specific changes in (a) average temperature, (b) total annual rainfall, and (c) average temperature and rainfall combined, all relative to the 1990–2000 baseline.²¹

In all specifications, the predicted proportional impacts of temperature and rainfall change are negative across all elevations. The proportional impacts of temperature change are predicted to be 2 to 10 times higher than those of rainfall change, depending on the GCM scenario and time horizon. Aggregate proportional production for 2026–2035 is predicted to reduce by between 5.1 and 7.8% under all scenarios. For 2046–2055 predicted reductions range between 8.7 and 11.6%. By the end of the century (2081–2090), production is predicted to reduce by between 16.2 and 23.3% under all scenarios. For the mean up-country estate this translates into end of the century annual production losses ranging from 329 (Scenario B1) – 466 (Scenario A2) tonnes. For the mean mid-country estate the corresponding figures are 295–415 tonnes, and for low country 95–133 tonnes. Absolute impacts for other time horizons and climate scenarios are shown in Supplementary Table 2.

6 Discussion and conclusions

Many studies have investigated the effects of weather and climate on annual crop yield and production (Auffhammer et al. 2012; Deschenes and Greenstone 2007; Deschenes and Kolstad 2011; Mendelsohn et al. 1994; Welch et al. 2010); however, far fewer have quantified the impact of weather and climate variations on perennial crops, particularly in developing country contexts (Boehm et al. 2016; Deschenes and Kolstad 2011). The purpose of this study is to estimate the impact of climate change on tea production in Sri Lanka. In an advance on many existing studies, we combine estate-specific monthly resolution data on tea production with a novel two-stage panel modelling approach to quantify the effects of climate change on tea production. As a first-stage, we estimate a fixed effect panel model of estate-specific tea production, driven by production inputs and weather. Estate-specific fixed effects are then used as the dependent variable in a second-stage regression to estimate the impacts of long-term variations in weather on production. These impacts are then combined with climate change predictions to estimate changes in tea production output for three time horizons under a range of climate scenarios.

We find that tea production in Sri Lanka will be negatively affected by predicted long-term changes in temperature and rainfall. Our results suggest that, averaged across all elevations, a 1 °C increase in average temperature will cause a 4.6% reduction in tea production. Similarly, an additional 100 mm of annual rainfall decreases tea production by around 1%.

The negative association between long-term average temperature and tea production can be explained by an optimum temperature for the shoot replacement cycle. Ideally, shoot

²¹ We do not have predictions of the number of wet days per month under future climate scenarios, so we cannot include the long-term impact of wet days per month in our production projections.

development occurs linearly at average temperatures between 18 and 25 °C. Temperatures outside this range are less favourable (Costa et al. 2007). Increased annual rainfall reduces tea production due primarily to increased cloud cover reducing photosynthesis (Wijeratne et al. 2007), and rain disrupting plucking.

Our findings also suggest that tea production will decrease by 3.5% if rainfall becomes more concentrated to the extent that there is one less wet day per month. This is consistent with the established notion that high intensity rainfall is detrimental for tea production, mainly due to the reduction in solar radiation associated with increased cloud cover and damage to tender buds of developing tea shoots (Carr 1972; Wijeratne et al. 2007).

Our results are consistent with Boehm et al.'s findings on the impact of East Asian monsoon dynamics on tea yield in China (Boehm et al. 2016). Our findings are also consistent with Seo et al.'s (2005) prediction that a 27% reduction in agricultural land value in Sri Lanka would follow from a 2 °C temperature increase. Wijeratne et al. (2007) predicted that increasing temperature would decrease tea yield in most regions, as we did, with the sole exception of the up country wet zone. However, Wijeratne et al. also predicted that tea yield would increase with increasing rainfall across all elevations. These findings differ from ours, but this could be explained by the difference in data collection periods and regression methodologies between the two studies.²²

Overall, our findings show that a hotter and wetter climate will have a detrimental effect on Sri Lankan tea production. In high, medium and low emissions futures, our predictions show a significant negative impact on tea production over the three time horizons, with effects worsening as climate change proceeds. In the near term, under the medium emissions scenario (A1B), aggregate tea production is predicted to decline by approximately 7.7% across all three elevations. In the medium term, this increases to approximately 10.7%, and by the end of the century to 22%.

In interpreting our results there are several caveats that should be taken into account. First, our analysis uses predictions derived from IPCC AR4 models because the downscaled data from AR5 for Sri Lanka were not readily available. Second, we do not consider all effects of extreme weather events on tea production, restricting our analysis to the effects captured by number of wet days alongside total rainfall. Third, as the dependent variable for the second-stage analysis comprised fixed effects from only 40 tea estates, only a limited number of variables could be included in the second-stage model. Strong correlations—evidenced by high VIFs—prevented us from including monsoonal effects or the average age of tea bushes on an estate in the second-stage model. Finally, our models use historical temperature data from the nearest weather station because estate-specific temperatures were not available.

In summary, the predicted negative impacts of climate change on Sri Lankan tea production are considerable. All tea in Sri Lanka is hand-picked, and the tea sector is the nation's largest employer, with a workforce of over 0.6 million. The welfare and social consequences of reduced production volume are therefore likely to be very considerable for the national economy. Other climate-susceptible perennial crops such as rubber, coconut and oil palm play similarly major roles in the economies of other developing countries. While COP21's objective of holding the increase in global average temperature to below 2 °C is commendable, much remains to be done. Our results suggest that the consequences of not achieving this target are likely to be severe for national economies of developing countries.

²² Wijeratne et al. used production data from 1975–1995, we used production data from 2000–2014; Wijeratne et al. used separate sole-driver regressions to identify weather effects, whereas we used our two-stage panel data multi-regressor approach.

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