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Economic impacts of climate change on perennial plantation tree crops: the case of tea production in Sri Lanka

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Abstract

Agriculture is one sector of the economy which is highly vulnerable to climate change because of the natural relationship between environment, particularly temperature and water availability, and agricultural productivity. Changing climate is increasingly affecting high-value perennial plantation crops such as tea, rubber, coconut, palm oil, and coffee which generate significant export revenues and provide a major source of employment for rural populations in developing countries. Many studies in the literature have focused on climate change impacts on major annual crops; however, to date, there have been very few assessments of the economic impacts of climate change on perennial plantation agriculture. This thesis therefore seeks to estimate the impacts of climate change on two important aspects of plantation agriculture - crop production and labour demand - for the case of the tea plantation sector in Sri Lanka, as an example of a high-value perennial plantation crop in a developing country. The thesis also aims to identify enablers and barriers of adaptation to climate change for this sector of Sri Lanka’s economy.

The impacts of climate change on production in Sri Lanka’s tea plantations are studied at estate-level (the primary decision making production unit) across all of the country’s tea growing regions using monthly resolution primary data for the period 2000-2014. The study employs a novel two-stage panel data approach to analyse weather and climate change effects on tea production and then to estimate production impacts for the short-, medium- and long-term future under three different global emissions scenarios. These analyses indicate that a hotter and wetter climate will have a detrimental effect on production. In high, medium and low emissions futures, the predictions show a negative proportional impact on production from increased rainfall and increased average temperature. On average across the data sample, a 12% decline in annual tea production is predicted under a high emissions scenario by 2050.

The impacts of climate change on labour demand in tea plantations in Sri Lanka are investigated by implementing a panel structural model of profit maximisation based on a normalised quadratic functional form. The analysis uses historical primary data on estate profits, input prices and output prices, together with monsoonal rainfall, temperature and wet days for years between 2002-2014 to quantify climate impacts on estates’ demand for labour. Anticipated changes in rainfall are predicted to reduce annual labour demand
by 2.6% across the tea plantation sector. This could have considerable social and welfare implications, particularly for the Indian Tamil women who comprise the majority of the sector’s workforce.

Plantation agriculture is likely to be highly vulnerable to climate change because of its reliance on rain-fed production, long economic life span and the inability to easily switch crops due to high upfront capital costs. These distinct differences between annual and perennial agriculture, and the important role which plantation cropping plays in developing world agriculture, suggest that it is important to identify factors which affect choice of climate adaptation options in perennial crop production. Comprehensive knowledge of available adaptation options is of utmost importance if Sri Lanka’s tea estate managers are to counteract production losses from climate change and maintain their competitiveness in the international market. This is also vital for efficient and effective channeling of society’s resources to address the consequences of climate change. Employing data derived from face-to-face interviews with 50 tea estate managers in Sri Lanka, this study examines factors affecting choice of preferred adaptation options, barriers to adaptation and associated policy implications for tea production in Sri Lanka, as an example of a perennial tree crop system in a developing country.

Tea estate managers are already adapting to a changing climate; however, particular adaptation methods are only adopted in some situations and locations. Multinomial logit analysis of data from estate manager interviews indicates that availability of information on climate change, company size, tea growing elevation, and observed increases in temperature and rainfall are key factors influencing the choice of preferred adaptation option. Analysis also finds that barriers such as a lack capital, inadequate access to near-term and medium-term climate knowledge, and poor governmental and institutional support may prevent estate managers from experimenting with new adaptation options. Policies should, therefore, be aimed at promoting new adaptation options through information exchange between stakeholders and integrating climate change adaptation with Sri Lanka’s national sustainable developmental goals. The primary message of the adaptation analysis in this study is that governmental and institutional support and involvement are critical requirements for facilitating effective adaptation.

Findings from the thesis will help inform decision makers of the likely impacts of climate change on plantation cropping systems, and provide insights into barriers to adaptation and potential policy responses to improve the effectiveness of adaptation.
JEL Classification: C33; D22; D24; J01; J23; Q12; Q54; Q58

Keywords: Economic impact; climate change; plantation agriculture; production function; structural model; labour demand; adaptation
Statement of Originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Rajapaksha Pedilage Dayani Gunathilaka
February 2018
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List of publications by candidate

Journal articles


Conference abstracts - presented during candidature


ALL PAPERS INCLUDED ARE CO-AUTHORED

Acknowledgement of Papers included in this Thesis

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To be named as an author, a researcher must have made a substantial scholarly contribution to the creative or scholarly work that constitutes the research output, and be able to take public responsibility for at least that part of the work they contributed. Attribution of authorship depends to some extent on the discipline and publisher policies, but in all cases, authorship must be based on substantial contributions in a combination of one or more of:

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- include in the list of authors only those who have accepted authorship
- appoint one author to be the executive author to record authorship and manage correspondence about the work with the publisher and other interested parties.
- acknowledge all those who have contributed to the research, facilities or materials but who do not qualify as authors, such as research assistants,

Chapter 5:
technical staff, and advisors on cultural or community knowledge. Obtain written consent to name individuals.

Included in this thesis are papers in Chapters 3, 4 and 5 which are co-authored with other researcher(s). My contribution to each co-authored paper is outlined at the front of the relevant chapter. The bibliographic details for these papers including all authors are:

Chapter 3:


Appropriate acknowledgements of those who contributed to the research but did not qualify as authors are included in each paper.

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Chapter 4:


Appropriate acknowledgements of those who contributed to the research but did not qualify as authors are included in each paper.

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Chapter 1 Introduction
1.1. Introduction

There is general agreement that the intensification of greenhouse gas emissions is raising the earth’s temperature (IPCC 2013). This process leads to several important consequences: melting glaciers, changes in patterns of precipitation, more frequent occurrence of extreme weather events and changes in seasons. Climate change impacts many different sectors of the economy such as agriculture, energy, health, infrastructure and buildings, resources and water supply all over the world at different intensities (UNFCC 2007). However, agriculture is one sector of the economy which is highly vulnerable to climate change because of the underlying relationship between environment and agricultural productivity, because plants’ biological processes lead to growth being dependent on temperature and water. Hence agriculture has been the focus for much of the existing literature on climate change impacts (Dell et al. 2014). Many studies report adverse impacts of climate change on agriculture with direct consequences for food security and economic and social development in various parts of the world (Schmidhuber and Tubiello, 2007; Wheeler and Braun, 2013). Consistent and considerable adverse consequences of climate change on agriculture in developing country contexts have been documented, since agriculture plays a central role in the economy of most developing nations (Auffhammer et al., 2012; Welch et al., 2012). Studies find that climate change will affect the agriculture sector in Sri Lanka mainly due to changes in the variability of rainfall, increases in temperature, and elevated CO2 concentration (Esham and Garforth 2013 b). As a consequence, Sri Lanka’s agricultural production is predicted to decrease by up to 20% by 2080 (Cline 2007).

The purpose of this thesis is to investigate the impact of climate change on production and labour demand in perennial plantation agriculture, specifically in the context of Sri Lanka’s tea sector as an example of perennial plantation tree crop in a developing country. The thesis also investigates preferred climate adaptation options of Sri Lankan tea estate managers, identifies key constraints on adaptation and suggests how these might be addressed. This chapter begins with a general definition of plantation agriculture, before describing the distinct contribution of perennial plantation cropping to the developing world in general, and to Sri Lanka specifically. The threats posed by climate change to Sri Lanka are briefly presented in the

\[\text{By including the term ‘tree’, the thesis focuses only on tree crops, so perennial crops such as vineyards are not included.}\]
subsequent section. Existing literature regarding the economic impacts of climate change on plantation crops, particularly in a developing world setting is then reviewed. This chapter concludes by outlining specific research questions and the contribution from this thesis.

1.2. Definition of plantation agriculture

Goldthorpe (1988) defines plantation agriculture as follows:

“The plantation mode of production is a distinct and economically viable system of agriculture typically growing perennial crops in the humid tropics. The distinctive feature of plantation agriculture is the organization of crop production within a bureaucratic internal structure. Plantation production is further characterized by the use of high input/high output technology compared to other tropical, cash cropping systems.

(Goldthorpe, 1988, p.38)

Plantation agriculture can also be distinguished from other forms of agriculture because plantation crops require processing by complex and expensive machinery in large-scale plants or factories. Apart from that, this type of export crop production requires storage and transport facilities of sufficient capacity to ensure viable operations. Furthermore, plantation agriculture also requires a highly specialized labour force who have acquired specific skills for particular operations within plantation crop production. For example, harvest gangs typically only undertake harvesting (i.e. tea pluckers, rubber tappers, oil palm harvesters); drainage gangs prepare and clear out planting holes and drains; pest and disease gangs focus on crop health and sanitation; weeders weed; sprayers spray; and estate factory workers are employed only in the factories (Goldthorpe, 1988).

1.3. Role of plantation agriculture in the developing world

The plantation agriculture sector has played a significant role in developing nations’ economies over many decades. This sector generates a sizable percentage of export earnings, provides a large number of employment opportunities, is a major source of food and income and also delivers some important ecosystem services for the producing countries (Alkan et al., 2009).
In an Asian context, Malaysia and Indonesia account for more than 85% of global oil palm production covering 6.7 million hectares of cultivated extent. Palm oil generates about 8% of gross national income and it is the fourth largest sector of the Malaysian economy (May, 2012). Palm oil is Indonesia’s most significant agricultural export and the country’s second largest agricultural product by revenue, providing almost two million employment opportunities (World Growth, 2011). Thailand, the world’s largest exporter of rubber, earns approximately US $12 billion from rubber annually, contributing 4.7% to annual export earnings in 2013 (Thai Trade Center, 2013). The smallholder sector in Malaysia and Indonesia accounts for 72% and 84% of the total national rubber production respectively (Bagnall-Oakeley et al., 1997).

Coconut is an important plantation crop in the Philippines, the world’s leading producer, followed by Indonesia, India and Sri Lanka. It is the highest net foreign earning sector of Philippine agriculture, contributing about 30% of total export earnings and providing significant employment opportunities (Philippine Coconut Authority, 2013).

Tea in Sri Lanka, as an example, is the country’s foremost export agricultural crop, generating 15% of foreign exchange earnings and providing employment for 10% of the workforce (Central Bank of Sri Lanka, 2015; Ganewatta et al., 2005). Sri Lanka is categorized as a lower middle income country (World Bank, 2016). Agriculture is an important sector in the national economy in terms of providing a source of food, export earnings and employment. The share of national GDP from agriculture is 7.8% and agriculture employs almost 28% of the total labour force (Department of Census and Statistics, 2014). The agriculture sector consists mainly of agricultural crops and livestock, with crops contributing 5.9% of GDP. Among agricultural crops, plantation crops such as tea, rubber and coconut make a significant contribution to the economy and are the largest employer, providing employment for 12% of the national work force. Export of plantation crop products generates 23% of foreign exchange earnings, with 15% of foreign exchange earnings coming from exporting tea (Central Bank of Sri Lanka, 2016).

1.4. Climate of Sri Lanka and threats posed by climate change

Sri Lanka is located in the Indian Ocean off between latitudes of 5° 55’ to 9° 51’ North and between longitudes of 79° 42’ to 81° 53’ East, off the south-eastern tip of India (Figure 1-1). The island is characterised by a tropical climate and is divided into three main climatic zones depending on average annual rainfall: the Dry zone (800-1,200 mm), the Intermediate zone
(1,200-2,000 mm) and the Wet zone (>2,000 mm). Sri Lanka receives rainfall from three mechanisms namely, monsoonal, convectional and expressional (due to low pressure conditions in the Bay of Bengal). Average temperature varies primarily with altitude, ranging from a high of 27°C in coastal areas to a low of 16°C in the central highlands (>1,200m above mean sea level) (Sri Lanka Department of Meteorology, 2016). Depending on the rainfall and topography, Sri Lanka is divided into 46 agro-ecological regions (AERs) (Chithranayana and Punyawardena, 2009). Climate experienced over a year is divided into four seasons; Inter-monsoon 1 (March-April), South-West monsoon (May-September), Inter-monsoon 2 (October-November) and North-East monsoon (December-February) (Figure 1-2). The highest rainfall, typically comprising about 60% of the annual total, is received during the South-West monsoon and the Inter-monsoon 2 periods (Premalal, 2009).

Figure 1-1 Sri Lanka's location in South Asia
Source: Google maps (2017)
The climate of different parts of Sri Lanka has been changing very rapidly over the last few decades. Annual air temperature anomalies (deviations from the long-term mean) have become increasingly positive, by approximately 0.3°C per decade (3°C per century), over the period 1951-2006 (Figure 1-3) (Sri Lanka Department of Meteorology, 2016). Annual mean maximum temperatures recorded in all weather stations in Sri Lanka show increasing trends, for example in coastal areas, the rate of increase in maximum temperature is high as 0.02°C (Premalal, 2009) (Figure 1-4). Studies also show that the rate of increase in night time annual mean minimum temperature is as high as 0.02°C per decade at high altitude (i.e. in Nuwara Eliya district). Moreover, extreme temperatures have increased in all parts of Sri Lanka, with extremely high temperatures being recorded more frequently in the eastern part of the island (Figure 1-5).
Figure 1-3 Average temperature anomaly (deviation from long-term mean) of Sri Lankan coastal areas over 1951-2006

Source: Sri Lanka Department of Meteorology (2016)

(a) Trends of maximum temperatures over 1961-2000
(b) Trends of minimum temperatures over 1961-2000

Figure 1-4 Rate of rise in maximum and minimum temperature (°C) per decade over the period 1961-2000 across different areas in Sri Lanka

Source: Premalal (2009)
Looking at rainfall records from 1880 onwards, years with rainfall below the long term average have become more frequent since 1980 (Figure 1-6), however, despite this overall reduction in mean annual rainfall, extreme rainfall events are becoming more frequent (Sanjeewani and Manawadu, 2017). These extreme events damage infrastructure, housing and cause considerable loss of life. For example, a severe landslide occurred in up-country (Koslanda in the Haldumulla division) killing 192 people due to the torrential inter-monsoon rains in 2014. Due to extreme rainfall in May 2016, over 300,000 people were directly affected by floods and landslide, over 300 people were killed and 4,400 houses damaged mainly in Ratnapura, Colombo and Galle (Low-country areas) (Sri Lanka Department of Meteorology, 2016).
May 2017, over 415,600 people were affected in 12 districts, with 289 killed and 3,000 houses destroyed due to floods caused by unusually heavy south-west monsoon rains (United Nations Sri Lanka, 2017) (Figure 1-6). Data from the United Nation’s Food and Agriculture Organisation (FAO) indicate that severe droughts followed by heavy rainfall have affected cropping areas in Sri Lanka, threatening the food security of some 900,000 people (FAO, 2017).

1.5. Climate change predictions for South Asia

This section presents future predictions for climate change for South Asia from the Intergovernmental Panel on Climate Change (IPCC, 2013). Increasing annual mean temperature in South Asia has been observed during the 20th century. Minimum and maximum temperatures across South Asia are predicted to increase by 0.8°C and 2.5°C, respectively, by 2065. Mean seasonal summer monsoon rainfall for South Asia as a whole is predicted to increase, and it is also very likely that rainfall extremes and frequency of extreme rainfall events will also increase. In South Asian countries, seasonal mean rainfall has varied inter-decennially over the past century. Over the Indian sub-continent, the observed increase in the number of monsoon break days (short, dry days during an otherwise wet period of monsoon rain) and the observed decline in the number of monsoon depressions are consistent with the overall decrease in seasonal mean rainfall.

Figure 1-6 Variability of annual rainfall around the long-term mean in Sri Lanka between 1880-2015

Source: Sri Lanka Department of Meteorology (2016)
However, according to the IPCC’s Representative Concentration Pathways 4.5 (RCP4.5) and higher end scenarios, there is predicted to be an increase in rainfall extremes from cyclones on the coasts of the Bay of Bengal, at the expense of a decrease in the number of weaker rainfall events. The frequency of heavy rainfall events is increasing over South Asia generally, while the frequency of light rain is decreasing. The impacts of climate change on food production and food security in many parts of Asia, where very large numbers of people already suffer from food insecurity, are predicted to cause a further decline agricultural productivity (IPCC, 2013; World Bank 2013). Intense heat waves have been shown to adversely affect the health of outdoor workers in South Asia, where many agricultural operations are still undertaken manually (Hyatt et al., 2010; Nag et al., 2007).
1.6. Review of the literature addressing climate change impacts on agriculture

Agriculture is one sector of the economy which is highly vulnerable to climate change since the natural relationship between environment and agricultural productivity is governed by plants biological processes which determine how plant growth is dependent on temperature and water. Hence agriculture has been the focus for much of the existing literature on climate change impacts (Dell et al., 2014).

Many studies report adverse impacts of climate change on agriculture with direct consequences for food security and economic and social development in various parts of the world. For example, Adams (1989), Adams et al. (1990) and Kaiser et al. (1993) quantify the effect of climate change on agricultural outputs by calibrating production functions on experimental data and using these estimates to forecast the impact of changing climate on US agriculture. Liverman and O'Brien (1991) use a similar approach and find climate change could bring a warmer and drier climate in Mexico, causing adverse consequences for rain-fed and irrigated agriculture. Rosenzweig and Parry (1994) find that developed countries could reap some benefits from global warming for cereal production due to increased carbon dioxide concentrations in the atmosphere, whereas developing countries may experience further losses potentially leading to food insecurity. Wijeratne et al. (2007) employ a field experimental approach in their analysis to assess the impact of climate change on productivity of tea lands in Sri Lanka and predict that increasing temperature would decrease tea yields in most regions.

Many studies indicate consistent and considerable adverse consequences of climate change on agriculture in developing country contexts. These adverse impacts can affect production, productivity and/or associated employment. 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; Dunn et al., 2015; Schlenker and Lobell, 2010). This process is relatively inexpensive for short-term annual crops compared to high-value perennial cropping systems. Annual crop farmers therefore have the capacity to switch into 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. Thus, the outcome of decisions made at the
present time may not appear until possibly decades later, by which time the climate is likely to have changed again (Dunn et al., 2015; Laderach et al., 2011). Whilst a large volume of research has been undertaken on the impact of climate change and adaptation on annual cropping systems, it is surprising that studies on the economic impacts of climate change on high-value developing world perennial plantation cropping systems such as tea, rubber, coconut and oil palm are very few in number (Boehm et al., 2016).

1.7. Rationale for the research

It appears that climate change poses challenges for perennial plantation cropping systems that may have large impacts on the national economies of many developing countries. The plantation agriculture sector plays an important role in the Sri Lankan economy and is a vital source of livelihood for the country’s predominantly rural population. Among plantation crops, tea is a key contributor to the economy and provides employment opportunities for more than 600,000 rural people, and specifically for a particular ethnic group (Sri Lankans of South Indian Tamil origin) for whom limited alternative employment opportunities are available.

Tea plantation crops are completely rain-fed and hence highly sensitive to temperature and rainfall dynamics, which are key climate factors affecting production, productivity and product quality. The plantation areas in Sri Lanka are already experiencing changes in temperature, rainfall and more frequent extreme weather events. Ongoing climate change is likely to increase these threats even further. In the absence of effective adaptation, increased climate variability and climate change are likely to have considerable negative impacts on tea production and rural livelihoods. In extreme cases, this could potentially pose serious social and welfare challenges in addition to the loss of foreign income from tea exports. There is therefore a need for effective adaptation actions to be identified and implemented to reduce climate change-related risks.

However, adaptation needs for different agricultural sectors: plantation agriculture (major export crops); annual agricultural crops (i.e. maize, chilli, potatoes, onion); minor export crops (i.e. cinnamon, cardamom, cocoa, nutmeg); vegetables and livestock, should be determined by firstly quantifying likely climate impacts and their potential socio-economic consequences. Depending on the nature and intensity of those impacts, sectors could have a number of
different adaptation needs, and hence different adaptation options could be appropriate to build adaptive capacity and reduce vulnerability.

The Sri Lanka National Climate Adaptation Plan for 2016-2025 identifies eight priority concerns for which climate adaptation is an urgent requirement. Four of these relate directly to plantation agriculture: export agriculture, food security, ecosystem services and biodiversity, tourism and recreation. Within export agriculture, two priority actions have been emphasized:

- conduct research studies to quantify climate change impacts on export agriculture crops
- develop research institutes’ capacity for conducting research about climate change impacts on export agriculture crops

Sri Lanka has also set 17 sustainable development goals (Department of Census and Statistics, 2017), the 13th of which is to take urgent action to combat climate change and its impacts. In the context of plantation agriculture and its dependent community, this goal is integral to several other goals such as the removal of poverty and achieving gender equality. For example, plantation communities comprise five per cent of the total Sri Lankan population and 10% of the total workforce. The majority of plantation workers are also women who are the primary income earners in their households. Sri Lanka’s 17 current sustainable development goals build upon achievement of successful delivery of the country’s earlier eight Millennium Development Goals (Institute of Policy Studies, 2016).

In line with all of the above priorities, there is a pressing need to conduct studies to quantify the impact of climate change on the tea plantation sector in Sri Lanka. Comprehensive studies of this problem, as an example of the more general issue of a plantation export agricultural crop in a developing country context, are very rare in the literature, and hence the present study aims to address this gap.

1.8. Research questions

This study seeks to assess the potential economic impacts of climate change on the tea plantation sector in Sri Lanka and to quantify the challenges that the sector faces in adapting to climate change.

More specifically, this research addresses three priority questions:
1. [Chapter 3] How will current and predicted future climate changes affect tea production in the Sri Lankan tea plantation sector?

2. [Chapter 4] To what degree will labour demand in tea plantations be affected by changes in climatic conditions?

3. [Chapter 5] Which factors affect choice of adaptation options in tea plantations, what are the key barriers to adaptation, and what are the associated policy implications?

In addition, a methodological reflection (presented as an Appendix to Chapter 4) (Appendix 4-1) explores why it is particularly challenging to quantify the elasticities of profit with respect to different components of climate for perennial plantation crops.

The rationale for Research Question 1 is that, as noted above (and augmented by topic-specific reviews in subsequent chapters), there have been very few studies of the economic impacts of climate change on plantation agriculture, particularly in developing country contexts. Moreover, most previous studies (for example Boehm et al. 2016 and Wijeratne et al. 2007) have estimated the economic impacts of climate change on crop production using aggregated data without considering adaptive responses such as variations in production inputs at the level of individual decision-making units (farms generally, but ‘estates’\(^2\) here in the Sri Lankan tea plantation sector).

The rationale for Research Question 2 is that the impact of climate change on labour demand in plantation agriculture is a little explored aspect of climate change economics. To the author’s knowledge, there appear to have been no studies on the effects of climate on labour demand in plantation agriculture in developing countries. Thus, the principal objective of Chapter 4 is to contribute to addressing this research gap.

The rationale for Research Question 3 is that to the best of our knowledge, no studies have yet empirically investigated the drivers of adaptation choice in perennial agriculture. Whilst a number of studies have discussed the impact of climate change on tea production (Costa, 2010; Gunathilaka et al., 2017; Wijeratne, 1996), they provide very little empirical analysis of the

\(^2\) ‘Estates’ are separate decision making units in the tea production sector in Sri Lanka, akin to individual farms in a different agricultural production context.
drivers of adaptation choice. To fill this knowledge gap, Chapter 5 analyses Sri Lankan tea estate managers’ perceptions of climate change impacts, factors which affect their choice of current and potential future adaptation options, and barriers to the uptake of these options. Understanding adaptation choices is important because in the absence of adaptation the productivity of agricultural crops is predicted to decline, leading to increases in the vulnerability of rural communities who are dependent on agriculture for their livelihood.

1.9. Conceptual Framework

In its research questions, the thesis uses the conceptual framework presented in Figure 1-8. This framework summarises the research questions of the study. It begins with the growing consensus that climate change is happening, leading to changes in climate variables such as temperature and rainfall, and more frequent incidences of extreme weather events. These climate changes and extreme weather shocks affect tea productivity, production and livelihoods by inducing changes in input usage and management practices. Econometric analyses on historical climate and variations in tea production, input usage and profitability are used to quantify the likely impacts of future predicted changes in climate on tea production and labour demand [answering Research Questions 1 and 2]. Analysis of data from semi-structured interviews with tea estate managers is used to quantify factors that influence choice of adaptation options [answering Research Question 3].
1.10. Organization of the thesis

This thesis takes the form of six chapters inclusive of an Introduction (Chapter 1) and a General Discussion (Chapter 6). Chapter 2 presents the criteria used to select the study sites and provides a detailed description of the data collection process which was instrumental for the study. A brief review of methodologies for estimating climate change impacts in the agricultural economics literature is also provided in Chapter 2, to augment the more specialised literature reviews in the papers presented as Chapters 3, 4 and 5. Research Question 1 is addressed in Chapter 3 via a reproduction of a paper published in *Climatic Change*. Research Question 2 is addressed in Chapter 4 via a reproduction of paper that has been revised and re-submitted to the *Australian Journal of Agricultural and Resource Economics*. Research
Question 3 is addressed in Chapter 5 via a reproduction of a paper published in *Environmental Science and Policy*. This thesis structure is in accordance with Griffith University guidelines and policy for a thesis presented in the form of published and unpublished papers (Appendix 1).

1.11. Published and submitted papers included as empirical chapters

Chapter 3:


Chapter 4:


Chapter 5:

References


Chapter 2 Data and Methods
2.1 Introduction

The previous chapter described research questions and structure of the thesis. This chapter provides a detailed description of the approaches and methods adopted in selection of Sri Lanka as the study site, the sampling procedure used to select tea estates for data collection, and the unique process of data collection itself. A brief review of methodologies for estimating climate change impacts in the agricultural economics literature is also provided to augment the more specialised literature reviews in the papers presented as Chapters 3, 4 and 5.

2.2 Sri Lanka as the location for the study

Sri Lanka is one of the major tea producing countries in the world and the second largest exporter of tea in the international market (Gunathilaka and Tularam, 2016). Sri Lankan tea production has been affected by climate change over the past few decades. The Sri Lankan climate is diverse due to geographic location and elevational differences across tea growing regions. Sri Lanka therefore provides an excellent location for investigating the impacts of climate change on tea production.

Sri Lanka is an island located at 7°N 81°E in the Asiatic Monsoon region. The island is characterised by a tropical climate with high humidity, particularly in the south west and mountainous areas. Temperature varies with altitude. The central highlands (from 1,200 m above mean sea level) are cooler, with mean daytime annual temperatures in the range 16°C - 20°C. The average temperature in low altitude areas is around 27°C. The difference between day and night temperatures varies from about 14°C to 18°C at low altitude. Sri Lanka is categorised into three main climate zones: Dry zone, Intermediate zone and Wet zone, based on annual rainfall (Figure 2-1). The Dry zone receives an average rainfall of 800-1,200 mm per year, whereas Wet zone receives more than 2,000 mm per year (De Silva et al., 2007). The country has two distinct dry and wet seasons, during which the island receives abundant rainfall from two monsoons; the South-West monsoon winds, also called “Kachchan” winds, blow from the Indian Ocean, whereas the North-East monsoon winds blow from the Bay of Bengal (Figure 2-2). Figures 2-2 and 2-3 depict, the Wet zone in which areas on windward slopes of the central highlands receive up to 2,500 mm of rain annually. However, approximately 1,000 mm of rainfall is received on leeward slopes in the east and northeast of the country. Most easterly and north easterly areas of the country comprise the Dry zone which receives significantly less rainfall.
Figure 2-1 Main climatic zones of Sri Lanka categorised based on annual rainfall
Figure 2-2 Monsoonal rainfall pattern showing South-West and East-West winds across central mountainous areas in Sri Lanka

Source: Sivapalan et al. (1986)
Sri Lanka produces mainly black tea and production continues year-round. Tea growing areas are concentrated in the central highlands and the southern inland areas of the country. There are three main types of tea, categorised according to altitude. These are high grown teas produced at elevations of 900 m and above, medium grown teas produced between elevations of 300 m and 900 m, and low grown teas produced from sea level up to 300 m\(^3\). Taking account of the uniqueness of flavours produced by different tea growing regions due to their diverse climatic conditions, for commercial purposes the Sri Lankan tea industry has identified six distinct tea growing regions, namely Uva, Kandy, Dimbula, Ruhuna, Nuwara Eliya, Udapussellawa (Figure 2-4).
Figure 2-4 Tea producing regions of Sri Lanka categorised based on six unique flavours (caused by diverse climatic conditions) for commercial purposes

Source: Sri Lanka Tea Board (2014)

2.3 Study site selection

Accounting for farmer adaptation behaviours is important in quantifying the economic impact of climate change on production. Hence, the researcher wished to ensure that the dataset would contain sufficient variation across key aspects of climate (e.g. temperature and rainfall) to observe adaptation responses such as adjustments to the input mix, use of different planting materials (vegetative propagated or seedling tea\(^4\)), shade tree management, soil conservation, and crop diversification. A ‘space for time’ approach\(^5\) was therefore employed, by collecting data from regions which experience different temperatures and rainfalls, thereby capturing a

\(^4\) Vegetatively propagated tea is obtained from asexual methods (i.e. shoots) whereas seedling tea is obtained by planting seeds. Vegetatively propagated tea typically produces more shoots and is thus likely to produce higher yields, however relatively less adaptable under changing climatic conditions.

\(^5\) A space for time approach is used when long time-series data on weather variation are not available. This approach substitutes weather variation across space, e.g. with elevation, as a proxy for the variation in weather which is expected to occur over time.
range of responses which tea estate managers might adopt when confronted with different aspects and intensities of climate change. A ‘space for time’ approach was required because it is extremely difficult to obtain estate records from more than a 15-year time sequence.

The finest stratification used in terms of variation in weather in Sri Lanka is termed an “agro-ecological region” (AER). In light of the importance of agro-ecology in designing and evaluating agricultural research and other land-use management programmes, Sri Lanka is divided into 46 AERs based on rainfall, soil and elevation (Chithranayana and Punyawardena, 2009; Chithranayana and Punyawardena, 2014) (Figure 2-5). However, tea is grown only in 22 AERs (Figure 2-6). Out of these 22 AERs, 13 AERs have already been identified by the Tea Research Institute of Sri Lanka as climate vulnerable tea growing areas. AERs WL1a, WL2a, WM2a, WM2b, IM2b and IM3c are designated as highly vulnerable areas, whereas WM1a, WM1b, WM3b, IM1a, IM2a, IU3a and IU3e are designated as vulnerable, based on analysis of climate variation over past 50 years (Wijeratne and Chandrapala, 2014).
Figure 2-5 Agro-ecological regions of Sri Lanka (adopted from Chithranayana and Punyawardena, 2009)
Locations for data collection were selected in 21 of the 22 tea-growing AERs. Tea estates in AERs on the western slopes of the central highlands receive most of their annual rainfall from the South-West monsoon, whereas estates on the eastern slopes receive most rainfall from the North-East monsoon (Figure 2-7). Sampling was designed to collect data from western and eastern slope estates within the same rainfall and elevation category to enable potential differences in climate change impacts from the two monsoons to be distinguished (Figure 2-8). Furthermore, estates from the 13 vulnerable and highly vulnerable AERs were over-sampled in the data collection to increase the visibility of potential climate effects (Table 2-1).

6 Unfortunately, permission for data collection was not granted for the one estate in IU3d, the 22nd AER.
The final data collection sample of 40 estates covered 17% of the full population of Sri Lankan tea estates. The tea estates from which data were collected are depicted in Figure 2-9.

Figure 2-7 Cross sectional view (X-X1 of Figure 2-6) of different tea growing elevations from sea level to up-country in Sri Lanka and selection of the estates based on elevation to avoid potential correlation between rainfall and elevation.

Figure 2-8 Tea-growing AERs categorised by rainfall and elevation. Annual rainfall categorised as follows: A – <1350mm, B – 1350 to 1850mm, C – 1850 to 2750mm and D – >2750mm.
Table 2-1 Selection of sample size based on AERs and four broad categories based on annual rainfall

<table>
<thead>
<tr>
<th>Category</th>
<th>AER and number of estates selected from each AER</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>WM3b 1 from 1, IU3e 2 from 8, IM3c 2 from 2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>sampled percentage 100%, 25%, 100%</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>IU3a 1 from 4, IU3b 2 from 10, IU3c 2 from 28, WU3 2 from 9, IM2b 1 from 3, IM2a 2 from 5, WM2b 2 from 3</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>sampled percentage 25%, 20%, 7%, 22%, 33%, 40%, 67%</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>WU2a 3 from 59, WU2b 2 from 28, WM2a 2 from 6, IM1a 2 from 5, IU2 2 from 23, WL2b 1 from 2, WL2a 2 from 27</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>sampled percentage 5%, 7%, 33%, 40%, 9%, 50%, 7%</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>WU1 2 from 22, WM1a 2 from 15, WM1b 2 from 11, WL1a 3 from 34</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>sampled percentage 9%, 13%, 18%, 9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>40</td>
</tr>
</tbody>
</table>

Note: Estates in highly climate vulnerable AERs (shown in bold letters) have been sampled at higher intensity, whilst still ensuring sampling coverage of the full range of AERs.

2.4 Data collection from estate records

The researcher personally visited the office of each of the 40 estates in the sample to obtain the required data. Data were collected from estate record books at monthly resolution over the period 2000-2014. Data collection took place between January and May in 2015.

Firstly, the researcher contacted Mr Niraj De Mel, former Chairman of the Tea Exporters Association of Sri Lanka and the Vice Chairman of the Colombo Tea Traders Association of Sri Lanka to get permission from each plantation company to access their estates’ data. With the consent of the chief executive officers of the plantation companies, all except one of the target estates granted permission for the researcher to collect data. To expedite data collection, the researcher obtained permission to take digital photographs of estate record books. This proved to be an effective strategy for completing on-site data collection successfully within a reasonable timescale. With help from three research assistants, data from one estate could typically be identified and photographed on-site within one long working day from 7 am to 8 pm. Estate officers kindly assisted by remaining in the estate offices until all pages of all relevant record books for that estate had been photographed. Many of the estate offices were located in remote rural areas where travel is slow and difficult due to challenging road
conditions (Figure 2-10). Hence the data collection team typically had to start the day at around 5 am to ensure that they arrived at estate offices sufficiently early to complete data collection.
Figure 2-9 Sample locations (estates displayed using dots) for the study. AER boundaries are added in black.
that day (Figure 2-11). At some estates, the researcher and research assistants had to search for older records in dusty cob web-filled rooms, whereas in other estates, historical record books were arranged in chronological order\(^7\) (Figure 2-12 and 13). Photographs were taken with seven different good cameras (ensuring readability of information) as even a fully charged camera ran out after several hours. These digital photographs were transferred from cameras to a computer for digital storage, in accordance with the storage protocols specified by Griffith University’s Research Ethics Committee. The average memory size of stored photographs of one estate was 24 GB.

Estate record keeping is standardised for all estates within the same plantation company, and seems to be well organized and accurate. All activities related to management and operation of the estate are recorded systematically in monthly account books in English. These estate monthly accounts provided the main source of data for this thesis. All expenditure items related to field (tea leaf production) and factory (tea processing) operations and revenues received are neatly recorded in monthly accounts (Figure 2-14 to 16). The estate offices prepare their account records regularly at the end of each month and send these records to the head office of their plantation company for reporting and verification. Annual external auditing of accounts is mandatory for all estates. Therefore, estate monthly account records are believed to be accurate. Estate records were also used as the data source in a previous study by Roberts (1989), but for fewer estates and only for Nuwara Eliya region over one year.

\(^7\) Head office of plantation companies has advised the estate offices to discard record books older than 5 years. However, fortunately there were records up to 15 years back in most of the estates.
Figure 2-10 Challenging access to tea estates in rural areas
Table 2-2 lists the full range of data on tea production, tea revenues and input costs obtained from each of the 40 tea estates for most months over the period 2000 – 2014. In addition to economic data, tea estates also kept records of monthly rainfall and the number of wet days per month, using data collected from a rain gauge near the estate offices.

After completing the data collection, the full set of monthly estate data were transcribed from the digital photographs into Excel spreadsheets. This was a time-consuming and difficult process. In total, the data transcription process took approximately eight months. The final cleaned panel data set consists of 6954 observations, comprising between 118 and 180 observations per month for each of 40 estates for most months from January 2000 to December 2014, inclusive. Monthly observations for the full 180-month duration were available for 28 estates. A complete set of monthly observations from January 2002 to December 2014 were available for 35 estates. The full 40-estate dataset was used for the production function analysis.
in Chapter 3, whereas the 35-estate balanced panel dataset was used for the labour demand analysis in Chapter 4.

2.5 Temperature data

As temperature data are not recorded at estate level, these data were collected from the Department of Meteorology of Sri Lanka (DOMSL) and the Natural Resource Management Centre (NRMC), Sri Lanka. DOMSL has established six sub-meteorological stations covering tea plantation areas that record temperature data daily. Minimum and maximum temperature data from 1990 to 2014 were purchased at monthly resolution for six weather stations. Temperature data for three weather station were collected from NRMC (Figure 2-17). Average temperature from the nearest weather station to the estate was used in the analyses.
2.6 Semi-structured interviews with tea estate managers

As a separate, but concurrently conducted, data collection exercise, managers of 50 tea estate were interviewed to obtain their views on drivers and constraints to adoption of climate adaptation options on their tea plantations. The interviews were conducted via a semi-structured questionnaire. Questionnaire design was informed by literature review and further refined by obtaining advice from Sri Lankan experts in tea agronomy, climate science and the economics of plantation agriculture. The semi-structured interviews were designed in accordance with best practice as outlined in Munn and Drever (1990), Gillham (2008) and Groves et al. (2011).

The administered questionnaire survey (Appendix 2), contained questions to obtain information on the following categories.

- Geographical location (Agro-ecological region and elevation of the estate)
- Socio-demographic characteristics of the estate manager (age, years of managerial experience in tea estates, level of education)
- Awareness of the terms “climate change” or “global warming”
- Perception and observations of changes in climate through time
- Observations of the impacts of climate change on tea production
- Adaptation options implemented currently, and managers’ preferred potential climate adaptation options
- Constraints to adaptation

2-14a Cover page of an estate monthly account for January 2001

2-14b Example page of a monthly account showing information on area harvested, monthly green tea leaf production, monthly processed tea production, profits per hectare, total profit per month for the estate

Figure 2-14 Example front page and summary of monthly performance of an estate
<table>
<thead>
<tr>
<th>Type</th>
<th>Data</th>
<th>Unit of measurement</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tea production</td>
<td>Green leaf production,</td>
<td>kg</td>
<td>Estate monthly accounts</td>
</tr>
<tr>
<td></td>
<td>Processed tea production</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Labour used</td>
<td>Person days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Expenditure on fertiliser</td>
<td>LKR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cultivated area</td>
<td>Ha</td>
<td></td>
</tr>
<tr>
<td>Weather</td>
<td>Monthly total rainfall</td>
<td>mm</td>
<td>Estate record books</td>
</tr>
<tr>
<td></td>
<td>Monthly total wet days</td>
<td>days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimum and maximum temperature</td>
<td>°C</td>
<td>Sri Lanka Department of Meteorology and Natural Resource Management Centre</td>
</tr>
<tr>
<td>Output price</td>
<td>Tea price</td>
<td>LKR/kg</td>
<td>Estate monthly accounts</td>
</tr>
<tr>
<td>Input prices</td>
<td>Labour wage</td>
<td>LKR/person day</td>
<td>Estate record books</td>
</tr>
<tr>
<td></td>
<td>Fertilizer price</td>
<td>LKR/kg</td>
<td>Estate monthly accounts</td>
</tr>
<tr>
<td></td>
<td>Electricity price</td>
<td>LKR/kWh</td>
<td>Sri Lanka Energy Authority</td>
</tr>
<tr>
<td></td>
<td>Fuel price</td>
<td>LKR/m³</td>
<td>Estate monthly accounts</td>
</tr>
<tr>
<td>Profit</td>
<td>Profits before tax</td>
<td>LKR/month</td>
<td>Estate monthly accounts</td>
</tr>
</tbody>
</table>
Example page of an estate’s monthly account showing information on the number of labour days, and expenditures on labour wages, attendance bonuses, holiday pay, chemicals, tools, fertilizer, fuel, packing materials and overheads per month for that estate.

Example page of a monthly account showing information on number of labour days, expenditures on labour wages, attendance bonus, holiday pay, chemicals, tools, fertilizer, fuel, packing materials and overheads per month of another estate.

Figure 2-15 Example page of monthly accounts showing expenditure on inputs
Figure 2-16 Example page of a monthly account showing information on rainfall and number of wet days of an estate
Prior to each interview, the respondent’s consent was obtained by presenting all the consent forms required under the relevant research ethics protocol. Ethics approval for the study was granted by the Griffith University Human Research Ethics Committee (GU Ref No: 2014/837) (Appendix 3). All participants provided their informed consent and the interviews were conducted at the estate offices. Each interview typically lasted 40 minutes.

2.7 Semi-structured interviews with chief executive officers (CEOs) of planation companies

Separate semi-structured interviews were conducted with CEOs of tea plantation companies to obtain their perspectives regarding barriers to adoption of climate adaptation options, and
current policies and legislation for assisting climate change adaptation. Typically, interviews lasted for one hour and were conducted at the head offices of plantation companies in the capital, Colombo. These interviews were based around the following semi-structured questions.

- What is your view of current climate change impacts in your tea estates in general?
- How do climate change impacts on your estates vary with tea growing region?
- Do you think that climate change is contributing to a decline in revenues from your tea estates, and if so how severe do you consider this effect to be?
- Have you currently implemented, or do you plan to implement, any alternative approaches to sustain your revenues against climate change? And what are those?
- Would you say that your tea estates provide other valuable services to the environment or to society, in addition to producing tea?
- What is your view regarding crop diversification, such as establishing tree plantations, which could generate payments for carbon storage?
- What do you consider to be the major barriers to adopting appropriate adaptation options?
- What other policies and/or recommendations would your company find helpful for sustaining revenues from tea production?

All interviews were recorded using a digital device. These scripts were transferred from the recording device to a computer for digital storage, in accordance with the storage protocols specified by Griffith University’s Research Ethics Committee. The recorded interviews were then transcribed for subsequent analysis. Data from these interviews were analysed using thematic analysis and multinomial logistic regression to provide insight into factors affecting uptake of adaptation options on tea estates [as described in detail in Chapter 5].

2.8 Methodologies for estimating climate change impacts in the agricultural economics literature

The Ricardian approach introduced by Mendelsohn et al. (1994) is regarded as one of the major methodological contributions from the agricultural and environmental economics literature for estimating the impact of climate on farm revenues. The underlying concept behind the Ricardian approach is that land values reflect underlying variation in gross margin potential due to differences in soil quality and climate. Seo et al. (2005) use a Ricardian approach to
assess the impact of climate change on Sri Lankan agriculture and then use their estimates under different climate scenarios to predict a very substantial reduction (27%) in agricultural land value following from 2°C increase in mean temperature, but also note that adverse impacts are offset to some extent by increasing rainfall.

Schlenker et al. (2005) and Schlenker et al. (2006) take a similar approach, but remark that hedonic regressions cannot be used on pooled data from both dry land and irrigated farms to obtain unbiased regression estimates. They predict significant reductions in US agricultural land values due to climate change. Schlenker et al. (2007) link farmland value to both water availability and long run climate and find that predicted changes in climate are likely to have a significant negative impact on the value of farmland in California. A related approach taken by Kelly et al. (2005) incorporates the effects of both actual and expected weather on farm profit and finds that climate change induces higher losses when extreme weather events are considered. However, all the above studies suffer the potential limitation, common to all hedonic approaches, of biases in regression estimates due to confounding of climate factors with unobserved drivers of agricultural productivity.

Of particular note, Deschênes and Greenstone (2007) contribute an important methodology for estimating the effect of climate change on farm profits and predict that significant large gains or losses are unlikely from US agriculture due to changing climate. This non-structural fixed-effects panel data approach regresses agricultural profits, instead of land values, on climatic drivers. Using a similar approach, Deschênes and Kolstad (2011) extend this work by evaluating the effect of two climate change scenarios for Californian agriculture and predict negative effects on aggregate agricultural profits over this century. Deschênes and Greenstone (2007) remains a vital contribution, but it has been subject to critiques by Fisher et al. (2012) who show that climate change effects on US agriculture are negative when the data errors of Deschênes and Greenstone (2007) are corrected.

Using a panel data yield response model, Schlenker and Lobell (2010) examine the impact of climate change on four crops in sub-Saharan Africa and document the negative impact of higher temperatures on yield. Guiteras (2009) also employs a similar approach to estimate climate change impacts on Indian agriculture using 40-year district-level panel data incorporating year-to-year weather variation on agricultural outputs across 200 districts in
India. Overall, Guiteras finds that higher temperatures reduce crop yields. Welch et al. (2010) provide the first analysis of the impact of temperature and solar radiation on rice yield in six rice-producing countries in Asia. Their findings show a decline in yield at higher minimum temperatures and an increase in yield at higher maximum temperatures. Yield estimations under moderate warming scenarios show overall reductions. Lobell et al. (2011) use regression analysis on panel data of de-trended rainfall and temperature for all countries in the world to identify declines in maize and wheat production, but varying effects for rice and soy beans. Auffhammer et al. (2012) employ a fixed-effect panel data model to quantify the impacts of monsoon characteristics and total rainfall on Indian rice production and find Indian rice producers and consumers are experiencing negative effects from climate change. 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. Their findings show that short-term variations in rainfall and solar radiation, from current and previous years, affect tea yield negatively.

Several studies focus on the impact of changing climate on rural income and livelihoods in developing country contexts. For example, Jayachandran (2006), employs agricultural wage data for 257 districts in India and finds that weather-driven agricultural productivity shocks are key determinants of labour supply elasticity and migration. More recent work by Colmer (2016) estimates weather-driven changes in agricultural productivity on labour demand in India and finds that labour reallocation from agriculture to the manufacturing sector minimizes adverse ramifications on rural incomes during weather shocks.

Other well-established methodologies for quantifying climate change impacts on agriculture include production function approaches, as implemented by Auffhammer et al. (2006) and Duncan et al. (2016), and structural models derived from a profit function, as implemented by Fezzi and Bateman (2011), Mullen et al. (2009) and Roberts (1989). Production function approaches are reviewed in Chapter 3; structural models derived from a profit function are reviewed in Chapter 4.
References


Chapter 3 The impact of changing climate on perennial crops: the case of tea production in Sri Lanka
STATEMENT OF CONTRIBUTION TO CO-AUTHORED PUBLISHED PAPER

This chapter includes a co-authored paper. The bibliographic details of the co-authored paper, including all authors, are:


My contribution to the paper involved:

Data collection, data preparation, data analysis, preparation of tables and figures and writing and compilation of manuscript.

(Signed) _____________________________ (Date) 08 - 02 - 2018
R P Dayani Gunathilaka

(Countersigned) _____________________________ (Date) 08 - 02 - 2018
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(Countersigned) _____________________________ (Date) 08 - 02 - 2018
Principal Supervisor: Associate Prof. James C R Smart

This Chapter is an exact copy of the journal article referred to above.
Foreword

The previous chapter, Chapter 2, described the approaches and methods adopted in selection of Sri Lanka as the study site, the sampling procedure used to select production units for data collection and the process of data collection. This chapter, Chapter 3, is the first result chapter of the thesis. To begin, this chapter extends the literature on impact of climate change on perennial plantation tree crops by quantifying, in the context of developing countries, how changing climate effects on tea production in Sri Lanka. Specifically, this chapter uses primary monthly panel data from 40 tea estates representing all tea growing regions in Sri Lanka over a 15-year period to estimate the impact of short-term variations in weather and long-term climate on tea production. In particular, this chapter uses a novel two-stage panel data analysis to investigate impact of historical and future predicted climate on tea production. The chapter addresses a gap in the literature by estimating impact of climate change on perennial plantation crop production.
The impact of changing climate on perennial crops: the case of tea production in Sri Lanka

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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.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-016-1882-z) contains supplementary material, which is available to authorized users.

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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 crop 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.

Keywords: two-stage panel data approach, weather variation, production predictions, farm level

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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 workforce (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 events8. Temperature increases of 0.4 °C 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 country9 (Wijeratne 1996; Wijeratne et al. 2007). Prior research has also identified the eight agro-ecological10 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, Dechenes 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)

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8 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).

9 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.

10 Agro-ecological regions (AER) are categorized based on rainfall, elevation and soil type. Sri Lanka comprises 46 AERs, of which 22 contain tea estates.
investigate the effects of monsoon variables on tea yield in China. However, in 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 approach\(^{11}\) 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.

**Background**

Several approaches have been used to explore links between weather, climate and agricultural outputs: linear models\(^{12}\), Ricardian methods\(^{13}\), profit functions\(^{14}\) 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.

\(^{11}\) We acknowledge the suggestions generously provided by Prof. Jeffery Vincent here.

\(^{12}\) 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.

\(^{13}\) 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.

\(^{14}\) 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.

**Methodology**

**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\(^{15,16}\) as production inputs.

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

(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, \(\alpha_i\), 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, \(\delta_t\), 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 \((\gamma_{eg})\) to account for annual shocks common to all estates in a given elevation (e.g. unusually dry years).

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\(^{15}\) 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).

\(^{16}\) 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.
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 days\textsuperscript{17} for each estate $i$ in each year-month $t$. Current and lag periods for temperature, rainfall and wet days were used in accordance with findings from previous agronomic studies\textsuperscript{18} (Costa et al. 2007; Wijeratne et al. 2007).

$X_{fit}$ is a vector of time varying, estate-specific non-weather variables which also affect tea production: area harvested\textsuperscript{19}, ratio of the area of vegetatively-propagated\textsuperscript{20}(VP) tea to the total area, fertiliser use\textsuperscript{21} 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\textsuperscript{22} (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):

$$\hat{\alpha}_i = \varphi + \sum_{n=1}^{N} p_n \overline{W}_{ni} + \sum_{m=1}^{M} \tau_m Z_i + \mu_i$$

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\textsuperscript{22} over the 15-year period 2000-2014 (i.e. estate-specific long-term average weather) are denoted by $\overline{W}_{ni}$. Other time-invariant control variables $Z_i$ included in the model were soil depth and two dummies for regions. $\varphi$ 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 equation 1 – the effects of changes in climate on tea production.

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

\textsuperscript{17}Tea shoot growth depends on both intensity and distribution of rainfall. Approximately 6-7 days of rainfall per month are required for ideal growth.

\textsuperscript{18}Phenological development of tea shoot usually takes 45-60 days, depending on elevation and other bio-physical factors.

\textsuperscript{19}Area harvested is largely fixed in the short-run because tea is a perennial crop; it can therefore be considered exogenous.

\textsuperscript{20}Planting materials obtained from asexual methods. Yield of vegetatively-propagated tea is higher than seedling tea.

\textsuperscript{21}Current, lag-1 and lag-2 variables in fertiliser were included to account for the time lag between application and effect.

\textsuperscript{22}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.
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.

\[
PREDICTED\ PROPORTIONAL\ IMPACT_i = \sum_{n=1}^{N} \rho_n \Delta W_{ni} \tag{3}
\]

Where \( \Delta W_{ni} \) is the predicted change in climate variable \( n \) for estate \( i \) and \( \rho_n \) 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.

**Study sites and data**

**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 in the supplementary material (SM) for a map.

Data detailing quantities of input factors and tea production were obtained directly from monthly accounts of tea estates over the period 2000-2014\(^{23}\). 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 et al. (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.

**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.

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\(^{23}\) 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.
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 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 30km 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 30km grid points within a 40km radius 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.

Results

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. 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.

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24 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.

25 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.
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 labour intensive and completely manual in Sri Lanka. Fertiliser was expected to be an important production input, and all 3 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% 26). Area harvested is not on its own a significant driver of total production; other inputs (e.g. labour and fertiliser) would also have to be increased as estate area increased to deliver increased total production.

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 (\( \rho_n \)), 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 100mm 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 27. The impact of regional variables is as expected; production from low-

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

27 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.
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).

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.

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 SM_Table 2.

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

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28We 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.
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 development occurs linearly at average temperatures between 18°C 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 studies29.

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.

29Wijeratne 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.
In summary, the predicted negative impacts of climate change on Sri Lankan tea production are considerable. They will carry far-reaching negative consequences for the national economy since the industry is the country’s major source of foreign exchange and also the nation’s largest employer, with a workforce of over 0.6 million. 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.

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Carr MKV (1972) The climatic requirements of the tea plant : A review. Expl Agric 8:1-14
FAO (2014) Report of working group on climate change. Food and Agriculture Organization, Intersessional Meeting of Intergovernmental Group on Tea
Table 1. Summary statistics on monthly weather parameters and production, grouped by elevation (up, mid and low country), over the period 2000-2014

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
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<td></td>
<td>Up</td>
<td>Mid</td>
<td>Low</td>
<td>Up</td>
</tr>
<tr>
<td>Average temperature (°C)</td>
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<td>0</td>
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<td>Fertilizer (kg)</td>
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Table 2. Impacts of weather and production inputs on natural log of tea production, ln(kg)

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

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

<table>
<thead>
<tr>
<th>Variables</th>
<th>Parameter estimates</th>
<th>P- values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean temperature (°C)</td>
<td>-0.0461</td>
<td>(0.0000)***</td>
</tr>
<tr>
<td>Rainfall (mm)</td>
<td>-0.0001</td>
<td>(0.0102)**</td>
</tr>
<tr>
<td>Wet days</td>
<td>0.0352</td>
<td>(0.0817)*</td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td>-0.0170</td>
<td>(0.0438)**</td>
</tr>
<tr>
<td>Mid country dummy</td>
<td>-0.0472</td>
<td>(0.5249)</td>
</tr>
<tr>
<td>Low country dummy</td>
<td>-0.5083</td>
<td>(0.0000)***</td>
</tr>
</tbody>
</table>

Notes: Dependent variable is fixed effects. Parameter estimates and P- values are rounded to 4 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
### 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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A2 (1)</td>
<td>A2 (4)</td>
<td>A2 (7)</td>
</tr>
<tr>
<td></td>
<td>A1B (2)</td>
<td>A1B (5)</td>
<td>A1B (8)</td>
</tr>
<tr>
<td></td>
<td>B1 (3)</td>
<td>B1 (6)</td>
<td>B1 (9)</td>
</tr>
<tr>
<td>(a) Average temperature (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up country</td>
<td>-0.04921</td>
<td>-0.08539</td>
<td>-0.16971</td>
</tr>
<tr>
<td></td>
<td>(0.00054)</td>
<td>(0.00068)</td>
<td>(0.00102)</td>
</tr>
<tr>
<td></td>
<td>-0.05434</td>
<td>-0.07537</td>
<td>-0.16218</td>
</tr>
<tr>
<td>Mid country</td>
<td>-0.04930</td>
<td>-0.08549</td>
<td>-0.16964</td>
</tr>
<tr>
<td></td>
<td>(0.00107)</td>
<td>(0.00132)</td>
<td>(0.00192)</td>
</tr>
<tr>
<td></td>
<td>-0.05432</td>
<td>-0.07517</td>
<td>-0.16208</td>
</tr>
<tr>
<td></td>
<td>-0.04567</td>
<td>-0.06547</td>
<td>-0.11122</td>
</tr>
<tr>
<td></td>
<td>(0.000129)</td>
<td>(0.00134)</td>
<td>(0.00214)</td>
</tr>
<tr>
<td></td>
<td>-0.04569</td>
<td>-0.06549</td>
<td>-0.11122</td>
</tr>
<tr>
<td>Low country</td>
<td>-0.04953</td>
<td>-0.08580</td>
<td>-0.17026</td>
</tr>
<tr>
<td></td>
<td>(0.00135)</td>
<td>(0.00156)</td>
<td>(0.00216)</td>
</tr>
<tr>
<td></td>
<td>-0.05444</td>
<td>-0.07552</td>
<td>-0.16294</td>
</tr>
<tr>
<td></td>
<td>-0.04575</td>
<td>-0.06594</td>
<td>-0.11189</td>
</tr>
<tr>
<td></td>
<td>(0.000128)</td>
<td>(0.00146)</td>
<td>(0.00233)</td>
</tr>
<tr>
<td></td>
<td>-0.05475</td>
<td>-0.06594</td>
<td>-0.11189</td>
</tr>
<tr>
<td>(b) Total annual rainfall (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up country</td>
<td>-0.01348</td>
<td>-0.02778</td>
<td>-0.06046</td>
</tr>
<tr>
<td></td>
<td>(0.00030)</td>
<td>(0.00035)</td>
<td>(0.00066)</td>
</tr>
<tr>
<td></td>
<td>-0.02219</td>
<td>-0.03103</td>
<td>-0.05574</td>
</tr>
<tr>
<td></td>
<td>(0.00041)</td>
<td>(0.00035)</td>
<td>(0.00069)</td>
</tr>
<tr>
<td></td>
<td>-0.00480</td>
<td>-0.02201</td>
<td>-0.05129</td>
</tr>
<tr>
<td></td>
<td>(0.00011)</td>
<td>(0.00009)</td>
<td>(0.00065)</td>
</tr>
<tr>
<td>Mid country</td>
<td>-0.01487</td>
<td>-0.02931</td>
<td>-0.06216</td>
</tr>
<tr>
<td></td>
<td>(0.00104)</td>
<td>(0.00138)</td>
<td>(0.00214)</td>
</tr>
<tr>
<td></td>
<td>-0.02238</td>
<td>-0.03169</td>
<td>-0.05771</td>
</tr>
<tr>
<td></td>
<td>(0.00137)</td>
<td>(0.00065)</td>
<td>(0.00224)</td>
</tr>
<tr>
<td></td>
<td>-0.00540</td>
<td>-0.02218</td>
<td>-0.05338</td>
</tr>
<tr>
<td></td>
<td>(0.00026)</td>
<td>(0.00025)</td>
<td>(0.00224)</td>
</tr>
<tr>
<td>Low country</td>
<td>-0.01569</td>
<td>-0.03062</td>
<td>-0.06263</td>
</tr>
<tr>
<td></td>
<td>(0.00098)</td>
<td>(0.00140)</td>
<td>(0.00253)</td>
</tr>
<tr>
<td></td>
<td>-0.02378</td>
<td>-0.03147</td>
<td>-0.05837</td>
</tr>
<tr>
<td></td>
<td>(0.00162)</td>
<td>(0.00076)</td>
<td>(0.00260)</td>
</tr>
<tr>
<td></td>
<td>-0.00630</td>
<td>-0.02224</td>
<td>-0.05441</td>
</tr>
<tr>
<td></td>
<td>(0.00014)</td>
<td>(0.00031)</td>
<td>(0.00258)</td>
</tr>
<tr>
<td>(c) Aggregate impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up country</td>
<td>-0.06269</td>
<td>-0.11317</td>
<td>-0.23017</td>
</tr>
<tr>
<td></td>
<td>(0.00040)</td>
<td>(0.00064)</td>
<td>(0.00071)</td>
</tr>
<tr>
<td></td>
<td>-0.07653</td>
<td>-0.10640</td>
<td>-0.21792</td>
</tr>
<tr>
<td></td>
<td>(0.00040)</td>
<td>(0.00046)</td>
<td>(0.00084)</td>
</tr>
<tr>
<td></td>
<td>-0.05049</td>
<td>-0.08745</td>
<td>-0.16248</td>
</tr>
<tr>
<td></td>
<td>(0.00066)</td>
<td>(0.00051)</td>
<td>(0.00073)</td>
</tr>
<tr>
<td>Mid Country</td>
<td>-0.06418</td>
<td>-0.1148</td>
<td>-0.23180</td>
</tr>
<tr>
<td></td>
<td>(0.00064)</td>
<td>(0.00086)</td>
<td>(0.00131)</td>
</tr>
<tr>
<td></td>
<td>-0.07770</td>
<td>-0.10686</td>
<td>-0.21979</td>
</tr>
<tr>
<td></td>
<td>(0.0008)</td>
<td>(0.00081)</td>
<td>(0.00145)</td>
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<tr>
<td></td>
<td>-0.05107</td>
<td>-0.08766</td>
<td>-0.16459</td>
</tr>
<tr>
<td></td>
<td>(0.00112)</td>
<td>(0.00086)</td>
<td>(0.00154)</td>
</tr>
<tr>
<td>Low country</td>
<td>-0.06521</td>
<td>-0.11642</td>
<td>-0.23289</td>
</tr>
<tr>
<td></td>
<td>(0.0005)</td>
<td>(0.00047)</td>
<td>(0.00096)</td>
</tr>
<tr>
<td></td>
<td>-0.07822</td>
<td>-0.107</td>
<td>-0.22132</td>
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<td>(0.00081)</td>
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<td></td>
<td>-0.05205</td>
<td>-0.08818</td>
<td>-0.16630</td>
</tr>
<tr>
<td></td>
<td>(0.00146)</td>
<td>(0.00086)</td>
<td>(0.00121)</td>
</tr>
</tbody>
</table>

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.
Fig. 1 Sample locations (displayed using dots) and agro-ecological regions (indicated by letters, using the designations of Punyawardena et al. 2003)
Chapter 4 The impact of climate change on labour demand in the plantation sector: the case of tea production in Sri Lanka
STATEMENT OF CONTRIBUTION TO CO-AUTHORED
PUBLISHED PAPER

This chapter includes a co-authored paper. The bibliographic details of the co-authored paper, including all authors, are:


My contribution to the paper involved:

Data collection, data preparation, data analysis, preparation of tables and figures and writing and compilation of manuscript.

(Signed) __________________________ (Date) 08 - 02 - 2018
R P Dayani Gunathilaka

(Countersigned) __________________________ (Date) 08 - 02 - 2018
Corresponding author of paper: R P Dayani Gunathilaka

(Countersigned) __________________________ (Date) 08 - 02 - 2018
Principal Supervisor: Associate Prof. James C R Smart

8th February 2018

This Chapter is an exact copy of the revised manuscript referred to above.
Foreword

The chapter that follows links the impact of climate change on another important aspect of the perennial plantation tree crop sector in developing country context: labour demand. Plantation agriculture remains a major employment provider for millions of people in rural areas in developing countries. Given the adverse impact of climate change on tea production in Sri Lanka’s tea plantation sector identified in the previous chapter, the current chapter quantifies the direct and indirect links between climate and labour demand in Sri Lanka’s tea plantations under climate change. Specifically, this chapter also employs a primary panel data set from a representative balanced panel of 35 tea estates over the period 2002-2014. To the author’s knowledge, this chapter is the first study that implements a profit function approach in a structural model using panel data to assess the impact of climate change on labour demand in plantation agriculture. More broadly, this chapter estimates labour demand under different climate scenarios over short-term and medium-term time horizons. The investigation also provides useful information to policy makers on potential welfare aspects of changing labour demand on the plantation community, which is mainly comprised of women workers.
The impact of climate change on labour demand in the plantation sector: the case of tea production in Sri Lanka

Abstract

Limited opportunities for crop switching, lengthy pre-harvesting periods, as well as the labour- and land-intensive nature of plantation crops, make the plantation sector particularly vulnerable to climate change. Surprisingly, however, the economic consequences of climate change on plantation crops are seldom analysed. This study employs a single-output profit function to estimate climate change impacts on labour demand in the tea plantation sector in Sri Lanka. Drawing on a unique primary panel dataset from a representative cross-section of 35 tea estates over the period 2002-2014, this study implements a structural model of estate profit maximisation based on a normalized-quadratic functional form. Estimated elasticities are used to quantify how labour demand is affected under predicted climate change. Our results show a negative relationship between rainfall in the south-west monsoon, north-east monsoon and the second inter-monsoon, and labour demand. In contrast, we find a positive relationship between rainfall in the first inter-monsoon and labour demand. Overall, the absolute impact of predicted changes in rainfall reduce labour demand by approximately 1,175,000 person days per year across the 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:
perennial crop, farm-level, profit function, seemingly unrelated regression, structural 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 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, Baten et al. 2010, Boehm et al. 2016).

Land managers attempt to maximise profits by adjusting levels of input use. This can be considered an adaptation strategy in the face of climate change. In plantation crop agriculture, land managers’ optimisation decisions are constrained due to limited opportunities for crop switching owing to the long-term nature of investments compared to annual cropping. In addition, the relatively long pre-harvesting period and the labour- and land-intensive nature of plantation crops compared to annual crops may also limit options for adjusting input levels. Production of plantation crops would also be expected to be relatively less elastic to output and input prices. This is because 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, Lobell et al. 2006).

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. Tea has been the
largest (by value) agricultural export of Sri Lanka over many decades (Wijeratne 1996, Ganewatta et al. 2005) and although the relative contribution of the industry to the national economy has declined from 17 per cent of GDP in the 1950s to around one per cent currently, foreign exchange earnings from tea remain a vital component of the economy (Herath and Weersink 2009, Central Bank of Sri Lanka 2014). For example, 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).

Secondly, the sector is an important source of employment for rural communities. The industry employs approximately 600,000 people, about seven per cent of the country’s labour force (Central Bank of Sri Lanka 2014), and over one million people are dependent on the industry for their livelihood. Sri Lanka’s tea-plantation sector is also unique in terms of its organization 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 percent 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.

A third reason why it is important to investigate climate change impacts on the Sri Lankan tea sector is that climate change and climate variability have become 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. 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)

“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)

This suggests that the sector has become more susceptible to changing weather patterns, primarily due to rain-fed management and the perennial nature of the crop. The Climate Change in Asia: Sri Lanka country report (ADB 1994) indicates that major plantation regions in Sri Lanka will experience a 10 per cent increase in rainfall in both dry and wet seasons by 2070. 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

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30 Tea growing regions in Sri Lanka can be grouped into three categories depending on elevation. These are low-country: mean sea level to 300m, mid-country: 300 to 900m, up-country: above 900m (Fig. 1).
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. According to the IPCC, annual precipitation is predicted to increase by three per cent, seven per cent and nine per cent at the 25th, 50th and 75th percentile predictions respectively for South Asia by 2060.

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 channeling of available resources by affected parties, and for the continuing sustainability of the sector itself.

The need for information on the likely impacts of climate change on plantation crop sectors more generally is becoming more and more pressing, given the significance of these sectors in developing economies. 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 characterized by perennial cropping patterns.

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 effect panel setting. The model is estimated for a sample of thirty-five tea
estates, at annual resolution over the 13-year period from 2002-2014. IPCC IV\textsuperscript{31} projections for temperature and rainfall are applied to model findings to forecast labour demand in the tea plantation sector under climate change.

In what follows we provide a brief literature review of studies estimating the impact of weather and climate variability on agriculture; Section 3 presents the theoretical framework for our analysis; in Section 4 we provide the model and empirical specification, followed by a description of study sites and summary data statistics in Section 5. Section 6 presents results. We conclude the paper with a discussion in Section 7.

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 \textit{et al.} (1994), the 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 Deschénes 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

\textsuperscript{31}We use IPCC AR4 data for predictions because downscaled data for Sri Lanka from IPCC AR5 are only available at coarse resolution.
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 (Pischke and Velling 1997, Hujer et al. 2006).

Several studies have used a structural profit function approach to explain farmer’s optimizing behaviour when confronted with changes in institutional and environmental factors. Examples include studies by Abrar and Morrissey (2006), Fezzi and Bateman (2011), Fisher and Munro (1983), Fisher and Wall (1990), Kherallah and Govindan (1999), Lang (2001), Mullen et al. (2009), Roberts (1989) and Suleiman (2001). These studies build upon the profit function with fixed endowments to derive input demand and output supply equations as a system. The approach we adopt here is similar, 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-form 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:

\[ \pi(p, w, z) = \max \{ py - wx : y \in Y(x, z) \} \]  

where \( \pi \) is maximised profit associated with competitive output price \( p \), a vector of exogenous input prices \( w \) for a vector of input factors \( x \), and a set of fixed or environmental factors (weather and land) \( z \). \( y \) is the output, and \( Y(x, z) \) 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:

\[ -x_i = \frac{\partial \pi}{\partial w_i} \]  

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, \( p \):

\[ y = \frac{\partial \pi}{\partial p} \]
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, 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:

\[
\overline{\pi}_{nt} = \alpha_n + \sum_{i=1}^{l-1} \beta_i \overline{w}_{ti} + \beta_o \overline{p}_{nt} + \sum_{g=1}^{G} \beta_g z_{ntg} + \sum_{i=1}^{l-1} \frac{1}{2} \beta_{ii} \overline{w}_{ti}^2 + \frac{1}{2} \beta_{oo} \overline{p}_{nt}^2
\]

\[ + \frac{1}{2} \sum_{g=1}^{G} \beta_{gg} z_{ntg}^2 + \sum_{i=1}^{l-1} \sum_{j=1}^{l-1} \beta_{ij} \overline{w}_{ti} \overline{w}_{tj} + \sum_{i=1}^{l-1} \beta_{io} \overline{w}_{ti} \overline{p}_{nt} + \sum_{i=1}^{l-1} \sum_{g=1}^{G} \beta_{ig} \overline{w}_{ti} z_{ntg} \]

\[ + \sum_{g=1}^{G} \beta_{og} \overline{p}_{nt} z_{ntg} \]  \[4\]

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. \( \overline{\pi}, \overline{p}, \text{and} \overline{w} \) are estate-specific profit, estate-specific output price, and input prices, all normalised by fuel price \( (w_f) \), the numeraire. The \( \alpha_n \) denotes a fixed effect for estate \( n \).

By applying Hotelling’s Lemma, the system of input demand equations is as follows:

\[
-x_i = \frac{\partial \overline{\pi}}{\partial \overline{w}_i} = \beta_i + \beta_o \overline{p}_{nt} + \beta_{ii} \overline{w}_{ti} + \sum_{j=1}^{l-1} \beta_{ij} \overline{w}_{tj} + \sum_{g=1}^{G} \beta_{ig} z_{ntg} \]  \[5\]

\((i=\text{labour, fertilizer, and electricity})\)
The $x_i$ here are the input demands for labour, fertiliser and electricity. The output supply equation is:

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

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:
\[
\begin{align*}
\bar{\pi}_{nt} &= f_1(\bar{p}_{nt}, \bar{w}_{ti}, \bar{z}_{ntg}; \beta_1), \alpha_{1,n}, u_{1,nt} \\
x_{fertilizer,nt} &= f_2(\bar{p}_{nt}, \bar{w}_{ti}, \bar{z}_{ntg}; \beta_2), \alpha_{2,n}, u_{2,nt} \\
x_{labor,nt} &= f_3(\bar{p}_{nt}, \bar{w}_{ti}, \bar{z}_{ntg}; \beta_3), \alpha_{3,n}, u_{3,nt} \\
x_{electricity,nt} &= f_4(\bar{p}_{nt}, \bar{w}_{ti}, \bar{z}_{ntg}; \beta_4), \alpha_{4,n}, u_{4,nt} \\
x_{tea,nt} &= f_5(\bar{p}_{nt}, \bar{w}_{ti}, \bar{z}_{ntg}; \beta_5), \alpha_{5,n}, u_{5,nt}
\end{align*}
\]

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 [7], together with relevant data and fitted values, are used to construct price elasticities (\(\epsilon\)) for profit, input demands and output supply with respect to input prices, the output price, and the different components of weather:

Elasticities of profit w.r.t. prices:
\[\epsilon_{\pi w_i} = \frac{\partial \pi}{\partial w_i} \cdot \pi, \quad \epsilon_{\pi p} = \frac{\partial \pi}{\partial p} \cdot p\]  

[8a]

Elasticities of profit w.r.t. weather:
\[\epsilon_{\pi z_g} = \frac{\partial \pi}{\partial z_g} \cdot \pi\]  

[8b]

Elasticities of input demands w.r.t. prices:
\[\epsilon_{x_i w_j} = \frac{\partial x_i}{\partial w_j} \cdot \frac{w_j}{x_i}, \quad \epsilon_{x_i p_n} = \frac{\partial x_i}{\partial p} \cdot \frac{p}{x_i}\]  

[8c]

Elasticities of input demands w.r.t. weather:
\[\epsilon_{x_i z_g} = \frac{\partial x_i}{\partial z_g} \cdot \frac{z_g}{x_i}\]  

[8d]

Elasticities of output supply w.r.t. prices:
\[\epsilon_{y w_j} = \frac{\partial y}{\partial w_j} \cdot \frac{w_j}{y}, \quad \epsilon_{y p} = \frac{\partial y}{\partial p} \cdot \frac{p}{y}\]  

[8e]

Elasticities of output supply w.r.t. weather:
\[\epsilon_{y z_g} = \frac{\partial y}{\partial z_g} \cdot \frac{z_g}{y}\]  

[8f]

Confidence intervals and significance levels for elasticities are obtained using non-parametric 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 [9], in which $\Delta z_{ng}$ 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 $\varepsilon_{\text{labour},z_g}$ denotes the elasticity of labour with respect to the relevant weather driver $g$.

$$\Delta x_{\text{labour},n} = \Delta z_{ng} \cdot \frac{\text{Labour}_n}{z_{ng}} \cdot \varepsilon_{\text{labour},z_g}$$

[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. These records provide information on estate-specific profits, tea price, expenditures on fertiliser, fuel and electricity, quantity of processed tea produced, person days labour input, rainfall, number of rainfall days (wet days) and elevation. Prices of labour, fertiliser, fuel, and electricity, and temperature data are obtained from relevant sources as described below. The 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-, Mid- and Up-country, the elevations of which are from sea level to 300m, between 300m

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32Tea 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.
and 900m, and above 900m respectively. The data panel comprises a cross section of 35 estates (Fig. 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 (person day). A national tea factory electricity price was calculated using as 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 meter 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 \( t \).

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\(^{33}\). Following the literature

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\(^{33}\) Rainfall is recorded daily by rain gauges on each estate and logged as part of routine estate record keeping.
(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 since tea estates do not record temperature data\textsuperscript{34} (Fig. 2).

[insert Fig.2 about here]

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 (1,200m 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 (Fernando and Wickramasuriya 2011, 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 receive rainfall, whereas the

\textsuperscript{34} Typically four to six estates share temperature data from the same weather station.
eastern side of the hills receive only dry winds. In contrast, the NE monsoon affects the entire island. The largest proportion of rainfall is received during this season.

Considering the delayed effects of rainfall and wet days on tea shoot growth\(^{35}\), 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.

[insert Table 2 about here]

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 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 30km 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 30km grid points within a 40km 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

\(^{35}\)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.
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 SUR cross equation-restricted system on a total of 455 observations. The adjusted $R^2$ of the estimated profit function is 0.65. Adjusted $R^2$ results for the input demand equations for labour, fertilizer, electricity and the output supply equation for processed tea are 0.94, 0.73, 0.88 and 0.94, respectively. Second order terms in labour, fertilizer 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 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 datasets.

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 (Hicks 2001, 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.

[insert Table 3 about here]
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 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 is 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 (Fig.3).

The impact of climate change on labour demand varies from estate to estate depending on 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. [insert Fig.3 about here]

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 anticipated change in SW monsoon rainfall on labour demand is predicted to approximately double between the near- 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. It should be noted, however, 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, Mouli et al. 2007). 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 two to four years from planting, 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% of annual average estate profits in our dataset 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 and by the behavioural responses of plantation workers. In regards 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, whilst the majority of days are sunny (Ranatunge et al. 2003, Fernando and Wickramasuriya 2011, 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 reduce labour demand by approximately 1,175,000 person days per year across the three tea estate regions; a reduction of 2.6%.

7.3. Implications for policy and future research

Our findings have significant policy implications as the plantation sector is 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 re-skilling 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), 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.

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Tea price (LKR/kg)</th>
<th>Labour price (LKR/person day)</th>
<th>Fertiliser price (LKR/kg)</th>
<th>Fuel price (LKR/m³)</th>
<th>Electricity price (LKR/kWh)</th>
<th>Total profit (LKR million/estate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>412.32</td>
<td>321.06</td>
<td>32.68</td>
<td>846.74</td>
<td>24.92</td>
<td>7.34</td>
</tr>
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<td>35.87</td>
<td>1245.59</td>
<td>24.78</td>
<td>2.00</td>
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<td>42.41</td>
<td>1710.93</td>
<td>23.61</td>
<td>18.51</td>
</tr>
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<td>341.00</td>
<td>42.60</td>
<td>1744.48</td>
<td>21.46</td>
<td>5.58</td>
</tr>
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<td>2007</td>
<td>493.69</td>
<td>315.00</td>
<td>46.61</td>
<td>1442.55</td>
<td>17.09</td>
<td>27.91</td>
</tr>
<tr>
<td>2008</td>
<td>413.02</td>
<td>294.00</td>
<td>63.61</td>
<td>1331.34</td>
<td>15.27</td>
<td>7.90</td>
</tr>
<tr>
<td>2009</td>
<td>503.43</td>
<td>375.74</td>
<td>62.79</td>
<td>1494.87</td>
<td>14.75</td>
<td>18.69</td>
</tr>
<tr>
<td>2010</td>
<td>458.25</td>
<td>384.18</td>
<td>43.07</td>
<td>1166.13</td>
<td>13.92</td>
<td>12.03</td>
</tr>
<tr>
<td>2011</td>
<td>393.53</td>
<td>424.79</td>
<td>32.98</td>
<td>1608.12</td>
<td>14.79</td>
<td>-14.52</td>
</tr>
<tr>
<td>2012</td>
<td>425.40</td>
<td>421.93</td>
<td>20.83</td>
<td>1354.21</td>
<td>13.74</td>
<td>6.38</td>
</tr>
<tr>
<td>2013</td>
<td>442.74</td>
<td>448.46</td>
<td>16.85</td>
<td>816.29</td>
<td>13.74</td>
<td>4.46</td>
</tr>
<tr>
<td>2014</td>
<td>427.39</td>
<td>451.63</td>
<td>18.96</td>
<td>1249.91</td>
<td>13.30</td>
<td>0.76</td>
</tr>
</tbody>
</table>

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 currency (LKR) (LKR 106.26 = AU$ 1 in December 2014) using deflation indices from the Central Bank of Sri Lanka (Central Bank of
Sri Lanka 2014). Data on output price (i.e. the price obtained for processed tea) were extracted from estates’ monthly accounts.

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

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

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; $\hat{s}(x)$ the standard deviation.
**Table 3** Estimated own-price and cross-price elasticities of input demand and output supply

<table>
<thead>
<tr>
<th>Elasticities of estate-level input demand and output supply with respect to the prices of inputs and output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{labour}}$</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Labour</td>
</tr>
<tr>
<td>Fertiliser</td>
</tr>
<tr>
<td>Electricity</td>
</tr>
<tr>
<td>Tea supply</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Labour elasticity with respect to weather variable</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWM-Rainfall</td>
<td>-0.047</td>
<td>***</td>
</tr>
<tr>
<td>NEM-Rainfall</td>
<td>-0.045</td>
<td>***</td>
</tr>
<tr>
<td>IM1-Rainfall</td>
<td>0.061</td>
<td>***</td>
</tr>
<tr>
<td>IM2-Rainfall</td>
<td>-0.042</td>
<td>***</td>
</tr>
<tr>
<td>SWM-Wet days</td>
<td>0.052</td>
<td>ns</td>
</tr>
<tr>
<td>NEM- Wet days</td>
<td>-0.0282</td>
<td>ns</td>
</tr>
<tr>
<td>IM1- Wet days</td>
<td>0.022</td>
<td>ns</td>
</tr>
<tr>
<td>IM2- Wet days</td>
<td>-0.006</td>
<td>ns</td>
</tr>
<tr>
<td>Jan-Mean temp</td>
<td>-0.111</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>------</td>
<td>----</td>
</tr>
<tr>
<td>May-Mean temp</td>
<td>0.366</td>
<td>ns</td>
</tr>
<tr>
<td>Aug-Mean temp</td>
<td>0.039</td>
<td>ns</td>
</tr>
<tr>
<td>Nov-Mean temp</td>
<td>-0.021</td>
<td>ns</td>
</tr>
<tr>
<td>Area</td>
<td>0.857</td>
<td>***</td>
</tr>
</tbody>
</table>

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.
**Fig. 1** Tea production locations in Sri Lanka, and the tea estates from which data were collected in the three different tea growing elevations.
Fig. 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 2002-2014.
Fig. 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.
References


Appendix 4-1

Can profit function approach be used for estimating climate change impacts on profits from plantation crops?

1. Introduction

Profit function of duality theory is a well-documented tool for estimating farm profits incorporating impacts from environmental variables, such as rainfall and temperature (Fisher and Munro 1983, Roberts 1989, Lang 2001, Fezzi and Bateman 2011). One of the important advantages of this method is its ability to retrieve elasticities of profits, input demand and output supply within agricultural production technologies. To date, however, this method has been applied only to estimate elasticities of profits, input demands and output supply for annual or short-term farming systems. In this note we employ a structural model derived from the profit function to analyse elasticities of profits from perennial plantation crops with respect to different elements of weather. Based on a case study on tea plantations in Sri Lanka, we argue that it will typically be problematic to use elasticities derived from profit function-based structural models to evaluate the impacts of changes in weather on profits from plantation crops that sell into the world market. In particular, it may not be appropriate to use profit function approaches to determine profit elasticities with respect to changing climate for plantation crops for which harvesting cost comprises a major proportion of production cost, and where there is a requirement to harvest to ensure yield and quality in subsequent growth seasons, irrespective of the prevailing market price for the output. Tea, our case study crop, is a prominent such example, although viticulture shares many of the same features. In such settings, we argue, it may be more appropriate to use well established production function approaches to quantify the impacts of climate change on production and then, subsequently, employ scenario-based analyses to quantify potential impacts on profits. We illustrate our proposal with an empirical application that derives weather elasticities via a profit function approach on data from a sample of 35 tea estates (primary decision-making units) from all tea growing regions of Sri Lanka. This study is presented as an Appendix to Chapter 4 of the main thesis.
2. The structural model of profit maximisation

Employing duality theory outlined by Lau and Yotopoulos (1972) to a multi-input, single-output profit function for the perennial cropping tea production system in Sri Lanka, we derive elasticities of profits with respect to weather variables via differentiation.

The profit maximisation problem confronting tea estates regards land and weather variables as fixed inputs or endowments. Here we use \( y \) to indicate the single plantation output (tea), \( p \) to indicate the competitive output price, \( w \) the vector of exogenous input prices, \( x \) the vector of input quantities and \( z \) the vector of fixed or environmental factors (e.g. land, temperature and rainfall). The single output profit function along with environmental factors (i.e. weather variables) can be written as:

\[
\pi(p, w, z) = \max\{py - wx : y \in Y(x, z)\}
\]  

where \( Y(x, z) \) indicates producible output combinations. Here, the profit function is homogenous of degree one and convex in input and output prices. Applying Hotelling’s Lemma (Hotelling 1932), we derive profit maximising levels of variable inputs and the plantation output.

\[ -x_i = \frac{\partial \pi}{\partial w_i} \]  
\[ y = \frac{\partial \pi}{\partial p} \]

3. The empirical illustration

The empirical model is specified as a normalised quadratic function because of several important advantages over alternative specifications such as translog, 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 (which comprise 35% of the dataset) (Fezzi and Bateman 2011 The normalised quadratic profit function is specified as:
\[ \bar{\pi}_{nt} = \alpha_n + \sum_{i=1}^{l-1} \beta_i \bar{w}_{ti} + \beta_o \bar{p}_{nt} + \sum_{g=1}^{G} \beta_g z_{ntg} + \frac{1}{2} \sum_{i=1}^{l-1} \beta_{ii} \bar{w}_{ti}^2 + \frac{1}{2} \beta_{oo} \bar{p}_{nt}^2 \\
+ \frac{1}{2} \sum_{g=1}^{G} \beta_{gg} z_{ntg}^2 + \sum_{i=1}^{l-1} \sum_{j=1}^{l-1} \beta_{ij} \bar{w}_{ti} \bar{w}_{tj} + \sum_{i=1}^{l-1} \beta_{io} \bar{w}_{ti} \bar{p}_{nt} + \sum_{i=1}^{l-1} \sum_{g=1}^{G} \beta_{ig} \bar{w}_{ti} z_{ntg} \\
+ \sum_{g=1}^{G} \beta_{og} \bar{p}_{nt} z_{ntg} \]

where \( n \) indexes estates, \( i \) indexes the inputs (labour, fertilizer and electricity), \( t \) indexes time in years and \( g \) indexes components of estate-specific weather (monthly average temperature, seasonal total rainfall and number of wet days per season). \( \bar{\pi}, \bar{w} \) and \( \bar{p} \) are estate-specific profit, input prices and estate-specific output price, normalised by fuel price (\( w_f \)) as a numeraire. \( \alpha_n \) is fixed effect for estate \( n \). This is the specification used in Chapter 4 to quantify impact of climate change on labour demand from tea plantations.

Equation [4] includes estate-specific fixed effects \( \alpha_n \) to counteract potential omitted variable bias that might otherwise arise due to correlations between time-varying drivers and unobserved estate-specific time invariant factors such as soil quality, geographic aspect and managerial ability.

We estimate a fully structural model, estimating the profit function simultaneously with demand functions for labour, fertiliser and electricity, and a supply function for tea, as a system of seemingly unrelated regressions (SUR). Estimating the full set of equations as an SUR system allows for potential error correlations across equations and improves the efficiency of parameter estimates by imposing cross-equation restrictions (Zellner 1962). The separate equations in the SUR system are all specified in least squares dummy variable (LSDV) format, using the estate-specific dummy variables \( \alpha_n \) to implement the fixed effects transformation.

The impact of climate change on profit can be quantified by estimating the elasticities of profit with respect to the separate components of weather. The elasticity of profit for estate \( n \) with respect to a particular component of weather \( g \) can be written as:

\[ e_{z_{ng}}^{\pi_n} = k_{ng} \cdot z_{ng} \frac{\bar{\pi}_n}{\pi_n} \]
Where $k_{ng}$ denotes the partial derivative of the profit function with respect to the relevant component of weather $g$, evaluated under conditions relevant to estate $n$:

$$k_{ng} = \frac{\partial \pi_n}{\partial z_{ng}} = \beta_g + \beta_{gg} z_{ntg} + \sum_{i=1}^{l} \beta_{ig} \bar{w}_{it} + \beta_{og} \bar{p}_{nt} \quad [6]$$

The elasticity of profit with respect to a particular component of weather for a particular estate can be constructed from [5] and [6] using estimated regression coefficients from the profit function [4] together with data detailing weather, input prices and the tea price for the relevant estate $(n)$. The change in estate-specific profits $\Delta \pi_n$ resulting from predicted climate change can then be estimated using localised predictions of the anticipated change in seasonal rainfall, number of wet days and temperature $\Delta z_{ng}$ via:

$$\Delta \pi_n = \Delta z_{ng} \cdot \frac{\pi_n}{z_{ng}} \cdot \epsilon_{z_{ng}} \quad [7]$$

Confidence intervals and significance levels for elasticities of profit with respect to the different components of weather can be obtained using non-parametric bootstrap techniques, following Laukkanen and Nauges (2014). Bootstrap re-sampling should be clustered by estate.

It is important to note the range of factors which affect the market price for tea from a Sri Lankan tea estate, and thus impact on tea estate profits, *ceteris paribus*. As noted earlier, because tea is an internationally marketed commodity, estate-specific tea prices are affected by exogenous factors such as the political and economic situation in tea-buying countries, and the levels and qualities of tea produced by other major tea-exporting countries (e.g. Kenya, China). However, these exogenous influences on estate-specific tea price, and hence on estate-specific profits, are not included in our regression system because relevant data are not available.

### 4. Data

This study uses a primary data collected from the monthly accounts and log books of tea estates. The dataset was used in Chapter 4 to assess the impact of climate change on labour demand in the tea plantation sector in Sri Lanka using the same structural model of profit maximisation. Details of the variables used and descriptive statistics are provided in Chapter 4.
5. Results and Discussion

The structurally-linked equations for profit, input demands and output supply were estimated as a fixed effects-transformed SUR cross equation-restricted system on a total of 455 observations (35 estates across 13 years). The adjusted $R^2$ of the estimated profit function is 0.65. Adjusted $R^2$ results for the input demand equations for labour, fertilizer, electricity and the output supply equation for processed tea are 0.94, 0.73, 0.88 and 0.94, respectively. Second order terms in labour, fertilizer and tea price in the profit function are not statistically different from zero, satisfying the condition for convexity in prices.

Table 1 reports estimated elasticities of profit with respect to input prices, output price, estate area and the separate components of weather. Profit elasticities with respect to the two key input prices (labour and electricity) and the output price are strongly significant and have the expected signs.

**Table 1** Elasticities of profits with respect to input prices, output price, components of weather and estate area

<table>
<thead>
<tr>
<th>Variable</th>
<th>Elasticity</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour price</td>
<td>-3.416</td>
<td>***</td>
</tr>
<tr>
<td>Fertiliser price</td>
<td>0.169</td>
<td>ns</td>
</tr>
<tr>
<td>Electricity price</td>
<td>-1.094</td>
<td>***</td>
</tr>
<tr>
<td>Tea price</td>
<td>7.453</td>
<td>***</td>
</tr>
<tr>
<td>SWM-Rainfall</td>
<td>0.045</td>
<td>ns</td>
</tr>
<tr>
<td>NEM-Rainfall</td>
<td>0.170</td>
<td>***</td>
</tr>
<tr>
<td>IM1-Rainfall</td>
<td>0.521</td>
<td>***</td>
</tr>
<tr>
<td>IM2-Rainfall</td>
<td>-0.054</td>
<td>ns</td>
</tr>
</tbody>
</table>

36 The $R^2$ results include the impact of the estate-specific dummy variables in each of the regressions.
Among the weather variables considered, inter-monsoon 1 rainfall, North-East monsoon rainfall, inter-monsoon 2 wet days, January and August mean temperature have statistically significant effect on the profits of tea estates. The elasticity of profits with respect to inter-monsoon 1 rainfall is as expected, with a 1% increase in inter-monsoon1 rainfall increasing profit by 0.5%. This can be explained by the characteristics of inter-monsoon 1 rainfall. This period of the year is characterised by sunny days with evening showers. This results in both high production with the desired high quality, compared to wet seasons such as the South-West and North-East monsoons. The magnitude of the elasticity of estate profits with respect to North-East monsoon rainfall is relatively low compared to that of inter-monsoon 1 rainfall, implying that a 1% increase in North-East monsoon rainfall increases annual profits by 0.17%. Higher rainfall, ceteris paribus number of wet days, will result in more cloud cover and therefore fewer hours of sunshine. Insufficient sun retards tea shoot growth. Higher rainfall results in higher soil moisture, leading to higher water content in the tea leaves. Both these factors reduce the quality of the end product, leading to lower prices for produced tea. Among
the wet days variables, the elasticity of profits with respect to inter-monsoon 2 is significant and negative, however very large in magnitude. This is probably because inter-monsoon 2 is also a favourable season for tea production characterised by both adequate sunshine and soil moisture so an increase in the number of wet days reduces profits from tea. Turning to the elasticities of profits with respect to temperature, January and August show statistically significant results. However, magnitudes of these elasticities are unexpectedly large.

Many of the profit elasticity estimates with respect to weather are not statistically significant. Also, mean estimates for several elasticities are large. This might be explained as follows. Tea price has a major effect on whether an estate makes positive or negative profit. Tea prices on the Colombo auction are driven mainly by international variations in tea supply and demand, so tea price is largely exogenous to individual estates (smaller price movements which reflect managerially-induced variations in quality of the processed product are an exception to this, but these have been purged from the estimation by the fixed effects transformation). Labour expenditure is invariably the largest component of production cost for tea estates (Hicks 2001). A peculiarity of plantation crops in general, which is especially prominent in tea production, is that in practice the estate manager has limited options for decreasing labour input to avoid negative profits when the tea price is low. This is because, unlike annual crops which could simply be ploughed-in rather than harvested and processed when crop prices are low, the tea crop must always be harvested to ensure production and quality are maintained through the next growth cycle. The profit outcome from a year in which the weather is conducive to high tea production is thus critically dependent on the tea price. If weather conducive to high tea production coincides with a high tea price, large expenditures on the labour necessary to bring in the harvest can easily be covered and a large profit will result. Conversely, when the tea price is low, a bumper crop is more of a curse than a blessing. Large labour expenditures will still have to be incurred to ensure production and quality into the future, even if these expenditures cannot be covered by the sale of processed tea.

In essence, when the tea price drops below the breakeven point this can completely reverse the apparent effect of weather on profits. The numerically large, but statistically insignificant, estimates of the mean elasticity of profit with respect to several of the weather variables in Table 1 are likely a consequence of this phenomenon. The effects of weather on production
and labour remain visible, however, because these relationships are not disrupted by the impact of an exogenous tea price (refer to Chapters 3 and 4 of the thesis).

Despite these difficulties, our study does identify sensible impacts from monsoonal rainfall, inter-monsoonal rainfall, inter-monsoonal wet days and January and August mean temperatures on profits. Estate-level profits remain very heavily influenced by the exogenous tea price because of the requirement to harvest mature tea continually to ensure that production capability and quality are maintained for future seasons. Consequently, our model finds it quite difficult to identify the effects of weather on profits because the impact of a bumper crop on profits depends crucially on the (exogenous) tea price. However, the dataset contains strong linkages between the different components of weather and tea production, and between the different components of weather and labour demand. These linkages are quantified through the production function analysis of Chapter 3 and the labour demand analysis of Chapter 4.

**Conclusion**

We show that profit function approach may not be appropriate tool to predict the impact of climate change on the profits of Sri Lankan tea estates. We suggest that this situation arises because of the tea crop must always be harvested – even when the exogenously determined tea price is low – to ensure production and quality are maintained through the next growth cycle, and because the labour required for harvesting comprises the largest component of production costs. Using primary data from 35 tea estates in Sri Lanka, we empirically illustrate that whilst a profit function-derived structural model is able to elucidate the link between weather variables and labour demand, it is unable to convincingly identify a link between all components of weather and profits. As such, it may be more appropriate to use the well-established production function approach to quantify the impact of climate change on tea production and then apply scenario-based analysis to estimate consequent impacts on profit.

The key conditions that give rise to this situation (harvesting cost comprising a major proportion of production cost, and the requirement to harvest to ensure yield and quality in subsequent growth seasons, irrespective of the prevailing exogenously-determined market price) are shared by other perennial plantation crops such as palm oil (Morcillo et al. 2013). The challenge identified here may therefore also be relevant to other economically important perennial plantation crops across the developing world.
References


Chapter 5 Adaptation to climate change in perennial cropping systems: options, barriers and policy implications
STATEMENT OF CONTRIBUTION TO CO-AUTHORED PUBLISHED PAPER

This chapter includes a co-authored paper. The bibliographic details of the co-authored paper, including all authors, are:


My contribution to the paper involved:

Data collection, data preparation, data analysis, preparation of tables and figures and writing and compilation of manuscript.

(Signed) __________________________ (Date) 08 - 02 - 2018
R P Dayani Gunathilaka

(Countersigned) __________________________ (Date) 08 - 02 - 2018
Corresponding author of paper: R P Dayani Gunathilaka

(Countersigned) __________________________ (Date) 08 - 02 - 2018
Principal Supervisor: Associate Prof. James C R Smart

This Chapter is an exact copy of the journal article referred to above.
Foreword

The final result chapter of the thesis that follows analyses tea estate managers’ perception on climate change, identifying factors affecting their adaptation to climate change, barriers for adaptation and associated policy implications. Plantation crops raise special economic issues compared to annuals, owing to long pre-harvesting period and the scale of the initial investment required for establishment. Impact of climate change has become a significant concern given the limited opportunities for crop switching for the above-mentioned reasons. This chapter takes the advantage of data collected from in-depth semi-structured interviews of tea estate managers regarding climate adaptation, as an example of decision makers of perennial plantation tree cropping units. Hence, the findings of this chapter have the important information for policy makers for the plantation agriculture sector of developing country context.
Adaptation to climate change in perennial cropping systems: Options, barriers and policy implications

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ABSTRACT

Plantation crops are likely to be highly vulnerable to climate change because of their long economic life span, their typically non-irrigated cropping patterns and the inability to easily switch crops due to high upfront capital costs. Hence the sector requires appropriately designed adaptation options to cope with on-going climate change. Studies on climate adaptation in perennial cropping systems are rare relative to those on annual crops. Based on a cross-sectional survey of 90 tea estate managers representing all tea growing areas in Sri Lanka, this study analyses factors affecting choice of preferred adaptation options, barriers to adaptation and associated policy implications for tea production as an example of a perennial tree crop system. Current adaptation options identified are crop diversification, self-reseeds, and shade trees establishment and management. All of these options are adopted in some situations and locations. All estate managers interviewed believe that climate change is happening and almost all are experiencing the negative impacts of climate change on tea production. Results from a multinomial logit analysis show that information on climate change, company size, tea growing elevation, and increase in temperature and rainfall are key factors influencing the preferred choice of adaptation option. Furthermore, results reveal that barriers such as lack of capital, inadequate access to non-rural and medium-term climate knowledge, and poor governmental and institutional support may prevent estate managers from experimenting with new adaptation options. Policies should, therefore, be aimed at promoting new adaptation options through information exchange between a wide range of stakeholders, and integrating climate change adaptation with Sri Lanka’s sustainable development goals. Governmental and institutional support and involvement would be instrumental in facilitating adoption of adaptation options such as dual-production of tea with valuable timber crops.

1. Introduction

Adaptation can be considered to be the search for ‘a better fit’ to changed conditions (Arthur and Van Kooten, 1992; Smit et al., 2005), and can be either incremental (‘tinkering around the edges’ of current practices), or transformative (deeper, more structural changes) (Moser and Eklundh, 2010). Effective adaptation to the particular stressors imposed by climate change is likely to require the latter approach (Richards and Howden, 2012). Transformative change is particularly challenging for the perennial plantation sector. The establishment of plantation crops is a lengthy process requiring considerable capital investment, particularly in comparison to annual crops. This typically constrains options for climate change adaptation such as crop switching (Burton and Lim, 2006; Lobell et al., 2006; Lobell and Field, 2011). In addition, plantation crops such as tea, rubber and coconut are typically rain-fed (non-irrigated). The distinct differences between annual and perennial crop farming, and the important role which perennial cropping plays in developing world agriculture, suggest that it is important to understand the factors which affect farmers’ choice of climate adaptation options in both annual and perennial crop farming.

Agrawal and Perrin (2009) argue that adaptation can happen from the top-down through changes in policies and institutions, and from the bottom-up via individual farm-level responses. Thus, agricultural adaptation can result from an intentional proactive or reactive response to any risk or change which modifies the business environment (Bayley et al., 2003). Many studies have analysed factors affecting farmers’ choice of climate adaptation options in annual crop and livestock production systems in different parts of the world. Sea and Mendelssohn

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Abstract

Plantation crops are likely to be highly vulnerable to climate change because of their long economic life span, their typically non-irrigated cropping pattern and the inability to easily switch crops due to high upfront capital costs. Hence the sector requires appropriately designed adaptation options to cope with on-going climate change. Studies on climate adaptation in perennial cropping systems are rare relative to those on annual crops. Based on a cross-sectional survey of 50 tea estate managers representing all tea growing areas in Sri Lanka, this study analyses factors affecting choice of preferred adaptation options, barriers to adaptation and associated policy implications for tea production as an example of a perennial tree crop system. Current adaptation options identified are crop diversification, soil conservation, and shade tree establishment and management. All of these options are adopted in some situations and locations. All estate managers interviewed believe that climate change is happening and almost all are experiencing the negative impacts of climate change on tea production. Results from a multinomial logit analysis show that information on climate change, company size, tea growing elevation, and increases in temperature and rainfall are key factors influencing the preferred choice of adaptation option. Furthermore, results reveal that barriers such as a lack of capital, inadequate access to near-term and medium-term climate knowledge, and poor governmental and institutional support may prevent estate managers from experimenting with new adaptation options. Policies should, therefore, be aimed at promoting new adaptation options through information exchange between a wide range of stakeholders, and integrating climate change adaptation with Sri Lanka’s sustainable developmental goals. Governmental and institutional support and involvement would be instrumental in facilitating adoption of adaptation options such as joint-production of tea with valuable timber crops.

Keywords: Climate adaptation, tea plantations, Sri Lanka, crop diversification, multinomial logit model, interviews
1. Introduction

At its broadest, adaptation can be considered to be the search for ‘a better fit’ to changed conditions (Arthur & Van Kooten, 1992; Smit et al., 2000). Adaptation to the particular stressors imposed by climate change is a relatively lengthy process and often demands substantial investment, in particular when it comes to perennial plantation crops with productive life spans of multiple decades (Lobell & Field, 2011). The establishment of plantation crops requires considerable capital investment and compared to annual crops, this typically constrains options for climate change adaptation such as crop switching (Burton & Lim, 2005; Lobell et al., 2006). In addition, plantation crops such as tea, rubber and coconut are typically rain-fed (non-irrigated). The distinct differences between annual and perennial crop farming, and the important role which perennial cropping plays in developing world agriculture, suggest that it is important to understand the factors which affect farmers’ choice of climate adaptation options in both annual and perennial crop farming.

Agrawal and Perrin (2009) argue that adaptation can happen from the top-down through changes in policies and institutions, and from the bottom-up via individual farm-level responses. Thus, agricultural adaptation can result from an intentional proactive or reactive response to any risk or change which modifies the business environment (Bryant et al., 2000). Many studies have analysed factors affecting farmers’ choice of climate adaptation options in annual crop and livestock production systems in different parts of the world. Seo and Mendelsohn (2008) estimate a multinomial logit model (MNL) of crop choices using data collected from 949 farmers across seven South American countries. They find that variations in temperature and rainfall are key determinants of decisions to switch between crops such as vegetables, fruits and rice. Similarly, Deressa et al. (2009) employ a MNL to identify the determinants of farmers’ choice of adaptation options under climate change in Ethiopia, based on a cross-sectional household survey of 1000 farmers. The authors find that education, gender, age, farm income, non-farm income, information on climate change, access to extension services, agro-ecological setting and temperature are significant determinants of adaptation choices. Based on a survey of 546 rice farmers, Alam (2015) explores factors affecting choice of adaptation options for water scarcity in a semi-arid region of Bangladesh. The author finds that more experience, better schooling, better access to electricity and institutional facilities, greater awareness of climate effects and secure tenure rights are key determinants of choice of alternative adaptation strategy. In a livestock farming context, Kabubo-Mariara (2008) investigate factors that affect choice of different livestock species under climate change in Kenya. The study finds that annual temperature, rainfall, age of head of household, household size and average education level of the household are the key drivers of livestock species choice.

To the best of our knowledge, no studies have yet empirically investigated the drivers of adaptation choice in perennial agriculture. Tea is an example of a perennial crop with an economic life span of about 30-50 years, and is a crop which provides a major source of revenue and employment in a number of developing countries (Alkan et al., 2009; Brouder et al., 2013). A number of studies have discussed the impact of climate change on tea production (Costa, 2010; Gunathilaka et al., 2017; Wijeratne, 1996), and whilst these studies mention potential adaptation options, they provide very little empirical analysis of the drivers of adaptation choice. To fill this knowledge gap, the present study analyses Sri Lankan tea estate managers’ perceptions of climate change impacts, factors which affect their choice of current and potential
future adaptation options, and barriers to the uptake of these options. The Intergovernmental Panel on Climate Change (IPCC) predicts increases in precipitation, temperature and extreme weather events for South Asia by 2060 (IPCC, 2013). The productivity of agricultural crops is predicted to decline, leading to increases in the vulnerability of rural communities who are dependent on agriculture for their livelihood. To the best of our knowledge, this is the first study to analyse factors affecting estate managers’ choice of climate adaptation options for plantation crops in a developing country context.

Tea is the foremost agricultural crop in Sri Lanka. The tea industry generates about 15% of national foreign exchange earnings and provides employment for about 7% of the total workforce. Over 600,000 employees and their dependents rely on the tea sector for their livelihood (Ministry of Plantation Industries, 2013). The plantation crop sector in Sri Lanka has, however, been adversely affected by changes in climate over recent decades (Central Bank of Sri Lanka, 2014; Gunathilaka et al., 2017; Wijeratne & Chandrapala, 2014). Both the larger plantation estate sector and the smallholding sector face challenges from climate change, raising questions about their long-term viability. The quantity and quality of tea are greatly influenced by climatic parameters, particularly rainfall and temperature (Boehm et al., 2016; Wijeratne et al., 2007). Therefore, in Sri Lanka there is particular concern over the tea sector’s vulnerability to climate change (Costa, 2010; Wijeratne, 1996).

Comprehensive knowledge of available adaptation options is of utmost importance if estate managers are to counteract production losses from climate change and maintain the competitiveness of Sri Lankan tea brands in the international market. This is also vital for efficient and effective channeling of available resources to address the consequences of climate change. Employing data derived from face-to-face interviews with 50 tea estate managers in Sri Lanka, this study focuses on the following research questions: (i) What are estate managers’ perceptions of climate change? (ii) Which adaptation options are estate managers currently adopting? (iii) Which factors influence the choice of preferred adaptation options? And (iv) What are the policy implications of preferred adaptation options for long-term sustainability?

The paper is structured as follows: Section 2 describes the study area, data and survey sample characteristics. Section 3 reports managers’ observations of the impacts of climate change on tea plantations. Section 4 describes a multinomial logit model of climate adaptation choice. Section 5 presents multinomial logit results. Section 6 discusses constraints on the choice of adaptation options, and Section 7 concludes with policy implications.

2. Study area and data collection

2.1. Sri Lanka’s tea sector: context and challenges

Historically, Sri Lanka’s tea plantations were owned and developed by the British, and managed by British private companies (Loh et al., 2003). Between 1972 and 1975, however, all foreign and locally-owned estates larger than 20 hectares were acquired by the government and vested under the Janatha Estate Development Board (JEDB) and the Sri Lanka State Plantations Corporation (SLSPC). JEDB and SLSPC managed 509 tea, rubber and coconut estates under the purview of the Ministry of Plantation Industries. Nationalised management through JEDB and SLSPC was not successful, and as a consequence between 1992 and 1993 the 509 estates were clustered into 23 Regional Plantation Companies (RPCs) with ownership
of these companies retained by the government. Initially, management of RPCs was based on 99 year leases, with 5 year management agreements with private agents. This short term management agreement proved insufficient to motivate adequate investment, and financial performance continued to be poor. In 1995 Government divested ownership of all RPCs to the private sector, while retaining ownership of the land on a shortened lease agreement of 50 years (Kularatne & Takeya, 2003).

Currently, there are 307 tea estates scattered across three major growing regions of the country, owned and operated by 21 different RPCs. Individual tea estates are managed centrally by a plantation company and usually possess their own processing facilities. This level of vertical integration constrains opportunities for crop switching as a climate adaptation strategy.

Further constraints on adaptation arise from the structure of the estate labour market. The estate sector operates with a large residential workforce who typically comprise Tamils originally brought from South India to Sri Lanka during British colonisation (Duncan, 2002). Labour operates under a centralized wage system, whereby plantation companies are required to increase the wages of plantation workers every three years (Sinnathamby, 1993). The number of workers and workdays in the estates are fixed for registered workers regardless of production, and worker productivity has not kept pace with wage increases; compared to other tea producing countries, Sri Lanka’s plantation workers harvest approximately 18 kg/labour day, while workers in Kenya, South India and Assam harvest 48, 38, 26 kg/labour day, respectively. As a consequence, Sri Lankan tea estates tend to deploy labour only for essential management practices, such as tea plucking, and ignore capital-intensive sustainable management operations such as soil conservation and replanting.

Sri Lanka is part of the Indian sub-continent and has a tropical climate. Tea growing areas are located in Sri Lanka’s wet zone (annual average rainfall – >2500 mm) and intermediate zone (average annual rainfall – 1750-2500 mm). Plantation areas receive most rain during two major monsoons: the South-West Monsoon between May and September, and the North-East Monsoon between December and February. Inter-monsoons also bring evening showers; hence peak tea production is normally recorded during these inter-monsoonal periods due to favourable conditions of soil moisture and sunshine. Average temperature varies with elevation, from around 28°C in the lowlands (‘low-country’), to approximately 20°C at mid elevations (‘mid-country’ between 300m and 900m), and 16°C at higher elevations (‘up-country’). Our study focusses only on the estate sector, rather than small holders, because time series data on climate, labour and production performance are available, and because the unique nature of the estate-resident labour force makes these workers particularly vulnerable to the consequences of a changing climate.

2.2. Survey

To obtain a representative sample of Sri Lanka’s 306 tea estates, in-depth semi-structured interviews were conducted on site with managers from 50 estates across Sri Lanka’s three tea-growing regions (Fig. 1). 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. The interviews took place between February and May 2015 and obtained data detailing the age and experience of managers, managers’ observations of changes in weather

37 The remaining two RPCs only manage coconut plantations, not tea.
and climate over their years in the industry, managers’ perceptions of climate change and climate-related risks to their estates, managers’ responses to climate change, constraints to adaptation and potential adaptation options. Interviews typically lasted about 40 minutes. All interviews were recorded and then transcribed for subsequent analysis.\textsuperscript{38} To obtain another perspective of potential adaptation options and constraints, three chief executive officers who manage eight regional plantation companies were also interviewed.

\textsuperscript{38} Ethics approval for the study was granted by [details removed for blind review]. All participants in this research provided their informed consent.
Fig. 1. The estates surveyed at each elevation in tea growing areas of Sri Lanka.
3. Results

3.1. Sample characteristics

All estate managers interviewed were male. This is to be expected because plantation management in Sri Lanka is heavily male dominated (Sivaram, 2000). Mean managed estate size was 322 ha (s.d. 131 ha), and managers were interviewed in all tea growing regions of Sri Lanka. Almost all of the 50 tea estate managers interviewed had more than 10 years of experience, and 26 managers had more than 20 years of experience in plantation management. Most managers were over 30 years of age and 92% had secondary-level education. Demographic characteristics of survey respondents are shown in Table 1.

3.2. Respondents’ observations of changes in climate

From data obtained during the in-depth interviews, estate managers have observed changes in the patterns of temperature, rainfall and extreme climate events (i.e. drought and high intensity rainfall). Tea growers are concerned by changes in weather patterns because the volume and quality of tea depends strongly on these patterns, and they also influence many operational management decisions (Boehm et al., 2016).

Table 1 Characteristics of sample respondents

<table>
<thead>
<tr>
<th>Individual characteristics</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age group</strong></td>
<td></td>
</tr>
<tr>
<td>20-29</td>
<td>4</td>
</tr>
<tr>
<td>30-39</td>
<td>28</td>
</tr>
<tr>
<td>40-49</td>
<td>38</td>
</tr>
<tr>
<td>50-59</td>
<td>24</td>
</tr>
<tr>
<td>60+</td>
<td>6</td>
</tr>
<tr>
<td><strong>Managerial experience</strong></td>
<td></td>
</tr>
<tr>
<td>1-9 years</td>
<td>2</td>
</tr>
<tr>
<td>10-19 years</td>
<td>46</td>
</tr>
<tr>
<td>20-29 years</td>
<td>38</td>
</tr>
<tr>
<td>30-39 years</td>
<td>6</td>
</tr>
<tr>
<td>40-49 years</td>
<td>8</td>
</tr>
<tr>
<td><strong>Education level</strong></td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td>92</td>
</tr>
<tr>
<td>Degree/Diploma</td>
<td>8</td>
</tr>
<tr>
<td><strong>Heard of the term climate change before?</strong></td>
<td>100</td>
</tr>
<tr>
<td><strong>Do you have sufficient information about climate change?</strong></td>
<td>18</td>
</tr>
<tr>
<td><strong>Access to longer-term climate projections?</strong></td>
<td>26</td>
</tr>
<tr>
<td><strong>Views about climate change</strong></td>
<td></td>
</tr>
<tr>
<td>I think that climate change is ongoing</td>
<td>100</td>
</tr>
<tr>
<td>I believe that human activities are mostly contributing to climate change</td>
<td>92</td>
</tr>
<tr>
<td>We are more affected by regional changes in climate than by global changes</td>
<td>66</td>
</tr>
<tr>
<td><strong>Preferred climate adaptation option</strong></td>
<td></td>
</tr>
<tr>
<td>Crop diversification</td>
<td>38</td>
</tr>
<tr>
<td>Soil conservation</td>
<td>32</td>
</tr>
<tr>
<td>Shade management</td>
<td>30</td>
</tr>
</tbody>
</table>

As indicated in Table 1, all survey respondents had heard of the term ‘climate change’ or ‘global warming’ and 78% of respondents reported personal experience of changes in rainfall patterns, the timing of monsoons and the frequency of occurrence of extreme weather events compared to about 15 or 20 years ago. All respondents recalled years and periods characterised
by drought and heavy intensity rainfall. Lack of information was mentioned as a primary constraint on adaptation action by 82% of respondents, with only approximately a quarter of respondents (26%) having access to longer term climate projections. The interviews were conducted at the estate offices and all of the offices had charts of decennial monthly rainfall and number of wet days displayed prominently.

All respondents believed that climate change is occurring, while 92% believed that human activities are responsible. Of the 50 respondents, 33 believed that the consequences they have observed arise due to regional change in climate, whereas 17 believed that observed consequences are the result of global changes in climate. Nearly all respondents (98%) said that they were experiencing the impacts of climate change on tea production. The changes in weather patterns in Fig. 2 were considered to be a consequence of climate change. All respondents said that they were undertaking adaptation options in an attempt to reduce financial losses due to climate change; however, managers’ preferred adaptation options differed.

3.3. Respondents’ observations on climate impacts

Respondents were asked to identify which particular climate change impacts they had observed on tea production during their time in estate management. When asked how sensitive tea production was to climate change on a 5-point Likert scale, 96% of managers said production was ‘very sensitive’ to climate change and the remaining 4% said that it was ‘sensitive’ to climate change.

Ninety eight percent of respondents stated that observed climate changes had negative consequences for tea production. Poor recovery of tea bushes leading to no or reduced crop, and wider distribution of pest, diseases and weeds were two commonly-cited adverse impacts:

“*In low country estates, we have never experienced blister blight. I took over this estate in 2008 and until 2012 we never had blister blight, however, this year and last year we had lot of blister, compared to last year, this year it is severe, we lost so much of crop due to blister because we were not ready with chemical spraying because we did not have this much severe blister blight earlier, so, I must say that the distribution of pest and diseases have changed due to climate change*.” [Manager #31, Low-country]

Some managers reported occasions when estates were unable to provide assured work for their casual labour force during drought. This reduces income security amongst poor rural workers:

“*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]

Approximately two thirds of respondents said that soil erosion has accelerated due to prolonged drought followed by high intensity rainfall:

“*even after a hell of a rain, our soil is dry, water does not retain in soil because top soil is washed off*” ……“*earlier we normally could start fertilizing after about two or three days of rain but now we are unable to do fertilizing after a rain because soil is dry*”. [Manager #38, Low-country]
Fig. 2. Managers’ observed changes in weather. The data labels show number of respondents.

Ninety percent of respondents said that they were experiencing poor attendance of field workers during excessive rain periods, and that they have to reduce working hours during thunderstorms because of the risk of lightning strikes. Managers also mentioned that production declines during excessive rains as a result of extended periods of cloud cover.

Many managers (76%) believed that the quality of processed tea declined due to extreme weather events:

“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]

Managers were asked about the effects of climate change on the ‘quality season’, that time of year when a particular region is able to produce its highest quality tea. Excessive rain during quality seasons was identified as a negative consequence of climate change. Specifically, managers in the Up-country (Uva and Nuwara Eliya areas) responded that in recent years they did not have a proper quality season due to heavy rains or prolonged drought:
“It’s sad, quality season has also been affected since recent years, we expect few showers only and blowing during July to September, last year it was a prolonged drought”. [Manager #21, Up-country]

Eighty eight percent of respondents mentioned that extreme weather events increased production costs, as clearly indicated by the following statement:

“During drought, we come across more off grades of processed tea, we don’t get much crop, during heavy rains we can’t expect much quality, so our cost of production is very high during those extreme weather events”. [Manager #41, Up-country]

In summary, the survey reveals that Sri Lankan tea plantations are experiencing negative consequences from climate change, in particular, increased costs of production, low production volumes and poor quality of tea, together with negative social consequences from reduced labour demand.

3.4. Adaptation options

Plantation managers stated that they have been carrying out a number of adaptation options to counteract the impacts of climate change. These options include crop diversification, soil conservation and shade tree management (Table 1).

“I think crop diversification is a good strategy for adaptation. We have identified some blocks to plant Eucalyptus. We are doing fuel-wood in a large scale. We have only selected marginal tea lands for diversifying with coffee.” [Manager #20, Mid-country]

“We practise soil conservation measures: Sloping Agricultural Land Technology system, terraces and draining wherever possible and plant grasses in bare lands.” [Manager #26, Up-country]

“Specially, in low country we should plant low shade and high shade. I believe it as a mandatory requirement. Because force of the rain is high and if it directly comes into the soil it will badly affect for tea.” [Manager #18, Low-country]

The three adaptation options were identified as their preferred option by roughly equal proportions of managers. For example, 38% of managers indicated crop diversification as their preferred adaptation option. Rubber, cinnamon, pepper, mandarin, cloves, cardamom and eucalypt species for fuel wood are commonly chosen. Soil conservation practices are the preferred option for 32% of the managers. Plantation managers assist soil conservation by adopting cultivation practices such as drainage (constructing and maintaining leader and lateral drains), mulching, cover cropping, planting rehabilitation grasses and incorporation of green manures. These soil conservation methods help to conserve soil moisture and reduce soil temperature. Shade management is the preferred adaptation option of 30% of the managers. Tea requires a certain level of shade for optimum growth and productivity. Shade trees are thus an important means of controlling temperature and protecting tea bushes from high intensity rainfall.
4. Identifying determinants of adaptation choice

Across the Sri Lankan survey sample, tea estates have chosen soil conservation, shade tree management and crop diversification as adaptation options. Our MNL analysis seeks to identify factors which influence estate managers’ choice of preferred adaptation option. In this section, following standard practice in the literature, an MNL is used to identify factors which influence estate managers’ choice of preferred adaptation option on their tea plantations in Sri Lanka.

In the MNL model, the dependent variable (i.e. preferred adaptation option) is a random categorical variable \( y \) with 1, 2, ..., \( J \) discrete values. Let \( z \) denote a vector of explanatory variables that differ across the individuals making the choices. Here \( z \) consists of different characteristics of the manager, estate and its environment. Assuming that the response categories are mutually exclusive and exhaustive, we have response probabilities \( P(y = j | z) \), \( j = 1, 2, \ldots, J \), which add up to one, and we have \( J-1 \) parameters. The MNL specifies for choice \( j = 1, 2, \ldots, J \):

\[
P(y = j | z) = \frac{\exp(z \beta_j)}{1 + \sum_{h=1}^{J} \exp(z \beta_h)}
\]  

[1]

Adaptation responses are as described in section 3.

Marginal effects of the explanatory variables are obtained by differentiating Eqn 1 with respect to the individual-specific explanatory variables. Choice probabilities are expressed relative to the probability of a base adaptation category – in this case, crop diversification. The derivatives of the choice probabilities provide a measure of the expected change in the probability of choosing a particular adaptation option following a unit change in an explanatory variable. For example, the marginal effect of explanatory variable \( x \) on the probability of choosing adaptation option \( k \) can be expressed as follows.

\[
\frac{\partial P_j}{\partial x_k} = P_j(\beta_{jk} - \sum_{j=1}^{J-1} P_j \beta_{jk})
\]  

[2]

Table 2 Independent variables in multinomial logit analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>S.D.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information on climate change</td>
<td>0.280</td>
<td>0.454</td>
<td>Dummy, 1 = yes, 0=otherwise</td>
</tr>
<tr>
<td>Large company</td>
<td>0.360</td>
<td>0.485</td>
<td>Dummy, 1 = large, 0=otherwise</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>A large company is defined as a company which earns &gt;3 billion LKR* revenue and &gt;3% for five-year average net profit margin</td>
</tr>
<tr>
<td>Elevation</td>
<td>1.740</td>
<td>0.777</td>
<td>Categorical, 1=up, 2=mid, 3=low</td>
</tr>
<tr>
<td>Increase in annual average temperature</td>
<td>0.114</td>
<td>0.604</td>
<td>Continuous, expressing the change in average temperature between the years 1990-1995 and 2009-2014</td>
</tr>
<tr>
<td>(°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase in annual total rainfall (mm)</td>
<td>198.22</td>
<td>809.37</td>
<td>Continuous, expressing the change in average annual rainfall between the years 1990-1995 and 2009-2014</td>
</tr>
</tbody>
</table>

*LKR = ‘Sri Lankan Rupees’ and 153 LKR = 1 USD $ [@ 2017 September exchange rates]
4.1. Specification of model variables

Potential explanatory variables were selected based on the literature, data availability and information obtained through the interviews. Key factors that could drive the choice of adaptation options can be broadly categorized as: climatic variables appropriate to the location of the estate (average annual temperature, average annual rainfall); elevation of the estate (up-, mid- and low-country); size of the parent company which owns the estate; and access to information on climate change. Explanatory variables used in the empirical estimation are described in Table 2. Estate managers expressed that they had observed changes in temperature, rainfall and occurrence of extreme climate events. Regression analysis therefore explored whether recorded changes in average temperature and total rainfall between 1990-1995 and 2009-2014 influenced the probability of estate managers preferring a particular adaptation option. Estate managers also expressed concern regarding access to longer term climate change projections; access to climate change information was therefore also included.

4.2. Drivers of preferred climate adaptation options

Various combinations of potential explanatory variables were tested and a final model was selected based on model fit, change in likelihood ratio and statistical significances. The selected model was tested for multicollinearity using variance inflation factors (VIF). VIFs for all explanatory variables (1.11-1.49) are well below the standard threshold of concern (10) (Wooldridge, 2013), confirming that the parameter estimates are unbiased.

The model was also tested for the validity of the independence of irrelevant alternatives (IIA) assumption by employing the seemingly unrelated postestimation procedure (SUEST), which is the recommended test of IIA for small samples (Weesie, 2000). The \( p \) value of the SUEST test ranges from 0.82 to 0.91, depending on which adaptation option is excluded. The SUEST test thus fails to reject the null hypothesis of IIA, indicating that the MNL model is appropriate for modelling tea estate managers’ choice of preferred climate adaptation option. The chi-squared statistic \( (\chi^2) \) of the resulting model is highly significant \( (p > 0.0006) \), suggesting strong explanatory power. Model results are shown in Tables 3 and 4. In MNL models the most important results are the marginal effects (Table 4) rather than the parameter estimates of the explanatory variables (Table 3).

**Information on climate change**

Marginal effects reported in Table 4 indicate that information on climate change has a significant and negative impact on the likelihood of preferring crop diversification as the adaptation option. Specifically, estate managers who indicate that they have received information on climate change, have a 46.5% lower probability of choosing crop diversification as their preferred adaptation option.

**Large company**

Estate managers employed by large companies are 59% more likely to prefer crop diversification, than estate managers employed by smaller companies. Whereas, estate managers employed by large companies were 32.8% and 26.2% less likely to prefer shade management and soil conservation, respectively, as adaptation options.
Table 3 Parameter estimates of the multinomial logit model of managers’ preferred choice of climate adaptation option

<table>
<thead>
<tr>
<th>Explanatory variables</th>
<th>Soil conservation</th>
<th>Shade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficients</td>
<td>P level</td>
</tr>
<tr>
<td>Information on climate change</td>
<td>2.751**</td>
<td>0.022</td>
</tr>
<tr>
<td>Large company</td>
<td>-2.527**</td>
<td>0.031</td>
</tr>
<tr>
<td>Tea growing elevation - Mid</td>
<td>-0.833</td>
<td>0.507</td>
</tr>
<tr>
<td>Low</td>
<td>-1.762</td>
<td>0.150</td>
</tr>
<tr>
<td>Increase in temperature</td>
<td>3.091***</td>
<td>0.009</td>
</tr>
<tr>
<td>Increase in rainfall</td>
<td>0.0002</td>
<td>0.773</td>
</tr>
<tr>
<td>Constant</td>
<td>0.291</td>
<td>0.734</td>
</tr>
</tbody>
</table>

Diagnostics
- Base category for climate adaptation: Crop diversification
- Number of observations: 50
- LR chi-square: 34.19
- Log likelihood: -37.58
- Pseudo R²: 0.31

***, **, * Significant at 1%, 5% and 10% probability level, respectively.

Table 4 Marginal effects from the multinomial logit climate adaptation model

<table>
<thead>
<tr>
<th>Explanatory variables</th>
<th>Crop diversification</th>
<th>Soil conservation</th>
<th>Shade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Marginal effects</td>
<td>P level</td>
<td>Marginal effects</td>
</tr>
<tr>
<td>Information on climate change</td>
<td>-0.465***</td>
<td>0.002</td>
<td>0.300</td>
</tr>
<tr>
<td>Large company</td>
<td>0.590***</td>
<td>0.001</td>
<td>-0.262*</td>
</tr>
<tr>
<td>Tea growing elevation - Mid</td>
<td>-0.053</td>
<td>0.799</td>
<td>-0.334*</td>
</tr>
<tr>
<td>Low</td>
<td>0.312</td>
<td>0.213</td>
<td>-0.339*</td>
</tr>
<tr>
<td>Increase in average annual temperature†</td>
<td>-0.231**</td>
<td>0.022</td>
<td>0.143***</td>
</tr>
<tr>
<td>Increase in average annual rainfall†</td>
<td>-0.064***</td>
<td>0.000</td>
<td>-0.050***</td>
</tr>
</tbody>
</table>

***, **, * Significant at 1%, 5% and 10% probability level, respectively.
†Indicates one standard deviation discrete increase from the mean.

Tea growing elevation

Broadly, tea estates in different tea growing elevations employ different adaptation methods as appropriate for the temperature and rainfall at their elevation. For example, managers of tea estates in mid- and low-country were 33.4% and 33.9% less likely to prefer soil conservation as an adaptation approach, compared to managers of up-country estates (the reference elevation category). Further, managers of mid-country tea estates are 38.8% more likely to prefer shade as an adaptation option compared to managers of up-country estates.

Increase in average temperature

Managers of estates which have experienced larger increases in average temperature between 1990-1995 and 2009-2014, are considerably less likely to prefer crop diversification as an adaptation option. For a one standard deviation increase in annual temperature, the probability
of an estate manager preferring crop diversification decreases by 23.1%, holding other independent variables constant at their means. Whereas, the probability of a manager preferring soil conservation and shade management as adaptation options increases by 14.3% and 8.8% respectively.

Increase in annual average rainfall

In contrast to the impact of rising temperatures, managers of estates which have experienced larger increases in average annual rainfall were more likely to choose shade management as their preferred adaptation option. A one standard deviation increase in rainfall increases the probability of an estate manager preferring shade management by 11.4%, holding other independent variables constant at their means.

5. Constraints on choice of adaptation option

Using information gathered through the in-depth interviews with the estate managers, we present a qualitative analysis of constraints and challenges which confront estate managers in implementing adaptation options. As might be expected, the most common constraint (expressed by 94% of respondents) was a lack of capital to invest in climate adaptation options (Fig. 3):

“companies are struggling to survive, we are not in a position to spend much for adaptation options since our cost of production is really high, we need to economically survive, however we believe that adaptation is necessary for sustainability”. [Manager #33, Up-country]

This indicates that managers recognise the need for adaptation, and would potentially be willing to take up adaptation options, however as many estates lack sufficient operating surpluses, opportunities for implementing adaptation options are severely constrained. Almost all respondents who stated insufficient capital as the main constraint on adaptation said that they would be willing to accept any assistance offered by the government or any other parties. Of respondents constrained by a lack of investment capital, 86% said that they were unable to fully implement their chosen adaptation option because of a lack of funds. The majority of respondents held the view that if there were established incentive schemes for adaptation, more estates would be willing to implement appropriate adaptation actions.

One potential source of capital to facilitate adaptation could be joint production of tea alongside fast-growing timber trees to access carbon credit payments. Under existing regulations, tea estates are excluded from the carbon trading process, thus locking them out from these potential revenue flows:

“Carbon sequestration has been much talked about. But nothing has come out of it. People have come out of proposals 5-6 years back but nothing has come, the matter is there is a procedure to enter into an agreement but that incurs high cost for obtaining it. If we could have a simple mechanism to go for it we are willing to get it...... as I am aware, cultivated crops are not included under the carbon trading process. However, if there is government and related institutional support to implement it, plantations are willing to go for it” [Chief Executive Officer – major tea plantation company, operating estates across all elevations]
A lack of information was mentioned as a primary constraint on adaptation action by 82% of respondents, this suggests that current information and awareness programmes regarding climate change and its impacts on tea production may be inadequate. Approximately three quarters of respondents (74%) said they obtained weather information only via daily forecasts and were not aware of any near-term or medium-term climate predictions. Other than information obtained through daily weather forecasts, internet and television, there appears to be no adequate source of information or extension services regarding climate change impacts on the tea sector. Approximately three quarters of managers (76%) also mentioned that they are not aware of any sources of this information other than from extension services related to tea:

“we need more and more awareness and information for adaptation options so we could try out and see”, “awareness programmes and information on especially climate change is totally lacking”. [Manager #3, Low-country]

Furthermore, managers said that they were advised by the Tea Research Institute to go for soil conservation and shade management as adaptation options, reserving crop diversification for marginal tea fields identified during the tea pruning cycle. This is consistent with the MNL finding that estate managers who had received information on climate change impacts (predominantly from tea extension services) were almost 50% less likely to prefer crop diversification as an adaptation option.

The third most commonly-stated constraint on climate adaptation was a lack of government and institutional support. For example:

“My solution is we should go for crop diversification. But we should have financial assistance and awareness programs from the government to go for these adaptation options. But this is not the situation”. [Manager #1, High-country]

Fig. 3. Constraints to adaptation
options. .... We can use marginal lands for timber programmes. But some other methods like intercropping programmes can be adopted. For that we need government and institutional support for selecting suitable blocks of land and appropriate crops for the area.”

[Manager #10, Up-country]

“As crop diversification we have planted rubber. We do not have plan for any other crops other than rubber. Cocoa may be a suitable crop for this area. But we need government and research institutions support to identify exactly whether it is a good crop for the area. We need more awareness programmes.”

[Manager #23, Mid-country]

Overall, a lack of capital, inadequate access to information and knowledge regarding climate change adaptation, and poor governmental and institutional involvement were commonly cited barriers to climate change adaptation. Hence, appropriate policies to rectify these shortcomings are required in order to help Sri Lanka’s tea industry adapt and prosper.

6. Policy implications and conclusions

This research has addressed a gap in the literature around factors affecting uptake of climate adaptation options in perennial agriculture. Uptake of preferred adaptation options in perennial cropping systems can be influenced by many factors. Comprehensive understanding of these factors is key for effective and efficient resource allocation, and for successful adaptation to climate change. We find that estate managers’ preferred option for climate adaptation is affected by some factors which are potentially amenable to policy intervention (access to information and company size), and by other factors which are largely outside policy reach (changes in the climate and estate elevation).

Managers of estates which have experienced higher increases in average temperature are more likely to adopt adaptation options such as soil conservation and shade establishment. This makes intuitive sense as both of these practices provide multiple benefits by establishing a cooler micro-climate. Estate managers who have experienced increases in annual rainfall are more likely to prefer shade management as an adaptation option. This may be because shade trees help to shelter tea bushes from the adverse physical effect of increasing rainfall. This suggests that there may be a role for addition research around adaptation strategies such as joint-production of tea and fuel wood trees which could further reduce the impact of increasing temperatures and higher rainfall.

Our results show that managers’ adaptation preferences differ significantly with elevation. For example, managers of mid-country and low-country estates are less likely to go for soil conservation than managers of up-country estates. This is probably because the steep up-country topography makes these estates more prone to soil erosion. Managers of mid-country estates are more likely to prefer shade as a climate adaptation option than managers of up-country estates. This is not surprising as up-country tea estates require less shade because temperatures are lower. The terracing and drains required for soil conservation are more expensive investments than tree planting for shade establishment. Up-country estate managers therefore have to be convinced about the long-term benefits of soil conservation before they commit such sizeable investments. This suggests that there is a strong need for further
elevation-based research on the impacts of climate change and the effectiveness of different adaptation measures for tea estates at different elevations.

Turning to factors which could potentially be addressed more directly by policy, estate managers with access to information on climate impacts and adaptation options are considerably less likely to prefer crop diversification. Tea estate managers receive information regarding climate change and adaption options through extension services provided by the Tea Research Institute. It is quite possible that these services provide advice which is biased towards retaining current levels of tea production, whether or not this is in the best interests of the estate, the agriculture sector, or the national economy under climate change. This suggests that there may be a role for government in providing tea estates with independent advice formulated around overall national adaptation and development goals.

The study further reveals that estate managers employed by larger companies are more likely to choose diversification as their preferred adaptation option. This is not surprising, as crop diversification requires significant capital investment compared to other adaptation options. This is particularly true for perennial crops such as tea, for which the rate of diversification is very low compared to annual crops; a consequence of the substantial initial investment committed to establish a plantation. Diversification options such as, for example, rubber, cinnamon and timber for fuel wood are less labour intensive in production than tea. Given that large companies are significantly more likely to diversify, this could have a substantial impact on labour demand in rural areas of Sri Lanka – with far-reaching implications for the national economy. This suggests that potential adaptation options for the tea industry – Sri Lanka’s largest agricultural employer – should be evaluated holistically to ensure compatibility with sustainable development across all facets of Sri Lanka’s agriculture. The survey reveals that tea estate managers feel that they require more information on climate change predictions and their associated impacts to assist their choice of appropriate adaptation options. Policies and practices related to climate adaptation should be modified in ways that leverage the agriculture sector as a whole, integrating across all related sub-sectors including plantations.

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Chapter 6 General Discussion
6.1. Introduction

The primary intention of this thesis is to estimate the impacts of climate change on tea production and labour demand for tea estates in Sri Lanka, and to identify factors determining and constraining estate managers’ preferred adaptation approach to climate change. To date the impacts of climate change on production, labour demand and adaptation are poorly understood in the context of plantation agriculture in developing country economies (Boehm et al., 2016; Gunathilaka et al., 2017; Parry et al., 2007). This lack of knowledge is of particular concern with regard to Sri Lanka achieving its sustainable development goals and executing its national climate adaptation plan (Department of Census and Statistics, 2017; Sri Lanka Climate Change Secretariat, 2015).

More specifically, this research addresses three priority questions:

1. How will current and predicted future climate changes affect tea production in the Sri Lankan tea plantation sector?
2. To what degree will labour demand in tea plantations be affected by changes in climatic conditions?
3. Which factors affect choice of adaptation options in tea plantations, what are the key barriers to adaptation, and what are the associated policy implications?

Results from Chapter 3 demonstrate that production on Sri Lanka’s tea estates is negatively affected by climate change and that the impacts vary across the different tea growing elevations. These impacts arise due to increases in average temperature, increases in rainfall and more frequent occurrence of extreme weather events. Tea production is predicted to decline considerably under all climate change scenarios studied.

Results from Chapter 4 quantify the negative relationship between rainfall in the South-West monsoon (May-September), North-East monsoon (December-February) and the Inter-monsoon 2 (October-November) and labour demand. Overall, the absolute impact of predicted changes in rainfall reduces labour demand by approximately 1,175,000 person days per year across the 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.
Turning to climate adaptation, results from Chapter 5 show that tea estate managers’ preferred adaptation choices are influenced by factors such as company size, tea growing elevation and the scale of observed increases in temperature and rainfall. Interviews with estate managers reveal that barriers such as a lack of capital, inadequate access to near-term and medium-term climate knowledge, and poor governmental and institutional support may prevent experimentation with new adaptation options.

6.2. Comparisons with the literature

6.2.1 Methodological comparisons

The use of production function approaches for assessing climate change impacts on crop production is well established (Deschênes and Greenstone, 2007; Deschênes and Kolstad, 2011; Fisher et al., 2012; Schlenker et al., 2005; Schlenker and Roberts, 2009; Welch et al., 2010). However, a well-recognised limitation of the production function approach in this type of study is its inability to account for farmer adaptation. In contrast to many other studies in the literature, our study accounts for farmer adaptation to a certain extent by including explanatory variables such as the proportion of vegetatively propagated tea in the total cultivated area and levels of inputs (i.e. fertiliser, labour) under changing weather and climate conditions. This important innovation derives from our access to estate-specific data. With regard to endogeneity issues arising from potential omitted variables or measurement error, this study uses a flexible production function specification which includes total production on the left-hand side and area harvested on the right-hand side with time dummies. Since area harvested is approximately fixed in the short-run—which it is for tea—are acts as an exogenous variable in this analysis.

A significant contribution from this thesis is the use of a two-stage panel approach for the production function analysis. A first-stage panel model estimates 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 as production inputs. A second-stage model is then run with the estate-specific fixed effects from the first-stage as its dependent variable. The approach confers several advantages. Separate estimation of both short-term weather effects (from stage one) and long-term climate effects (from stage two) for the same production
technology is particularly advantageous in terms of perennial cropping systems. In addition, the approach enables long-term climate effects to be identified with reduced risk of confoundment.

Turning to labour demand, reduced form approaches are frequently used to estimate labour demand directly from driving variables (Hujer et al., 2006; Pischke and Velling, 1997), particularly in the absence of production-unit data. However, if farm-level economic data (i.e. data on profits, input and output prices) are available this facilitates analysis at the level of individual decision-making units, where farmers’ behavioural choices should be most apparent. Moreover, when data are available from individual decision-making units there is no requirement to assume constant returns to scale, (as is typically necessary in reduced form approaches) (Fezzi and Bateman, 2011). Access to farm-level data from known locations to which environmental characteristics can be attached is typically very difficult because most published agricultural farm-level databases omit precise locations for confidentiality reasons (Henning and Henningsen, 2007; Lacroix and Thomas, 2011; Lansink and Peerlings, 1996). However location-specific farm-level data provide the most comprehensive information for model estimation using the structural approach (Fezzi and Bateman, 2011). In light of the above, the normalised quadratic form structural model used in this study appears to be the most appropriate option for analysing the impact of changing climate on labour demand at estate level.

Unfortunately, alternative functional forms such as the translog could not be explored in this study because negative profits are common across the dataset. Another important fact is that plantation crop systems require large initial investment in capital that is only fully recovered after a number of years. As a consequence, tea plantation management entails long-run production decision-making that probably discourages producers from maximising short-run profits. In light of the above, future applications of duality-derived structural models in perennial plantation crop production require careful consideration when choosing assumptions regarding the economic behaviour of farmers.

With regard to methodological approaches for identifying factors affecting choice of climate adaptation options, discrete choice methods have commonly been used in the literature to
identify the relative importance of different attributes in determining farmers’ choice of adaptation approach. Some applications of this method in agriculture include, Breustedt et al. (2008) who investigate German farmers’ willingness to adopt genetically modified oilseed and demand for novel technology; Hubbell et al. (2000) who estimate the potential demand for genetically modified Bt cotton in the North and South Carolina, Georgia and Alabama; Qaim and De Janvry (2003) who analyse adoption of new technologies for Bt cotton in Argentina, and Kolady and Lesser (2006) which analyse adoption of technologies and factors influencing Bt eggplant farmers in Maharashtra, India. In contrast, this thesis uses an interview-based approach, rather than choice experiments, to collect data regarding tea estate managers’ preferred adaptation options. In analysing preferred adaptation options from interview data, the two most commonly-used models are the multinomial logit and probit. The multinomial logit and probit models allow the analysis of decisions across multiple numbers of categories, enabling the estimation of choice probabilities for those different categories (Maddala, 1986; Wooldridge, 2010). The main limitation of the multinomial logit model is the underlying assumption of independence of irrelevant alternatives. As discussed in Chapter 5, our model is consistent with this property.

This thesis used a thematic qualitative analysis of interview-derived data to explore estate managers’ perceptions regarding barriers to adaptation. This approach has been used extensively in the literature, probably because of its ability to obtain more nuanced information compared to quantitative alternatives (Barnes and Toma, 2012; Battaglini et al., 2009; Elrick-Barr et al., 2017; Kragt et al., 2017; Mertz et al., 2009).

6.2.2 Economic impacts of climate change on plantation crops

Prior to this thesis, there were only two papers specifically dealing with the implications of climate change for tea production (Boehm et al., 2016; Wijeratne et al., 2007). Wijeratne et al. (2007) employ a field experimental approach in their analysis to assess the impact of climate change on the productivity of tea lands in Sri Lanka, whereas Boehm et al. (2016) use aggregated production data at provincial resolution (Chinese province39) in a yield response (Ordinary Least Squares linear regression) model to quantify the impact of monsoonal rainfall

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39 Boehm et al. state data at provincial resolution as a limitation for their study for inferences because province is a large geographical area.
and temperature on tea production in tea growing provinces in China. In contrast, this thesis uses monthly-resolution data on inputs and output from individual production units (i.e. individual tea estates) to assess the impact of predicted climate change on tea production. Strong statistical significances were found between increasing average temperature, increasing rainfall and declining tea production. A positive relationship between the number of wet days per month (ceteris paribus) and production was also identified. This is consistent with the findings of Boehm et al. (2016), but differs from Wijeratne et al (2007) in some respects. As mentioned in Chapter 3, Wijeratne et al used simple linear regressions to identify weather impacts from estate-specific production data from 1975 – 1995, whereas this thesis uses multiple panel data regressions on production data from 2000 – 2014.

In another plantation crop – coffee – Laderach et al. (2011) find that traditional coffee growing regions in Nicaragua may disappear and be replaced by new regions due to climate change. The authors argue that appropriate site-specific mitigation and adaptation strategies are required, in both the short and long-run, to ensure continuing coffee supply and to support improved livelihoods for rural farmers.

Turning to labour demand, to the best of the author’s knowledge there have been no previous studies of climate change-specific impacts on labour demand in Sri Lanka’s tea plantation sector. In one of the only other studies to investigate climate change impacts on agricultural labour in the developing world, Colmer (2016) finds that increasing temperature is associated with increasing labour migration from agriculture to manufacturing in India. Colmer’s study suggests that this migration could help to offset unemployment in the agriculture sector as the climate changes. However, Colmer (2016) finds that migration behaviour is influenced by factors such transferability of skills, resistance to relocation, and gender. Several of these factors are also highly relevant in the context of tea plantation workers in Sri Lanka, particularly gender issues, as the majority of estate workers are female.

Regarding adaptation, to the author’s knowledge, no previous studies specifically address factors affecting choice of climate adaptation option in the perennial plantation tree crop sector. Perceptions of winegrowers regarding the impacts of climate change are assessed by Battaglini et al. (2009). However, these authors do not use econometric analysis to identify factors
affecting winegrowers’ choice of adaptation options. Findings from Battaglini et al.’s qualitative analysis show that viticulturists need considerably improved access to timely research-derived information on future climatic conditions and new climate-related threats for vineyards to assist adaptation to changing climatic conditions. This mirrors findings in this thesis that it would be helpful for tea estate managers to have better information on the likely impacts of climate change and the predicted extent of climate change to assist informed decision making about adaptation.

Many of other studies on barriers and enablers to adaptation have been conducted on annual agricultural crops in different parts of the world (Bryant et al., 2000; Deressa et al., 2009; Grothmann and Patt, 2005; Hassan and Nhachena, 2008; Mertz et al., 2009; Seo and Mendelsohn, 2008; Takahashi et al., 2016). Different studies find that various factors affect annual crop farmers’ adaptation to climate change, including farmers’ level of education, income, information access, extension services, agro-ecological setting, and the scale of changes in rainfall and temperature. Findings from this thesis are in general agreement with findings from the annual agricultural literature, but distinct characteristics relevant for tea estates, such as company size and tea growing elevation, are noteworthy additions.

There appear to have been no previous studies regarding barriers to adaptation specifically for perennial plantation crops. Previous studies have, however, addressed farmer adaptation and associated barriers in viticulture (Battaglini et al., 2009; Dunn et al., 2015; Hadarits et al., 2010; Lereboullet et al., 2013). Although the nature of plantation tree crop management is different to the management of vineyards, it may be important to compare our findings with these studies since grapes are also a perennial crop. This thesis finds that shortage of capital, lack of information on climate change, and poor governmental and institutional support are cited frequently by tea estate managers’ as barriers to adaptation. Similar to this study, Battaglini et al. (2009) find that winegrowers require access to timely information provided through targeted research on future climatic conditions, and their likely consequences, to support adaptation decision making. The relevant time horizon for this future climatic information varies with the nature of the crop. For example, Dunn et al. (2015) find that accurate climatic predictions over the longer term (i.e. over decades and longer) would be useful to vine growers in Australia since viticulture planning involves time horizons from years to decades, and the time delay
from establishment to commencement of effective harvest is very lengthy. This thesis also finds that limited access to information on climate predictions is a constraint that could prevent tea estate managers implementing appropriate adaptation options. This research also supports the findings of Hadarits et al. (2010) from in-depth semi-structured interviews with 46 grape growers and wine makers in Maule region in Chile, that producers’ ability to adapt to climate change is constrained by social, economic and political circumstances, including availability of economic capital, education, institutional arrangements and organizational abilities. It also supports the work of Lereboullet et al. (2013) who find that limited financial capital is a major constraint in preventing viticulture growers from implementing traditional, as well as potentially innovative, adaptation strategies. Such inability to adapt is likely to increase climate risks.

6.3. Wider implications of the research for the plantation sector in Sri Lanka and other less developed countries

This section discusses the potential implications of this study’s findings to Sri Lanka’s plantation sector as a whole, and to perennial plantation agriculture in other less developed countries such as Kenya, Vietnam and Bangladesh. Plantation crops raise special economic issues compared to annuals, owing to long pre-harvesting period and the scale of the initial investment required for establishment. The impact of climate change has become a significant concern given the limited opportunities for crop switching for the above-mentioned reasons. These same constraints are likely to affect climate adaptation in other plantation tree crops, with climate-induced changes in production potentially carrying substantial economic, social and welfare consequences for the country as a whole. At the producer level, plantations have been affected by climate change as they incur additional expenses to maintain sustainability of production to compete in the international market. Mostly, producers try to modify cultivation and management practices according to weather and climatic conditions aiming to maximise profits. These modifications typically include soil conservation practices to minimise the adverse impact on production which follows from loss of top soil through erosion due to increasingly extreme rainfall patterns, and increased use of fertilisers and pesticides to address longer dry seasons and heavy rains. Heavy rains wash off top soil together with the nutrients required by plants and therefore lead to additional application of fertilisers. Similarly, during heavy rains and dry seasons, outbreaks of pests and diseases are common.
The impact of climate change on the estates’ level of production, and also hence on profits, have begun to cause serious socio-economic issues related to working conditions on some plantations, particularly those operating in highly climatic-vulnerable areas in Sri Lanka (Anonymous, 2012; Sathisraja, 2016). Because estates are trying to survive under the pressure of high costs of production, they tend to cut down on the provision of free social services for estate workers. This may lead to lower quality housing, reductions in expenditure on health and safety, and conversion of regular workers to casual or short-term employment. This could lead to discrimination in terms of gender if lay off decisions are based on productivity, because it is widely accepted in estate management that, on average, productivity of males is higher than that of females. Importantly, these follow-on consequences of climate change in the plantation sector are very likely to affect Sri Lanka’s ability to meet its national sustainable development goals – in particular the goals around zero poverty, zero hunger, good health and well-being, quality education, and gender equality - all of which are all intended to be achieved by 2030. Implementation and monitoring of appropriate policies aligned with the national climate adaptation plan is thus recommended to maintain sustainability of Sri Lanka’s plantation sector within the broader aim of contributing towards delivery of the national sustainable development goals.

It is reasonable to assume that the adverse impacts of climate change on plantation agriculture are also likely to increase elsewhere in South Asia and South-East Asia, following IPCC predictions (IPCC, 2013). A very significant proportion of people in these regions depend on agriculture for their livelihoods, hence the associated socio-economic repercussions are likely to be large. Most plantation crops are marketed internationally, and hence adverse impacts of changing climatic conditions on production and profitability are likely to be significant for the producing countries’ economies. An obvious example here is Kenya, for which the plantation crop sector generates a sizable percentage of export earnings, provides employment for a large number of workers, is a major source of food and also contributes to the delivery of important ecosystem services such as carbon sequestration, soil retention and ecotourism. Elsewhere, Boehm et al. (2016) state that 80 million rural people are involved in tea production in China; Duncan et al. (2016) document that Assam tea in India contributes 17% of world tea production and provide livelihoods for 1.2 million workers; Alkan et al. (2009) indicate tea production is the main livelihood for many people in developing countries such as China, India, Sri Lanka,
Indonesia, Kenya and Turkey, and Xue et al. (2013) quantify delivery of important ecosystem services from tea plantations in China.

6.4. Future research directions

Although relevant caveats were mentioned in each individual results chapter, this section presents some important additional suggestions for improvement and identifies opportunities for future research. In Chapter 4, anticipated changes in monsoonal rainfall were shown to be likely to have a significant impact on labour demand from the tea plantation sector. However, significant effects on labour demand could not be established through a normalised quadratic profit function derived structural approach for anticipated changes in temperature or in the number wet days per season (as a proxy for rainfall intensity). A significant negative impact of temperature on tea production was established in Chapter 3, so it is somewhat surprising that a corresponding impact could not be identified for labour demand in Chapter 4. This may be because the normalised quadratic functional form assumed for the profit function in the structural model requires the data to behave in a way (i.e. profits to be maximised) which obscures the temperature effect when the necessary global curvature is imposed. The significant proportion of negative profit observations in the estate-specific profit dataset prevented the use of other functional forms, such as the translog, which are less restrictive in this regard. Exploration of more flexible functional forms, which can accommodate negative profits, therefore remains an important consideration for future research.

Furthermore, functional forms embody assumptions and constraints regarding farmer behaviour. A peculiarity of perennial tree crop production, which is particularly true for tea, is that producers need to persist with harvesting even when market prices are low in order to maintain yield and quality in the future. High labour costs, coupled with exogenous downward movements in the international market price, are therefore likely to result in low or negative profits. Imposing unrealistic assumptions regarding input flexibility in these types of perennial crop production may not be appropriate, especially when the requirement is to estimate labour demand. Future research could therefore consider alternative methodological approaches such as Nerlovian and Directional distance functions (Chambers et al., 1998; McWhinnie and Otumawu-Apreku, 2013) or negative indicator methods (Bos and Koetter, 2011) which can
handle negative observations without the imposition of such a strong set of structural assumptions.

Alternative approaches such as real-options models (Ihli et al., 2014; Luong and Tauer, 2006; Odening et al., 2005) that allow for pricing of risk and uncertainty could also be explored, as could models featuring the intertemporal dynamics of production decisions, such as those employed by Vasavada and Chambers (1986), Fernandez-Cornejo et al. (1992) and McLaren and Cooper (1980) for understanding farmers adjustment behaviours.

Another limitation of the current study is that it does not consider the broader issue of general labour availability in the plantation sector within Sri Lankan agriculture. Over recent years, plantations have faced critical labour shortages, particularly for harvesting operations. Workers from plantations located closer to urban areas tend to out-migrate, looking for employment as domestic workers or in garment factories. Females, in particular, also often migrate to Middle-Eastern countries for employment (Chandrabose, 2015). However, in this thesis these effects could not be addressed due to the unavailability of time series data on estate labour out-migration. Labour availability is likely to be an important driver which should be considered in future research, provided the relevant data can be collected.

Another limitation of the current study is associated with the global nature of the tea market. Sri Lanka is one of the world’s major tea producers, so a significant change in Sri Lankan tea production could have an impact on the world market price for tea. This is a question that should be addressed within a general equilibrium framework for the world tea market, combining macro data on total production and market prices from all major tea-producing countries. A general equilibrium approach lies well outside the scope of this thesis, but could usefully be considered for future research.

With regard to analysing estate managers’ preferences for adaptation options, and associated enablers and constraints, another limitation of the current study is the modest sample size (50 interviews) used in the multinomial logit analysis in Chapter 5. Collecting primary data by personal visits and face-to-face interviews is an extremely time consuming and costly task. However, it is likely that additional insights could be obtained if a larger survey sample of face-to-face interviews with estate managers could be collected. This remains an important
opportunity for future research, provided researchers are able to obtain the necessary funding and resources.

Overall, more research is required to better understand climate change impacts on tea production, labour demand from tea plantations and other welfare issues, not only in Sri Lanka’s plantation sector but also in the country’s smallholder tea production sector. It is well understood that smallholders are unlikely to record and retain long time series data on production, however, alternative methodological approaches such as the state contingent method (Mallawaarachchi et al., 2017; Pizer, 1999) should enable likely climate change impacts on this sector to be assessed. It will be particularly important to conduct further research to quantify the impact of increasing frequency of extreme weather events on crop production and labour demand since such phenomena are common to all tea-growing regions, with prolonged droughts, extreme rainfall, floods and landslides causing particular concern. From a scientific perspective, updated downscaled climate modelling predictions will be required to quantify these impacts and facilitate future research to quantify a more complete set of economic impacts from climate change.

6.5. Conclusions

In conclusion, the predicted negative impacts of climate change on Sri Lankan tea production are considerable. Significant negative impacts are predicted on tea production in high, medium and low emissions futures, over the short, medium and long term [i.e. over 25 year, 50 year and 75 year time horizons], with effects worsening as climate change proceeds. Under a high emissions scenario, by mid-century, production from the estate sector is predicted to decline by 12%. This will carry far-reaching negative consequences for the national economy since the industry is the country’s major source of agriculturally-derived foreign exchange earnings and also the nation’s largest employer.

This research also finds a negative relationship between rainfall in the South-West monsoon, North-East monsoon and Inter-monsoon 2, and labour demand. In contrast, we find a positive relationship between rainfall in Inter-monsoon 1 and labour demand. Overall, however, anticipated changes in rainfall are predicted to reduce labour demand by approximately 2.6% across the tea plantation sector. This is likely to have considerable adverse social and welfare
implications, particularly for the women who comprise the majority of the sector’s workforce and are the primary active income generators in a plantation household.

The thesis shows that tea estate managers believe that climate change is happening, and almost all managers are acknowledging negative impacts from climate change on tea production. The availability of information on climate change, company size, tea-growing elevation, and the scale of increases in temperature and rainfall are all key factors which influence managers’ preferred choice of adaptation option. Furthermore, barriers such as a lack of capital, inadequate access to near-term and medium-term climate knowledge, and poor governmental and institutional support may prevent estate managers from experimenting with new adaptation options. Policies should, therefore, be aimed at promoting new adaptation options through information exchange between a wide range of stakeholders, and towards integrating climate change adaptation with Sri Lanka’s sustainable developmental goals. Governmental and institutional support and involvement will be instrumental in facilitating adoption of adaptation options in tea plantations. Better integrated strategic adaptation plans, which should be evaluated holistically, are more likely to assist sustainable development across all facets of Sri Lankan agriculture.
References


Appendices

Appendix 1


Inclusion of papers within the thesis

Overview


HGR candidates may include one or more papers within the body of their thesis where such papers have been produced under supervision and during the period of candidature, and where the quality of such papers is appropriate to Doctoral or Masters (Research) level research. A thesis prepared in this way is a different thesis format, it is not a different degree. There are several advantages to incorporating a thesis in this way:

- Preparing papers for publication saves time when preparing the thesis for examination as papers may make up one, or several, chapters within the thesis.
- It is to your advantage to publish work from your thesis as a means of disseminating your research, and developing your writing skills.
- It may improve the quality of your thesis as part of your thesis has already been subjected to peer review.
- Examiners may have more confidence in your thesis if they can see that you have already published your research. In addition, you will have already met one of the criteria of examination, with the thesis suitable for publication.

As a (candidate) requirement, all doctoral candidates are expected to have at least one peer-reviewed output accepted for publication during candidature [https://www.griffith.edu.au/higher-degrees-research/current-research-students/candidature-requirements/publication]. Whilst not compulsory, candidates are encouraged to include this publication in the body of the thesis due to the advantages as outlined above.

Requirements for inclusion of papers within the thesis

Higher degree by research is a program of independent supervised study that produces significant and original research outcomes, culminating in a thesis, essay, or equivalent (refer to Higher Degree by Research Thesis [https://www.griffith.edu.au/higher-degrees-research/current-research-students/thesis/preparation/inclusion-of-papers-within-the-thesis]). Inclusions of papers within a thesis is not a suitable thesis format for all research projects, for example collaborative projects where there may be several coauthors for each paper which may make it difficult for the examiner to establish the independence of the candidates work; where primary data is not collected, or results obtained, until late in the candidature; or where the research will not produce a logical sequence of papers that are able to be presented as an integrated whole. Candidates should also take into account whether the thesis format is an accepted practice within their discipline and likely to be received well by the thesis examiners (refer also to the examination requirements below). Candidates are required to consult with their supervisor(s) early in their candidature to determine if this thesis format is appropriate. It is expected that candidates will identify as part of the confirmation of candidature milestone [https://www.griffith.edu.au/higher-degrees-research/current-research-students/candidature-requirements/confirmation] if their thesis is to be prepared in this format.

Candidates should consult their Group specific guidelines in addition to the requirements detailed below.

Candidates are also encouraged to attend the workshop [https://www.griffith.edu.au/higher-degrees-research/news-events/training-events/workshops] on preparation of papers within a thesis offered by the Griffith Graduate Research School.

Refer also to the Griffith University Code of Conduct for the Responsible Conduct of Research [http://dstore.griffith.edu.au/search/Pages/results.aspx?ap=research&%20conducts%3Atrue%20conducts&%20read%3Atrue%20conducts], specifically the sections pertaining to publication ethics and the dissemination of research findings, and authorship.

Status of papers

A thesis may include papers that have been submitted, accepted for publication, or published.

Some disciplines may specify a version for the status of papers requirement, refer to your Group specific guidelines.

Type of papers

Papers are defined as a journal article, conference publication, book or book chapter. Papers which have been rejected by a publisher may not be included unless they have been substantially rewritten to address the reviewers comments, or have since been accepted for publication. Some disciplines may specify a version for the type of papers requirement, refer to your Group specific guidelines.

Number of papers

A thesis may be entirely or partly composed of papers. A paper may be included as a single chapter if the paper contributes to the argument of the thesis, or several papers may form the core chapters of the thesis where they present a cohesive argument. Where a thesis is entirely comprised of papers, there is no minimum requirement for the number of papers that must be included (except as noted below) and/or a matter of professional judgment for the supervisor and the candidate. Overall, the material presented for examination needs to reflect the research thesis standard required for the award of the degree. For example, PhD candidates, on the basis of a program of independent supervised study, must produce a thesis that makes a significant and original contribution to knowledge and understanding in the relevant field of study. This remains a matter of professional judgment for the supervisor and the candidate.

Where a thesis is entirely composed of papers, some disciplines may specify a minimum number of papers to be included, refer to your Group specific guidelines.

Authorship

The candidate should normally be principal author that is, responsible for the intellectual content and the majority of writing of the text of any work included in the body of the thesis. Where a paper has been coauthored, the candidate is required to have made a substantial contribution to the intellectual content and writing of the text. Coauthored work in which the candidate was a minor author can only be used and referenced in the way...
common to any other research publication cited in the thesis. A signature from the corresponding author is required in order to include co-authored material in the body of the thesis, refer to the declarations section below.

For co-authored papers, the attribution of authorship must be in accordance with the Griffith University Code for the Responsible Conduct of Research (https://policies.griffith.edu.au/pdf/gdps/12092019/Responsible%20Conduct%20of%20Research.pdf), which specifies that authorship must be based on substantial contributions in one or more of:

- conception and design of the research project
- analysis and interpretation of research data
- drafting or making significant parts of the creative or scholarly work or critically revising it so as to contribute significantly to the final output.

Some disciplines may specify a variation to the authorship requirement, refer to your Group specific guidelines.

Quality of papers

Candidates should endeavour to publish their research in high quality peer reviewed publications. Papers to be included in the body of the thesis should be published (or submitted for publication) in reputable outlets that are held in higher regard in the relevant field of research. Candidates should consult their supervisor(s) for advice on suitable publications specific to their research discipline. Some disciplines may specify quality standards that must be met for papers to be included, refer to your Group specific guidelines.

The library also provides support and advice to candidates on choosing a journal. Candidates are advised to note in particular advice in order to avoid predatory publishers.


Copyright

As copyright in an article is normally assigned to a publisher, the publisher must give permission to reproduce the work in the thesis and put a digital copy on the institutional repository. Information on how to seek permission is available at: Copyright and Articles in thesis (https://futuresecures.griffith.edu.au/copyright-matters/copyright-guides-for-candidates/articles-in-thesis).

If permission cannot be obtained, students may still include the publication in the body of the thesis, however following examination the relevant chapter(s) will be redacted from the digital copy to be held by the Griffith University Library so that the copyright material is not made publicly available in the institutional repository. Students are required to advise the copyright status of each publication included in the thesis via a declaration to be inserted in the thesis, as detailed below.

Students requiring further advice regarding copyright issues can contact the Information Policy Officer (https://www.griffith.edu.au/services/library/library-business-details.php?library=16723944&campus=Ambynt) on (07) 3735 5695 or copyright@griffith.edu.au.

Group and discipline requirements

Some Groups or Elements may specify additional requirements for including papers within a thesis, refer below:

- Arts, Education and Law
- Griffith Health

Format of thesis

General

Consult the thesis preparation and formatting guidelines (https://www.griffith.edu.au/ugrassesearch/current-research-students/thesis-preparation) for general information about the requirements for formatting the thesis. Some disciplines may specify a variation to the thesis format requirements below, refer to your Group specific guidelines.

Structure of Thesis and linking Chapters

The structure of the thesis will vary depending on whether the thesis is partly or entirely comprised of papers. Whatever the format, the thesis must present as a coherent and integrated body of work in which the research objectives, relationship to other scholarly work, methodology and strategies employed, and the results obtained are identified, analysed and evaluated.

In general every thesis should include a general introduction and general discussion to frame the internal chapters. The introduction should outline the scope of the research covered by the thesis and include an explanation of the organisation and structure of the thesis. The general discussion should draw together the main findings of the thesis and establish the significance of the work as a whole, and should not just restate the discussion points of each paper.

It is important that candidates explicitly argue the coherence of the work and establish links between the various papers/chapters throughout the thesis. Linking text should be added to introduce each new paper or chapter, with a foreword which introduces the research and establishes its links to previous papers/chapters.

Depending on the context of the papers) and nature of research, a research methods chapter may also be necessary to ensure that any work that is not included in the paper(s), but is integral to the research, is appropriately covered. Any data omitted from a paper may also be included as an addendum to the thesis.

For further information on the thesis structure, refer to the following examples of acceptable ways to format the thesis when including papers.

- See Examples of Table of Contents (https://www.griffith.edu.au/__data/assets/pdf_file/0007/567726/Examples-of-Table-of-Contents.pdf)

Format of papers

The papers may be rewritten for the thesis according to the general formatting guidelines; or they can be inserted in their published format, subject to
Pagination
Candidates may repaginate the papers to be consistent with the thesis. However, this is at the discretion of the candidate.

Declarations
All theses that include papers must include declarations (https://www.griffith.edu.au/higher-degree-research/document-research-students/thesis/preparation/formatting) which specify the publication status of the paper(s), your contribution to the paper(s), and the copyright status of the paper(s). The declarations must be signed by the corresponding author (where applicable). If you are the sole author, this still needs to be specified. The declaration will need to be inserted at the beginning of the thesis, and for any co-authored papers, additional declarations will need to be inserted at the beginning of each relevant chapter. You may wish to consult the declaration requirements for inclusion of papers (https://www.griffith.edu.au/higher-degree-research/document-research-students/thesis/preparation/formatting) diagram to ensure that you insert the correct declaration(s) within the thesis. Please note that completion of the declaration(s) does not negate the need to comply with any other University requirement relating to co-authored works as outlined in the Griffith University Code for the Responsible Conduct of Research (https://www.griffith.edu.au/higher-degree-research/document-research-students/candidate/requirements/publishing).
Appendix 2

**SEMI-STRUCTURED INTERVIEW – TEA ESTATE MANAGERS**

[Interview will only be undertaken if respondent has provided informed consent, as evidenced by completion of a Consent Form.]

<table>
<thead>
<tr>
<th>Geographical location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What is the agro-ecological region of the estate?</td>
</tr>
<tr>
<td>2. What is the elevation (tea growing region) of the estate?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Socio-demographic characteristics of manager</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Can you tell me your age and your experience in tea estate management?</td>
</tr>
<tr>
<td>4. Can you tell me about your educational qualifications?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Climate change</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Have you heard of the term ‘climate change’ or ‘global warming’?</td>
</tr>
<tr>
<td>6. What is your view about climate change?</td>
</tr>
<tr>
<td>7. Do you believe that climate change is real?</td>
</tr>
<tr>
<td>8. According to your knowledge, what sort of things are causing climate change?</td>
</tr>
<tr>
<td>9. Which changes in climate have you observed during your time in estate management?</td>
</tr>
<tr>
<td>10. Can you tell me more about your observations of changes in temperature?</td>
</tr>
<tr>
<td>11. Can you tell me more about your observations of changes in rainfall pattern and distribution?</td>
</tr>
<tr>
<td>12. How sensitive is tea production in your experience to ongoing climate change?</td>
</tr>
<tr>
<td>13. How do you receive information on climate change?</td>
</tr>
<tr>
<td>14. What is your opinion about the availability of information on climate change?</td>
</tr>
<tr>
<td>15. How do you think tea production will be affected by future climate changes?</td>
</tr>
<tr>
<td>Question</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>16. How has tea production been affected by drought?</td>
</tr>
<tr>
<td>17. Can you describe how high intensity rainfall has affects tea?</td>
</tr>
<tr>
<td>18. How has climate change affected soil condition on your estate?</td>
</tr>
<tr>
<td>19. What do you think about pest and disease incidences and changes in climate?</td>
</tr>
<tr>
<td>20. Have climate disasters caused damages to infrastructure, property, landslides or loss of lives on your estate?</td>
</tr>
<tr>
<td>21. Tell me about your observations on labour participation during extreme weather events?</td>
</tr>
<tr>
<td>22. Please describe how you think tea production will be affected overall by climate change.</td>
</tr>
<tr>
<td>23. What changes in climate have you observed during the quality season over past years?</td>
</tr>
<tr>
<td>24. Can you describe your current adaptation measures to climate change?</td>
</tr>
<tr>
<td>25. What is your preferred adaptation option? Why?</td>
</tr>
<tr>
<td>26. Have any constraints prevented you from adopting preferred climate adaptation option? Can you tell me about them?</td>
</tr>
</tbody>
</table>
HREC Final Report - Complete

Fri, Jun 16, 2017 at 3:42 PM

rims@griffith.edu.au <rims@griffith.edu.au>
To: j.smart@griffith.edu.au, a.tularam@griffith.edu.au,
rpdayani.gunathilaka@griffithuni.edu.au
Cc: research-ethics@griffith.edu.au

Dear Dr Jim Smart

I write in relation to your approved protocol "NR: Economic approaches for identifying robust climate change adaptation options for plantation crops: A case study on tea production in Sri Lanka - (Qualitative phase)" (GU Ref No: 2014/837).

I can confirm your Final Ethical Conduct Report has been received and your protocol has now been recorded as ‘Complete’.

Ms Marnie Lawson