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The impact of climate change on labour demand in the plantation sector: the case of tea production in Sri Lanka*

Rajapaksha P. D. Gunathilaka, James C. R. Smart, Christopher M. Fleming and Syezlin Hasan†

Limited opportunities for crop switching and lengthy preharvesting periods make the plantation sector particularly vulnerable to climate change. Surprisingly, however, the economic consequences of climate change on plantation crops are seldom analysed. Drawing on a unique primary panel data set from a representative cross section of 35 tea estates in Sri Lanka over the period 2002–2014, this study implements a structural model of estate profit maximisation to estimate the elasticity of labour demand with respect to different components of weather. Results indicate a negative relationship between labour demand and rainfall in the south-west monsoon, the north-east monsoon and the second inter-monsoon. A positive relationship is found between labour demand and rainfall in the first inter-monsoon. Overall, predicted changes in rainfall by 2050 are anticipated to reduce labour demand by approximately 1,175,000 person-days per year across Sri Lanka's tea plantation sector. This is likely to have considerable social and welfare implications, particularly for the Indian Tamil women who comprise the majority of the sector's workforce.

Key words: farm level, perennial crop, profit function, seemingly unrelated regression, structural panel model.

1. Introduction

Plantation crops such as tea, rubber, coconut and oil palm have been major contributors to the economies of developing nations for many decades (Sivaram 2000; Alkan *et al*. 2009). Profitability in these plantation sectors is likely to be directly affected by changes in crop productivity due to ongoing climate change (Gunathilaka *et al*. 2017). Consequent impacts of climate

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†Rajapaksha P. D. Gunathilaka (email: rpdayani.gunathilaka@griffithuni.edu.au) and James C. R. Smart are with School of Environment, Australian Rivers Institute, Griffith University, Nathan, Queensland 4111, Australia. Rajapaksha P. D. Gunathilaka is at Department of Export Agriculture, Uva Wellassa University, Badulla, Sri Lanka. Christopher M. Fleming is at Business School, Griffith University, South Bank, Queensland 4101, Australia. Syezlin Hasan is at Australian Rivers Institute, Griffith University, Nathan, Queensland 4111, Australia.

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change on employment opportunities are likely to be a major concern to governments of developing nations because plantation sectors provide regular employment for a significant percentage of the agricultural workforce in countries such as Sri Lanka, Kenya, Vietnam and Bangladesh (Wijeratne 1996; Boehm *et al*. 2016).

The intensity of impacts varies across different geographical regions and different agricultural systems. For example, farmers dealing with annual crops continuously switch crops based on criteria such as climatic conditions, market conditions and productivity (Deschênes and Greenstone 2007). This process is relatively inexpensive for short-term annual crops compared to high-value perennial cropping systems. Therefore, annual crop farmers have the capacity to switch to alternative options that will potentially reduce the impacts of climate change. However, perennial cropping systems require longer lead times to make changes either by the producer or at other levels in the supply chain. Furthermore, plantation crops must typically be harvested continuously in order to maintain productivity and harvest quality into the future; this is particularly true for tea (Costa *et al*. 2007). These characteristics are likely to make profitability and labour demand in plantation crop sectors particularly vulnerable to a changing climate (Burton and Lim 2005).

This paper studies the economic impacts of climate change on demand for inputs, particularly labour, for tea plantations in Sri Lanka. Sri Lanka's tea industry is an important case study for several reasons. Firstly, tea has made a major contribution to the national economy since the establishment of the plantation production system by the British in the 1860s. In 2014, the tea sector generated 15 per cent of total export earnings and accounted for 75 per cent of agricultural exports (Central Bank of Sri Lanka 2014; Herath and Weersink 2009).

Secondly, the sector is an important source of employment for rural communities, employing approximately 600,000 people, or about seven per cent of the country's labour force (Central Bank of Sri Lanka 2014). Sri Lanka's tea plantation sector is also unique in terms of its organisation and workforce. Tea estates are managed by private companies on a lease agreement, with land ownership retained by the government. The majority of the sector's workforce is from a particular ethnic group (Indian Tamils) who have been given Sri Lankan citizenship. These employees (predominantly women) reside on the estates, employment is passed from generation to generation, and employed labourers (as opposed to casual workers) are generally provided with assured work (25 days of employment per month). Estate workers' remuneration is regulated nationally via strong trade unions, and estates provide welfare facilities such as childcare, healthcare and schools. The workers in these estate communities comprise five per cent of the total Sri Lankan population, but typically have lower levels of education (Samarasinghe 1993). These workers may, therefore, find alternative employment opportunities hard to come by.

Thirdly, climate change and climate variability are recognised as serious challenges for the sustainability of Sri Lankan tea production (Wijeratne *et al*. 2007; Gunathilaka *et al*. 2017). According to Gunathilaka *et al*. (2017), tea production is predicted to decline by 12 per cent by mid-century, with the largest impact predicted for up-country tea estates.[1] Interviews with estate managers reveal that extreme weather events have caused considerable crop losses, reduced labour-days and made it difficult for estates to undertake management practices as planned.

> ‘we are unable to make good tea during excessive rainy periods because of high water content in leaves, however we can make fine teas in dry weather and fetch good price, but, prolonged drought hampers production and even premium price cannot counteract losses due to drop in production during droughts’. [Manager #30, Up-country] (Gunathilaka *et al*. 2018, p. 111)

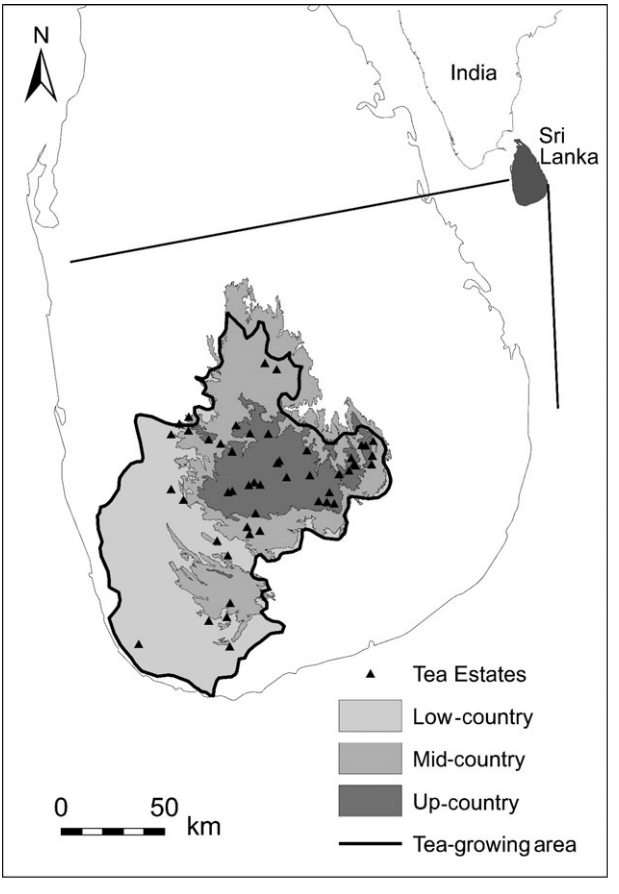

Figure 1 Tea production locations in Sri Lanka and the tea estates from which data were collected in the three different tea-growing elevations. Source: Gunathilaka *et al*. (2018).

[1] Tea-growing regions in Sri Lanka can be grouped into three categories depending on the elevation. These are low-country: mean sea level to 300 m, mid-country: 300 to 900 m and up-country: above 900 m (Figure 1).

'last year this time we could not offer work continuously, we had to cut down two or three work days per week'.[Manager #9, Up-country] (Gunathilaka *et al.* 2018, p. 111)

According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), increases in precipitation, temperature and extreme weather events are predicted for South Asia by 2060. Generally, a decline in the productivity of agricultural crops has been predicted with medium confidence and with high agreement among climate models and scenarios (Hijioka *et al.* 2014). The AR5 report also notes, with high confidence, that the vulnerability of rural communities in Asia who are dependent on agriculture for their livelihood is expected to increase.

Given the importance of the tea plantation sector in Sri Lanka, for all of the reasons stated above, an understanding of the potential consequences of climate change on labour demand within the sector should be based on a comprehensive analysis of weather variations alongside economic data (i.e. input and output prices). Improved understanding of the likely consequences is vital for efficient and effective channelling of available resources by affected parties and for the continuing sustainability of the sector itself.

Our findings contribute to the literature that quantifies the economic impact of climate change on plantation crops in developing countries. There appear currently to be no estate-level studies of climate change impacts on the labour force requirements of plantation crops which are characterised by perennial cropping patterns and long productive lifespans.

In this paper, we quantify the impact of climate change on tea estates' labour demand. Our approach uses production duality theory to estimate estate-level profits in which input prices, output prices and fixed endowments are exogenously determined, and choice of input mix provides an opportunity for adaptation. We employ a normalised quadratic profit function system in a fixed-effects panel setting. The model is estimated for a sample of 35 tea estates, at annual resolution over the 13-year period from 2002 to 2014. IPCC IV[2] projections for temperature and rainfall are applied to model findings to forecast labour demand in the tea plantation sector under climate change.

2. Background

The literature on the impact of climate change on farm profits and input demands mainly focuses on either the Ricardian approach, non-structural panel regression approaches or structural profit function-based approaches utilising duality theory. Introduced by Mendelsohn *et al.* (1994), the

[2] We use IPCC AR4 data for predictions because downscaled data for Sri Lanka from IPCC AR5 are only available at coarse resolution.

Ricardian approach uses land prices, which are regarded as a function of climate, to recover the net impact of climate change on agricultural productivity. Di Falco and Veronesi (2013) provide a recent example of this approach. Non-structural panel regression approaches, for example as implemented by Deschênes and Greenstone (2007), use profit as the dependent variable and climate variables, soil factors and socio-economic variables as regressors. Non-structural panel regression approaches have also been used to estimate labour demand in annual cropping situations directly as a function of weather and other drivers (Colmer 2016).

In the structural profit function approach, dating back to Hotelling (1932) and May and Samuelson (1948), producers' optimisation behaviour is analysed through indirect retrieval of information on production technologies. The functional form of the profit function is estimated by collating economic information such as input and output prices, which are exogenous to the dependent variable of interest – agricultural profit. The many advantages of the structural profit function approach have been established in the literature: ease of application; robustness of estimations; and the ability to derive information on input demand and output supply functions within the production technologies, accounting for farmer adaptation (Shumway and Gottret 1991). A related strategy is to estimate reduced form input demand and output supply equations within a structural model framework. This reduced form approach is typically used where data on profits from individual production units cannot be obtained directly, for example when analysing labour markets at regional or state resolution across sectors in an economy (Hujer *et al.* 2006).

Several studies have used a structural profit function approach to explain farmer's optimising behaviour when confronted with changes in institutional and environmental factors. Examples include studies by Fisher and Munro (1983), Roberts (1989), Fisher and Wall (1990), Kherallah and Govindan (1999), Lang (2001), Suleiman (2001), Abrar and Morrissey (2006), Mullen *et al.* (2009) and Fezzi and Bateman (2011). These studies build upon the profit function with fixed endowments to derive input demand and output supply equations as a system. We adopt a similar approach, although we use a structural panel data model to account for unobserved heterogeneities across tea estates when estimating climate effects on profits and input demands using spatially and temporally disaggregated data. To our knowledge, this paper is the first implementation of a profit function approach in a structural model using panel data to account for unobserved heterogeneity when assessing the impact of climate change on labour demand in plantation agriculture.

3. Theoretical framework

Assuming profit-maximising behaviour by producers, we apply duality theory to a multi-input, single-output profit function (Lau and Yotopoulos

1972) for Sri Lanka's tea production system, with the inclusion of climate variables. Differentiation of the profit function with respect to input prices and the output price, using Hotelling's lemma (Hotelling 1932), produces a system of input demand and output supply equations. We choose a normalised quadratic profit function because of several important advantages, namely its self-dual characteristic (Shumway and Gottret 1991; Lusk *et al.* 2002), retention of global curvature across all data points (Lopez 1985) and the ability to handle negative profits (Fezzi and Bateman 2011). The profit function is defined as follows:

$$\pi(p, \mathbf{w}, \mathbf{z}) = \max\{py - \mathbf{wx} : y \in Y(\mathbf{x}, \mathbf{z})\}, \tag{1}$$

where π is maximised profit associated with competitive output price p, a vector of exogenous input prices $\mathbf{w}$ for a vector of input factors $\mathbf{x}$ and a set of fixed or environmental factors (weather and land) $\mathbf{z}$. y is the output, and $Y(\mathbf{x}, \mathbf{z})$ indicates the output set for given environmental factors, often regarded as endowments. For the assumption of profit-maximising behaviour to hold, a set of regularity conditions (Diewert 1971) must be met: monotonicity; convexity; homogeneity of degree one in input prices; and symmetry. The first derivative of the profit function with respect to input price w_i produces the input demand function:

$$-x_i = \frac{\partial \pi}{\partial w_i}, \tag{2}$$

where x_i is the profit-maximising quantity of input i. The output supply function y is the partial derivative of the profit function with respect to the output price, p:

$$y = \frac{\partial \pi}{\partial p}, \tag{3}$$

where y is the output quantity that results in maximised profit.

4. Model specification and estimation

4.1 Profit function system

We specify a normalised quadratic profit function which is a flexible form of the true profit function. We normalise by dividing profit, input prices and output price by the price of one input (fuel). This imposes the linear homogeneity condition for profit with respect to prices. Symmetry ($\beta_{ij} = \beta_{ji} \quad \forall i, j = 1, \ldots, 4$) is imposed via appropriate cross-equation restrictions.

The quadratic profit function is specified as follows:

$$\overline{\pi}_{nt} = \alpha_n + \sum_{i=1}^{I-1} \beta_i \bar{w}_{ti} + \beta_o \bar{p}_{n,t} + \sum_{g=1}^{G} \beta_g z_{ntg} + \frac{1}{2}\sum_{i=1}^{I-1} \beta_{ii} \bar{w}_{ti}^2 + \frac{1}{2}\beta_{oo}\bar{p}_{nt}^2 + \frac{1}{2}\sum_{g=1}^{G} \beta_{gg} z_{ntg}^2 + \sum_{i=1}^{I-1}\sum_{j=1}^{J-1} \beta_{ij} \bar{w}_{ti}\bar{w}_{tj} + \sum_{i=1}^{I-1} \beta_{io} \bar{w}_{ti}\overline{p}_{nt} + \sum_{i=1}^{I-1}\sum_{g=1}^{G} \beta_{ig} \bar{w}_{ti} z_{ntg} + \sum_{g=1}^{G} \beta_{og} \bar{p}_{nt} z_{ntg}, \tag{4}$$

where n indexes estates, i indexes the inputs (labour, fertiliser and electricity), t indexes time in years and g indexes components of weather: estate-specific monthly total rainfall; estate-specific number of wet days per month; and monthly mean temperature. $\overline{\pi}$, $\bar{p}$ and $\bar{w}$ are estate-specific profit, estate-specific output price and input prices, all normalised by fuel price (w_f), the numeraire. The α_n denotes a fixed effect for estate n.

By applying Hotelling's lemma, the system of input demand equations is as follows:

$$-x_i = \frac{\partial \pi}{\partial \bar{w}_i} = \beta_i + \beta_{io}\bar{p}_{nt} + \beta_{ii}\bar{w}_{ti} + \sum_{j=1}^{J-1} \beta_{ij}\bar{w}_{tj} + \sum_{g=1}^{G} \beta_{ig} z_{ntg}, \tag{5}$$

(i = labour, fertiliser and electricity).

The x_i here are the input demands for labour, fertiliser and electricity. The output supply equation is as follows:

$$y = \frac{\partial \pi}{\partial \bar{p}} = \beta_o + \beta_{oo}\bar{p}_{nt} + \sum_{i=1}^{I-1} \beta_{io}\bar{w}_{ti} + \sum_{g=1}^{G} \beta_{og} z_{ntg}, \tag{6}$$

where y is tea supply.

Monotonicity and convexity do not necessarily hold with this formulation, but were confirmed after estimation. The monotonicity property holds for the normalised quadratic profit function only if the estimated values of input demand and output supply are positive. Convexity is satisfied necessarily if the all leading diagonal elements of the Hessian with respect to normalised prices are non-negative. The sufficiency condition for convexity is that all principal minors are non-negative.

We implement a fixed-effects transformation by including estate-specific dummy variables as intercepts. The fixed-effects transformation is able to remove endogeneity due to omitted estate-specific time-invariant factors. This approach is required for our data because tea price, a key driver of profit, depends on tea quality, and tea quality will likely vary due to estate-specific time-invariant factors such as soil type, geographical aspect and managerial expertise which are not recorded in the data.

We estimate the profit function simultaneously with demand functions for labour, fertiliser and electricity and with a supply function for tea as a structural model system. Estimating the set of equations as a system with relevant cross-equation restrictions improves the efficiency of parameter estimates (Zellner 1962). The structural system of equations for estate n in year t is as follows:

$$\begin{cases} \bar{\pi}_{nt} = f_1(\bar{p}_{nt}, \bar{\mathbf{w}}_{ti}, \mathbf{z_{ntg}}; \boldsymbol{\beta_1}), \boldsymbol{\alpha_{1,n}}, \mathbf{u_{1,nt}} \\ x_{\text{fertiliser},nt} = f_2(\bar{p}_{nt}, \bar{\mathbf{w}}_{ti}, \mathbf{z_{ntg}}; \boldsymbol{\beta_2}), \boldsymbol{\alpha_{2,n}}, \mathbf{u_{2,nt}} \\ x_{\text{labour},nt} = f_3(\bar{p}_{nt}, \bar{\mathbf{w}}_{ti}, \mathbf{z_{ntg}}; \boldsymbol{\beta_3}), \boldsymbol{\alpha_{3,n}}, \mathbf{u_{3,nt}} \\ x_{\text{electricity},nt} = f_4(\bar{p}_{nt}, \bar{\mathbf{w}}_{ti}, \mathbf{z_{ntg}}; \boldsymbol{\beta_4}), \boldsymbol{\alpha_{4,n}}, \mathbf{u_{4,nt}} \\ y_{\text{tea},nt} = f_5(\bar{p}_{nt}, \bar{\mathbf{w}}_{ti}, \mathbf{z_{ntg}}; \boldsymbol{\beta_5}), \boldsymbol{\alpha_{5,n}}, \mathbf{u_{5,nt}}. \end{cases} \quad (7)$$

Vectors $\alpha_{1,n}$ to $\alpha_{5,n}$ are estate-specific fixed effects. Vectors $u_{1,nt}$ to $u_{5,nt}$ are idiosyncratic errors which are assumed to have zero mean, but can be correlated across equations. Appropriate parameter estimates from equation (7), together with relevant data and fitted values, are used to construct price elasticities (ϵ) for profit, input demands and output supply with respect to input prices, the output price and the different components of weather:

$$\text{Elasticities of profit w.r.t. prices: } \epsilon_{\pi w_i} = \frac{\partial \pi}{\partial w_i} \cdot \frac{w_i}{\pi}, \epsilon_{\pi p} = \frac{\partial \pi}{\partial p} \cdot \frac{p}{\pi} \quad (8a)$$

$$\text{Elasticities of profit w.r.t. weather: } \epsilon_{\pi z_g} = \frac{\partial \pi}{\partial z_g} \cdot \frac{z_g}{\pi} \quad (8b)$$

$$\text{Elasticities of input demands w.r.t. prices: } \epsilon_{x_i w_j} = \frac{\partial x_i}{\partial w_j} \cdot \frac{w_j}{x_i}, \epsilon_{x_i p_n} = \frac{\partial x_i}{\partial p} \cdot \frac{p}{x_i} \quad (8c)$$

$$\text{Elasticities of input demands w.r.t. weather: } \epsilon_{x_i z_g} = \frac{\partial \pi}{\partial z_g} \cdot \frac{z_g}{x_i} \quad (8d)$$

$$\text{Elasticities of output supply w.r.t. prices: } \epsilon_{yw_j} = \frac{\partial y}{\partial w_j} \cdot \frac{w_j}{y}, \epsilon_{yp} = \frac{\partial y}{\partial p} \cdot \frac{p}{y} \quad (8e)$$

$$\text{Elasticities of output supply w.r.t. weather: } \epsilon_{yz_g} = \frac{\partial y}{\partial z_g} \cdot \frac{z_g}{y} \quad (8f)$$

Confidence intervals and significance levels for elasticities are obtained using nonparametric estate-clustered bootstrapping with 500 replications (Laukkanen and Nauges 2014).

4.2 Quantification of climate change impacts on labour demand

The elasticity of labour demand with respect to the weather variables obtained from (8d) can be directly multiplied by the predicted future changes in climate to infer the impact of anticipated future changes in climate on estate-specific labour demand and hence on labour demand in the Sri Lankan tea plantation sector as a whole. To illustrate, we estimate the predicted impact of climate change on labour responses, $\Delta x_{\text{labour},n}$ in equation (9), in which Δz_{ng} represents the estate-specific predicted change in a particular weather variable under IPCC AR4 projections for Sri Lanka (Ahmed and Suphachalasai 2014) with respect to a baseline of 1990–2000 and $\epsilon_{\text{labour},z_g}$ denotes the elasticity of labour with respect to the relevant weather driver g.

$$\Delta x_{\text{labour},n} = \Delta z_{ng}.\frac{\text{Labour}_n}{z_{ng}}.\epsilon_{\text{labour},z_g}. \quad (9)$$

5. Data

This study uses estate-level data on economic, physical and climate variables, obtained primarily from tea estate monthly accounts and log books.[3] These records provide information on estate-specific profits, estate-specific tea price, estate-specific expenditures on fertiliser, fuel and electricity, estate-specific quantity of processed tea produced, estate-specific person-days labour input, estate-specific rainfall, estate-specific number of rainfall days (wet days) and estate-specific elevation. Prices of labour, fertiliser, fuel and electricity, and temperature data are obtained from relevant sources as described below. The

[3] Tea plantation companies in Sri Lanka maintain a well-managed record-keeping system which is centrally monitored by the head office of plantation companies. In addition, an annual external audit is mandatory for each estate. Hence, estate records are regarded to be a source of accurate information.

analysis employs data for the period 2002–2014, the maximum duration for which log books were available at many of the estates. The sample for the analysis contains estates representing all three tea-growing regions in Sri Lanka, namely low, medium and high altitudes, the elevations of which are from sea level to 300 m, between 300 and 900 m, and above 900 m, respectively. The data panel comprises a cross section of 35 estates (Figure 1) over 13 years, containing a total of 455 observations.

5.1 Input prices

Input prices considered were the prices of labour, fertiliser, fuel and electricity in Sri Lankan rupees (LKR). The centrally negotiated national labour wage for plantation workers was used as the labour price for all estates (LKR/person-days). A national tea factory electricity price was calculated using a weighted average of peak and off-peak electricity charges implemented by the Energy Authority of Sri Lanka. To reflect differences in transport cost, separate fertiliser prices were calculated per tea-growing elevation using estate-specific data from two estates per elevation. The 'fuel' input in this analysis is fuel wood used to dry green tea in the estate's tea factory. We used prices in LKR per cubic metre of fuel wood consumed in each factory across the years of the study. Profits before taxes were directly extracted from estate monthly accounts. The monthly profit figures match the total revenue from sale of processed tea, less total expenditures for the given month. For our analysis, we use total annual profits for estate n in year t (Table 1).

5.2 Input and output quantities, climatic data and cropping area

Processed tea sold is reported in kg per year. Input quantities are total labour (field and factory), fertiliser, fuel and electricity recorded in person-days, kg, m^3 and kWh, respectively. Data for these factors were extracted directly from tea estate monthly accounts.

For each estate, total rainfall per month and the number of wet days per month (a measure of rainfall distribution) were obtained directly from estate record books.[4] Following the literature (Wijeratne *et al*. 2007; Gunathilaka *et al*. 2017), we use temperature data from the nearest weather station obtained from the Sri Lankan Department of Meteorology as tea estates do not record temperature data[5] (Figure 2).

[4] Rainfall is recorded daily by rain gauges on each estate and logged as part of routine estate record keeping.

[5] Typically, four to six estates share temperature data from the same weather station. Measurement error in the driving variables can lead to inconsistent estimates; however, given that almost all of the variables in the model are estate specific, or reported without measurement error (from estate-specific log books or nationally negotiated price agreements), inclusion of geographically relevant proxies for non-estate-specific variables is unlikely to pose a major problem.

5.3 Construction of variables

The dependent variable in our main profit function is the estate-specific total profit per year. Average annual input prices and average area cropped were constructed from monthly input prices and monthly cropping area, respectively.

The methodology used for constructing weather variables was derived from the literature (Seo *et al.* 2005; Wijeratne *et al.* 2007; De Silva and Sonnadara 2016) and reflects the likely impacts of Sri Lanka's monsoonal rainfall pattern, rainfall volume and rainfall distribution on tea production and thus profits. In addition, we would expect seasonal rainfall patterns to have an effect on labour demand, either directly or indirectly via their impact on tea leaf production.

Temperature in Sri Lanka varies with altitude. The central highlands (1,200 m above mean sea level) are cooler, with mean temperatures ranging from 16°C to 20°C, whereas the average temperature at low altitudes is around 27°C. The difference between day and night-time temperatures varies from about 14°C to 18°C. Approximately 80 per cent of Sri Lanka's rainfall is essentially governed by two main monsoon patterns: the south-west (SW) monsoon from May to September; and the north-east (NE) monsoon from December to February. Inter-monsoonal rains occur during the transition between the main monsoons due to convectional activity (De Silva and Sonnadara 2016). The first and second inter-monsoons occur from March to April and October to November, respectively. During the SW monsoon, the windward side of the central hills receives rainfall, whereas the eastern side of

Table 1 Annual mean input prices and profits across 35 tea estates, expressed in 2014 LKR

Year	Tea price (LKR/kg)	Labour price (LKR/ person-days)	Fertiliser price (LKR/kg)	Fuel price (LKR/m^3)	Electricity price (LKR/kWh)	Total profit (LKR million/ estate)
2002	412.32	321.06	32.68	846.74	24.92	7.34
2003	414.08	353.00	35.87	1245.59	24.78	2.00
2004	487.42	345.80	42.41	1710.93	23.61	18.51
2005	444.89	341.00	42.60	1744.48	21.46	5.58
2006	457.49	321.83	34.04	2121.35	22.20	9.96
2007	493.69	315.00	46.61	1442.55	17.09	27.91
2008	413.02	294.00	63.61	1331.34	15.27	7.90
2009	503.43	375.74	62.79	1494.87	14.75	18.69
2010	458.25	384.18	43.07	1166.13	13.92	12.03
2011	393.53	424.79	32.98	1608.12	14.79	−14.52
2012	425.40	421.93	20.83	1354.21	13.74	6.38
2013	442.74	448.46	16.85	816.29	13.74	4.46
2014	427.39	451.63	18.96	1249.91	13.30	0.76

Note: Mean tea prices and total profits vary across the estates; however, other prices vary only over time, except for fertiliser prices which differ across regions. All prices are converted to 2014 Sri Lankan rupees (LKR) (LKR 106.26 = AU$ 1 in December 2014) using deflation indices from the Central Bank of Sri Lanka (2014). Data on output price (i.e. the price obtained for processed tea) were extracted from estates' monthly accounts.

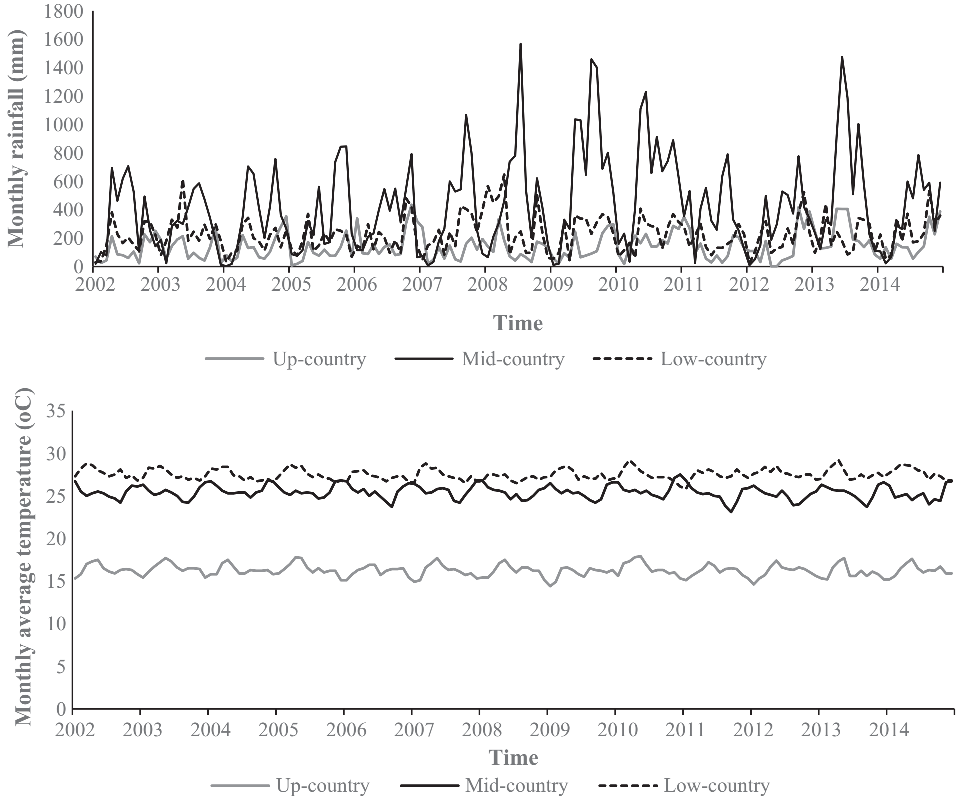

Figure 2 Time series plots of rainfall (top) and temperature (bottom) for representative estates and weather stations from the three different tea-growing elevations in Sri Lanka from 2002 to 2014.

the hills receives only dry winds. In contrast, the NE monsoon affects the entire island. The largest proportion of rainfall is received during this season.

Given the delayed effects of rainfall and wet days on tea shoot growth,[6] and thus on profits, we construct linear and squared terms in the total rainfall received and the number of wet days for the two main monsoons and the two inter-monsoons. Following Seo *et al*. (2005), we construct mean temperature variables for January, May, August and November to represent the temperature during the NE monsoon, SW monsoon and inter-monsoons, respectively. Summary statistics for the weather variables are given in Table 2.

5.4 Climatic change predictions

The predicted impact of climate change on estate-level profit and estate-level labour demand is assessed using climate change predictions from the general

[6] Tea shoot growth takes approximately 45–60 days from emergence of the bud. The effects of rainfall and wet days were, therefore, lagged over a 2-month delay in the analysis.

Table 2 Definition of weather variables and summary statistics across estates in the data sample

Variable	Definition	$\bar{x}$	$\hat{s}(x)$
SWM-Rainfall	May–September total rainfall (mm)	1032.38	789.35
NEM-Rainfall	December–February total rainfall (mm)	566.65	388.90
IM1-Rainfall	March–April total rainfall (mm)	505.17	237.50
IM2-Rainfall	October–November total rainfall (mm)	742.56	332.74
SWM-Wet days	May–September total number of wet days	60	26
NEM- Wet days	December–February total number of wet days	31	11
IM1- Wet days	March–April total number of wet days	26	7
IM2- Wet days	October–November total number of wet days	36	7
Jan-Mean temp	January mean temperature °C	21.55	4.57
May-Mean temp	May mean temperature °C	23.86	4.19
Aug-Mean temp	August mean temperature °C	23.11	4.33
Nov-Mean temp	November mean temperature °C	22.39	4.28

Note: SWM, NEM, IM1 and IM2 denote south-west monsoon, north-east monsoon, the first inter-monsoon and the second inter-monsoon, respectively. $\bar{x}$ is the mean; $\hat{s}(x)$ is the standard deviation.

circulation models (GCM) (ECHAM5 = European Centre/Hamburg Model and MRI = Meteorological Research Institute), based on two scenarios: A2 and A1B from the Special Report on Emissions Scenarios in AR4 (IPCC 2007). The two scenarios, A2 and A1B, represent high and medium emissions futures, respectively.

The Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES) provides spatially downscaled climate predictions on a 30-km grid for two time windows: short-term (2026–2035) and medium-term (2046–2055), from a baseline of (1990–2000) (Ahmed and Suphachalasai 2014). We calculate inverse distance-weighted averages from 30-km grid points within a 40 km radius to obtain predicted monsoonal rainfall for the estates in our sample. In order to obtain the predicted change in labour demand, predicted monsoonal rainfall was then multiplied by the corresponding elasticity relating labour demand to the relevant component of weather elasticity.

6. Results

6.1 Profit function estimates and price elasticities

The five structurally linked equations in (7) were estimated as a fixed-effects-transformed seemingly unrelated regression (SUR) cross-equation-restricted system on a total of 455 observations.[7] The adjusted R^2 of the estimated profit function is 0.65. Adjusted R^2 results for the input demand equations for labour, fertiliser, electricity and the output supply equation for processed tea

[7] The robust Hausman test indicated that a fixed-effects specification is more appropriate than a random-effects specification in this application (Prob > F = 0.0000).

are 0.94, 0.73, 0.88 and 0.94, respectively. Second-order terms in labour, fertiliser and tea price in the profit function are not statistically different from zero, satisfying the condition for convexity in prices.

Table 3 presents own-price and cross-price elasticities at the means, calculated using the estimated parameters from the SUR system. Consistent with the economic theory, the own-price elasticities show the expected signs, satisfying the necessary conditions for convexity. All of these input price elasticities are less than unity. The estimated values of input demand and output supply are positive, fulfilling the monotonicity condition for the profit model. The input price elasticities, except for electricity, and the output price elasticity are statistically significant, as determined by bootstrapping across 500 estate-clustered, resampled data sets. The price elasticity of labour suggests that labour price has a considerable impact on labour demand. The mean elasticity of labour demand with respect to labour price is −0.34. Labour constitutes the highest cost input into tea production, comprising about 65 per cent of total variable cost (Herath and Weersink 2007). Mean own-price elasticity of fertiliser is −0.49, indicating a relatively large impact on fertiliser demand. Own-price elasticity of electricity is not significant. Own-price elasticity of tea is significant at the 10 per cent level, but of a fairly low magnitude.

6.2 Elasticities of labour with respect to weather

Our main interest is the impact of monsoonal rainfall, wet days and temperature on the demand for labour in tea production. The corresponding elasticities of labour demand with respect to weather and estate area are shown in Table 4. The elasticities of labour with respect to all monsoonal rainfall variables are highly significant. Increasing SW monsoon, NE monsoon and inter-monsoon 2 rainfall decreases demand for labour, although the impacts are modest. The mean elasticity of labour with respect to SW monsoon, NE monsoon and inter-monsoon 2 rainfall is −0.045, −0.047 and −0.042, respectively. The underlying fact is that labour has a

Table 3 Estimated own-price and cross-price elasticities of input demand and output supply

	Elasticities of estate-level input demand and output supply with respect to the prices of inputs and output			
	P_{labour}	$P_{\text{fertiliser}}$	$P_{\text{electricity}}$	P_{tea}
Labour	−0.337***	−0.023	0.016*	0.298***
Fertiliser	−0.124	−0.494***	0.028	0.468***
Electricity	0.148*	0.049	−0.019	−0.166*
Tea supply	−0.094***	−0.028***	0.006*	0.073*

Note: *Significant at 10% level; **significant at 5% level; ***significant at 1% level; determined by 500 bootstrap replicates from the data set.

Table 4 Elasticities of labour demand with respect to weather and estate area

Variable	Labour elasticity with respect to weather variable	Significance
SWM-Rainfall	−0.047	***
NEM-Rainfall	−0.045	***
IM1-Rainfall	0.061	***
IM2-Rainfall	−0.042	***
SWM-Wet days	0.052	ns
NEM-Wet days	−0.0282	ns
IM1-Wet days	0.022	ns
IM2-Wet days	−0.006	ns
Jan-Mean temp	−0.111	ns
May-Mean temp	0.366	ns
Aug-Mean temp	0.039	ns
Nov-Mean temp	−0.021	ns
Area	0.857	***

Note: *Significant at 10% level; **significant at 5% level; ***significant at 1% level; ns – not significant; determined by 500 bootstrap replicates from the data set.

direct link with tea production and this is reflected in our model. These results are consistent with Gunathilaka *et al.* (2017) who find that increasing total rainfall has a negative impact on tea production. In contrast, inter-monsoon 1 rainfall has a positive, but again only modest, impact on labour demand (0.061).

Neither of the monsoonal wet day variables has a significant impact on labour demand, nor do any of the temperature variables – according to our specification. Various different specifications were tested, featuring combinations of temperatures from different months. We could not, however, identify any statistically significant elasticities of labour demand with respect to temperature. The sign of the labour elasticity with respect to November temperature is consistent with prior findings from Seo *et al.* (2005).

The sign and magnitude of the elasticity of labour demand with respect to estate area are intuitive. On the whole, increasing area increases demand for labour in tea production: a 0.86 per cent increase in labour-days follows from a one per cent increase in the area planted with tea. On average, in the tea plantation sector, approximately 2.5 units of labour are required per hectare of tea (Sivaram 2000); this may increase to approximately 4 units, depending on the productivity of a given block of land (Sivaram 2000). The production function analysis by Gunathilaka *et al.* (2017) also found a large impact of area on the labour requirement for tea estates in Sri Lanka (estimated labour elasticity was 0.9).

6.3 Impact of predicted climate on labour demand

We now proceed to quantify the impact of predicted climate on labour responses in our sample of tea estates. Specifically, we estimate changes in labour demand for predicted monsoonal rainfall under GCM model scenarios A2 and A1B for two different time horizons (2026–2035; 2046–2055). The predicted changes are shown separately by elevation level for changes in SW monsoon, NE monsoon, inter-monsoon 1 and inter-monsoon 2 rainfall, all relative to the 1990–2000 baseline (Figure 3).

The impact of climate change on labour demand varies from estate to estate depending on the size. We observe that some estates show large impacts relative to others. Absolute changes of estate-specific labour demand are averaged according to elevation. In all climate scenarios, the absolute impact of predicted changes in rainfall in all periods is negative across all elevations.

The absolute impact of predicted changes in SW monsoon rainfall for 2026–2035 is estimated to reduce labour demand by 1,447 person-days annually for the mean up-country estate. Out of all rainfall factors, the impact of SW monsoon rainfall is the highest under all scenarios. The impact of the

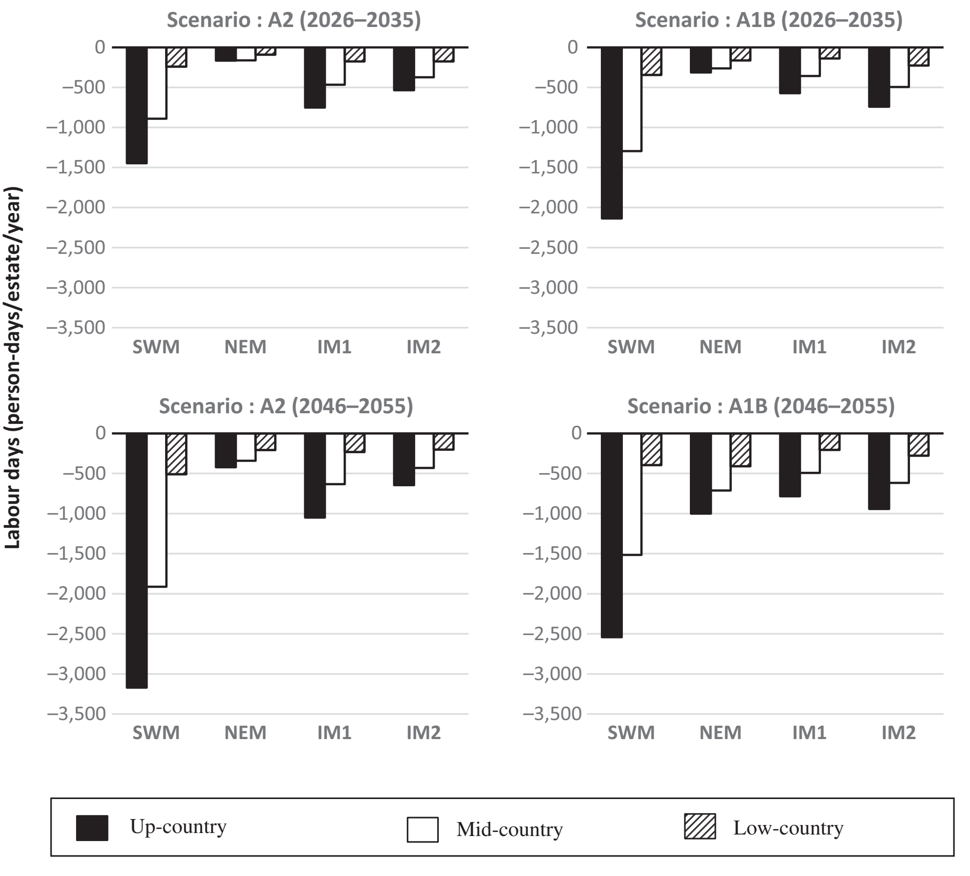

Figure 3 Climate change impacts on labour demand for the average estate (person-days per year), by tea-producing elevation under climate change scenarios A2 and A1B and time horizons 2026–2035 and 2046–2055, compared to a 1990–2000 baseline. Impacts of rainfall during south-west monsoon, north-east monsoon, inter-monsoon 1 and inter-monsoon 2 are shown separately.

anticipated change in SW monsoon rainfall on labour demand is predicted to approximately double between the near-future and medium-term future. The absolute reduction in labour demand for 2046–2055 due to the change in NE monsoon rainfall is predicted to be two to three times larger than in 2026–2035 under both climate scenarios. By mid-century, for the mean up-country estate, the aggregate predicted reduction in labour demand across all seasons ranges from 5,268 (Scenario A1B) to 5290 (Scenario A2) person-days per year. The corresponding figures are 3,316 (A2) and 3,336 (A1B) for the mean mid-country estate and 1,152 (A2)–1,289 (A1B) for the mean low-country estate. This will translate into a much larger reduction in labour-days when the numbers of estates at each elevation are considered. For example, annual losses of labour-days from all three tea estate regions are predicted to reach almost 1,175,000 person-days per year by mid-century.

7. Discussion and conclusion

The objective of this study is to estimate the impact of climate change on labour demand in Sri Lanka's tea estate sector. This is one of very few studies to address the issue for a perennial plantation crop in a developing country. We employ a unique estate-level panel data set across 35 estates and 13 years. The 35 tea estates in our sample cover a wide range of tea-growing climatic regions, all three tea-growing elevations and a representative range of estate sizes. We use a structural system of profits, input demands and output supply across individual estates – the separate decision-making units in Sri Lanka's tea plantation sector. The structural model provides a strong theoretical basis for our analysis and allows us to explore climate change adaptation decisions of individual decision-makers – the key objective of our study. However, it should be noted, that this approach makes strong assumptions regarding the functional form of the profit function from which the labour demand function is derived. The normalised quadratic profit function and its derived input demand and output supply functions fit well to the observed data, lending strong support to our choice of functional form.

7.1 Own-price elasticities

The relatively low magnitude of the own-price elasticity of labour demand (−0.34) reflects the labour-intensive nature of tea harvesting, which remains a fully manual process. Mechanical harvesting cannot deliver the required tea leaf quality, and machinery access is not feasible in the steep terrain of tea estates where shade trees are interspersed among rows of tea bushes (Satyanarayana *et al.* 1990). Our estimate of the own-price elasticity of fertiliser (−0.49) is consistent with that of Roberts (1989) (−0.508), also for tea plantations in Sri Lanka. The low magnitude of the own-price elasticity of tea supply (0.07) can be explained by the long time period taken for supply of a perennial crop to adjust to changes in commodity price. Tea has a gestation period of 2–4 years from planting and a typical productive lifespan of 45–50 years, and this limits managers' response to output price changes. Furthermore, unlike annual crops, an estate manager cannot suspend harvesting when tea price is low because this would likely lead to lower production quantity and quality in subsequent harvesting rounds. As noted, labour required for harvesting is the biggest variable cost component of tea production. This inability to suspend harvesting when tea price is low therefore has very considerable adverse implications for profitability. This helps explain why 35 per cent of annual average estate profits in our data set are negative.

7.2 Labour elasticities with respect to weather

The finding of an inverse relationship between rainfall and labour demand during both monsoons and the October–November inter-monsoon can be explained by increased cloud cover reducing tea growth, thus reducing the quantity of tea to be harvested, and by the behavioural responses of plantation workers. In regard to the latter, higher rainfall (particularly when associated with thunderstorms) discourages worker turnout:

> 'Workers absences are high during rainy days because they engage in re-roofing their houses and are scared of thunder and lightning'.[Manager #15, Mid-country]

In contrast, the positive relationship between rainfall and labour demand during the March–April inter-monsoon period can be explained by the relatively low rainfall during this period occurring mainly in the evenings, while the majority of days are sunny (Ranatunge *et al*. 2003; De Silva and Sonnadara 2016). This helps to increase tea production without discouraging worker attendance.

Having identified the links between tea production and labour use in plantations, our study estimates the impact of predicted climate change on labour demand. Under both climate scenarios modelled, predicted increases in rainfall by 2050 during both monsoons and the October–November inter-monsoon are estimated to reduce labour demand, as will the predicted decrease in rainfall during the March–April inter-monsoon. These effects in combination are predicted to reduce labour demand by about 3,254 person-days per year for the average estate. Overall, the absolute impact of predicted changes in rainfall reduces labour demand by approximately 1,175,000 person-days per year across the three tea estate regions: a reduction of 2.6 per cent.

7.3 Implications for policy and future research

Our findings have significant policy implications as the plantation sector is the Sri Lanka's largest employer, employing seven per cent of the total national workforce. Potential consequences become even more significant when it is realised that those most affected will be women from the Tamil immigrant community for whom limited alternative employment opportunities exist. Further, these women are typically the primary income earners for their predominantly low-income households. Appropriately designed policies to assist the tea estate sector to adapt to climate change thus have the potential to deliver considerable social and welfare benefits for the rural plantation community and the agricultural labour force in general. Strategies for managing the consequences of climate change could include encouraging crop diversification, increasing educational and reskilling opportunities for plantation workers and facilitating opportunities for expansion of eco-tourism (Jolliffe and Aslam 2009).

Perennial plantation crops such as rubber, oil palm and coconut in other developing countries share many of the labour-related characteristics of tea production in Sri Lanka. For example, the crop must be harvested regularly by almost exclusively manual methods if production is to be maintained for future seasons, irrespective of current market conditions. These other perennial plantation crops are also susceptible to changing climate (Devakumar *et al*. 1999; Peiris *et al*. 2004), and they deliver substantial foreign exchange earnings and typically employ significant numbers of agricultural workers. Our findings suggest that structural models based on primary data from individual production units are a useful approach for quantifying the likely impacts of climate change on labour demand in such settings. Given the scarcity of existing research around climate change impacts in perennial cropping, particularly in the developing world, there is a clear opportunity to replicate our methods for important perennial plantation crops elsewhere.

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