INTEGRATING SEASONAL CLIMATE FORECASTS WITH ROBUSTA COFFEE MODEL ACROSS THE AGRICULTURAL LANDSCAPES OF VIETNAM

A Thesis submitted by

Vivekananda Mittahalli Byrareddy

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ABSTRACT

Seasonal climate variations, extreme climatic events, particularly drought, and management practices such as fertiliser application and irrigation are among the factors affecting substantially Robusta coffee (*Coffea canephora*) production. In Vietnam, which is the world's largest Robusta coffee-producing country, the enhanced climate variability in recent decades significantly affected coffee production. Improved seasonal climate forecasts (SCF) integrated to Robusta coffee models are critical to reducing climate risk and capitalising on the opportunities. However, the methods to harness such integrated forecasting systems at the required temporal and spatial scales remain very much unknown or underutilised in Vietnam.

This Ph.D. project research aimed at addressing this vital question by developing an integrated SCF-Robusta coffee production model for yield forecasting, capable of simulating reliably Robusta coffee growth and predict yield under different environmental conditions and management practices at the regional scale. Specifically, we aimed to (1) characterise the fertiliser and irrigation management practices across the study area (the Central Highlands region of Vietnam) and develop empirical relationships between yields, fertiliser and irrigation; (2) assess drought impacts on coffee yield and profit, and the effectiveness of the mitigation strategies; (3) investigate the improvement of the simplified biophysical Robusta coffee model, the USQ-Robusta coffee model, through the integration of fertiliser and irrigation components; and (4) test the capability of integrating SCF and the modified version of the USQ-Robusta coffee model to forecast probabilistic coffee yields at sufficient lead times.

Farms data including management practices and coffee yield were collected randomly across the four major Vietnamese Robusta coffee-producing provinces (Dak Lak, Dak Nong, Gia Lai and Lam Dong) from 558 farmers over ten years (2008–2017). Climate data were retrieved from the US National Aeronautics and Space Administration's Prediction Of Worlwide Energy Resources website. SCF derived from five selected prediction systems were sourced from the Climate Change Service website and from the University of Southern Queensland-Centre for Applied Climate Sciences (USQ-CACS)'s seasonal climate forecasting system.

Four types of chemical (urea, blended NPK, superphosphate and potassium chloride) and two types of natural (organic compost and lime) fertilisers were used routinely across the study provinces. The overuse of chemical fertilisers (double the recommended rates of N:P:K at 192:88:261 kg ha^{-1}) did not result in higher yields in the majority of cases. The analysis of irrigation practices showed that, with adequate management practices, substantial water savings can be achieved: up to 26% reduction annually from the current levels (909 - 1818 L $plant^{-1}$). With irrigation being typical in coffee farming, the majority of surveyed farmers adopted mulching in drought years and were best rewarded compared to their counterparts who did not (10% increase in gross margins on average). Our study also revealed that while drought reduced Robusta coffee yield by 6.5% on average, its impacts on gross margins were noticeable, with a 22% decline on average from levels achieved in average-rainfall-condition years. Improving the impacts of water stress on yield throughout the growth season in the USQ-Robusta coffee model resulted in better model performance. The existing water stress component was modified based on crop water requirements derived from the CROPWAT model. Prediction errors were reduced: up to 21% decrease of RMSE. Further, the probabilistic yield forecasting using SCF for May to November 2019 showed satisfactory results generally, with the median yield variance ranging from 0.26 to 0.29 t ha^{-1}.

Improved management of fertiliser and irrigation, and crop diversification are options to enhance the profitability of coffee farming systems. This research knowledge could serve as a decision support tool for farmers and the coffee industry in business planning and climate risk management.

Keywords: Robusta coffee, seasonal climate forecasts, biophysical model, irrigation, fertiliser, drought adaptation strategy

CERTIFICATION OF THESIS

This Thesis is the work of ***Vivekananda Mittahalli Byrareddy*** except where otherwise acknowledged, with the majority of the authorship of the papers presented as a Thesis by Publication undertaken by the Student. The work is original and has not previously been submitted for any other award, except where acknowledged.

Vivekananda Mittahalli Byrareddy — *23 February 2020*

Ph.D. Candidate — Date

Endorsement

Prof. Roger C. Stone — *23 February 2020*

Principal Supervisor — Date

Prof. Shahbaz Mushtaq — *23 February 2020*

Associate Supervisor — Date

Dr Louis Kouadio — *23 February 2020*

Associate Supervisor — Date

Student and supervisors signatures of endorsement are held at the University.

STATEMENT OF CONTRIBUTION

The articles produced from this study were a joint contribution of the student and supported by the supervisory team. The details of the scientific contribution of each author in the publications are provided below:

- **Article I:** Vivekananda Byrareddy, Louis Kouadio, Shahbaz Mushtaq, and Roger Stone, (2019). "Sustainable production of Robusta coffee under a changing climate: A 10-year monitoring of fertiliser management in coffee farms in Vietnam and Indonesia". *Agronomy* 9: 499. (*Impact Factor: 2.259 and SNIP: 1.266, Scopus rated Q1, 84th percentile in Agronomy and crop science*).
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  The overall contribution of Vivekananda Byrareddy was 60% to the concept development, analysis, drafting and revising the final submission; Louis Kouadio contributed 30% to concept development, statistical analysis and providing critical technical inputs; Shahbaz Mushtaq and Roger Stone contributed 5% each respectively, for editing and provided the comments on the manuscript.

- **Article II:** Vivekananda Byrareddy, Louis Kouadio, Jarrod Kath, Shahbaz Mushtaq, Vahid Rafiei, Michael Scobie, and Roger Stone (2020). "Win-win: Improved irrigation management saves water and increases yield for Robusta coffee farms in Vietnam". *Agricultural Water Management 241:106350.* (*Impact Factor: 3.542 and SNIP: 2.109, Scopus rated Q1, 94th percentile in Earth-Surface processes*).
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  Article IV: Vivekananda Byrareddy, Louis Kouadio, Torben Marcussen, Shahbaz Mushtaq, and Roger Stone (2020). "Improving the prediction of Robusta coffee yields at the regional scale using a simplified biophysical crop model". (To be submitted to European Journal of Agronomy)

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Major contribution in collaborative research papers generated from this study data:

Louis Kouadio, Ravinesh C Deo, Vivekananda Byrareddy, Jan F Adamowski, Shahbaz Mushtaq, Van Phuong Nguyen (2018). "Artificial intelligence approach for the prediction of Robusta coffee yield using soil fertility properties". Computers and Electronics in Agriculture *155*: 324-338. (*Impact Factor: 3.171. and SNIP: 1.833, Scopus rated Q1, 98th percentile in* Horticulture).
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Jarrod Kath, Vivekananda Mittahalli Byrareddy, Alessandro Craparo, Thong Nguyen-Huy, Shahbaz Mushtaq, Loc Cao, Laurent Bossolasco (2019). "Not so robust: Robusta coffee production is highly sensitive to temperature". Global Change Biology 2020;00:1–12. (Impact Factor: 8.88 and SNIP: 2.614, *Scopus rated Q1,99th percentile in* Global and Planetary Change).
DOI : https://doi.org/ 10.1111/gcb.15097

Jarrod Kath, Vivekananda Mittahalli Byrareddy, Alessandro Craparo, Thong Nguyen-Huy, Shahbaz Mushtaq, Loc Cao, Laurent Bossolasco (2019). "Adverse temperature and rainfall interactions negatively influence coffee bean characteristics". (To be submitted to Climate Risk Management).

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ABBREVIATIONS

Abbreviations	Definition
C3S	Climate Change Service
CACS	Centre for Applied Climate Sciences
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici
CWR	Crop Water Requirement
DWD	Deutscher Wetterdienst
ECMWF	European Centre for Medium-Range Weather Forecasts
ETc	Crop evapotranspiration
FAO	Food and Agricultural Organization of the United Nations
GCM	General Circulation Model
GSOV	General Statistics Office of Vietnam
ICO	International Coffee Organisation
IDH	Sustainable Trade Initiative
IPCC	Intergovernmental Panel on Climate Change
IWR	Irrigation Water Requirement
K_2O	Potassium
KCl	Potassium chloride
LAI	Leaf Area Index
LF	Large-scale farms
MAPE	Mean Absolute Percentage Error
MARD	Ministry of Agriculture and Rural Development
M.A.S.L	Meters above sea level
Mg	Magnesium
N	Nitrogen
NASA	National Aeronautics and Space Administration
NCHMF	Hydro-Meteorological Forecasting of Vietnam
NPK	Blended NPK
P_2O_5	Phosphate
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
RUE	Radiation Use Efficiency
S	Sulphur
SCF	Seasonal Climate Forecasts
SF	Small-scale farms
SFRI	Soils and Fertilisers Research Institute
SLA	Specific Leaf Area
SMS	Sustainable Management Services
SOI	Southern Oscillation Index
SP	Superphosphate
TCI	The Climate Institute
UKMO	United Kingdom Meteorological Office
USQ	University of Southern Queensland

Abbreviations	Definition
VND	Vietnamese Dong
WASI	Western Highland Agriculture and Forestry Science Institute

Chapter 1

Introduction

1.1 Background

Coffee is one of the top traded agricultural commodities worldwide (Capa et al. 2015; De Beenhouwer et al. 2015), with Vietnam being the second-largest producing country and largest Robusta coffee (*Coffea canephora*) exporting country (60% of global Robusta exports) (FAO 2016). The annual variation in Robusta coffee production is often obvious because of changes in rainfall patterns and variable growing conditions. In this regard, seasonal climate forecasts (SCF) are essential aids to crop husbandry practices. SCF are now being routinely released with the expectation that this information will improve crop and resource management.

Over the longer term, global circulation models that project climate variations and changes indicate a likely increase in mean temperatures and altered precipitation levels in Vietnam (IPCC 2014). In Vietnam, the overall temperature in the Central Highlands is expected to increase by 1.8ºC by 2050 (Bunn et al. 2015). As a result of temperature changes, current areas of Robusta coffee production in the Central Highlands are in general, expected to decrease significantly by 2050 (Laderach et al. 2011). However, regions where no coffee is grown currently may well become suitable in the future, especially in the higher altitudes around the Central Highlands (Laderach et al. 2011; Bunn et al. 2015). As a result, traditional coffee-growing regions would be reduced in size, or even disappear, and new areas may appear with the shifting of coffee production to higher elevations (Laderach et al. 2011). Therefore, the coffee industry needs to develop appropriate site-specific mitigation and adaptation strategies for both the short and long terms to guarantee coffee supply as well as to support improved livelihoods for rural communities (Laderach et al. 2011). Although the Central Highlands region may become suitable for coffee growing, it is problematic because it is among the most drought-prone regions in Vietnam (Nguyen 2005). Considerable crop losses have been reported in recent decades. In the years 2015-2016 the Central Highland region was profoundly affected by drought, resulting in 152,000 ha of agricultural land being impacted (Nguyen 2005). Therefore, there is a need for the development of sustainable coffee farming systems to manage drought risks and thus to minimise the socio-economic impact on the farm families. For these reasons, mitigation and adaptation strategies such as irrigation, diversification of coffee farms through intercropping with fruit trees or agroforestry, are adopted (DaMatta 2004; Dias et al. 2007).

Climate and weather-related risk assessments consider factors that may go wrong in farm system management due to changing environmental conditions (Ramesh et al. 2010). Coffee production has been found to be particularly sensitive to variations in precipitation and temperature, the two most important determinants of climatic suitability (Chemura et al. 2016). Any scientific breakthroughs in SCF capabilities are much more likely to have an immediate and positive impact if they are conducted and delivered within such a framework (precipitation and temperature) with decisions aided by simulation output. These decisions range from tactical crop management options to commodity marketing and to policy decisions (Meinke and Stone 2005).

Skillful seasonal models for predicting El Niño/Southern Oscillation variations would allow a more accurate prediction of global rainfall distributions, thus leading to better management of world agricultural production as well as improving profits and reducing risks for farmers. But the current ability for such a prediction is limited. The Southern Oscillation Index (SOI) phase system (Stone et al. 1996) provides the rainfall probability distributions 3–6 months in advance for regions worldwide, and can readily be incorporated into various crop management systems (Stone et al. 1996; Stone et al. 2000). There has been a growing interest in integrating SCF into crop simulation models because of the potential to add value to agricultural production. Probabilistic crop yield forecasts are directly relevant to farmers for planning farm activities and exploring market opportunities. Integrated SCF-crop modelling may play a genuine, but limited, role in efforts to support climate risk management in agriculture, but only if used appropriately and with an understanding of its capabilities and limitations (Hansen and Indeje 2004; Hansen 2005).

In Vietnam, the dry season (January - April) coincides with flowering and fruit set stage and irrigation is crucial to achieve satisfactory yield levels (Carr 2001; Amarasinghe et al. 2015). It has been documented that farmers are applying double the irrigation amounts than is recommended by the Vietnam Ministry of Agriculture and

Rural Development (MARD), often exceeding the crop water requirement (D'haeze et al. 2005; D'haeze 2008; Amarasinghe et al. 2015; MARD 2016). Over-irrigating has led to excessive ground water tapping and a decline in water tables (D'haeze et al. 2003; Nguyen and Sarker 2018). Coffee is harvested as a cherry; this includes pulp and parchment which are often not returned to the field and so are lost to the system (Krishnan 2017). Moreover, substantial rates of chemical fertilisers are being used in Robusta coffee production than in other crops in Vietnam (Dzung et al. 2011; Kuit et al. 2013). Hence, there is a need for developing improved sustainable irrigation and fertiliser management strategies in coffee farms.

1.2 Statement of Problem

Because the year-to-year climatic variations due to global warming has already altered rainfall patterns in several coffee-growing regions worldwide, and given this trend is likely to continue or worsen in the coming years, it is fundamental to broaden our understanding of climate variability and associated changes and their impact on coffee production in these regions. Vietnam is one of the few countries that receives the majority of its rainfall in a single rainfall regime (NCHMF 2014), whereby coffee crops are subjected to a 4–5 months drought period. Thus, farmers rely on irrigation to synchronize flowering and bud initiation, save the plant during the dry periods and boost their production.

Crop simulation models have been widely used to describe systems and processes at different levels and spatial scales: from the genotype to the plant level, from the farm scale to the region to the national to the global scale. However, it is essential to ensure the effective dissemination of the outcomes to the potential beneficiaries (farmers, trading firms, governments and other decision-makers). Coffee yield forecasting relies substantially on the quality and availability of model's inputs, and on the assumption that weather and climate are the main factors affecting bean yields. The studies on Robusta coffee models for yield forecasting are very limited. The Centre for Applied Climate Sciences of the University of Southern Queensland (USQ-CACS) has developed a simplified, process-based biophysical model for simulating Robusta coffee growth (hereafter referred to as USQ-Robusta coffee model) at the regional scale to investigate the potential for probabilistic coffee yield forecasting within a SCF-crop modelling system in Vietnam (Kouadio et al. 2015).

Although the interannual climate variability was captured satisfactorily by the model in three of the major Robusta coffee-producing provinces (Dak Lak, Gia Lai, and Lam Dong) (Kouadio et al. 2015), further improvements were necessary to better take into account crop water requirements throughout the growth season, as well as the potential impacts of fertilisers on yield.

To date, the majority of coffee trading companies estimate coffee production based solely on field and farmer surveys. Besides being time-consuming and labour-intensive, such methodologies of production estimates involve assumptions that are often not appropriate under in-season climate variability conditions. This approach also critically affects the final important production forecasts leading to errors in yield estimation. With the integration of SCF with a proper coffee model which targets coffee growing regions, a substantial reduction in the error/risk of weather/climate variables in production forecasting is likely. Additionally, utilising SCF on a year-by-year basis can substantially facilitate longer-term climate change adaptation through incrementally shifting farm and agribusiness management practices according to the seasonal (and long term) forecasts, even though these forecasts are necessarily probabilistic. Currently, due to a lack of appropriate SCF, it is difficult for farmers to make timely decisions on farming practices like irrigation, fertiliser use, pesticide application and time of harvest. Therefore, advanced SCF is likely to help farmers and agribusiness in making decisions relating to on-farm practices, which can reduce the cost of cultivation and increase profits. Importantly, the use of SCF can improve the accuracy of production estimates which helps the coffee industry in its strategic decisions. The integrated Robusta production model will study the SCF on the crop periodically combined with irrigation and fertiliser use.

1.3 Research Aims and Objectives

The main purposes of this research are to: (1) investigate the improvement of the USQ-Robusta coffee model for predicting yield at the regional scale through the development and embedding of modules which capture the impacts of irrigation and fertilizers on yield; and (2) investigate the capability of the integrated SCF-crop modelling system for coffee yield forecasting with sufficient lead times. Such yield outlooks would have considerable applications in the global coffee industry (farmers and, especially, traders) to improve risk management significantly in the industry. Specifically, this project aims to:

1. characterise the fertiliser and irrigation management practices across the study area (the Central Highlands region of Vietnam) and develop empirical relationships between yields, fertiliser and irrigation.

2. investigate both the impact of drought on coffee yield and profit, and the factors influencing the adoption of drought risk management strategies.

3. finally, integrate fertiliser and irrigation components into the current SCF - Robusta coffee model for improved yield or production prediction.

1.4 Scope and Limitations

To achieve these objectives, the work was segmented into distinct tasks as follows:

a) The fertiliser amount, types and patterns were characterised using 10-year (2008-2017) survey data collected across the major Robusta coffee-producing provinces in Vietnam (Dak Lak, Dak Nong, Gia Lai, and Lam Dong). The different fertiliser management strategies and the potential for improved sustainable fertiliser management in coffee farms were also reviewed.
b) Irrigation management designs and strategies, and crop water requirement across the provinces were investigated. We quantified the potential coffee yield gain to additional irrigation during the critical irrigation period using hierarchical Bayesian modelling.
c) Using the 10-year (2008-2017) survey data, the drought impact on yield and financial returns was assessed. Coffee farmers' perceptions on drought and its effects were reviewed. Periodically, drought occurs across the Vietnamese coffee-growing provinces, resulting in noticeable impacts on yield and economic returns. We investigated the drought mitigation strategies adopted across the study provinces and their drivers using logit regression modelling.
d) Coffee yield forecasting and SCF are essential for the coffee industry and farmers for relevant business decisions like planning farm operations, marketing, risk management, etc. We investigated two approaches of embedding new components dealing with irrigation and fertiliser into the USQ-

Robusta coffee model. Further, we assessed the capability of the modified USQ-Robusta coffee model coupled with SCF data from five prediction systems to forecast coffee yields at sufficient lead times (up to 6 months before harvest).

There are various limitations to our study. These include:

Lack of availability of historical rainfall distribution, lack of soil types and fertility status, impact of pests and disease, impact of planting densities/other intercrops and availability of varietal type data, the variety was not considered in the analyses, so this prevented the development of a very refined integrated Robusta model

1.5 Thesis Organisation

This thesis is presented as a Ph.D. by publications and is subdivided into four main chapters. A general conclusions section that summaries the findings and contributions of this study was included.

A total of four high-quality articles produced from this research, are presented below:

- **Article I:** Vivekananda Byrareddy, Louis Kouadio, Shahbaz Mushtaq, and Roger Stone, (2019). "Sustainable production of Robusta coffee under a changing climate: A 10-year monitoring of fertiliser management in coffee farms in Vietnam and Indonesia". *Agronomy* 9: 499. (*Impact Factor: 2.259 and SNIP: 1.266, Scopus rated Q1, 84th percentile in Agronomy and crop science*).
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- **Article II:** Vivekananda Byrareddy, Louis Kouadio, Jarrod Kath, Shahbaz Mushtaq, Vahid Rafiei, Michael Scobie, and Roger Stone (2020). "Win-win: Improved irrigation management saves water and increases yield for Robusta coffee farms in Vietnam". *Agricultural Water Management* 241: 106350. (*Impact Factor: 3.542 and SNIP: 2.109, Scopus rated Q1, 94th percentile in Earth-Surface processes*).
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- **Article III:** Vivekananda Byrareddy, Louis Kouadio, Shahbaz Mushtaq, Jarrod Kath, and Roger Stone (2019). "Coping with drought: Lessons learned from Robusta coffee growers in Vietnam". Climate Services (Under review, submitted on 09 February 2020). (Impact Factor: 3.66 and SNIP: 1.381, *Scopus rated Q1,81st percentile in Atmospheric Science*).
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- **Article IV:** Vivekananda Byrareddy, Louis Kouadio, Torben Marcussen, Shahbaz Mushtaq, and Roger Stone (2020). "Improving the prediction of Robusta coffee yields at the regional scale using a simplified biophysical crop model". (To be submitted to European Journal of Agronomy).

The ***first objective*** of this study (subdivided into two studies) was to review and understand the fertiliser use patterns and irrigation management strategies across the Robusta coffee-growing provinces in Vietnam. In Chapter II (***Article I*)**, the analysis shows that four inorganic fertilisers (blended NPK, superphosphate, potassium chloride and urea) and two natural fertilisers (compost and lime) were routinely used in Vietnam. Moreover, inorganic fertilisers were applied at constant high rates from year to year. Chapter III (***Article II***) reviewed the irrigation requirements and potential yield gain by applying additional irrigation. We found that in dry years various irrigation amounts were applied: between 1364 and 1818 L tree^{-1} in Dak Lak and Gia Lai; and between 909 and 1364 L tree^{-1} in Dak Nong and Lam Dong. The relationships between yields, irrigation amounts and fertiliser rates, derived from the hierarchical Bayesian modelling served as basis for the analyses in Chapter IV.

The ***second objective*** of this study (Chapter IV / ***Article III***) investigated 1) farmers' perceptions of drought and its impact on yield and resources, 2) the drought impacts on yield and economic returns, and 3) mitigation strategies adopted by farmers. Overall, our results show that coffee yields were reduced by 6.5% in drought years; the economic impact was 22% compared to average rainfall conditions years. The majority of farmers (58%) adopted mulching as drought mitigation strategy, with financial benefits being on average 10.2% compared to their counterparts who do not adopt mulching. The chances of adopting mulching as mitigation strategy increased with one unit increase in rainfall at the start of the season.

The ***third objective*** of this study (Chapter V / ***Article IV***) investigated two approaches for embedding fertiliser and irrigation components into the current version of the USQ-Robusta coffee model to reduce prediction errors. We also reviewed the integration of SCF into the improved version of the USQ-Robusta for probabilistic yield forecast at the regional scale. Overall, the improved Robusta coffee model captured satisfactorily the interannual yield variability in the study provinces; good agreements between predicted and observed yields were also found. Coupling SCF from five prediction systems to the improved version of the USQ-Robusta model showed that coffee yields can be forecast at sufficient lead time (up to six months before harvest) using such a system.

A schematic flowchart is presented in Fig. 1.1 to depict the links between the studies and articles of this thesis.

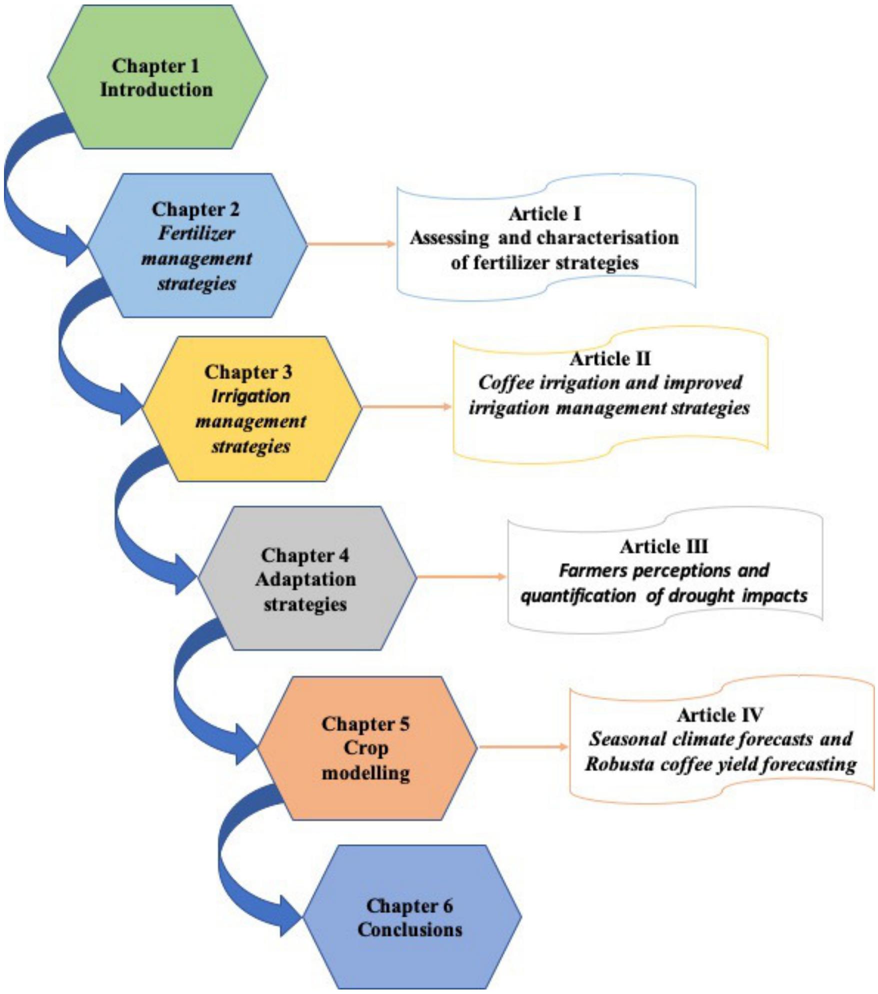

Fig. 1.1. Flow diagram of the thesis

1.6 Summary

Robusta coffee is critically important for the economy and farmers of Vietnam but also requires substantial irrigation due to climate variability leading to scarcity of water resources. Developing clear recommendations for improved irrigation water management, comparative assessment and advice of fertiliser use is critical to profits and, while maintaining or increasing yield is, therefore, an essential knowledge need for the coffee industry. Conducting traditional crop surveys, and estimating and forecasting the production/yields over large areas is a challenging task. The coffee stakeholders are facing difficulties in business planning and risk management with the current yield forecasting techniques. The improved Integrated SCF-Robusta Coffee Model is expected to assist in handling the risks in coffee production based on different weather and climate forecasting scenarios and is thus likely to assist stakeholders in the coffee industry in making far better business decisions. This research knowledge is expected to be used in other coffee-producing countries as a benchmark for developing crop forecasting models.

Chapter 2

Fertiliser management strategies - A critical review

Article I: A 10-year monitoring of fertiliser management in coffee farms in Vietnam*

Vivekananda Byrareddy, Louis Kouadio, Shahbaz Mushtaq, Roger Stone

Centre for Applied Climate Sciences, Institute for Life Sciences and the Environment, University of Southern Queensland, Toowoomba, 4350 Queensland, Australia

*Note: This chapter is derived from the full paper entitled "Sustainable production of Robusta coffee under a changing climate: A 10-year monitoring of fertiliser management in coffee farms in Vietnam and Indonesia". Agronomy 9: 499. http://dx.doi.org/10.3390/agronomy9090499.

Abstract

Assessing and prescribing fertiliser use is critical to profitable and sustainable coffee production, and this is becoming a priority concern for the Robusta coffee industry. In this study, annual survey data of 558 farms across selected Robusta coffee-producing provinces in Vietnam between 2008 and 2017 were used to comparatively assess the fertiliser management strategies. Specifically, we aimed to characterise fertiliser use patterns in the key coffee-growing provinces and discuss the potential for improving nutrient management practices. Four types of chemical (blended NPK, superphosphate, potassium chloride and urea) and two of natural (compost and lime) fertilisers were routinely used in Vietnam. Farmers in Vietnam applied unbalanced quantities of chemical fertilisers (i.e., higher rates than the recommendation of $N:P_2O_5:K_2O$ at 192:88:261 kg ha^{-1}) and at a constant rate between years, without resulting to higher yields in the majority of cases. The overuse of chemical fertilisers in Vietnam threatens the sustainability of Robusta coffee farming. Nevertheless, there is a potential for improvement in nutrient management and

sustainability of Robusta coffee production by adopting the best local fertiliser management practices.

1. Introduction

Coffee is one of the top-traded agricultural commodities worldwide (Capa et al. 2015; De Beenhouwer et al. 2015). It is cultivated in over 50 countries and covers more than 11 million ha around the world (ICO 2019). Coffee plays a crucial role in the economies of producing countries (e.g., the gross domestic product largely depends on coffee export revenues with the sector employing an important proportion of the rural population (Krishnan 2017; ICO 2019). The two economically important coffee species—Arabica (*Coffea arabica* L.) and Robusta (*C. canephora* Pierre ex A. Froehner)—account for about 99% of world coffee production (DaMatta et al. 2007; Kamala Bai 2011; ICO 2019) with Arabica representing roughly 60%.

Producing healthy coffee plants throughout the growth cycle, particularly during sensitive phenological stages (flowering, cherry development, and bean filling) requires sufficient levels of mineral nutrients such as nitrogen (N), phosphorus (P) and potassium (K) in the soil to avoid any nutrient stress (Snoeck and Lambot 2008; Coffee Guide 2014). This pre-supposes suitable environmental conditions (air temperature, water availability, the intensity of sunshine, soil type, wind and land topography) and other management practices (such as pest and disease control and pruning) (DaMatta et al. 2007; Descroix and Snoeck 2008). In perennial crops like coffee, fertilisers applied to replace the nutrients removed during the harvest and address the nutrient need during the following growth cycle. Coffee is harvested as a cherry; this includes pulp and parchment which are often not returned to the field and so are lost to the system (Willson 1985). It has been estimated that the major nutrients removed in one ton of coffee green beans maybe 33–63 kg N, 2–11 kg P_2O_5 and 47–67 kg K_2O depending on soil type and fertiliser application (Willson 1985; Descroix and Wintgens 2008; Snoeck and Lambot 2008; Jessy 2011; Coffee Guide 2014). In the Central Highlands of Vietnam, the nutrient removal from Robusta coffee farms has estimated to average 33 kg N, 1 kg P_2O_5 and 30 kg K_2O for each ton per hectare of green beans harvested (ignoring nutrient losses from leaching and erosion) (Tiemann et al. 2018).

In the coffee industry, sustainability has become a paramount concern over the past several years. Developing sustainable agricultural production systems involves dealing with various and interrelated aspects including water management, land capability and use, biodiversity, energy, soil quality, farm production and productivity, and socio-economic issues (Pretty 2008; Kouadio and Newlands 2015). Of particular interest for coffee is the implementation of environmentally-friendly and sustainable production practices (Krishnan 2017). The coffee industry's growth in the major producing countries is expected to be fueled over the next years given an increased activity at both consumer and trade levels from both domestic and foreign players. Given its economic importance and the environmental risks and vulnerabilities that its production could pose or face, the coffee industry requires special attention.

The main purpose of this study was to provide a detailed characterisation of one of the most important management practices in coffee production—fertiliser application—for the top coffee-producing regions in South-East (SE) Asia, namely Vietnam. Assessing and prescribing fertiliser use is critical to ensure profitable and sustainable coffee production systems.

Vietnamese coffee production averaged 1.46 million metric tons during 2014–2017 for about 597,000 hectares harvested (GSOV 2017) and coffee production is dominated by Robusta coffee—95% in Vietnam (D'haeze et al. 2005; GSOV 2017). The production of Vietnam represents about 40% of global Robusta coffee production (Amarasinghe et al. 2015; FAO 2016), and ranks second worldwide (FAO 2016).

In Vietnam, a combination of factors including local institutional reforms in the 1980s, state-sponsored migration, suitable land for production and infrastructure investment in irrigation, has accelerated the expansion of coffee farms and led to an increase in coffee production over the 1990s and 2000s. The total coffee area has risen from around 22,000 ha in 1980 to approximately 665,000 ha by 2017 (Dung et al. 2009; GSOV 2017). Although the total Vietnamese coffee area has increased by only 33% over 2004–2017 (GSOV 2017), the trend is likely to be on expanding producing areas, but with the potential effect of imbalanced fertiliser application (D'haeze et al. 2005; Tiemann et al. 2018).

Using annual survey data of 558 farms across selected Robusta coffee-producing provinces in Vietnam during the 2008–2017 period (with a total of 5580 observations), the main objective of this study was to comparatively assess fertiliser management strategies. Specifically, the paper aimed to address the following questions: 1) what fertilisers (chemical and organic) were used in Robusta coffee farms over the last ten years?; 2) were there different fertiliser management practices between provinces?; 3) what are the potentials for improved sustainable fertiliser application in Robusta coffee farms? Few papers or published reports have dealt with such topic in Vietnam. As such, our findings will provide further insight into the fertiliser management in Robusta coffee farms in these countries and could help in adopting environmentally-friendly coffee management practices.

2. Materials and methods

2.1. Study areas

The study areas in Vietnam located in four provinces of the Central Highlands region are—Dak Lak, Dak Nong, Gia Lai and Lam Dong (Fig. 2.1). These are the leading provinces producing Vietnamese Robusta coffee, accounting for more than 90% of the national production (GSOV 2017). Robusta coffee is typically grown as an unshaded and clean-weeded monocrop in Central Highlands (D'haeze et al. 2017).

A humid tropical climate dominates the Central Highlands region. Climate data over 30 years (1985–2014) showed that the total annual rainfall ranged from 1800 to 3000 mm across the four study provinces (Fig. A2.1). Maximum temperatures were usually above 24 °C, and the average monthly solar radiation ranged from 428 to 698 MJ m^{-2}. Two main types of soils in the Central Highlands region are reddish-yellow acrisols and reddish-brown ferrosols, with coffee trees, are cultivated mostly on the latter (Tien 2015; Tiemann et al. 2018).

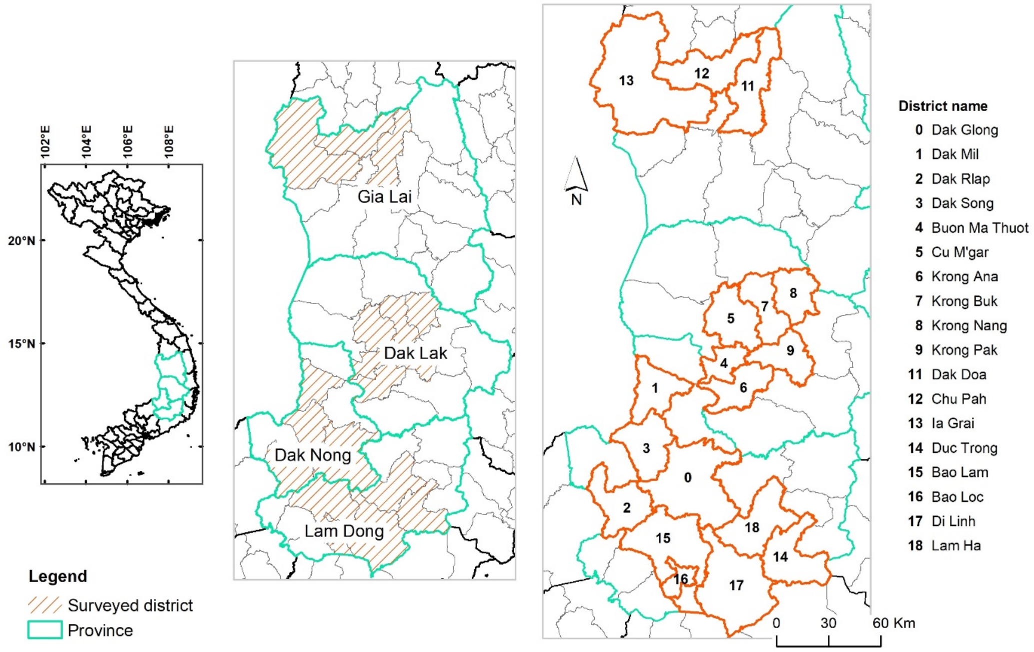

Fig. 2.1. Location of study areas across Vietnamese Robusta coffee-producing provinces. (Source: https://gadm.org/).

2.2. Study design: Annual monitoring of fertilisation management–farmers survey

Data were collected within the Sustainable Management Services (SMS) programme implemented by ECOM Agroindustrial Corporation since 2005 across coffee-producing countries in the Asia Pacific region including Vietnam. The main objective of the SMS programme is to promote more sustainable coffee production and to strengthen traceability and transparency throughout the coffee supply chain. Through the SMS programme, coffee farmers are regularly trained on various aspects of farm management practices (such as balanced fertilisation and soil nutrition improvement, tree stock management, pest and disease control, irrigation, farm bookkeeping, farm diversification and farm certification).

Coffee farm activities are monitored throughout every crop season, with three to four farm surveys each year with farm data collected using designed questionnaires. Questionnaires were translated into the local languages and local agronomists who speak these languages conducted the interviews. Data were managed through the SMS database within ECOM. Farmers also keep their data using farm books, given such information is also valuable in certification programmes.

Within the SMS programme, more than 5000 coffee farmers are enrolled in Vietnam (as of 2018). For this study, a representative random sampling was performed to compile the data from the SMS database over the 2008–2017 period. The selection was based on differences in climate, the proportion of coffee areas, water resources and farm sizes. A total of 558 farmers were selected across 18 districts in the four provinces in Vietnam (Table 2.1). Data of the 2008–2017 period were collected during the last quarterly farm survey in 2017 from 558 farms (5580 observations in total). All farm data were cross-checked with those of the SMS database to verify their consistency.

The data collected consisted of farm characteristics (i.e., altitude, farm area, age of trees, plant density, and yield) and the type and proportion of fertilisers applied. In Vietnam, the differences in management practices related to the irrigation methods, which were either manual or sprinkler. The sampling was carried out in such a way that it represented both irrigation methods. All the data were anonymised before any analysis was performed in this study.

Table 2.1. Sampling design: numbers of districts and participant farmers in Vietnam.

	Vietnam				Total
Province	Dak Lak	Dak Nong	Gia Lai	Lam Dong	4
Number of districts	6	4	3	5	18
Number of farmers	180	120	93	165	558
Total observation	1800	1200	930	1650	5580

Source: survey data 2008–2017.

2.3. Data analyses

The rates of chemical fertilisers were expressed in the total rate of each of the major nutrients nitrogen (N), phosphate (P_2O_5) and potassium (K_2O) in order to have a common basis for comparisons. The recommended fertiliser rates for Robusta coffee were from the Western Highlands Agriculture and Forestry Science Institute (WASI), in Vietnam (MARD 2003; World Bank 2004; Tien 2015; WASI 2015). Although sulphur (S) and magnesium (Mg) are essential nutrients for Robusta coffee, few farmers reported these nutrients during the surveys. These nutrients were therefore discarded in our analyses.

We assessed first the year-to-year variability of fertiliser application at the selected provinces over the 10-year period. Then, the differences in fertiliser application within province and between provinces were compared using a one-way analysis of variance (ANOVA) (significance level = 0.05). The analyses were done according to the farm size. Two groups of farm size were defined for Vietnamese Robusta coffee farms: ‘small-scale’ and ‘large-scale’ farms corresponding to farms with area ≤1 ha, and area >1 ha, respectively. These thresholds were based on those adopted by (World Bank 2004; Marsh 2007) when classifying coffee smallholders.

Further, we assessed the potential for improved fertilisation management strategies, i.e., reducing nutrient rates while maintaining the current levels of Robusta coffee yields. Based on the ranges of observed coffee yields and recommended nutrient rates, the surveys data were analysed under three scenarios of nutrient rates in all provinces.

All the data and statistical analyses were carried out using the R Language and Environment for Statistical Computing (R Core Team 2018) and Microsoft® Office Excel (Redmond, WA, USA).

3. Results

3.1. Background information from the survey

Overall the area of coffee farms ranged from 0.1 to 11.2 ha, with 60% being of size >1 ha (Table 2.2). The planting density ranged from 1000 to 1100 plants ha^{-1}. The farms surveyed were predominantly (67%) located between 500 and 900 M.A.S.L with only 18% of the farms below 500 M.A.S.L and 15% above 900 M.A.S.L (Table 2.2). The age of coffee farms varied between 3 and 29 years in 2008 (start year of the study period), with 89% of the farms being under 20 years old. Fertilisers were applied four times throughout the crop season. Generally, the first application occurs during the blossoming/setting (March–April); the second at the onset of the monsoon (June); the third application occurs during the cherry development stage (August–September); and the last round of application taking place during the bean filling and bud wood development stage (October–November).

Four types of chemical (urea, blended NPK, superphosphate, and potassium chloride) and two types of natural (compost and lime) fertilisers were recorded during the 10-year period across the four study provinces in Vietnam (Table 2.2). Most farmers applied all the four chemical fertilisers: 79% for blended NPK, 98% for superphosphate and potassium chloride, and 100% for urea. The common nutrient content $N–P_2O_5–K_2O$ for blended NPK fertiliser during the survey was 16–8–16 (Table 2.3).

Table 2.2. Characteristics of coffee farms surveyed during the 2008–2017 period in selected provinces in Vietnam and the total number of monitored farms per year was 558.

	min	**max**	**average**
Farm size (ha)	0.1	11.2	1.72
	Small (≤1 ha)	**Large (>1 ha)**	
Farm size group (%)	40	60	
	min	**max**	**average**
Age of tree (years)	3	29	13.2
	≤10 years	**10– 20 years**	**>20 years**
Trees (%)	28	61	11
	≤500 m	501–900 m	
Farm altitude (%)	18	67	15
	Chemical	**Organic**	
Fertiliser users (%)	NPK (79%)	Compost (81%)	
	Super phosphate (98%)	Lime (19%)	
	Potassium chloride (98%)		
	Urea (100%)		

Source: Survey data 2008–2017.

Table 2.3. Fertiliser types recorded in surveyed Robusta coffee farms and their nutrient contents. The recommended nutrient rates for two targeted yield levels in Vietnam (MARD 2003; World Bank 2004; Tien 2015; WASI 2015) are provided.

	Vietnam		
	N (%)	P_2O_5 (%)	K_2O (%)
NPK	16	8	16
Urea	46		
Superphosphate		16	
Potassium chloride			60
	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
Recommendation #1 (2.5–3.0 ton ha^{-1})	192	88	261
Recommendation #2 (3.0–4.0 ton ha^{-1})	248	116	317

3.2. Year-to-year variability of fertiliser use in Robusta coffee farms

The spatial distributions of the 10-year average of the chemical fertilisers as applied during 2008-2017 in Vietnam (urea, blended NPK, superphosphate, and potassium chloride) are provided in Fig. A2.2. For comparison purposes, the observed rates of chemical fertilisers were expressed in the total rate of each of the major nutrients nitrogen (N), phosphate (P_2O_5) and potassium (K_2O) using the values provided in Table 2.3.

3.2.1. N, P_2O_5 and K_2O uses during 2008–2017

In Vietnam, urea and blended NPK, which contributed to total N rates, were included in fertiliser management strategies of most of the surveyed farmers every year (Table 2.2), with their respective rates varying between 1000 to 1400 kg ha^{-1} and 400 to 800 kg ha^{-1} (Fig. A2.2). The dominant nutrients provided through the chemical fertilisers during 2008–2017 in all provinces were N and K_2O, regardless of the farm size (Fig. 2.2). For example in Dak Nong, the amounts of K_2O were among the highest compared to the three remaining provinces Dak Lak, Gia Lai and Lam Dong. For all nutrients and in all provinces, 2014 was the year with lower rates applied (Tables 2.4 and A2.1).

Comparing the average rates of each nutrient N, P_2O_5 and K_2O within a given province over the 10-year survey, our analyses revealed that there was no statistical difference between the rates of P_2O_5 and K_2O applied every year, irrespective of the province and farm size (Table A2.1). With regard to the average rates of N, small-scale farmers in each of the provinces applied similar N rates (i.e., not statistically different, $p > 0.05$) in the majority of the study years, except in 2014 (Table 2.4), though there seemed an alternate use of low and high N rates from year to year after 2011. This alternative trend was also found in large-scale farms across all provinces. Large-scale farmers in Lam Dong were among those applying different (statistically significant, $p < 0.05$) N rates from year to year. In the remaining provinces Dak Lak, Dak Nong or Gia Lai, similarities between years with lower N rates or between years with higher N rates were found (Table 2.4).

Table 2.4. Comparison of nitrogen rates (N kg ha^{-1}) between years according to the farm size in Vietnamese Robusta coffee-producing provinces. Number with a similar letter in a given row are not statistically different ($p > 0.05$). SF: small-scale farms; LF: large-scale farms.

		2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Dak Lak	SF	379a	379a	402a	402a	379a	402a	351b	402a	379a	402a
	LF	388ab	388ab	411a	411a	388ab	411a	365b	411a	388ab	411a
Dak Nong	SF	435ab	435ab	477a	477a	435ab	477a	408b	477a	435ab	477a
	LF	435ab	435ab	480a	480a	435ab	480a	407b	480a	435ab	480a
Gia Lai	SF	369ab	369ab	403a	403a	369ab	403a	347b	403a	369ab	403a
	LF	381ab	381ab	398a	398a	381ab	398a	359b	398a	381ab	398a
Lam Dong	SF	464ab	464ab	504a	504a	464ab	504a	422b	504a	464ab	504a
	LF	475b	475b	511a	511a	475b	511a	438c	511a	475b	511a

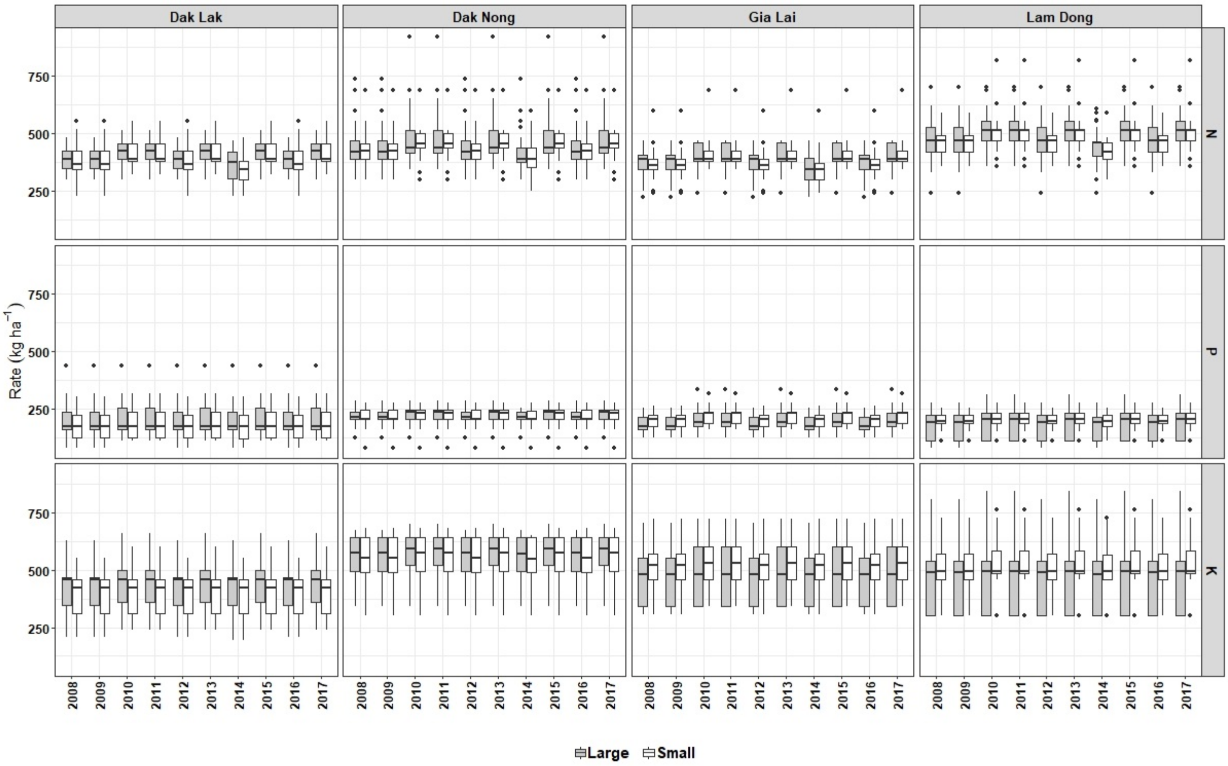

Fig. 2.2. Year-to-year variations of nutrient rates in large- and small-scale Robusta coffee farms for each of the study provinces in Vietnam during the 2008–2017 period. The rates of nitrogen (N), phosphate (P_2O_5, referred to as P) and potassium (K_2O, referred to as K) were calculated based of the nutrient contents of each the chemical fertilisers recorded (see Tables 2.2 and 2.3). In the boxplot, upper and lower borders of the box represent the 3rd and 1st quartiles, respectively. The line within the box represents the median value. Bars extend to the minimum and maximum values. Outliers are represented by black circles. Small-scale farms have area ≤1 ha; large-scale farms have area >1 ha.

3.3. Comparisons of fertiliser use in Robusta coffee farms between provinces

Generally, small-scale farm holders in Dak Lak and Gia Lai applied similar N rates during the study period ($p > 0.05$; Table 2.5). The average rates ranged from 369 to 403 kg ha^{-1} and were lower and statistically different from those applied in Dak Nong and Lam Dong. Across these latter provinces, homogenous patterns of N rates were observed (i.e., not statistically different, $p > 0.05$; Table 2.5), with average values ranging from 408 to 504 kg ha^{-1}. Likewise, in large-scale farms in Dak Lak and Gia Lai, similar N management strategies were adopted. A difference was found in large-scale farms between Dak Nong and Lam Dong was observed, with those in the Lam Dong applying higher N rates (438–511 kg ha^{-1}) (Table 2.5).

Regarding P_2O_5 and K_2O, small-scale farmers in Dak Lak behaved differently from those in Dak Nong, Gia Lai and Lam Dong. Lesser rates of P_2O_5 and K_2O were applied, with average values ranging from 177 to 195 kg ha^{-1}, and 400 to 418 kg ha^{-1}, respectively (Table 2.5). The respective rates of P_2O_5 and K_2O in the other provinces ranged from 190 to 224 kg ha^{-1}, and from 496 to 558 kg ha^{-1}, on average. In large-scale farms, P_2O_5 and K_2O management strategies were similar across Gia Lai and Lam Dong in all years, i.e., no statistically different rates applied ($p > 0.05$; Table 2.5). The common pattern between these provinces and Dak Lak was only found for P_2O_5 management. In Dak Nong, large-scale farmers behaved differently from their counterparts in the three other provinces, applying higher rates of P_2O_5 and K_2O in all years.

Table 2.5. Comparison of fertiliser use between provinces in small- and large-scale farms in Vietnam during 2008–2017. For a given farm size group, numbers with a similar letter in a given row are not statistically different ($p > 0.05$).

Year	Small-scale				Large-scale			
	Dak Lak	Dak Nong	Gia Lai	Lam Dong	Dak Lak	Dak Nong	Gia Lai	Lam Dong
	N (kg ha^{-1})							
2008	379b	435a	369b	464a	388c	435b	381c	475a
2009	379b	435a	369b	464a	388c	435b	381c	475a
2010	402b	477a	403b	504a	411c	480b	398c	511a
2011	402b	477a	403b	504a	411c	480b	398c	511a
2012	379b	435a	369b	464a	388c	435b	381c	475a
2013	402b	477a	403b	504a	411c	480b	398c	511a
2014	351b	408a	347b	422a	365c	407b	359c	438a
2015	402b	477a	403b	504a	411c	480b	398c	511a
2016	379b	435a	369b	464a	388c	435b	381c	475a
2017	402b	477a	403b	504a	411c	480b	398c	511a
	P_2O_5 (kg ha^{-1})							
2008	181b	216a	202ab	191ab	193b	215a	184b	183b
2009	181b	216a	202ab	191ab	193b	215a	184b	183b
2010	195b	224a	216ab	201ab	205ab	225a	199b	191b
2011	195b	224a	216ab	201ab	205ab	225a	199b	191b
2012	181b	216a	202ab	191ab	193b	215a	184b	183b
2013	195b	224a	216ab	201ab	205ab	225a	199b	191b
2014	177b	215a	202a	190ab	187b	214a	184b	182b
2015	195b	224a	216ab	201ab	205ab	225a	199b	191b
2016	181b	216a	202ab	191ab	193b	215a	184b	183b
2017	195b	224a	216ab	201ab	205ab	225a	199b	191b
	K_2O (kg ha^{-1})							
2008	402b	549a	509a	496a	423c	557a	471bc	473b
2009	402b	549a	509a	496a	423c	557a	471bc	473b
2010	418b	558a	525a	515a	440c	574a	486bc	486b
2011	418b	558a	525a	515a	440c	574a	486bc	486b
2012	402b	549a	509a	496a	423c	557a	471bc	473b
2013	418b	558a	525a	515a	440c	574a	486bc	486b
2014	400b	547a	509a	495a	419c	556a	471b	472b
2015	418b	558a	525a	515a	440c	574a	486bc	486b
2016	402b	549a	509a	496a	423c	557a	471bc	473b
2017	418b	558a	525a	515a	440c	574a	486bc	486b

3.4. Organic fertilisers use in Robusta coffee farms in vietnam

In Vietnam, compost and lime were the natural fertilisers used in the surveyed farms. Compost was prepared from coffee husks, cuttings from orchards and fields and animal manure. These materials were composted using microbial solutions and were applied once decomposed. Given the lack of adequate materials and its time-consuming preparation, farmers used to divide their farms in two and applied compost in alternate years. All Robusta coffee farmers surveyed in Dak Lak were applying compost in the same years (Table A2.3) at between 8 and 20 ton ha^{-1}, higher rates than applied in the other provinces (Fig. A2.3). In Dak Nong and Lam Dong, most of the farmers followed the same pattern while using compost in alternate years. The lowest average compost rates were recorded at Lam Dong (~10 ton ha^{-1}). Lime was applied at 1–2 ton ha^{-1} across the four provinces with the lowest rates observed in Lam Dong (Fig. A2.3).

3.5. Potential for reducing nutrient rates in Robusta coffee farms

Different yield levels (<2.5 ton ha^{-1}, between 2.5 and 3 ton ha^{-1}, and >3 ton ha^{-1}) were analysed under three different rates for each of the nutrients N, P_2O_5 and K_2O. To investigate as to whether those nutrient rates can be reduced while maintaining current yield levels, the recommended rates of N, P_2O_5 and K_2O for attaining 2.5–3 ton ha^{-1} (recommendation #1 in Table 2.3) were chosen to define the different categories of nutrient rates used in our analysis (Tables 2.6 and 2.7).

Small-farmers in Dak Nong and Lam Dong applied predominantly >384 kg ha^{-1} of N, with corresponding yields up to 2.95 ton ha^{-1} (Table 2.6, blocks B and D). In Dak Lak and Gia Lai the majority applied between 192 and 384 kg ha^{-1}, with the corresponding yield up to 2.89 ton ha^{-1} (Table 2.6, blocks A and C). In those provinces, there were small-scale farmers who applied >384 kg ha^{-1} of N, while achieving similar yield levels than those applying up to 50% less, suggesting that a reduction of N rates in these farms is possible. In large-scale farms across all provinces, however, the majority of farmers applied >384 kg ha^{-1} N, with varying yield levels achieved depending on the province (Table 2.7). Although large-scale farmers were applying between 192–384 kg ha^{-1}, only a very limited number achieved yields >2.5 ton ha^{-1}.

In P_2O_5 management, there are opportunities to reduce the current rates and maintain the current coffee yield levels for small-scale farmers in provinces like Gia Lai and Lam Dong. In three out of four provinces most small-holders farmers applied >176 kg ha^{-1}: 85%, 74%, 77% of farmers in Dak Nong, Gia Lai and Lam Dong, respectively (Table 2.6, blocks B1, C1 and D1), with corresponding respective yields up to 2.87, 2.89 and 2.95 ton ha^{-1}. In Gia Lai and Lam Dong, particularly, similar yield levels were reported for P_2O_5 rates varying between 88 and 176 kg ha^{-1}, suggesting a potential for reducing P_2O_5 rates. In large-scale farms, such potentials existed in Dak Lak and Gia Lai. In these provinces, although the majority of large-scale farmers applied between 88–176 kg ha^{-1}, with corresponding yields up to 3.3 ton ha^{-1} (Table 2.7, blocks A and C), farmers who were applying >176 kg ha^{-1} and were achieving in some instance <2.5 ton ha^{-1}, could have improved their management strategies and achieved better yield levels while reducing P_2O_5 rates.

Regarding K_2O management, K_2O was predominantly applied between 261 and 522 kg ha^{-1} in both small- and large-scale Robusta coffee farms across Dak Lak, Gia Lai and Lam Dong (Tables 2.6 and 2.7). In Dak Nong the dominant category was >522 kg ha^{-1} (62% and 63% for small- and large-scale farms, respectively) with corresponding coffee yields of up to 3.45 ton ha^{-1} on average (Tables 2.6 and 2.7, blocks B1–2). For this latter province, some farmers 12% and 20% of the sample in small-and large-scale farms, respectively—reported similar yield levels (up to 3.29 ton ha^{-1}) while applying 261 to 522 kg ha^{-1}, suggesting the potential for reducing K_2O rates. However, for the remaining three provinces, no conclusive indication can be drawn from our dataset regarding the potential of reducing K_2O rates while achieving satisfactory yield levels.

Table 2.6. Variations of Robusta coffee yields under different categories of N, P_2O_5 and K_2O rates in small-scale farms for each of the study provinces in Vietnam. Pct. sample: sample distribution from all the 2008–2017 dataset (expressed in %); Avg. yield: average coffee yield (ton ha^{-1}).

	N (kg ha^{-1})			P_2O_5 (kg ha^{-1})			K_2O (kg ha^{-1})		
Levels	≤192	192–384	>384	≤88	88–176	>176	≤261	261–522	>522
A. Dak Lak									
A1. Pct. sample									
< 2.5	-	34	30	1.9	34	28	2	59	3
2.5–3.0	-	15	15	0.1	17	13	1	27	2
> 3.0	-	3	3	-	3	3	-	6	0
A2. Avg. yield									
< 2.5	-	2.11	2.14	2.01	2.12	2.14	2.17	2.11	2.29
2.5–3.0	-	2.81	2.84	2.56	2.84	2.82	2.86	2.82	2.87
> 3.0	-	3.6	3.45	-	3.4	3.62	-	3.47	4.21
B. Dak Nong									
B1. Pct. sample									
< 2.5	-	9	57	1	8	57	-	26	40
2.5–3.0	-	2	23	1	3	22	-	8	17
> 3.0	-	2	7	1	1	6	-	4	5
B2. Avg. yield									
< 2.5	-	2.13	2.13	2.03	2.16	2.13	-	2.14	2.13
2.5–3.0	-	2.85	2.86	2.92	2.82	2.87	-	2.84	2.87
> 3.0	-	3.19	3.41	3.13	3.34	3.39	-	3.26	3.45
C. Gia Lai									
C1. Pct. sample									
< 2.5	-	25	20	-	12	33	-	27	18
2.5–3.0	-	22	15	-	10	27	-	19	18
> 3.0	-	9	9	-	4	14	-	7	11
C2. Avg. yield									
< 2.5	-	2.28	2.22	-	2.31	2.23	-	2.26	2.24
2.5–3.0	-	2.89	2.86	-	2.86	2.89	-	2.89	2.87
> 3.0	-	3.43	3.35	-	3.35	3.41	-	3.35	3.42
D. Lam Dong									
D1. Pct. sample									
< 2.5	-	3	34	-	10	28	-	26	11
2.5–3.0	-	4	29	-	8	25	-	23	10
> 3.0	-	2	28	-	5	24	-	16	14
D2. Avg. yield									
< 2.5	-	2.14	2.19	-	2.21	2.18	-	2.19	2.17
2.5–3.0	-	2.96	2.95	-	2.96	2.95	-	2.95	2.95
> 3.0	-	3.36	3.46	-	3.44	3.46	-	3.43	3.48

Table 2.7. Variations of Robusta coffee yields under different categories of N, P_2O_5 and K_2O rates in large-scale farms for each of the study provinces in Vietnam. Pct. sample: sample distribution from all the 2008–2017 dataset (expressed in %); Avg. yield: average coffee yield (ton ha^{-1}).

	N (kg ha^{-1})			**P_2O_5 (kg ha^{-1})**			**K_2O (kg ha^{-1})**		
Levels	≤192	192–384	>384	≤88	88–176	>176	≤261	261–522	>522
A. Dak Lak									
A1. Pct. sample									
< 2.5	-	24	36	0.6	30	30	7	47	6
2.5–3.0	-	9	24	0.3	17	16	3	26	5
> 3.0	-	2	5	0.1	3	3	-	5	1
A2. Avg. yield									
< 2.5	-	2.18	2.19	2.14	2.18	2.19	2.13	2.19	2.21
2.5–3.0	-	2.74	2.77	2.71	2.76	2.76	2.75	2.75	2.82
> 3.0	-	3.27	3.23	3.06	3.27	3.22	-	3.24	3.23
B. Dak Nong									
B1. Pct. sample									
< 2.5	-	5.7	44	-	8	42	-	17	33
2.5–3.0	-	4	36	-	6	34	-	16	24
> 3.0	-	0.3	10	-	1	9	-	4	6
B2. Avg. yield									
< 2.5	-	2.24	2.19	-	2.21	2.2	-	2.24	2.18
2.5–3.0	-	2.83	2.8	-	2.81	2.8	-	2.8	2.8
> 3.0	-	3.29	3.31	-	3.27	3.31	-	3.29	3.32
C. Gia Lai									
C1. Pct. sample									
< 2.5	-	23	29	-	27	25	-	35	17
2.5–3.0	-	14	20	-	18	15	-	23	10
> 3.0	-	7	7	-	6	9	-	9	6
C2. Avg. yield									
< 2.5	-	2.16	2.12	-	2.12	2.16	-	2.12	2.18
2.5–3.0	-	2.79	2.82	-	2.8	2.82	-	2.81	2.79
> 3.0	-	3.26	3.28	-	3.3	3.25	-	3.29	3.24
D. Lam Dong									
D1. Pct. sample									
< 2.5	-	2	24	0.2	8	18	-	19	7
2.5–3.0	-	3	35	0.6	12	25	-	28	10
> 3.0	-	3	33	0.2	11	25	-	25	11
D2. Avg. yield									
< 2.5	-	2.24	2.24	2.39	2.26	2.23	-	2.24	2.24
2.5–3.0	-	2.88	2.83	2.79	2.82	2.83	-	2.83	2.83
> 3.0	-	3.34	3.32	3.28	3.31	3.33	-	3.32	3.33

4. Discussion

4.1. Were coffee farmers following the fertiliser recommendations?

In Vietnam, the recommended rates of N, P_2O_5 and K_2O in Robusta coffee farms vary according to the targeted yield (Table 2.3). The rates of nutrients applied in Robusta coffee farms in Vietnam during the 10-year survey were generally higher than those recommended. Compared to countries such as Thailand, or the Philippines (Marsh 2007), coffee farmers in Vietnam are applying noticeably higher rates of fertilisers. The general trend of overusing fertilisers found in this study was in line with the conclusions from previous studies (D'haeze 1999; D'haeze et al. 2005; Marsh 2007; Tien 2015; Tiemann et al. 2018), although in these studies only one or two provinces were involved. We observed form the surveyed farmers, generally apply higher than recommend fertiliser rates for guaranteed higher/targeted yields regardless of the soil types and soil conditions. This is an important aspects and part of an ongoing analysis in the de-risk project at CACS, USQ, Australia and would be part of the future publication.

One of the findings of this study by assessing all the major coffee-producing provinces in Vietnam indicates that farmers were generally following similar practices in terms of the rates of fertilisers applied across those provinces. The monitoring also revealed that Vietnamese Robusta coffee farmers tended to follow an "aggressive" approach while applying fertilisers—"the more fertilisers you can apply, the better your plants stay nutrient-stress free throughout the growth cycle and increase your capacity to maintain the same yield performance from year to year". However, the relationships between the coffee yields and fertiliser rates showed no strong correlation between the yield and fertiliser rate (Fig. A2.4). The high use of fertilisers in Vietnam could also be explained, in part, by the affordability of fertilisers to most coffee farmers through governmental subsidies (Minot 1998; The Voice Of Vietnam 2014; Thang and Phuc 2016). In addition, the price of coffee beans has been satisfactory to farmers over the last decade (despite its volatility) (Fig. 2.3).

In Vietnam, the recommended rates of lime and compost were 1 ton ha^{-1} $year^{-1}$ and 5–8 ton ha^{-1} $year^{-1}$, respectively (depending on the targeted yield of 2.5–4.0 ton ha^{-1}) (WASI 2015). The rates recorded were generally greater than those recommended, but given the alternate application might not be sufficient to meet the requirement each season. It was not clear whether the alternations of low and high applications of N, P_2O_5 and K_2O observed, at least between 2012 and 2017, could be related to the alternate use of organic fertilisers during these particular years. It was out of the scope of this study to determine the N, P_2O_5 and K_2O concentrations in compost in the surveyed farms. Further investigations across the study areas on the combined use of chemical and organic fertilisers, and on the farmers' perceptions about such uses, would provide valuable guides in the best fertiliser management practices in Vietnam.

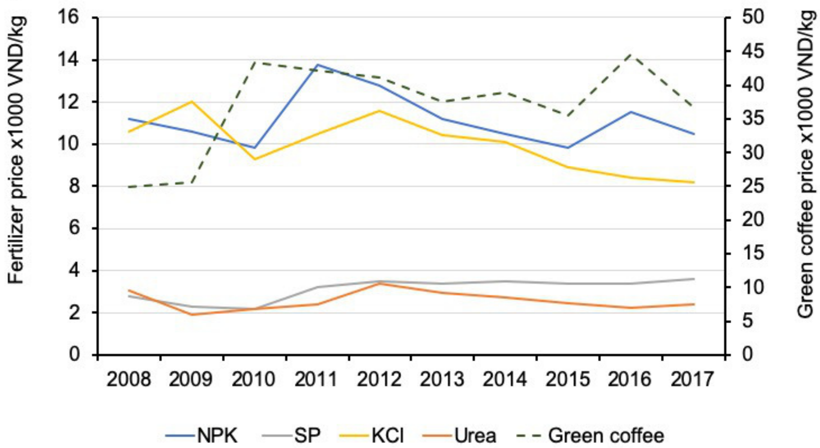

Fig. 2.3. Average prices of the top three fertilisers and green Robusta coffee in Vietnam during the 2008–2017 period. Coffee prices were sourced from the International Coffee Organization (http://www.ico.org/new_historical.asp). VND: Vietnamese Dong. NPK: blended NPK; SP: superphosphate; KCl: potassium chloride.

4.2. Challenges for a sustainable management of fertilisers

Robusta coffee farmers in Vietnam were applying high rates of chemical fertilisers at constant rates from year to year. More chemical fertilisers are being used in coffee production than in other crops in Vietnam (Dzung et al. 2011; Kuit et al. 2013). Although intensive fertiliser use in Robusta coffee farms has led to increased yields during the previous decades (Scherr et al. 2015; Minh et al. 2016), the dependence on chemical fertilisers may not be sustainable in the long term. Such intensive use of chemical fertiliser can reduce soil fertility through increased soil acidity, reduction of beneficial microorganisms, increased unstable aggregates leading to erosion and degradation (Dung et al. 2009; Kouadio et al. 2018). Intensive use of fertiliser can also impact water quality, thereby leading to sustainability issues. Chemical fertilisers such blended NPK, when applied intensively over long periods, could also cause the depletion, or accumulation, of other plant nutrients in the soil (Kebede and Mikru 2005). This could lead to reduced yields and production (Nyalemegbe et al. 2010; Nguyen and Sarker 2018; Tiemann et al. 2018).

Investigating the potential for reducing nutrient rates in coffee farms in Vietnam based on our dataset showed that there are opportunities for reducing the higher rates observed during the study period by up to 50% in some instances, depending on the nutrient and farm size, while achieving current yield levels (Tables 2.6 and 2.7). However, for nutrients like K_2O, no conclusive indication can be drawn from our dataset regarding the potential of reducing the current rates while achieving satisfactory yield levels. This is because there were few or no reports in the majority of the selected provinces of such patterns. Optimum management of fertilisers involving lower rates than those recorded during the survey could still maintain satisfactory yields. For example, Bruno et al. (2011) reported that a routine nitrogen fertiliser rate of 600 kg ha^{-1} could be reduced by one-third without decreasing the production of coffee beans in commercial Arabica coffee farms in Brazil. Similar conclusions were drawn in Costa Rica (Hergoualc'h et al. 2008). Further research is therefore needed to investigate fertiliser use efficiencies in farm conditions, especially in Vietnam, and improve current fertiliser management practices for sustainable production.

The optimal combined use of chemical and organic fertilisers to ensure satisfactory bean yields is of great interest for Robusta coffee farms in Vietnam. The use of organic fertilisers, such as compost, in coffee farms has been shown to improve soil texture, provide a better environment for beneficial microorganisms and to increase water-holding capacity and efficient nutrient use (Dzung et al. 2011; Coffee Guide 2014). Our survey noticed a lack of understanding about nutrient requirements and the role of balanced nutrient supply for coffee plants in the study provinces. In Vietnam, particularly, a large proportion of N–P_2O_5–K_2O fertilisers are blended locally by state-owned enterprises, creating vested interests in the status quo (IDH 2013). Such challenges could be addressed by means such as:

(1) capacity-building and training to shift farmers' practices and raise their awareness of the potential damages of fertiliser overuse to the environment;

(2) establishing demonstration farms to increase the confidence of farmers for adopting best management practices;

(3) introducing policies and incentives encouraging farm diversification (such as agroforestry) to help farmers not to rely solely on coffee for farm profit.

5. Conclusions

We documented the management of fertilisers (chemical and organic) in Robusta coffee farms across selected provinces in Vietnam during the 2008–2017 period. Four types of chemical (urea, blended NPK, superphosphate and potassium chloride) and two types of natural fertiliser (organic compost and lime) were used routinely. Because achieving high yields and maintaining such levels are among the key drivers of fertiliser application in Robusta coffee farms in Vietnam, chemical fertilisers were generally applied in unbalanced proportions, posing threats to the sustainability of such farming activities, the environment and, more broadly, to the economies of this country.

Our findings showed that there is a potential for improvement in terms of fertiliser management and sustainability of Robusta coffee production. Adopting integrated fertility management practices, increasing the awareness of farmers regarding sustainable practices, and introducing policies to encourage farm diversification are among the options to improve the profitability of coffee farming while ensuring environmentally-friendly crop management practices in these two coffee-producing countries.

This chapter focused on the characterization of the patterns of fertiliser management practices across each of the study provinces. Further analyses based on the chemical fertiliser will be undertaken to investigate the relationships between coffee yields and fertiliser under different climatic conditions (see Chapters 3 and 5). The outcomes of this analysis will serve as basis for integrating the impacts of fertilisers on Robusta coffee yield into the USQ-Robusta – SCF model (Chapter 5).

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Appendices 2

Table A2.1. Average rates of phosphate (P_2O_5) and potassium (K_2O) according to farm size in Vietnamese Robusta coffee-producing provinces. The annual rates of each nutrient in a given farm size group were not statistically significant ($p > 0.05$). *SF*: small-scale farms; *LF*: large-scale farms.

		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
		Dak Lak									
P_2O_5 (kg ha^{-1})	SF	181	181	195	195	181	195	177	195	181	195
	LF	193	193	205	205	193	205	187	205	193	205
K_2O (kg ha^{-1})	SF	402	402	418	418	402	418	400	418	402	418
	LF	423	423	440	440	423	440	419	440	423	440
		Dak Nong									
P_2O_5 (kg ha^{-1})	SF	216	216	224	224	216	224	215	224	216	224
	LF	215	215	225	225	215	225	214	225	215	225
K_2O (kg ha^{-1})	SF	549	549	558	558	549	558	547	558	549	558
	LF	557	557	574	574	557	574	556	574	557	574
		Gia Lai									
P_2O_5 (kg ha^{-1})	SF	202	202	216	216	202	216	202	216	202	216
	LF	184	184	199	199	184	199	184	199	184	199
K_2O (kg ha^{-1})	SF	509	509	525	525	509	525	509	525	509	525
	LF	471	471	486	486	471	486	471	486	471	486
		Lam Dong									
P_2O_5 (kg ha^{-1})	SF	191	191	201	201	191	201	190	201	191	201
	LF	183	183	191	191	183	191	182	191	183	191
K_2O (kg ha^{-1})	SF	496	496	515	515	496	515	495	515	496	515
	LF	473	473	486	486	473	486	472	486	473	486

Table A2.2. Percentages of farmers applying organic fertilisers during 2008-2017 in the study provinces in Vietnam.

	Compost				Lime			
	Dak Lak (N = 180)	**Lam Dong** (N = 165)	**Dak Nong** (N = 120)	**Gia Lai** (N = 93)	**Dak Lak** (N = 180)	**Lam Dong** (N = 165)	**Dak Nong** (N = 120)	**Gia Lai** (N = 93)
2008	100	79	41	58	78	38	41	52
2009	0	21	60	47	24	61	59	48
2010	100	79	41	58	78	38	41	52
2011	0	22	60	47	24	62	59	48
2012	100	79	41	58	78	38	41	52
2013	0	22	60	47	24	62	59	48
2014	100	79	41	58	78	38	41	52
2015	0	22	60	47	24	62	59	48
2016	100	79	41	58	78	38	41	52
2017	0	22	60	47	24	62	59	48

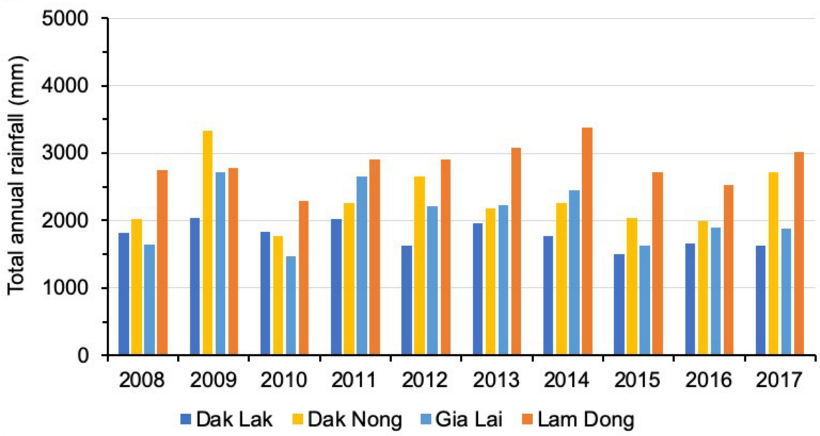

Fig. A2.1. Total annual rainfall at the study provinces in Vietnam (Dak Lak, Gia Lai, Dak Nong, and Lam Dong) during the period 2008-2017.

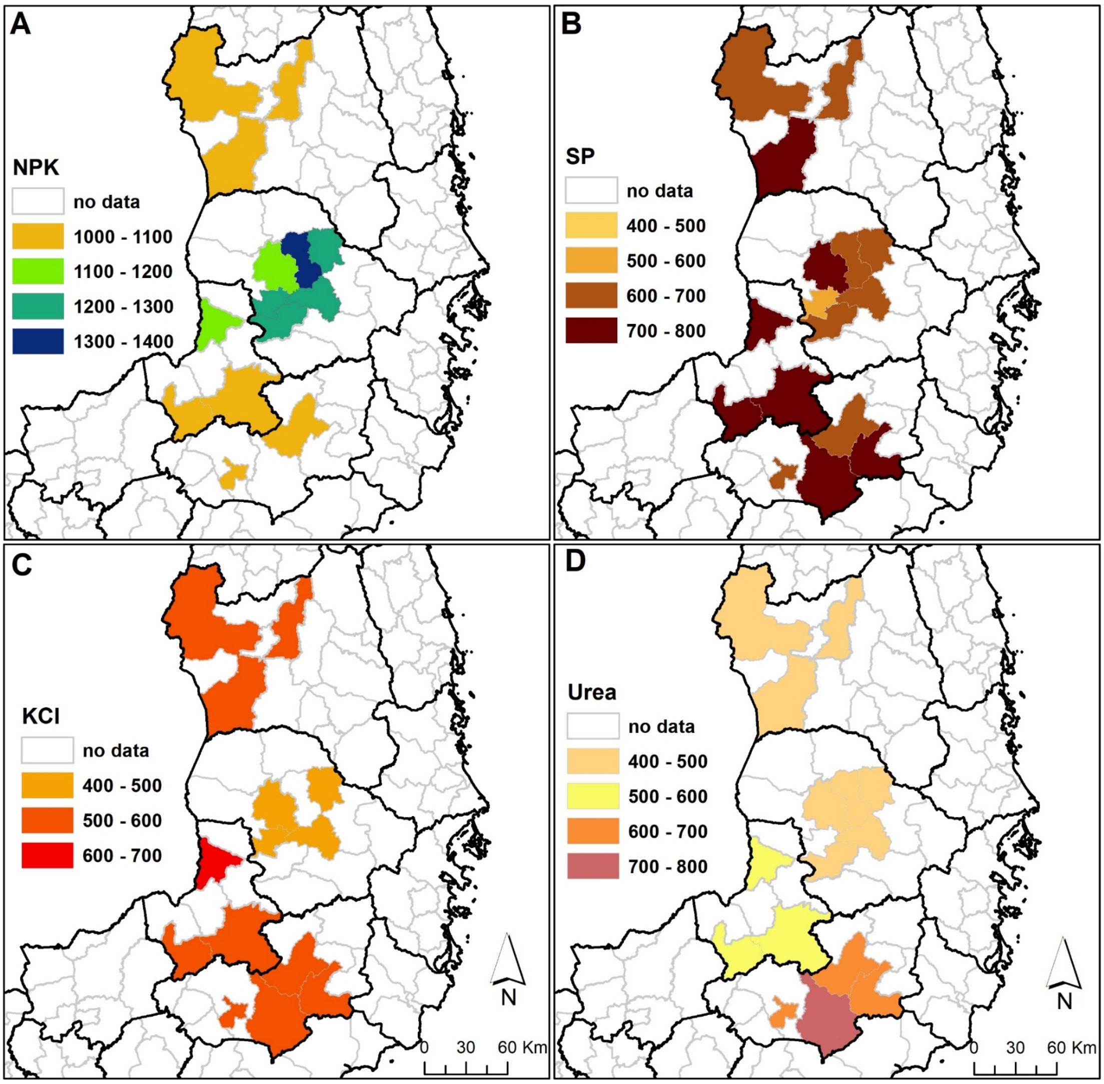

Fig. A2.2. 10-year average (2008-2017) of the fertiliser rates applied across the surveyed districts in Vietnam. (A) blended NPK; (B) superphosphate, SP; (C) potassium chloride, KCl; and (D) Urea. The averages are expressed in kg ha^{-1}.

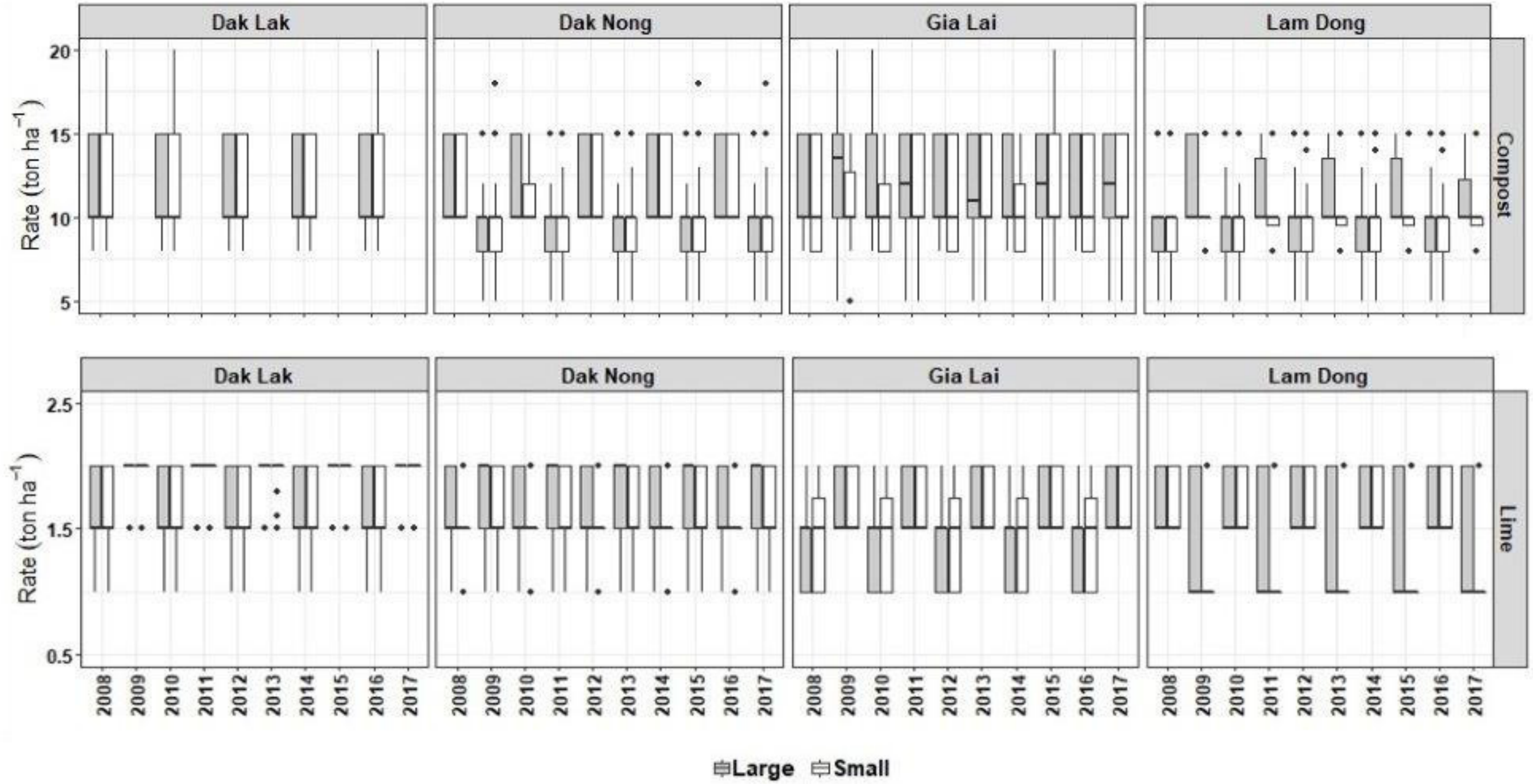

Fig. A2.3. Year-to-year variations of natural fertilisers compost and lime in surveyed Robusta coffee farms in Vietnamese (Dak Lak, Dak Nong, Gia Lai and Lam Dong coffee-producing provinces during 2008-2017. (Note differences on the y-axis.)

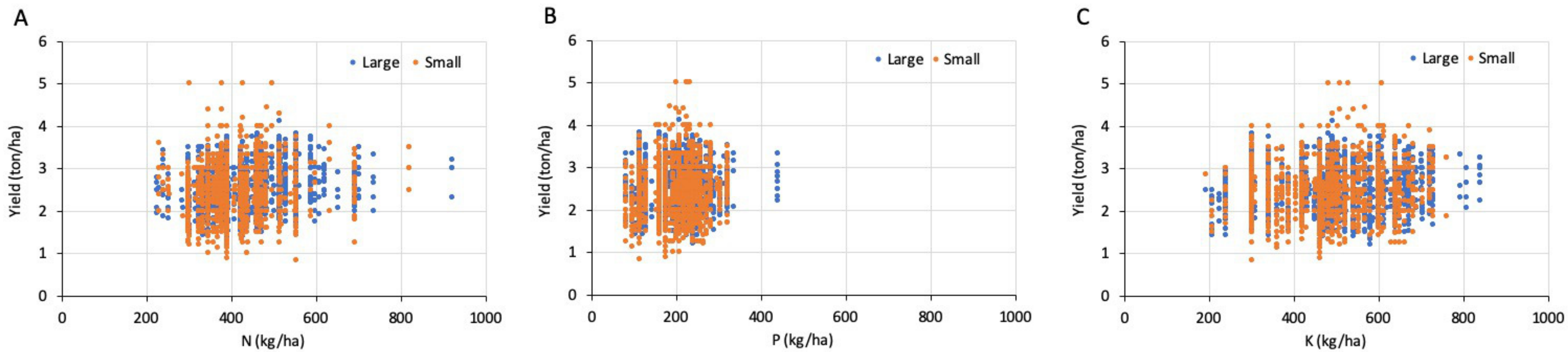

Fig. A2.4. Scatterplots of Robusta coffee bean yields versus annual total amounts of nitrogen (N), phosphate (P_2O_5, referred to as P) and potassium (K_2O, referred to as K) in the study provinces in Vietnam (A-C) during 2008-2017. All data of the 10-year period are presented according to the farm size group (small- and large -scale). Source: Survey data 2008-2017.

Chapter 3

Coffee irrigation requirement and improved irrigation management strategies

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Article II: Win-win: Improved irrigation management saves water and increases yield for Robusta coffee farms in Vietnam

Vivekananda Byrareddy[1], Louis Kouadio[1], Jarrod Kath[1], Shahbaz Mushtaq[1], Vahid Rafiei[1], Michael Scobie[2], Roger Stone[1]

[1] Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, Queensland 4350, Australia
[2] Centre for Agricultural Engineering, University of Southern Queensland, Toowoomba, Queensland 4350, Australia

Abstract

Robusta coffee is critically important for the economy and farmers of Vietnam, but also requires substantial irrigation leading to dwindling water resources. Developing clear recommendations for improved irrigation water management, while maintaining or increasing yield is, therefore, an essential knowledge need for the coffee industry. We analyse 10-cropping-year data (2008/2009 – 2017/2018) of 558 farms across four major coffee-producing provinces in Vietnam's Central Highlands using CROPWAT and hierarchical Bayesian modelling to (1) characterise irrigation management strategies in the surveyed Robusta coffee farms, (2) identify irrigation requirements under different climatic conditions, and (3) investigate the potential for improved irrigation management strategies. In average rainfall years, the majority of farmers in Dak Nong and Lam Dong supplied equivalent to 455–909 L tree^{-1} (assuming 1100 plants ha^{-1}) with corresponding average yields ranging from 2149 to 3177 kg ha^{-1}. In Dak Lak and Gia Lai the predominant range was equivalent to 1364–1818 L tree^{-1} (corresponding average yields: 2190 to 3203 kg ha^{-1}). In dry years more

water was supplied through irrigation at various levels depending on the province: varying between 1364–1818 L tree^{-1} in Dak Lak and Gia Lai, and 909–1364 L tree^{-1} in Dak Nong and Lam Dong. Our study also shows that irrigation water can be reduced by 273 to 536 L tree^{-1} (300–590 m^3 ha^{-1}) annually from the current levels in average rainfall years while still achieving average yield levels greater than 3000 kg ha^{-1}. In dry years reductions of 27 to 218 L tree^{-1} (30–240 m^3 ha^{-1}) are possible. With adequate management of the key crop practices affecting coffee yields, substantial water savings at the provincial scale could be achieved. Thus, our findings could serve as a basis for province-specific irrigation water management in Robusta coffee farms that will not only reduce overall water use but also potentially maintain satisfactory yield levels.

1. Introduction

Low and unreliable rainfall conditions, especially during critical growth stages, can make coffee production challenging in leading coffee-producing countries and impact negatively on the entire global coffee sector. To cope with such adverse patterns and assist with better plant growth conditions and satisfactory yield levels over years, coffee farmers rely on irrigation (D'haeze et al. 2005a; Assis et al. 2014; Amarasinghe et al. 2015; Perdoná and Soratto 2015; Sakai et al. 2015; Boreux et al. 2016; Liu et al. 2016). Irrigation amounts in coffee vary depending on the annual rainfall distribution, the severity of the dry season, and soil type and depth (Carr 2001). In Robusta coffee (*Coffea canephora* Pierre ex A. Froehner) production systems in Vietnam, the second-largest coffee-producing country globally (GSOV 2017; ICO 2019), the need for irrigation during the dry season (January-April) and its role in controlling the timing of flowering is of great importance for achieving high yield (Carr 2001; Amarasinghe et al. 2015).

Coffee production in Vietnam is dominated by Robusta coffee, which accounts for 95% of the national production (GSOV 2017). The irrigation application as advised by the Vietnam Ministry of Agriculture and Rural Development (MARD) is 400 L tree^{-1} per round in three rounds a year, that is 1200 L tree^{-1} year^{-1}, assuming 1100 plants per hectare (MARD 2016; UTZ 2016). However, irrigation data from previous studies indicated an average amount often twice the recommended application amount in provinces like Dak Lak (D'haeze 1999; Luong and Tauer 2006; D'haeze 2008). The major source of irrigation water in coffee-producing provinces in the Central Highlands region is groundwater (Cheesman and Bennett 2005; D'haeze et al. 2005b). Excessive groundwater exploitation, associated with variable rainfall patterns (Hoegh-Guldberg et al. In press), causes groundwater tables to decline and, if not properly addressed, threatens the natural refilling of aquifers, as well as the livelihoods of populations relying on the coffee industry (Minderhoud et al. 2017; Lee et al. 2018).

While characterising Robusta coffee farms under irrigation in Dak Lak, D'haeze (1999) denoted that irrigation amounts usually exceeded the crop water requirement, endangering water resources across this province. Subsequent studies confirmed such conclusions (D'haeze et al. 2003; D'haeze et al. 2005b; Amarasinghe et al. 2015; Nguyen and Sarker 2018). They also outlined strategies for improved irrigation water use and sustainable production in Robusta coffee farms. These include the reduction of irrigation supply during average climatic conditions and capacity building of farmers to better understand on-farm water and input management (D'haeze et al. 2005b; Amarasinghe et al. 2015). These studies were, however, limited to either one district or one province. As such, they might not provide sufficient insights for developing region-specific best irrigation management practices across the Vietnamese coffee-producing provinces, where different environmental conditions are found. Better irrigation management practices while ensuring satisfactory coffee bean yield are therefore key to sustainable coffee production in Vietnam.

Using data of 558 Robusta coffee farms over 10 years (2008/2009 – 2017/2018), the main objective of this study was to provide further insights into existing irrigation management strategies in Robusta coffee farms in Vietnam. Specifically, we aimed to (1) characterise irrigation management patterns and quantify crop water requirements throughout the season in four major Vietnamese Robusta coffee-producing provinces; (2) quantify the potential coffee yield gain to additional irrigation during the critical coffee growth period (blossoming through to fruit set) using hierarchical Bayesian modelling approach, and (3) identify the potential for improved province-specific irrigation management strategies. The findings of this study could serve as a basis for capacity building on best irrigation management practices in Robusta coffee farms in Vietnam and other regions with similar coffee growing conditions.

2. Materials and methods

2.1 Study area

Robusta coffee is typically grown as an un-shaded and clean-weeded monocrop in the Central Highland provinces (Fig. 3.1). Two main soils dominate the Central Highlands region: reddish-yellow Acrisols and reddish-brown Ferrosols, with coffee mostly cultivated on Ferrosols (Tien et al. 2015; Tiemann et al. 2018). A humid tropical climate dominates the Central Highlands. The January-April (JA) period corresponds to the dry season, followed by a rainy season from May to October. Maximum temperatures were normally above 24°C throughout the year, and the average monthly solar radiations ranged from 428 to 698 MJ m^{-2}. Annual rainfalls varied on average between 1800 and 3000 mm in these regions, with more than 2/3 falling during the monsoon season between May and October.

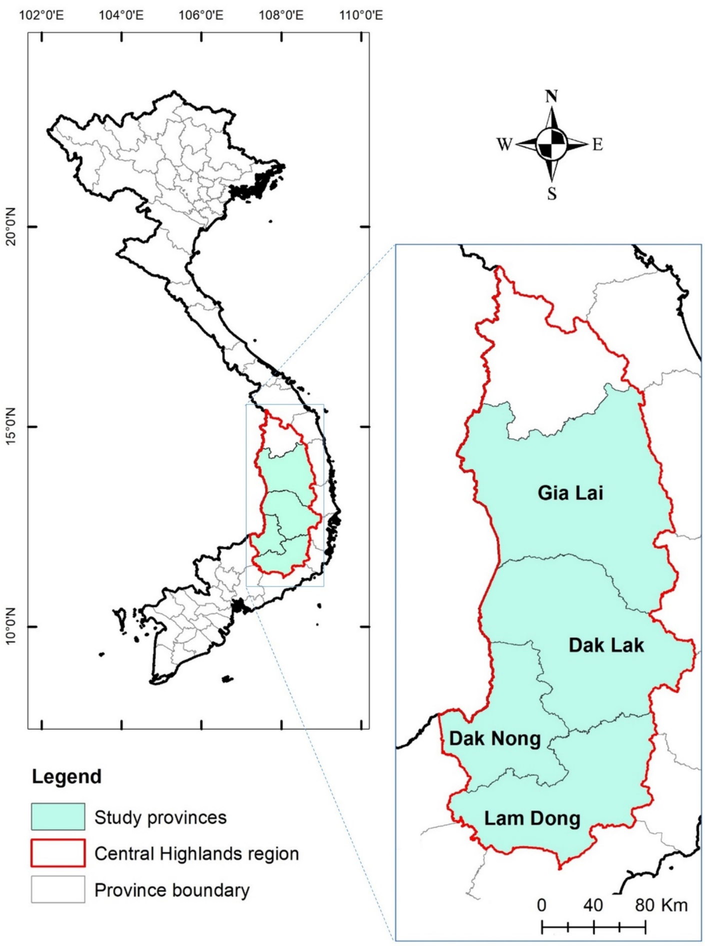

Fig. 3.1. Location of the major coffee-producing provinces in Vietnam. (Source: https://gadm.org/).

2.2 Farm data

Data were collected within the Sustainable Management Services (SMS) program implemented by ECOM Agroindustrial Corporation since 2005 in Vietnam, with more than 5000 coffee farmers enrolled within the program (as of 2018). Coffee farm activities are regularly monitored throughout every crop season, with three to four farm surveys each year and farm data collected using designed questionnaires. Data were managed through the SMS database within ECOM, in addition to records, which are keept by individual farmers.

For this study, a representative sampling was used to compile the data from the SMS database over the 2008–2017 period. The selection was based on differences in farm size, the proportion of coffee areas, climate, and water resources. 558 farmers were selected across 18 districts in the study provinces: 180, 120, 93 and 165 farmers in Dak Lak (6 districts), Dak Nong (4 districts), Gia Lai (3 districts), and Lam Dong (5 districts), respectively. Data of the 2008–2017 period were collected during the last quarterly farms survey in 2017 (5580 observations in total). All farm data were cross-checked with those of the SMS database to verify their consistency. Basin and sprinkler irrigation are the two traditional irrigation methods in Vietnam. The sampling was carried out in such a way that it represented both irrigation methods. The source of irrigation water is mainly from the dug open wells at farms and/or nearby lakes, depending on the province. Plants are irrigated during the dry season (January-April) which coincides with the critical crop stages of blossoming and fruit set. Farmers were trained to monitor the water discharge time by the pump so that they can control the irrigation volumes and keep records.

The farm data collected consisted of farm characteristics (altitude, farm area, age of trees, plant density, and area harvested), coffee yield, amount and frequency of irrigation, and type and proportion of fertilisers applied. Coffee is a perennial crop. In some farms there existed a difference in plant age within the farm due to plant rejuvenation. Nevertheless, the majority of the surveyed coffee farms were matured plantations and were more than 10-years old. All the data were anonymised before any analysis performed in this study.

2.3 Calculations of coffee water and irrigation requirements

The CROPWAT program (version 8) (FAO 2018) was used to determine the potential crop water requirement (CWR) in Robusta coffee farms for each of the study provinces over 2008–2017. All the calculation procedures were based on Allen et al. (1998) and Steduto et al. (2012). The input data were daily climate data (maximum and minimum temperatures, relative humidity, rainfall, sunshine hours, and wind speed), soil data (available water capacity, field capacity, wilting point, and infiltration rate), coffee crop data (phenological stage duration, depletion coefficient, root depth, crop coefficient, yield response factor, and crop height), and observed irrigation data. Soil and crop data used in the calculations are presented in Table 3.1.

Soil data were sourced from Vietnam Soils and Fertilisers Research Institute (http://www.sfri.org.vn). Coffee crop data were retrieved from Allen et al. (1998) and Steduto et al. (2012). Climate data at the district scale from 2008 to 2017 were retrieved from National Aeronautics and Space Administration (NASA)'s Tropical Rainfall Measuring Mission website (https://pmm.nasa.gov/trmm) for rainfall, and Prediction Of Worldwide Energy Resources website (https://power.larc.nasa.gov/) for the remaining climate variables (maximum and minimum temperatures, relative humidity, sunshine hours, and wind speed). The use of satellite-based weather data were justified by the lack of all variables required in CROPWAT at the district scale across the study provinces (only observed rainfall data were available for the majority of districts). Climate data at the district scale were used to take into account the spatial variability of data such as rainfall.

CWR, which corresponds to the amount of water that needs to be supplied to the crop, was calculated as $\mathrm{CWR} = \mathrm{ET_0} \times \mathrm{K_c}$, where ET_0 refers to the reference crop evapotranspiration, and K_c is the crop coefficient. ET_0 was calculated using the FAO Penman-Monteith equation (Allen et al. 1998). CWR was computed under standard conditions, i.e. disease-free, non-limiting nutrient and soil water conditions, and, as such, corresponds to the potential CWR. CWR and effective rainfall were calculated over the January-April (to reflect the sensitive crop stages, as well as irrigation periods) and January-December periods. The irrigation water requirement during the January-April (JA) period was then calculated as the difference between CWR and effective rainfall and was compared against the applied irrigation amounts for each Robusta coffee farms across the selected provinces. We assumed a seepage loss of 20%, that is 80% irrigation efficiency (Amarasinghe et al. 2015).

Table 3.1. Soil and crop parameters used for the calculations in CROPWAT. Red loamy soils are found predominantly in Dak Lak, Dak Nong and Gia Lai; Grey loamy soils are found predominantly in Lam Dong. Soil data were sourced from the Vietnam Soils and Fertilisers Research Institute (SFRI) (http://www.sfri.org.vn). Crop parameters were retrieved from Allen et al. (1998), Steduto et al. (2012) and Amarasinghe et al. (2015).

Soil parameter	Soil type			
	Red Loamy soil	Grey Loamy soil		
Total available soil moisture (mm m^{-1})	180	160		
Initial available soil moisture (mm m^{-1})	144	128		
Maximum rain infiltration rate (mm d^{-1})	30	40		
Initial soil moisture depletion (%)	20	20		
Maximum rooting depth (m)	9	9		
Crop parameter	Crop stage			
	Initial	Development	Mid-season	Late season
Kc (-)	0.93	0.95	0.95	0.93
Stage (d)	85	85	85	110
Rooting depth (m)	1.5	1.5	1.5	1.5
Critical depletion fraction (-)	0.5	0.5	0.5	0.5
Yield response factor (-)	1	1	1	1
Crop height (m)	3	3	3	3

2.4 Empirical relationships between coffee yield and irrigation

Coffee yields were modelled using hierarchical Bayesian modelling, which included random effects to account for potential spatial and temporal correlations. The full model for response variable *y* (i.e. coffee yield) at site *i* at time *j* was as follows:

$$y_{ij} \sim N(\mu_{ij}, \sigma^2) \quad (3.1)$$

with $\mu_{ij} = \alpha + \sum_{j=1}^{p} \beta_j \, x_{ij} + \varepsilon_{\text{year}[j]} + \varepsilon_{\text{site}[i]} + \varepsilon_i$

where α is the intercept; β are the p linear effect parameters and x_{ij} are the (i^{th} level of the j^{th} covariate) p covariates. Error (ε) terms are random spatial effects for year and site, with each being modelled as identically and independently distributed random variables. ε_i are the residuals (i.e. the unstructured random effects).

The predictor variables or covariates were a year (to detrend yields), JA effective rainfall, effective irrigation (effective irrigation is 80% of the supplied irrigation, assuming 20% as seepage loss), and fertiliser. Urea and NPK were the dominant chemical fertilisers applied in all four Robusta coffee-producing provinces during the study period (Byrareddy et al. 2019). Predictors were standardized ($x-\mu_x/\sigma_x$) so effect sizes could be compared (Gelman and Hill 2007). Effective rainfall and effective irrigation were fit with a second-degree polynomial. Two-way interactions between these predictors were included as well. All models were fit using the integrated nested Laplacian approximation from the INLA package (Rue et al. 2009; Lindgren and Rue 2015).

Using the model outputs, the potential yield gain corresponding to the amount of irrigation that needs to be applied in order to achieve the maximum possible yield was investigated for each province. We further assessed the potential for improved irrigation management strategies for each province. Based on the ranges of reported Robusta coffee yields, irrigation amounts, and calculated CWR, two scenarios for coffee yields - average and locally feasible (hereafter referred to as recommended yield) - were analysed for different categories of irrigation amounts and induced water stresses. All data and statistical analyses were performed using the R (R Core Team 2018).

3. Results

3.1 Climate patterns and irrigation practices across the study provinces during 2008–2017

Overall, the total annual rainfall varied between 900 and 2600 mm in all study provinces during 2008–2017, with lower amounts recorded in 2014 (Fig. 3.2a). Increasing annual rainfall was recorded between 2008–2010, and 2014–2017 in the majority of the provinces; the exception was Lam Dong where the annual rainfall decreased between 2008 and 2009. Dak Lak and Gia Lai received less rainfall on average than Dak Nong and Lam Dong. Dak Nong and Gia Lai experienced more dry years during the 2008–2017 period (7 out of 10 years) than Lam Dong or Dak Lak (Table 3.2). In Dak Lak years were particularly dry during 2015–2017. In Lam Dong rainfall patterns were predominantly normal over the study period. Focusing on the critical Robusta coffee growth period of January-April, less than 600 mm rainfall was recorded generally in all provinces, with even lower amounts (< 200 mm) at Gia Lai in 9 out of 10 years (Fig. 3.2b). For this province JA average rainfall during 2008–2017 was only 144 mm, compared to Dak Nong which received around 270 mm on average during the same period if the 2012 exceptional JA rainfall (Fig. 3.2b) is discarded in the calculations.

Irrigation was applied one to four times per year during 2008–2017 across the Robusta coffee-producing provinces (Tables 3.3 and A3.1). The volumes differed significantly between provinces depending on the year ($p < 0.05$; Table A3.1). Plant densities in the surveyed farms were on average 1100 trees ha^{-1}. Dak Lak and Gia Lai were the provinces with higher irrigation amounts (on average 1345 and 1445 L tree^{-1} year^{-1} (148 and 159 mm year^{-1}), respectively), compared to Dak Nong and Lam Dong (on average 973 and 918 L tree^{-1} year^{-1} (107 and 101 mm year^{-1}), respectively) (Table 3.3). In the majority of years, the amounts applied in Dak Lak and Gia Lai were statistically similar ($p > 0.05$). Likewise, the amounts applied in Dak Nong and Lam Dong did not differ statistically (Table A3.1). The irrigation amounts reported also varied depending on rainfall patterns during January-April. For instance, in 2012 or 2017, irrigation was predominantly applied in January-February (2012) or February (2017) in all provinces, with amounts ranging between (327 and 382 L tree^{-1}) 36 and 42 mm. Only at Gia Lai did some farmers irrigated from January to March (Table A3.1).

Table 3.2. Rainfall patterns across the districts in the selected Robusta coffee-producing provinces during 2008–2017. Rainfall records from 1985 to 2014 were used. For the January-December period, dry (D), normal (N) and wet (W) years correspond to years belonging to percentiles 0–30, 30–70, and 70–100, respectively. Likewise, for the January-April period, below-average (BA), average (A) and above-average (AA) years correspond to years belonging to percentiles 0–30, 30–70, and 70–100, respectively.

		January-December										January-April									
Province	District	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Dak Lak	Buon Ma Thuot	D	N	N	D	D	D	D	D	D	N	BA	AA	BA	BA	AA	AA	BA	BA	BA	A
	Cu Mugar	D	N	N	D	D	D	D	D	D	N	BA	AA	BA	BA	AA	AA	BA	BA	BA	A
	Krong Ana	D	N	N	D	D	D	D	D	D	N	BA	A	BA	BA	AA	AA	BA	BA	BA	A
	Krong Buk	D	N	N	D	D	D	D	D	N	N	BA	AA	BA	BA	AA	AA	BA	BA	BA	AA
	Krong Nang	D	D	W	D	D	D	D	D	D	N	BA	AA	BA	BA	AA	AA	BA	BA	BA	AA
	Krong Pak	D	N	N	D	D	D	D	D	N	N	BA	AA	BA	A	AA	AA	BA	BA	BA	A
Dak Nong	Dak GLong	D	D	N	D	D	D	D	D	N	N	BA	A	BA	BA	AA	AA	BA	BA	BA	A
	Dak Mil	D	N	N	D	D	D	D	D	D	N	BA	AA	BA	BA	AA	AA	A	BA	BA	A
	Dak RLap	D	D	N	D	D	D	D	D	N	W	BA	AA	BA	BA	AA	AA	A	BA	BA	A
	Dak Song	D	N	N	D	D	D	D	D	N	N	BA	A	BA	BA	AA	AA	A	BA	BA	A
Gia Lai	Chu Prong	D	D	N	D	D	D	D	D	D	N	BA	AA	BA	A	AA	AA	A	BA	BA	A
	Dak Doa	D	N	N	D	D	D	D	D	D	N	BA	A	BA	BA	AA	AA	A	BA	A	A
	Ia Grai	D	N	D	D	D	D	D	D	D	N	BA	AA	BA	A	AA	AA	A	BA	BA	A
Lam Dong	Bao Lam	D	D	N	D	D	D	D	D	N	N	BA	AA	A	BA	AA	AA	BA	BA	BA	A
	Bao Loc	D	D	N	D	D	D	D	D	W	W	BA	AA	BA	A	AA	AA	BA	BA	BA	A
	Di Linh	D	D	W	D	D	N	D	D	W	W	BA	AA	BA	A	AA	AA	BA	BA	BA	A
	Duc Trong	D	D	W	D	D	N	D	D	N	N	BA	AA	BA	A	AA	AA	BA	BA	BA	A
	Lam Ha	D	D	N	D	D	N	D	D	N	N	BA	AA	BA	BA	AA	AA	BA	BA	BA	A

Source: NASA's Tropical Rainfall Measuring Mission and Prediction Of Worldwide Energy Resources website (https://pmm.nasa.gov/trmm).

Table 3.3. Mean irrigation amounts (Irrig. app.), irrigation water requirement (IWR) and crop water satisfaction (WS) during the January-April period for selected Robusta coffee-producing provinces in Vietnam during 2008–2017. IWR was calculated as the difference between crop water requirement (CWR; calculated using CROPWAT (See section 2.3)) and effective rainfall. WS was the ratio between water input (effective rainfall + irrigation supplied) and potential crop water requirement. Numbers in parentheses are the standard deviations.

	Variables	Units	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Dak Lak	IWR	mm	369 (44)	229 (46)	358 (32)	307 (55)	205 (39)	204 (42)	347 (48)	416 (32)	408 (39)	210 (31)
(N = 180)	Irrig. round	(n)	4	3	4	4	2	4	4	4	3	1
	Irrig. app.	mm	189 (10)	144 (7)	189 (10)	189 (10)	85 (4)	185 (10)	174 (10)	172 (8)	114 (9)	36 (3)
	WS	%	50	73	55	64	69	88	54	41	34	57
Dak Nong	IWR	mm	304 (39)	158 (18)	307 (18)	278 (20)	159 (9)	137 (14)	261 (12)	356 (15)	377 (13)	110 (15)
(N = 120)	Irrig. round	(n)	3	3	2	3	2	3	3	3	2	1
	Irrig. app.	mm	136 (22)	126 (11)	77 (9)	137 (21)	77 (7)	134 (21)	123 (21)	127 (21)	86 (19)	39 (5)
	WS	%	58	86	50	63	76	93	64	47	39	79
Gia Lai	IWR	mm	342 (43)	304 (48)	357 (28)	328 (31)	246 (27)	246 (22)	345 (28)	398 (15)	399 (44)	302 (12)
(N = 93)	Irrig. round	(n)	4	3	4	4	3	4	4	4	3	2
	Irrig. app.	mm	191 (10)	145 (7)	191 (10)	191 (10)	131 (6)	186 (10)	176 (10)	173 (7)	113 (9)	93 (6)
	WS	%	56	56	53	59	68	78	55	45	36	46
Lam Dong	IWR	mm	419 (22)	246 (5)	365 (47)	296 (26)	223 (9)	204 (36)	387 (36)	445 (27)	443 (58)	230 (25)
(N = 165)	Irrig. round	(n)	3	3	2	3	2	3	3	3	2	1
	Irrig. app.	mm	124 (18)	124 (18)	83 (12)	125 (17)	80 (8)	122 (15)	118 (13)	98 (25)	76 (9)	36 (3)
	WS	%	37	67	41	59	65	78	41	30	30	49

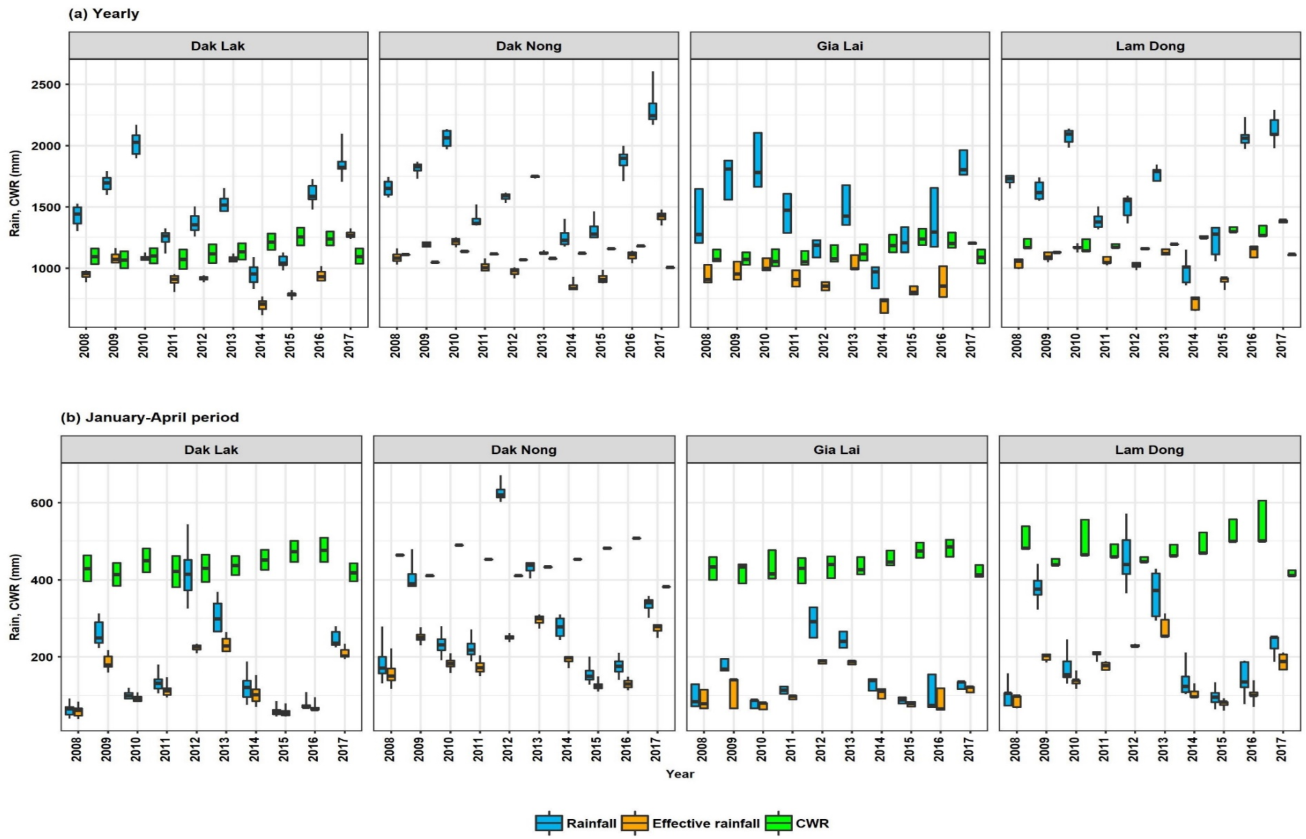

Fig. 3.2. Boxplots of the yearly (**a**) and January to April (**b**) rainfall, effective rainfall and crop water requirement (CWR) during 2008–2017 for each of the study provinces. CWR and effective rainfall estimates were calculated using CROPWAT. Upper and lower border of the boxes represent the 3rd and 1st quartile, respectively. The line within the box represents the median value. Bars extend to the minimum and maximum values. Note relatively low variations of CWR values for Dak Nong (both periods) and Lam Dong (yearly).

3.2 Comparisons between irrigation requirements and water input (rainfall and irrigation)

CWRs were higher than effective rainfall during the JA period in all the study provinces, and varied on average between 380 and 570 mm (5% to 51% of CWR satisfied; Fig. 3.2b). Given coffee plants require a period of induced water stress (Carr 2001), the irrigation amount and frequency need to be managed accordingly by farmers. The percentages of crop water satisfaction during 2008-2017, expressed as the ratio between water input (sum of JA effective rainfall and irrigation) and CWR, varied between 34–88%, 39–93%, 36–78%, and 30–78%, for Dak Lak, Dak Nong, Gia Lai, and Lam Dong, respectively, depending on the year (Table 3.3).

From the engagement with farmers during the survey, irrigation plans (e.g., when to start and how much and how often to irrigate) were typically made based on rainfall during November-December of the previous year, as well as JA rainfall patterns. Analysing the data according to rainfall patterns during January-April show that farmers in Gia Lai supplied a generally similar amount of irrigation in above-average and average seasons (Table 3.4). In the remaining provinces (Dak Lak, Dak Nong and Lam Dong) the mean irrigation amounts applied during above-average JA periods were relatively higher than those in average JA periods. However, such variations have to be interpreted cautiously, particularly in Dak Lak and Lam Dong where the number of surveyed districts experiencing average rainfall conditions during January-April represented less than the third of the total cases during 2008–2017 (Table 3.2). The relatively high irrigation amounts recorded during above-average JA rainfall conditions in provinces like Dak Lak or Gia Lai is because in those years rainfall was received towards the end of April. Above-average JA rainfall conditions were recorded across all provinces in 2012 and 2013 (Table 3.4), with irrigation limited only to January-February in 2012 (irrigation was also applied in March at Gia Lai) (Table A3.1). However in 2013 the total amount of irrigation applied was among the highest during the study period, regardless of the province; suggesting that farmers were rather adopting a no-risk behaviour even though rainfall patterns seem favourable (Table A3.1). High irrigation amounts did not result necessarily in higher Robusta coffee yields (Table 3.4). For example in Dak Nong, Robusta coffee yields were similar in both average or above-average years, although more irrigation was supplied in above-average years.

Table 3.4. Mean irrigation amounts and Robusta coffee yields according to January-April rainfall patterns for each of the study provinces in Vietnam during 2008–2017. For a given category, the means were calculated with all years belonging to that category. Refer to Table 3.2 for year classification. Numbers in parentheses are the standard deviations.

Year classification	Below-average rainfall		Average rainfall		Above-average rainfall	
	Irrigation (mm)	Yield (kg ha^{-1})	Irrigation (mm)	Yield (kg ha^{-1})	Irrigation (mm)	Yield (kg ha^{-1})
Dak Lak	171 (29)	2380 (47)	80 (64)	2540 (447)	127 (51)	2499 (503)
Dak Nong	113 (32)	2465 (435)	87 (46)	2556 (522)	110 (31)	2530 (486)
Gia Lai	174 (29)	2462 (451)	144 (41)	2744 (434)	155 (26)	2639 (564)
Lam Dong	103 (25)	2790 (498)	80 (43)	3056 (390)	109 (25)	2800 (499)

3.3 Relationships between irrigation and Robusta coffee yields

Since the yield is the result of all processes occurring during the growth cycle and given fertiliser application was not limited to January to April, the year classification based on total annual rainfall (Table 3.2) was used in the modelling approach. Year-to-year coffee yield variability is provided in Fig. A3.1. The relationships between coffee yield and each of the predictors varied according to the rainfall patterns and province (Fig. 3.3). Effective irrigation and JA effective rainfall strongly influenced coffee yield in Dak Lak in dry years (Fig. 3.3b). Likewise, in Gia Lai irrigation influenced Robusta coffee yields positively in dry years, though marginally compared to Dak Lak. In normal years in Dak Lak, JA effective rainfall influence on yield was low; but irrigation tended to negatively impact on yields (Fig. 3.3a). Such adverse impact of irrigation on yield in normal years was also found in Dak Nong and Gia Lai. In Dak Nong in dry years or in Lam Dong in normal years all selected predictors influenced Robusta coffee yield in similar ranges (Fig. 3.3).

Within the limits of rainfall conditions observed during the study period, we analysed the variations of Robusta coffee yield according to the interaction between effective irrigation and JA effective rainfall. In normal years, a combination of higher effective rainfall and irrigation often had no effect on coffee yields and/ or was even be detrimental (Fig. 3.4a). This is because the water stress-induced from effective rainfalls in those years was beneficial to yields. In Dak Lak and Dak Nong, the highest coffee yields were found at effective rainfall levels ≥ 200 mm (Dak Lak) or ≥ 300 mm (Dak Nong) and effective irrigation ≤ 40 mm (≤ 364 L $tree^{-1}$). In these provinces, the lowest yields were found predominantly under a for combination of high effective rainfall and high effective irrigation. In Gia Lai effective rainfall ranging from ~125 to 175 mm (~1136 - 1591 L $tree^{-1}$) coupled with an effective irrigation ≤ 75 mm (≤ 682 L $tree^{-1}$) resulted in the highest coffee yields reported (Fig. 3.4a). An exception to these patterns was observed for Lam Dong where highest coffee yields seemed to result from combined high effective rainfall and effective irrigation in normal years (Fig. 3.4a). In dry years there was an increase in coffee yields for increased irrigation in Dak Lak and Gia Lai (Fig. 3.4b). In Lam Dong low yields were associated with higher effective irrigation (> 90 mm (> 818 L $tree^{-1}$)); higher yields, however, were recorded for effective irrigation < 90 mm mm (< 818 L $tree^{-1}$) (Fig. 3.4b).

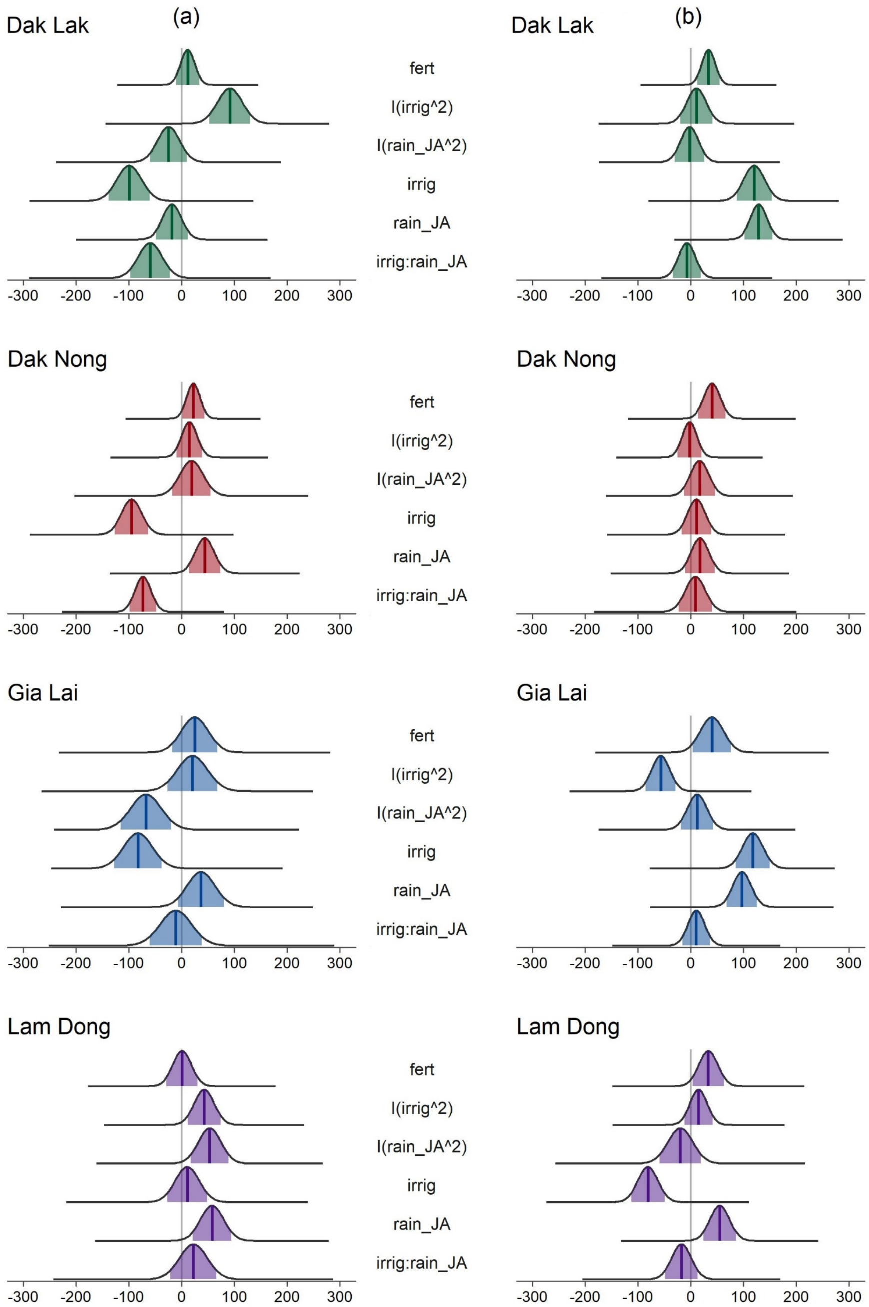

Fig. 3.3. Standardised parameter estimates of model predictors. The model for each of the study provinces was determined using data for average-rainfall condition (**a**) and below-average-rainfall condition (**b**) years separately (see Table 3.2 for year classification). *fert, irrig* and *rain_JA* refer to fertilisers (urea + NPK), effective irrigation supplied (80% of the reported supply) and effective rainfall during January-April, respectively; *I(irrig^2)* and *I(rain_JA^2)* correspond to the square value of *irrig* and *rain_JA*, respectively; and *irrig:rain_JA* is the interaction between *irrig* and *rain_JA*.

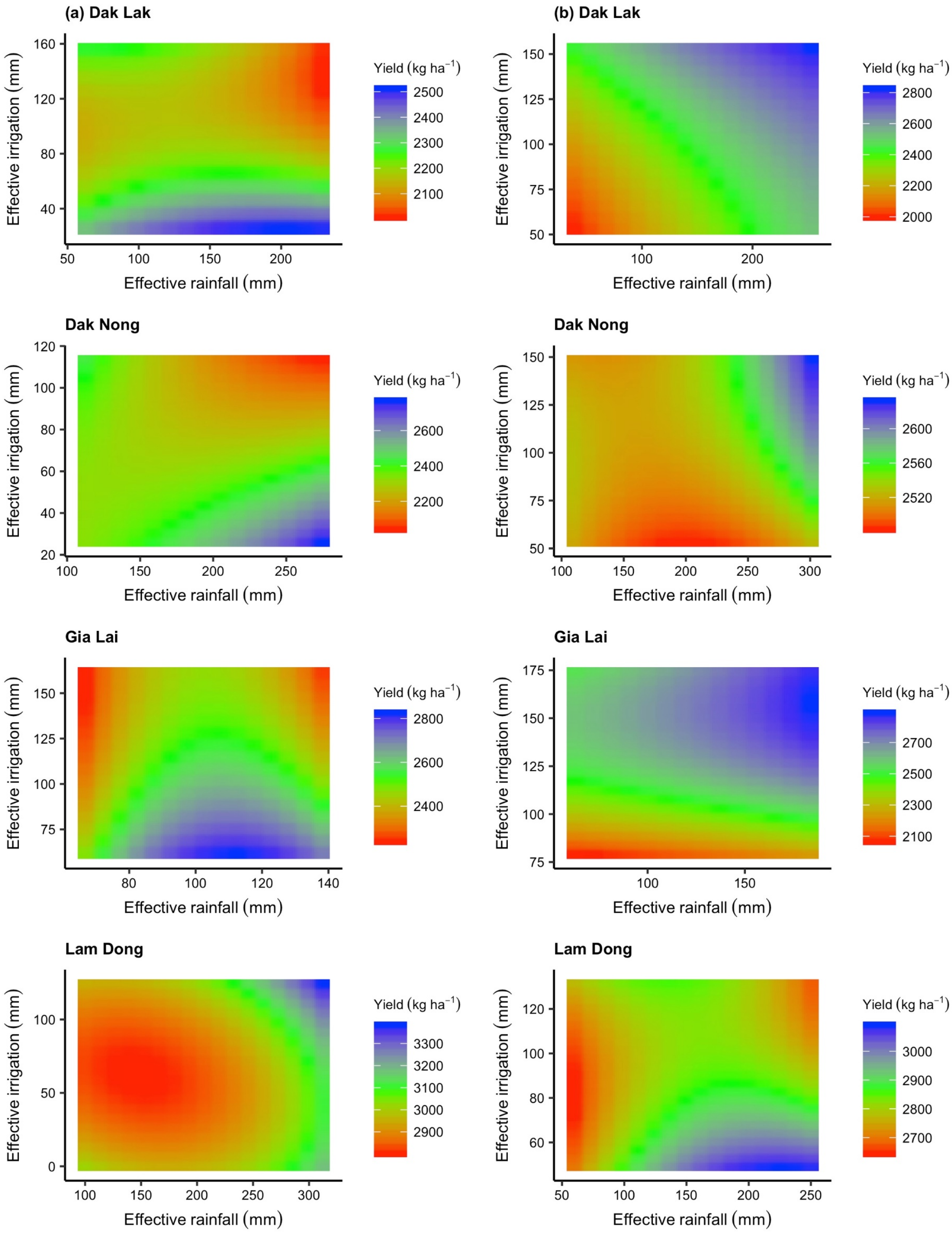

Fig. 3.4. Variation of predicted Robusta coffee yield according to the effective rainfall during January-April and effective irrigation for each of the study provinces in average-rainfall condition (**a**) and below-average-rainfall condition (**b**) years (see Table 3.2 for year classification). The effective irrigation was assumed as 80% of the irrigation supplied. (Note different ranges on x and y axes.)

The analysis of potential yield gain to additional irrigation (Fig. 3.5) shows that, overall, the potential yield gain was up to 180 and 410 kg ha^{-1} in normal and dry years, respectively. In normal years yield gains in Lam Dong were up to 180 kg ha^{-1} for additional irrigation up to 60 mm (545 L tree^{-1}) (Fig. 3.5a). The gain was marginal (< 40 kg ha^{-1}) in Dak Lak for additional irrigation up to 40 mm (364 L tree^{-1}), but no yield gain afterwards. Additional irrigation did not result in coffee yield gain in Dak Nong or Gia Lai. In dry years (Fig. 3.5b), there was a strong yield gain for additional irrigation in provinces such as Dak Lak and Gia Lai, which typically received less rainfall. Indeed, the gain in Gia Lai was up to 405 kg ha^{-1} for additional irrigation ranging from 20 to 80 mm (182 - 727 L tree^{-1}). In Dak Nong, such gain was marginal (up to 50 kg ha^{-1}), whereas there was no gain in Lam Dong (Fig. 3.5b).

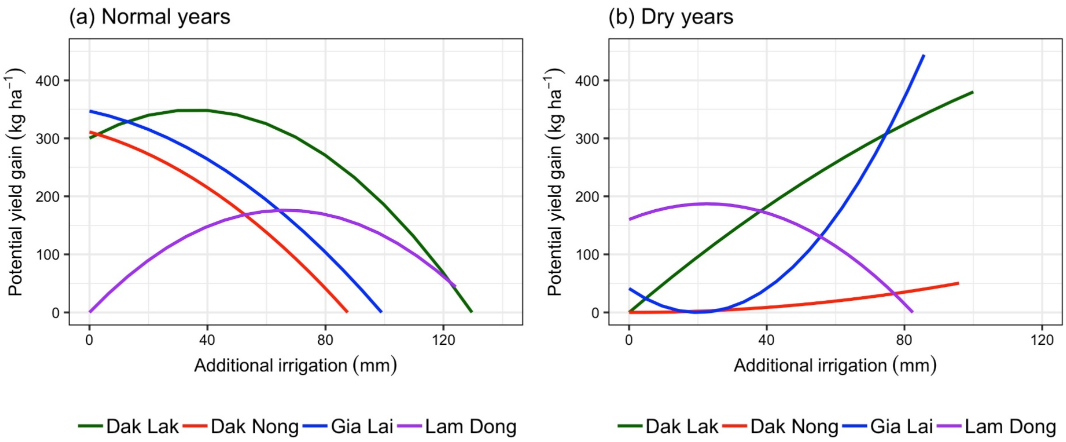

Fig. 3.5. Potential Robusta coffee yield gain versus additional irrigation as observed during 2008–2017 for each of the study provinces in average-rainfall condition (**a**) and below-average-rainfall condition (**b**) years (see Table 2.2 for year classification).

3.4 Potential for improved irrigation management strategies

Based on the ranges of Robusta coffee yields across the selected provinces, we investigated the variation of irrigation supply (< 50 mm (< 455 L tree^{-1}), 50–100 mm (455 - 909 L tree^{-1}), 100–150 mm (909 - 1364 L tree^{-1}) and 150–200 mm (1364 – 1818 L tree^{-1})) at different levels of Robusta coffee yields for each of the provinces. In Dak Nong and Lam Dong the majority of coffee farmers supplied 455 – 909 L tree^{-1} in normal years, with corresponding average yields ranging from 2149 to 3177 kg ha^{-1} (Table 3.5). In dry years, the predominant range of irrigation supply was 909 – 1364 L tree^{-1}. In both provinces higher coffee yields (> 3000 kg ha^{-1}) were also reported for irrigation supply < 455 L tree^{-1}in normal years, or between 455 - 909 L tree^{-1} in dry years; suggesting a potential for reducing irrigation supply while achieving better yield levels. Similar conclusions can be drawn for Dak Lak and Gia Lai in normal years. In Dak Lak farmers applying higher amounts (1364 - 1818 L tree^{-1}) could reduce the supply to (909 – 1364 L tree^{-1}) or even < 455 L tree^{-1}, and still achieve the same level of yield. Likewise, in Gia Lai there were cases where yields > 3000 kg ha^{-1} were achieved with (455 - 909 L tree^{-1}) irrigation (Table 3.5). In dry years the pattern in these two provinces was slightly different in terms of irrigation amounts and corresponding yields > 3000 kg ha^{-1}. Although the predominant irrigation supply in both provinces was 1364 - 1818 L tree^{-1}, only in Dak Lak irrigation water of 455 - 909 L tree^{-1} can be applied and result in such high yields. In Gia Lai, during dryer years high irrigation was often associated with higher yields and so the potential of irrigation reductions during dry conditions may be limited (Table 3.5).

With the aim of finding out which satisfactory and recommended yield levels can be achieved while reducing irrigation supplies, we further evaluated the effect of induced water stress on coffee yields based on the calculated CWR (Fig. 3.6). For recommended coffee yield set to 3000 kg ha^{-1}, there could generally be a reduction of 30 to 59 mm (273 - 536 L tree^{-1}) of irrigation supply from current levels applied (80 to 159 mm (727 - 1445 L tree^{-1})) to reach the average yields in normal years. In Dak Lak a farmer with a current yield level of 2540 kg ha^{-1} and irrigation supply of 80 mm (727 L tree^{-1}) can reduce this supply to 50 mm (455 L tree^{-1}) (through an increase of induced water stress) and reach 3000 kg ha^{-1}. The higher potential reduction of irrigation was found for Gia Lai during normal years, resulting in 9% increase in yield from average to recommended yield levels (Fig. 3.6). In dry years reducing in irrigation supply from 3 to 24 mm (27 - 218 L tree^{-1}) can occur while still achieving yield levels of around 3000 kg ha^{-1}, although this does vary between provinces. Gains in yield from current average levels to locally recommended levels while reducing irrigation supply varied depending on the province: 5% to 18% in normal years and 7% to 26% in dry years, with lower and higher percentages found in Lam Dong and Dak Lak, respectively, in both year categories (Fig. 3.6).

Table 3.5. Variation in Robusta coffee yields under different levels of irrigation supply for each of the study provinces in Vietnam.

	Irrigation application levels (mm)							
	Summaries of dry years				Summaries of normal years			
	< 50	50-100	100-150	150-200	< 50	50-100	100-150	150-200
Dak Lak								
A. Sample distribution (no)								
> 3000		22	5	207	31		4	2
2500-3000		73	40	339	112		30	27
2100-2500		73	103	248	35		95	87
≤ 2000		13	26	81	2		79	36
B. Average yield (kg ha^{-1})								
> 3000		3239	3000	3166	3101		3000	3000
2500-3000		2649	2564	2652	2662		2593	2586
2100-2500		2242	2187	2224	2275		2149	2186
≤ 2000		1752	1723	1697	1730		1649	1679
Dak Nong								
A. Sample distribution (no)								
> 3000		18	130	25	45	7	2	
2500-3000		64	223	44	40	53	13	
2100-2500		46	147	31	5	134	22	
≤ 2000		9	63	10		22	17	
B. Average yield (kg ha^{-1})								
> 3000		3237	3135	3204	3123	3151	3145	
2500-3000		2637	2651	2654	2667	2623	2673	
2100-2500		2172	2193	2189	2226	2187	2142	
≤ 2000		1681	1659	1639		1751	1614	
Gia Lai								
A. Sample distribution (no)								
> 3000			37	164		55	6	2
2500-3000		2	87	181		33	11	14
2100-2500			82	107		3	22	34
≤ 2000			18	24			25	12
B. Average yield (kg ha^{-1})								
> 3000			3116	3203		3214	3073	3165
2500-3000		2605	2635	2671		2752	2601	2541
2100-2500			2193	2190		2320	2069	2168
≤ 2000			1692	1770			1716	1770
Lam Dong								
A. Sample distribution (no)								
> 3000		218	254	4	75	76	69	4
2500-3000		93	190		18	59	23	
2100-2500		46	215	8	1	48	1	
≤ 2000		5	26			9		
B. Average yield (kg ha^{-1})								
> 3000		3255	3258	3365	3253	3177	3272	3633
2500-3000		2727	2719		2754	2695	2738	
2100-2500		2216	2248	2229	2400	2149	2400	
≤ 2000		1640	1585			1744		

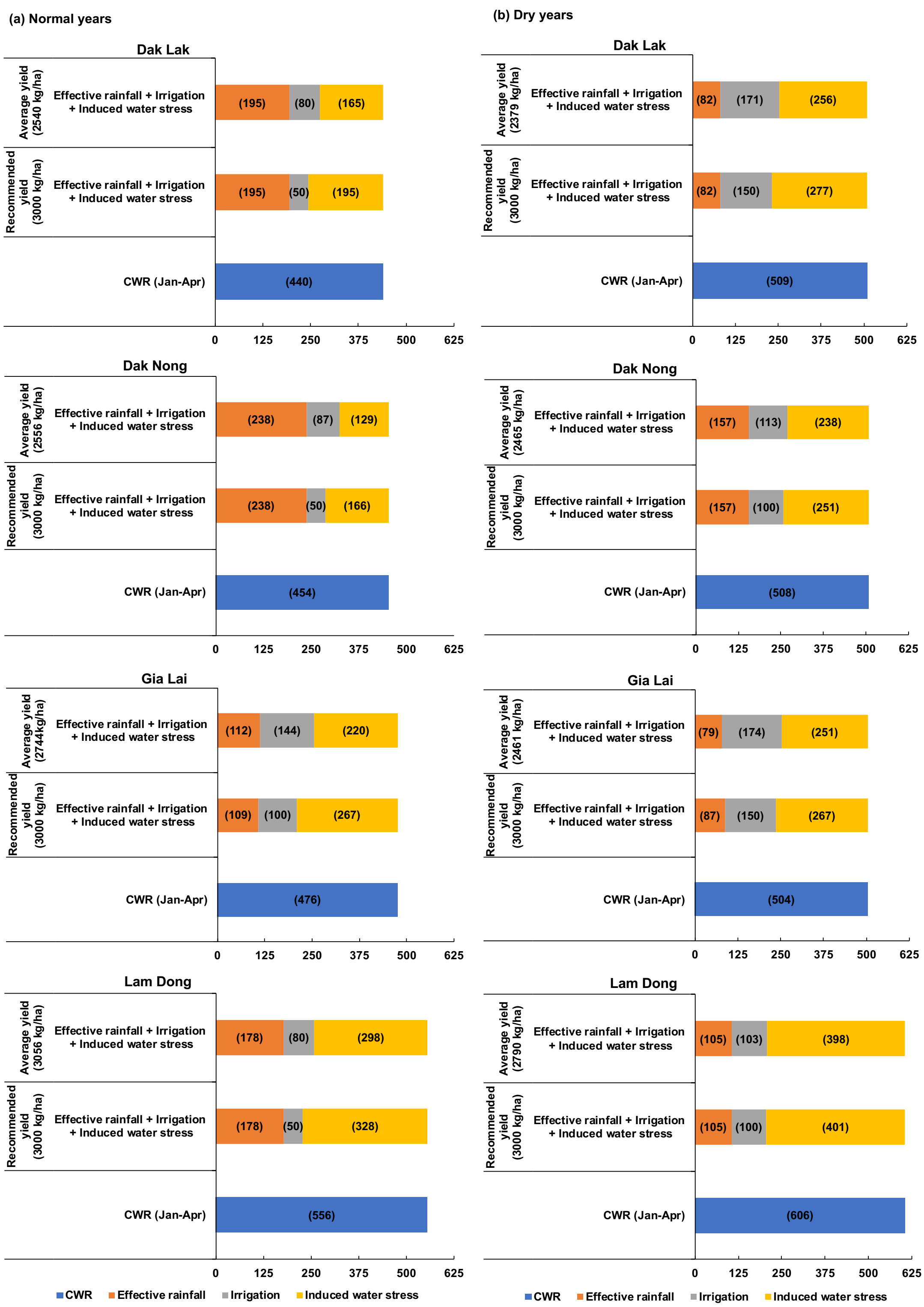

Fig. 3.6. Variations of effective rainfall, irrigation and induced water stress under different Robusta coffee yield scenarios in Dak Lak, Dak Nong, Gia Lai and Lam Dong for average-rainfall condition (**a**) and below-average-rainfall condition (**b**) years (see Table 3.2 for year classification). *CWR* correspond to the potential crop water requirement during January-April. CWR and Effective rainfall estimates were calculated using CROPWAT.

4. Discussion

We analysed the potential for improved irrigation management practices in four major Robusta coffee-producing provinces in Vietnam. The surveyed coffee farmers applied variable irrigation amounts depending on the province, with similarities of practices found in provinces presenting similar rainfall patterns (Dak Lak and Gia Lai on one side, and Dak Nong and Lam Dong on the other). Compared to the official amount recommended (132 mm year^{-1} (1200 L tree^{-1}); MARD (2016)), irrigation supplies were generally higher than this threshold in surveyed farms across Dak Lak and Gia Lai; lesser or similar irrigations amounts than the threshold were applied in the remaining provinces Dak Nong and Lam Dong (Table 3.3). The relatively low annual rainfall received in Dak Lak and Gia Lai can justify the relatively high irrigation water supplies in these provinces. Other reasons could be the biased assumption persisting in the mindset of some farmers that the more irrigation you supply the higher your coffee yields, and the slow adoption of new official recommendations. The previous official recommendation for irrigation amount was 650 L tree^{-1} round^{-1} in three rounds yearly, that is 215 mm year^{-1} (Cheesman et al. 2007). In line with D'haeze et al. (2003) or Amarasinghe et al. (2015) who highlighted over-irrigation practices in Dak Lak, our results indicate that such practices have not changed over the years.

Irrigation during January-April impacted positively Robusta coffee yields in dry years; but an excessive water supply resulted in adverse effects in normal years, which is in line with the conclusions of D'haeze (2008) and Amarasinghe et al. (2015). The first irrigation is supplied for inducing and synchronous flowering in case rainfall is delayed, and maximize the potential yield. The exception found in Lam Dong in normal years (highest coffee yields associated with combined high effective rainfall and effective irrigation; Fig. 3.4a) could be explained by the adoption of the grafting technique in that province over the last five years. Through grafting the number of productive branches are increased. With such an increase in productive branches, high coffee yields would be achieved with high irrigation supplies under good rainfall conditions. Our study also shows that there is a potential of reducing irrigation supply to 273 - 536 L tree^{-1} (30 to 59 mm) annually from the current levels in normal years and achieve yield levels of > 3000 kg ha^{-1} (Fig. 3.6). In dry years that reduction could be 27 - 218 L tree^{-1} (3 to 24 mm). Assuming a density of 1100 plants ha^{-1}, such savings in normal years are equivalent to 300–590 m^3 ha^{-1} (30–240 m^3 ha^{-1} in dry years) depending on the provinces. These amounts can also vary according to the irrigation method since, in our study, the sampling was carried out in order to represent equally basin and sprinkler irrigation methods. Nonetheless, with the study provinces having coffee areas ranging from 80,000 ha (Gia Lai) to 202,000 ha (Dak Lak) (GSOV 2017), the irrigation water savings could be noticeable at the provincial scale. The adoption of smart watering technology for irrigation could also help in water savings, along with labour and energy for coffee farmers. It is important to stress that reaching the locally recommended yield levels cannot be possible without managing properly the other crop practices affecting Robusta coffee yields (e.g., fertilisation, pruning, etc.). Hence, the need to build or reinforce the capacity of farmers about those aspects too.

Given the dependency of Robusta coffee production on irrigation supplies in dry seasons in Vietnam, climate variability can notably influence both seasonal irrigation planning and day-to-day irrigation scheduling. Robusta coffee farmers in the study provinces typically made their irrigation schedules based on rainfall during November-December of the previous year, as well as January-April rainfall patterns. Although the study period spanned 10 years, and above-average January-April rainfall patterns were found during two to three years across the selected provinces (Table 3.2), the change in irrigation supplies between 2012 and 2013 (years both ranked as above-average January-April period on records) highlight the potential of using seasonal climate forecast (SCF) to aid in irrigation planning. The beneficial use of SCF in decision-making on farms has been demonstrated for cereals, cotton and sugar (see for examples Meinke and Stone (2005)). Integrating local SCF to coffee production modelling would potentially help increase the preparedness of Robusta coffee farmers in terms of irrigation activities.

5. Conclusion

The climate variability and over-use of water for irrigating Robusta coffee in Vietnam pose several threats including the reduction of coffee yield and product quality, reduction of ground and surface water resources, with the corollary of limited water supply for household consumption and the production of hydropower. It could also affect other agricultural water users such as irrigated rice farming. Ensuring better irrigation management strategies should become an integral part of the farm management system in Robusta coffee, so that positive environmental and socio-economic benefits can be established throughout the coffee supply chain for consistent and sustainable production. As such, the findings of our study are a good start and could help guide further investigations for improved province-specific irrigation water management in Robusta coffee farms in Vietnam. Increasing farmers' awareness about environmental issues related to excessive irrigation in coffee farms and reinforcing/building their capacity on best irrigation practices are therefore crucial for water conservation and sustainable coffee production in the study provinces.

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Appendices 3

Table A3.1. Monthly average irrigation amounts (mm) applied in Robusta coffee farms in selected Vietnamese provinces during the study period 2008–2017. Numbers in parentheses are the standard deviations. Annual means for each year within the province with similar letters indicate they are not significantly different ($p > 0.05$). N is the number of farmers surveyed each year.

Year		Dak Lak (N = 180)	Dak Nong (N = 120)	Gia Lai (N = 93)	Lam Dong (N = 165)	Year		Dak Lak (N = 180)	Dak Nong (N = 120)	Gia Lai (N = 93)	Lam Dong (N = 165)
2008	Jan.	52 (4)	49 (6)	52 (3)	41 (6)	2013	Jan.	47 (5)	47 (3)	47 (4)	39 (4)
	Feb.	46 (4)	39 (5)	47 (4)	42 (6)		Feb.	46 (4)	39 (5)	47 (4)	42 (6)
	Mar.	46 (3)	39 (5)	47 (4)	42 (6)		Mar.	46 (4)	39 (5)	47 (4)	42 (6)
	Apr.	46 (4)	39 (4)	47 (4)			Apr.	46 (4)	39 (4)	47 (4)	
	Mean	***48b***	***42a***	***48b***	***42a***		***Mean***	***46b***	***41a***	***47b***	***41a***
2009	Jan.	52 (4)	50 (5)	52 (3)	41 (6)	2014	Jan.	37 (6)	36 (3)	36 (4)	35 (3)
	Feb.	46 (4)	39 (5)	47 (4)	42 (6)		Feb.	46 (4)	39 (5)	47 (4)	42 (6)
	Mar.	46 (4)	39 (5)	47 (4)	42 (6)		Mar.	46 (4)	39 (5)	47 (4)	42 (6)
	Apr.						Apr.	46 (4)	39 (4)	47 (4)	
	Mean	***48b***	***42a***	***48b***	***42a***		***Mean***	***44b***	***38a***	***44b***	***40c***
2010	Jan.	52 (4)		52 (3)		2015	Jan.	42 (5)	41 (3)	42 (4)	36 (3)
	Feb.	46 (4)	38 (5)	47 (4)	41 (6)		Feb.	39 (6)	37 (5)	38 (6)	36 (5)
	Mar.	46 (4)	39 (5)	47 (4)	42 (6)		Mar.	46 (4)	39 (5)	47 (4)	45 (5)
	Apr.	46 (4)		47 (4)			Apr.	46 (4)	39 (4)	47 (4)	
	Mean	***48b***	***39a***	***48b***	***42c***		***Mean***	***43b***	***39a***	***43b***	***38a***
2011	Jan.	52 (4)	50 (5)	52 (3)	41 (6)	2016	Jan.				
	Feb.	46 (4)	39 (5)	47 (4)	42 (6)		Feb.	39 (5)	39 (5)	39 (6)	38 (5)
	Mar.	46 (4)	38 (5)	47 (4)	42 (6)		Mar.	39 (7)	39 (5)	39 (6)	38 (5)
	Apr.	46 (4)	39 (4)	47 (4)			Apr.	36 (3)	35 (3)	36 (3)	
	Mean	***48b***	***42a***	***48b***	***42a***		***Mean***	***38a***	***38a***	***38a***	***38a***
2012	Jan.	39 (6)	38 (6)	39 (6)	38 (5)	2017	Jan.			52 (3)	
	Feb.	46 (4)	39 (5)	47 (4)	42 (6)		Feb.	36 (3)	39 (5)	42 (3)	36 (3)
	Mar.			47 (4)			Mar.				
	Apr.						Apr.				
	Mean	***42d***	***38a***	***44b***	***40c***		***Mean***	***36c***	***39a***	***47b***	***36c***

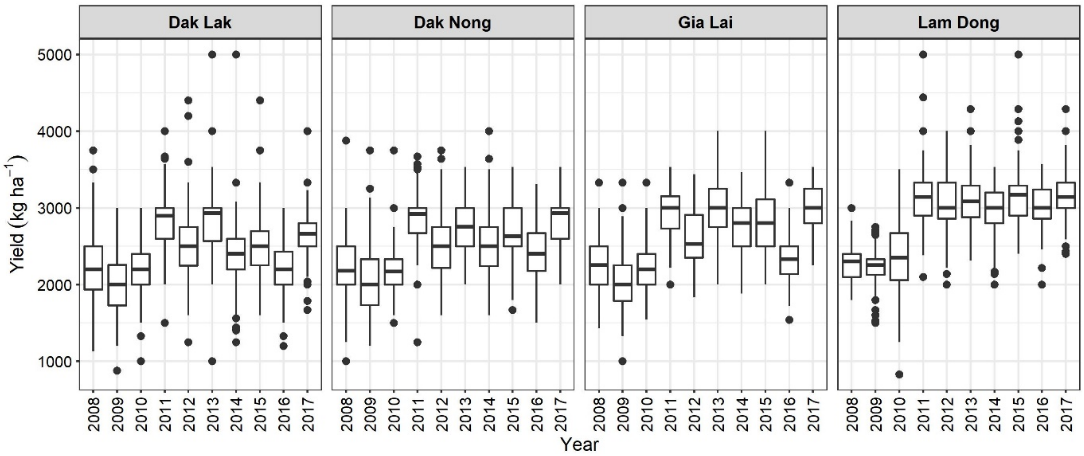

Fig. A3.1. Inter-annual variability of Robusta coffee yields during 2008–2017 for each of the study provinces. Upper and lower border of the boxes represent the 3rd and 1st quartile, respectively. The line within the box represents the median value. Black circles are the outliers.

Chapter 4

A review of farmers' perceptions on drought and quantification of drought impacts in Robusta coffee farms in Vietnam

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Article III: Coping with drought: Lessons learned from Robusta coffee growers in Vietnam

Vivekananda Byrareddy, Louis Kouadio, Shahbaz Mushtaq, Jarrod Kath, Roger Stone

Centre for Applied Climate Sciences, Institute for Life Sciences and the Environment, University of Southern Queensland, Toowoomba, QLD 4350, Australia

Abstract

Improved understanding of the effectiveness and uptake of drought mitigation strategies is critical to ensure the best strategies are developed. Here, using 10 years (2008-2017) of farm data from 558 farmers distributed across four major Robusta coffee-producing provinces in Vietnam, we first sought coffee farmers' perceptions on drought and its impacts, then, quantified the yield and financial impacts, and finally, assessed the effectiveness of mitigation strategies. Our result shows that, while drought reduced Robusta coffee yield by 6.5% on average across all provinces, the impacts on gross margins were noticeable, with 22% decline on average from levels achieved in average-rainfall-condition years. The yield reduction was found to be consistent with farmers' perceptions about the drought impact (on average 9.6%). With irrigation being typical in coffee farming in Vietnam, in drought years the majority of surveyed farmers (58%) adopted mulching and were best rewarded with an increase in economic benefits by 10.2% compared to their counterparts who did not. Furthermore, the chances of adopting mulching as an adaptation strategy decreased generally for one-unit increase in perceived drought impact or when shifting from surface water to groundwater in drought years. Such chances increased with one-unit increase in rainfall at the start of the season. Although coffee farming remained profitable in drought years, our findings have potential relevance for the design of policies to

address drought risks and encourage more resilient adaptation strategies for Vietnam and other coffee-producing countries experiencing similar climatic conditions.

1. Introduction

Drought is an extreme weather-induced disaster which can cause considerable damage to the livelihoods and assets of a large number of people, national economies, and ecosystems (Kogan 1997; Redmond 2002). With the projected changes in spatio-temporal patterns of extreme weather events during this twenty-first century, coupled to increasing vulnerability of terrestrial ecosystems (IPCC 2013; IPCC 2014; Schwalm et al. 2017; Slette et al. 2019), the sustainability of agricultural production in several countries faces major challenges worldwide. Indeed, any adverse impacts on agriculture would be detrimental to the economy of countries in which the agricultural sector constitutes an important pillar.

Vietnam is the world's second-largest coffee-producing and exporting country (FAO 2019; ICO 2019a; ICO 2019b). Ninety-seven per cent of coffee beans are produced in the Central Highlands region; a region listed among the most drought-prone ones in the country (Nguyen 2005; Vu et al. 2015; GSOV 2017; ICO 2019a). Considerable crop losses due to drought events have been reported during the past decades. For example, in 2015-2016 all the provinces in Central Highlands (Dak Lak, Dak Nong, Gia Lai, Kon Tum, and Lam Dong) were affected severely by drought, resulting in ca. 152,000 ha of agricultural land areas impacted and direct economic losses of VND 6,004 billion (about US$ 269 million) (Grosjean et al. 2016; MARD 2016; World Bank 2017). Reductions up to 25% of the total production of green coffee beans (relative to that in average-rainfall-condition years) were observed in Central Highlands during the 1997-1998 or 2010-2011 droughts (Nguyen 2005; MARD 2016). Droughts also affect rivers discharges and water reservoirs. For instance, water reservoirs across the Central Highlands declined by up to 50% of their average levels in 2016 consecutive to drought, resulting in lower groundwater tables across the region (CCAFS-SEA 2016).

In vulnerable coffee-growing regions, several drought mitigations and adaptation strategies are being implemented to build longer-term resilience and to ensure sustainable and profitable production. At farm scale, these strategies typically include irrigation, water-saving technologies, conservation of soil water through mulching, shade management (e.g. shading systems with tree species, agroforestry, etc.), and diversification of farm activities (DaMatta 2004b; Dias et al. 2007; Silva et al. 2008; Worku and Astatkie 2010; Haggar and Schepp 2012; Jassogne et al. 2013; Assis et al. 2014; Bisang et al. 2016; Boreux et al. 2016). It is critical to improve our understanding of current drought mitigation and adaptation strategies to better manage future drought risks. Thus, improved quantification of the economic impacts of the drought mitigation and adaptation strategies in coffee farming systems deserve particular attention, especially for a complete assessment of the implications and effectiveness of such strategies.

Although a number of studies have dealt with drought in the coffee farming system in Vietnam (Nguyen 2005; Haggar and Schepp 2012; CCAFS-SEA 2016), they're generally focused onto one province or were limited to 2- to 3-year data. Using 10-year (2008-2017) archival materials and survey data for 558 farmers distributed across the major Vietnamese Robusta coffee-producing provinces, the objectives of this study were to (1) investigate coffee farmers' perceptions and responses to drought, (2) assess the yield and financial impacts of drought, and estimate the economic impacts of drought mitigation strategies, and (3) examine the drivers that influence the adoption of mitigation strategies. Coffee is one of the top-traded agricultural commodities in the world, generating substantial gross revenues annually and contributing critically to the gross domestic product of coffee-producing countries such as Vietnam (TCI 2016; ICO 2019a). The findings of this study, therefore, will have potential relevance for the design of policies to address drought risks and encourage more resilient adaptive strategies for both Vietnam and other coffee-producing countries experiencing similar climatic conditions.

2. Material and methods

2.1 Study area and data

Farmers were randomly selected across four Vietnamese coffee-producing provinces in the Central Highlands–Dak Lak, Dak Nong, Gia Lai, and Lam Dong (Fig. 4.1)–to represent districts dominated by coffee farmers dependent primarily upon coffee production for household income. A total of 558 farmers were selected across 18 districts in the study provinces: 180 farmers in Dak Lak (six districts), 120 in Dak Nong (four districts), 93 in Gia Lai (three districts), and 165 in Lam Dong (five districts). These four provinces accounted for more than 90% of the national coffee production for about 581,000 hectares harvested on average during 2014-2017 (GSOV

2017). A humid tropical climate characterises them: daily average maximum temperatures are normally above 24°C; the average monthly solar radiation varies between 400 and 700 MJ m^{-2}; and total annual rainfalls range from 1800 to 3000 mm (NCHMF 2018; Byrareddy et al. 2019). Coffee is typically grown as an unshaded and clean-weeded monocrop (D'haeze et al. 2017), with 95% of plantations dominated by Robusta (*Coffea canephora*) (GSOV 2017; ICO 2019a). High rates of chemical fertilisers and intensive use of irrigation water are typical in Robusta coffee farming in the study provinces (D'haeze et al. 2005; Marsh 2007; Byrareddy et al. 2019).

Farm data in this study period were made possible thanks to the SMS programme implemented by ECOM Agroindustrial Corporation in Vietnam, within which more than 5000 coffee farmers are enrolled (as of 2018). Data are managed through the SMS database within ECOM. Farmers also keep their data using farm books, given such information is used in certification programmes. Coffee farm activities are monitored throughout every season, with three to four farm surveys each year with farm data collected using designed questionnaires (Byrareddy et al. 2019). These questionnaires included sections on demography, farming system, perception on drought frequency and drought impact on coffee plants, responses to drought events, and access to climate information and agricultural extension services. The data also included information about coffee production, irrigation and fertiliser data, costs of production, and household incomes. Data for the 2008-2017 period were collected during the last quarterly farm survey in 2017 from the 558 farms. All farm data were cross-checked with those of the SMS database to verify their consistency. All the farmers had access to seasonal rainfall forecasts from hydro-meteorology department through newspapers and television broadcasts.

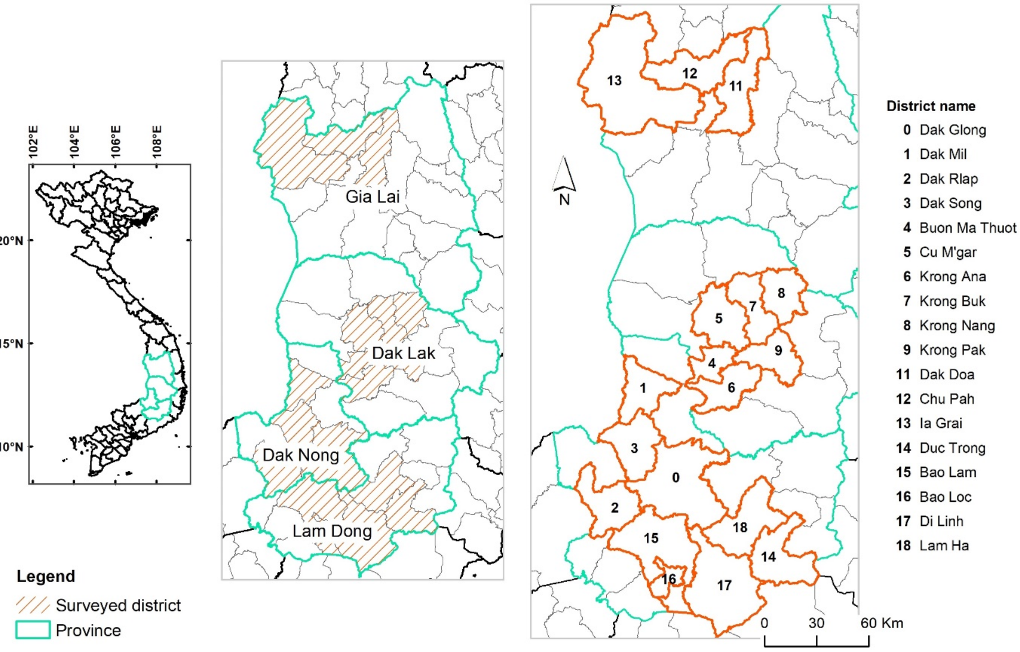

Fig. 4.1. Location of study areas across Vietnamese Robusta coffee-producing provinces. (Source: https://gadm.org/).

2.2 Classifying drought periods

In this study, we considered meteorological droughts, which are usually related to precipitation deficiencies over a specific region (Wilhite and Glantz 1985; American Meteorological Society 1997; Redmond 2002). Gridded annual rainfall data (0.25° x 0.25° spatial resolution) for a 30-year period (1985-2014) were used to classify each year of the 2008-2017 period. For each district in a given province, the 30 annual rainfall amounts were first ranked. Years with an annual rainfall below the 20th percentile were classified as 'drier years' (hereafter referred to as 'drought years'); 'average-rainfall-condition years' were years with annual rainfall within the 30th and 70th percentiles, and 'above-average-rainfall-condition years' indicated years with annual rainfall greater than the 70th percentile. All rainfall data were sourced from the US National Oceanic and Atmospheric Administration website (https://www.ncdc.noaa.gov/cdr). Over the 2008-2017 period, four to six years out of 10 were classified as drought years, depending on the district and province. The years 2011, 2012, 2014 and 2015 were common to the majority of districts in all provinces (Table 4.1). 2008 was also classified as drought year for Dak Lak, Dak Nong and Gia Lai, with more drought years (6) found for all districts in the latter province.

Table 4.1. Years when the drought was experienced during the 2008–2017 period for each of the study Robusta coffee-producing provinces in Vietnam. 'Drought years' (D) were defined as years when the total annual rainfall was below the 20th percentile; 'average-rainfall-condition years' (ARc) were years with annual rainfall within the 30th and 70th percentiles; and 'above-average-rainfall-condition years' (AARc) indicated years with annual rainfall greater than the 70th percentile.

Province	District	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total of drought years
Dak Lak	Buon Ma Thuot	D	ARc	ARc	D	D	ARc	D	D	ARc	ARc	**5**
	Cu Mugar	D	ARc	ARc	D	D	ARc	D	D	ARc	ARc	**5**
	Krong Ana	D	ARc	ARc	D	D	ARc	D	D	ARc	ARc	**5**
	Krong Buk	D	ARc	ARc	D	D	D	D	D	ARc	ARc	**6**
	Krong Nang	D	ARc	AARc	D	D	ARc	D	D	ARc	ARc	**5**
	Krong Pak	D	ARc	ARc	D	D	ARc	D	D	ARc	ARc	**5**
Dak Nong	Dak GLong	D	ARc	ARc	D	D	ARc	D	D	ARc	ARc	**5**
	Dak Mil	D	ARc	ARc	D	D	ARc	D	D	ARc	ARc	**5**
	Dak RLap	D	ARc	ARc	D	D	ARc	D	D	ARc	AARc	**5**
	Dak Song	D	ARc	ARc	D	D	ARc	D	D	ARc	ARc	**5**
Gia Lai	Chu Prong	D	ARc	ARc	D	D	ARc	D	D	D	ARc	**6**
	Dak Doa	D	D	ARc	D	D	ARc	D	D	ARc	ARc	**6**
	Ia Grai	D	ARc	ARc	ARc	D	D	D	D	D	ARc	**6**
Lam Dong	Bao Lam	ARc	ARc	ARc	D	D	ARc	D	D	ARc	ARc	**4**
	Bao Loc	ARc	ARc	ARc	D	D	ARc	D	D	AARc	AARc	**4**
	Di Linh	ARc	D	AARc	D	D	ARc	D	D	AARc	AARc	**5**
	Duc Trong	ARc	D	AARc	D	D	ARc	D	D	ARc	ARc	**5**
	Lam Ha	ARc	D	ARc	D	D	ARc	D	D	ARc	ARc	**5**

2.3 Data analysis

2.3.1 Drought mitigation strategies and their economics

For each drought mitigation strategy i in drought year j, the gross margin (*GM*) in a given surveyed farm was calculated as follows:

$$GM_{ij} = \left(Production_j \times \overline{Price}\right) - CP_{ij} \quad (4.1)$$

where $Production_j$ is the Robusta green coffee production (beans yield × area harvested) in year j; $\overline{Price}$ is the 10-year (2008-2017) average coffee price; and CP_{ij} refers to the costs of production in year j for drought strategy i.

Prices for green coffee beans and costs of production were all expressed in real prices (US$) using the Consumer Price Indices for Vietnam during the 2008-2017 period (GSOV 2019). The 10-year average real price used in our study was US$ 1.29 kg^{-1}. The costs of production included costs related to electricity, fuel, labour, and inputs (e.g. fertilisers, agrochemicals). The price of irrigation per application in the surveyed farms was computed as the cost of the fuel, electricity, and labour needed.

2.3.2 Factors influencing the adoption of drought mitigation strategies

We hypothesised that there is a statistical association between a set of farm-specific variables (socio-economic and environmental characteristics) and the strategy adopted. To investigate this relationship the logit regression model was used. The logit model can be written as follows (Gelman and Hill 2007):

$$Pr(Y_i = 1) = Logit^{-1}(X_i\beta) \quad (4.2)$$

where Y_i refers to the outcome variable, which is the mitigation strategy; β is a vector of coefficients of the covariates (explanatory variables) X_i. The outcome variable is a binary variable coded as 1 = strategy based on mulching (irrigation + mulching), and 0 = no strategy (irrigation alone). Covariates included the socioeconomic and environmental characteristics of surveyed farmers. They were X_1= gender, X_2 = farm ownership, X_3 = farming experience, X_4 = farm size, X_5 = 10-year average farm income (from coffee and non-coffee), X_6 = 10-year average rainfall at the start of the cropping season, X_7 = water source, X_8 = irrigation method, and X_9 = drought impact level on yield as perceived by the farmer (Table 4.2). Continuous covariates (X_3, X_5,

X_6, and X_9) were standardised [mean(x)/2×sd(x)] to allow the direct comparison of effect sizes (Gelman and Hill 2007).

Furthermore, we hypothesised that the adoption of a drought coping strategy is positively associated to farm ownership, farming experience, farm income (used as a proxy of wealth in our study), rainfall at the start of the cropping season, and the perceived drought impact level. A mixed effect is expected for variables related to gender, age of farmer, farm size, water source, and irrigation method. All surveyed farmers had access to agricultural extension and climate information services. Consequently, this factor was not included in the model. All the statistical analyses were carried out using the R Language and Environment for Statistical Computing (R Core Team 2019).

Table 4.2. Explanatory variables hypothesised in the logit model.

Variable	Variable specification	Hypothesis
X_1	Gender of the respondent (i.e. farm's head): 1 for male, 0 for female	+/-
X_2	Farm ownership: 1 for the tenant, 0 for owner	+
X_3	Farming experience (years)	+
X_4	Farm size: 1 for smallholder (area ≤ 1 ha), 0 for large holder (area < 1 ha)	+/-
X_5	10-year (2008-2017) average farm income from coffee and non-coffee (US$)	+
X_6	10-year (2008-2017) average rainfall at the start of the cropping season, i.e. November-December total rain (mm)	+
X_7	Water source: 1 for groundwater, 0 surface water	+/-
X_8	Irrigation method: 1 for the basin, 0 sprinkler	+/-
X_9	Drought impact level (i.e. farmer's perception of drought impact on yield) (%)	+

3. Results

3.1 Participant background information

Table 4.3 presents the socio-demographic and farm characteristics of the surveyed farmers. Male farmers predominantly managed Robusta coffee farms in the selected provinces; with only 17% heads of the farm being female out of the 558 farmers interviewed. The highest proportion of female farmers was found in Dak Lak. This province also had the relatively highest proportion of tenant farmers (39%) (Table 4.3).

In Dak Nong and Lam Dong all the participants were, however, owners. Farming experience varied from 18 to 24 years on average depending on the province, with farmer's age ranging from 30 to 70 (as of 2017). Variable farm sizes were found, with average sizes ranging from 1.4 to 2.4 ha. Coffee trees were relatively young across the selected provinces, with more than half of them being < 20 years old. Coffee farming was the main source of income for the surveyed farmers (Table 4.3, Fig. A4.1). All farmers in Dak Lak, Dak Nong and Gia Lai (only 22 farmers in Lam Dong) had additional incomes from fruit trees or pepper (Fig. A4.1).

Table 4.3. Distribution of participants' sociodemographic and farm characteristics. The total number of surveyed farms was 558.

	Dak Lak (N= 180)		**Dak Nong** (N = 120)		**Gia Lai** (N = 93)		**Lam Dong** (N = 165)		**All provinces** (N = 558)	
	Mean ± standard deviation									
Farmer's age (year)	50 ± 7		46 ± 9		55 ± 9		52 ± 8		51± 8	
Farming experience (year)	23 ± 6		18 ± 6		21 ± 7		24 ± 5		22 ± 6	
Farm size (ha)	1.4 ± 1.0		1.8 ± 1.5		1.5 ± 1.3		2.2 ± 1.6		1.7 ± 1.4	
Age of tree (year)	24 ± 5		19 ± 4		21 ± 4		23 ± 4		22 ± 5	
Proportion of farmers[1] (%) according to:										
Gender	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
	22	78	17	83	17	83	12	88	17	83
Ownership	Owner	Tenant	Owner	Tenant	Owner	Tenant	Owner	Tenant	Owner	Tenant
	61	39	100	0	78	22	100	0	84	16
Income (US$ 1000)										
< 5	42		32		31		34		34	
5-10	37		36		43		38		38	
> 10	22		33		26		28		28	

[1]: Head of the farm.

3.2 Farmers' perceptions of drought

Our survey was structured so that farmers could state whether drought events occur every year, or biennially, or once in three years. They were also asked to indicate when the impact was felt on their coffee plantations and to subjectively quantify the impact level on coffee production. Overall, farmers associated drought to a deficit of rainfall during the cropping season, comparative to average-rainfall-condition years. The majority of respondents in Dak Lak (57%), Gia Lai (54%) and Lam Dong (64%) reported an occurrence of drought once in three years (Table 4.4). In Dak Nong, 57% of the interviewees reported the occurrence to be biennial. Virtually none of the participants experienced drought every year.

When asked to provide (subjectively) a level of drought impact on coffee production, the average yield reduction indicated by the surveyed farmers ranged from 7.6% (Lam Dong) to 12.2% (Dak Lak); the overall average value is 9.6% (all provinces data pooled). The majority of surveyed farmers in Dak Nong (70%), Gia Lai (70%) and Lam Dong (82%) indicated 5 to 10% of their coffee production decreased due to drought. In Dak Lak there was no clear indication, with 70 farmers (39%) reporting a decrease in coffee production up to 10%, and 86 (48%) reporting 10-15% decrease (Table 4.4).

3.3 Drought impact on Robusta coffee

Before analysing the economics of the drought coping strategies, the differences in yields and gross margins between drought and average-rainfall-condition years were quantified for each province using the 2008-2017 historical data. Overall Robusta coffee yield reduction due to drought was on average 6.5% (all provinces considered; Fig. 4.2a), compared to that in average-rainfall-condition years. Likewise, gross margins declined by 22% in drought years compared to those in average-rainfall-condition years: from US$ 1144 ha^{-1} to US$ 892 ha^{-1} (all provinces considered; Fig. 4.2b).

More specifically, in Dak Lak and Gia Lai the yield reduction due to drought was 9% and 14%, respectively, with the difference in yields between drought and average-rainfall-condition years being statistically significant ($p < 2e^{-16}$). The corresponding decreases in gross margins were on average from US$ 1097 ha^{-1} to US$ 748 ha^{-1}, and US$ 1189 ha^{-1} to US$ 616 ha^{-1}, respectively (Fig. 4.2b). In Dak Nong and Lam Dong, coffee yields in drought and average-rainfall-condition years were statistically similar on average ($p = 0.3$ and $p = 0.076$, respectively; Fig. 4.2a). However, in Dak Nong, gross margins in drought years were reduced by 20% on average compared to their levels in the average-rainfall-condition year (from US$ 913 ha^{-1} to US$ 730 ha^{-1}); whereas in Lam Dong gross margins did not statistically differ between average-rainfall-condition and drought years ($p = 0.7$; Fig. 4.2b). The relatively shorter data period (10 years) used to assess objectively coffee yield reduction due to drought could explain, partly, the differences found from farmers' assessments. Indeed, although 94% of the surveyed farmers had more than 10 years of coffee farming experience, no historical yield data spaning that farming experience were available. It is also worth mentioning that apart from drought yield reductions can be related to the biennial bearing effect on coffee yield, i.e. alternation of high and low coffee bean productions (DaMatta 2004a).

Table 4.4. Distribution of the surveyed farmers according to their perception on drought frequency and drought impact on Robusta coffee production in Dak Lak, Dak Nong, Gia Lai and Lam Dong. Drought frequency is classified based on the results of maximum drought occurrence.

		Dak Lak (N= 180)	**Dak Nong** (N = 120)	**Gia Lai** (N = 93)	**Lam Dong** (N = 165)	**All province** (N = 558)
		Proportion of farmers (%)				
Drought frequency						
	Every year	0	1	0	0	0.2
	Once in 2 years	43	76	46	36	50.3
	Once in 3 years	57	23	54	64	49.5
Year when drought impact is felt on crop						
	Same year	57	58	54	42	53
	Following year	43	42	46	58	47
Impact level on coffee yield (%)						
	Less (0-5)	0	6	2	8	4
	High (5-10)	39	70	70	82	65
	Very high (10-15)	48	19	28	9	26
	Severe (> 15)	13	5	0	0	4

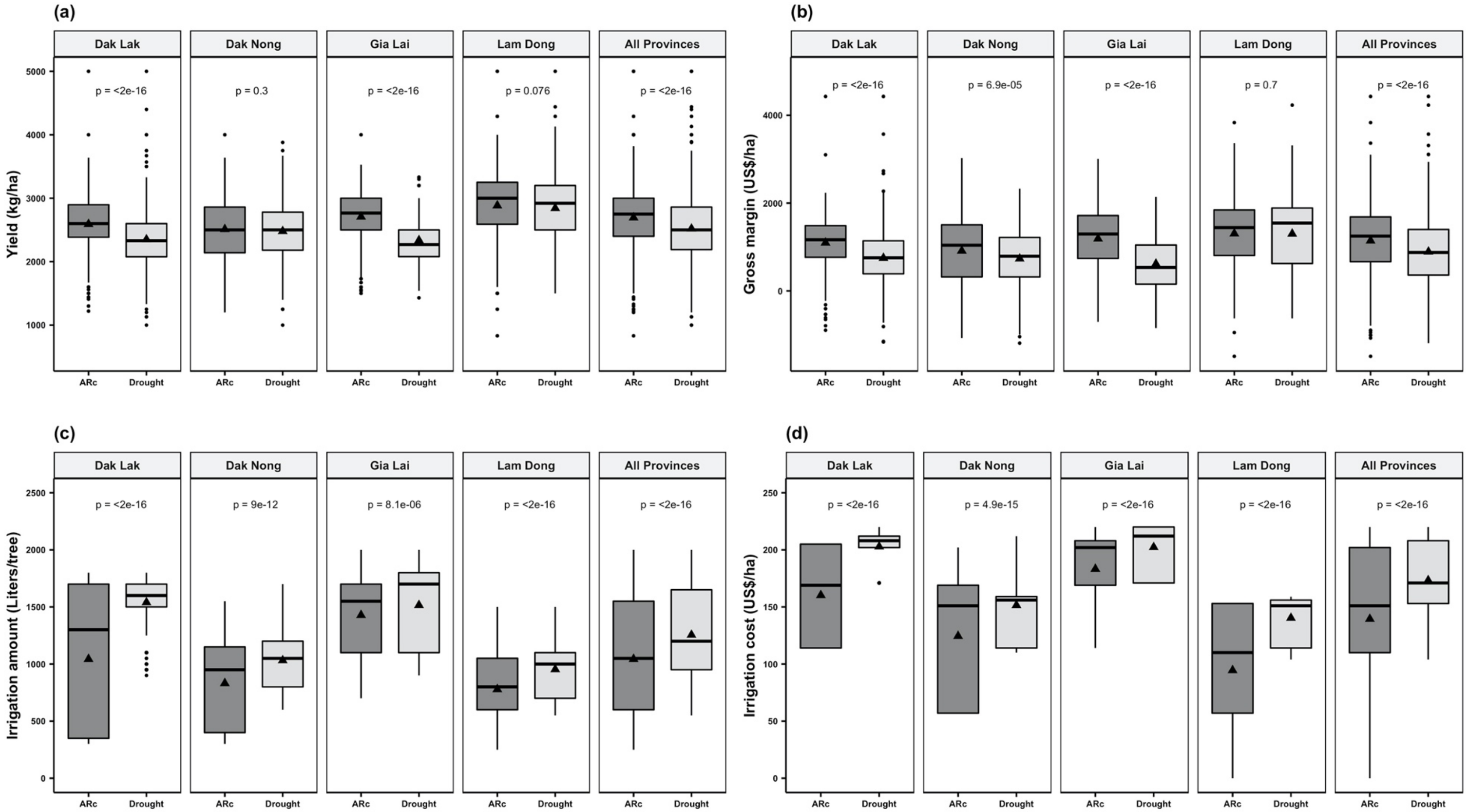

Fig. 4.2. Boxplots of (a) Robusta coffee yields, (b) gross margins from coffee farming, (c) irrigation amount, and (d) irrigation cost according to rainfall pattern (drought and average-rainfall-condition, ARc) for the study Vietnamese Robusta coffee-producing provinces during 2008-2017. Upper and lower border of the boxes represent the 3rd and 1st quartiles, respectively. The line within the box represents the median value, and black triangle is the mean value. Bars extend to the minimum and maximum values. Black circles are the outliers. For each province, the p-values from the t-test comparing mean values are shown (significant difference at $p < 0.05$).

3.4 Drought coping strategies and their economics during 2008-2017

To cope with the adverse effects of drought, the survey revealed that farmers adopted mulching as a coping strategy, in addition to irrigation which was already included in their management practices. Farmers rely on irrigation for synchronous Robusta coffee blossoming, and for maintaining high yield levels in both drought and average-rainfall-condition years. Nevertheless, in drought years, this practice is implicitly used as coping strategy. Shade trees, which are known as a drought strategy (Boreux et al. 2016), were not found as such among the surveyed farmers in Vietnam. In our analysis, mulching (consisting of pruned branches and leaves from coffee trees or other trees in surrounding areas) was defined as the drought coping strategy (hereafter referred to as S1); the usual irrigation practice being referred to as S0.

Irrigation was predominantly supplied through basin across the study provinces (60% of the 558 surveyed farmers; Table 4.5), with frequencies varying between 2 and 4 rounds per year in drought years. In drought years, the amounts and costs of irrigation increased compared to those in average-rainfall-condition years across all provinces, though with varying levels according to the province (Figs. 4.2c and 4.2d). The average increase in irrigation costs for all four provinces was 24% (US$ 139 ha^{-1} to US$ 173 ha^{-1}), with higher increases recorded in Dak Lak (27%) and Lam Dong (49%) (Fig. 4.2d).

A total of 324 Robusta coffee farmers surveyed (58%) adopted S1 to cope with drought (Table 4.5). The breakdown by province shows that those in Dak Nong and Lam Dong predominantly relied on S1, while the majority of their counterparts in Dak Lak (65%) and Gia Lai (57%) preferred to keep irrigation alone to cope with the adverse effects of drought (Table 4.5). In terms of yield difference (Fig. 4.3), for all the provinces, yields in S1 were on average, 7.7% higher than those in S0 (Fig. A4.2a). The highest average yields were observed in Lam Dong, regardless of the strategy: they ranged from 2285 to 3051 kg ha^{-1}, and 2277 to 3156 kg ha^{-1} for S0 and S1, respectively. In Dak Lak there was no statistical yield difference between farmers adopting S1 or S0 in drought years ($p > 0.05$; Fig. 4.3a): coffee yields ranged from 2206 to 2863 kg ha^{-1}, and 2203 to 2848 kg ha^{-1} for S0 and S1, respectively.

Farmers adopting S1 were generally best rewarded than those relying only on irrigation in drought years, with the overall average gain being US$ 10.2% ha^{-1} (Fig. A4.2b). The gross margins in S1 were US$ 974, 917, 1132, and 1369 ha^{-1} on average, for Dak Lak, Dak Nong, Gia Lai and Lam Dong, respectively (Fig. 4.4b-d). The respective differences in gross margins from their counterparts adopting S0 were 6, 17, 11, and 9%, and were statistically significant in the majority of provinces ($p < 0.05$), when considering all drought years pooled together. The only exception was Dak Lak.

When comparing farmers with unprofitable coffee farming activity in drought years, the highest proportions occurred in 2008 in Dak Lak, Dak Nong and Gia Lai (Table A4.2). The majority of them were among those applying S0: 66% and 64% in Dak Lak and Gia Lai, respectively. The opposite was found in the remaining provinces Dak Nong and Lam Dong, though in this latter only 17 farms out of the 165 surveyed were concerned with such losses (Table A4.2). Irrespective of the province, these numbers noticeably decreased in subsequent drought years (up to five farms), suggesting, in part, improved resilience to drought.

Table 4.5. Distribution of the surveyed farmers according to drought mitigation strategies, irrigation frequency and methods in the study Vietnamese Robusta coffee-producing provinces.

	Dak Lak (N = 180)	**Dak Nong** (N = 120)	**Gia Lai** (N = 93)	**Lam Dong** (N = 165)	**All provinces (N = 558)**
	Proportion of farmers (%)				
Mitigation strategy					
No strategy (S0)	65	36	57	13	42
Mulching (S1)	35	64	43	87	58
Irrigation frequency (rounds/year)					
2	20	37	10	44	29
3	20	49	30	56	39
4	60	13	60	0	32
Irrigation method					
Basin	46	61	48	84	60
Sprinkler	54	39	52	16	40

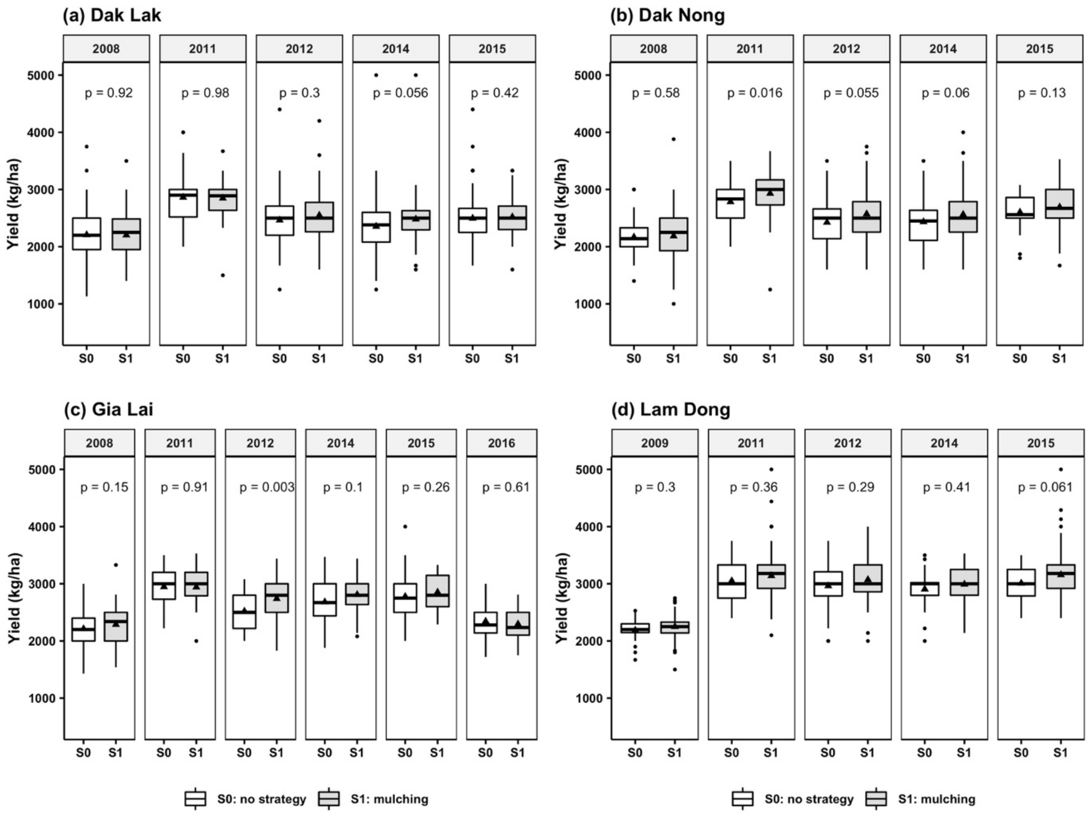

Fig. 4.3. Boxplots of Robusta coffee yields according to drought mitigation strategy for (a) Dak Lak, (b) Dak Nong, (c) Gia Lai, and (d) Lam Dong in drought years during the 2008-2017 periods. Upper and lower border of the boxes represent the 3rd and 1st quartiles, respectively. The line within the box represents the median value, and the black triangle is the mean value. Bars extend to the minimum and maximum values. Black circles are the outliers. For each province, the p-values from the t-test comparing mean values are shown (significant difference at $p < 0.05$).

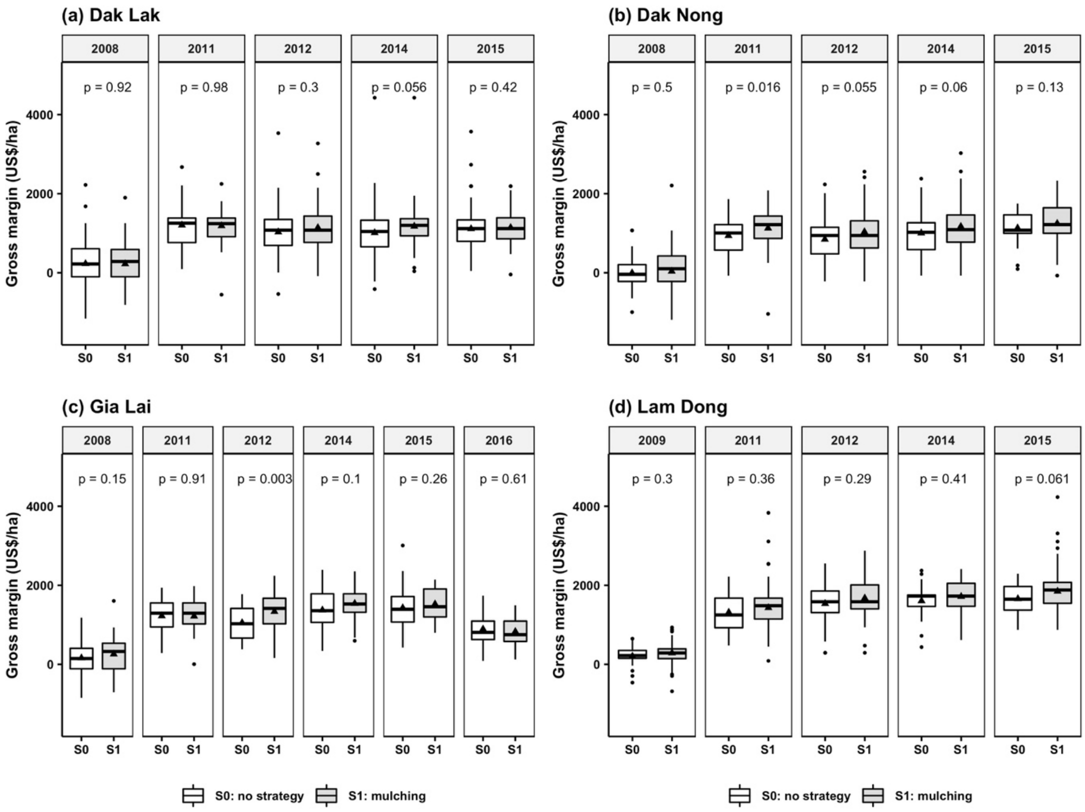

Fig. 4.4. Boxplots of gross margins according to drought mitigation for (a) Dak Lak, (b) Dak Nong, (c) Gia Lai, and (d) Lam Dong in drought years during the 2008-2017 periods. Upper and lower border of the boxes represent the 3rd and 1st quartiles, respectively. The line within the box represents the median value, and the black triangle is the mean value. Bars extend to the minimum and maximum values. Black circles are the outliers. For each province, the p-values from the t-test comparing mean values are shown (significant difference at $p < 0.05$).

3.5 Factors influencing the adoption of the drought mitigation strategies

A logit model was used to examine the factors that influence the adoption of drought mitigation strategies. We applied this model to overall data (i.e. all provinces pooled) and as well as on individual province data. Overall, the model shows a good fit and significance level, for all provinces as well as for the individual provinces, as shown by the Log Likelihood values in Table 4.6. Considering all the provinces altogether, only rainfall at the start of the season had a positive and significant effect on the adoption of S1 ($p < 0.01$; Table 4.6). Other variables that positively, but not significantly affect the adoption of S1 included household income, farming experience, and gender. Farm size, irrigation method, farm ownership and perceived drought level negatively and significantly ($p < 0.05$) influence the adoption of S1.

At the level of each province, varying patterns were found for the potential factors influencing the adoption of S1 (Tables 4.6, A4.1 and A4.2). For example, for one unit increase in household incomes (holding all other variables at a constant value) the odds of adopting S1 (as opposed to S0) in Dak Nong, Gia Lai and Lam Dong were 16%, 2% and 1%, respectively (Table A4.2). In Dak Lak, while for one unit increase of their incomes farmers were less likely to adopt S1, the perceived drought impact on coffee yield or farming experience, however, increased the chances of its adoption by 21% and 62%, respectively; even though such increase/decrease remained not statistically significant ($p > 0.05$) (Tables 4.6 and A4.2). Rainfall at the start of the season positively and significantly ($p < 0.01$) affected the adoption of S1 in Dak Lak and Dak Nong: the odds of adopting S1 (as opposed to S0) were 3.4% and 6.1% higher, respectively, for one unit increase of rainfall (Table A4.2). Whilst in Gia Lai and Lam Dong there were 35% and 85% lesser chances of adopting S1 for one unit increase of rainfall at the start of the season.

Table 4.6. Coefficient estimates of factors influencing the adoption of mulching as drought coping strategy in the selected Vietnamese Robusta coffee-producing provinces.

	Dak Lak	**Dak Nong**	**Gia Lai**	**Lam Dong**	**All Provinces**
Variable	**Coefficient estimate (standard deviation)**				
Income[a]	-0.683 (0.525)	0.147 (0.567)	0.023 (0.823)	0.010 (0.543)	0.036 (0.247)
Rain[b]	1.235** (0.360)	1.808*** (0.578)	-0.424 (0.641)	-1.910*** (0.540)	0.660*** (0.208)
Farming experience	0.481 (0.364)	-0.280 (0.445)	-0.034 (0.491)	-0.546 (0.514)	0.032 (0.190)
Farm size (1 for smallholder, 0 for large-holder) [c]	-1.274* (0.655)	0.087 (0.513)	0.949 (0.661)	-0.625 (0.548)	-0.518** (0.251)
Irrigation method (1 for basin, 0 for sprinkler)	-0.530 (0.576)	-0.171 (0.562)	0.016 (0.609)	0.081 (0.783)	-0.556** (0.241)
Water source (1 for groundwater, 0 for surface water)	0.758 (0.480)	0.324 (0.430)	0.251 (0.689)	0.495 (0.603)	-0.178 (0.205)
Gender (1 for male, 0 for female)	0.115 (0.430)	0.128 (0.570)	0.803 (0.724)	1.074* (0.647)	0.24 (0.258)
Farm ownership (1 for tenant, 0 for owner) [d]	-1.431*** (0.391)		-3.210*** (1.162)		-2.031*** (0.320)
Impact level	0.190 (0.352)	-0.321 (0.423)	-0.101 (0.508)	-0.724 (0.490)	-0.773*** (0.214)
Constant	-0.589 (0.649)	0.545 (0.593)	-0.738 (0.948)	1.198* (0.613)	0.775*** (0.277)
Observations	180	120	93	165	558
Log Likelihood	-99.946	-70.069	-51.172	-54.228	-319.751
Akaike Information Criterion	219.891	158.139	122.345	126.456	659.503

[a] 10-year (2008-2017) average income

[b] 10-year (2008-2017) average of rainfall total at the start of each season (November-December)

[c] Smallholder: farm size ≤ 1 ha; large-holder: farm size > 1 ha

[d] All farmers in Dak Nong and Lam Dong were owners (no estimate provided for 'farm ownership')

Statistical significance: *: $p < 0.1$; **: $p < 0.05$; ***: $p < 0.01$.

4. Discussion

We illustrated through a comparative assessment that while the surveyed farmers in Dak Lak, Dak Nong, Gia Lai and Lam Dong shared certain climatic conditions, their perceptions and responses to drought varied. The drought was generally associated with a deficit of rainfall during the coffee season (November of year-1 to October of year+1), comparative to average-rainfall-condition years. The majority of respondents in Dak Lak, Gia Lai and Lam Dong reported an occurrence of drought once in three years, with varying adverse effects on their Robusta coffee production. Although the yield reduction due to drought was < 7% on average across all provinces, the impacts on gross margins were noticeable, with a 22% decline on average from levels achieved in average-rainfall-condition years. To cope with these adverse effects, the surveyed farmers relied only on mulching in addition to irrigation.

It was expected that the chances of adopting mulching across the Robusta coffee-producing provinces would increase for one unit increase in the perceived drought impact level or for farmers with more experience. The opposite, however, was found among the surveyed farmers in three out of four study provinces (Table 4.6 and A4.1). Several factors can explain such results including the frequency of drought events as perceived by farmers and the resulting yield reductions, the availability and affordability of water for irrigation until then, as well as the affordability of agrochemicals compared to other coffee-producing countries. For example, the once-in-three-years drought occurrence reported by the majority of farmers and yield reduction predominantly estimated between 5 and 15% suggest that coffee trees, grown consistently under intensive fertiliser and irrigation use (D'haeze et al. 2005; Marsh 2007; Byrareddy et al. 2019), were able to recover from any negative effects between each drought events. Our analysis indicated that the amounts of irrigation applied in drought years in S1 or S0 strategies were statistically similar ($p > 0.05$; Fig. A4.3) in the majority of provinces (Dak Lak, Dak Nong and Gia Lai). Such an indifferent irrigation use could be explained by a "no-risk" attitude farmers can have while willing to achieve or sustain high coffee yield regardless of the rainfall pattern. Farmers might not find it urgent to adopt water conservation-based strategy to cope with drought. As drought events are expected to be recurrent, and likely more severe (IPCC 2014) there is a need to increase farmer's awareness on the availability of water for irrigation under the changing climate and help prepare for better drought management. The reliance on water resources (groundwater and river flows) to achieve high yields (Marsh 2007; Haggar and Schepp 2012) could be detrimental to the sustainability of the whole farming system during prolonged drought events in the study provinces. It also increases the vulnerability to climate change given its currently perceived and expected adverse impacts on agricultural water availability across the Vietnamese coffee-producing provinces (Haggar and Schepp 2012; Parker et al. 2019; Pham et al. 2019).

Various benefits of mulching have been documented for several crops, including coffee. In addition to reducing weed competition or improving soil moisture and texture, mulches also supply nutrients to soils, albeit at varying levels depending on the quality of the mulch materials, climatic conditions and soil types (Chalker-Scott 2007; Kader et al. 2017; Nzeyimana et al. 2019; Qu et al. 2019). Relatively higher average coffee yields were found in the surveyed farms where mulching was used in drought years (compared to those using irrigation alone) across three out of four selected Robusta coffee-producing provinces in Vietnam (Fig. 4.3). Fertilisers management (type, rate and frequency) and soil fertility differ between provinces or between farms within a specific province (Tiemann et al. 2018; Byrareddy et al. 2019). Although mulching may have helped improve plant growth and increase yields, differences in yields between drought coping strategies could also be explained by such factors. The impact of other crop management practices such as pruning, harvest methods, pesticides and herbicides applications can be ruled out since they were generally similar across the surveyed farms (Byrareddy et al. 2019).

More resilient coffee production systems are expected to sustain less damage and to recover more quickly when exposed to climate risk. It is critical to implement policies for optimum use of water for irrigation in coffee areas in Vietnam since there are opportunities in the study provinces to reducing water for irrigation while achieving satisfactory yield levels (e.g., 3000-4000 kg ha^{-1}), (Amarasinghe et al. 2015; Byrareddy et al. 2020). Moreover, although there were examples of pepper planted as shade or windbreak trees in few farms (25 out of 558 farms), the farmers in question did not consider this as a drought mitigation/adaptation strategy. Instead, they were concerned about the competition for irrigation water from such trees and subsequent reduction of their coffee yield potential in drought conditions. Shade trees, when associated with good management practices, can benefit coffee farming systems by improving soil water infiltration and soil conservation, reducing water and heat stress, and often increasing berry production (Souza et al. 2012; Boreux et al. 2016; Meylan et al. 2017). However, the complex functioning and interactions between coffee and shade trees remain a challenge that has to be thoroughly investigated to increase the chances of adopting this practice in Robusta coffee farms in Vietnam.

Based on data spanning the 2008-2017 period, the majority of Robusta coffee farms (> 75%) achieved positive gross margins in drought years despite the adverse financial impacts of drought, mostly because of the availability and affordability of water for irrigation. Lower water tables after drought events can be observed across the study provinces (CCAFS-SEA 2016), implying that irrigation costs, namely electricity charges, would increase in water-scarce conditions. Moreover, if the government decides to put a price on water, the negative financial impacts of drought can be even greater and detrimental to Robusta coffee farming systems in Vietnam. Our findings show that so far incremental adaptation strategies (irrigation + mulching) have allowed coffee producers to alleviate the impacts of drought. However, with an increase in drought frequency and severity, and considering sustainability, some incremental response may not be sufficient. For the future expansion of coffee areas, transformational responses, which may include relocation to suitable environmental conditions, may be worth considering.

5. Conclusions

We investigated farmers' perceptions and responses to drought, drought impacts on yield and gross margins in four major Robusta coffee-producing provinces in Vietnam and determined the economics of strategies adopted to cope with the adverse effects of drought. From the strategies adopted to cope with the harmful effects of drought on their coffee production, farmers adopting a combination of irrigation and mulching achieved positive gross margins than those relying on only irrigation. Although Robusta coffee farming was generally profitable for all farmers in drought years, the current irrigation-based strategies need to be diversified or improved to build up a strong resilience given the projected changes in rainfall patterns across the study provinces. Building the resilience of Robusta coffee farmers in a changing climate also implies an incremental adaptation process to more variable climate conditions. With the benefit of adopting mulching in addition to irrigation to cope with drought, as demonstrated in this study (at least for provinces such as Dak Nong, Gia Lai and Lam Dong), farmers would make it an integral part of their management practices, and even be able to improve it. As such, this study could serve as a basis for the design of policies to address drought risks and encourage more resilient adaptive strategies.

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Appendices 4

Table A4.1. Number of Robusta coffee farms where there was no profit in drought years during the 2008-2017 period. Drought mitigation strategies (S0): no strategy (irrigation alone), (S1): mulching (irrigation + mulching).

Province	District	Year	Drought strategy	Number of farms with negative gross margin	Total
Dak Lak (N = 180)	Buon Ma Thuot, Cu M'gar, Krong Ana, Krong Buk, Krong Nang, Krong Pak	2008	S0 S1	47 24	71
	Cu M'gar	2011	S1	1	1
	Krong Nang, Krong Pak	2012	S0 S1	1 1	2
	Krong Ana, Krong Buk, Krong Pak	2014	S0	5	5
	Krong Nang	2015	S1	1	1
Dak Nong (N = 120)	Dak Glong, Dak Mil, Dak Ralp, Dak Song	2008	S0 S1	23 36	59
	Dak Mil	2011	S0 S1	1 1	2
	Dak Glong, Dak Mil, Dak Ralp, Dak Song	2012	S0 S1	1 4	5
	Dak Glong, Dak Song	2014	S0 S1	1 1	2
	Dak Mil	2015	S1	1	1
Gia Lai (N = 93)	Chu Prong, Dak Doa, Ia Grai	2008	S0 S1	21 12	33
Lam Dong (N = 165)	Di Linh, Duc Trong, Lam Ha	2009	S0 S1	5 12	17

Table A4.2. Odds ratios of factors influencing the adoption of mulching as drought coping strategy. Odd ratios are the exponentiated values of coefficient estimates (see Table 4.6).

	Dak Lak	**Dak Nong**	**Gia Lai**	**Lam Dong**	**All Provinces**
Variable			**Odd ratios**		
Income [a]	0.505	1.158	1.023	1.010	1.036
Rain [b]	3.437***	6.099***	0.654	0.148***	1.934***
Farming experience	1.618	0.756	0.967	0.579	1.032
Farm size (1 for smallholder, 0 for largeholder) [c]	0.280**	1.090	2.583	0.535	0.596**
Irrigation method (1 for basin, 0 for sprinkler)	0.589	0.842	1.016	1.084	0.573**
Water source (1 for groundwater, 0 for surface water)	2.135	1.383	1.286	1.640	0.837
Gender (1 for male, 0 for female)	1.122	1.136	2.232	2.928*	1.272
Farm ownership (1 for tenant, 0 for owner) [d]	0.239***		0.040***		0.131***
Impact level	1.210	0.725	0.904	0.485	0.461***
Constant	0.555	1.724	0.478	3.314**	2.170***
Observations	180	120	93	165	558
Log Likelihood	-99.946	-70.069	-51.172	-54.228	-319.751
Akaike Information Criterion	219.891	158.139	122.345	126.456	659.503

[a] 10-year (2008-2017) average income.

[b] 10-year (2008-2017) average of rainfall total at the start of each season (November-December).

[c] Smallholder: farm size ≤ 1 ha; largeholder: farm size > 1 ha.

[d] All farmers in Dak Nong and Lam Dong were owners (no estimate provided for 'farm ownership').

Statistical significance: **: $p < 0.05$; ***: $p < 0.01$.

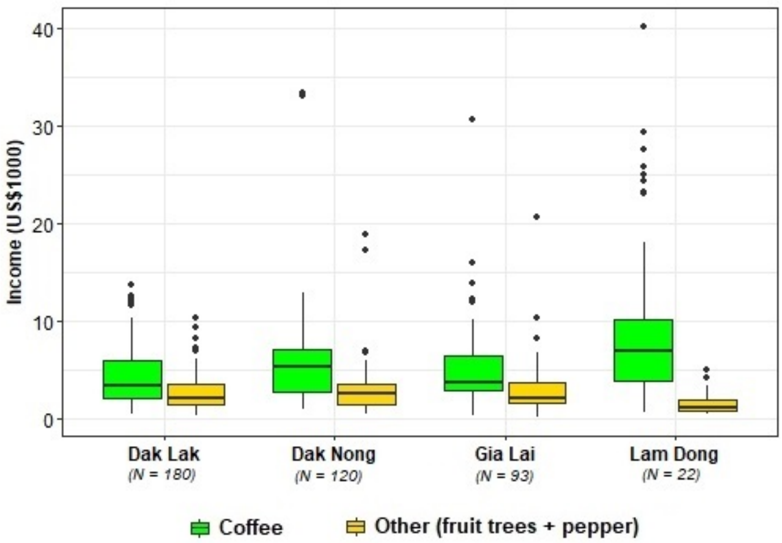

Fig. A4.1. Sources of household incomes (2008-2017 averages) of the surveyed farmers for each of the selected Vietnamese Robusta coffee-producing provinces. Only farmers having both sources of revenues were considered, i.e. in Lam Dong 22 out of 165 farmers. Upper and lower border of the boxes represent the 3rd and 1st quartiles, respectively. The line within the box represents the median value. Bars extend to the minimum and maximum values. Black circles are the outliers.

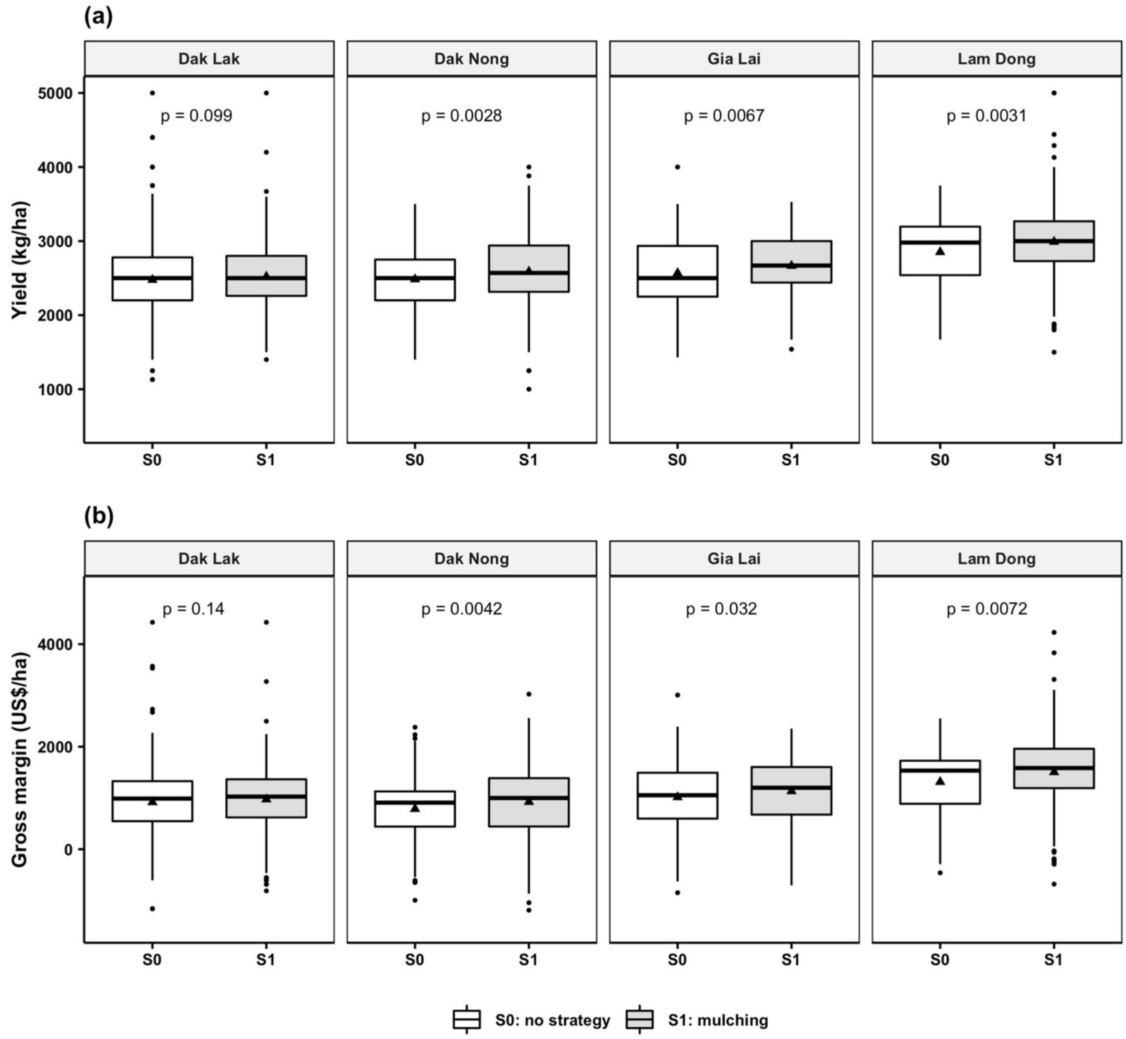

Fig. A4.2. Boxplots of (a) Robusta coffee yields and (b) gross margins according to drought mitigation strategy in drought years during the 2008-2017 periods. Upper and lower border of the boxes represent the 3rd and 1st quartiles, respectively. The line within the box represents the median value, and black triangle is the mean value. Bars extend to the minimum and maximum values. Black circles are the outliers. For each province, the p-values from the t-test comparing mean values are shown (significant difference at $p < 0.05$).

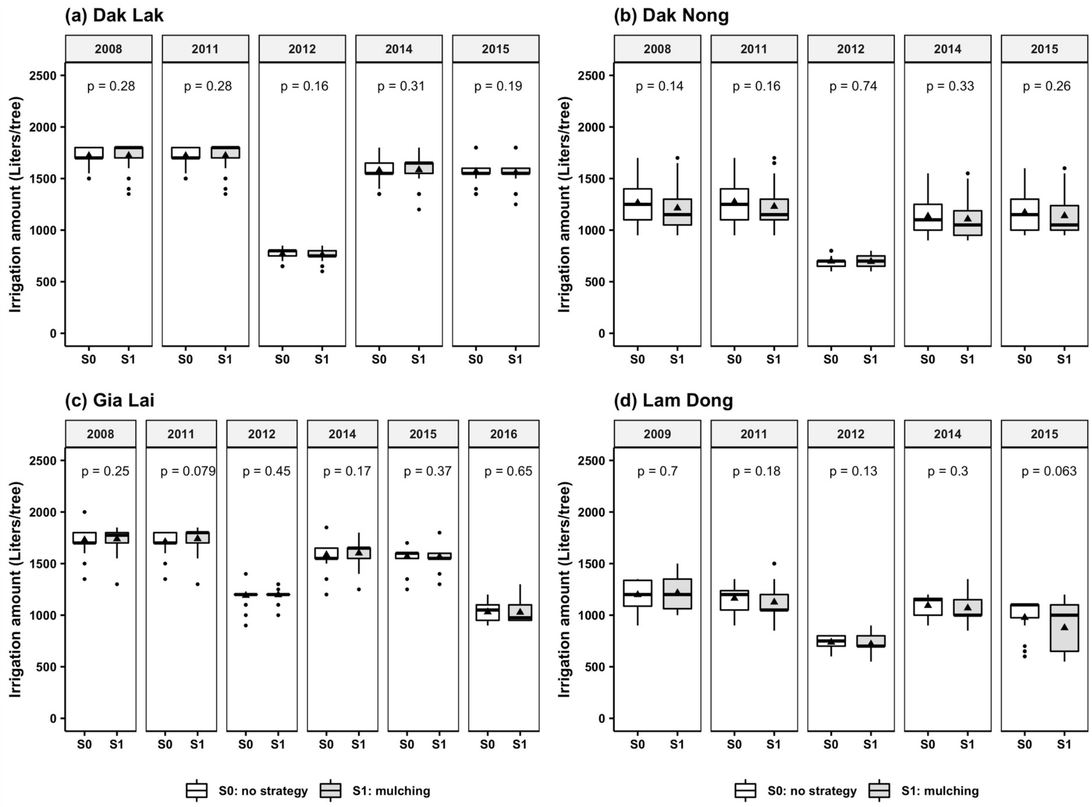

Fig. A4.3. Boxplots of irrigation amounts according to drought mitigation strategy for (a) Dak Lak, (b) Dak Nong, (c) Gia Lai and (d) Lam Dong in drought years during the 2008-2017 periods. Upper and lower border of the boxes represent the 3rd and 1st quartiles, respectively. The line within the box represents the median value, and black triangle is the mean value. Bars extend to the minimum and maximum values. Black circles are the outliers. For each province, the p-values from the t-test comparing mean values are shown (significant difference at $p < 0.05$).

Chapter 5

Seasonal climate forecasts and Robusta coffee yield forecasting

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Article IV: Improving the prediction of Robusta coffee yields at the regional scale using a simplified biophysical crop model

Vivekananda Byrareddy, Louis Kouadio, Torben Marcussen, Shahbaz Mushtaq, Roger Stone

Centre for Applied Climate Sciences, Institute for Life Sciences and the Environment, University of Southern Queensland, Toowoomba, QLD 4350, Australia

Abstract

This chapter builds upon the works on the development of a simplified, process-based biophysical model for simulating Robusta coffee growth (hereafter referred to as USQ-Robusta coffee model), and the integration of the model within a seasonal climate forecasts (SCF)-crop modelling system for coffee yield forecasting at the regional scale in Vietnam. Here, we first explore two approaches of integrating irrigation and fertiliser management practices based on the results from Chapters 2 and 3, and expert knowledge. Then we assess the performance of the modified biophysical model for the four major Robusta coffee-producing provinces in Vietnam (Dak Lak, Dak Nong, Gia Lai and Lam Dong), and discuss its potential use within an integrated SCF-crop modelling system for coffee yield forecasting. The first approach of including irrigation management practices relied on a better integration in the USQ-Robusta coffee model of the plant water balance throughout the growth season. The existing water stress factor was modified based on crop water requirements derived from the CROPWAT model. In the second approach, penalty/gain coefficients, derived from empirical statistical relationships between yields, irrigation amounts and fertiliser rates, were applied to the potential yield as simulated by the USQ-Robusta coffee model at the end of the simulation process using defined rules. These rules were based on the rainfall pattern of the simulation year and the potential deviation of the predicted yield from that of average-rainfall-conditions year. Further, we test the

capability of integrating SCF and the modified version of the USQ-Robusta coffee model to forecast probabilistic coffee yields, and discuss the benefits of such a system for the coffee industry in Vietnam. Overall, the modified version of the model resulted in better performance compared to the default version. For the majority of the provinces the prediction errors were reduced: MAPE were reduced by 2% on average; RMSE were reduced from 0.22 to 0.19 t ha^{-1}, 0.29 to 0.23 t ha^{-1}, and 0.30 to 0.25 t ha^{-1}, for Dak Lak, Dak Nong and Lam Dong, respectively. The probabilistic yield forecast using GCM seasonal forecast for May to November 2019 period, showed that the median yield variance ranged from 0.26 to 0.29 t ha^{-1}. Compared to the historical yield variance, a reduction in coffee yield was likely to occur for the 2018/2019 season.

1. Introduction

Seasonal climate forecasts (SCF) have the potential to improve farmers overall operational management of agricultural production through better decision-making, thereby increasing farm profits (Hammer et al. 2000; McCrea et al. 2005; Meinke and Stone 2005; Stone and Meinke 2005; Meza et al. 2008; Carr and Owusu-Daaku 2016; Bruno Soares et al. 2018; Parton et al. 2019). Indeed, SCF provide farmers with opportunities to better match management decisions (e.g., crop/variety selection, sowing time, sowing area, fertiliser application, harvesting, marketing, etc.) to pending climatic conditions (Hammer et al. 2000; Meinke and Stone 2005; Parton et al. 2019). SCF can benefit regional yield simulations even more than point-scale simulations, as rainfall forecast skill tends to improve with the scale of aggregation. Smaller spatial scales would have flatter probabilities, and climatological probabilities would have a lesser net effect on the forecast and, in turn, on the decisions made on its basis. (Gong et al. 2003). Linking SCF with crop models can produce useful information for strategic and tactical decisions in farm operations, and provide insightful outlook on yield and crop quality (Stone and Meinke 2005; Han et al. 2017; Iizumi et al. 2018; Jha et al. 2019). Several systems or tools coupling SCF and crop models exist. An example is the use of SCF in sugarcane industry in Australia for yield forecasting, harvest management and irrigation management to improve risk management and decision making capabilities (Everingham et al. 2002). Yield variations are influenced by variable rainfall patterns are a concern to farming and trading industry. Using the historical climate data combined with the yield knowledge in the region, the expected yield probability can be derived. The industry could use the SCF for likely expected production volume for strategic management of supply and demand (Meinke and Hammer 1997; Zinyengere et al. 2011). SCF has benefits to commercial agriculture operations if the information is used continuously and applied effectively in farming decisions (Klopper et al. 2006). Another example is the Climate-Agriculture-Modeling and Decision Tool (CAMDT), which aims at facilitating the transformation of probabilistic SCFs into crop responses (rice crop) that can help decision makers adjust crop (planting dates and cultural operations) and water management practices and improve their outcomes (Han et al. 2017). Coupling SCF and crop models for Arabica or Robusta coffee has not been fully explored yet and deserve attention because of the importance of this crop to the rural economies of many tropical countries worldwide.

Several studies have dealt with the modelling of coffee crop, ranging from statistical to process-based approaches (Gutierrez et al. 1998; van Oijen et al. 2010b; Rodríguez et al. 2011; Coltri et al. 2015). Process-based models are developed to understand the weather- and nutrient-driven dynamics and constraints of the plant trophic level (Gutierrez et al. 1998; van Oijen et al. 2010b; Rodríguez et al. 2011; Rahn et al. 2018). These were developed for Arabica coffee (*Coffea arabica*). Process-based modelling of Robusta coffee bean yield/production at larger spatial scale (e.g. regional scale) is very limited. So far, research efforts have been focusing on the impacts of climate change and variability on coffee productivity and distribution (land suitability) on a national to global scale e.g., (Davis et al. 2012; Bunn et al. 2015; Craparo et al. 2015). With this background, the Centre for Applied Climate Sciences of the University of Southern Queensland (USQ-CACS) has developed a simplified, process-based biophysical model for simulating Robusta coffee growth (hereafter referred to as USQ-Robusta coffee model) at the regional scale to investigate the potential for probabilistic coffee yield forecasting within a SCF-crop modelling system in Vietnam (Kouadio et al. 2015) (see Section 2). Although the interannual climate variability was captured satisfactorily by the model in three of the major Robusta coffee-producing provinces (Dak Lak, Gia Lai, and Lam Dong) (Kouadio et al. 2015), further improvements were necessary to better take into account crop water requirements throughout the growth season, as well as the potential impacts of fertilisers on yield. In Vietnam coffee production is noticeably influenced by irrigation and fertilisers (see Chapters 2, 3 and 4). The embedding of modules/equations dealing with irrigation and fertiliser would help improve the coffee growth simulation in the USQ-Robusta coffee model.

The main objective of this study was to investigate the inclusion of two key farm management practices (i.e., irrigation and fertiliser) within the USQ-Robusta coffee model to develop an improved SCF-Robusta coffee modelling system for coffee yield forecasting at the regional scale. Specifically, we first explored two approaches of integrating these two management practices based on the results from Byrareddy et al. (2019) and Byrareddy et al. (2020) (see Chapters 2 and 3), and expert knowledge (i.e., agronomists, crop physiologists). Expert knowledge was necessary for defining the percentage of daily biomass reduction according to the phenological stage and water stress level under the environmental conditions in Vietnam. Secondly, we assessed the performance of the modified biophysical model for the four major Robusta coffee-producing provinces in Vietnam (Dak Lak, Dak Nong, Gia Lai and Lam Dong). Thirdly, we tested the capability of linking SCF with the modified version of the USQ-Robusta coffee model to forecast probabilistic coffee yields and discussed the benefits of such a system for the coffee industry in Vietnam. The Central Highlands region of Vietnam (which encompasses the major Robusta coffee-producing provinces) is among the most drought-prone Vietnamese regions, with considerable crop losses due to drought events being reported during the past two decades (Nguyen 2005; Vu et al. 2015; GSOV 2017a; ICO 2019). Thus, such an integrated SCF-Robusta coffee modelling system could offer substantial benefits to coffee growers and industry through increased profitability, better logistical arrangements and preparedness for extreme events such as droughts and floods.

2. The USQ-Robusta coffee model

In this section we describe the main processes of the default USQ-Robusta coffee model and its calibration and testing phases (Kouadio et al. 2015), before inclusion of new modules.

2.1 Description of growth and development processes

The USQ-Robusta coffee model is a simplified, process-based biophysical model that simulates the potential growth and development of coffee plants at a daily time step at the regional scale, based on weather data (minimum and maximum temperature, solar radiation, and rainfall) and information from the previous growing season (i.e. harvest date and yield). Three main processes are involved during the simulation (Fig. 5.1). They are: (1) radiation interception by leaves following the Beer-Lambert law (Swinehart 1962); (2) conversion of the intercepted radiation into biomass based on the radiation use efficiency; and (3) accumulation of crop biomass and allocation to different organs according to source-sink rules specific to coffee plants (DaMatta et al. 2007; van Oijen et al. 2010b). No disease or pest impacts on yield are considered; as such the yield value predicted is a potential value. In the following sub-sections, we describe the main equations used for simulating biomass production and assimilates partitioning into the different organs.

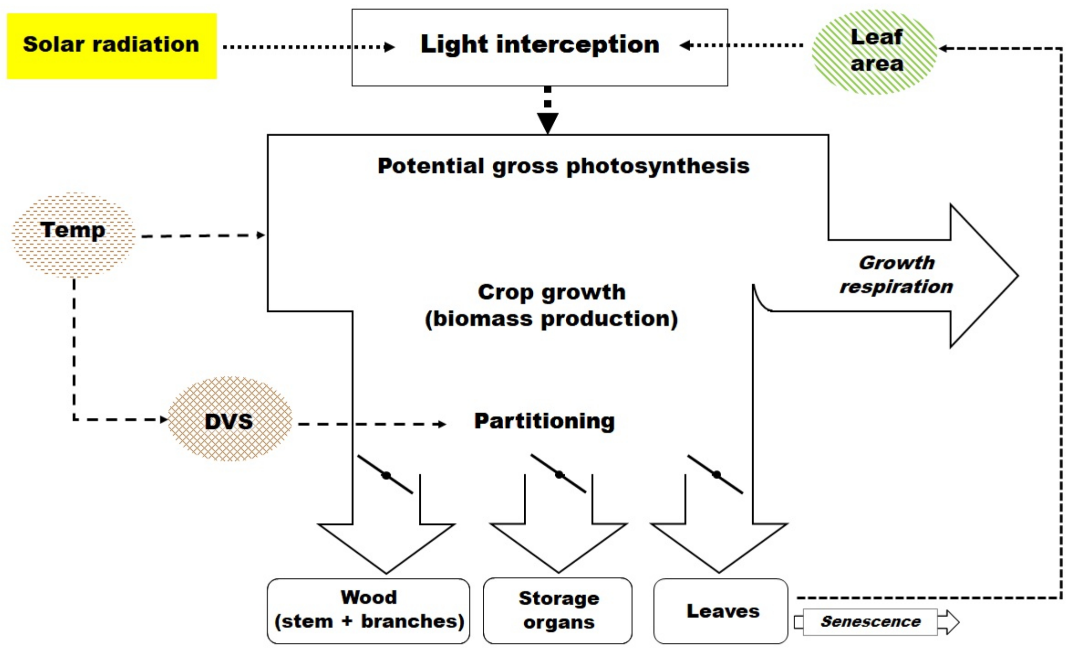

Fig. 5.1. The general structure of the biophysical Robusta coffee model. *Temp* refers to air temperature; and *DVS* refers to the phenological stage.

2.1.1 Biomass production (active growth)

The phenology of Robusta coffee trees includes two stages: the vegetative phase occurring before flowering and the reproductive phase or fruit development between flowering and harvest. Phenology is driven by the accumulation of growing degree-days. The daily biomass production is simulated in two steps. First, the light interception is calculated using the Beer-Lambert law (Eq. 5.1).

$$PAR_i = E_a \times E_c \times R_g \times (1 - e^{-K \times LAI}) \quad (5.1)$$

where PAR_i is the intercepted photosynthetic active radiation on day i (MJ m^{-2} d^{-1}); R_g is the daily solar radiation (MJ m^{-2} d^{-1}); *Ea*, *Ec* and *K* refer to the maximum interception efficiency, photosynthetically active fraction of solar radiation, and extinction coefficient, respectively (unitless).

The intercepted solar radiation is converted into biomass as follows:

$$\Delta Biom = E_b \times PAR_i \times \left(cost_{respi} - Biom_{veg}\right) \times STRESS \quad (5.2)$$

where $\Delta Biom$ is the daily increment in biomass (g m^{-2}); *Eb* is the light energy conversion efficiency (g MJ^{-1}); $cost_{respi}$ refers to the respiration cost of vegetative organs (unitless); $Biom_{veg}$ is the vegetative biomass (leaves + wood) already produced; and *STRESS* is a drought stress factor (unitless).

The drought stress factor is applied to the daily biomass production based on the number of days over the growing season where rainfall is below a given threshold.

2.1.2 Biomass partitioning

Prior to flowering, newly produced biomass is allocated as vegetative biomass. A factor related to pruning is considered during this phase following van Oijen et al. (2010b). The equations are as follows:

$$Biom_{wood} = Biom_{wood} \times \left(1 - K_{recep}\right) \tag{5.3}$$

$$Biom_{leaves} = Biom_{leaves} \times \left(1 - \left(K_{recep}/1.7\right)\right) \tag{5.4}$$

where $Biom_{wood}$ and $Biom_{leaves}$ are wood and leaves biomasses, respectively (both expressed in g m^{-2}); and K_{recep} is the percentage of pruning (unitless). The value 1.7 is an empirical factor related to the pruning and obtained from field experiments (unpublished data).

From flowering onwards, the newly produced biomass is allocated priority to storage organs according to a sink rule (i.e., fruit demand). When the fruit demand is satisfied, the excess biomass production is re-allocated to the vegetative growth.
Fruit demand is related to the number of fruits and is assumed proportional to the wood biomass grown after the last flowering and the potential of fruit growth. It is calculated as follows (Eq. 5.5).

$$BiomFruit_{dem} = UnitFruit_{dem} \times NF \tag{5.5}$$

where *NF* is the number of fruits (number per m^2) and $UnitFruit_{dem}$ corresponds to the potential of fruit growth. $UnitFruit_{dem}$ follows a sigmoidal function according to Cannell (1985) (Eq. 5.6). $UnitFruit_{dem}$ and *NF* are calculated as follows:

$$UnitFruit_{dem} = \frac{\Delta(ST_{t-1};ST_t) \times Kfruit}{1 + e^{-(ST-(TempREC/2)/cFruit)}} \tag{5.6}$$

$$NF = Fruit_{pot} \times BiomWood_{SLF} \tag{5.7}$$

where $Fruit_{pot}$ is the maximum number of fruits per kg of newly produced wood (number per kg); $BiomWood_{SLF}$ is the wood biomass grown after the last flowering (g m^{-2}); $\Delta(ST_{t-1}; ST_t)$ is the difference of degree days between time steps *t-1* and *t*; *Kfruit* is the slope of the biomass accumulation in fruit (unitless); *ST* is sum of temperature above the base temperature (°C); *TempREC* is the sum of degree-days between flowering and harvest (degree-days); and *cFruit* is the maximum fruit biomass (unitless).

If the fruit demand is not satisfied by the newly produced biomass, a proportion of leave biomass is remobilized (Eq. 5.8).

$$PotRem_{leaf} = K_{rem} \times Biomass_{leaves} \tag{5.8}$$

where $PotRem_{leaf}$ is the potential remobilization of biomass from leaves (g m^{-2}); K_{rem} is the maximum rate of remobilization (unitless); and $Biomass_{leaves}$ corresponds to leaves biomass.

2.1.3 Biomass reallocation into leaves and woody parts of the tree (passive growth)

The elaboration of bean yield is based primarily on the determination of the potential number of fruits according to the wood newly formed. Each fruit represents a sink of assimilates that can be fulfilled by assimilates newly produced and reallocated among the plant. After fruit setting, the daily proportion of assimilates ($\Delta Biom_{Veg}$) is allocated to leaves (Eq. 5.9) and wood (Eq. 5.10).

$$\Delta Biom_{leaves} = \left(\Delta Biom_{Veg} \times L_{percent}\right) - \left(Biom_{leaves} \times T_{sene}\right) - Rem_{leaf} \tag{5.9}$$

$$\Delta Biom_{wood} = \Delta Biom_{Veg} \times \left(1 - L_{percent}\right) \tag{5.10}$$

where $\Delta Biom_{leaves}$ and $\Delta Biom_{wood}$ refer to the biomass re-allocated to leaves and wood, respectively (both expressed in g m^{-2}); $L_{percent}$ is the percentage of leaves in newly formed biomass (unitless); T_{sene} is the senescence rate of leaves; and Rem_{leaf} is the biomass of leaves that was removed to supply the demand from fruits (g m^{-2}).

2.2 Initialization of the wood and leaves biomass at the start of the simulation

We assumed that the coffee tree has already started producing fruits. At the start of each simulation (i.e., date of the harvest in simulation Year -1) the above-ground vegetative biomass ($Biom_{Veg}$) is initialized based on the coffee bean yield of the previous growing season ($Yield_{ref}$) (Eq. 5.11).

$$Biom_{Veg} = Biom_{wood} + Biom_{leaves} \quad (5.11)$$

with $Biom_{wood} = K_{biom} \times Yield_{ref} + I_{biom}$ and $Biom_{leaves} = (LAI \times AP)/SLA$.

where K_{biom} and I_{biom} are two coefficients related to the above-ground biomass after the previous harvest (both unitless); *SLA* is the specific leaf area (m^2 kg^{-1}); *AP* is the ground surface occupied by each plant (m^{-2}); and *LAI* is the leaf area index (m^2 m^{-2}).

Given LAI dynamics in coffee trees are strongly influenced by management practices on farms (DaMatta et al. 2007; Silva et al. 2009; Costa et al. 2019), we assumed that the initial LAI value considered (i.e., at the start of the growth simulation) is also proportional, to some extent, to the bean yield from the previous season. In our case we determined the initial LAI value as $LAI_{init} = K_{LAI} \times Yield_{ref} + I_{LAI}$; where K_{Lai} and I_{Lai} are two coefficients related to the above-ground biomass after the previous harvest (both unitless).

2.3 Calibration and evaluation of the USQ-Robusta coffee model

Climate and yield data for Dak Lak, Gia Lai and Lam Dong were used for calibrating and evaluating the USQ-Robusta coffee model (Kouadio et al. 2015): data for Gia Lai and Lam Dong were used for calibration, and those for Dak Lak were used for the evaluation. Climate data for the 2001-2014 period were sourced from the National Centre for Hydro-Meteorological Forecasting of Vietnam (NCHMF 2014). Yield data were sourced from the General Statistics Office of Vietnam (GSOV 2017b). Yield data for Gia Lai and Lam Dong spanned the period 2001-2014. For Dak Lak, observed yield data for the period 2007-2014 were considered because during 2001-2004 Dak Nong was not officially created yet and Dak Lak data used to include those of Dak Nong.

The initial parameter values were derived from the CAF2007 model, which was developed to estimate the potential productivity of Arabica coffee agroforestry systems (van Oijen et al. 2010b). The value of each parameter was varied during the model calibration phase within the likely ranges of reported values. These reported values were derived from literature (DaMatta et al. 2007; Silva et al. 2009; van Oijen et al. 2010a,b; Schleppi et al. 2011), from field observations data from the *Centro Agronómico Tropical de Investigación y Enseñanza* (CATIE) research station at Turrialba, Costa Rica, or across the study regions in Vietnam. At each variation, the predicted yields were compared to the observed ones until the best combination (i.e., the model which outputs resulted in less errors) was found. A list of the model parameters and their values after calibration is presented in Table 5.1.

Table 5.1. Parameters of the USQ-Robusta coffee model

Parameter	Description	Unit	Default	Range for testing [a]	Value after calibration
E_a	Maximum interception efficiency	-	0.95	n.a. [b]	0.95
E_c	Photosynthetically active fraction of global radiation	-	0.48	n.a.	0.48
E_b	Light energy conversion efficiency	$g\ MJ^{-1}$	$16.5\ 10^{-4}$	n.a.	$16.5\ 10^{-4}$
K	Light extinction coefficient	$m^2\ m^{-2}$	0.76	n.a.	0.76
T_{sene}	Senescence rate of leaves	-	$6.4\ 10^{-4}$	n.a.	$6.4\ 10^{-4}$
$cost_{respi}$	Respiration cost of vegetative organs	-	$7.6\ 10^{-5}$	n.a.	$7.6\ 10^{-5}$
Kfruit	Slope of the biomass accumulation in fruits	-	$6.9\ 10^{-4}$	n.a.	$6.9\ 10^{-4}$
K_{rem}	Potential of remobilization of assimilates from leaves to fruits	-	$20.8\ 10^{-4}$	n.a.	$20.8\ 10^{-4}$
cFruit	Maximal fruit biomass	-	327	300-600	400
$Fruit_{pot}$	Maximal number of fruits per kg of newly produced wood	$n\ kg^{-1}$	2000	1100-2500	1350
Tmaxfruit	Maximal rate of biomass allocated to fruits	-	0.55	0.55-0.65	0.61
SLA	Specific leaf area	$m^2\ kg^{-1}$	18	18-27	18
K_{recep}	Percentage of pruning	-	0.28	0.20-0.50	0.33
KLai	Parameter used to initialize LAI at the start of the growth season according to the yield from the previous cropping season		4.5	1.5-5.5	4.4
ILai	Parameter used to initialize LAI at the start of the growth season according to the yield from the previous cropping season		-4.5	-6.5 - -1.5	-2.3
Kwood	Percentage of newly formed wood in biomass at initialization	-	0.43	0.33-0.48	0.40
$L_{percent}$	percentage of leaves in newly formed biomass	-	0.24	0.20-0.35	0.30
T_0	Base temperature	° C	12	10-15	12
TempREC	Degree-days between flowering and harvest	°Cd	2000	2000-3200	2800
TempFLO	Degree-days between harvest and flowering	°C d	1600	900-2500	1200
DR_{min}	number of dry days before drought stress	n	15	10-20	15
DR_{max}	number of dry days to reach maximal drought stress	n	85	75-105	90
RainThreshold	rain threshold for a dry day	mm	3	3-7	3
MaxDroughtStress	maximal value of drought stress	-	0.02	0.010-0.050	0.024

[a]: The ranges of values used were derived from literature (DaMatta et al. 2007; Silva et al. 2009; van Oijen et al. 2010a,b; Schleppi et al. 2011), from field observations data from the CATIE research centre or across the study regions in Vietnam.

[b] : not applicable. The default values were derived from the CAF2007 model (van Oijen et al. 2010b) and field experiments carried out at the CATIE research centre.

For coffee growth simulations, the start date of each season was set at November 1 each year and the simulations were carried out until October 31 of the following year. Overall, the results showed good agreement between the predicted and observed yields. Root mean square errors (RMSE) were 0.223 t ha^{-1} (calibration) and 0.220 t ha^{-1} (testing) (Fig. 5.2). The model captured satisfactorily the interannual yield variability for all three provinces (Fig. A5.1).

The USQ-Robusta coffee model is written using the R Language and Environment for Statistical Computing (R Core Team 2018), which allows some flexibility for coupling or adding new modules/components.

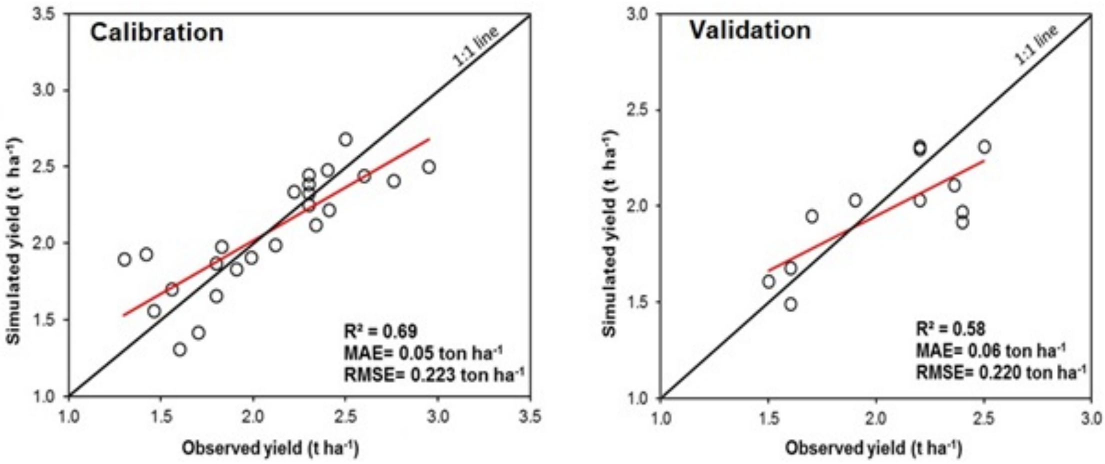

Fig. 5.2. Performance results of the USQ-Robusta coffee model during the calibration and testing phases.

3. Materials and methods

3.1 Data

Gridded daily climate data (maximum and minimum temperatures, relative humidity, rainfall, sunshine hours, and wind speed) for the 2007-2017 period sourced from the NASA POWER website (https://power.larc.nasa.gov/) were used to investigate the integration of fertiliser and irrigation components within the USQ-Robusta coffee model. The spatial distribution of the grids selected for each of the study provinces Dak Lak, Dak Nong, Gia Lai, and Lam Dong are presented in Table 5.2 and Fig. 5.3.

Official yield data (2008-2017; GSOV 2017a), as well as irrigation and fertiliser data from the 2008 – 2017 farms surveys were also used. These data have already been described in Byrareddy et al. (2019) and Byrareddy et al. (2020) (See Chapters 2 and 3, Sections 2.2 and 2.2).

SCF were sourced from the Climate Change Service website (https://climate.copernicus.eu/seasonal-forecasts). They are produced regularly at the global scale on a monthly time step based on data from several state-of-the-art seasonal prediction systems and cover a period of six months. The prediction systems are provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), the United Kingdom Meteorologcial Office (UKMO), METEO-France, the German Weather Service (Deutscher Wetterdienst, DWD), and the Euro-Mediterranean Center on Climate Change (Centro Euro-Mediterraneo sui Cambiamenti Climatici, CMCC). For the study provinces in Vietnam, monthly data were retrieved and downscaled at the daily time step for their use within the USQ-Robusta coffee model. This was carried out through the in-house USQ-CACS SCF tool (https://cacs.usqresearch.edu.au/cacs/; https://deriskseasia.org/).

Table 5.2. Selected grids for each of the provinces

	Dak Lak	**Dak Nong**	**Gia Lai**	**Lam Dong**
Grids	VN13, VN18, VN19, VN23	VN11, VN12	VN27, VN28, VN33	VN7, VN8

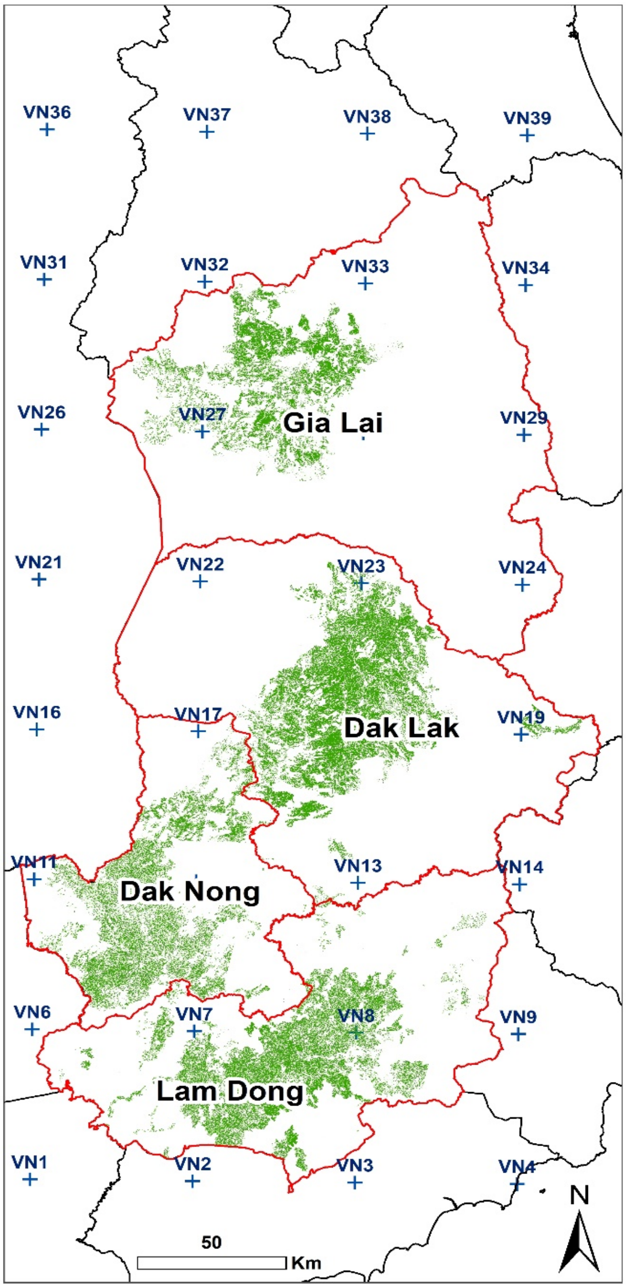

Fig. 5.3. Map of grid points falling within the boundaries of the study provinces Dak Lak, Dak Nong, Gia Lai and Lam Dong. Green areas represent coffee crop mask (Source: Ecomtrading, Vietnam).

3.2 Description of the approaches used for integrating irrigation and fertiliser components into the USQ-Robusta coffee model

3.2.1 First approach: new water stress component based on crop water requirements throughout the season

In the default version of the USQ-Robusta model, the total number of days with rainfall below a given threshold over the whole season is used to determine the proportion of water stress affecting biomass production (see Section 2.1.1). Given water stress can affect coffee growth differently according to the phenological stage, it is therefore important to consider water stress factors accordingly. In this approach of integrating crop water requirements (CWR) according to the phenological stages, we divided the coffee growth period for the study provinces into three different periods: November-December, January-April, and May-October.

CWR were calculated using the CROPWAT software (FAO 2018). CWR are defined here as "the depth of water needed to meet the water loss through evapotranspiration (ETc) of a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment" (Doorenbos and Pruitt 1992). CWR values were computed under standard conditions, i.e. disease-free, non-limiting nutrient and soil water conditions, and, as such, corresponds to the potential CWR. All the calculation procedures were based on Allen et al. (1998) and Steduto et al. (2012). The input data included daily climate data (maximum and minimum temperatures, relative humidity, rainfall, sunshine hours, and wind speed), soil data (available water capacity, field capacity, wilting point, and infiltration rate), coffee crop data (phenological stage duration, depletion coefficient, root depth, crop coefficient, yield response factor, and crop height), and observed irrigation data. Soil and crop parameters used in the calculations are presented in Chapter 3 (see Section 2.3). Soil data were sourced from the Soils and Fertilisers Research Institute (SFRI) of Vietnam (http://www.sfri.org.vn). Coffee crop data were retrieved from Allen et al. (1998) and Steduto et al. (2012).

Depending on the phenological stage and water stress levels (expressed through the number of days with rainfall below ETc), different coefficients of biomass reduction were applied (Table 5.3). The values of these coefficients were derived from the information collected during the surveys and expert knowledge (i.e., agronomists, crop physiologists). We also checked the literature for such relationships in other coffee-producing countries.

Table 5.3. Rules used for defining the percentage of daily biomass reduction according to the phenological stage and water stress level. The daily biomass reduction coefficient is applied to the newly produced biomass in the model.

Condition	Period	Consecutive days with rain < ETc (days)	Daily biomass reduction (%)
A. Start of the season (less sensitive phenological stage)			
Normal	Nov - Dec	10	0
Dry	Nov - Dec	20	5
Very dry	Nov - Dec	30	10
B. Flowering-fruit set (sensitive phenological stage)			
Normal	Jan - Apr	10	0
Dry	Jan - Apr	20	15
Very dry	Jan - Apr	30	30
C. Cherry development-maturation (less sensitive phenological stage)			
Normal	May - Oct	10	0
Dry	May - Oct	20	10
Very dry	May - Oct	30	15

3.2.2 Second approach: applying penalty/gain coefficients to the simulated potential yield

For each province, a hierarchical Bayesian modelling approach was used to determine empirical relationships between observed coffee yields (dependent variable), and the total annual rates of nutrients N, P_2O_5 and K_2O, and monthly irrigation amounts for January to April (explanatory variables). The approach was similar to that used in Chapter 3. Please refer to Section 2.4 for the description.

Coffee yields were then predicted using these relationships for different rainfall patterns (i.e., average, below-average, and above-average rainfall conditions), as described in Chapter 4 Section 2.2 (Table 4.1) for the full distributions of nutrient rates and irrigation amounts (minimum, maximum and mean values) which were recorded in the province during the 10-year surveys. Deviations from average-rainfall conditions were then calculated. Thus, if the deviation is negative a penalty coefficient was applied to the potential yield simulated by the default version of the USQ-Robusta coffee model at the end of the simulation process. Conversely, if the deviation is positive, a gain coefficient is applied.

Gridded climate data for the period 1985-2014 were used for calculating the 30-year average rainfall value for each province, and for classifying years according to rainfall pattern (Table 4.1). This approach relied on the surveys of 558 farmers randomly distributed across the provinces. The coefficients calculated for different rainfall patterns thus are a good indicator of yield variations according to fertiliser rates and irrigation amounts.

3.2.3 Performance of the modified USQ-Robusta model

The two versions of the modified USQ-Robusta coffee model were run using gridded daily climate data over the period 2001-2017. For each of the provinces, simulations were performed separately for all the selected grids falling within the province (Table 5.2). As highlighted in Section 2.3, Dak Nong was created officially in 2004. It was previously part of Dak Lak, so coffee yield data for Dak Lak used to include this province. In the model runs, yield data for the period 2001-2005 for Dak Lak and Dak Nong were replaced by the average yields of the period 2007-2017 (no yield data recorded officially in 2006 in all provinces).

The predicted yields at the province level were calculated as the average of all grid-level predicted yields. We also investigated running the modified versions of the USQ-Robusta coffee model using the average values of grid-level climate data as inputs to simulate the yield at the province level.

To assess how a statistical model would perform if it is to be used for probabilistic yield forecasting, we carried out a stepwise regression modelling for each of the provinces using the observed data for the 2008-2017 period (official yields, irrigation and fertiliser rates) and the gridded climate data for 2007-2017. The dependent variable was the official coffee yield. The potential explanatory variables were the average total fertiliser rates, average total monthly irrigation, cumulative sum of growing degree days and total rainfall amounts over October-December, January-April, and May-October. Year was also considered as explanatory variable to account for any technology trend. Before carrying out the stepwise regression, explanatory variables highly correlated were removed to reduce collinearity. Correlations between variables are presented in Fig. A5.6 and A5.7. A 10-fold cross-validation was used during the stepwise process to select the final model (i.e., best model based on the Akaike's Information Criterion).

The performance of the two modified versions of the USQ-CACS Robusta model, as well as that of the statistical multiple linear model, was assessed using three statistical indicators: MAPE (mean absolute percentage error), RMSE and R^2 (coefficient of determination) (Eqs. 5.12 - 5.14). The lesser value of MAPE or RMSE, the better the model. The closest to 1 the value of R^2, the better the model is. The equations are as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{i=N}(Y_i^{m} - Y_i^{p})^2} \qquad 5.12$$

$$MAPE = \frac{1}{N}\sum_{t=1}^{N}\left|\frac{Y_i^{m} - Y_i^{p}}{Y_i^{m}}\right| \qquad 5.13$$

$$R^2 = 1 - \frac{\sum_{i=1}^{i=N}(Y_i^{m} - Y_i^{p})^2}{\sum_{i=1}^{i=N}(Y_i^{m} - \bar{Y}_i^{m})^2}, \quad \text{where } 0 \leq R^2 \leq 1 \qquad 5.14$$

Where N is the number of sample years N=10, Y_i^{m} is the *i*th observed value, $\bar{Y}_i^{m}$ is the mean observed value, (Y_i^{p} is the *i*th predicted value, and $\bar{Y}_i^{p}$ is the mean predicted value.

The lesser value of MAPE (or RMSE), the better the model performs. The closest to 1 the value of R^2, the better the model is.

All data and statistical analyses were performed using the R Language and Environment for Statistical Computing (R Core Team 2018).

3.2.5 Coupling SCF and the USQ-Robusta model for coffee yield forecasting

The USQ-Robusta model is developed for helping the coffee industry to prepare for climate variability and planning agricultural activities. The integrated USQ-Robusta model coupling with SCF systems, through which targeted seasonal climate and probabilistic yield forecast are provided for the key coffee regions as required (Kouadio et al. accepted). Given SCF cover a period of six months, probabilistic yield forecasts can therefore be issued with a lead time up to six months. Here, SCF data from the five predictions systems (ECMWF, UKMO, DWD, METEO-France, and CMCC) for May to November 2019 period were used as inputs in the modified version of the USQ-Robusta model (with best performance) to estimate the potential Robusta coffee yield for the season 2019/2020.

4. Results

4.1 First approach: new water stress factors based on crop water requirements throughout crop growth

The results of the model performance using the first approach on including irrigation aspects in the USQ-Robusta model are presented in Fig. 5.4. Overall, the modified version of the model resulted in better performance compared to the default version. For the majority of the provinces the prediction errors were reduced: MAPE were reduced by 2% on average; RMSE were reduced from 0.22 to 0.19 t ha^{-1}, 0.29 to 0.23 t ha^{-1}, and 0.30 to 0.25 t ha^{-1}, for Dak Lak, Dak Nong and Lam Dong, respectively (Fig. 5.4). For Gia Lai, the inclusion of new water stress factor results did not improve the model performance.

The two aggregation methods used for the gridded climate data and predicted yields resulted in similar performance: when using the average of the grid-level climate data as inputs in the model to simulate the provincial yield, the best model performance were found for Dak Lak, Dak Nong and Lam Dong (Fig. A5.2). This suggests that the grid-level climate data can be used indifferently in the USQ-Robusta coffee model without affecting the quality of the predictions.

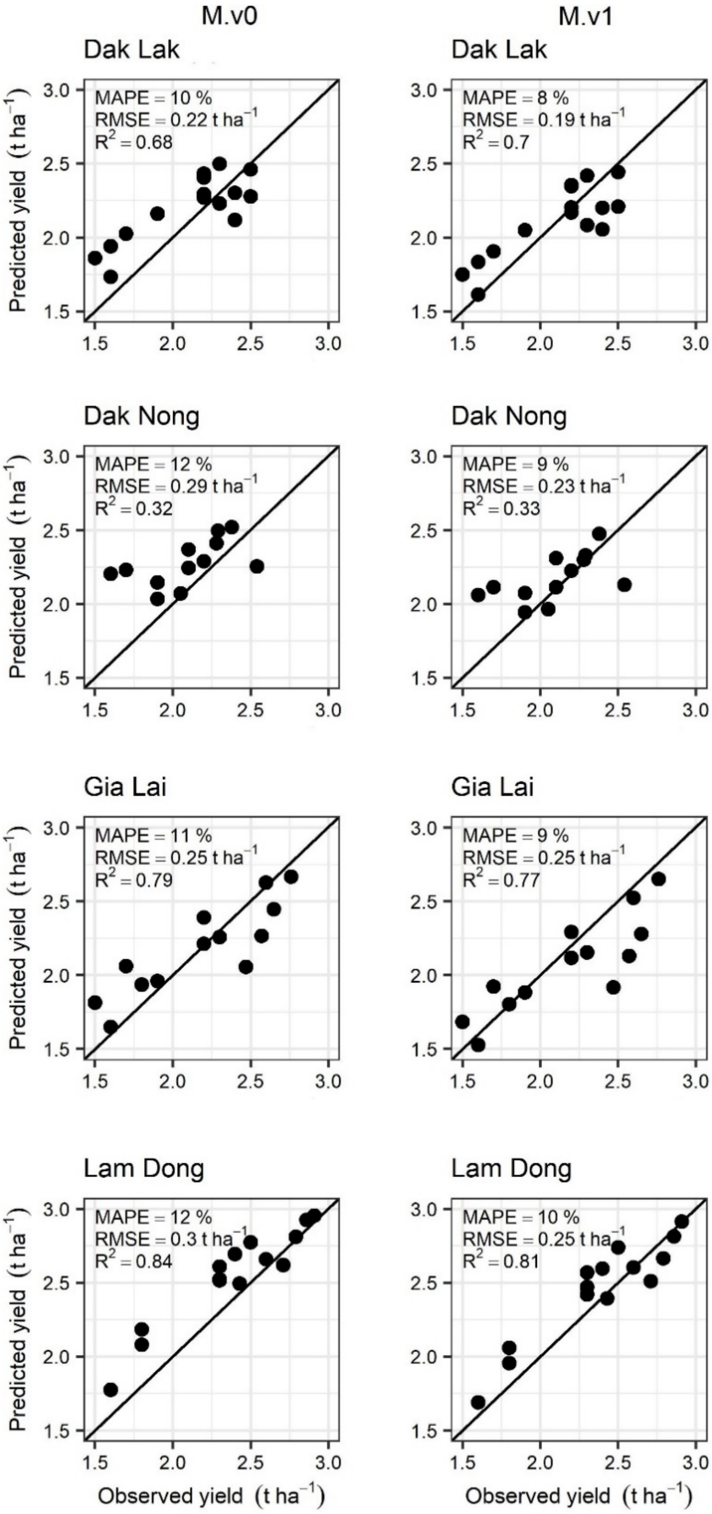

Fig. 5.4. Comparison of the performance of the default (M.v0) and modified (M.v1) versions of the USQ-Robusta coffee model for each of the Vietnamese Robusta coffee-producing provinces. The modified version of the model (M.v1) is based on the inclusion of crop water requirements throughout the growth season. The average of grid-level predicted yields was considered as the provincial predicted yield.

4.2 Second approach: use of penalty/gain coefficients

The penalty coefficients derived from the hierarchical Bayesian models are provided in Table 5.4. For the majority of the provinces (three out of four) the predicted yields during below-average rainfall conditions were less than those for average rainfall condition years (Table 5.4). In below-average rainfall conditions, the penalty coefficients for the average application of fertiliser and irrigation ranged from -9.3 to -1.4 across the provinces (Table 5.4). Robusta coffee yields in Dak Lak and Gia Lai were likely to be more impacted negatively in below-average rainfall conditions (reduction varying between 9.3% and 13.7% to the potential yield, respectively), compared to Dak Nong and Lam Dong. During above-average-rainfall conditions, coffee yields are likely to be reduced depending on the rate of fertilisers and irrigation applied. For instance, using mean values of fertiliser rates and irrigation amounts, penalty coefficients were found for the majority of the provinces, except Dak Nong (Table 5.4).

Table 5.4. Mean, minimum and maximum values of the penalty/gain coefficients applied to predicted Robusta coffee yields for each of the study provinces in Vietnam. The coefficients were derived from hierarchical Bayesian models according to the rainfall pattern.

	Penalty/Gain coefficients (%)			
	Dak Lak	Dak Nong	Gia Lai	Lam Dong
Rainfall pattern	Mean values of fertiliser rates and irrigation amounts			
Below-average conditions	-9.3	-1.2	-13.7	-1.4
Average conditions	1.0	1.0	1.0	1.0
Above-average conditions	-3.5	0.8	-2.5	-2.9
	Minimum values of fertiliser rates and irrigation amounts			
Below-average conditions	6.5	-1.1	9.3	1.9
Average conditions	1.0	1.0	1.0	1.0
Above-average conditions	26.0	9.5	4.4	-21.3
	Maximum values of fertiliser rates and irrigation amounts			
Below-average conditions	-17.3	3.6	-43.6	-19.6
Average conditions	1.0	1.0	1.0	1.0
Above-average conditions	-19.8	12.2	3.7	20.4

The performance comparison results of between the default version of the USQ-Robusta coffee model and the modified version using the penalty/gain coefficients are presented in Figs 5.5, A5.3-A5.5. Generally, the reduction in prediction errors was moderate over the ranges of fertiliser rates and irrigation amounts as recorded during the 10-year surveys. For example, if we consider the mean values of fertilisers and irrigations, only 1% of reduction in MAPE was found for the majority of the provinces (Fig. 5.5). RMSE values decreased from 0.29 to 0.28 t ha^{-1}, and from 0.30 to 0.28 t ha^{-1} in Dak Nong and Lam Dong, respectively. In Dak Lak and Gia Lai no improvement was found (Fig. 5.5). Similar performance patterns were found when using the average of the grid-level climate data as inputs in the modified version of the model to simulate the provincial yields (Figs A5.3-A5.5).

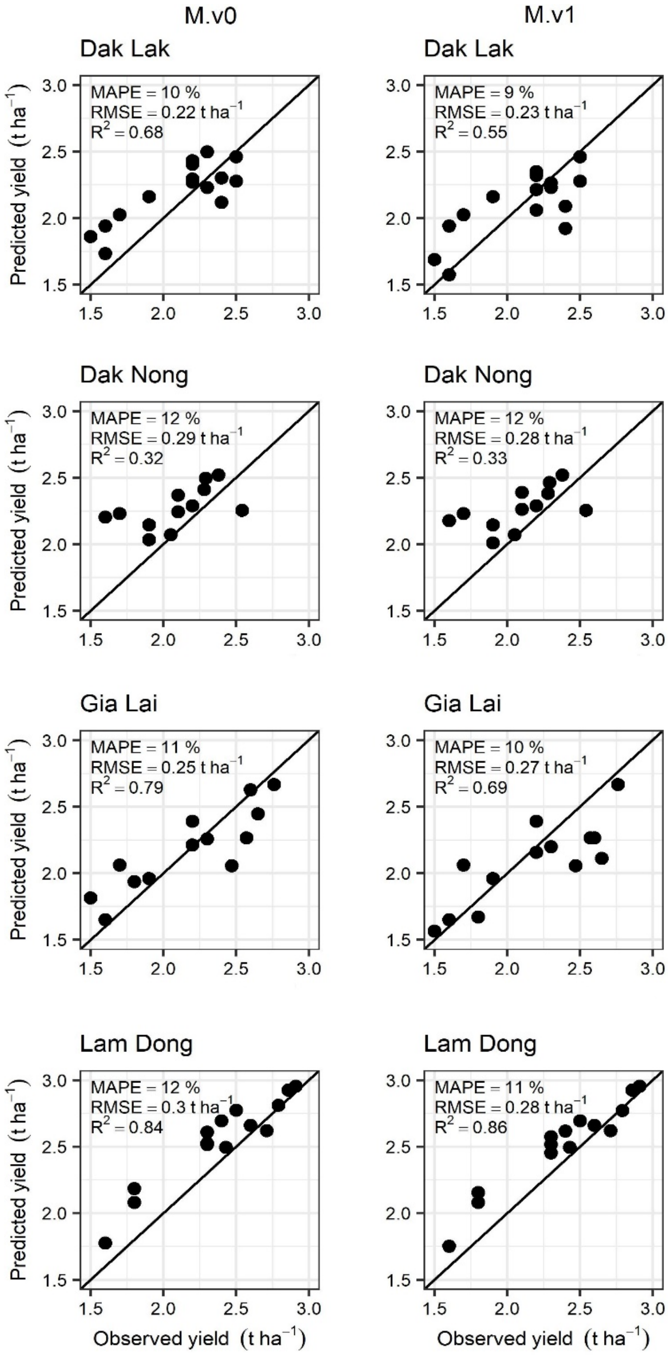

Fig. 5.5. Comparison of the performance of the default (M.v0) and modified (M.v1) versions of the USQ-Robusta coffee model for each of the Vietnamese Robusta coffee-producing provinces. The modified version of the model (M.v1) is based on penalty/gain coefficients (mean values). Penalty/gain coefficients are related to the impacts of fertiliser + irrigation on coffee yields as observed during the 2008-2017 surveys.

4.3 Comparison of the two approaches

A summary of model improvement using the two approaches is presented in Table 5.5. From the two approaches used to integrate irrigation and fertiliser components into the USQ-Robusta model, that based on crop water requirements and associated water stress according the phenological stage yielded in better statistical performance for Dak Lak, Dak Nong and Lam Dong. For Gia Lai no improvement was found, irrespective of the approach of integration. Modifying the default water stress factor in the USQ-Robusta coffee model can help capture more effectively the impact of climate variability on coffee yields. Such a feature can be explored further through additional research works for irrigation scheduling. With the determination of the number of days with strong water deficit and stress and the likely impacts these stresses can have on biomass production and yield, one can simulate the potential water required to alleviate the stress and improve crop performance.

Table 5.5. Summary of performance indicators of the USQ-Robusta coffee model before (default) and after (M.v1a, M.v1b) modifications. In M.v1a the modifications were based on the inclusion of new crop water stress factors; in M.v1b they were based on the inclusion of penalty/gain coefficients. Runs were performed using grid-level climate data separately and the average predicted yield was considered as the provincial predicted yield. For M.v1b, results from the use of the mean values of penalty/gain coefficients were presented.

	Default			M.v1a			M.v1b		
	MAPE (%)	**RMSE ($t\ ha^{-1}$)**	**R^2**	**MAPE (%)**	**RMSE ($t\ ha^{-1}$)**	**R^2**	**MAPE (%)**	**RMSE ($t\ ha^{-1}$)**	**R^2**
Dak Lak	10	0.22	0.68	8	0.19	0.70	9	0.23	0.55
Dak Nong	12	0.29	0.32	9	0.23	0.33	12	0.28	0.33
Gia Lai	11	0.25	0.79	9	0.25	0.77	10	0.27	0.69
Lam Dong	12	0.30	0.84	10	0.25	0.81	11	0.28	0.86

The results of the multiple linear regression between yields and climate, fertiliser and irrigation are provided in Table 5.6. The selected predictors were predominantly related to the climate for most of the provinces, except Dak Nong where no predictor was selected. Low values of R^2 were found for all the provinces. Despite the low values of RMSE and MAPE (Table 5.6), the use of such statistical models for farm activities planning based on SCF might be difficult to undertake. The results obtained are strongly influenced by the size of the dataset used and might not capture the overall picture. Compared to the USQ-CACS Robusta model, the regression models were relatively of poor quality at regional scale. In such cases, the use of process-based crop models would be more suitable to investigate the impacts of environmental conditions and management practices on coffee growth and production.

Table 5.6. Model equations and statistical indicators of model performance.

	Model equation*	MAPE (%)	RMSE (kg ha^{-1})	R^2
Dak Lak	$Y = -24408.71 + 14.58\,Year - 0.528\,Rain_{JA} - 0.8537\,GDD_{Flo}$	2.3	62.45	0.71
Dak Nong	$Y = 2174$	7.6	194.5	0.0
Gia Lai	$Y = 5239.707 + 14.715\,N - 26.683\,Irr_{Jan} + 10.908\,Irr_{Apr} - 2.524\,GDD_{Flo}$	6.5	185.0	0.34
Lam Dong	$Y = -1068.1854 + 1.0015\,Rain_{JA\_OD} - 0.5722\,GDD_{Flo} + 2.2921\,GDD_{Hvst}$	6.7	191.54	0.21

* $Rain_{JA}$ refers to the total rainfall during flowering (January-April); $Rain_{JA\_OD}$ refers to the total rainfall during flowering and harvest (January-April and October-December); GDD_{Flo} and GDD_{Hvst} refer to the cumulative growing degree days during flowering (January-April) and harvest (October-December), respectively; N is the rate of nitrogen; Irr_{Jan} and Irr_{Apr} refer to the monthly amount of irrigation in January and April, respectively.

4.4 Risk management decisions and potential application of SCF in the Robusta coffee industry in Vietnam

The coffee farmers and trading companies risk management decisions under climatic conditions are presented in Table 5.7. Probabilistic coffee yield forecasts are critical to the whole coffee industry, from farmers to agribusinesses and governments. With the knowledge of SCF and probabilistic yield forecast, farmers make decision on irrigation scheduling, culture operations like fertiliser application, pruning type to be implemented, harvest planning and marketing of coffee. Similarly, the coffee trading industry uses for business risk management (supply and demand studies), impact on coffee quality and financial decisions. The SCF's application are used to manage crop production risk a raising from climate variability (variation in rainfall patterns and droughts) and farmers are the potential users in farm management (Hammer et al. 2000). The industry could use the SCF for likely expected production volume for strategic management of supply and demand (Meinke and Hammer 1997; Zinyengere et al. 2011).

Table 5.7. Farmer and trading company decisions basis SCF and yield forecast.

SCF	Farmers	Trading company
Dry	• Apply more irrigation. • Pruning of more branches. • Slightly reduces fertiliser quantity. • Speculate for coffee beans selling.	• Expects lower production and plans to buy coffee in advance and stock. • Reduces trading quantity for the year. • Quickly buys the required quantity of coffee at the beginning of the season. • Shares SCF information with customers and makes business plan.
Wet	• Apply no or less irrigation. • More split application of fertiliser. • Slightly reduce branches. • Delayed harvest and uses mechanical dryers for drying coffee cherries. • Sell coffee beans immediately after harvest if got damage due to rains.	• Expect harvest delay and plan to stock from previous season. • Expect damage to quality of coffee beans and plans to buy quickly the good quality beans. • Shares SCF information with customers and makes business plan.
Normal	• Apply irrigation on need basis. • Normal pruning (retain more branches). • Apply regular fertiliser quantity. • Targets to achieve higher yields • Sell half the production quantity immediately after the harvest and speculate for higher coffee prices for the remaining stock	• Buys coffee beans when required due to availability, and speculate to buy and sell. • If SCFs indicate dry forecast for the coming season, then plans to buy more quantity when the coffee prices are low • Shares SCF information with customers and makes business plan

Source: Survey data 2008-2017

4.5 Robusta coffee yield prediction using SCF and the USQ-Robusta coffee model

Although the coffee season starts generally in November in Vietnam, Robusta coffee yields can be predicted with at most six months of lead time given the availability of SCF. We tested the capability of the modified USQ-Robusta coffee model with best performance of predicting coffee yield using GCM seasonal forecast for May to November 2019 period. Yield variances (anomalies) for the coming harvest for Dak Lak are shown in Fig. 5.6. All the five prediction systems indicated similar yield variance for this province. The median yield variance ranged from 0.26 to 0.29 t ha^{-1}. Compared to the historical yield variance, a reduction in coffee yield is likely to occur. These results are experimental since SCF for Vietnam for agricultural purposes and crop modelling are still being assessed. Therefore, Fig. 5.6 should be interpreted cautiously.

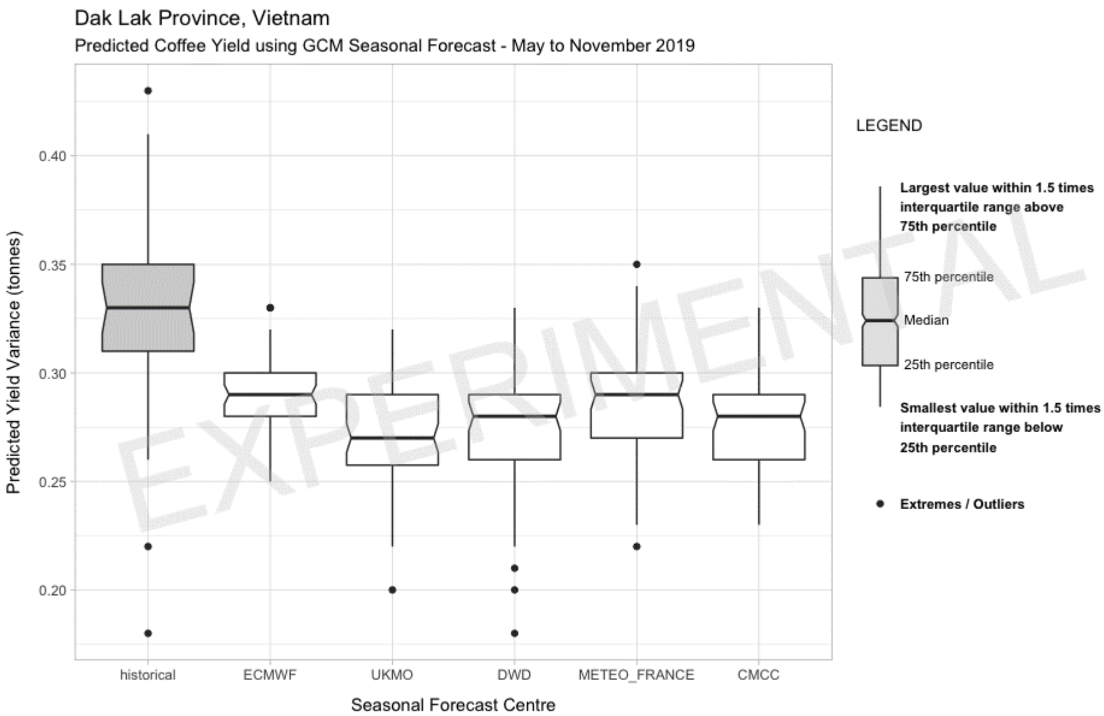

Fig. 5.6. Comparison of probabilistic Robusta coffee yield forecast for Dak Lak province based on Seasonal climate forecast issued from five prediction systems with a lead time of six months before harvest. The prediction systems are provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), the United Kingdom Meteorologcial Office (UKMO), METEO-France, the German Weather Service (Deutscher Wetterdienst, DWD), and the Euro-Mediterranean Center on Climate Change (Centro Euro-Mediterraneo sui Cambiamenti Climatici, CMCC).

5. Discussion

We investigated two approaches of integrating irrigation and fertiliser management practices into the USQ-Robusta coffee for improving the simulation of coffee yield at the regional scale (i.e., province) in Vietnam. Modifying the water stress component in the default USQ-Robusta coffee model by redefining the impacts of these stresses on biomass according to the phenological stage resulted in a reduction of prediction errors in most cases. Despite its moderate capability of improvement, the second approach, which is based on penalty/gain coefficients, remains helpful for assessing the potential impacts of variable rates of fertilisers and monthly irrigation amounts across the Vietnamese coffee-producing provinces.

The definition of the coefficient values used in both approaches (Tables 5.3 and 5.4) was based on expert knowledge and empirical relationships. Although the model parameters were varied within the reported plausible ranges, for the use of the new USQ-Robusta coffee model in a different environment (e.g., a different country) a parametrization may be required, along with modifying the coefficient values for water stress and fertiliser impact. With the aim of keeping the structure of the model as simple as we can, neither pests and diseases impacts nor soil nitrogen processes were taken into account. The integration of such aspects can be explored further for reducing the prediction errors and broaden the capabilities of the model. Other research paths include the built-up of a good soil database from experimental data to investigate soil nitrogen processes in coffee farms and facilitate the inclusion of such aspects in the model. Under the De-Risk project in Southeast Asia (https://deriskseasia.org/), experimental work on soil nitrogen process and irrigation in Robusta coffee farms is being carried out in the Central Highlands of Vietnam. This would help collecting more biophysical data and improve the model.

Given the difficulty of determining accurate LAI values we used in our model empirical coefficient values based on the yield of the previous season. Because of the exhaustiveness of methods proposed, and the fact destructive sampling of trees is often required (Costa et al. 2019), the determination of LAI in coffee farms can be difficult. Coltri et al. (2015) proposed an empirical relationship for calculating Arabica coffee above-ground biomass and LAI using simple field measurements and agrometeorological data in Brazil. Although substantial seasonal variations were found in their study, their approach can be investigated in the case of Vietnam and help define more accurately the initial values of above-ground biomass and LAI used in the model.

It is expected to develop a complete integrated SCF-Robusta coffee yield forecasting system which will use categorical indicators of climate drivers (e.g. Oceanic Niño index, Southern Oscillation Index, Tropical Pacific sea surface temperatures.) and simulated coffee yields to provide probabilistic yield forecasts. This will allow the examination of the probabilistic yield anomaly (likelihood of exceeding the long-term median or average) associated with the prevailing climate pattern in the year of forecast throughout the coffee season at the provincial scale. SCF and crop yield outlooks offer substantial benefits to coffee growers and industry stakeholders through increased profitability, better logistical arrangements and preparedness for extreme events such as floods and droughts.

6. Conclusions

To improve the capability of the USQ-Robusta model to predict coffee yield at the regional scale, two approaches of embedding new components related to irrigation and fertiliser management practices were assessed. These approaches included the integration of a new water stress component dealing with water stresses based on specific phenological stages, and the use of empirical penalty/gain coefficients applied to the simulated (potential) yield according to rules based on rainfall patterns. Overall, the first approach resulted in good performance statistical indicators in predicting Robusta coffee yields for the four major coffee-producing provinces in Vietnam, with the interannual climate variability also being captured satisfactorily. Further, the modified USQ-coffee model was used with SCF data from five prediction systems to estimate the potential coffee yields of the cropping season 2019/2020 for the study provinces. The results showed that Robusta coffee yields can be forecast using the improved integrated SCF-USQ-Robusta coffee model to satisfactory levels of accuracy at 2 to 6-month lead time, depending on the availability of SCF. Such a system could serve as a decision support tool for the coffee industry in Vietnam and other Robusta coffee-producing countries (providing relevant parameterizations are performed beforehand).

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Appendices 5

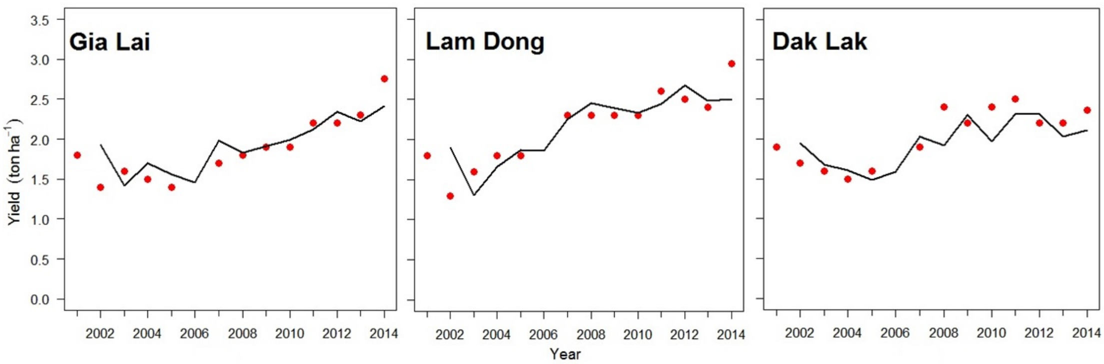

Fig. A5.1. Comparison between observed (red dots) and simulated (black line) Robusta coffee regional yield for the Gia Lai, Lam Dong and Dak Lak, Vietnam.

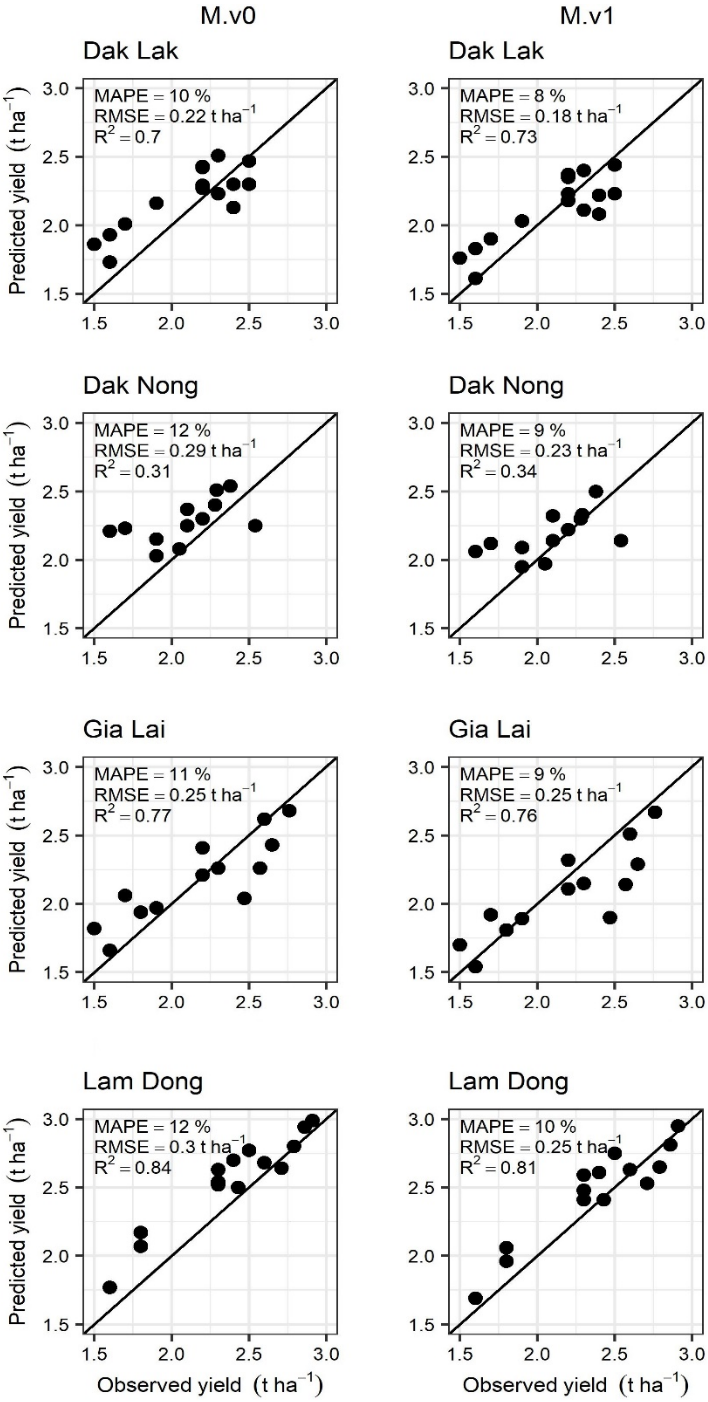

Fig. A5.2. Comparisons of the performance of the default (M.v0) and modified (M.v1) versions of the USQ-Robusta coffee model for each of the Vietnamese Robusta coffee-producing provinces. The modified version of the model (M.v1) is based on the inclusion of crop water requirements. The average grid-level climate data were used as inputs in the model to obtain the provincial predicted yield.

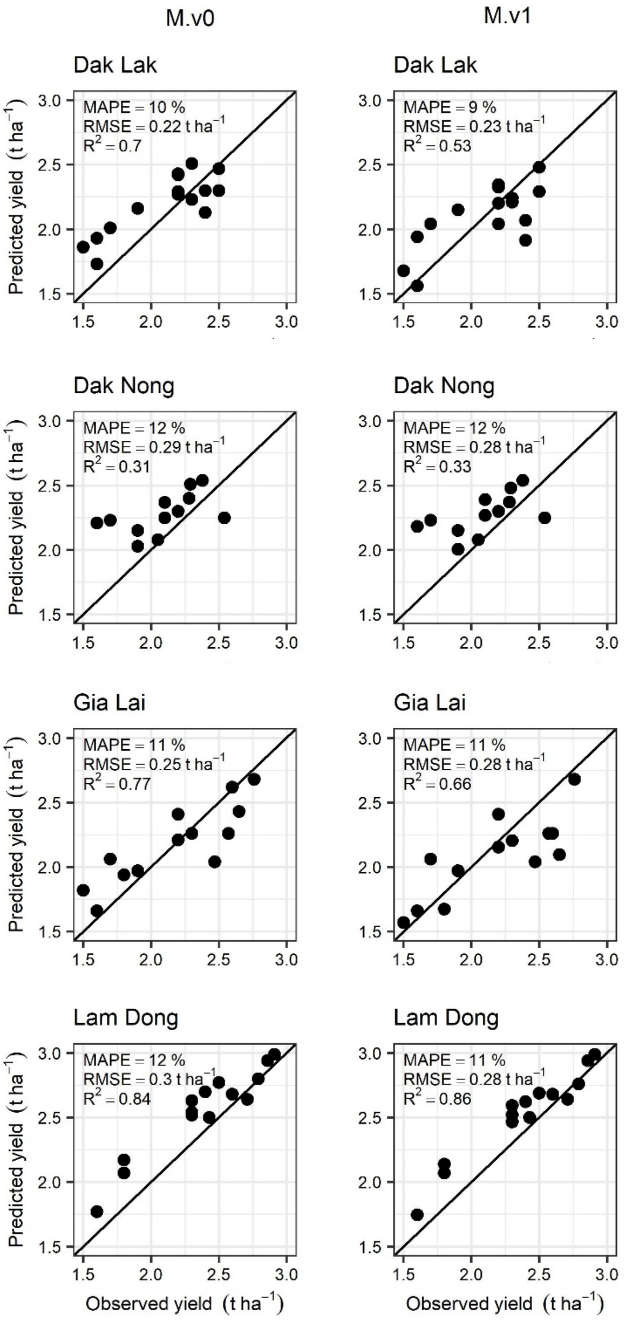

Fig. A5.3. Comparisons of the performance of the default (M.v0) and modified (M.v1) versions of the USQ-Robusta coffee model for each of the Vietnamese Robusta coffee-producing provinces. The modified version of the model (M.v1) is based on penalty/gain coefficients (mean values). The penalty/gain coefficients are related to the impacts of fertiliser + irrigation on coffee yields as observed during the 2008-2017 surveys. The average grid-level climate data were used as inputs in the model to obtain the provincial predicted yield.

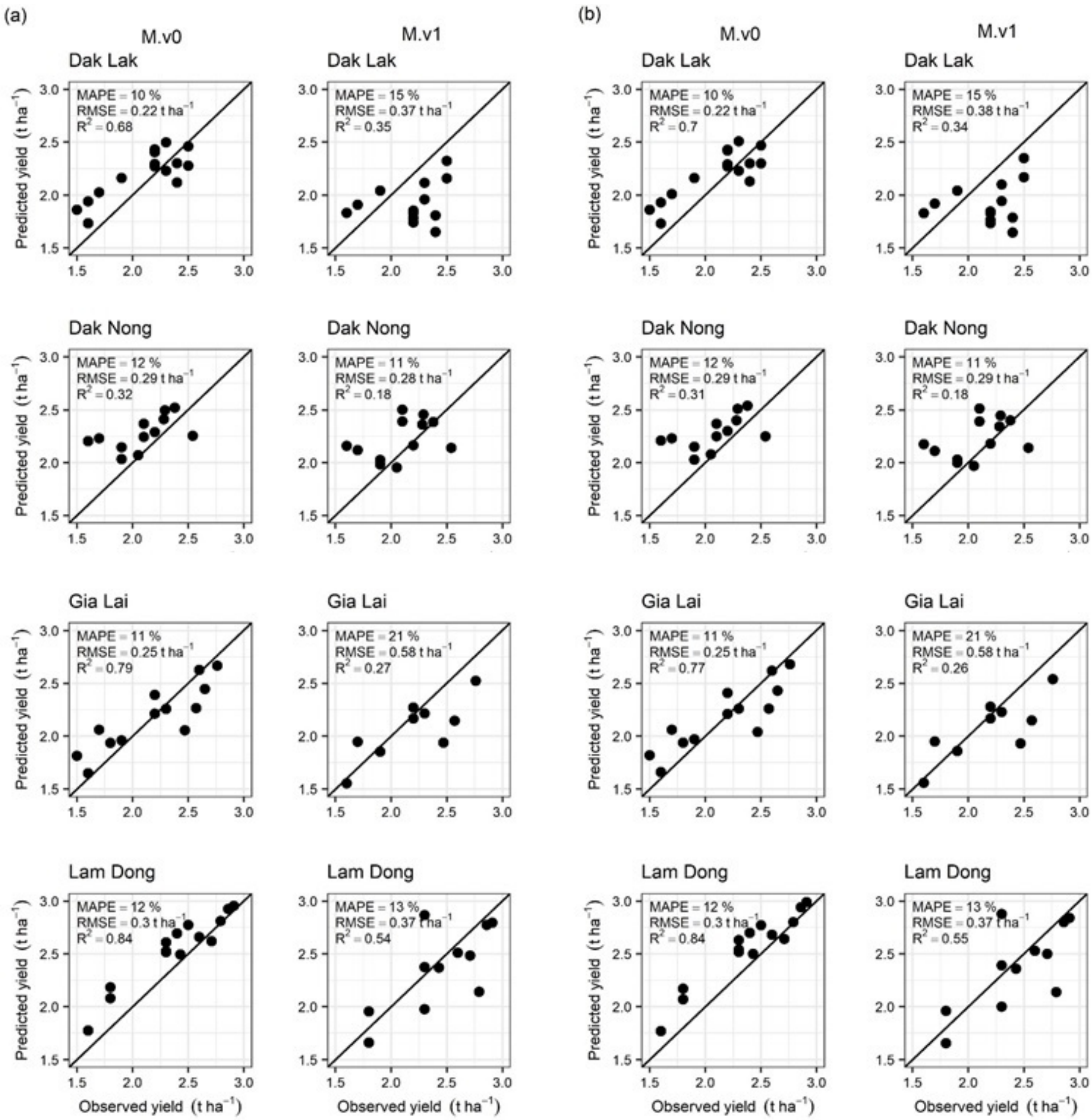

Fig. A5.4. Comparisons of the performance of the default (M.v0) and modified (M.v1) versions of the USQ-Robusta coffee model for each of the Vietnamese Robusta coffee-producing provinces. (a) grid-level predicted yields were averaged to obtain the predicted yield at the province level; (b) the average grid-level climate data were used as inputs in the model to obtain the provincial predicted yield. The modified version of the model (M.v1) is based on penalty/gain coefficients (maximum values). Penalty/gain coefficients are related to the impacts of fertiliser + irrigation on coffee yields as observed during the 2008-2017 surveys.

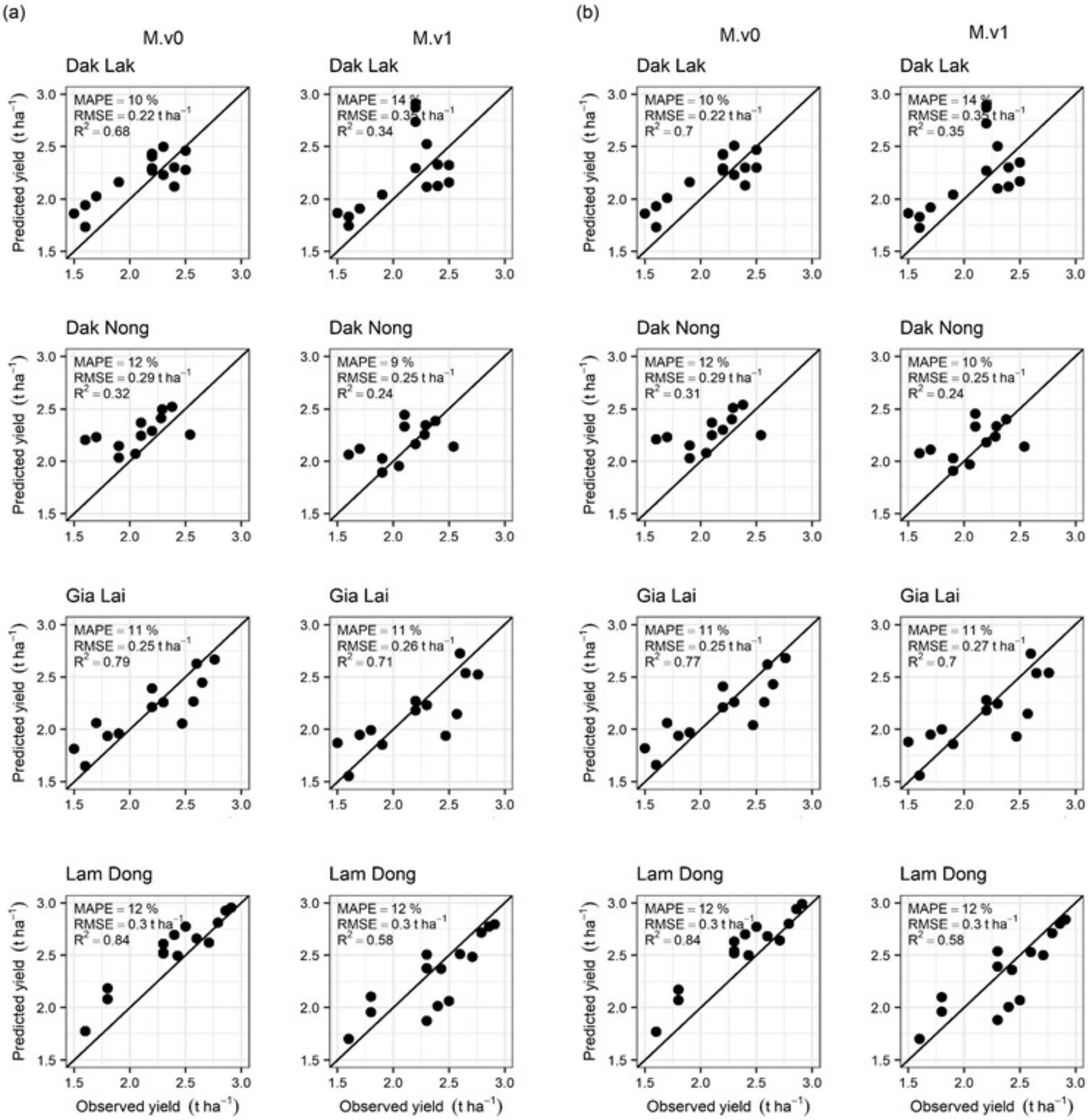

Fig. A5.5. Comparisons of the performance of the default (M.v0) and modified (M.v1) versions of the USQ-Robusta coffee model for each of the Vietnamese Robusta coffee-producing provinces. (a) grid-level predicted yields were averaged to obtain the predicted yield at the province level; (b) the average grid-level climate data were used as inputs in the model to obtain the provincial predicted yield. The modified version of the model (M.v1) is based on penalty/gain coefficients (minimum values). Penalty/gain coefficients are related to the impacts of fertiliser + irrigation on coffee yields as observed during the 2008-2017 surveys.

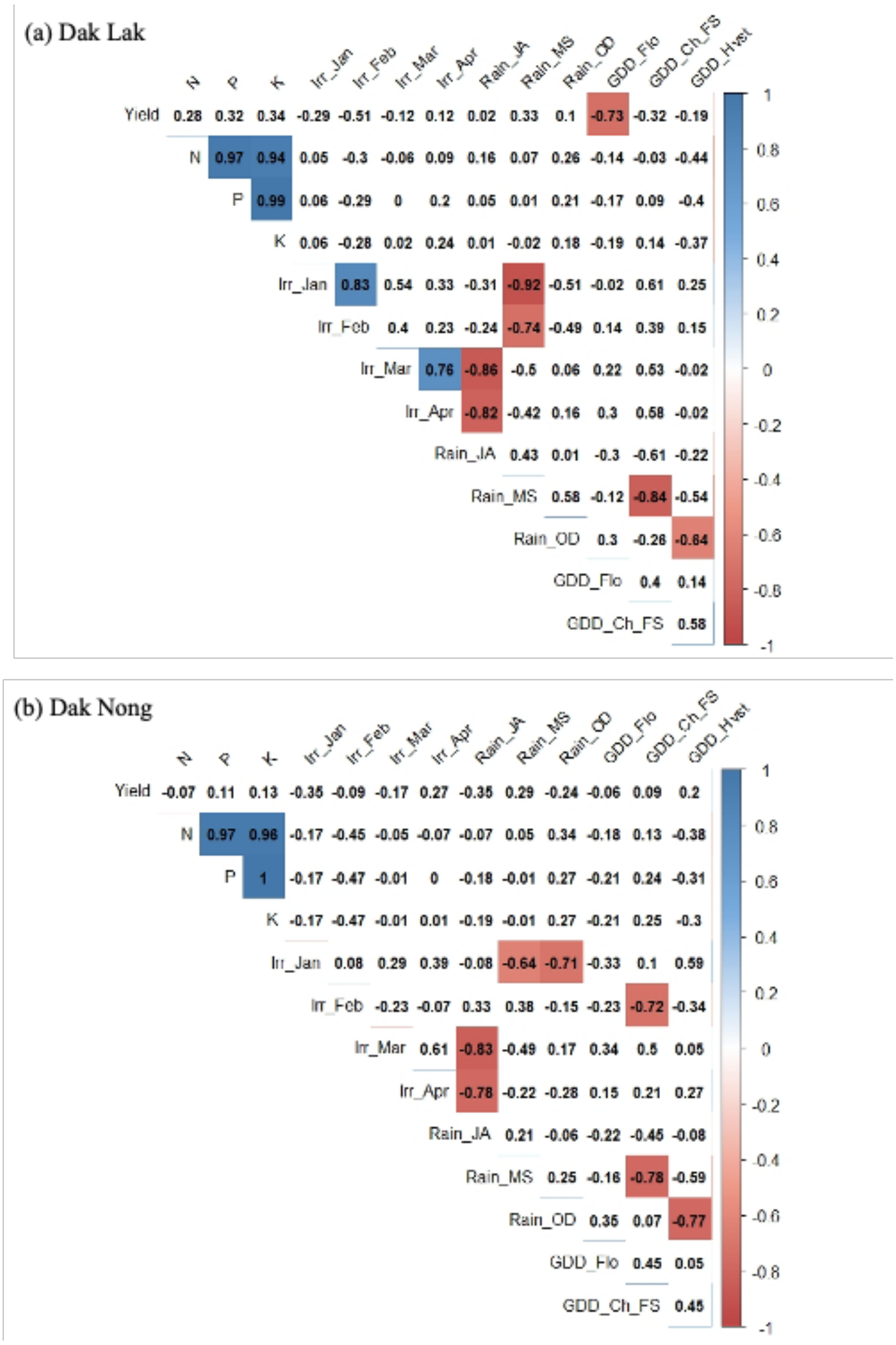

Fig. A5.6. Correlations between all the variables used for the multiple linear regression modelling. (a) Dak Lak and (b) Dak Nong. Rain_JA, Rain_MS and Rain_OD refer to the total rainfall during the months January-April, May-September, and October-December, respectively; GDD_Flo, GDD_Ch_FS and GDD_Hvst refer to the cumulative growing degree days during January-April, May-September, and October-December, respectively; N, P and K correspond to the rates of nitrogen, phosphorous and potassium, respectively; Irr_Jan, Irr_Feb and Irr_Mar refer to the monthly irrigation amounts for January, February, March and April, respectively. Highlighted values correspond to significant correlations ($p < 0.05$).

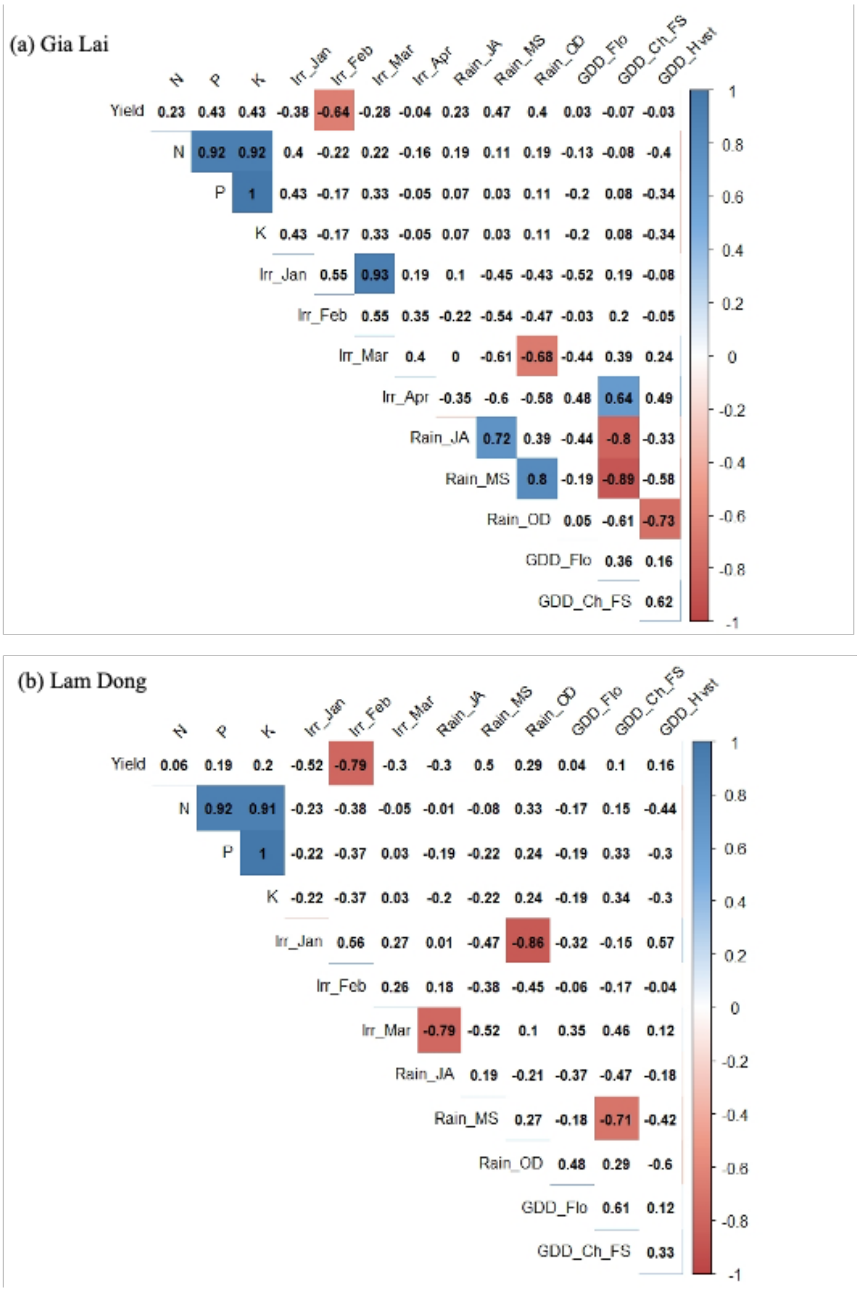

Fig. A5.7. Correlations between all the variables used for the multiple linear regression modelling. (a) Gia Lai and (b) Lam Dong. Rain_JA, Rain_MS and Rain_OD refer to the total rainfall during the months January-April, May-September, and October-December, respectively; GDD_Flo, GDD_Ch_FS and GDD_Hvst refer to the cumulative growing degree days during January-April, May-September, and October-December, respectively; N, P and K correspond to the rates of nitrogen, phosphorous and potassium, respectively; Irr_Jan, Irr_Feb and Irr_Mar refer to the monthly irrigation amounts for January, February, March and April, respectively. Highlighted values correspond to significant correlations ($p < 0.05$).

Chapter 6

Conclusions

This research study shows a detailed analysis of fertiliser types and strategies over ten consecutive years in coffee farms of Vietnam. The study also examined coffee farmers' perceptions on drought and its impacts, then quantified the yield and financial impacts, and finally, assessed the effectiveness of mitigation strategies. The study has identified the irrigation requirements under different climate conditions and with adequate management of the key crop practices affecting coffee yields, and how substantial water savings could be achieved at the provincial scale. This study has developed an improved Robusta coffee production forecast model using climate data and SCF, which can provide advance information about coffee yields long before harvest starts. The findings of this study can, therefore, provide valuable information and industry risk management to coffee producers . However, the study, with limited time, retains several challenges that need to be investigated further. This conclusion will briefly present the important results and significant contributions of this study in the below subsections. Finally, potential future research work is suggested at the end of this chapter.

6.1 Summary of important findings

This study has investigated the fertiliser management strategies between 2008 - 2017 in Vietnam. Four types of chemical (blended NPK, superphosphate, potassium chloride and urea) and two of natural (compost and lime) fertilisers were routinely used in Vietnam. The monitoring of fertiliser use revealed that Vietnamese Robusta coffee farmers tended to follow an "aggressive" approach while applying fertilisers— "the more fertilisers you can apply, the better your plants stay nutrient-stress free throughout the growth cycle and increase your capacity to maintain the same yield performance from year to year". However, the relationships between the coffee yields and fertiliser rates showed no strong correlation between the yield and fertiliser rate. The overuse of fertilisers in coffee farms of Vietnam threatens the sustainability of the eco-system. There is a potential for improved fertiliser management for sustainable Robusta coffee production.

The study probed irrigation requirements under different climatic conditions and the potential for improved irrigation strategies in Robusta coffee in Vietnam. Variable irrigation amounts were applied depending on the province and rainfall patterns. In average rainfall years, the majority of farmers in Dak Nong and Lam Dong supplied 455–909 L tree^{-1} (assuming 1100 trees ha^{-1}) with corresponding average yields ranging from 2149 to 3177 kg ha^{-1}. In Dak Lak and Gia Lai the predominant range was 1364–1818 L tree^{-1} (corresponding average yields: 2190 to 3203 kg ha^{-1}). Our study also shows that irrigation water could be reduced by 273–536 L tree^{-1} (300–590 m^3 ha^{-1}) annually from the current levels in average rainfall years while still achieving average yield levels greater than 3000 kg ha^{-1}. In dry years reductions of 27–218 L tree^{-1} (30–240 m^3 ha^{-1}) are possible. With adequate management of the key crop practices affecting coffee yields, substantial water savings at the provincial scale could be achieved.

The effectiveness and uptake of drought coping strategies across Vietnamese Robusta coffee-producing provinces are investigated. Our result shows that, while drought reduced Robusta coffee yield by only 6.5% on average across all provinces, the impacts on gross margins were noticeable, with 22% decline on average from levels achieved in average-rainfall-condition years. With irrigation being central to coffee farming in Vietnam, in drought years the majority of surveyed farmers (58%) adopted mulching and were best rewarded with an increase in economic benefits by 10.2% compared to their counterparts who did not. The results from the logit regression model show the chances of adopting mulching as an adaptation strategy increased with one unit increase in rainfall at the start of the season. Robusta coffee farming was generally profitable for all farmers in drought years.

The study on the coffee model has investigated the possibilities of integration of irrigation and fertilizer components into the existing USQ-Robusta coffee model. The integrated model was built on two approaches: (1) first by integrating the water stress factor and (2) second by integrating the fertilizer and irrigation component by penalty/gain coefficients derived from the statistical yield prediction (from the survey data of 2008-2017). The model integrated with water stress factor (first approach) showed satisfactory results in terms of statistical performance indicators (MAPE, RMSE and R^2). Further, the model was integrated with SCF for probabilistic yield forecasting at the regional scale. The SCF and yield forecast are issued at lead time ranging between 2 - 6 months based on the SCF availability. This knowledge is used by coffee farmers and industry stakeholders for making risk management decisions, like timing of irrigation, fertilizer application, anticipation of market situation and possible weather impact on production and coffee bean quality.

6.2 Significance and scientific contribution of the study

This research study has explored the fertiliser use patterns that are characterised in the key coffee-growing provinces and discusses the potential for improved nutrient management. Our findings showed that there is a potential for improvement in terms of fertiliser management and therefore, for sustainability of Robusta coffee production. Adopting integrated fertility management practices, increasing the awareness of farmers towards good agricultural practices, and introducing policies to encourage crop diversification in coffee farms are among the options to increase returns of coffee farming while ensuring environmental-friendly crop management practices in Vietnam. Potentials for improved irrigation strategies in Robusta coffee production in Vietnam were examined and found water savings from 27–536 L $tree^{-1}$ (30–590 $m^3 ha^{-1}$) depending on the province and year. Thus, our findings could serve as a basis for province-specific irrigation water management in Robusta coffee farms that will not only reduce overall water use but also potentially maintain satisfactory yield levels. Significant reduction in yields was observed in drought years when farmers predominantly adopted irrigation + mulching. Our findings have potential relevance for the design of policies to address drought risks and encourage more resilient adaptation strategies. Implementing the relationships between coffee yield and fertiliser and irrigation derived from the first two studies, while the fourth study found that the interannual coffee yield variability was captured satisfactorily and yield prediction accuracy improved using the process-based Robusta coffee model. Moreover, integrating SCF into the Robusta coffee model allowed satisfactory probabilistic yield forecasting with sufficient lead times.

This research study will support the value and recognition of fully integrated SCF relevant to Robusta coffee production in Vietnam with long lead times, which will further help an enhanced understanding of production variation with the potential intra-seasonal climate variations. The study also presents an adequate methodological framework for modelling detailed SCF integrated with agronomic practices. The output of this research (i.e., the integrated SCF-Robusta coffee production model) could be used in other coffee producing regions and countries in regard to yield forecasting. It is expected that this integrated climate and crop modelling knowledge and information will be used as a benchmark for better decision making and risk management for all the stakeholders in the coffee industry. Improved management of fertiliser and irrigation, and crop diversification are options to improve the profitability of coffee farming systems.

Finally, this work aligns well with other work in the crop/climate research community and will support the integration of climate science modelling in agricultural production, and commodity trading systems. Globally, it will also help to manage risk and returns in commodity, insurance and financial markets.

6.3 Recommendation for future work

Our study noticed a lack of understanding about fertiliser management and the role of balanced nutrient supply for coffee trees in the study provinces. Farmers in Vietnam applied unbalanced quantities at higher rates than recommended and at a constant rate between years. The future studies can examine the overall soil health conditions and its impact on coffee production as a way of investigating the overuse of chemical fertilisers and its impact on the environment. To identify the drivers influencing application of high quantity of fertiliser and financial impact on the coffee farms in long run.

In addition to fertiliser, irrigation is the key component in Vietnam to achieve high yields compared to other coffee origins; the overuse could affect the water table and the availability of water to other agricultural actives. Therefore, further investigations are required for improved province-specific irrigation management techniques in Robusta coffee farms. In Vietnam, drought events frequently occur (once in 2 or 3 years) in the coffee belt and therefore there is a need to investigate water use and its impact on the groundwater level in the Central Highlands of Vietnam.

The modelling framework can be further improved by paying attention to the following: (1) include new parameters or modules to take into account pest and disease damage; (2) explore the possibilities of including soil nitrogen balance; (3) assess the robustness of the Integrated SCF-Robusta Production Model in other coffee-producing countries; and (3) refine the existing phenology processes which can improve the forecast results.

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