AN INTEGRATED SYSTEMS MODEL FOR SUSTAINABLE AGRICULTURAL DEVELOPMENT UNDER CHANGING CLIMATE: A CASE STUDY IN A COFFEE PRODUCTION SYSTEM IN VIET NAM

A thesis submitted by

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Abstract

Drought events pose a major threat to agricultural production and food security in many regions globally, and this is expected to affect millions of people, more than the number affected by any other climate-related phenomena. A changing climate and growing demand for food driven by increasing population and economic growth are exacerbating the shortage of water, placing further pressure on farming systems. In many developing countries, a reduction in crop yields and livestock productivity and an increase in costs incurred for farming, for example, in irrigation, as a consequence of drought, have led to significant losses in income for many farmers, exacerbating the vulnerability of rural livelihoods.

As the frequency and severity of drought is expected to increase in many regions over coming decades, as a result of changing climatic conditions, the need for drought risk mitigation and adaptation is imperative. The agricultural sector is generally the most vulnerable to drought impacts; thus, it is crucial to identify and evaluate potential strategies to ensure agricultural sustainability. However, agricultural adaptation is a relatively complex, multidimensional and multiscale process, which poses challenges to policy-makers. This process is highly dependent on the complexity of the climate system, ecosystems, and human systems where various factors interact in dynamic and non-linear ways. Thus, adaptation planning for drought must be designed with due consideration to possible integrated effects of other policy decisions and of the trade-offs and synergies between adaptation and different management strategies.

To better understand the factors driving the impacts of drought on crop production, a systems dynamic approach has been applied as the primary research methodology in this study. Specifically, our aims are to explore the complex interactions between factors associated with drought and agricultural production, and examine how these might impact agricultural sustainability, using a case study in a coffee production system in Viet Nam. In the first stage, the study identified the relevant climatic factors, particularly drought-related drivers that influence coffee production globally, using a systematic quantitative literature review approach. A causal loop model grounded in systems thinking theory was then developed for the coffee production system in Dak Lak Province, Viet Nam to examine the interdependencies and feedbacks among system variables, including non-climatic drivers, based on this review and data retrieved from interviews with relevant stakeholders. Following this, a system dynamics model was designed, based on the causal loop model, in order to simulate the dynamics of drought impacts on coffee production in Dak Lak Province and evaluate a number of policy intervention scenarios. Results of policy scenario analyses indicate that drought conditions are expected to exacerbate problems related to water shortages for irrigation but that the dynamics generated from the interactions between factors related to water and land-use are of greater importance. It is these interactions that drive the sustainability of coffee production in the region, and their impacts could be substantially minimized through applying intervention strategies, including improved farm level water-saving irrigation practices and technologies and regional level control of land use and development. Overall, the model findings add noteworthy insights into drought and water resources management for sustainable crop production in the province, which demonstrates the significance of developing a systems framework in addressing complex natural resource-related issues under the uncertainty associated with changing climatic conditions. The outcomes of this research are expected to serve as important decision-support tools that can inform both strategic policy-making and adaptation to drought in a changing climate system.

Certification of Thesis

This Thesis is the work of **Yen Hoang Pham** 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.

Principal Supervisor: **Dr Kathryn Reardon-Smith**

Associate Supervisor: **Professor Ravinesh Deo**

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

Statement of contribution

The publications generated from this thesis were a joint contribution of the student and other authors with a majority of the research led and completed by the student. The details of the scientific contribution of each author are provided as below:

1. Journal article 1: Pham Y, Reardon-Smith K, Mushtaq S, Cockfield G (2019) The impact of climate change and variability on coffee production: a systematic review. *Climatic Change* 156:609-630. https://doi.org/10.1007/s10584-019-02538-y

[Scopus Rank Q1, 93rd percentile in Atmospheric Science, Impact Factor 4.134]

(Incorporated as Chapter 4)

Author	Statement of contribution
Yen Pham (candidate)	Conceptualization and design (90%) Analysis and interpretation (85%) Drafting and production (80%)
Kathryn Reardon-Smith	Conceptualization and design (5%) Analysis and interpretation (10%) Drafting and production (10%)
Shahbaz Mushtaq	Conceptualization and design (5%) Analysis and interpretation (5%) Drafting and production (5%)
Geoff Cockfield	Drafting and production (5%)

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Author	Statement of contribution
Yen Pham (candidate)	Conceptualization and design (90%) Data collection (100%) Analysis and interpretation (90%) Drafting and production (85%)
Kathryn Reardon-Smith	Conceptualization and design (5%) Analysis and interpretation (5%) Drafting and production (10%)
Shahbaz Mushtaq	Conceptualization and design (5%)
Ravinesh C Deo	Analysis and interpretation (5%) Drafting and production (5%)

3. Journal article 3: Pham Y, Reardon-Smith K, Deo RC (2021) Evaluating management strategies for sustainable crop production under changing climate conditions: A system dynamics approach. *Journal of Environmental Management* 292:112790. https://doi.org/10.1016/j.jenvman.2021.112790

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Kathryn Reardon-Smith	Conceptualization and design (5%) Analysis and interpretation (5%) Drafting and production (10%)
Ravinesh C Deo	Conceptualization and design (5%)

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   https://modsim2019.exordo.com/files/papers/698/final_draft/phamY.pdf

2. **Pham, Yen** and Reardon-Smith, Kathryn and Mushtaq, Shahbaz and Kotir, Julius (2020) Feedback modelling of the impacts of drought on coffee production in Viet Nam. In: *The 3rd Asia Pacific System Dynamics Conference*, 2-4 Feb 2020, Brisbane, Australia.

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Table of contents

List of figures

List of tables

List of acronyms

BAU	Business-as-usual
CaNaSTA	Crop Niche Selection in Tropical Agriculture
CERES	Crop Environment Resource Synthesis
CFE	Carbon Fertilisation Effect
CGE	Computable General Equilibrium
CLD	Causal Loop Diagram
CLIMEX	Climate Change Experiment
EPIC	Environmental Policy Integrated Climate
GDyn	Dynamic Global Trade Analysis Project model
GIS	Geographical Information System
GTAP	Global Trade Analysis Project
Ha	Hectare
Km^2	Square Kilometre
Km^3	Cubic Kilometre
MaxEnt	Maximum Entropy
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SAM	Social Accounting Matrix
SDM	Species Distribution Modelling
SFM	Stock-and-Flow Model
TERM-H2O	The Enormous Regional Model
VND	Viet Nam Dong

Chapter 1. Introduction

1.1. Background

Climate change poses challenges to sustainable agricultural production, which is an activity highly dependent on weather and climatic conditions and more sensitive to climatic extremes than many other economic activities (IPCC 2014; Mendelsohn 2008). Drought, among other natural disasters, is a major driver of crop failure and food insecurity in many regions globally, and is expected to affect millions of people in the future, more than the number affected by any other climate-related phenomena (Romm 2011; Sheffield and Wood 2008). A changing climate and increasing demand for food, driven by population growth, rising incomes and production of bio-fuels, are aggravating this problem (Logar and van den Bergh 2013; Pandey and Bhandari 2009). Reduced crop yields and livestock productivity and increasing costs of agricultural production, as a consequence of drought, have led to losses in income for many farmers, exacerbating the rural vulnerability experienced in many developing countries (Gies et al. 2014; Siwar et al. 2009).

A significant number of regions globally have experienced severe drought events, including America, Africa, Southern and Central Europe and Australasia, causing significant losses and damages to socio-economic sectors, particularly, the agricultural sector, as water is essential to production. Severe and prolonged drought has led to reduced crop productivity and farming income, insufficient employment in farming areas due to outmigration, increased food prices and decreased demand for non-agricultural goods. In addition, drought can drive increasing death rates of livestock and losses to wildlife and fish habitat. The impacts of drought on agriculture are likely to arise from the interaction between climatic conditions and human factors, including water demand and use, and changes in land use and land cover, and might be exacerbated by over-exploitation of natural resources such as water and land (Gies et al. 2014; Lal et al. 2012).

As drought is likely to increase in frequency and severity in many regions globally in this century, as a result of changing climatic conditions coupled with population growth and increasing incomes (Field et al. 2014), the need for drought risk mitigation and adaptation is imperative. Generally, agricultural production is considered the sector most vulnerable to drought impacts, especially in developing countries (Knox et al. 2011); thus, it is crucial to identify and evaluate potential adaptation and management strategies to minimize vulnerability and ensure agricultural sustainability. However, adaptation to climate change and variability is a complex process given its multiple dimensions and scales (Bryan et al. 2009), which is challenging to decision-makers. This process is highly dependent on the complexity of the climate system, ecosystems, and other management systems (Anandhi 2017) where various factors interact in dynamic and non-linear ways. Thus, adaptation planning for drought must be designed with consideration of the possible combined effects from other policy decisions and of the trade-offs and synergies between different adaptation and management strategies. Although numerous studies have focused on drought impacts on agricultural production and potential solutions to minimize these impacts, there has been little effort to develop a holistic approach that explores and quantifies the interactions and feedbacks between the interconnected systems (Gies et al. 2014; Rhoades et al. 2014; Wang and Davies 2015). Understanding this complexity is critically important to better support comprehensive and effective decision-making processes on drought management and mitigation for sustainable and viable agricultural development.

In an attempt to address the above-mentioned research gap, a systems thinking and dynamic approach was applied in this thesis, which aimed to develop a modelling framework to explore and capture the dynamic complexity emerging from the interactions between drought and ecological and socio-economic factors that, in combination, impact agricultural production. A suite of policy intervention scenarios was designed, analysed and evaluated to identify plausible strategies that could be applied in reality. This improved understanding provides a significant contribution to policy decision-making, in response to climate change and drought, for agricultural sustainability. The modelling framework can also serve as a decision-support tool to address issues associated with the management of water resources and climate-driven impacts, particularly in the agricultural and natural resource management sectors.

1.2. Study rationale

System dynamics modelling, grounded in the theory of non-linear dynamics (Sterman 2000), with concentration on the mental models of individuals or groups (Turner et al. 2016), is increasingly used to improve understanding of complex issues such as agricultural production and natural resource management problems. The interdisciplinary and multidimensional natures of these contemporary issues associated with ecological and human systems require holistic frameworks for better analysis of their complexity and uncertainty. To date, there have been only limited applications of system dynamics within the field of agricultural production in consideration of the changes in climatic conditions and the dynamics inherent in socio-economic systems. Given successful applications of system dynamics modelling in agriculture and water management related issues (Sušnik et al. 2012; Turner et al. 2016), this research aims to explore the ability of the system dynamics approach to increase understanding and inform management in the field of agricultural production under changing climatic conditions, using a case study in the coffee production system in Dak Lak Province, Viet Nam.

1.3. Research aims and objectives

Given the challenges of drought on agricultural sustainability and the underlying research gaps discussed above, the central aim of this study is to develop a modelling framework using a system dynamics approach that can support decision-making on drought management for sustainable coffee crop production in Dak Lak Province, Viet Nam. This project aim is achieved through addressing three specific research questions:

- What are the potential direct and indirect drought-related impacts on global coffee production?
- What are the causal dynamics driving the impacts of drought on coffee production that have been observed in the case study region?
- How could these dynamics influence coffee production over time and what are the implications for decision-making on drought management for sustainable coffee production in the case study region?

Three research objectives are addressed to answer the research questions:

(1) To identify bioclimatic drivers related to drought that influence the sustainability of coffee production. This is achieved through a systematic quantitative literature review of the potential impacts of climate change and drought on global coffee production (Chapter 4 – Research article 1).

(2) To identify climatic and non-climatic factors associated with drought, including the ecological and socio-economic dynamics, and capture the underlying drivers and their interactions and feedback structures that influence coffee production and the livelihoods of coffee farm households in Dak Lak

Province, Viet Nam. This was completed by incorporating the key drivers investigated in Objective 1, additional literature review and stakeholder engagement and developing an integrated conceptual system model of drought-related impacts on coffee production using causal loop modelling (Chapter 5 – Research article 2).

(3) To construct a system dynamics simulation model and evaluate alternative policy intervention scenarios to support decision-making on drought response for sustainable coffee production. This was completed by simulating over time the reinforcing and balancing feedback loops formulated in the conceptual model developed in Objective 2 using a stock-and-flow system dynamics simulation model (Chapter 6 – Research article 3).

Figure 1.1 below denotes the model development process to address research objectives, which includes five distinct research phases.

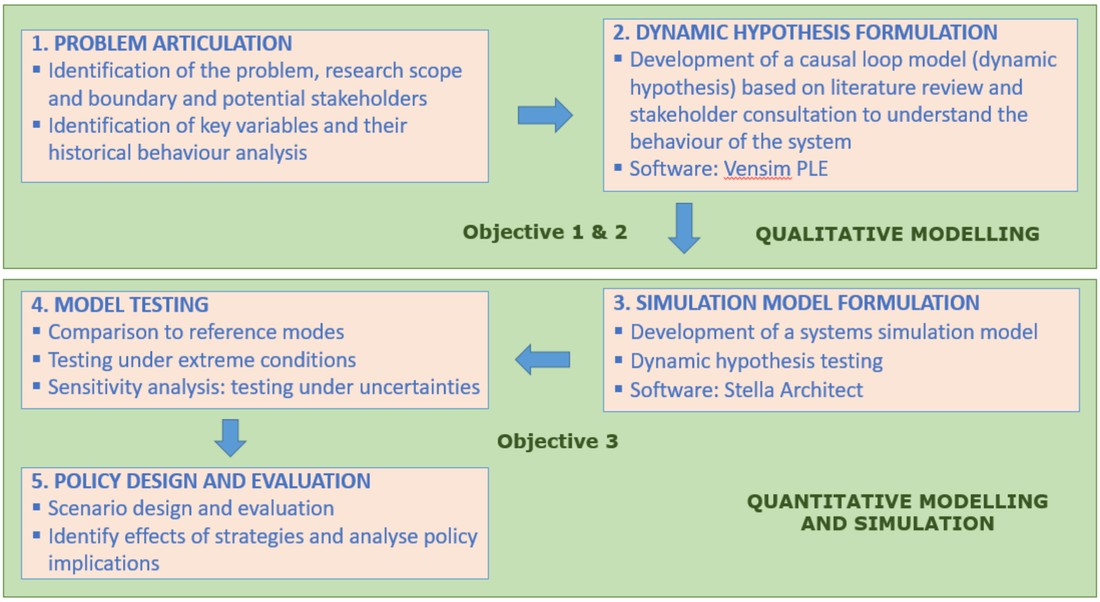

Figure 1.1. Overview of research design

(adapted from Maani and Cavana 2007)

1.4. Overall contribution

While there has been substantial research into drought impacts on crop production systems and the development of plausible drought adaptation strategies, little effort has been made to develop a systematic approach to quantify the interrelationships of drought-related systems including agricultural production, water, land and other socio-economic systems. Unlike other systems modelling approaches that cannot readily incorporate feedback mechanisms (such as Bayesian networks), the model developed within this project has the capability to simulate closed-loop thinking which focuses on the interdependency of variables rather than linear relationships (Richmond 1993). In the context of a changing climate, as we experience in the current era, exploring the impacts of drought on the agricultural sector through a systematic lens has significant advantages, particularly as it can enable improved understanding of the non-linear interconnections and feedback mechanisms that determine the dynamic behaviour of the agricultural production system in relation to other drought-related systems. This approach is also able to identify the underlying structures of the systems under investigation, flag potential side-effects and unanticipated outcomes of relevant policy and management decisions and enable analysis and evaluation of different intervention scenarios in response to drought. The findings that emerge from the model can be translated into policy frameworks and recommendations for improved drought management for sustainable agricultural production, while the developed model may also act as a decision-support tool for relevant policy-making process. Further, the conceptual model provides a graphical representation of the system that is easy for stakeholders to understand, making it a valuable tool for stakeholder engagement. A further contribution of this research project is improved understanding of the applicability of system dynamics to agriculture and water resource management, which remains relatively limited, particularly in the context of changing climatic conditions.

1.5. Thesis structure and organization

This thesis is organized into seven chapters (Figure 1.2) that demonstrate significant contributions to knowledge. The first chapter introduces the key issues and the rationale for the research investigation, with an outline of the research problem, aims and objectives and a brief description of the overall contribution. Chapter 2 provides a detailed review of the current literature that examines in detail the impacts of drought on agricultural production, potential adaptation and management strategies and the modelling methods applied to evaluate the impacts of drought and climate change on crop production. The purpose of Chapter 3 is to provide a rationale and description of system dynamics modelling – the primary methodology that was applied in the thesis – and specific research methods used to address the research questions. Chapter 3 also introduces the case study area of Dak Lak Province, Viet Nam, with background information related to agricultural production in the context of drought and water shortages.

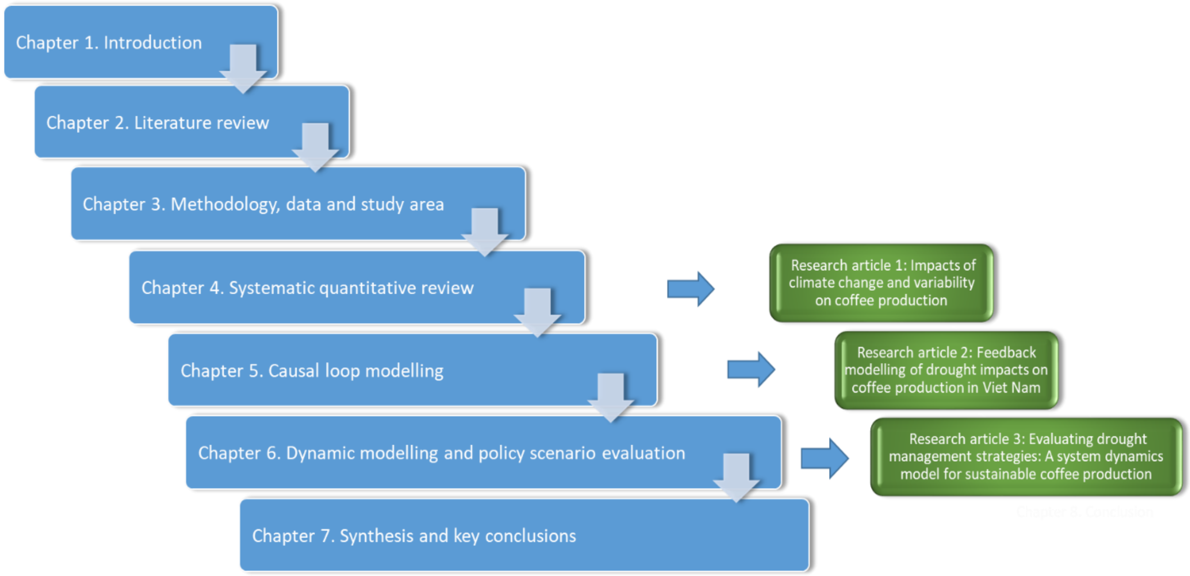

Figure 1.2. Outline of the thesis structure

Chapters 4 to 6 describe the empirical results of the thesis presented as individual research articles that have been either published or under review, all in high ranked peer-reviewed journals. Specifically, Chapter 4 (as a published journal article) explores and identifies the impacts of climate change and climate variability, specifically drought, on coffee production. This chapter forms a basis for the qualitative conceptual model developed in the next chapter. Based on the results of participatory research with stakeholder engagement, Chapter 5 (also a published journal article) develops a dynamic hypothesis or a conceptual model in the form of a Causal Loop Diagram that maps the interrelationships between key variables of the system related to drought impacts on coffee production and analyses the dynamics influencing these impacts. Building on these results, Chapter 6 (as a journal article under review) describes an integrated stock-and-flow simulation model and the different tests conducted to improve understanding of the key dynamics of the system, and provides an analysis and evaluation of potential intervention strategies to support policy-making on drought management for sustainable coffee production in the case study area.

Finally, Chapter 7 provides a synthesis of key research outcomes stemming from the individual chapters and discusses the contributions and limitations of the study and recommendations for future research. Supplementary materials are provided in the appendices, including the human ethics approval and the equations developed in the system dynamics simulation model.

Chapter 2. Literature review

Chapter overview

This chapter provides a background to the study and reviews the key issues associated with the impacts of drought on crop production and adaptation and management strategies in response to climate change and drought. This is followed by a critical analysis of current approaches used to model the impacts of climate change and drought on agricultural production and response measures. The chapter finishes with a section that briefly outlines the challenges of addressing drought impacts, the knowledge gaps in the existing literature, and the imperative to adopt a holistic approach for comprehensive drought management.

2.1. Drought impacts on crop production

Drought is considered to be a major threat to crop production and food security in many regions globally. There is also a moderate level of confidence in climate predictions showing that drought intensity, frequency and duration are likely to increase in many regions in this century, primarily as a result of reduced precipitation and increased evapotranspiration coupled with growing population and demand for food, water and other resources (IPCC 2014). This ongoing challenge is expected to affect millions of people in the future, more than the number affected by any other climate-related phenomena (IPCC 2014; Romm 2011; Sheffield and Wood 2008).

Over recent decades, many regions globally have experienced some of the worst drought events on record, including America, Africa, Southern and Central Europe and Australasia (Freire-González et al. 2017). In the USA, direct losses to agriculture from the 1988 drought event were estimated to be US$30 billion, accounting for almost 40% of the total costs of the damage, second only to the 2005 Hurricane Katrina – the most costly natural disaster in the USA (Elliot et al. 2018). In China, drought events have driven annual losses of over 27 million tons in grain production during the past two decades and the areas of crop production damaged by drought more than doubled from the 1950s to the beginning of the current century. In 2002, during what has been termed the Millennium Drought, Australia's grain yield dropped by almost 60% (Karoly 2003); while severe drought in Russia in 2010 led to a ban on wheat exports and significant increases in global food prices (Chen et al. 2014). Approximately 40% of maize-producing regions in Africa are frequently affected by drought, causing estimated losses in yield of 10-25% (Fisher et al. 2015), while in Indonesia drought events resulted in serious paddy rice failure and water shortages, damaging more than 12,000 hectares annually over 2004-2011 (Nurrahman and Pamungkas 2014). Pandey and Bhandari (2009) reported that household income in India dropped by 25-60% and the rate of poverty increased by 12-33% as a result of moderate drought that affected approximately 30% of the country's rice-growing areas. While adversely affecting agricultural production and food security, severe and prolonged drought events are also likely to drive out-migration due to farm employment shortages, over-exploitation of natural resources and reduced demands for non-agricultural goods (Birthal et al. 2015).

The impacts of drought can be classified as "direct", "indirect" and "intangible" (i.e. non-market damages) within their categorical representations of "economic", "social" and "environmental" drought events (Logar and van den Bergh 2013; Stahl et al. 2016). Direct damages generally imply a loss in economic sectors, such as agriculture with declining availability of water resources and reduced crop and livestock production, whereas indirect damages occur as a result of impacts on the whole economy; for example, through decreased employment and increased food prices (Logar and van den Bergh 2013; Meyer et al. 2013). Drought can also produce non-market or intangible costs associated with environmental (e.g. biodiversity losses), health (e.g. malnutrition and famine), and social (e.g. migration, social conflicts over water supply) impacts (Logar and van den Bergh 2013; Meyer et al. 2013). Accordingly, modelling of the effects of drought on agriculture necessitates a whole-of-system approach, particularly in the current phase of a changing and highly variable climate system.

Agriculture is considered the sector that is most vulnerable to extreme weather events including drought (IPCC 2014). Drought impacts span all socio-economic development sectors, and thus require a systematic approach to risk management, including better drought planning and management of future events (Freire-González et al. 2017). It is likely that inter- and trans-disciplinary approaches, capturing expert knowledge and advocacy from a wide range of impacted sectors and stakeholders will improve understanding of drought impacts and enable more effective assessment and management options. Literature on the impacts of climate change, including drought on agriculture, has been growing significantly in recent years. However, a detailed analysis of the integrated impacts of extreme climatic events such as drought remains rather limited. The following sections provide an overview of adaptation to climate change and drought events in agriculture and current approaches to drought assessment and to better inform adaptation.

2.2. Adaptation to drought and climate change in agriculture

Adaptation to the adverse impacts of climate change, and more specifically to drought, is crucial for achieving agricultural sustainability, food security and poverty reduction in the face of projected climate change and climate variability. In many developing countries, adaptation is a fundamental aspect of agricultural planning to ensure food security and also to maintain sustainable livelihoods for the rural poor, given that agricultural production is often their primary source of income.

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, adaptation options comprise a variety of actions that can be categorized into three groups: structural or physical, social and institutional (Noble et al. 2014). Structural or physical options in agricultural production include technological (e.g. new crop varieties, efficient irrigation) and ecosystem-based (e.g. shade trees) measures, engineered and built environment (e.g. water storage) and services (e.g. food banks). Social options might comprise educational (e.g. awareness raising, participatory action research), informational (e.g. early warning systems) and behavioural (e.g. livelihood diversification, changing cropping practices, patterns and planting dates) solutions. Institutional measures involve economic options (e.g. crop insurance), laws and regulations (e.g. land zoning, water regulations) and government policies and programs (e.g. integrated water resource management) (Noble et al. 2014).

To minimize the vulnerability to climate change and drought and also to exploit the localised benefits to farmers and other stakeholders, a variety of adaptive measures and management strategies might be adopted, enabling better responses to adverse climate-driven impacts. Given the diversity of drought characteristics, these measures can be implemented at different spatial scales ranging from an individual farm to industry-wide and also different levels of government (Anandhi 2017; Habiba et al. 2012). A range of adaptation practices and management strategies have been adopted to respond to drought impacts on crop production, including adjustments in cropping patterns and diversification of crop varieties (Anik and Khan 2012; Howden et al. 2007), as proactive measures to manage risks to agricultural production. In Africa, for example, new crop cultivars (Deressa et al. 2009) and amended planting dates (Bryan et al. 2009) have been applied by farmers, while in Europe whole cropping systems have been restructured with the introduction of new crops, more efficient water usage (Huntjens et al. 2010) and crop rotation practices (Willaume et al. 2014) in response to drought events. Drought-tolerant crop cultivars (Mutekwa 2009; Tao et al. 2011), improved irrigation and water harvesting technologies and techniques, agronomy and agroforestry (Falloon and Betts 2010; Olesen et al. 2011; Piao et al. 2010) are among the range of other adaptation measures implemented to cope with drought. In other regions, diversifying sources of income through off-farm livelihoods and activities that are not dependent on climate (Ifejika Speranza and Scholz 2013; Sun et al. 2012) are likely to reduce the impacts of drought. Generally, adaptive measures to climate change and drought, either short-term adjustments or long-term strategies, should be adopted through a proactive approach to increase the resilience and reduce the vulnerability of agricultural systems to climate-driven risks. However, many of the current responses remain largely reactive due to constraints to adaptation, including limited resources (e.g. funding, technology and knowledge) and institutional barriers that restrict effective implementation of proactive measures (Klein 2014).

The choice of adaption strategies depends on a range of factors, including a robust and realistic modelling approach that ultimately aims to identify options to enhance agricultural sustainability. Models should balance the ecological and socio-economic trade-offs and the benefits and interests associated with particular decisions (Habiba et al. 2012). In many cases, adaptive practices may help farmers to decrease the vulnerability of their farming systems to drought, but these may also lead to higher economic costs with lower income in normal years (Pandey and Bhandari 2009). In other cases, autonomous adaptation implemented by farmers may maximize individual profits but threaten longer-term socio-economic outcomes. For example, in China, farmers changed their farming practice from double-cropping rice cultivation to mono-cropping (e.g. rice, cotton, and cereals) to reduce exposure to seasonal rainfall deficits and thus decrease the vulnerability of local farming to drought (Lei et al. 2016). However, given that rice is a staple food, while such transformations may help individual farmers to gain higher income, they could at the same time undermine regional grain security due to the abandonment of rice production (Lei et al. 2016). As such, any proposed adaptation measures should be tailored into specific settings, with consideration given to the local socio-economic and environmental conditions.

In the context of the present discussion, there are other potential risks that may occur in the adaptation process. Well-intended actions – such as those that might address short-term climate variability but not be suitable for long-term climate change – may become maladaptive (Barnett and O'Neill 2013). Coping responses in such cases might lead to increased vulnerability and higher social costs (Smithers and Smit 1997; Ziervogel et al. 2008). Planned strategies, in interaction with other development actions, might also create undesirable consequences (Chapman and Darby 2016). For instance, groundwater extraction is considered an adaptation measure to climate change to ensure that agricultural water demands can continue to be met. However, depleted groundwater tables as a result of overexploitation have increased potential risks to local ecosystems and other systems including agricultural production, tourism and recreation opportunities (Oppenheimer et al. 2014).

In a logical sense, adaptation is a relatively complex process driven by dynamic interactions between the unanticipated biophysical consequences induced by climate change and the effects generated by socio-economic systems that might not be able to compensate for unexpected changes in the environment (Ifejika Speranza and Scholz 2013). It is crucial that studies on adaptation are conducted with systematic consideration of the possible effects of relevant management decisions and of the factors determining the possible trade-offs and synergies associated with different strategies (Chapman and Darby 2016). Implementing appropriate adaptation measures and management strategies is imperative to alleviate the adverse consequences of climate change and drought on agricultural production. To strengthen national and local adaptation plans, studies on climate change impacts and adaptation measures need to be improved by applying empirical socio-economic analysis (Guo et al. 2017) that are specific to each local context. However, there is still a lack of detailed research that quantitatively examines potential adaptation to climate change in agriculture (Chalise and Naranpanawa 2016) and assesses the effectiveness of adaptive processes adopted by farmers (Lei et al. 2016), thus requiring additional studies that can address these knowledge gaps.

2.3. Current modelling approaches on the impacts of drought and climate change on agricultural production

As described above, drought can produce both direct and indirect economic impacts. Indirect losses can be estimated based on input-output analysis, computable general equilibrium or non-market valuation approaches while direct costs in agriculture are measured using crop production functions and crop market prices or econometric models with consideration of the influences of various factors such as water availability or crop price (Lopez-Nicolas et al. 2017).

Numerous studies have examined the impacts of drought, mainly its economic aspects, applying various modelling techniques such as mathematical programming and statistical analysis models. Approaches for assessing drought impacts depend on the type of impact, either direct or indirect, and the level of aggregation, including farm, regional or whole economy (Birthal et al. 2015).

The computable general equilibrium (CGE) model and its extended and descendent models (e.g. GTAP (the Global Trade Analysis Project), TERM-H_2O (the Enormous Regional Model), SAM (the Social Accounting Matrix), and GDyn (the dynamic GTAP model)) have been widely applied to analyse the negative impacts of climate change and drought on macro-economic variables, including GDP and food consumption, and micro-economic variables such as crop productivity, food prices and livelihoods. These models have been designed at a global level (Calzadilla et al. 2014); regional level, such as applications in the Asia-Pacific, Africa and America (Bandara and Cai 2014; Hertel et al. 2010); national level, including Nepal (Chalise and Naranpanawa 2016), Mexico (Boyd and Ibarrarán 2009) and South Africa (Calzadilla et al. 2014); and local level, such as the southern Murray-Darling Basin in Australia (Wittwer and Griffith 2011).

CGE models enable interrelationships and feedback between sectors of the economy and climate change to be captured, as well as estimation of the costs of climate change-related drought and benefits of drought adaptation measures to the whole economy (Boyd and Ibarrarán 2009). They can consider each region as a discrete economy and handle numerous regions and sectors (CoPS 2017). Ex-ante simulations separating the impacts of climate change from other influencing factors can be produced in CGE models, and are considered to be more advantageous than ex-post approaches (Pauw et al. 2011). Another strength of regionalized CGE models compared with the purely macro-economic models is that they allow us to examine the direct and indirect impacts of climate change at both national and local levels (Pauw et al. 2011). However, one of the limitations of these studies in the agricultural context is the inconsistency among various estimates due to the limited availability of crop yield data, especially in developing countries.

Although CGE models have been generally used to quantify the effects of climate change on agriculture, further research is required as there is still a lack of detailed analysis of the bio-physical aspects of climate change impacts (Chalise and Naranpanawa 2016) and of quantitative assessments and incorporation of adaptation practices and policies (Bandara and Cai 2014; Chalise and Naranpanawa 2016).

Another limitation of CGE models is that the technical coefficients characterizing factors, such as yield, land use and revenue, might result in incorrect conclusions in terms of policy advice if there is misspecification of adaptation options or overspecialization with regard to a single crop (Connor et al. 2014). Besides, CGE model parameters such as elasticities and coefficients of production functions can rapidly become outdated (Gil et al. 2011).

Statistical analysis (e.g. exploring historical relationships between climate factors and agricultural production) and crop modelling (e.g. simulating the impacts of climate change in the future using process-based biophysical models) have also been used to examine potential impacts of climate change on agriculture. In China, for example, panel data analyses (e.g. regression models) and crop modelling (e.g. CERES model) have been applied to address this issue (Chen et al. 2014; Guo et al. 2017; Wang et al. 2014). However, most of these studies do not adequately reflect the influence of socio-economic variables (e.g. farmers' responses to climate) in relation to agricultural production (Tao et al. 2009; Wang et al. 2014). There have been several studies on partial or general equilibrium models used to simulate the impacts of such factors, but they are still rare and are associated with significant uncertainties (Erda et al. 2005; Wang et al. 2014). For example, application of crop models have revealed shortcomings in analysing climate change impacts on agriculture when considering the effect of CO_2 fertilization (Lin et al. 2005; Wang et al. 2014).

Assessments of adaptation options can be conducted using top-down (e.g. scenario- and modelling-driven approaches to measure the potential impact), or bottom-up (e.g. addressing socio-economic responses to climate change starting at local levels such as farm scale), or policy-based approaches (e.g. evaluating current policy within a risk management framework) (Noble et al. 2014). Top-down methods with the wide use of crop models are often applied (Tao and Zhang 2013; Xiong et al. 2005) while bottom-up applications remain limited. Further, a majority of studies use macro-level and qualitative analysis based on local case studies while quantitative analysis and large-scale case studies are relatively rare (Chen et al. 2014; Wang et al. 2014; Xia et al. 2008). Only a few studies have introduced quantitative analysis to assess adaptation options, with the application of a simulation model to explore adaptation options for water scarcity and an econometric model to analyse the choices of farmers on the structure of crops and irrigation methods under various climatic conditions (Chen et al. 2014).

As an alternative to panel data analysis, a range of process-based models has been developed to evaluate the effect of drought events on crop production at different scales. For instance, in the USA, the field-scale CERES-Maize model was employed to test its capability to reproduce historical drought impacts and also to predict the future trends and effects of agricultural technology changes on drought sensitivity of maize production systems (Elliott et al. 2018). Such models applied at relatively large spatial scales have the capability to reproduce past events with a high level of accuracy where good yield data are available; however, in developing countries, this remains a challenge due to the limited availability of district-level data (Elliott et al. 2018). Compared to statistical models that are largely data-driven, process-based models have greater merits in characterizing the historical impacts of drought as they are able to investigate more explicitly the root causes of such impacts, and thereby improve model predictability (Elliott et al. 2018). They can also consider changes in technology and management and their interactions with extreme events (Elliott et al. 2018).

Econometric models have been widely applied to investigate the negative impacts of drought at the macro-economic, regional (Birthal et al. 2015; Salami et al. 2009) and crop levels (Chen et al. 2014; Quiroga and Iglesias 2009). For example, Birthal et al. (2015) applied an econometric model to analyse the inversely proportional relationships between yield and the frequency and severity level of drought events in India. Li et al. (2011) developed a model that incorporated economic factors, such as the price and profitability of crop yields, and technological variables apart from climatic drivers to examine the influence of climate change in China and the USA. Compared with previous studies using crop models, such as CERES-maize, EPIC or statistical models, consideration of economic and technology factors in econometric models can also help to avoid a potential overestimation of the real impacts of climate change (Li et al. 2011). However, while several adaptation measures to drought events were mentioned briefly in these studies, explicit analysis of the contribution of adaptation strategies to reducing the impacts of drought in agriculture was largely absent due to limited availability of data.

Uncertainty and the complexity of impacts of changing climatic conditions warrant a more holistic perspective that considers both the biophysical processes associated with climatic changes and the environmental and socioeconomic dynamics. Traditional frameworks for drought assessment neither adequately take into account the factors driving drought impacts nor capture the complexity of their interdependencies and interactions (Freire-González et al. 2017). For a more comprehensive and robust evaluation of climate-driven impacts and adaptation, an integrated approach that consider these processes is likely to assist policy-makers in improving understanding of the complex impacts of drought and the possible trade-offs that are associated with alternative strategies for drought planning and management. The following chapter in this thesis provides an introduction to and the rationale for the application of the systems thinking and dynamic modelling approach – a comprehensive modelling framework – to investigate agricultural and natural resource management issues given their multi- and inter-disciplinary aspects.

Chapter 3. Methodology, methods and study area

Chapter overview

This chapter outlines the rationale for using a system dynamics modelling approach – the methodology applied in the thesis and specific research methods employed to address the research questions. The chapter starts with a justification for a systems approach, followed by a detailed description of the systems thinking and dynamic modelling process. The next section of the chapter provides an overview of specific techniques applied in this thesis to achieve the research objectives, including a systematic quantitative literature review and the mixed-methods approach for qualitative and quantitative data collection and analysis. The data used in the modelling conducted in this research include primary data collected from interviews involving different stakeholders in Viet Nam and secondary data derived from an intensive review of government reports, regulatory documents and the results of surveys conducted by international and non-governmental organizations. These data and the inputs generated from the systematic quantitative review were used to inform the next stages of the research, including articulation of the research problem, development of the causal loop model, and the design, calibration and testing of the dynamic simulation model. Finally, this chapter provides an introduction to Dak Lak Province of Viet Nam – the case study area of this research – including background information related to agricultural production in the context of drought and water shortages.

3.1. Theoretical approach

It is widely acknowledged that drought impacts on an economic sector are driven by multiple interacting and dynamic factors that are not associated with that individual sector alone. More specifically, risks associated with drought in the agricultural sector are likely to be influenced by decisions made in forest, land and water resources management sectors, which are frequently determined by different sectors and relevant authorities (UNDP 2011). Growing demand for natural resources and subsequent conflicts in their management, driven by human-use systems, are also exacerbating drought impacts (UNDP 2011; Wilhite 2011). For instance, increasing demand for agricultural expansion in many developing countries has resulted in excessive exploitation of groundwater and conversion of forested land for cultivation and livestock grazing, leading to water shortages for farming and directly and indirectly intensifying the impacts of drought on a range of other socio-economic sectors. Thus, it is crucial to develop and adopt comprehensive approaches to capture the interrelationships and feedback between drought and related systems such as water resources, agriculture, and forest and land management. However, there has been little effort to bring together these systems to quantitatively examine the interdependencies between them and relevant adaptation policies (Gies et al. 2014).

Traditional approaches applied in the assessment of the impacts of natural disasters such as drought have not adequately considered all factors contributing to the economic aspects of these impacts; nor do they reflect the complex interactions among elements that determine strategic policy-making (Freire-González et al. 2017). Specifically, methods such as statistical analysis and crop modelling often do not capture the influence of socio-economic variables in relation to agricultural production or take into account the effects of adaptation strategies in reducing the impacts of drought (Tao et al. 2009; Wang et al. 2014). To effectively address drought impacts, a comprehensive approach that considers the trade-offs in relation to alternative management strategies is needed, with some consideration also given to the socio-economic benefits and costs and potential consequences on the economy (Freire-González et al. 2017). Systems thinking and dynamics modelling, which are the core research tools applied in this research, are innovative approaches used to examine dynamic systems where behaviours and relationships of the system's components are complex and ambiguous (Bosch et al. 2007; Maani and Cavana 2007). Unlike linear modelling approaches that simply focus on causal relationships, systems thinking and dynamic modelling approaches provide a robust framework and methodology through which complex non-linear interdependencies and interactions among the system's components that produce the system's dynamic behaviour can be clarified (Bosch et al. 2007).

Systems thinking and system dynamics approaches are increasingly applied to improve understanding of the complexity of ecological and socio-economic systems. By incorporating all constituent elements of the system, these approaches represent a holistic framework to complex and ambiguous problems by considering the 'whole' system and the interrelationships of the system's components (Bosch et al. 2007; Maani and Cavana 2007). Seeing a system through the lens of the interactions between its constituent parts allows the root causes of a problem to be identified rather than just its symptoms (Maani and Cavana 2007). Further, these methods can enable the generation of long-term solutions to improve the existing situation (Maani and Cavana 2007), identifying the unintended consequences of various policy decisions related to the system and testing the possible impacts of intervention measures before applying them in reality (Sherwood 2002). Potential policy and management strategies are therefore able to be analysed, evaluated and improved.

A growing number of studies have employed systems thinking and dynamics modelling in agriculture- and natural resource-related disciplines and proven to be useful (Turner et al. 2016). These include using system dynamics to address hydro and water resource management issues (Sun et al. 2017; Wang et al. 2011) and to evaluate climate change impacts and adaptation on water and agricultural systems (Chapman and Darby 2016; Gohari et al. 2017).

However, only a limited number of studies have applied systems thinking and dynamics modelling approaches to investigate drought impacts in the agricultural sector, and to explore potential strategies that can be adopted for effective drought response and management. To date, these include drought management alternatives for livestock production (Rhoades et al. 2014), and strategies at the river-basin scale in Canada (Wang and Davies 2015) and the regional level in East Africa (Gies et al. 2014). An integrated framework that combined system dynamics with other modelling frameworks was also applied for a comprehensive analysis of the interrelationships between drought-related systems including land and water use systems (Agusdinata

2016; Gies et al. 2014). (A more detailed discussion of these studies is provided in Chapters 6 and 7).

To fill this knowledge gap, this study aims to implement a system dynamics approach and further evaluate the impacts of drought on crop production with consideration of interactions with environmental and socio-economic dynamics. This approach is well suited to this purpose because it allows the inclusion of not only the climatic, ecological and socio-economic dimensions but also their dynamic processes and interactions within an integrated system. This can therefore enable a comprehensive analysis and assessment of the behaviour over time of the whole system, and the formulation of appropriate intervention strategies that can inform better decision-making.

3.2. Research methodology and stages of research

The application of systems thinking and dynamic modelling approaches is an iterative process of five phases (Figure 3.1), including: (1) problem articulation; (2) formulation of a dynamic hypothesis; (3) development of a simulation model; (4) model testing; and (5) policy design and evaluation (Maani and Cavana 2007; Sterman 2000). This research will apply all of these five phases to explore potential response strategies to drought impacts to support decision-making on sustainable coffee production in Dak Lak Province – a major coffee-growing region in the Central Highlands of Viet Nam.

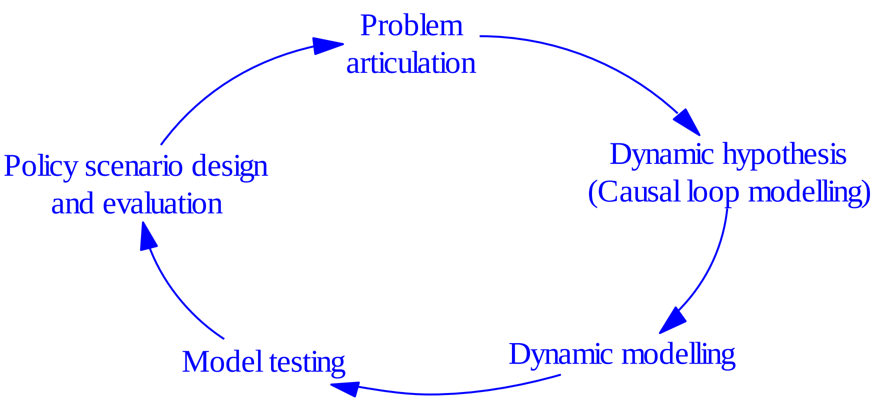

Figure 3.1. The five-phase process of system dynamics modelling

(Adapted from Sterman 2000)

Problem articulation

As a common phase in most problem-solving approaches, the primary aim of problem articulation is to define the real problem and its root causes, clarify the purpose of developing the model used to address it, and establish the scope and boundary of the research. Behaviour over time, or 'reference mode behaviour', is a useful tool in system dynamics which, through graphical representation, aids understanding of trends and variation in key variables relating to the problem over time and of the underlying feedbacks in the system (Maani and Cavana 2007).

To achieve the first research objective and to produce a good basis for causal loop modelling, the first phase of the project is to structure the following elements associated with the problem under investigation:

- Problem articulation: What are the real problems that need to be addressed and what are their root causes?
- Study scope and boundary: What are the system scope and boundaries? Who are the potential key stakeholders?
- Key variable identification: What are the key variables that need to be considered in the study and what are their historical and expected behaviours?

(Sterman 2000)

For this research, the direct and indirect impacts of drought and other climate-related factors on coffee production was first identified through a systematic literature review. An additional literature review specific to the case study area was then implemented to identify potential impacts of drought on coffee production. Historical behaviour over time of key variables such as coffee area, production and yield, precipitation, forest area and population were analysed to understand the underlying dynamics of the system and formed the basis for model development. The next step in the problem structuring phase is data collection for model development through stakeholder consultation. This process included semi-structured interviews with key stakeholders including experts and farmers involved in drought and coffee production issues. Interviews and discussions with stakeholders aimed to identify and confirm the key variables of the system under investigation, i.e. the drivers of drought and factors exacerbating the impacts of drought on coffee production and farmers' livelihoods, and the causal relationships between variables. Some data regarding coffee production such as coffee area, yield, production, irrigation methods and costs, production costs and farm revenues were also collected to build an understanding of data trends, and to provide a basis for validating the causal relationships of some of the key variables in the system.

Formulation of a dynamic hypothesis

The next step in the systems dynamic modelling process is to formulate a hypothesis that describes the dynamics characterizing the problem, and particularly, the underlying feedbacks present in the system (Sterman 2000). A range of techniques can be used to develop the dynamic hypothesis and define the model boundary including model boundary chart, subsystem diagrams, causal loop diagrams, stock and flow maps and policy structure diagrams (Sterman 2000). In this project, *causal loop diagram* was the main tool applied to represent the causal relations between variables present in the system (e.g. factors driving drought and exacerbating it impacts).

A causal loop diagram (CLD) reveals the causal links and feedback structures present in a system by capturing the hypotheses about the dynamics characterizing the problem and the mental models of individuals or groups (Sterman 2000). CLDs graphically capture underlying feedbacks in the system by showing not only the interrelationships between the system's elements but also the interactions between them (Sterman 2000).

CLDs consist of variables (factors) connected by arrows (links) that indicate the causal relations among these variables (Figure 3.2). An arrow can be labelled as '+', when an increase in one variable (e.g. births) leads to an increase in another variable (e.g. population), or as '-', when an increase in one variable (e.g. deaths) leads to a decrease in another variable (e.g. population) (Maani and Cavana 2007).

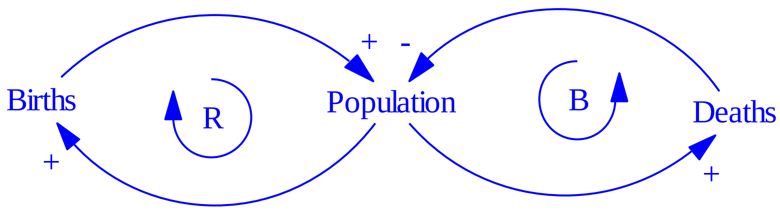

Figure 3.2. An example of a CLD with reinforcing and balancing loops

Feedback loops characterized in a CLD can be *reinforcing* (R) or *balancing* (B). Reinforcing loops represent a growing or declining action whereas balancing loops counteract or self-regulate change to seek a stable state (Maani and Cavana 2007).

System archetypes and leverage points

In systems thinking, *leverage* refers to long-term and fundamental changes that can reverse a trend or break a vicious cycle while *system archetypes* are generic structures or templates that represent different situations requiring interventions (Maani and Cavana 2007; Senge 1991). Leverage points are used to target long-term and fundamental interventions rather than 'quick-fix' actions merely aimed at addressing the symptoms of the problem (Maani and Cavana 2007). Policy interventions can be established based on leverages recognized in system archetypes stemming from CLDs.

Formulation of a simulation model

After setting the model boundary and conceptual model for the system through CLDs, a simulation model is developed to test dynamic hypotheses. This step moves to a detailed model structure with relevant equations, parameters, behavioural relationships and initial conditions (Sterman 2000). This simulation model allows modellers to quantitatively test interactions between variables. Specifically, in this study, the final CLD was then converted into a *Stock-and-Flow Model* (SFM) to enable quantitative simulation of drought impacts to test outcomes over time. A SFM model (Figure 3.3) consists of *stocks* (e.g. population) that accumulate over time within the system, *flows* (e.g. births, deaths) that increase or decrease the stock, *converters* or *auxiliary variables* (e.g. birth rate, death rate) that adjust flows and *connectors* that link components in the model (Gies et al. 2014; Maani and Cavana 2007). Auxiliaries can be constants, graphical relationships or mathematical functions, which are connected to flows and stocks to characterize feedback loops influencing the behaviour of the system over time.

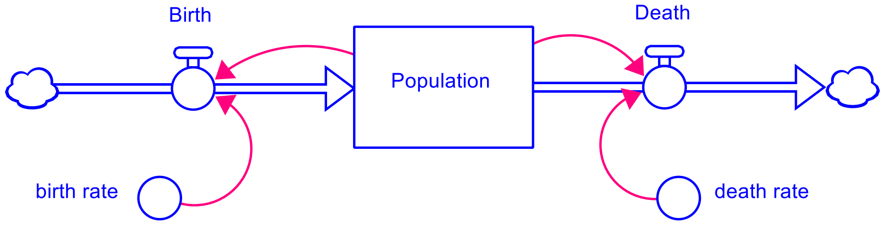

Figure 3.3. An example of the key elements of a Stock-and-Flow model

The SFM of drought impacts in this study was developed using the *Stella Architect* software (Version 2.0 from isee systems, one of leading designers of Systems Thinking and Dynamic Modelling software, *https://www.iseesystems.com*). Based on the conversion from the final CLD to the SFM, the data required for simulation were defined. Initial values for the stocks and other parameters in the model were accessed from the data collected in the first two phases of this study. In cases where historical or observed data were not publicly available, reasonable assumptions were made based on the current literature and/or expert opinions. Not all loops in the CLD were converted into the SFM due to limited data availability and insufficient knowledge about the whole system, which was addressed by the use of assumptions, leading to possible uncertainties and errors in the simulation model. However, the aim of model development was to understand the dynamic behaviours of key variables of the system, not to focus on the precise predictions of the variables (Kotir et al. 2016).

Model testing

Before a model can be adopted for decision-making and policy analysis, where applicable, it is necessary to test its soundness and robustness. Model testing might involve structural and behavioural validity tests performed to check if the model structure can adequately represent the structure of the system it represents and if the model can generate adequate behaviour compared to the patterns observed in reality (Barlas 1989; Sterman 2000).

For behaviour pattern evaluations, the reference mode behaviour of key parameters is reproduced and compared with actual trends (e.g. behaviour over time graphs) using a statistical parameter called the *discrepancy coefficient* (U) to measure the divergence (Barlas 1989). Values of U range from 0 (perfect predictions) to 1 (worst predictions) and a model may be considered good to average where U ranges between 0.4 to 0.7 (Barlas 1989).

For structural assessment of the model, the model behaviour is validated through simulations under extreme conditions to detect possible model errors. For example, coffee yield should decline or drop nearly to, but never below, zero if all water resources are exploited under extreme drought events. The conservation of matter test is also applied to check if the model is violating the basic physical laws; this means that a stock must never become negative and the change in a stock at any step must be equal to the net flow, which is the sum of inflows minus outflows. For example, a stock such as water availability should equate to the sum of all water inflows, including runoff and groundwater recharge, minus the sum of all water outflows, including water consumption and evaporation.

The dimensional consistency test is used to inspect the units of measurement for all variables to detect any flaws due to unit errors, and to examine the model equations for questionable parameters and relationships assigned to them. Structural verification means that all structural components of the model should produce acceptable behaviour as anticipated; specifically, reinforcing and balancing feedback loops should reveal accurate polarities and behaviours (Barlas 1989; Sterman 2000).

The model testing phase also includes sensitivity analysis to assess the model behaviours under various simulated conditions and identify policy options given uncertainties in assumptions (Maani and Cavana 2007; Sterman 2000). Key parameters such as coffee production and coffee harvest area are selected for sensitivity analysis in order to discover those that most influence the model's dynamic behaviour. Several steps were performed in the sensitivity analysis, including selecting parameters and graphical functions whose values were based on uncertain information or that are likely to impact the model behaviour, and then adjusting each by ±10% of their initial values while keeping other variables fixed. In the last step, parameters that were found to significantly affect the behaviour of the model were analysed based on common knowledge (Maani and Cavana 2007).

Policy design and evaluation

Finally, the model, customized to suit its purpose, is used for scenario design and evaluation and policy implications. This step involves reproducing new strategies and decision rules in the model; examining the effects of policies to detect unintended consequences; analysing the sensitivity of the system's response to policy recommendations under alternative scenarios and given uncertainties; and investigating interactions within the different scenarios (Sterman 2000). In this study, a range of policy intervention strategies are designed and simulated based on the results of sensitivity analysis. These are purposely used to identify plausible strategies to support strategic drought management planning for sustainable coffee production in the context of the present study region in Viet Nam.

3.3. Research methods

3.3.1. Systematic quantitative review

In setting the basis for model development under this research project and identifying indirect and direct climate-driven impacts, particularly those of drought on coffee production, a systematic quantitative literature review was conducted. This stage was deemed necessary to properly identify potential inputs essential for the formulation of the system dynamics model, and therefore forms a core basis for Objective 1 of the research project. The systematic quantitative literature review methodology was adapted from Pickering and Byrne (2014), and is a comprehensive, explicit, reproducible and quantifiable approach to the examination of literature, selection and analysis of relevant research papers, and identification of knowledge gaps (Pickering et al. 2015); in this study, this then formed the basis to achieve the next objectives.

The process for undertaking a systematic quantitative literature review and making significant contributions using synthesis of existing literature includes 15 steps (Figure 3.4). The first two steps are designed to clearly define a specific topic and clarify potential research questions to be addressed by the proposed literature review. Key words or search terms are then carefully selected, after potential trial and error, to enable an effective search in online databases and identification of relevant publications (Step 3). In the next step, suitable academic databases are selected for the search process, whereas Step 5 involves evaluating these publications, generally through reading the title, abstract and keywords to decide if they are relevant and whether they should be included. A set of criteria for inclusion must be carefully considered to ensure that the outcomes are reproducible, thus ensuring a rigorous methodology. A customized database is then designed (Step 6), including appropriate categories and sub-categories for analysis and evaluation on the topic. Next steps involve entering about 10% of the identified publications into the database, testing categories and sub-categories as well as criteria for data inclusion and category revision, if needed. Step 9 requires entering all publication into the database and Step 10 involves producing summary tables which include the number and/or the percentage of all publications in various categories and sub-categories. The remaining steps are to structure and write the review. These include drafting the methods section (Step 11), assessing the tables of results including the type of published literature on the topic (Step 12), drafting the results and discussion section (Step 13) and the remaining parts of the review (Step 14). In the last step, revising the review paper and identifying possible limitations of the systematic review are required before submission (Pickering and Byrne 2014).

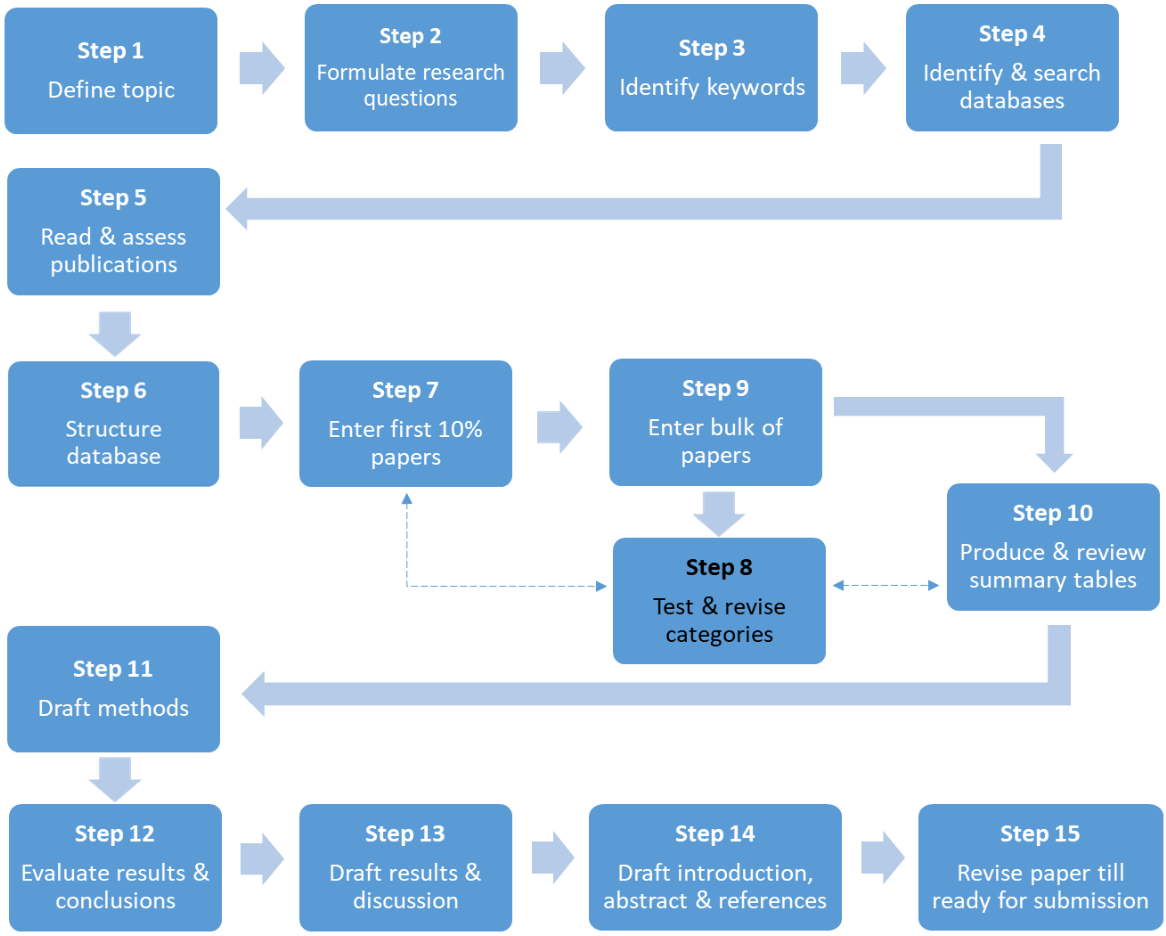

Figure 3.4. Key steps in conducting a systematic quantitative literature review (Adapted from Pickering and Byrne 2014)

In mapping the process of identifying and selecting publications for the proposed review that is used to inform the rest of the project design, this research project adapted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework designed by Moher et al. (2009). This helps to systematically track the process of the review, identify and analyse the knowledge gaps and make recommendations for future research (Figure 3.5). Applying this systematic review approach in this research project enabled the detailed identification and examination of the types and characteristics of potential climate-driven impacts, particularly drought, on coffee production; analysis of the impacts and adaptation measures involved and evaluation of the methods applied to analyse the impacts; and investigation of the potential research gaps for future research to better support sustainable coffee production, globally (Pham et al. 2019).

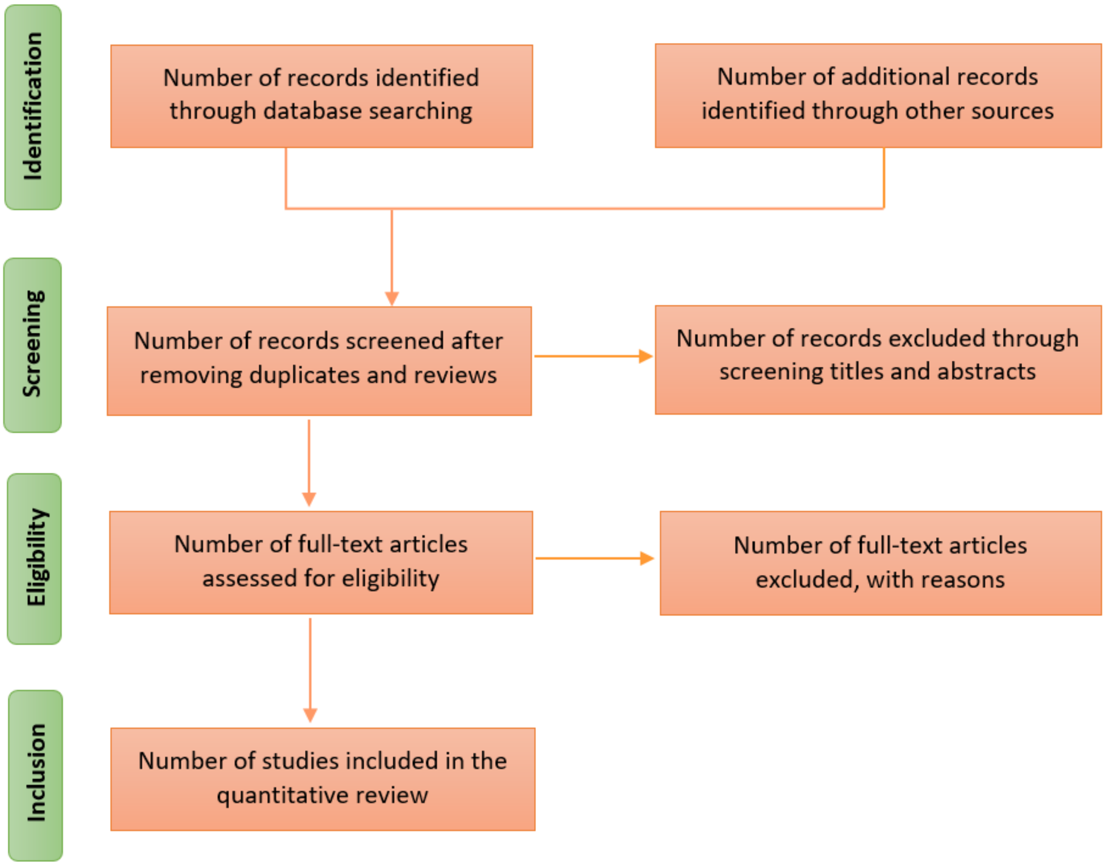

Figure 3.5. Steps taken in the systematic review

(Adapted from Moher et al. 2009)

3.3.2. Data collection and analysis

This thesis is based on a mixed methods research strategy, where the methodology and research approach include the collection, analysis and inference of both qualitative and quantitative data in a particular study, to attain a deeper and more accurate level of understanding to address research questions (Johnson et al. 2007). Qualitative and quantitative methods generally entail various tools for data collection, such as interviews or surveys; data types, including textual and numerical; and data analysis techniques, such as statistical and thematic approaches to support addressing research questions (Tashakkori and Creswell 2007). In this research project, such a diverse range of methods for data collection were applied to build the system dynamics model.

Data used in this research comprise the primary qualitative data retrieved from interviews through an intensive process of stakeholder consultations; these data were enriched using secondary data derived from existing literature. Approaches for data collection such as interviews, focus group discussions, and workshops may enable the capture of the ‘mental models” of individuals or organisations with diverse knowledge, perspectives, backgrounds and values, reflecting their observations and experiences, which might not be reflected by numerical or textual data (Forrester 1992; Turner et al. 2016). This might help to unravel the dynamics of the problems and enhance a deeper level of understanding (Maani and Cavana 2007).

For this project, the process of consultation was conducted through an interview of 60 individuals engaged in drought management and/or coffee production related issues in Viet Nam. These participants included policy-makers at the national and local levels, researchers from universities and non-governmental agencies, coffee farm households and other representatives from the coffee industry.

A semi-structured interview, which has proven useful in systems thinking and dynamic modelling approaches (Sterman 2000), was designed for this research. This technique allows interviewed stakeholders to leave the pre-set questions to discuss other issues of interest. Interview questions were developed to assist with problem structuring and identification of causal links among system variables. Interviews were conducted in Ha Noi, the capital of Viet Nam with the participation of key policy makers from national authorities and experts and in Dak Lak Province, the case study area, where local authorities, researchers, coffee farmers and other relevant stakeholders were represented.

The results of the interviews were coded by applying the method of Kim and Andersen (2012) as a large amount of data was produced during the consultation. This coding approach enables systematic coding of qualitative data to general causal diagrams for system dynamics modelling. A more detailed explanation of the specific steps of data collection and analysis methods, including stakeholder identification, interview structure and the coding process is provided in the published research article presented in Chapter 5.

This project also involved a large volume of data from different secondary sources to assist the model development phase, simulation and calibration stages, and to inform policy scenario analysis and evaluation, as part of the mixed-method research design. These sources included:

- Publicly available data: These include annual and monthly precipitation data from the National Centre for Hydro-Meteorological Forecasting of Viet Nam Meteorological and Hydrological Administration, and demographic and coffee-related statistics from or calculated based on data from the General Statistic Office at national and provincial levels, Dak Lak People's Council and Department of Agriculture and Rural Development.
- Regulatory documents including the 2014 decision on approval of the sustainable coffee production plan to 2020 of the Ministry of Agricultural and Rural Development of Viet Nam, the 2017 resolution on sustainable coffee development in Dak Lak Province to 2020 with orientation towards 2030, the 2015 resolution on water resources development in sustainable coffee areas in the period of 2015-2020 with orientation towards 2025 and the 2007 provincial decision on water sources management of the People's Council of Dak Lak Province.
- Water resources data: Water resources figures and trends including water supply, demand, consumption and extraction were collected from different available sources including reports from governmental agencies and surveys from international and non-governmental organizations.

The above mentioned data were used to not only verify the causal relationships formulated based on interviews of relevant stakeholders before qualitative modelling development but also to provide inputs for the simulation and calibration of the quantitative model and inform the analysis and evaluation of policy intervention scenarios. Further details on data used in this project are provided in the relevant published journal articles (Chapter 5 & 6).

3.4. Case study background

The focus region in this research is Dak Lak, which is one of six provinces of the Central Highlands, a major administration region in Viet Nam (Figure 3.6). Dak Lak was selected as the case study area because it is a region that is both frequently affected by drought and also a key coffee-producing hub, locally and globally, on which the livelihoods of many smallholder farmers reliant on coffee production depend.

The total area of this province is 13,125.37 km^2 and its average elevation ranges from 400-800m above sea level. This plateau experiences both monsoon tropical and temperate climates and is characterised by basaltic soil types suitable for agricultural production, particularly the cultivation of perennial crops such as coffee, cocoa, black pepper and rubber (DONRE 2014).

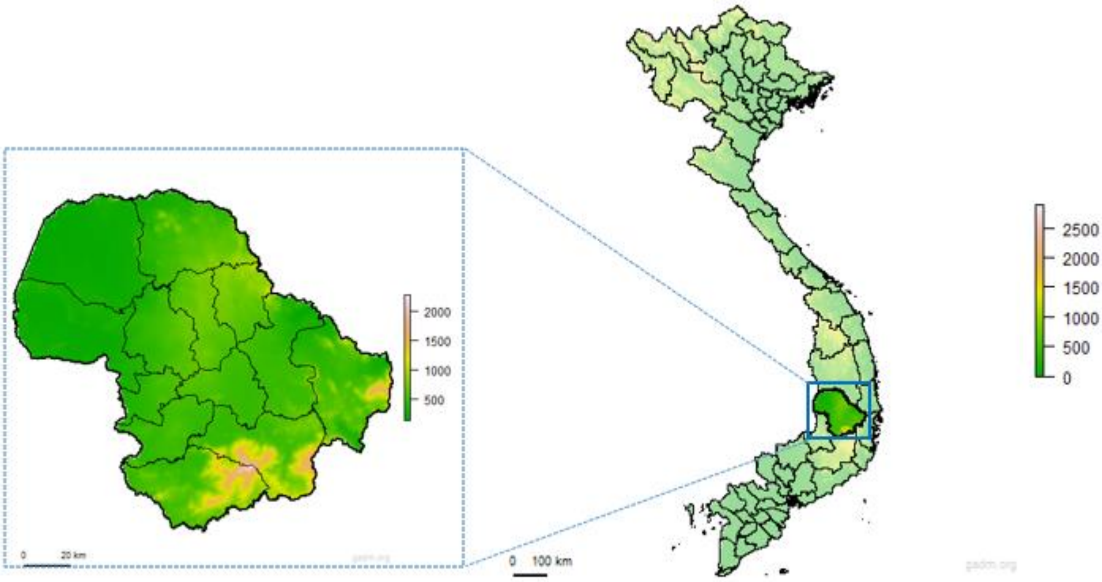

Figure 3.6. Location of Dak Lak Province with elevation above sea level (Source: https://gadm.org/)

The climate in Dak Lak Province has two distinct seasons: a rainy season from May to October with rainfall accounting for approximately 85% of the total annual precipitation; and a dry season from November to April with low rainfall, reduced humidity, high evaporation and frequent and severe drought events (Figure 3.7). The average annual temperature at Buon Ma Thuot station in Dak Lak is 23.8°C. The region is greatly exposed to frequent drought events, placing more pressure on water resources, particularly in the dry season, and damaging agricultural production (DONRE 2014). As a result of changes in climatic conditions, drought in Viet Nam is predicted to occur with increasing severity in terms of frequency, extent and duration over coming decades (IMHEN and UNDP 2015).

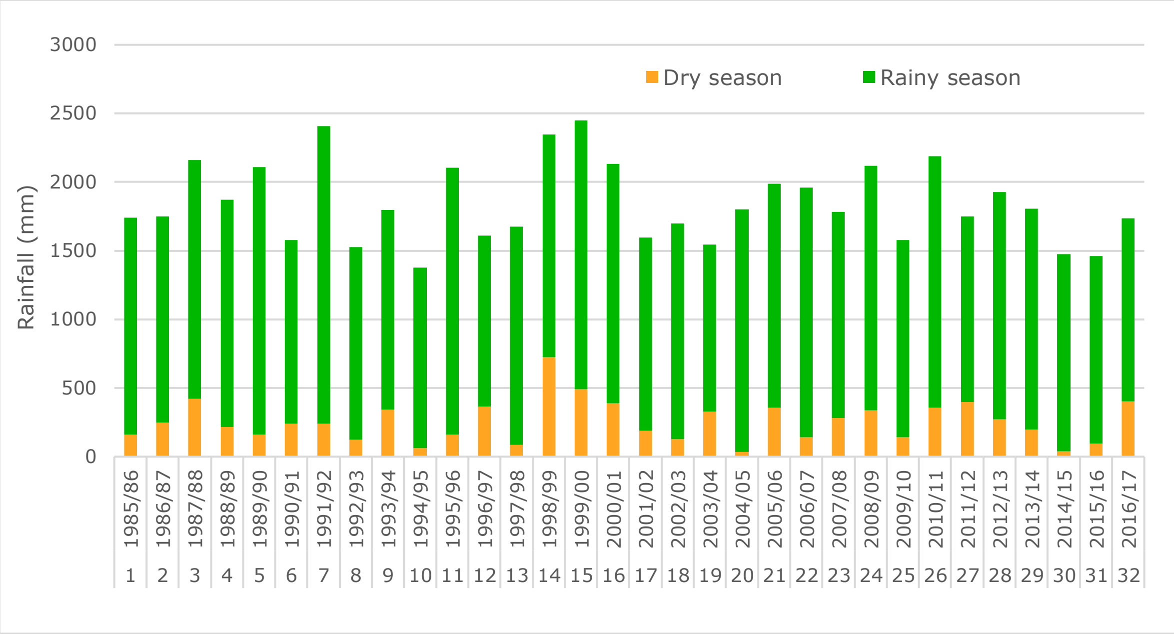

Figure 3.7. Rainfall in dry season and rainy season at Buon Ma Thuot station, Dak Lak Province (Source: NCHMF 2019)

In Dak Lak, agricultural production occurs on more than 40% of the total land area of 13,158 km^2, with relatively equal shares between annual and perennial cropped areas (GSO 2018). Main annual crops are rice, maize, sweet potato and cassava while perennial crops include coffee, pepper, cashew, rubber and tea. Approximately 70% of the total cropped area of perennial crops in the province is occupied by coffee while the remaining area is for rubber (13%), pepper (9%), cashew (7%) and fruits and other crops (GSO 2018). Agricultural water demand accounts for more than 80% of the total water demand in the province, of which irrigation water demand for coffee cultivation occupies over 20% (JICA 2018).

Viet Nam is the second largest coffee producing and exporting country, accounting for over 40% of the total Robusta coffee output of the world (ICO 2019). More than 90% of the total coffee production area of the country is in the Central Highlands (GSO 2018). Dak Lak Province on this plateau is the largest coffee-producing region with approximately 35% of the total Robusta coffee production of the country (GSO 2018). Coffee production in this province supports the livelihoods of approximately 200,000 smallholder farmers who represent a large proportion of production, despite the fact that this is from small cultivation areas averaging about one ha each (Marsh 2007; Technoserve and IDH 2013).

Sustainable coffee production in the province is crucial, both nationally and globally, but this is threatened by significant declines in water resource availability due to drought events, particularly in the dry season. For example, in 2014-2016, as a result of an extreme El Nino-related drought event, more than 19,000 households were short of domestic water and 60,000 ha of perennial crops, mostly coffee and pepper, failed in the province (Grosjean et al. 2016). Drought affected approximately 30% of the total coffee area in Dak Lak (DCP 2016).

Coffee production in the region is highly dependent on irrigation in the dry season, when there is both limited rainfall and high evaporation, with irrigation water extracted from both surface and groundwater sources. Many coffee smallholders irrigate inefficiently, often using double the amount of water required in the belief that coffee yield will be maximised (CHYN 2015). During drought, there were reports of conflicts in water resource management between coffee irrigation and domestic users (CIAT 2012).

Water resources in the Central Highlands are under pressure (IPSARD 2015). Apart from excessive and inefficient use of water for irrigation, key drivers of declining water resource availability include deforestation, driven by agricultural expansion, commercial logging, forest fires and economic growth policies; increasing water demand for hydropower development; and changes in rainfall patterns induced by climate change (CCAFS-SEA 2016; IPSARD 2015; Walz et al. 2016).

Numerous solutions have been implemented to cope with drought in Viet Nam. These include improvements in infrastructure including water storage facilities, pumping stations, and canal and ditch networks for increasing water delivery; selection of more drought-resistant crop varieties; and monitoring of irrigation systems (GoV 2017; JAT 2016; Oxfarm-Vietnam and Kyoto-University 2007). However, such responses remain largely reactive, mostly due to the failure to effectively institutionalise drought management. There is still a lack of policy for drought-prone regions, and little support for proactive adaptation. Also, while many countries have applied the disaster management cycle, including risk and crisis management, these approaches have not yet been applied in Viet Nam (MARD 2017). Furthermore, in many drought events, interventions have mostly focused on post-impact solutions, usually in the form of emergency relief (IMHEN and UNDP 2015), which is not a proactive response aimed at building resilience to drought.

Various research projects in relation to drought have been conducted, particularly for the Central Highlands region. While these studies have mostly focused on climate forecasts and recovery solutions (MARD 2017), there remains a lack of empirical research with detailed survey and data collection within affected regions. Systematic analysis of the underlying causes and drivers of drought and its associated impacts on the agricultural sector, as well as the effectiveness of potential coping measures, is virtually non-existent.

Dak Lak was selected as a case study area because it is a region that is frequently affected by drought and it is crucial to ensure the livelihoods of many farmers dependent on coffee production while also maintaining its position as a key coffee-producing hub locally and globally.

In this study, meteorological drought events were considered, which is a "prolonged absence or marked deficiency of precipitation" (Trenberth et al. 2014) in a period of months or years (Vu et al. 2015). The classification of dry years was referred from the national technical standards on hydraulic structures (QCVN04-05: 2012/BNNPTNT), of which the amount of annual rainfall is 85% of the probability of occurrence year of long term annual rainfall records for the period of 1985 to 2017 (JICA 2018).

Given evidence that Viet Nam has been exposed to frequent and extreme drought events and that Vietnamese farmers are highly reliant on government and donors for relief from drought impacts while understanding of drought management remains limited, studies of drought impacts on the agricultural sector are of great importance. This study will contribute to better understanding of the underlying drivers of drought and their impacts on crop production and farmers' livelihoods. In addition, it will support the formulation of drought response strategies for agricultural sustainability in Viet Nam. These strategies are expected to reduce the dependence of farmers on post-disaster aid and to improve their resilience to future drought risks. The conceptual and simulation models designed within this study can be a basis for developing similar models in other contexts or regions to support decision-making on drought management.

Chapter 4. The impact of climate change and variability on coffee production: A systematic review

Chapter overview

This chapter provides a critical review of the current literature on the impacts of climate change and climate variability, specifically drought, on the production of coffee – the second-most globally traded commodity after crude oil. Using a systematic quantitative approach, the chapter describes the sources, types, characteristics and levels of climate-driven impact on coffee production, the approaches applied to assess the impacts, and the adaptation options considered in published research, and the potential knowledge gaps and recommendations for future research. The outcomes of this chapter contribute towards addressing Objective 1 of the research through providing inputs for the development of the system dynamics model in the subsequent chapters.

Citation

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The impact of climate change and variability on coffee production: a systematic review

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Abstract
Coffee is one of the most important globally traded commodities and substantially contributes to the livelihoods of millions of smallholders worldwide. As a climate-sensitive perennial crop, coffee is likely to be highly susceptible to changes in climate. Using a systematic approach, we explore evidence from the published academic literature of the influence of climate change and variability, specifically drought, on coffee production. A number of mostly negative impacts were reported in the current literature, including declines in coffee yield, loss of coffee-optimal areas with significant impacts on major global coffee-producing countries and growth in the distribution of pest and disease that indirectly influence coffee cultivation. Current research also identified positive effects of climate change such as increases in coffee-producing niche, particularly in areas at higher altitudes; however, whether these gains might offset losses from other production areas requires further investigation. Other advantages include increases in pollination services and the beneficial effects of elevated carbon concentration, leading to potential yield improvements. Future priorities should focus on major coffee-growing regions projected to be adversely affected by climate change, with specific attention given to potential adaptation strategies tailored to particular farming conditions such as relocation of coffee plantations to more climatically suitable areas, irrigation and agroforestry. The majority of studies were based in the Americas and concentrated on Arabica coffee. A broader spread of research is therefore required, especially for the large growing regions in Asia and for Robusta coffee, to support sustainable production of the global coffee industry.

1 Introduction

The agricultural sector is expected to be substantially affected by climate change because of the sensitivity of crops to increasing temperature and water shortages (Mendelsohn 2008; Ramirez-Villegas and Challinor 2012). Apparent negative effects include declines in crop yield

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and quality and increases in pest and disease infestation, leading to reductions in crop production worldwide (IPCC 2014). These pose significant challenges to smallholder farmers, many of whom are dependent on rain-fed cultivation and have limited access to financial and technical support (Cohn et al. 2017; Holland et al. 2017) that could help them to respond to changing climatic conditions.

There has been a growing concern for coffee, a crop that is grown by over 25 million mostly smallholder farmers in more than 60 countries throughout the tropics (Jayakumar et al. 2017) and that is highly sensitive to local climate (DaMatta and Ramalho 2006). Coffee yield is strongly determined by climatic conditions, particularly during the vegetative and reproductive phases of the plant (Tavares et al. 2018). Increasing temperatures and precipitation shortages have negative impacts on flowering, fruiting and bean quality (Gay et al. 2006; Lin 2007). Furthermore, climate variables also control the incidence of serious pests and diseases such as coffee leaf rust and coffee berry borer which could reduce coffee yield and quality and increase production costs.

Coffee is the second-most globally traded commodity after oil (Davis et al. 2012) and contributes significantly to the socio-economic development of many tropical developing countries and the livelihoods of more than 120 million people worldwide (TCI 2016). Coffee production has doubled during the last 30 years, amounting to over 169 million bags in 2018 (ICO 2019b). The gross revenue of coffee production was estimated at US$11.6 billion per year during 2000–2012 while the total value of the entire coffee sector was more than US$173 billion in 2012 (ICO 2014). Brazil makes up about 36% of the world's production, followed by Vietnam (17%), Colombia (8%) and Indonesia (6%) (ICO 2019b). Apart from substantially contributing to agricultural GDP, coffee production provides millions of jobs and supports poverty alleviation (Chemura et al. 2016; Laderach et al. 2017). More than 70% of global coffee is cultivated by smallholder growers in Africa, Asia and the Americas with many of them relying on coffee as their major source of income (Fridell et al. 2008). In addition to social and economic benefits, coffee plantations, particularly shaded farms, also generate significant ecosystem services including biodiversity conservation (Jha et al. 2014), carbon sequestration (van Rikxoort et al. 2014) and soil protection (Meylan et al. 2017).

Globally, Arabica *(Coffea arabica)* and Robusta *(Coffea canephora)* coffees make up approximately 99% of global coffee production (Jayakumar et al. 2017). Arabica, which is often used in speciality coffees, grows best at 18–22 °C, while Robusta is of lower quality but hardier and productive at 22–28 °C (Magrach and Ghazoul 2015). Bean quality and yield of both species decline outside these optimum temperature ranges (Magrach and Ghazoul 2015), suggesting significant sensitivity to shifts in climatic conditions. Further, as coffee plantations have, on average, a 30-year lifespan and can remain productive for more than 50 years (Bunn et al. 2015b), they are likely to be subjected to the influence of climate change and variability. Smallholder coffee farmers might also be highly vulnerable to changes in climate as adaptation in perennial crops like coffee may take several or even many years to take effect (Laderach et al. 2017). From a socio-economic perspective, understanding the extent of climate-driven impacts on coffee production and the benefits of potential adaptation strategies will be of vital importance to maintaining and improving coffee productivity and profitability and sustaining the livelihoods of smallholder producers all over the world.

This review assesses current research on the impacts of climate change and variability, specifically drought, on coffee production. We systematically examined the literature to determine: (i) the geographic distribution of the research; (ii) the types and characteristics of the impacts investigated; (iii) the methods used to analyse the impacts; (iv) the adaptation measures involved; and (v) any potential research gaps. On this basis, we identify target areas for future research to better support sustainable and viable coffee production.

2 Methods

Using the methods outlined in Pickering and Byrne (2014), we conducted a systematic quantitative review of the academic literature on climate-driven impacts on coffee production. This is a robust systematic and reproducible approach used to comprehensively survey, select and categorise the literature on a particular research topic (Pickering et al. 2015).

Applying a set of key search terms, we surveyed the literature in three scholarly electronic databases (Scopus, Web of Science and Science Direct) in October–November 2018 to identify relevant papers. The string of key search words used were combinations of 'coffee' and 'climate', 'climatic', 'ENSO', 'El Niño', 'La Niña', 'drought', 'impact', 'effect', 'yield', 'production' and 'productivity'. We searched within the abstract, title and keyword database categories of original research papers published in peer-reviewed English language academic journals. Publications such as review articles, book chapters, reports and conference proceedings were excluded. However, reference lists in review papers and in the original research articles were checked for additional academic papers missed in the initial search.

Climate change and variability and drought are also likely to influence the entire coffee supply chain including harvesting and processing activities; however, such impacts were not included in this review as our focus was on direct and indirect impacts of climate on coffee yield (i.e. tonnes of coffee harvested per hectare) and coffee production (i.e. tonnes of coffee harvested in an area of cultivation).

We used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram (Moher et al. 2009) to track the process of identifying and selecting relevant papers for this study (Fig. 1). Using the key search terms listed, we found 339 journal and review articles in the three above-mentioned databases plus an additional 28 articles from the citation lists of these, from which we excluded 171 duplicates and any review articles. We then excluded 162 articles that were neither relevant nor sufficiently focused on the impacts of climate change or variability or drought on coffee production. Finally, a total of 34 relevant peer-reviewed articles was selected to be fully examined in this study.

Data on each article were recorded in a customised database, including information on geographic distribution and spatial scale of studies and types of methods used to investigate the impacts. Characteristics, sources and outcomes of impacts and adaptation and management practices mentioned in the literature were also entered into the database to identify patterns and gaps and to inform future research recommendations.

3 Results and discussion

A total of 34 peer-reviewed research articles that specifically discussed the impacts of climate change or climate variability or drought, either directly or indirectly, on coffee production were fully examined. These papers were published in 17 different journals (Table S1 in the Electronic supplementary material), with the majority in the journals *Climatic Change* and

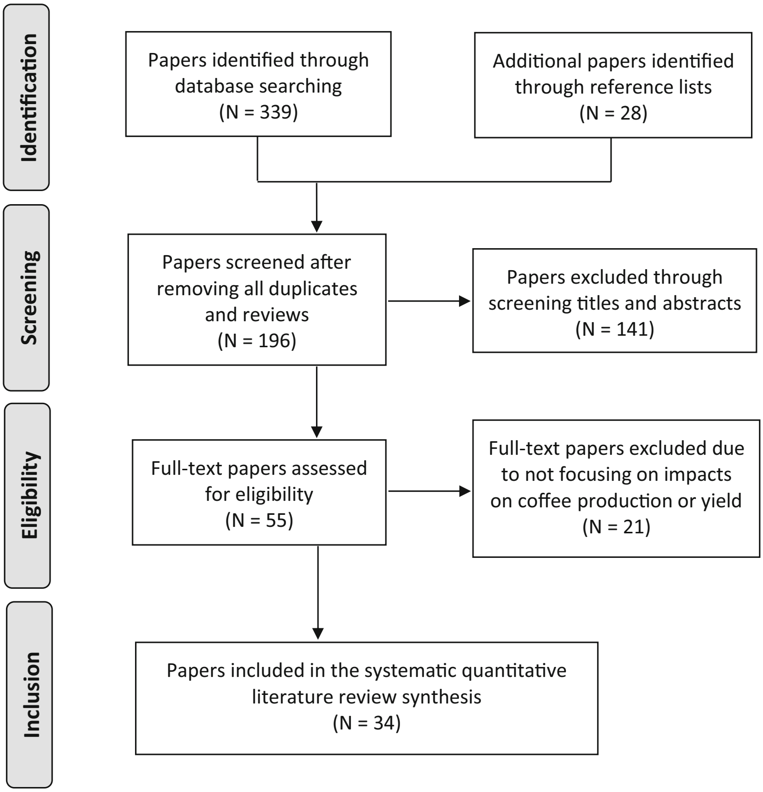

Fig. 1 Steps taken for the systematic quantitative literature review (adapted from Moher et al. 2009), *N*, number of original research papers

PLoS One (eight articles each). The journal *Regional Environmental Change* had three articles and the journal *Mitigation and Adaptation Strategies for Global Change* had two, while each of the remaining 13 journals had just one article.

Much of this research had been recently published (71% between 2014 and 2018), indicating an increasing interest in the potential impacts of climate variability and change on coffee production (Fig. S1 in the Electronic supplementary material).

Existing research mostly focused on Arabica (79%) with less consideration given to both coffee species, Arabica and Robusta (15%) (Table S1). No study solely concentrated on Robusta, despite this variety accounting for approximately 40% of global production (ICO 2019b). One explanation for this may be that many of the studies included in this review were conducted in the Americas where Arabica predominates. Another reason could be the greater heat tolerance of Robusta which might therefore be considered less vulnerable to rising temperatures than Arabica (Chengappa et al. 2017). However, Robusta may be susceptible to increasing intra-seasonal variability in temperatures (Bunn et al. 2015b), thus could still be negatively affected by changing climatic conditions. Given the decreasing bioclimatic suitability for Robusta production projected in some global studies, further research for this coffee species, particularly at finer spatial scales is necessary.

3.1 Geographic distribution of the research

Research in the papers included in this review was predominantly from the Americas (19 papers) with a majority of studies based in Central America (12 papers). Seven papers focused on coffee production in Africa and four in Asia (Fig. 2). Four papers reported on global studies covering all three of these continents (Table 1).

Most studies in the Americas were conducted in Brazil (six papers), followed by Mexico and Nicaragua (four papers each). The remaining research was limited to one or two papers per country in all three continents. The predominance of research in the Americas might reflect the fact that the world's top ten coffee-producing countries in this continent account for more than half of total global coffee production (Fig. 2). On the other hand, research from countries in Asia, where many of the other major coffee producers of the world are located, was relatively limited with only a small number of studies having been undertaken in large coffee-growing countries, including India and Indonesia. Interestingly, there were no papers targeted at regional, national or local levels for Vietnam, which is the world's second largest coffee-producing country with 17% of global coffee production (ICO 2019a). While Asia is expected to be negatively affected by climate change (Field et al. 2014), more research on climate-driven impacts on coffee is needed to support sustainable coffee development in regions with significant levels of production, particularly where communities are highly dependent on coffee cultivation.

Research into climate-driven impacts on coffee production has to date also been limited in scale (Table 1). Many of current studies primarily consider national (14 papers) and sub-national (11 papers) scales of production with less attention given to regional (or multinational) (four papers) or global scales (four papers). This is potentially because coffee data at large spatial scales are reportedly inadequate and uncertain (Eriyagama et al. 2014) while results of small-scale research are not easily extrapolated globally (Bunn et al. 2015a).

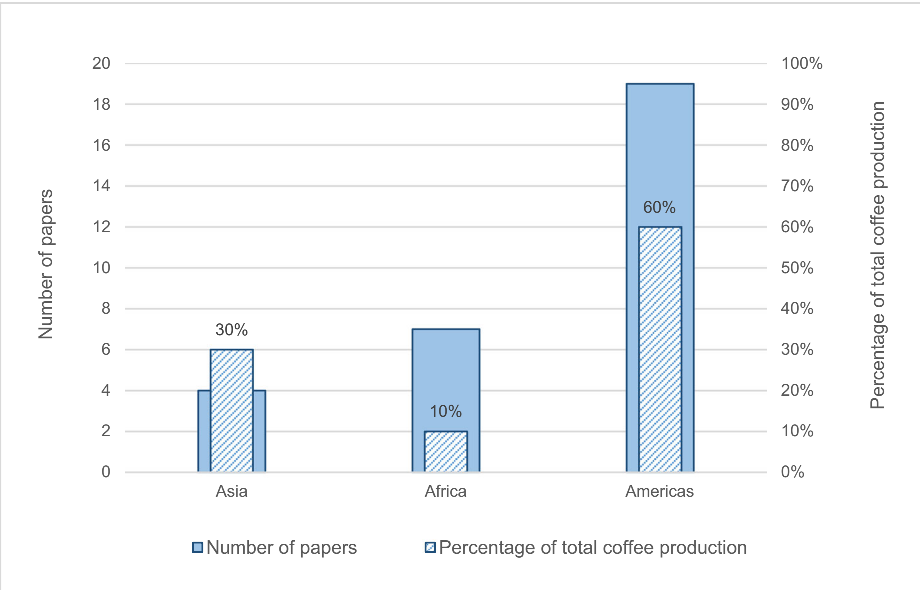

Fig. 2 Number of papers by continent reviewed and continental percentage of total global coffee production (ICO 2019b)

Table 1 List of reviewed original research papers on climate-driven impacts on coffee production published to November 2018

Reference	Location	Spatial scale	Source of impact	Method	Type and overall result of impact						
					P	S	Q	PE	DI	PS	Main finding
Global											
Bunn et al. (2015a)	Global	G	CC	Modelling (random forest)		±					An overall global loss of suitable areas for coffee by 2050s
Bunn et al. (2015b)	Global	G	CC	Modelling (support vector machines, random forest, MaxEnt)		±					A global loss of 50% of suitable areas by 2050
Magrach and Ghazoul (2015)	Global	G	CC	Modelling (MaxEnt)		±		–			A drop of 56% of current suitable areas for Arabica and 55% for Robusta by 2050. Future suitable areas for Robusta could be double. Distribution of coffee berry borer would increase
Ovalle-Rivera et al. (2015)	Global	G	CC	Modelling (MaxEnt)		±					An average loss of 19% of global suitable areas by 2050
The Americas											
Imbach et al. (2017)	Latin America	R	CC	Modelling (MaxEnt)		±				±	A loss of 73–88% of suitable areas by 2050. A drop of 8–18% in bee richness in future suitable areas, but pollination services are expected to continue
Baca et al. (2014)	Mesoamerica (Mexico, Nicaragua, Guatemala and El Salvador)	R	CC	Modelling (MaxEnt)		–					Reductions of at least 40% of suitable areas in 28% of total areas; 20–40% in 34% of areas and under 20% in 36% of areas by 2050
Harvey et al. (2018)	Central America (Costa Rica, Honduras and Guatemala)	R	CC	Interview	–			–	–		Negative impacts on yield and increases in pest and disease outbreak
Avelino et al. (2015)	Central America and Colombia	R & N	CV	Document analysis	–				–		A decline of 31% in production for 2008–2011 compared with 2007 in Colombia; 16% for 2012–2013 compared with 2011–2012 in Central America
Bastianin et al. (2018)	Colombia	N	CV	Modelling (econometric model)	±						Coffee production gains benefits from El Niño but loses from La Niña
Bacon et al. (2017)	Nicaragua	N	D & CV	Surveys, interviews, focus groups and modelling (statistical analysis)	–				–		Harvest losses of 60–72% from 2011–2012 to 2013–2014
Laderach et al.	Nicaragua	N	CC	Modelling (MaxEnt and CaNaSTA)		±	±				

Table 1 (continued)

Reference	Location	Spatial scale	Source of impact	Method	Type and overall result of impact						
					P	S	Q	PE	DI	PS	Main finding
(2017)											A loss of 10–25% of currently suitable areas by 2050. A decline in suitability to produce good quality coffee beans. Suitability will move to higher elevations
Fain et al. (2018)	Puerto Rico	N	CC	Weighted overlay analysis in GIS		–					A loss of 60–84% of highly suitable municipalities by 2070
Alves et al. (2011)	Brazil	N	CC	Modelling (non-linear regression)					–		A shift toward the south in areas favourable for coffee rust
Ghini et al. (2011)	Brazil	N	CC	GIS spatial analysis					–		A decrease in the incubation period and thus more severe epidemics
Ghini et al. (2008)	Brazil	N	CC	GIS spatial analysis				–			An increase in pest infestation and number of generations
Verhage et al. (2017)	Brazil	N	CC	Modelling (Arabica coffee yield model)	±						Yield will reduce by 7.5% in 2040–2070 but can increase 0.8% due to CFE
Junior et al. (2006)	Brazil	SN	CC	Modelling (agricultural zoning)		–					A reduction of 41 and 70% of suitable areas if temperature increases by 1 and 3 °C, respectively
Tavares et al. (2018)	Brazil	SN	CC	Modelling (agroclimatic zoning)	–	–					Losses of 36–64% of current suitable areas and 25% of Arabica yield by 2100
Estrada et al. (2012)	Mexico	SN	CC	Modelling (econometric model)	–						Costs of climate change for coffee production are estimated to be 3 to 14 times (273–1273 million dollars) the current value of coffee
Gay et al. (2006)	Mexico	SN	CC	Modelling (econometric model)	–						A drop of 19–34% in production by 2020
Schroth et al. (2009)	Mexico	SN	CC	Modelling (MaxEnt)		–					A strong decline of 98% of currently highly suitable areas by 2050s
Rahn et al. (2014)	Nicaragua	SN	CC	Modelling (MaxEnt)	–	–					A decrease of climatic suitability for coffee cultivation
Guido et al. (2018)	Jamaica	SN	D	Interview and focus group	–						Lower quality and quantity of coffee, leading to lower production
Asia											
Ranjitkar et al. (2016)	Nepal	N	CC	Modelling (an ensemble of 19 SDM algorithms)		–					A drop of 72.6 ± 4.4% of current suitable areas by 2050. Only 11.9 ± 2.3% of new areas become suitable for coffee

Table 1 (continued)

Reference	Location	Spatial scale	Source of impact	Method	Type and overall result of impact						
					P	S	Q	PE	DI	PS	Main finding
Schroth et al. (2015)	Indonesia	N	CC	Modelling (MaxEnt)		±					An overall loss of 33% of suitable areas by 2050
Chengappa et al. (2017)	India	SN	CV	Interview	±						A decrease in Arabica yield and an increase in Robusta in the past 10 years
Jayakumar et al. (2017)	India	SN	CV	Modelling (statistical analysis)	±						A decline in production during 2001–2006 due to rising temperature. Arabica yield was adversely impacted during strong El Niño years
Africa											
Jaramillo et al. (2011)	East Africa	R	CC	Modelling (CLIMEX)				–			An increase in number of pest generations from 5 to 10/year
Kutywayo et al. (2013)	Zimbabwe	N	CC	Modelling (boosted regression trees and generalised linear models)				–			An increase in suitable areas for the pest by 16–62% by 2080
Chemura et al. (2016)	Zimbabwe	N	CC	MaxEnt		±					A loss of 8.3–13.8% of suitable areas by 2050
Moat et al. (2017)	Ethiopia	N	CC	Modelling (an ensemble of 6 SDM methods)		±					A decline of 39–59% of current suitable areas by 2100
Craparo et al. (2015)	Tanzania	N	CC	Modelling (statistical analysis)	–						A loss of 244 ± 41 kg/ha in yield by 2030 and 145 ± 41 kg/ha by 2060 without adaptation
Davis et al. (2012)	Ethiopia, Sudan and Kenya	SN	CC	Modelling (MaxEnt)		–					Reductions of 65–100% of suitable localities; 38–90% of suitable areas by 2080
Rahn et al. (2018)	Uganda and Tanzania	SN	CC	Modelling (process-based model)	±						A decline of 32% in yield at low altitude areas by a 2.5-degree temperature increase without carbon fertilisation effect (CFE) consideration. If with CFE, negative impacts can be offset by 13–21%

G, global; *R*, regional; *N*, national; *SN*, sub-national; *CC*, climate change; *CV*, climate variability; *D*, drought; *P*, production; *S*, suitability; *Q*, quality; *PE*, pest; *DI*, disease; *PS*, pollination services; '+' positive impact; '–' negative impact

3.2 Sources and types of impacts

In this assessment, sources of impacts were classified into three groups: climate change, climate variability and drought. Impacts were also categorised as direct (i.e. variations in yield or production or in bioclimatically suitable areas for coffee cultivation) and indirect (i.e. changes in coffee quality or in the distribution of pests or diseases or pollination services).

In total, 12 studies examined direct impacts of climate change or climate variability, while only two addressed direct impacts of drought on coffee yield or production. Seventeen studies analysed direct impacts of climate change on bioclimatic suitability for coffee cultivation, driving changes in optimal coffee-growing areas. The remaining studies reported indirect impacts of climate variability or climate change with ten studies on pest and disease distribution and one each on pollination activities and coffee quality (Table 1).

Much of the literature reviewed focused on the influence of climate change or climate variability, indicating increasing recognition of their potential impacts on coffee production. In contrast, the number of studies on drought impacts was small despite reports of severe droughts in some coffee-growing areas such as Central America (Baca et al. 2014; Guido et al. 2018). As drought is a major climatic constraint for coffee production (DaMatta and Ramalho 2006) and expected to increase in frequency and severity in many regions across the world under climate change (Field et al. 2014), more research specifically on its impacts and on adaptation solutions should be considered for drought-prone coffee cultivation areas. Further, current research is dominated by studies that project changes in the distribution of areas suitable for growing coffee, with less consideration given to analysis of direct effects on coffee yield, or indirect effects on pest and disease distribution as a result of changes in climate. As some of the major coffee pests and diseases will likely benefit from rising temperatures, more research on their responses to changing climatic conditions and on adaptation mechanisms to minimise exposure and vulnerability of the coffee crop to these risks is needed.

3.3 Methods used in the research

A variety of research methods has been used to investigate coffee's exposure to climate risks. Quantitative methods (29 papers) were predominant over qualitative methods (four papers), with only one study using mixed methods.

Qualitative approaches used interviews (four papers), focus groups (two papers), household surveys (one paper) and document analysis (one paper) to explore the influence of climate change or climate variability or drought either directly on coffee production or indirectly on pest and disease distribution. Further application of these methods in future research would benefit assessments on climate-driven impacts and adaptation of coffee production systems as they can provide context-specific information including the perceptions and experiences of local farmers and their responses to climate change.

Quantitative studies included a range of modelling approaches aimed at investigating the influence of climate variability and change in coffee production systems (Table 1). Many studies used machine-learning techniques (15 papers), particularly Maximum Entropy (MaxEnt; 13 papers), of which most focused on current and future climatic suitability for coffee cultivation.

MaxEnt is a popular method for determining the spatial distribution and the environmental niche of species (Elith et al. 2011; Merow et al. 2013). Its predominance is probably due to its ability to easily extrapolate (Fitzpatrick et al. 2013) and provide improved outputs with presence-only species data (Elith et al. 2011; Mateo et al. 2010) compared with other correlative ecological niche models. MaxEnt has been widely used to project species distribution ranges in ecology (Merow et al. 2013) and might be suitable for a climate-sensitive crop such as coffee, especially in the context of data limitations in many coffee cultivation areas, as noted above.

Other types of ecological niche modelling employed, included machine-learning techniques such as random forest (four papers), boosted regression trees (three papers) and support vector machines (two papers) and regression-based methods such as generalised linear model (three papers), generalised additive model (two papers) and multivariate adaptive regression splines (two papers).

Fewer studies applied statistical analysis (four papers) and econometric models (three papers) to analyse direct impacts of climate change or climate variability on coffee production, or on changes in pest and disease distribution. Several studies used other modelling methods such as agricultural zoning (two papers) and other types of species distribution modelling (two papers).

While studies using MaxEnt or other bioclimatic modelling approaches have estimated the potential distribution in areas of suitability for coffee production under current and future climates, they have yet to include phenotypic plasticity (Nicotra et al. 2010) or mechanistic processes to predict the responses (Rahn et al. 2018) of the coffee plant to changes in climate or the effect of adaptation measures. For example, the potential influence of carbon fertilisation on coffee physiology as a result of rising carbon dioxide in the atmosphere could, if considered, provide somewhat different results. Elevated carbon concentration might enhance the photosynthetic process and increase yield (Ghini et al. 2015; Rodrigues et al. 2016), potentially mitigating, at least partially, the harmful impacts of warming climatic conditions on coffee yield (Verhage et al. 2017). Thus, projections that failed to take this into account might have over-estimated yield impacts (Rahn et al. 2018). However, Moat et al. (2017) argued that increasing drought stress, together with the potential effects of deforestation on local climate, could outweigh this beneficial influence in the long run. These interactions depend on particular contexts and therefore require further investigation.

The use of mechanistic or process-based models to analyse potential climate-driven impacts on coffee production in current research was limited, being represented by one study (Rahn et al. 2018) which explored responses of the coffee plant to interactions between atmospheric carbon dioxide enhancement, increased temperature and water scarcity and the efficacy of shade management. Mechanistic modelling has been widely applied in agricultural research into the impacts of climate change on the performance of crops such as wheat, maize and rice (Kang et al. 2009; White et al. 2011). Such models could be a valuable approach to better understanding climate change impacts, including the effect of modified microclimate under management practices on coffee production systems, allowing analysis of interactions between climate, soil and coffee plant parameters (Rahn et al. 2018). However, uncertainties may arise where there are insufficient data on coffee performance and ecological conditions for model calibration (Luedeling et al. 2014), which might be the case for many coffee-producing regions.

Correlative species distribution models have been broadly applied to predict potential shifts in the distribution of species under scenarios of future climate (Franklin 2010; Kearney et al. 2010). These methods exclusively focus on geographic distribution and generally involve only location data and corresponding environmental conditions of existing areas (Luedeling et al.

2014; Machovina and Feeley 2013). Future species distribution is projected solely based on the relationship between current distribution assuming to remain constant and climate (Dormann 2007; Thuiller et al. 2005) without taking account of the species' genetic structure and the influence of limiting factors, biotic interactions and other disturbances and processes that may be affected by changing climatic conditions (Evans et al. 2016; Fitzpatrick and Hargrove 2009). Process-based models, on the other hand, are able to capture the dynamics underpinning species distributions across spatial and temporal scales—including physiology, biotic interactions and other factors—under environmental change, and hence can provide more credible projections than species distribution modelling (Evans et al. 2016). Nevertheless, these models generally require many parameters for estimations, thus involve large data requirements which often cannot be met due to limitations at high resolutions (Dormann et al. 2012). Application of process-based models, particularly for planning adaptation of coffee production systems to climate change deserves additional examination.

Current studies on climate change impacts on the suitability of coffee-growing areas use a range of climate models with diverse levels of spatial resolution, ranging from 30 arc-seconds (1 km^2) to 30 arc-minutes (50 km^2), which may explain the wide range of reported estimates. Coarse spatial resolutions may fail to capture local characteristics such as the heterogeneous topography of coffee-growing areas. Uncertainties and errors may increase due to the process of downscaling and interpolating climate projection data (Fain et al. 2018) where agricultural landscapes exhibit topographic heterogeneity (Daly et al. 2003). Low temporal and spatial resolution of climate models also pose challenges in linking climate scenarios to biological responses, including pest or disease development, which entail daily or even hourly data (Ghini et al. 2008, 2011). The use of models with high spatial and temporal resolution would benefit climate impact simulations, facilitating the capture of non-homogenous topographies and thus better representing microclimatic characteristics (Tavares et al. 2018) and reducing uncertainties through the use of more refined climate data (Ghini et al. 2011).

Assessment of uncertainties related to climate variables and scenarios, interpolation processes used for climate projection data, model parameters, socio-economic factors and interactions between the coffee plant and the environment is still limited in current research. Only a few studies (Estrada et al. 2012; Rahn et al. 2018; Verhage et al. 2017) partly or explicitly analysed uncertainty. One suggested solution for minimising uncertainties due to biased representation of suitable climate is to incorporate outputs from a multimodel ensemble to provide improved predictions (Bunn et al. 2015b; Ranjitkar et al. 2016). It should be noted that ensemble modelling, however, might produce incorrect outcomes resulting from errors and biases in the individual species distribution models (Beaumont et al. 2016).

3.4 Impacts of climate variability and change on coffee production

Of all studies investigating the impacts of climate variability and change or drought on coffee production examined in this review, 20 indicated negative impacts and 14 reported mixed results (Table 1). Four papers using qualitative approaches described observed negative consequences on coffee production and on the distribution of pests and diseases, and only one paper presented mixed effects, with perceived declines in Arabica but increases in Robusta yield in India (Chengappa et al. 2017). Quantitative studies, on the other hand, demonstrated more varied results, specifically in projected outcomes under climate change scenarios. However, none of the current studies reviewed suggested wholly positive outcomes.

Of studies on the direct impacts on coffee yield or production, nine papers indicated negative outcomes and five revealed both positive and negative results. Harvest losses due to drought and climate variability were reported mostly in the Americas and could be as much as 70% (Bacon et al. 2017). Fewer studies analysed reductions in coffee production as a result of climate change; such impacts were identified in Tanzania (Craparo et al. 2015), Mexico (Estrada et al. 2012; Gay et al. 2006) and Brazil (Verhage et al. 2017). Studies showing mixed results included positive outcomes of El Niño intra-decadal climate phases on coffee production and exports in Colombia (Bastianin et al. 2018), increases in Robusta yield in India due to climate variability (Jayakumar et al. 2017) and in Arabica yield in Brazil and Nicaragua owing to carbon fertilisation effect (Rahn et al. 2018; Verhage et al. 2017).

In terms of suitability for growing coffee, all relevant studies revealed decreases or losses in areas suitable for coffee. Bunn et al. (2015b) indicated an overall global loss of up to 50% of optimal areas for both types of coffee by 2050, which is in line with other global studies (Bunn et al. 2015a; Ovalle-Rivera et al. 2015) with large parts of major coffee producers such as Brazil, Vietnam, Honduras and India becoming unsuitable. In studies at regional and national levels, the greatest reductions in suitability were projected for Ethiopia, Sudan and Kenya (up to 90% by 2080; Davis et al. 2012), Puerto Rico (84% by 2070; Fain et al. 2018), Mexico (98% by the 2050s; Schroth et al. 2009); and Latin America (88% by 2050; Imbach et al. 2017).

Key drivers of projected shifts in bioclimatic suitability for coffee cultivation are temperature and precipation variables. Global studies indicated that precipitation factors such as annual and seasonal precipitation were of less importance compared with temperatures in determining suitability (Bunn et al. 2015b; Ovalle-Rivera et al. 2015). In contrast, national (Chemura et al. 2016) and sub-national (Rahn et al. 2014) studies revealed that the amount and distribution of precipitation significantly influence coffee suitability. Despite recent improvements in the simulation of changes in precipation patterns, there is currently greater confidence in the ability of climate models to predict surface temperature changes (IPCC 2014). Increasing certainty in predicting future precipitation patterns at all scales will likely improve projections on coffee-favourable areas.

While a majority of existing literature specified substantial reductions in the suitability of coffee-growing areas globally, regionally and nationally, a few papers indicated that, under a changing climate, areas which are currently less optimal for coffee cultivation may become more productive. For example, several studies projected increases in coffee-suitable areas in South America, East and Central Africa and Asia (Bunn et al. 2015b; Magrach and Ghazoul 2015; Ovalle-Rivera et al. 2015; Schroth et al. 2015). Generally, suitability is predicted to shift to higher altitudes by many studies. Globally, Bunn et al. (2015b) indicated that areas at higher latitudes may be less affected while Ovalle-Rivera et al. (2015) suggested that they might decline in suitability, particularly in South America. Some regions projected to be favourable for coffee cultivation are open land such as those in East Africa (Bunn et al. 2015b; Ovalle-Rivera et al. 2015) but others, particularly in the Amazon basin, Asia and Central Africa, are currently under forest cover (Bunn et al. 2015b), protected areas (Schroth et al. 2015) or other agricultural land uses (Magrach and Ghazoul 2015). The continued expansion of coffee production to meet growing global demand (ICO 2019a) might generate economic opportunities in some regions but induce adverse socio-economic and environmental impacts associated with deforestation for coffee cultivation (Gaveau et al. 2009; Meyfroidt et al. 2013) elsewhere. Furthermore, open land at high elevations might be remote (Schroth et al. 2015) or too steep for growing coffee (Bunn et al. 2015a) and operating farming machinery (Tavares et al. 2018) or have soil that is too shallow (Bunn et al. 2015a; Chemura et al. 2016) or poor (Schroth et al. 2015). Shifting coffee-growing areas upslope might also incur conflicts with protected areas with significant ecosystem service values or other land uses with crops in higher demand than coffee (Magrach and Ghazoul 2015). Therefore, the feasibility of offsetting losses from areas with declining suitability by expansion or shifts to ‘new’ coffee-optimal areas needs additional investigation. Explicit research on future distribution of climatically favourable regions for coffee production which identifies and assesses potential conflicts and trade-offs with existing land uses, particularly at local scales, is required.

Negative results of indirect climate-related impacts on coffee production were reported in all studies on pests and diseases (ten papers), pollination services (one paper) and coffee quality (one paper). These included expected increases in the distribution of pests such as the coffee berry borer (Magrach and Ghazoul 2015) and coffee white stem borer (Kutywayo et al. 2013) and in their reproductive rate (Jaramillo et al. 2011). Diseases such as coffee rust already damaged large parts of production areas in Colombia, Central America and Nicaragua (Avelino et al. 2015; Bacon et al. 2017). There were projected decreases in the incubation period of coffee rust which may result in more severe epidemics (Ghini et al. 2011) and in future pollinator richness in Latin America (Imbach et al. 2017) which may affect coffee production. One study, in Nicaragua, also suggested that the quality of coffee beans may be negatively impacted (Laderach et al. 2017).

In summary, most of the current literature indicates negative consequences of climate change and variability or drought on coffee production. However, positive impacts including increases in coffee yield or in suitability of coffee-cultivating areas, particularly at higher elevations, are also reported on all three coffee-producing continents. Climate change might also bring other advantages, such as growth in pollination activities owing to increasing bee richness (Imbach et al. 2017), resulting in positive effects on coffee yield (Roubik 2002). Some coffee cultivation areas may also benefit from elevated carbon concentration, which may enhance the photosynthetic rate (Trumble and Butler 2009) and heat tolerance of the plant, leading to crop growth and yield improvements (DaMatta et al. 2016; Rodrigues et al. 2016). Further work is needed to investigate the potential of pollination services and carbon fertilisation effect to counteract negative impacts of climate change on coffee production.

3.5 Adaptation measures

Adaptation and management practices were identified by more than 70% of total studies (25 papers), of which agroforestry, either through intercropping or shading, was most common (18 papers), followed by irrigation and efficient use and management of water (12 papers), development of new cultivars that are drought and heat-stress resistant and/or pest and disease tolerant (ten papers) and diversification of cropping patterns or livelihood activities (nine papers) (Fig. 3). Other measures included relocation of coffee plantations to more bioclimatically suitable areas (six papers), crop insurance (three papers), off-farm livelihoods (two papers),and shifts from Arabica to Robusta or cocoa (two papers).

Existing studies indicated that climate variability and change have directly or indirectly affected global coffee production to varying extents, with the majority of these indicating negative impacts. However, most did not quantitatively take account of the influence of adaptation measures which, if adopted, could potentially reduce these impacts. Quantitative analysis of adaptation was limited to just one study which demonstrated the beneficial effects of shade trees on coffee yield at lower elevations (Rahn et al. 2018).

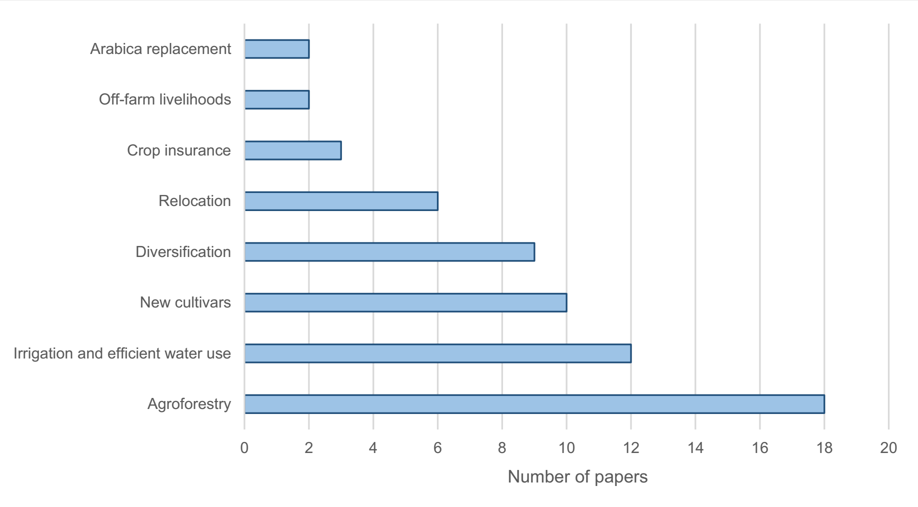

Fig. 3 Adaptation measures considered in the 34 reviewed studies

Relocation of coffee plantations to areas more climatically suitable for cultivation, particularly cool regions at higher altitudes (Laderach et al. 2017), was recommended in a number of studies examining coffee suitability. However, migration to higher elevations might lead to increased pressure on local ecosystems and might be challenged by topography and soil characteristics (Chemura et al. 2016), land tenure rights (Schroth et al. 2009), access to infrastructure (Moat et al. 2017) and ability and willingness of farming communities (Chemura et al. 2016; Magrach and Ghazoul 2015). While high elevations might be more climatically suitable for coffee, additional investigation is needed, with particular attention placed on potential opportunities and challenges, to ensure viable and sustainable coffee development in these areas.

Given the challenges associated with shifting coffee production to more climatically favourable areas, various in situ strategies should be further examined, including irrigation and shading existing coffee plantations to mitigate the adverse impacts of rising temperatures and drought stress and diversification to encourage alternative crops or income sources to assist coffee producers to cope with the impacts of declining coffee yields.

As a result of increasing temperatures and changes in precipitation, irrigation is considered one of the most important adaptive responses in many coffee-growing regions. Optimal use of water may include improved water storage and delivery (Baca et al. 2014; Chemura et al. 2016) through creating tanks and tube-wells and deepening existing bore-wells (Chengappa et al. 2017; Jayakumar et al. 2017) to enable irrigating coffee, particularly during droughts and dry periods. Surface water extraction from rivers and streams might be a cost-effective (Moat et al. 2017) temporary solution but is likely to be constrained during prolonged dry spells or droughts.

Drip, supplemental full or deficit irrigation has been demonstrated to improve coffee quality in Ethiopia (Tesfaye et al. 2013) and productivity in Brazil (Fernandes et al. 2016), especially in periods of water scarcity. However, investment in irrigation infrastructure including storage and transportation systems or in technologies like drip irrigation or water harvesting (Baca et al. 2014; Chengappa et al. 2017) is likely to be resource and labour intensive and costly and thus will be disadvantageous for small growers with limited capital and access to finance (Bryan et al. 2013). Such technological adaptation measures will likely require substantial government or industry support.

Agroforestry systems were mentioned as a potential adaptation strategy for coffee production systems which may benefit from shading or inter-cropping with other crops. Inter-cropping coffee with banana and *macauba*, for example, has proven more profitable than mono-cropping in Africa and South America; such systems reportedly reduce air temperatures and photosynthetic active radiation and increase coffee yield and productivity (Moreira et al. 2018; van Asten et al. 2011).

Shade trees may create a microclimate that provides various socio-economic and ecological benefits, including improved coffee quality (Nesper et al. 2017; Vaast et al. 2006), increased diversity of income sources (Chengappa et al. 2017; Jezeer et al. 2018) and provision of ecosystem services (Cerda et al. 2017; Meylan et al. 2017). Specifically, shading could reduce the mean and maximum air temperatures experienced by the coffee plants compared with full-sun coffee systems (Ehrenbergerová et al. 2017; Moreira et al. 2018), lower wind speeds (Pezzopane et al. 2011) and the risk of landslides (Philpott et al. 2008), enhance pest suppression (Jaramillo et al. 2013) and pollination activities (Jha et al. 2014) and improve soil conservation and water quality (Meylan et al. 2017).

Coffee grown under shade cover, however, might be less productive due to competition with shade trees for water (Ehrenbergerová et al. 2017; Rahn et al. 2018), light (Charbonnier et al. 2013) and nutrients (van Oijen et al. 2010). Additional research into the microclimate dynamics of shade systems, the selection of appropriate tree species, densities and technologies and the interactions between coffee physiology and shade trees under various climatic conditions will be necessary. Shade systems may also vary in their effects (positive or negative) on pests and diseases subject to specific environmental conditions (Jonsson et al. 2015; Liebig et al. 2016). Greater insight into potential synergies and trade-offs in shaded coffee plantations is needed to ensure appropriate responses to climate change in coffee production systems.

Other adaptation measures mentioned in current research involve opportunities to diversify coffee farmers' sources of income—such as off-farm labour, alternative cropping systems including fruit tree production (Bacon et al. 2017) and multicrop cultivation including pepper on shade trees (Chengappa et al. 2017)—and introduction of coffee varieties with better tolerance to high temperatures and pest and disease pressures (Ovalle-Rivera et al. 2015; Schroth et al. 2009). While smallholder farmers, using existing resources, might have the capacity to develop shading systems in coffee plantations and produce a variety of other crops, technological solutions such as development of new cultivars will require significant government or industry investment of capital, labour and expertise. A shift from Arabica to Robusta is recommended for zones at low altitudes in Nicaragua where significant reductions in climatic suitability for Arabica is projected (Laderach et al. 2017) and has been implemented in India to confront coffee white stem borer caused by climate variability (Chengappa et al. 2017). Improved profitability of Robusta in comparison with Arabica owing to its lower cultivation costs and higher yield was reported by Indian producers (Chengappa et al. 2014). Nevertheless, Arabica is considered superior in beverage quality to Robusta and realises higher prices; thus, whether and where it can be replaced by the latter require further examination. Crop insurance against the increased risks of extreme events has been implemented to assist coffee producers in Mexico but with limited success due to inadequate government funding and coordination (Schroth et al. 2009).

In summary, a variety of adaptation measures to manage climate-driven impacts on coffee production are identified in the literature. However, several qualitative studies have indicated that, while most farmers were aware of the impacts of climate on their farming and livelihoods, they were not active in adopting these measures into their management practices (Chengappa et al. 2017; Harvey et al. 2018). Adaptation should be tailored to specific farming conditions and socio-economic contexts and consider the capacity of coffee farmers, who are mostly smallholders, to access finance, credit, resources and technologies. Temporal challenges required for some adaptation measures, such as replanting with new cultivars for heat-stress tolerance and agroforestry systems which might take several years or even decades to become effective (Eske and Leroy 2008; Laderach et al. 2017), should also be taken into account. Raising awareness, building capacity, enhancing knowledge and experience exchange and providing technical and financial support should be emphasised to facilitate adaptation implementation and strengthen farmer resilience to climate variability and change. An integrated approach that incorporates flexible strategies might be required to address interactions between agricultural and ecological aspects of change (Hannah et al. 2017). Finally, a combination of appropriate policy measures, technical solutions and research outcomes and recommendations is crucial to facilitate adaptation processes amongst coffee smallholders.

4 Key conclusions and knowledge gaps

This paper offers a systematic quantitative analysis of the academic literature on the impacts of climate change and variability and drought on coffee production. An array of mostly negative outcomes was found in current studies. These included declines in coffee yield and in areas of suitability for coffee cultivation and increases in the distribution of pests and diseases that indirectly influence coffee production. Globally, indications are that there will likely be a loss of coffee-optimal areas with considerable impacts in major coffee-growing countries such as Brazil and Vietnam. Suitability is generally projected to shift to higher altitudes. Some areas of lower suitability might become more productive in the future but many of them are currently under other crops or forest cover. Investigation is required to evaluate whether gains in coffee-growing niche in ‘new’ areas might compensate for losses with declining suitability in other areas, with particular attention given to trade-offs with existing land uses. Further research on future distribution of coffee-favourable space with consideration to potential ecological and socio-economic impacts and associated opportunities and challenges is necessary to better support sustainable coffee development.

Our selection criteria may have excluded relevant publications from other sources including peer-reviewed literature published in non-English language journals and ‘grey’ literature such as reports and conference proceedings. Despite this, the review reveals some significant knowledge gaps on the topic. These include the disproportionate concentration of current studies in the Americas with less attention given to Asia where a number of countries are amongst the world’s major coffee producers. The predominance of current research in the Americas has drawn more focus of the research on Arabica with limited consideration of Robusta, particularly at national and sub-national scales, and of the influence of climate change on coffee suitability rather than coffee yield or pest and disease distribution. As the risks of pest and disease outbreaks are likely to increase, there is a need for research on these pressures under changing climatic conditions. Further, little research has specifically analysed the impacts of drought on coffee production in contrast to the more extensive literature on the effects of climate variability and change. Apart from relocating coffee plantations to more favourable areas, potential in situ adaptation measures suggested in the literature included agroforestry, irrigation and water management, development of new varieties and diversification of alternative crops or livelihoods. However, quantitative analysis on the effects of adaptation in mitigating climate change impacts was notably absent due to limitations in the modelling approaches applied in the research.

A range of models was employed to investigate the influence of climate change with the majority focused on the distribution of bioclimatic suitability for coffee cultivation, using bioclimatic modelling approaches including machine-learning and regression-based techniques. Due to the limited ability of correlative species distribution models to incorporate underlying factors and dynamic processes and their interactions operating across spatial and biological scales, we suggest further exploration of process-based models for coffee production systems such as those developed and widely applied for wheat, rice and maize. This will generate improved analysis of climate-driven impacts and of the effects of adaptation and management strategies to support decision-making for sustainable coffee production.

Further, increased knowledge is required regarding positive influences on coffee production, including the potential of elevated carbon concentration to offset negative impacts of warmer conditions and of pollination activities.

Finally, there is a need for inclusion of socio-economic factors and detailed analysis of the rationale of suggested response measures along with their quantified benefits in adapting coffee to climate change. While the economic benefits of these measures under changing climatic conditions are uncertain, a thorough evaluation for specific farming contexts will likely be beneficial to coffee farmers. Given the long lifespan of coffee plantations, a focus of research on these issues could mitigate some of the long-term consequences of climate change on the coffee industry and on the livelihoods of many smallholder farmers throughout the tropics.

In total, 34 relevant peer-reviewed journal articles were found and analysed in this review, which is a relatively small number compared with studies on climate change impacts on other crops such as wheat, maize and rice (Challinor et al. 2014; Knox et al. 2016; White et al. 2011). Given the significant contribution of the coffee sector to global socio-economic development, particularly to the livelihoods of millions of smallholders, more research on the climate-driven impacts is required for coffee production systems. This should focus on the direct and indirect effects on yield, particularly in production areas across Asia, on Robusta coffee and on the efficacy of adaption in maintaining the sustainability and viability of the coffee industry.

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[Climatic Change] Supplementary material

The impact of climate change and variability on coffee production: A systematic review

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Table S1. Number of original research papers on climate-driven impacts on coffee production

Fig. S1. Number of papers per year and the cumulative number of papers from 2006 to 2018

Table S1. Number of original research papers on climate-driven impacts on coffee production

Category	Number of papers
Journal	
Climatic Change	8
PLoS ONE	8
Regional Environmental Change	3
Mitigation and Adaptation Strategies for Global Change	2
Others	13
Coffee species	
Arabica	27 (79%)
Robusta	0 (0%)
Mixed	5 (15%)
Not specified	2 (6%)

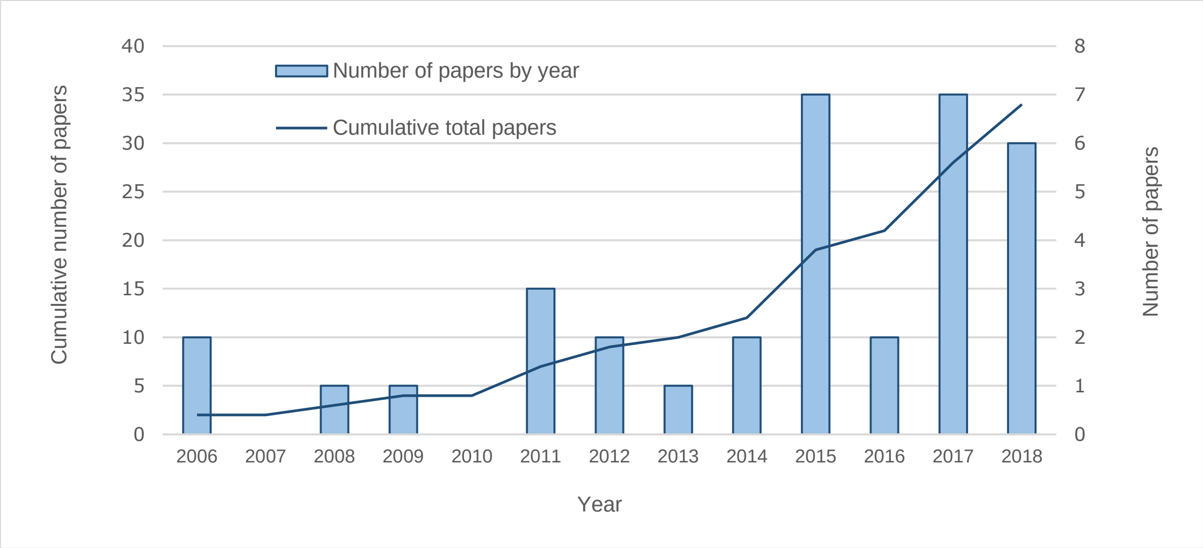

Fig. S1. Number of papers per year and the cumulative number of papers from 2006 to 2018

Chapter 5. Feedback modelling of the impacts of drought: A case study in the coffee production system in Viet Nam

Chapter overview

Chapter 5 describes the application of system dynamics modelling, particularly the causal loop diagram, to examine the dynamics interrelationships and feedback structures among factors associated with drought that influence coffee production in Dak Lak Province, Viet Nam – the world's largest Robusta coffee-producing country. The chapter introduces the necessary steps of the system dynamics approach for causal loop modelling and the approaches for data collection and analysis used in model development. The chapter then describes the model in detail; analyses system archetypes, which are underlying structures that explain the unintended consequences of management decisions; and identifies leverage points where appropriate interventions can be made to address those consequences for sustainable coffee production. The results of this chapter address Objective 2 of the research and provide a basis for the system dynamics simulation model described in Chapter 6.

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Feedback modelling of the impacts of drought: A case study in coffee production systems in Viet Nam

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ABSTRACT

Drought is a major cause of crop failure and livelihood insecurity, affecting millions of people across the world. A changing climate, increasing population and economic growth are exacerbating water shortages, further interrupting agricultural production. Assessing and minimizing the impacts of drought require a thorough understanding of the interrelationships and interactions between the climate system, ecosystems and human systems. In this paper, we apply causal loop modelling grounded in systems thinking theory to examine the interdependencies and feedback processes among factors associated with drought that impact crop production using a case study of Robusta coffee production systems in Viet Nam – the world's second-largest coffee producing country. Our model, underpinned by qualitative data from consultation with a range of stakeholders, indicates that water depletion affecting coffee cultivation is not solely attributed to rainfall insufficiency but an outcome of complex interactions between climate and socio-economic systems. Our analysis highlights that uncontrollable coffee expansion, largely at the expense of forested areas, is partly the unintended consequence of policy decisions, including those encouraging migration and perennial crop development. Growing water demand in the region, including the demand for irrigation water driven by the ever-increasing area under coffee cultivation, as well as inefficient irrigation practices are placing significant pressure on water resources. A changing climate may exacerbate the problem, further impacting coffee cultivation, unless adaptation practices occur. A number of potential interventions are suggested, including explicit zoning of coffee-growing areas; awareness raising for wide adoption of optimal irrigation practices; converting Robusta coffee monocultures to diversified systems; and strictly protecting existing forests coupled with afforestation and reforestation. These interventions should be simultaneously implemented in order to adequately address drought and water scarcity for coffee production and build resilience to climate and market risks.

1. Introduction

Drought is one of the major causes of crop failure and livelihood insecurity, affecting millions of people across the world each year. Declining crop yields and livestock productivity coupled with rising production costs as a result of drought cause revenue shortfalls for

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farm households, while these problems are likely to increase under a changing climate, increasing population and economic growth (Gies et al., 2014; IPCC, 2014; Mishra and Singh, 2010).

Many regions of the world have endured some of the worst droughts on the record. The 1988 drought in the USA cost an estimated US$80 billion (2013 dollar value) and was the second most costly weather disaster in the country after the 2005 Hurricane Katrina, with 40% of costs resulting from agricultural losses (Elliott et al., 2018). The 2002–2003 dry period during the major 'Millennium Drought' of 1997–2009 in Australia caused a fall of 40% in total grain and beef industry incomes, contributing to a 1% drop in GDP (Howden et al., 2014). In many areas of the country, water storages had still not returned to pre-drought levels several years after drought, severely disrupting irrigated cropping areas and significantly reducing farm incomes (ABARES, 2012). In the Europe, the costs associated with droughts over a recent 30 year period was approximately €100 billion (EC, 2007). In Russia, severe drought in 2010 caused a ban on grain exports, which contributed considerably to a hike in the global food price (Dronin and Kirilenko, 2011; Wegren, 2011).

Extended and severe droughts have also occurred in developing countries in Asia and Africa, severely affecting agriculture productivity and the livelihoods of millions people. Since the 1950s until the start of the 21st century, the yearly average crop areas affected by drought in China more than doubled, from about 11.5 million hectares to 25 million hectares (Chen et al., 2014). Approximately 40% of maize areas in Africa are impacted by occasional droughts, leading to yield losses of 10–25% (Fisher et al., 2015) while in India, a drought year can result in a 25–60% reduction in household income (Birthal et al., 2015).

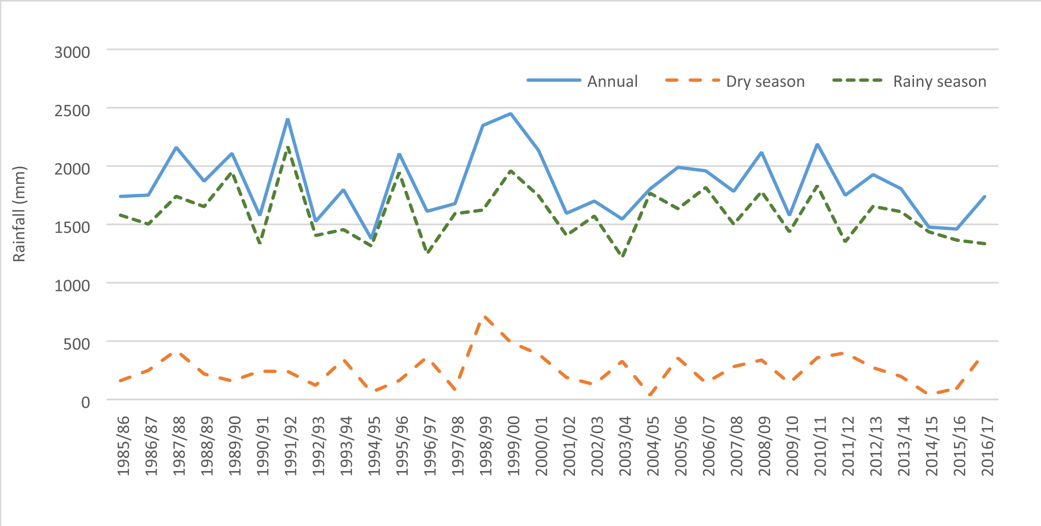
The prospect of global climate change and more frequent and severe drought events raises concern and the need for mitigation and adaptation strategies, especially when there is increasingly strong evidence in extant studies of the adverse impacts of climate change on crop yields and production and on global food supply, food prices and other agricultural systems (Cai et al., 2016; Calzadilla et al., 2014; Hertel et al., 2010; IPCC, 2014).

To effectively assess climate-related impacts, specifically drought, on one particular system—for example, a crop production system—it is necessary to take into account the influence of the interconnected systems, such as population dynamics and land and water availability, which, in turn, are often driven by climate and crop production systems. Given the complex nature and interactions between the climate system, ecosystems and human systems, a holistic approach aimed at addressing these interconnections and their complexity is required to support comprehensive decision-making on drought management.

System dynamics (Forrester, 1961), a sub-field of systems thinking (Richmond, 1994), is a modelling approach used to examine dynamic systems with complex interactions between system components. Unlike linear approaches that simply focus on cause-and-effect relations, this approach, based on the concept of closed-loop thinking (i.e. thinking in terms of interdependencies) (Richmond, 1994), can unravel feedback structures between interrelated elements producing system behaviours. Further, it allows testing of the effects of intervention strategies before these are applied in reality (Maani and Cavana, 2007).

Application of system dynamics in addressing water management related issues has been growing and proven to be useful (Sušnik et al., 2012; Turner et al., 2016). For drought management, a number of studies have used system dynamics to examine drought impacts on natural and human systems and explore potential management strategies. Examples include an integrated water resources model based on system dynamics for water resource planning and drought management (Wang and Davies, 2015) and a combined hydrologic and system dynamics model for simulating interactions between drought-affected systems (Gies et al., 2014). These studies incorporated the interconnections of human-ecological systems into simulation models through interrelated components—such as population, food production, water availability and socio-economic welfare—to quantify multiple drought impacts and the effects of various management decisions. Another example is a conceptual model based on the *limits to growth* and *tragedy of the commons* system archetypes, which examined multiple direct and secondary impacts of drought on agricultural production areas (Shahbazbegian and Bagheri, 2010). One of the significant findings of this study was that a region with abundant water might be more vulnerable to drought and less adapted to water scarcity conditions than a dry region due to its greater reliance on water availability. Modelling to support robust policy design requires the incorporation of the mental models of all system stakeholders (Turner et al., 2016) with diverse knowledge, perspectives, assumptions and values. The mental data of different individuals is a valuable information source for the modelling process as numerical or written data may not adequately reflect their observations and experiences (Forrester, 1992). System dynamics emphasises the role of stakeholder participation in identifying the feedback processes generating the behaviours of the problem under investigation (Turner et al., 2016), thus enhances a shared understanding of the problem's dynamics and facilitates proactive and transparent decision-making in complex systems.

In this study, based on systems thinking theory, we investigate the interrelationships and feedbacks among factors associated with drought that impact on crop production using a case study in coffee production systems in Viet Nam, the world's second-largest coffee producer contributing 17% of global total output (ICO, 2019b). Over half a million smallholder farmers in the country, many of them owning approximately one ha of farmland on average, are dependent on coffee cultivation for their livelihoods (ICO, 2019a). Sustainable coffee development is crucial, both nationally and globally, given coffee is one of the most traded commodities of the world (Davis et al., 2012); however, the sustainability of this industry is threatened by increasingly severe water shortages for irrigation in the dry season. Given the limited research on climate-related impacts, specifically drought, on coffee production systems (Pham et al., 2019), this study applies a systems-level view to gain a better understanding of the complex feedback structures and behaviours influencing the impacts of drought on these systems. Using data sourced from current literature and interviews of a wide range of relevant stakeholders, a dynamic hypothesis was built to improve a holistic understanding of the dynamics driving drought impacts on coffee production. The approach adopted and the results of this study contribute to providing a robust foundation for comprehensive decision-making on sustainable agricultural production and drought risk management in coffee production systems, which can apply to other cropping systems.



	Monthly rainfall (mm)												Annual rainfall (mm)
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Average (1985-2017)	6.0	4.4	29.8	93.6	244.3	241.8	258.1	307.2	331.0	201.0	98.9	25.7	1841.8
2016	23.2	0.7	0.0	12.3	247.6	310.1	111.2	203.2	376.2	116.9	150.3	113.7	1665.4

Fig. 1. Rainfall at Buon Ma Thuot station, Dak Lak Province (Source: NCHMF, 2019).

2. Case study area

Viet Nam is the world's largest Robusta coffee producer and exporter, equating to more than 40% of global Robusta volume (ICO, 2019b). Coffee production contributes more than 10% of Viet Nam's national agricultural export turnover (ICO, 2019a) with Robusta coffee (*Coffea canephora*) accounting for approximately 96% of the total coffee production (ICO, 2019a). Coffee is mainly grown in the Central Highlands, within which Dak Lak province is the largest coffee-growing region with more than 200,000 ha or over 30% of the total coffee cultivation area of the country (GSO, 2018).

The Central Highlands is a mountainous area with a temperate tropical climate strongly influenced by monsoons and especially favourable for the cultivation of perennial crops. The region has distinct dry and rainy seasons with the total annual rainfall generally sufficient for Robusta production (Fig. 1). However, the dry season, which generally occurs from November until April, receives limited rain coupled with high evaporation; thus, irrigation is necessary to break flower bud dormancy and initiate fruit set to attain high yields (Amarasinghe et al., 2015).

The region is highly exposed to natural disasters, of which drought is considered the most severe with affected areas increasing year by year. In 2016, drought stressed more than 56,000 ha (27.5%) and fully damaged over 2% of the total coffee area of Dak Lak province (DCP, 2016). A rise in temperature coupled with high variability in rainfall is projected for the Central Highlands in the latest climate change scenarios (MONRE, 2016). Coffee irrigation is thus threatened by declining water availability during the prolonged dry season. Numerous activities have been implemented in the region to cope with drought; however, such responses have not yet proven effective and remain largely reactive with interventions mostly focusing on post-impact management, usually in the form of disaster relief (IMHEN and UNDP, 2015). Reliance on the government and aid from donor countries and organisations is not a sustainable response to drought as it does not result in a resilient population capable of sustaining itself during and after future drought events (Gies et al., 2014). Addressing this challenge is crucial to ensuring the province's position as a key coffee-growing hub of the country and sustaining the livelihoods of many smallholder farmers reliant on coffee production.

3. Methods

3.1. System dynamics modelling

In this study, system dynamics, based on "the theory of non-linear dynamics and feedback control" (Forrester, 1961; Sterman, 2000), with a focus on the mental models of stakeholders (Turner et al., 2016), was applied to understand the underlying structures and dynamics driving drought impacts on coffee production in Dak Lak province.

Overall, the application of system dynamics is an iterative process involving five phases: (1) problem structuring; (2) formulation of a dynamic hypothesis; (3) development of a simulation model; (4) model testing; and (5) design and analysis of potential policies/management strategies (Maani and Cavana, 2007; Sterman, 2000). There is an array of steps in each phase but the number of phases

Table 1
Study stakeholder groups interviewed.

Stakeholder category	Stakeholder group	Total interviewed (60)
Research	Academia	4
	Research bodies	10
Government	National authorities	5
	Local authorities	6
Local community	Commune officers	5
	Coffee farmers	17
Private sector	Non-governmental organizations	6
	Industry	7

and steps to be followed is decided by the modeller, depending on the problems faced. As this study aims to improve an understanding of the dynamics influencing drought impacts on coffee production, the first two phases were applied. Based on the results of this work, the remaining three phases will then be implemented to explore and test potential interventions.

3.1.1. Problem structuring

As a primary step in most problem-solving methods, the main purpose of problem structuring is to define the real problem and its underlying causes, clarify the purpose of model development, set up the scope and boundaries of the study and identify potential stakeholder groups (Sterman, 2000). This may involve a literature review and consultation with a wide range of stakeholders (Maani and Cavana, 2007), as was applied in this study.

3.1.2. Formulation of a dynamic hypothesis

Once the problem has been clearly defined, the next step is to develop a hypothesis or a theory that explains the dynamics characterising the problem, particularly the underlying feedback structure within the system (Sterman, 2000). In this study, causal loop modelling was applied to aid hypothesis development. This dynamic hypothesis will be tested with a simulation model, contributing to policy design and evaluation at the later stage of the research.

Causal loop diagrams (CLDs) reveal causal connections and feedback mechanisms within a system by capturing dynamic hypotheses about the causes of the problem and the mental models of individuals or teams (Sterman, 2000). CLDs comprise variables linked by arrows showing causal relationships between variables. If an increase (or decrease) in variable A leads to a corresponding increase (or decrease) in variable B, a '+' can be labelled on the head of the arrow, indicating a positive causality. Another possibility is that the two variables move in reverse directions. In this case, the arrow will be denoted by '-' (Maani and Cavana, 2007).

CLDs use reinforcing (R) or positive and balancing (B) or negative feedback loops to represent feedback processes influencing the behaviour over time of the system. Reinforcing loops characterize growing or declining actions while balancing loops counteract or self-regulate to seek equilibrium or a specified target (Maani and Cavana, 2007). A CLD may involve 'delays' (//) – the time lag between a cause and its effects, often responsible for trade-offs between short- and long-term policy outcomes and might result in unintended consequences (Sterman, 2000).

3.1.3. System archetypes and leverages

In systems dynamics, system archetypes are used to understand common patterns of system behaviour, which reflect the underlying structures of the system under investigation (Braun, 2002; Wolstenholme, 2003). From those structures, leverages can be identified, which often involve long-term actions or interventions aimed at addressing the real causes of problems, taking into account both context and external factors (Maani and Cavana, 2007).

3.2. Data collection

Data used in this study include primary data collected from interviews and secondary data from the literature. The primary data collection involved:

- Stakeholder identification: A number of techniques, including literature review, web-based search and chain referral sampling were applied to identify and select interview participants. In this study, participants included decision-makers and managers from national and local authorities; researchers and officers from universities, research institutes and non-governmental organizations; local coffee farmers; and other coffee supply chain representatives who are involved in drought management and/or coffee production (Table 1).
- Interviews: A semi-structured interview method, demonstrated to be effective in model formulation (Sterman, 2000), was applied in this study. This approach enables participants to leave the pre-defined questions to follow areas of interest in more detail at any time. Interview questions were designed to assist with identifying the problem and causal relationships between variables in the system under investigation. The pre-set questions were adjusted to suit each group of stakeholders, including, but not limited to:
  - What are the causes and drivers of drought, and the factors that exacerbate drought?
  - What are the main water sources used for irrigating coffee? What are the factors that affect water availability for irrigation in the region?

Table 2
Coding chart example (adapted from Kim and Andersen, 2012).

Main argument: There is a decline in water availability due to rapidly growing coffee areas and increasing water exploitation for irrigation			
Causal structure	*Cause variable*	Coffee area	Irrigation
	Effect variable	Irrigation	Water availability
	Relationship type	Positive	Negative
Variable behaviour	*Cause variable*	Rapidly growing	Over irrigation
	Effect variable	Increasing	Declining

Table 3
An example of words-and-arrow diagrams of causal arguments (adapted from Kim and Andersen, 2012).

Cause	Effect	Relationship type (+/−)	Words-and-arrow diagrams
Coffee area	Irrigation	+	Coffee →+ Irrigation
Irrigation	Water availability	−	Irrigation →- Water availability

Table 4
Main issues identified from stakeholder interviews.

Agricultural production	Socio-economic development	Bioclimatic factors
Annual and perennial crop expansion	Population growth	Climate change and variability
Increasing irrigation demand	Migration	Rainfall variability
Excessive water extraction	Deforestation	Temperature rise
Groundwater depletion	Production activities	Drought
Fluctuations in crop prices	Residential development	Water shortages
	Rising water demands	

- How has drought directly and indirectly impacted coffee yield and farmers' livelihoods?
- What measures or practices that the local authorities and farmers have adopted in response to drought?
- What are the potential policies or strategies and other techniques and practices that could assist coffee farmers to cope with drought impacts?
- What are the pros and cons of strategies and management practices to mitigate drought impacts on coffee production?

3.3. Data analysis

Interview results were coded using the coding process of Kim and Andersen (2012). This method aims to systematically code qualitative data to produce causal maps for system dynamics modelling. Conceptualisation of relationships in the system was informed by the diverse mental models originating from different individuals (Kim and Andersen, 2012).

The first step of coding involved identifying data themes so that the main problems and system boundary could be determined. Some codes emerged directly from the interview data while others were generally used terms stemming from the literature. Codes were iteratively classified, clustered and reviewed until the main patterns of themes could be detected (Kim and Andersen, 2012).

The second step identified variables and their causal connections through detailed analysis of participant responses. For example, a participant might state that there has been a decline in water availability and then provide additional information relating to this argument, including rapidly growing coffee areas coupled with over irrigation which have contributed to decreasing water resources. Variable behaviours and causal relationships could then be identified; in this case, a positive link between coffee areas and irrigation and a negative link from irrigation to water availability were made, meaning an increase in coffee areas would lead to a subsequent increase in irrigation and decrease in water availability (Table 2). During this phase, a great number of coding charts were produced to capture every argument about the system structures and supporting justifications (Kim and Andersen, 2012).

The third step in the process transformed the variables and causal arguments documented in the coding charts into diagrams of words and arrows (Table 3). These were then reviewed and verified by examining secondary data from governmental and non-governmental organizations, where available, before translation into a CLD which was reviewed and validated by academic and industry stakeholders throughout its formulation.

4. Results and discussion

4.1. Problem structuring

In total, 60 stakeholders were interviewed to identify key issues relating to drought that impact on coffee production systems in Dak

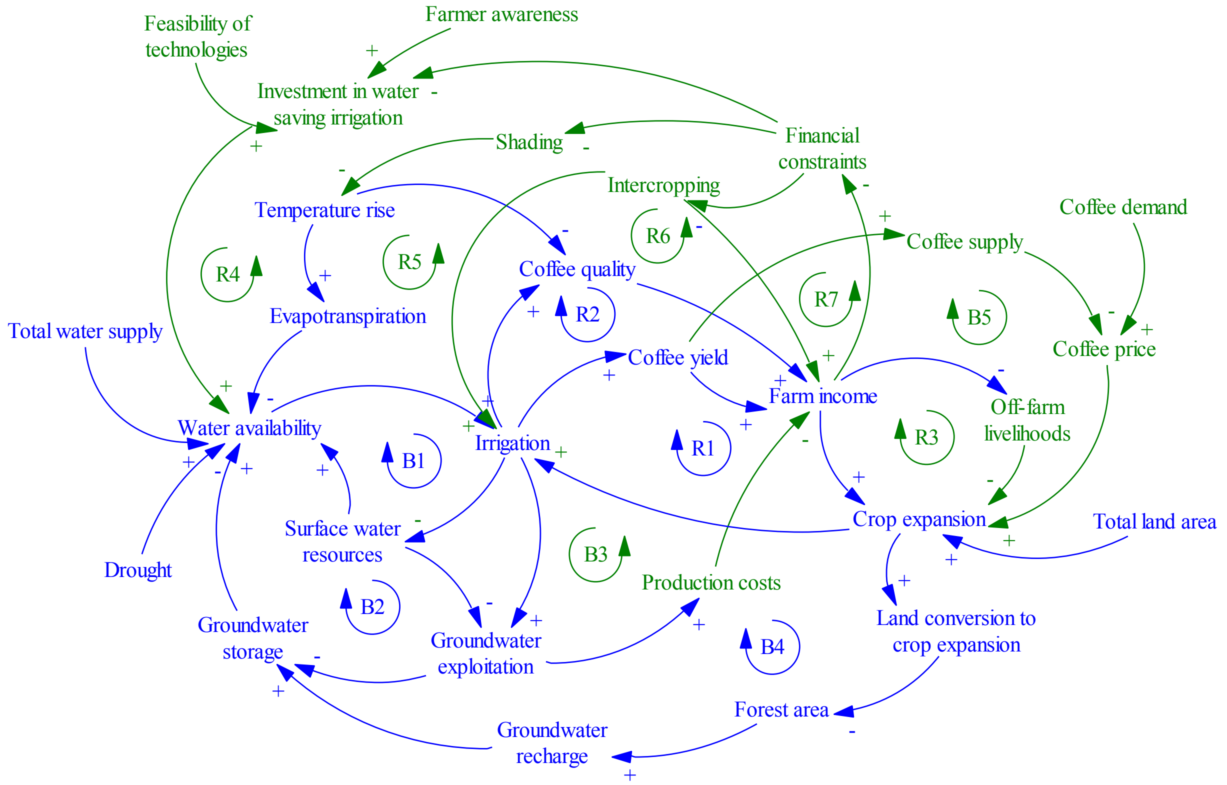


Fig. 2. Agricultural production sub-model (R: reinforcing loop, B: balancing loop, +: positive relationship, –: negative relationship, and blue colour representing overlapping variables and relationships with other sub-models). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Lak province. Analysis of participant responses revealed a number of main themes, which were categorised into three groups: agricultural production, socio-economic development and bioclimatic factors (Table 4).

Participants were aware that changing climate conditions, particularly increasing extreme events such as drought, have had adverse impacts on coffee production. They also acknowledged other influencing factors including widespread conversion of forestland into crop cultivation, uncontrollable agricultural expansion and over-exploitation of water resources in the region. The interrelationships between these factors are analysed in more detail in the following sections.

4.2. Formulation of the causal loop model

The aim of our causal loop model is to capture the main dynamics of the system, specifically the factors and interactions driving drought impacts on coffee cultivation—based on the mental models of stakeholders and behaviours over time of system variables—rather than replicate all influences of the entire coffee production process. Hence, the CLD is presented in three parts to enable focus on the key structural elements driving system behaviours. Details of the structure of all feedback loops in each sub-model are provided in Table A1 in the Appendix.

4.2.1. Agricultural production sub-model

The first element of our dynamic hypothesis depicts how the use of water resources for irrigation impacts crop production, especially coffee cultivation in Dak Lak (Fig. 2). As illustrated in the reinforcing loop R1, irrigation is crucial for coffee growth and a key to achieving high yields (Amarasinghe et al., 2015) due to uneven seasonal rainfall. Interviewed participants also noted the importance of irrigation in maintaining high coffee quality (loop R2). When severe droughts occurred, driving water scarcity for irrigation, a number of small-scale farmers with limited access to finance and credit left their farms to seek off-farm jobs, potentially interrupting coffee production. Participants emphasised that this trend might dominate in the context of increasing drought events, which is portrayed in the reinforcing loop R3.

Water management in Dak Lak is challenged by a number of issues associated with the uncontrollable expansion of perennial cropping, particularly coffee, coupled with the inefficient use of water for irrigation. Historically, coffee areas expanded rapidly with much of this expansion occurring outside the planned areas and unable to be controlled by the authorities (D'haeze et al., 2005b). Notably, many of these locations are not favourable for growing coffee due to climatic and soil constraints coupled with limited access

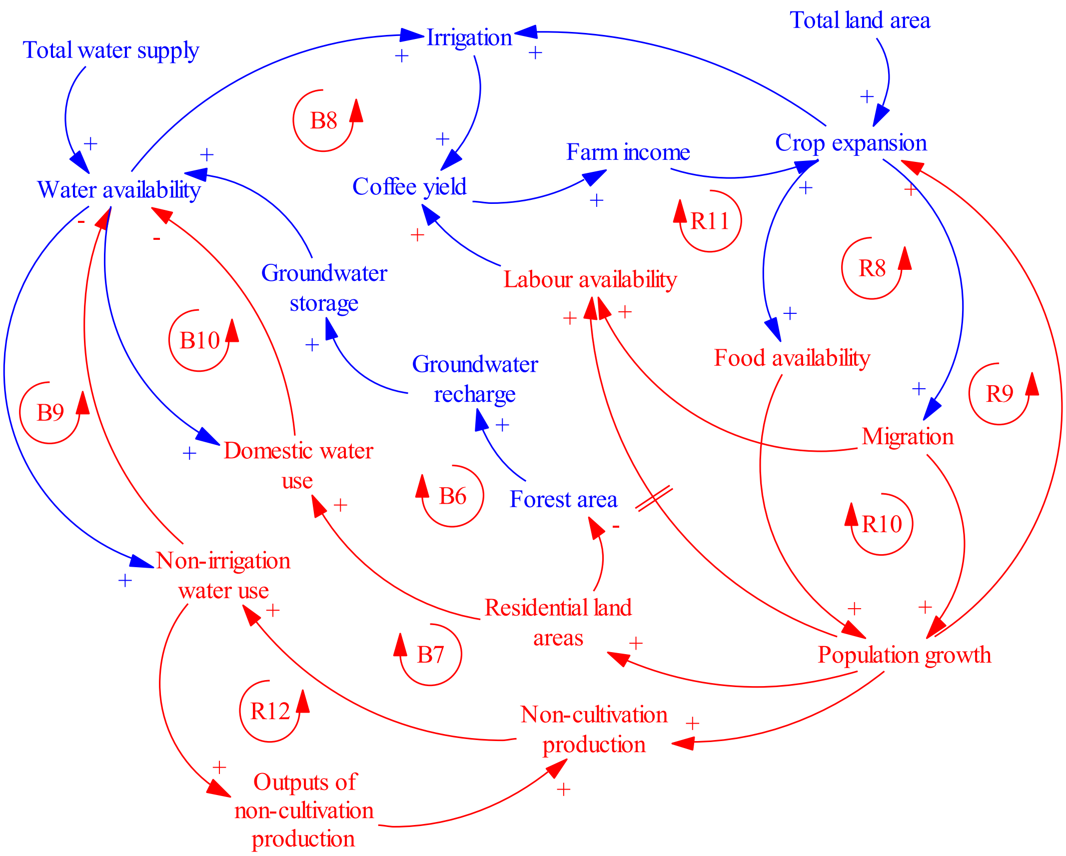


Fig. 3. Socio-economic sub-model.

to water resources. Large areas of forest have also been converted to coffee and other perennial industrial crops, potentially contributing to a fall in groundwater levels as depicted in the balancing loop B4. For instance, a significant increase in deforestation occurred in Dak Lak coinciding with the coffee boom in the 1990s (D'haeze et al., 2005a). From 2005 to 2010, expansion of coffee and other perennial crops occurred over the existing cultivated land, indirectly causing further forest clearance (Meyfroidt et al., 2013).

Apart from rising water demand associated with the considerable increase in coffee area, common irrigation practices are generally highly inefficient and unsustainable. Farmers often apply more than double the volume of water recommended for the coffee plant as this practice is considered 'insurance' for higher yields (Technoserve, 2013). Currently, the major water source used for irrigating coffee in Dak Lak is groundwater from private wells, though surface water resources are also extracted during the dry season (loops B1–B2).

While it may compensate for soil water deficit in the dry season, excess irrigation water will most likely not infiltrate to groundwater levels (CHYN, 2015). A large number of participants observed groundwater depletion in the dry season over the past years while others faced drying wells. Many farmers indicated that additional wells had been drilled during recent severe droughts. Even with more intensive extraction of groundwater resources, i.e. to depths of more than 100 m, these droughts still disrupted production across a large portion of coffee-growing areas in the province. Over-exploitation of groundwater may also reduce farmers' gross income as production expenses increase in parallel with pumping and labour costs (loop B3).

Despite the potential declines in coffee production caused by limited water resources indicated in the balancing loops, our dynamic hypothesis also describes other reinforcing phases which may counteract this process but do not currently dominate in the case study area. Specifically, participants recognised the importance of water saving technologies such as drip irrigation, which could reduce irrigation volume (loop R4), and of adaptation measures including planting shade trees to mitigate the impacts of rising temperatures and evapotranspiration (loop R5). While participants identified existing barriers in finance and techniques required to implement advanced irrigation technologies, they noted that intercropping coffee with other commercial crops such as black pepper and fruit trees, which require less water and rounds of irrigation than coffee, is likely to improve their incomes while contributing to sustaining coffee yield, particularly during severe droughts (loops R5–R7).

4.2.2. Socio-economic sub-model

The second component of the model analyses the influence of socio-economic dynamics on coffee expansion in the province (Fig. 3). Participants identified population growth, fuelled by massive migration to the province in recent decades, providing an

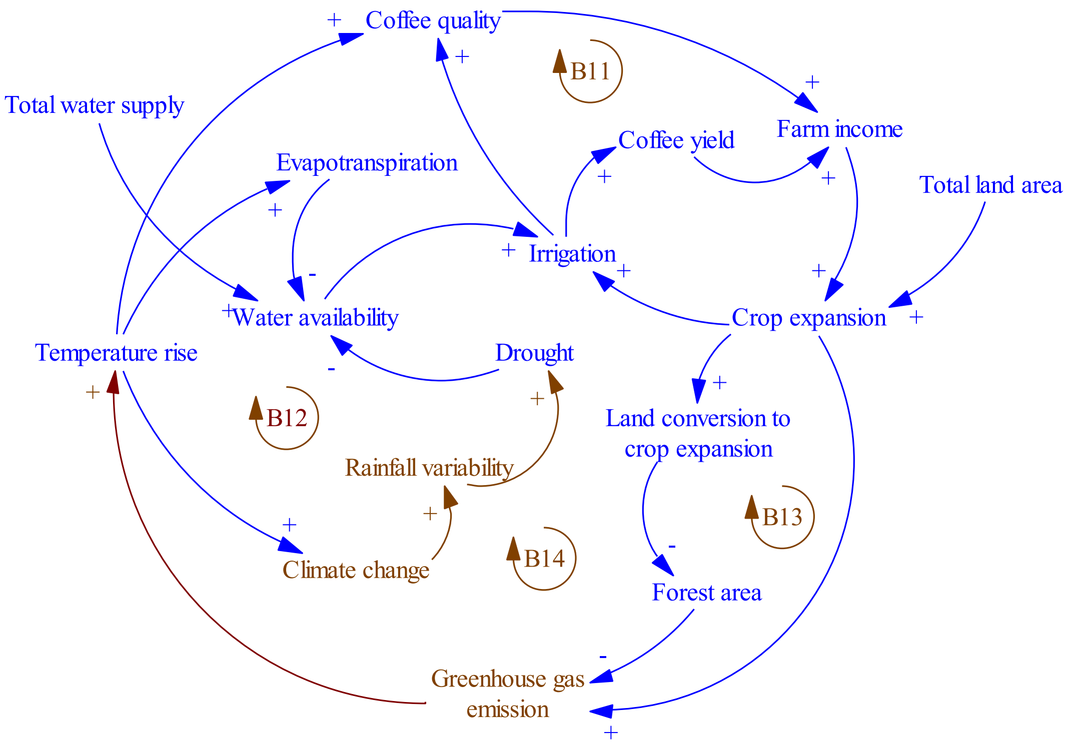


Fig. 4. Bioclimatic sub-model.

increased labour force for agricultural production, as one of the key drivers for crop expansion in Dak Lak (loops R9–R11). Crop expansion in turn drives population growth by providing food as illustrated in loop R8.

Production activities, including industry, aquaculture and livestock have also increased (loop R12) as a result of population growth – an input dangle or external driver of this reinforcing loop (Sherwood, 2002). Consequently, rising water demand in parallel with expansion of these activities and of residential areas has affected water availability in the province, indirectly affecting supply for coffee irrigation (loops B6–B7, B9–B10). Further, forest areas are still declining, driven by ongoing conversion to cropping and residential areas (JICA, 2018). Participants acknowledged that forest loss due to this conversion might contribute to reduced groundwater recharge (loop B8). These negative impacts are exacerbated by changing climate conditions as presented in the third sub-model of the CLD.

4.2.3. Bioclimatic sub-model

In the last component of the causal loop model, our dynamic hypothesis examines bioclimatic factors influencing water availability for coffee production in Dak Lak (Fig. 4). In our interviews, participants stated that a warmer climate has been observed with water shortages and droughts becoming more severe in the dry season, affecting irrigation. An increase in the erratic distribution of rainfall and in the number and intensity of drought periods has negatively affected coffee quality due to poor coffee berry development (loop B11). Climate change may accelerate the frequency of extreme events such as floods and droughts (Field et al., 2014), making water resource management a critical issue. There was broad consensus that increasing temperature and subsequent rising evapotranspiration may exacerbate drought impacts and adversely affect coffee yield and quality in the region (loop B11–B12).

Forest loss contributes to increasing emissions of greenhouse gases (Fearnside and Laurance, 2004; van der Werf et al., 2009), potentially exacerbating global warming (Fearnside, 2000). In addition, crop expansion in general and coffee production in particular also contribute to growing atmospheric greenhouse gas concentrations through emissions resulting from cultivation and processing activities, particularly the use of fertilizers, pesticides, energy, water and other inputs (Martins et al., 2015; van Rikxoort et al., 2014). Consequently, these may lead to changes in temperature and precipitation, which in turn, affect crop production (loops B13–B14).

This last sub-model involves only balancing feedback loops which counteract growth of coffee production due to water resource constraints driven by bioclimatic factors. Participants emphasised the dominance of balancing processes, which potentially persist over time, if effective management or adaptation strategies are not adopted.

4.2.4. The final model

In total, the final causal loop model comprises 12 reinforcing and 14 balancing feedback loops (Fig. 5). The model indicates that a decline or interuption in coffee production in Dak Lak during drought periods is most likely not solely a consequence of climate-related impacts but of interactions between a number of factors contributing to reduced water availability for irrigation. Climate change in

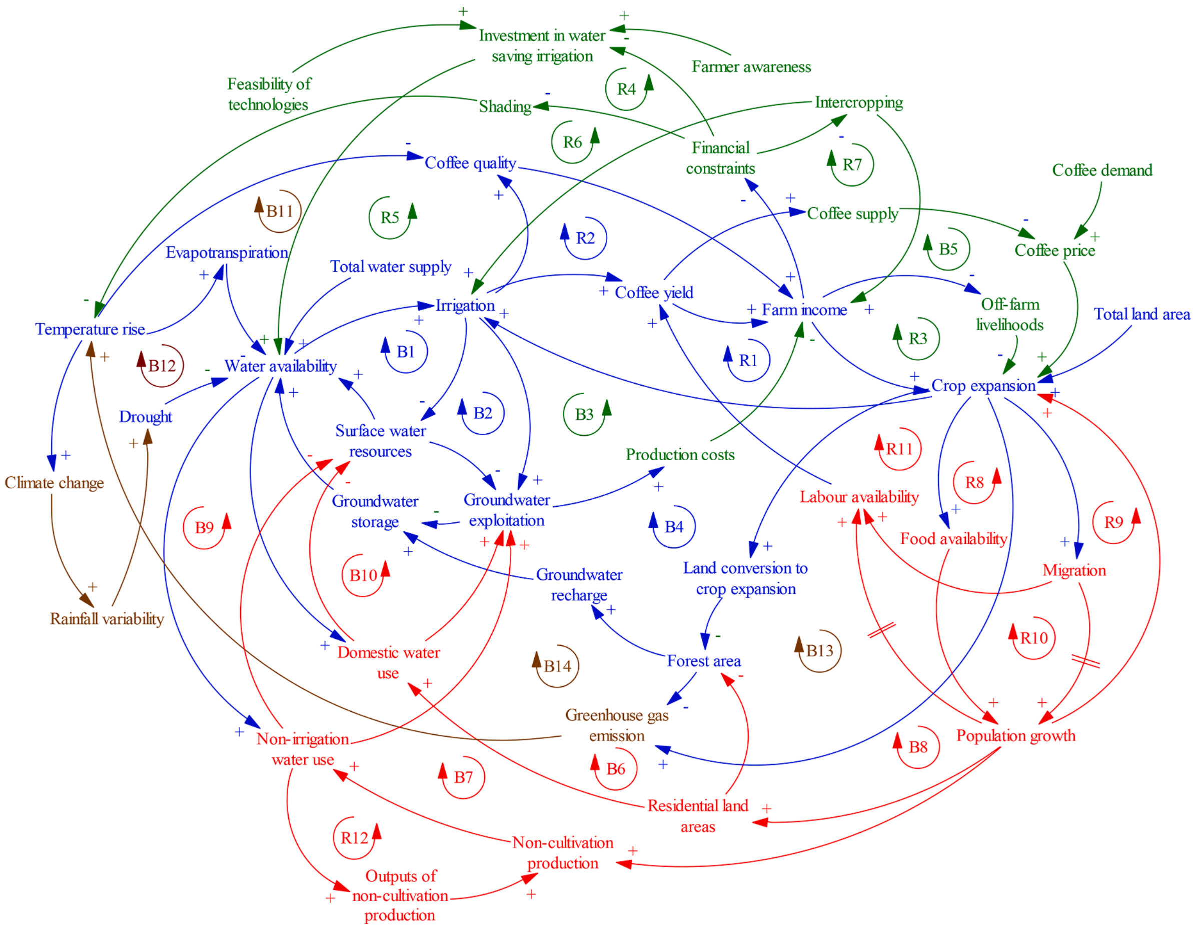


Fig. 5. The integrated causal loop model of drought impacts on coffee production in Dak Lak province, Viet Nam (green colour: agricultural production sub-model, red colour: socio-economic sub-model, brown colour: bioclimatic sub-model, blue colour: overlapping variables and relationships between sub-models). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

general and drought in particular might exacerbate water shortages, as illustrated in the bioclimatic sub-model, but our dynamic hypothesis reveals that the existing situation is also driven by the socio-economic dynamics of the region. Specifically, water resource depletion is likely to be asssociated with substantial changes in land use, particularly the large conversion of forestland to industrial crops, mostly coffee, in recent decades, as explained in the agricultural production sub-model. Crop production has expanded in response to export market demands, with much of that out of the control of authorities and in areas that are not optimal, as in the case of coffee, causing water imbalance in the region. Other causes of declining water availability might include increases in production activities other than cultivation and in residential development driven by population growth, placing further pressure on regional water resources, as analysed in the socio-economic sub-model.

The final model indicates that coffee production in Dak Lak has been reinforced by irrigation and labour availability. This trend would likely continue, as illustrated in the majority of reinforcing loops mentioned above, if there were no limits to growth in the system, including total land area and total water availability of the region. It is these limiting factors that restrict growth of coffee production, a tendency that is increasingly dominant in the dry season. Unless appropriate interventions are adopted, coffee cultivation is likely to be disrupted in the future as the system reaches the carrying capacity of critical natural resources. The *limits to growth* system archetype presented below further demonstrates how balancing loops constrain growth of finite resources-based systems.

4.3. System archetypes and leverage points

System archetypes derived from the final model enable analysis of a number of underlying structures of the system and identification of potential leverages resulting from these structures. They also help in explaining the unintended consequences of several management decisions when long-term behaviours of system variables are not easily foreseen or acknowledged due to trade-offs with

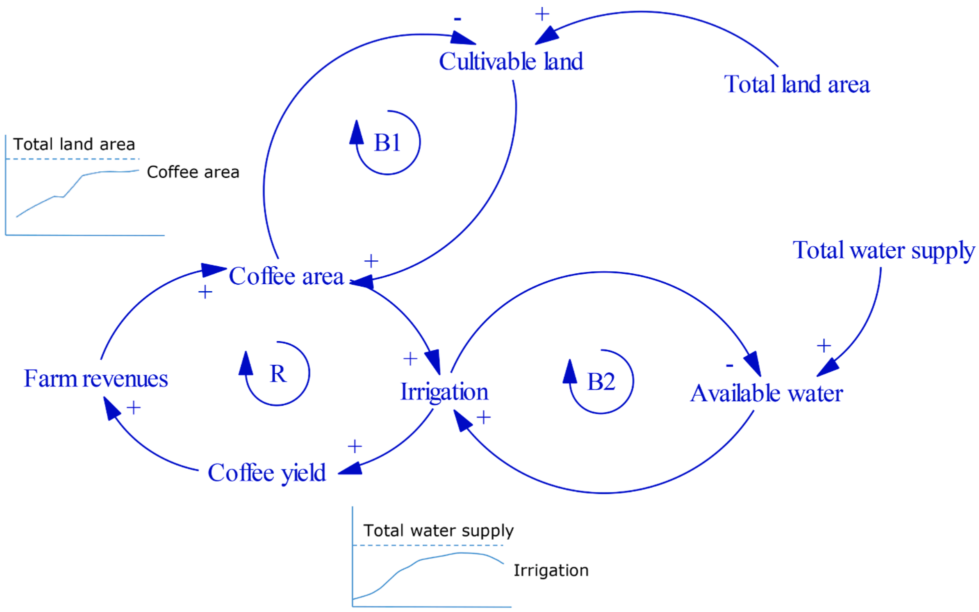


Fig. 6. *Limits to growth* – the limits of land and water resources for coffee expansion.

immediate benefits.

4.3.1. Limits to growth

The *limits to growth* system archetype describes growth of an action until the system reaches its peak because there will always be factors that eventually restrict growth (Braun, 2002; Wolstenholme, 2003). This archetype comprises two phases, with reinforcing feedback processes accelerating growth or expansion of the system while balancing processes slow or even reverse this due to limits such as a resource constraint (Senge, 1991).

As illustrated in Fig. 6, coffee production in Dak Lak is heavily reliant on irrigation (reinforcing loop R) and has expanded with the availability of local land and water resources and weak enforcement of land ownership and water management (Ahmad, 2001). In 2011, the coffee area reached approximately 200,000 ha and has remained above this, exceeding the current provincial plan by over 20,000 ha.

The balancing loops, however, indicate that there are factors, including total land area and total water supply that limit the expansion of coffee production. Land and water are not infinite resources and will ultimately halt growth in coffee production (balancing loops B1 and B2). Coffee expansion has directly and indirectly encroached on forestland and is likely to exceed the water capacity of the region. Unless strict control mechanisms are effected, this expansion will continue at the expense of existing forests and water security.

Leverages for the *limits to growth* situation can lie in both reinforcing and balancing loops. These may be to either weaken or remove the factors that restrict growth in balancing processes or constrain growth in reinforcing processes, depending on whether growth or constraint is the ultimate goal. In this instance, spatially explicit zoning of coffee-growing areas should be adopted to mitigate pressure on water and land resources. Strong measures are needed to stabilise coffee-growing areas and ban cultivation in fragile zones (Ahmad, 2001) that are not favourable to cropping or under forest cover, while substitute livelihoods are required to provide local communities. Research on alternative cropping systems, particularly those that are more drought resistant and water efficient (D'haeze et al., 2005b), will be beneficial in these areas. Other solutions, identified in the balancing loops, might include strengthening measures on forest protection in combination with afforestation and reforestation to sustain forested areas in order to increase groundwater recharge. Promoting technologies such as drip irrigation and water harvesting (Baca et al., 2014; Perdona and Soratto, 2015) would be potential strategies to increase water availability for coffee irrigation. However, the implementation of technological adaptation options requires substantial labour, technical and financial resources (Harvey et al., 2018; Lopez-Nicolas et al., 2017) and adequate infrastructure to ensure smooth operation and maintenance, which might hinder widespread adoption by small-scale farmers. Several participants indicated barriers to applying technologies such as drip irrigation, including high upfront investment and maintenance costs and the difficulty of installing equipment in small coffee areas.

It is argued that behaviour change in irrigation practices is a fundamental requirement for water conservation and prerequisite for the viability and sustainability of coffee production. Continuous training and communication of the benefits of optimized irrigation practices for coffee cultivation should be high priority and promoted along with economic incentives and technological solutions supported by government and industry.

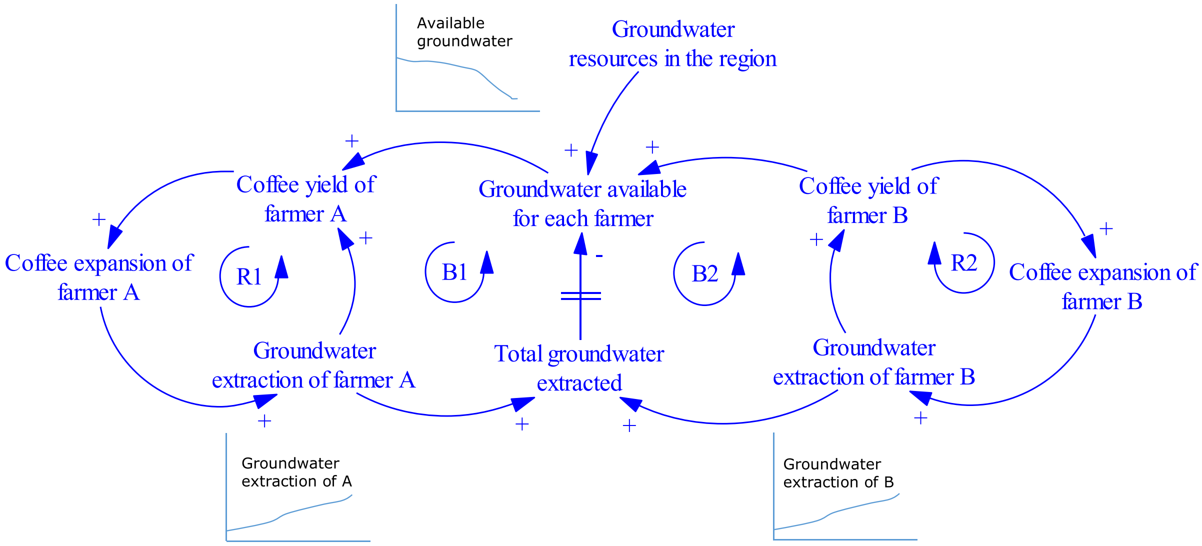


Fig. 7. *Tragedy of the commons* – the impact of groundwater over-exploitation.

4.3.2. Tragedy of the commons

The sustainability of the coffee industry in Viet Nam is challenged by limitations associated with natural capital, as is common in any resource-based sector. The *tragedy of the commons* system archetype is a circumstance where a common pool resource is over-used (Hardin, 1968). This happens when everyone wants to gain benefit from the resource, causing over-exploitation and undesirable effects for all concerned (Maani and Cavana, 2007).

In Dak Lak, coffee farmers freely dig or drill private wells to extract groundwater for irrigation in the dry season (reinforcing loops R1–R2 in Fig. 7) due to weak enforcement of provincial water resource management regulations (Ahmad, 2001). As each farmer tries to maximize his/her net gain from groundwater resources in the belief that this will lead to higher yields, groundwater levels decline, decreasing the net gain for all over time (balancing loops B1–B2). Subsequently, everyone suffers from decreasing availability of groundwater for irrigation.

Amarasinghe et al. (2015) found that coffee yields would reach 4 tonnes/ha with irrigation limited to approximately 400 L/plant/irrigation round (three rounds/year), significantly lower than the actual irrigation amount applied by many farmers. Widespread adoption of such a water saving irrigation regime may save labour and energy expenditure for farmers and reduce water use for coffee cultivation.

Management strategies for this archetype might involve restrictions on groundwater exploitation through application of water taxes or fees to reflect the social costs of water in coffee production (Ahmad, 2001). However, these might widen the gap between high and low income households and not adequately address groundwater depletion problems (D'haeze et al., 2005b). Previous attempts at groundwater pricing and licensing in Dak Lak failed due to weak enforcement (Ahmad, 2001). In 2007 and 2016, the province updated regulations on water resource management; however, interviewed participants indicated that most of the existing private wells were constructed without the permission of authorities.

While the application of such instruments might be challenging, extensive awareness raising amongst coffee farmers about water resource limits and the benefits of optimal irrigation practices should be high priority as this may be a more feasible and effective option to prevent further groundwater depletion.

4.3.3. Fixes that fail

The *fixes that fail* system archetype was identified to explain the success of Viet Nam's coffee industry and the unanticipated outcomes of well-intended 'quick-fix' action aimed at addressing the symptoms of a problem. While often successful in the short term, such fixes derived from linear cause-and-effect thinking may create unintentional or even harmful longer-term consequences that reinforce the original problem (Braun, 2002; Turner et al., 2016).

One of the most important factors driving the achievements of the coffee industry in Viet Nam is the labour force stemming from substantial migrations to the Central Highlands after the country's reunification, which was encouraged by the government through the New Economic Zone program (Ha and Shively, 2008). The total coffee area and coffee production in the region remained relatively low until the implementation of this organised migration program. With the increased labour coupled with the climatic and soil suitability, significant expansion of coffee production occurred, stimulating spontaneous immigration into the region (Ahmad, 2001; Ha and Shively, 2008). From 1975 to 2000, the population of the Central Highlands increased from 1.5 million to 4.2 million with more than half a million settlers in Dak Lak province (Marsh, 2007). Coffee areas in the province grew in parallel, leading to a boom in production from less than 200,000 ton in the 1990s to over 450,000 ton by 2001 (GSO, 2002). In the late 1990s, Viet Nam emerged as

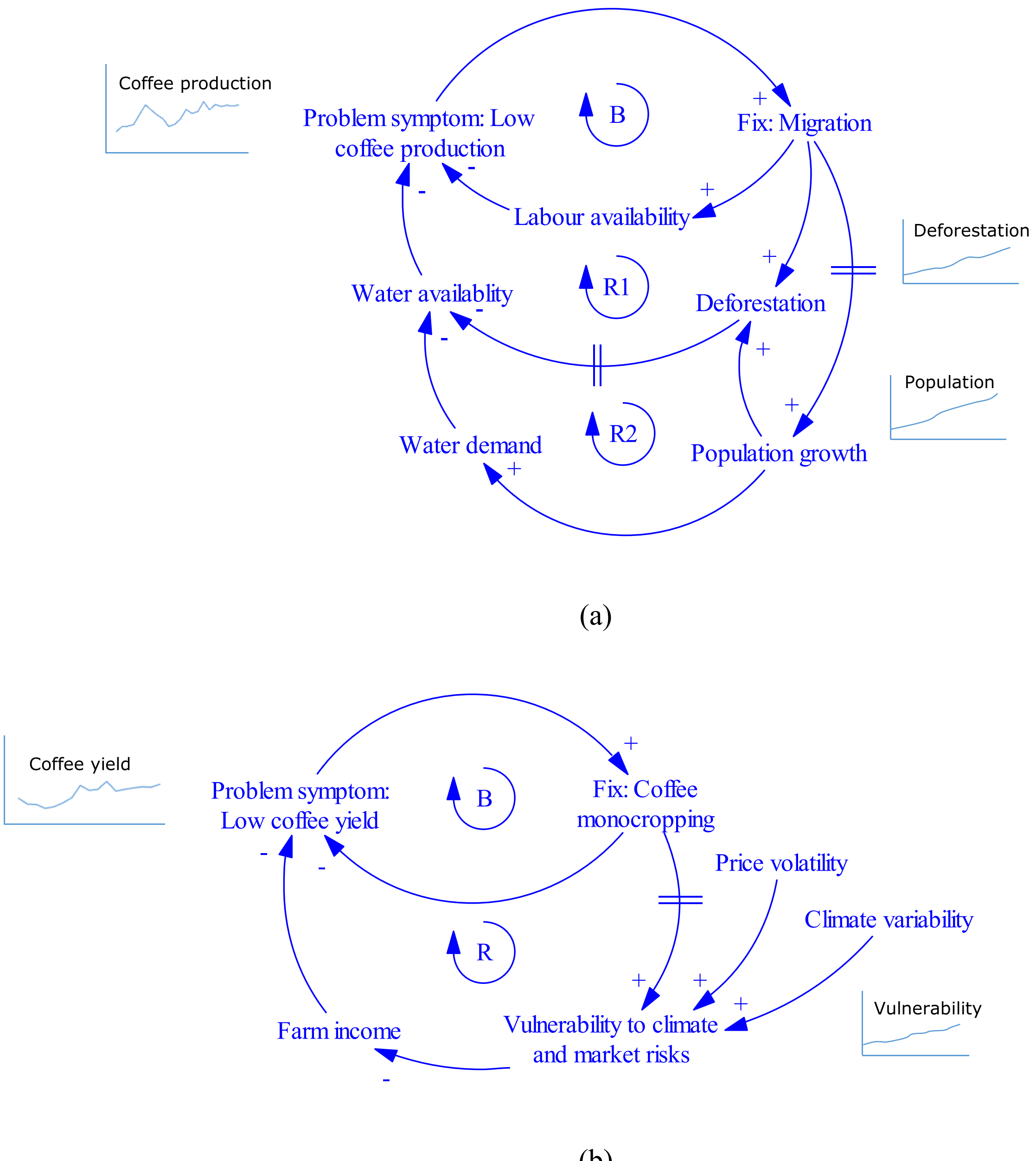


Fig. 8. *Fixes that fail* – the side effects of quick fixes aimed at improving coffee production through (a) migration program and (b) coffee monocultures.

one of the world's largest producers and exporters of green coffee beans, second only to Brazil (ICO, 2002).

While this migration contributed substantially to meeting local needs for agricultural labour and to the subsequent growth in coffee cultivation, large-scale immigration in the region also caused severe damage and destruction to forest resources, predominantly where these were converted to allow agricultural expansion (De Koninck, 1999).

Subsequent rapid regional population growth as a result of this migration program has further increased demands for agricultural expansion and residential development, driving additional deforestation and rising water demand. As a result of reduced vegetation cover, groundwater recharge is likely to decrease (Ahmad, 2001; D'haeze et al., 2005a), contributing to increasing water shortages for crop production and other water use sectors.

Fig. 8a illustrates this unexpected side effect of a well-intended action. The migration policy, supported by perennial crop expansion policies, brought immediate benefits for agricultural production, particularly boosting coffee output (balancing loop B), but caused long-term negative effects on forest and water resources and eventually on coffee production (reinforcing loop R1). As the regional population continues to grow, this trend continuously intensifies water demand due to the dominance of the reinforcing loop R2, contributing to reduced water availability for coffee production. Consequently, in the long run, along with projected increased risks of climate change and variability, water shortages will most likely become more severe, potentially leading to crop failure.

To tackle these consequences, the reinforcing process could be weakened by reducing the pressure on regional forest and water resources resulting from the increasing population, which is the main driver of declining water availability. While controlling population growth and the subsequent water demand (reinforcing loop R2) is not likely to be solely addressed within the scope of the agricultural sector, other solutions aiming at deforestation (reinforcing loop R1) might be more feasible to mitigate population pressure. Afforestation and reforestation programs need to be further promoted while existing forests should be strictly protected to avoid further deforestation and thus avert water resource depletion. More importantly, alternative livelihoods should be identified and encouraged to meet the demands of the growing population, particularly of the poor living on the edge of the forest, and to alleviate the motives driving forest clearance for agricultural expansion. Given the history of coffee expansion at the expense of forest loss in Dak Lak over many decades, it is noted that resolving the consequences of population growth and deforestation is a difficult task, requiring coordination of various sectors at all levels to provide comprehensive and feasible solutions. However, without addressing the trade-off between crop expansion and forest protection, it is most likely that further undesirable consequences including watershed degradation will eventuate.

The coffee industry in Viet Nam also largely owes its success to the mono-cropping system of Robusta, which entails lower production costs, greater pest and disease resistance and potentially higher yields than Arabica (*Coffea arabica*). Intensive irrigation and fertilizer application has boosted Robusta yield to more than 2.3 tonnes/ha on average, one of the highest globally (ICO, 2019a).

However, widely practiced Robusta monocultures represent another *fixes that fail* archetype in the system, with some unintentional effects, including their higher vulnerability to the impacts of changing climate conditions (Fig. 8b). Dense coffee plantations without shade or windbreak trees or other crops grown in conjunction have become prevalent, on the expectation of achieving optimal productivity. However, this type of system is likely to be more vulnerable to changes in climate conditions compared to shaded or intercropped systems which can effectively modify the micro-climate (Jassogne et al., 2013; Moreira et al., 2018). Mono-cropping systems are also more susceptible to market fluctuations. Specifically, a drop in coffee prices would affect large numbers of coffee farmers relying on this single crop, as occurred when the world prices collapsed during 2000–2005 (Meyfroidt et al., 2013). Conversely, high global prices are likely to reinforce monoculture expansion, as happened in the 1990s (Marsh, 2007), and motivate forest clearance for new coffee-growing land with the promise of higher profits. With limited restrictions on production or quotas in the global coffee market (Marsh, 2007; Technoserve, 2013), volatility in coffee prices will most likely continue, negatively impacting farmers solely reliant on coffee monocultures.

Shading or intercropping have been applied in a number of coffee plantations in the region to reduce the risks associated with market variations, especially when coffee prices drop, and changing climate conditions including high temperatures and increasing evapotranspiration. However, study participants highlighted barriers in applying these practices, including limited capital and access to finance of many small landholders. Some farmers were also reluctant to adopt shaded or diversified farming as this would impact the area for coffee and, they believed, reduce economic returns. Given that the influence of climate change and market fluctuations cannot be effectively controlled at the local level, replacing coffee monocultures with diversified cropping systems and/or incorporating shade trees to increase the resilience of coffee systems would likely provide multiple economic and environmental benefits for farmers (Cerda et al., 2017; Schroth et al., 2009). Support from government and industry along with awareness raising is required to help farmers apply these practices to better adapt to climate and market risks.

Studies in Africa and the Americas show that diversified coffee agroforestry systems, especially with the presence of shade cover (Lin, 2010), can increase resilience to changing climate conditions (Gidey et al., 2019; Moreira et al., 2018). In terms of economic returns, these systems might deliver equally (van Asten et al., 2011) or better coffee yields than comparable monoculture systems (Jezeer et al., 2018; Perdona and Soratto, 2015). However, coffee and shade trees or other crops in such systems may also compete for water, light and nutrients (Charbonnier et al., 2013; van Oijen et al., 2010), particularly in adverse environmental conditions such as water shortages (van Kanten and Vaast, 2006). There is a lack of research on whether economic benefits compromise ecosystem services (Cerda et al., 2017) or environmental performance in coffee agroforestry systems. Further consideration should be given to such systems as they might be less resilient to extreme weather such as drought than full-sun farming, as can be seen in cocoa cultivation systems (Abdulai et al., 2018).

In Dak Lak, a number of coffee smallholders have initiated diversification of conventional Robusta coffee systems with black pepper, avocado, durian and other fruit trees to generate shade canopies while improving their incomes. Nonetheless, the efficiency of application of such practices, including their overall economic and environmental performance, remain uncertain, requiring further comprehensive assessments. Overall, shade tree presence in coffee plantations in the region is limited (IDH, 2019), possibly due to the infancy of the application, which requires time to demonstrate results, as well as a lack of technical and financial resources as emphasized by study participants. In intensive cultivation systems dependent on irrigation, such as the Robusta system in Viet Nam, the whole farm management requires redesign to better accommodate the requirements for water, lights and nutrients of both coffee and other crops. Detailed research on suitable shade tree or crop species and appropriate techniques applicable to coffee production is necessary to enable the evaluation of potential synergies and trade-offs; hence informed responses to climate change.

5. Conclusions

The results of this study indicate that the current drought and water scarcity situation in Dak Lak province in Viet Nam is the outcome of complex interactions between bioclimatic, agricultural production and socio-economic factors. Uncontrollable coffee expansion, largely at the expense of forested areas, is partly the consequence of policy decisions promoting migration and perennial crop development. These decisions, along with global coffee demand and trade liberalization (D'haeze et al., 2005a) and weak enforcement of land tenure, have underpinned overproduction of coffee, contributing to declining water availability in the region.

Using system dynamics, this research developed a causal loop model that captured the dynamic interconnections and feedbacks among variables driving drought impacts on coffee production. Our dynamic hypothesis indicates that water depletion in the dry season affecting coffee production might not be solely attributed to rainfall variability. Rising demand for agricultural water caused by ever-increasing cultivation areas as well as inefficient irrigation practices are also highly influential drivers of water scarcity in the region, while factors such as deforestation and growing water demand from activities other than agriculture, driven by population growth, place further pressure on regional water resources. A changing climate may exacerbate the problem and continue to negatively affect coffee cultivation, specifically Robusta mono-cropping systems which are susceptible to adverse impacts.

By applying system dynamics, this study not only detected numerous direct and indirect drivers associated with water availability for coffee cultivation, but also revealed their interactions through reinforcing and balancing feedback loops. These loops highlight the non-linear dynamics of the system. At a particular time, some loops dominate and strongly influence the trajectory of the system. For example, coffee production is intensified by reinforcing processes and would continue to grow if there were no limiting factors in the system. However, the dominance of loops also changes over time. Coffee production may be interrupted by drought due to water resource limits, as illustrated by balancing processes in the model. These shifts in loop dominance produce the complex behaviours of the system. Hence, it is necessary to understand not only the system components but also how they interact. Given the interactions driven by socio-economic dynamics analysed above, it is likely that, in the absence of appropriate intervention strategies, water shortages in the region may even occur well before a meteorological drought event. Although groundwater recharge takes place during the rainy season, it may not be sufficient for coffee irrigation in the following dry season.

Coffee production may be further interrupted by balancing processes; thus, to properly address water scarcity for coffee production, a set of interventions aimed at weakening these processes is needed. These comprise policies that control deforestation and over-expansion of coffee production including explicit zoning of coffee-growing areas with restrictions in unsuitable and forested areas. Research on alternative cropping systems, especially those that require less water and can withstand prolonged drought, is necessary to provide farming community with diversified or alternative livelihoods.

Economic incentives, including water taxes and pricing schemes to discourage over-extraction, and adoption of water saving irrigation technologies and other water harvesting and storage techniques to improve water use efficiency should be considered. While these measures require substantial time and resources, promotion of optimized irrigation practices through increasing awareness and behaviour change amongst local farmers may contribute to averting water depletion while sustaining yields and increasing income through reduced irrigation expenditure. Diversifying Robusta monocultures with other crops or trees may also improve the resilience of coffee plantations to the impacts of changing climate conditions and market variations while improving incomes; however, further consideration should be given to trade-offs associated with water use, particularly in cultivation systems depending on irrigation like the Robusta system in Viet Nam. Additional research is required to evaluate the overall socio-economic and environmental performance of such systems at large scales, particularly in relation to the pressure on regional water resources, to ensure improved farm management in the context of drought.

These interventions, particularly zoning of coffee cultivation areas, rationalized irrigation practices and diversified systems, should be simultaneously implemented, as it is most likely that none of them will sufficiently address the dynamics of water scarcity for coffee production on its own. These adjustments will likely assist the coffee industry to better adapt to potential climate and market risks while maintaining its viability and sustainability.

Our research aimed to produce a dynamic hypothesis to understand not only the constituent parts of the system but the interactions underpinning the complexity of system behaviour. System dynamics was applied to analyse the dynamics of drought and its impacts on coffee cultivation by capturing feedback structures generating the current patterns of system behaviour. The causal loop diagram developed is a qualitative conceptual model based on hypotheses primarily derived from the mental models of our participants. A great number of variables are excluded in our model, including factors related to political dimensions and coffee markets that influence coffee area expansion, as they are considered exogenous to the model boundary and scope. Modelling might be expanded to include an increased range of factors so it will never be completed. However, as the purpose of our model was to capture the main dynamics of the system to enable investigation of the interactions driving drought impacts, rather than to model the whole system, such exogenous variables can be addressed in future larger-scale studies. The adoption of other novel methods such as fuzzy cognitive mapping (Mourhir et al., 2017) to unravel and contrast farmers' and other stakeholder perceptions in future studies can also provide a greater and instructive outcome. While causal loop modelling primarily based on mental models might be a potential limitation, it is not required to be comprehensive prior to simulation model development; capturing significant feedbacks among system components is most important (Sterman, 2000). Simulation modelling is the only practical way for testing the conceptual model (Sterman, 2000) and is currently in progress. Despite a lack of data and in-depth variables, a simulation model has been developed based on the dynamic hypothesis (causal loop model) generated from this study in combination with a range of assumptions which can be tested upon the historical data of a few variables where available. Simulating the interactions between system elements over time, and designing and evaluating potential intervention scenarios for sustainable coffee production will greatly improve our understanding of the problem in Dak Lak province, providing an informative example for the analysis of other similarly complex challenges elsewhere.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Structure of feedback loops presented in the integrated causal loop model.

Loop name	Feedback loop	Feedback structure
Agricultural production sub-model	R1	Irrigation →+ Coffee yield →+ Farm income →+ Crop expansion →+ Irrigation
	R2	Irrigation →+ Coffee quality →+ Farm income →+ Crop expansion →+ Irrigation
	R3	Irrigation →+ Coffee yield →+ Farm income →– Off-farm livelihoods →– Crop expansion →+ Irrigation
	R4	Investment in water saving irrigation →+ Water availability →+ Irrigation →+ Coffee yield →+ Farm income →– Financial constraints →– Investment in water saving irrigation
	R5	Shading →– Temperature rise →+ Evapotranspiration →– Water availability →+ Irrigation →+ Coffee yield →+ Farm income →– Financial constraints →– Shading
	R6	Shading →– Temperature rise →– Coffee quality →+ Farm income →– Financial constraints →– Shading
	R7	Intercropping →+ Farm income →– Financial constraints →– Intercropping
	B1	Irrigation →– Surface water resources →+ Water availability →+ Irrigation
	B2	Irrigation →+ Groundwater exploitation →– Groundwater storage →+ Water availability →+ Irrigation
	B3	Groundwater exploitation →+ Production cost →– Farm income →+ Crop expansion →+ Irrigation →+ Groundwater exploitation
	B4	Crop expansion →+ Land conversion to crop expansion →– Forest area →+ Groundwater recharge →+ Groundwater storage →+ Water availability →+ Irrigation →+ Coffee yield →+ Farm income →+ Crop expansion
	B5	Coffee price →+ Crop expansion →+ Irrigation →+ Coffee yield →+ Coffee supply →– Coffee price
Socio-economic sub-model	R8	Population growth →+ Crop expansion →+ Food availability →+ Population growth
	R9	Migration →+ Population growth →+ Crop expansion →+ Migration
	R10	Population growth →+ Labour availability →+ Coffee yield →+ Farm income →+ Crop expansion →+ Migration →+ Population growth
	R11	Crop expansion →+ Migration →+ Labour availability →+ Coffee yield →+ Farm income →+ Crop expansion
	R12	Non-cultivation production →+ Non-irrigation water use →+ Outputs of non-cultivation production →+ Non-cultivation production
	B6	Population growth →+ Residential land areas →+ Domestic water use →– Water availability →+ Irrigation →+ Coffee yield →+ Farm income →+ Crop expansion →+ Food availability →+ Population growth
	B7	Population growth → Non-cultivation production → Non-irrigation water use →– Water availability →+ Irrigation →+ Coffee yield →+ Farm income →+ Crop expansion →+ Food availability →+ Population growth
	B8	Population growth →+ Residential land areas →– Forest area →+ Groundwater recharge →+ Groundwater storage →+ Water availability →+ Irrigation →+ Coffee yield →+ Farm income →+ Crop expansion →+ Food availability →+ Population growth
	B9	Non-irrigation water use →– Water availability →+ Non-irrigation water use
	B10	Domestic water use →– Water availability →+ Domestic water use
Bioclimatic sub-model	B11	Climate change →+ Rainfall variability →+ Drought →– Water availability →+ Irrigation →+ Coffee quality →+ Farm income →+ Crop expansion →+ Greenhouse gas emission →+ Temperature rise →+ Climate change
	B12	Temperature rise →+ Evapotranspiration →– Water availability →+ Irrigation →+ Coffee yield →+ Farm income →+ Crop expansion →+ Greenhouse gas emission →+ Temperature rise
	B13	Land conversion to crop expansion →– Forest area →– Greenhouse gas emission →+ Temperature rise →+ Climate change →+ Rainfall variability →+ Drought →– Water availability →+ Irrigation →+ Coffee yield →+ Farm income →+ Crop expansion →+ Land conversion to crop expansion
	B14	Climate change →+ Rainfall variability →+ Drought →– Water availability →+ Irrigation →+ Coffee yield →+ Farm income →+ Crop expansion →+ Greenhouse gas emission → Temperature rise →+ Climate change

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Chapter 6. Evaluating management strategies for sustainable crop production under changing climate conditions: A system dynamics approach

Chapter overview

Chapter 6 starts with a description of the required steps for developing and testing a system dynamics simulation model, including proposed assumptions, parameters, simulation time and scope for model development and calibration. The chapter then describes and discusses all sectors of the stock-and-flow simulation model, including the coffee production, water resources and population and socio-economic development sectors. The chapter also analyses in detail the results of various types of assessments, including structural and behavioural tests, to check if the model is able to represent the real system, and sensitivity analysis to identify the parameters that most influence the dynamics of the system the model reproduces. This is followed by a section that investigated the outcomes of all simulation runs, including potential scenarios that might occur in the case study area and plausible policy intervention scenarios that might be adopted to address the impacts of drought on coffee production. The results of the policy scenario evaluation have significant potential to inform decision-making on drought management for sustainable and viable coffee production in Dak Lak Province, Viet Nam and to contribute to the wider application of system dynamics modelling in the agricultural sector under a changing climate.

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Evaluating management strategies for sustainable crop production under changing climate conditions: A system dynamics approach

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Systems thinking

ABSTRACT

The increasing frequency and severity of drought pose significant threats to sustainable agricultural production across the world. Managing drought risks is challenging given the complexity of the interdependencies and feedback between climate drivers and socio-economic and ecological systems. To better understand the dynamics that drive the impacts of drought and water scarcity on crop production, a system dynamics model has been developed to explore complex interactions between factors in associated with drought and agricultural production, and examine how these might impact agricultural sustainability, using a case study in a coffee production system in Viet Nam. The model shows that water- and land-use drivers and their interactions with ecological and socio-economic factors play a more significant role than drought in determining the sustainability of coffee production. Results of policy scenario analyses indicate that drought conditions might exacerbate problems related to water shortages for irrigation but their impacts could be substantially minimized through applying intervention strategies, including restriction of the total area of land available for coffee production (to ~ 190,000 ha) and a 25% reduction in the irrigation amount per hectare of coffee compared to the common practices. Overall, the model findings add significant insight into drought and water resources management for sustainable crop production and the developed model can serve as a decision-support tool to inform strategic policy-making.

1. Introduction

The magnitude of climate change, including the potentially increasing frequency and intensity of extreme events such as drought, poses major threats to agricultural production in many regions across the world (IPCC, 2014; Wilhite et al., 2014). Higher temperatures and increased water scarcity as a consequence of changes in precipitation patterns are adversely impacting water availability, sustainable crop production and food supply (Hertel et al., 2010; Iglesias and Garrote, 2015). Changes in climate patterns at local, regional and global levels and their consequences on agricultural and land and water resources systems are complex issues, as they involve numerous interdependencies and feedback that cannot adequately be addressed based on linear problem-solving approaches (Turner et al., 2016). A holistic and dynamic framework is therefore necessary to better understand and manage multidisciplinary problems involving the uncertainty and complexities and to implement effective adaptation measures (Howden et al., 2007; Mirchi et al., 2012; Turner et al., 2016).

System dynamics, a discipline that is based on a whole-of-system perspective and non-linear feedback theory (Forrester 1961, 1969; Sterman, 2000), is increasingly used to enhance understanding of complex problems that are inherent in socio-economic and ecological systems (Mirchi et al., 2012; Turner et al., 2016). System dynamics modelling allows feedback interactions among interdependent system components that drive the behaviour over time of the system to be incorporated (Ford, 1999; Sterman, 2000) and simulated within the same model (Sušnik et al., 2012). This exercise enables the analysis and evaluation of key dynamics of the system and the identification of policy interventions that can be leverages to beneficially change the behaviour of the system over time. This holistic framework, which considers all elements of the system, is well suited to addressing complex problems associated with human and ecological systems, given their

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interdisciplinary and multidimensional nature.

System dynamics modelling has been applied in water resource planning and management across the world, aiming to improve understanding of the current behaviour of related systems and to inform strategic policy-making based on analyses of the dynamics of the system under various changing conditions or intervention scenarios (Turner et al., 2016). Examples include assessment of the impacts of water scarcity and the effectiveness of water conservation policy measures (Qaiser et al., 2011; Sušnik et al., 2012), water supply and demand management instruments and socio-economic policy scenarios (Sun et al., 2017; Wang et al., 2011). These can be tailored for sustainable water resource utilization and management at a catchment, river-basin and national scale. Application of system dynamics is also extended to an evaluation of the impacts of changes in climate and socio-economic development, and of climate change adaptation (Chapman and Darby, 2016; Gohari et al., 2017) and mitigation (Dace et al., 2015) strategies on water and land resources and associated livestock and crop production systems.

For drought management, a limited number of studies have applied system dynamics approaches to examine the interconnected systems affected by drought including population, water availability, agricultural production and other socio-economic development sectors, including the research of Gies et al. (2014) and Shahbazbegian and Bagheri (2010). System dynamics simulation models are also integrated with other hydrological modelling tools such as the Soil & Water Assessment Tool – SWAT (Agusdinata, 2016; Gies et al., 2014) to enable a detailed investigation of the interdependencies of drought-affected systems. One of the significant findings of this research is that a water-abundant region is likely to be more vulnerable to drought than a dry region due to the greater reliance of the local economy on water resources for agricultural production without proactive adaptation measures to water shortages conditions (Shahbazbegian and Bagheri, 2010). Using a system dynamics approach enables an evaluation of potential adaptation policies to drought aimed at averting rather than reacting to its impacts (Agusdinata, 2016), consequently, informing proactive policy responses suitable for drought risk mitigation. Such policies might include investments in improved water infrastructure to increase water availability and efficient water use measures such as drip irrigation, and agroforestry (Gies et al., 2014). Adaptive measures for effective drought management should be tailored to each specific region, as the interactions between drought-related systems and their impacts are diverse between regions. For example, in Gwangdong Province in Korea, outcomes of simulation modelling by Lee et al. (2012) indicate that proper allocation of water resources and early control mechanisms of water levels are of greater importance than the expansion of reservoir capacity.

Although the models developed in the above studies are able to simulate the impacts of drought and water scarcity over time on related systems, there remains a lack of analysis of the dynamics of such systems in response to changes in climate, such as precipitation variability, and changes in ecological and socio-economic conditions. To address this gap, this study aims to implement a system dynamics approach to evaluate the impacts of drought on crop production with consideration to interactions with the environmental and socio-economic dynamics in response to changes in climate conditions. To fulfil this need, the present investigation is based on a case study of the coffee production system in Dak Lak Province, Viet Nam – the world's second-largest coffee-producing country where water resource management and drought mitigation response are critical elements of sustainable agricultural production. This study area is highly significant because Dak Lak is a major coffee-growing region, contributing more than 30% of the total coffee output of the country. A detailed description of the case study area can be found in the prior work of Pham et al. (2020). Coffee production systems are vulnerable to changing climate conditions (Bunn et al., 2015; Chemura et al., 2016; Jaramillo et al., 2011) and drought (Guido et al., 2018; Venancio et al., 2020) with decreases in coffee yield and loss of optimal coffee-growing areas likely to significantly affect coffee-producing countries and the livelihoods of millions of smallholder farmers (Pham et al., 2019). It is therefore necessary to examine climate-related impacts on coffee production and the opportunities for timely and proactive responses. Adopting the system dynamics methodology enables a comprehensive analysis and assessment of the behaviour over time of the whole coffee production system in interactions with changes in the ecological and socio-economic processes, and the formulation of appropriate intervention strategies that can inform decision-making.

The specific objectives of this research paper are as follows: (1) To build a modelling framework and adopt the merits of system analysis to better understand the dynamic behaviour of the Dak Lak coffee production system in response to various scenarios of climatic and non-climatic factors of the system given changing conditions; and (2) To evaluate potential intervention scenarios that can be used to inform policy recommendations, aimed at ensuring a sustainable and resilient coffee production system in the context of the case study region.

This study considers the notion that there are typically five key phases in the system dynamics modelling process. These include (1) problem structuring, (2) development of a dynamic hypothesis (*i.e.,* qualitative causal loop modelling), (3) formulation of a quantitative simulation model, (4) model testing, and (5) design and evaluation of scenarios (Maani and Cavana, 2007; Sterman, 2000). A prior study conducted by Pham et al. (2020) developed a causal loop diagram relevant to drought impacts on coffee production in Dak Lak using the first two phases of this process, with data retrieved from literature and interviews of 60 coffee experts and farmers in Viet Nam. The present study builds on this earlier work, applying the final three phases. This includes the development of a quantitative simulation-based model that is tested through various structural and behavioural assessments. The study also provides new pathways for the design and evaluation of a range of intervention scenarios against the business-as-usual scenario to support policy responses for the sustainability of coffee production in the study region.

2. Research methods and model development

2.1. Model design

While causal loop modelling is often useful in capturing the feedback structures influencing system behaviour, it is of qualitative nature so unable to simulate the dynamics of the system. Simulation models are therefore used to quantitatively model the dynamics – that is, the behaviour over time – of the system in order to understand the interactions between system components. The variables in the simulation model stemming from the causal loop diagrams are replicated as *stocks* that are the accumulations occurring in the system (e.g. population), *flows* that represent changes to stocks (either increases or decreases) during a period of time (e.g. births, deaths) and *converters* or *auxiliary variables* (e.g. birth rate, life expectancy) that are intermediate variables which can adjust flows (Maani and Cavana, 2007). Stocks, flows, and auxiliaries that can be constants, graphical relationships or mathematical functions, are connected to represent feedback loops that influence the dynamics of the system.

In this research paper, Stella Architect software (Version 2.0 from isee systems, one of developers of Systems Thinking and Dynamic Modelling software, https://www.iseesystems.com) is used to develop the stock-and-flow simulation model. The model structure includes three interrelated sectors, including coffee production, water resources, and population and socio-economic development that are restructured from the causal loop model formulated in Pham et al. (2020). Not all feedback loops were simulated in this study due to a lack of highly reliable data for the model inputs, which is often the case for regional farming locations in developing countries. Notwithstanding this constraint, the primary interrelationships that influence the dynamics of the system were able to be replicated in the developed model, and these were sufficient to simulate the impacts of drought on coffee production.

2.2. Model assumptions

- *Model run time:* The developed model was simulated in quarter-yearly time-steps over the period 2008–2050 with the calculation of stocks, flows and converters in each time-step adopted for the whole simulation phase. Model testing was then conducted for the 10 year period from 2008 to 2017, in order to compare simulated results of the model with historical data of key variables obtained from the Department of Agriculture and Rural Development of Dak Lak Province and the General Statistics Office, including coffee production, coffee area, harvested coffee area, coffee yield and the total population. The length of the simulation was more than 40 years to enable the long-term dynamics of the system under the influence of alternative intervention scenarios to be captured.

- *Model scope:* The boundary of the model was established to align with the boundary of the causal loop model as previously developed by Pham et al. (2020). To that extent, the causal factors such as coffee prices that might drive coffee expansion in the region, and pests, fertilisers and coffee varieties that influence coffee yield, were not included in the simulation model. As the model purpose is to focus on the impacts of drought and water availability on coffee production, these drivers to coffee production were considered as exogenous variables to the model scope and thus not accounted for.

- *Input data and model development parameters:* To enable the simulation, the model involves the identification of all relevant parameters including the initial values for stocks at the start of the simulation, and constants and graphical functions that represent auxiliary variables. Almost all initial values for stocks are data for the year 2008 (Table 1), except for rainfall figures which are observed data for Buon Ma Thuot station, Dak Lak Province from 2008 to 2017. Demographic and coffee-related figures were obtained from or calculated based on data from the General Statistic Office at national and provincial levels while data on water supply, demand and consumption were synthesized from publicly available published sources. Where data were not available, assumptions were made based on current literature and experts' suggestions collected from stakeholders in the study reported in Pham et al. (2020).

Auxiliary variables such as birth rate, coffee price, and evapotranspiration rate were assumed to remain unchanged in the simulation model. The sensitivity analysis presented in Section 2.5 below indicated that changes in these variables did not affect the dynamics of the system under investigation.

Graphical functions or dimensionless multipliers illustrate the effect of one element of the model on another element. They are used to adjust the value of variables through graphs that represent non-linear relationships between two variables where empirical data were not available (Maani and Cavana, 2007). These multipliers are dimensionless because the x-axis is the ratio between two variables with the same unit while the y-axis is the multiplier with no units. For example, the graphical function used for the "effect of irrigation on coffee production" dimensionless multiplier adjusts coffee production during the simulation based on the actual irrigation per hectare of coffee (Table S.1 in Supplementary material). The curve shape indicates that the y-axis multiplier increases at a decreasing rate, meaning it increases rapidly at first and then increases more slowly as the x-axis ratio (the actual irrigation/normal irrigation ratio) increases. When the actual irrigation is close to 0, the x-axis ratio will be also close to 0, making the multiplier close to 0. When this ratio increases but remains below 1, the multiplier will increase but not more than 1, making coffee production increase but not more than the normal production. When this ratio increases above 1, the multiplier will increase to slightly more than 1 but will soon reach its limit, because coffee production will not be able to increase infinitely in response to just an increase in the irrigation volume.

Table 1
The initial values of key parameters used in the system dynamics model.

Variable	Initial value	Unit	Reference
Coffee production sector			
Coffee area	182,434	Hectares	DARD (2018a)
Total arable land	182,434*1.15	Hectares	Assumption based on Dak Lak People's Council (2017)
Average number of jobs per hectare of coffee	2	Jobs/hectare	Assumption based on IDH and Technoserve (2013)
Initial harvest	173,233	Hectares	DARD (2018a)
Coffee production	415,494	Tonnes	DARD (2018a)
Normal coffee irrigation per ha	2500	Cubic metre/hectare	DARD (2018b)
Water resources sector			
Available surface water	1000	Million cubic metre	Assumption based on JICA (2018)
Available groundwater	600	Million cubic metre	Assumption based on NAWAPI (2018)
Actual recharge rate	3	%/year	JICA (2018)
Actual return flow rate	36.9	%/year	JICA (2018)
Actual surface flow rate	12.9	%/year	JICA (2018)
Evapotranspiration rate	10	%/year	Assumption
Groundwater storage capacity	700	Million cubic metre/year	NAWAPI (2018)
Surface water storage capacity	1850	Million cubic metre/year	DWRM (2019)
Allowable groundwater withdrawal fraction	0.55		Assumption based on NAWAPI (2018)
Population sector			
Population	1.715	Million people	GSO (2012)
Birth rate	1.96	%/year	GSO (2012)
Death rate	0.54	%/year	GSO (2012)
Immigration rate	0.37	%/year	GSO (2012)
Emigration rate	0.71	%/year	GSO (2012)
Initial labour force	888,422	People	GSO (2012)

2.3. Model description

The simulation model is an integrated model including three interconnected sectors that interact to create the behaviour over time of the system. Variables in one sector may influence variables in other sectors. The discussion below focuses on individual sectors in order to enable detailed analysis of the interrelationships between variables and the structural and behavioural assumptions of the model.

2.3.1. Sector 1: Coffee production

The coffee production sector shows the interrelationships between the area and output of coffee in Dak Lak and the factors influencing these (Fig. 1). Coffee production, total coffee area and harvested coffee area are presented as stocks for this sector and interconnected through various variables. In our model, coffee production is assumed to depend on irrigation and labour availability, as other factors including coffee varieties and fertilisers are excluded. Coffee area is determined by the total area of arable land in the region, the ratio between labour and job availability and coffee production. The total allowable arable land – the maximum land area available for coffee production – is assumed to be approximately 210,000 ha, or more than 15% of the total coffee area in 2008 – the first year of simulation. This figure enables close-to-reality simulation of coffee expansion dynamics, given historical data on the total coffee area over 2008–2017 in the case study area (Table S.2 in Supplementary material). The labour/job availability ratio, which is determined by the labour force divided by the number of jobs in coffee plantations, is one of the factors that can influence the expansion of the coffee area (IDH and Technoserve, 2013). Coffee expansion is also influenced by coffee production; the more coffee production increases,

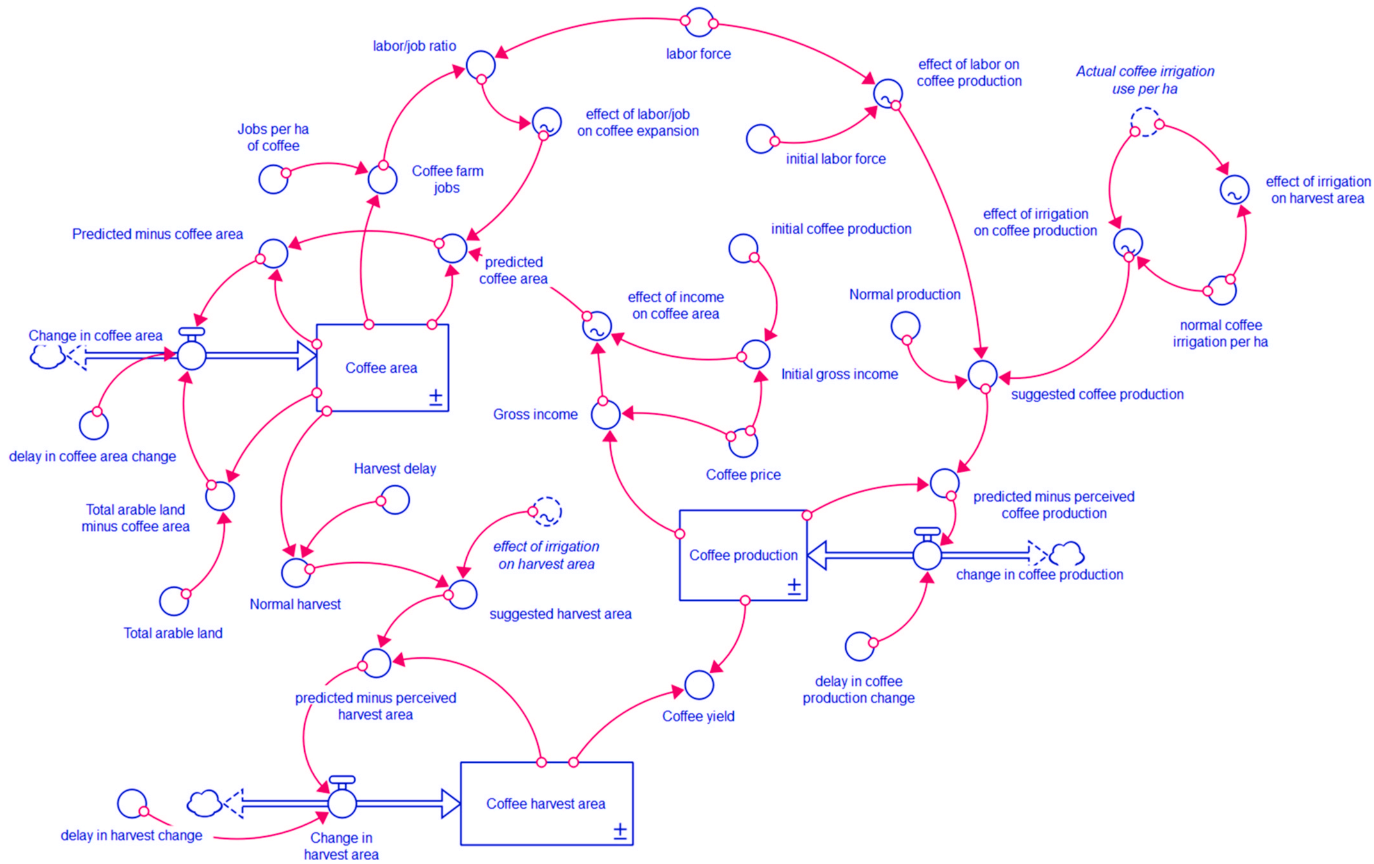

Fig. 1. Coffee production sector.

the higher the income farmers might achieve and the more the coffee area is expanded. Harvested coffee area is influenced by the total coffee area with a delay in harvesting due to a time lag in the maturation of coffee beans, and the irrigation volume applied. Actual irrigation water use for coffee per hectare determines coffee production and harvested area, and this is governed by the total irrigation water amount and the total coffee area. Coffee yield (tonnes/hectare) is simply defined by total coffee production per harvested coffee area.

2.3.2. Sector 2: Water resources

Fig. 2 depicts the water resource sector and how this can influence coffee production. There are only two seasons in Dak Lak province, rainy season and dry season, with water resources mainly recharging in the rainy season when rainfall accounts for approximately 85% of total annual rainfall. Available surface water depends on surface water inflows, which include runoff from precipitation and return flow from groundwater to rivers, and surface water outflows, which comprise evapotranspiration, surface water consumption and surface water overflow (JICA, 2018). Surface water use is, in turn, determined by available surface water and surface water demands from various sectors. Domestic and industrial water demands depend on population and socio-economic development, which is investigated in the following sector. As water demand for coffee production contributes significantly to the total water demand of the agricultural sector in Dak Lak (JICA, 2018), agricultural water demand is quantified on the basis of irrigation water demand for coffee. Surface water overflow depends on the capacity of the surface water reservoirs. When available surface water plus the net flow (total inflow minus total outflow) exceeds storage capacity, overflow will occur.

Groundwater availability is governed by groundwater inflow, which mainly recharges in the rainy season (CHYN, 2015), and groundwater outflows, which include evapotranspiration, groundwater consumption and groundwater overflow. Similarly, groundwater water use is dependent on available groundwater, and agricultural (mostly irrigation), domestic and industrial water consumption demands, as described in the following sector. Approximately 60% of irrigation water volume for coffee is extracted from groundwater through dug and drilled wells while the remainder is withdrawn from surface water resources including reservoirs, artificial ponds, rivers, lakes and streams (D'haeze et al., 2005b). Irrigation in the coffee production system occurs in the dry season while groundwater is mostly recharged in the rainy season. Thus, in the event of drought, farmers frequently face drying wells as water extraction is likely to reach the maximum groundwater withdrawal capacity. Due to the heterogeneous topography of Dak Lak, the capacity of groundwater extraction might vary due to several factors; however, this is excluded from our model due to limited data and information. Groundwater overflow is influenced by the groundwater storage capacity and occurs when groundwater supply exceeds the storage capacity of the groundwater system.

Surface and groundwater consumption will determine the actual irrigation surface and groundwater amount available for each hectare of coffee, and thus, coffee production and harvested area, as described for the previous sector.

2.3.3. Sector 3: Population and socio-economic development

In our model, population is considered as one of the main drivers of both the coffee production and water resources sectors (Fig. 3). Population growth, triggered by massive migration to Dak Lak in previous decades, provides an increased labour force for coffee production, leading to further coffee expansion (Pham et al., 2020). In our model, population dynamics are determined by birth and immigration as inflows and death and emigration as outflows. The birth rate and death rate are assumed to remain unchanged during the simulation period. As available jobs on the coffee farms attract more migrants to the province,

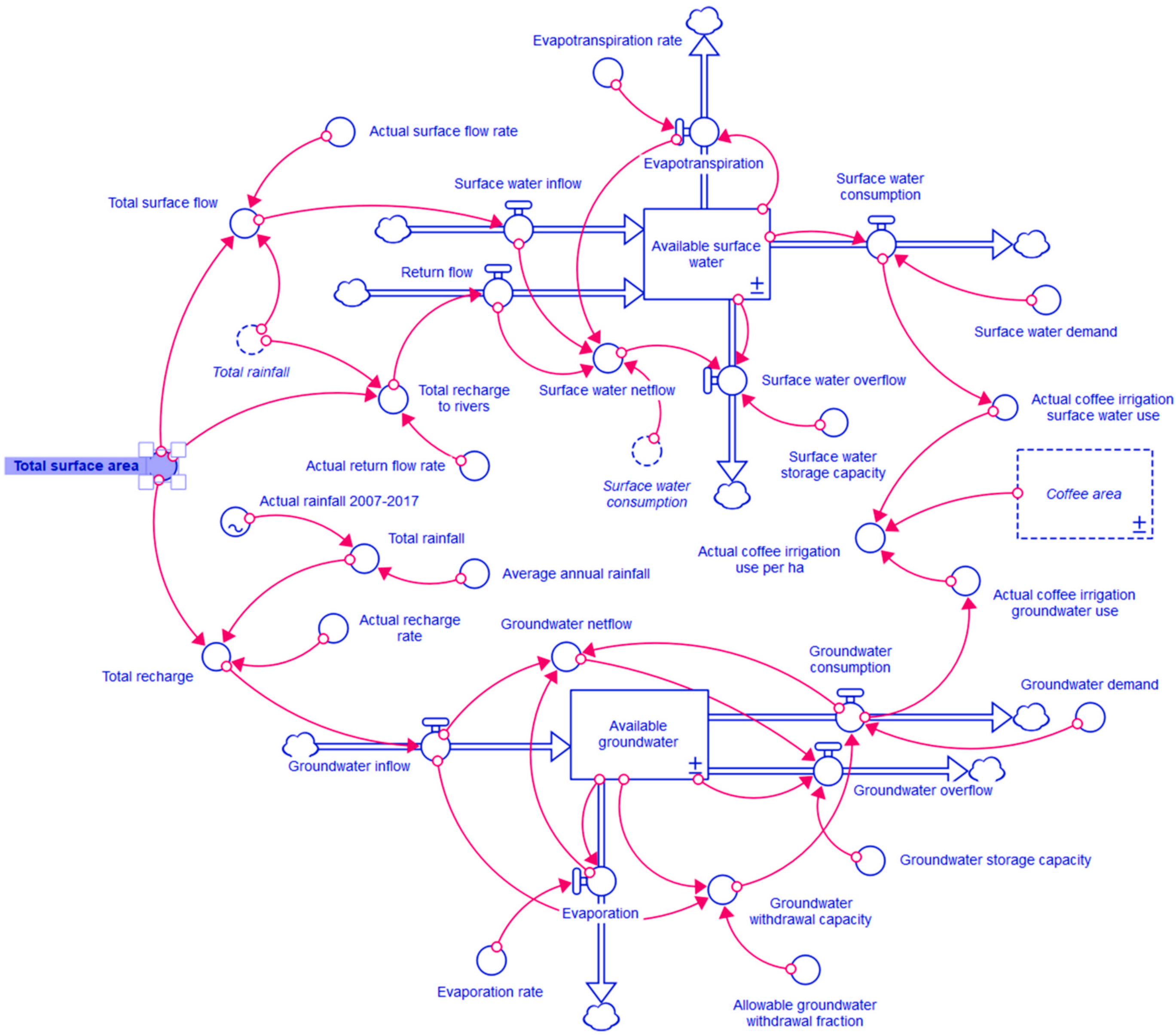

Fig. 2. Water resource sector.

immigration is influenced by a dimensionless multiplier called job attractiveness, which is defined based on the ratio between the labour force and available jobs in the coffee farms. As the labour/job ratio decreases to less than 1, job attractiveness will increase due to more jobs available than labour, attracting higher levels of immigration (Table S.1 in Supplementary material). The emigration rate is influenced by water availability. Smallholder farmers might leave the province for employment outside in the context of water shortages due to severe or long-lasting droughts.

Population increase, in turn, leads to growing domestic and industrial water demands. These demands are linked to the size of the population, domestic and industrial water demand per capita, and the availability of surface and groundwater. Agricultural water demand, which is also indirectly fuelled by population growth, is simplified through quantifying irrigation water demand for coffee production and modelled in the agricultural and water sectors above.

2.4. Model testing

The simulation model was tested using structural and behavioural validity tests to check if the model structure can adequately represent the structure of the real system and if the model can generate adequate behaviour compared to the patterns observed in reality (Barlas, 1989; Sterman, 2000). For structural assessment of the model, conservation of matter, dimensional consistency and structural verification tests were applied, while for model behaviour validation, extreme condition and behaviour reproduction tests were undertaken (Barlas, 1989; Sterman, 2000).

The conservation of matter test is to check if the model violates the basic physical laws; this means that a stock must never become negative and the change in a stock at any step must be equal to the net flow which is the sum of inflows minus outflows. For example, a stock such as available groundwater will never drop below zero and a change in this stock should be equal to the sum of groundwater inflows minus the sum of groundwater outflows which, in the water resource sub-model, include groundwater consumption, evapotranspiration and groundwater overflow. The dimensional consistency test is to inspect the units of measure for all variables to detect any flaws due to unit errors, and to examine the model equations for questionable parameters and relationships assigned to them. Structural verification means that all

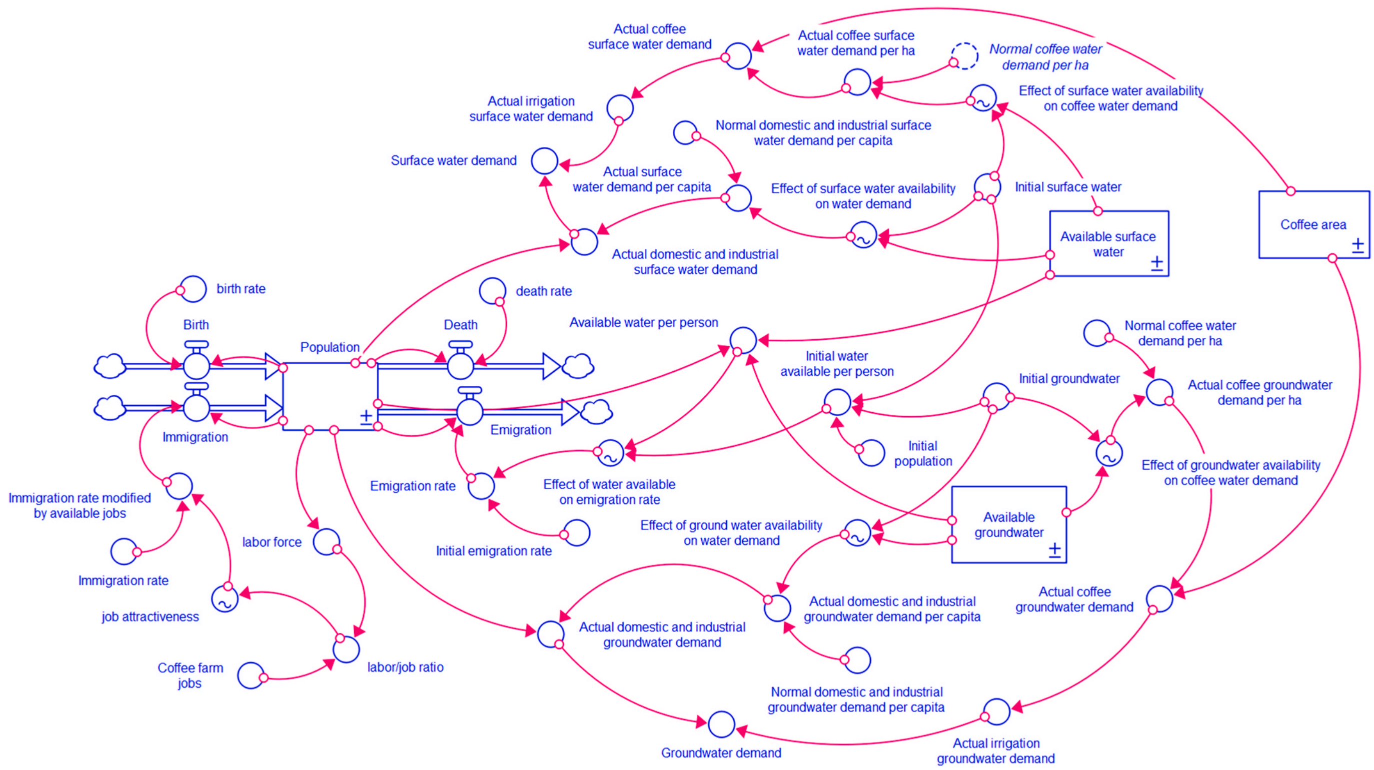

Fig. 3. Population and socio-economic sector.

structural components of the model should produce acceptable behaviour as anticipated; specifically, reinforcing and balancing feedback loops should reveal accurate polarities and behaviours (Barlas, 1989; Sterman, 2000).

The extreme condition test is to check if the model produces acceptable behaviour when extreme values such as zero or infinity are applied in model inputs (Sterman, 2000). For example, if there were no precipitation and water inflow running to the catchment, available water, harvested coffee area and production should all collapse after potential delays, meaning that the model structure replicates the real system it represents. In this study, two extreme conditions including extreme values for precipitation and for population-related variables were applied to test the robustness of the model.

For behaviour pattern evaluation, a discrepancy coefficient (U) was used at the final step, after the model passed all prior validation tests, to measure the divergence between the simulated behaviour and observed data of main variables (Barlas, 1989). The values of U range from 0 (perfect predictions) to 1 (worst predictions); a model may be considered as good to average where U ranges between 0.4 and 0.7 (Barlas, 1989). In this study, four key parameters were selected for the model behaviour pattern validation: total population, harvested coffee area, coffee production and coffee yield. The simulated trends of these variables were compared to their historical data over ten years from 2008 to 2017 and reflected in the values of U.

2.5. Sensitivity analysis

Since there are uncertain values for a number of parameters and structural relationships in the simulation model, sensitivity analysis was undertaken to increase confidence in the robustness of the conclusions given the uncertainty in the model's assumptions (Sterman, 2000). This allows evaluation of how the model will behave in response to variations in model parameters (Maani and Cavana, 2007) and identification of the variables that most affect the dynamics of the system, enabling the generation of informed policy recommendations for decision-making (Sušnik et al., 2012). Several steps were performed in the sensitivity analysis, including selecting parameters and graphical functions whose values were based on uncertain information or that are likely to impact the model behaviour, and then adjusting each by ±10% of their initial values while keeping other variables fixed. In the last step, parameters that were found to significantly affect the behaviour of the model, as presented in the Supplementary material, were analysed to form a basis for the design of intervention scenarios (Maani and Cavana, 2007). In the following section, we present results of the sensitivity analysis of the model that represent how coffee production and harvested area behave based on changes in selected model parameters and graphical functions.

2.6. Policy scenario design and evaluation

Policy design and analysis play an essential role in the modelling process (Sterman, 2000). This often includes simulation of the model with a range of policy parameters using the existing model structure, then adjustment of the model structure to examine the influence of various policies on decision-making (Maani and Cavana, 2007). Based on the sensitivity analysis which resulted in a set of parameters that most influence the behaviour of the model over time (Figure S.1 in Supplementary material), a suite of policy scenarios was developed and simulated between 2008 and 2050 to understand how coffee production might change under different conditions. This process consisted of a number of trials with various combinations of model parameters, which were adjusted to examine the behaviour of the model under these changes. Specifically, scenarios with changes in individual parameters selected in line with current provincial development plans and existing studies (e.g. a 10% decrease in the total land area available for coffee, representing land-use control for coffee production that meets local management's objectives) and a combination of these scenarios were run. It would likely be advantageous to involve stakeholders including decision-makers and researchers in this step through consultation workshops on policy design and analysis (Maani and Cavana, 2007). While logistical constraints meant that this was unable to be undertaken within this study, this would be beneficial in future research.

In the base-case or business-as-usual scenario (S1), policy interventions were assumed to be absent over the simulation period. Five policy scenarios were then simulated (Table 2) under three conditions: normal rainfall (equal to the average annual value), low and high rainfall (15% lower and 10% higher, respectively, than the average value). Latest climate change scenarios for this region project possible increases in annual rainfall but decreases in the dry season in the coming decades (MONRE, 2016). Whereas it is not possible to predict drought conditions over a certain period in the future, a scenario where rainfall reduces by 15% compared to the average value (representing the drought status in the region) was simulated to investigate how dry conditions impact coffee production. The high-rainfall scenario represents water abundance for irrigation and socio-economic development in line with climate change scenarios developed by the Ministry of Natural Resources and Environment (MONRE, 2016) with rainfall predictions for Dak Lak. Details of each scenario simulated for analysis of potential policy intervention measures are presented below:

- *Land-use control (S2):* In this scenario, coffee expansion is limited by reducing the total area of arable land available for coffee. Coffee cultivation in the region has been growing beyond the planned areas, taking over existing cultivated or forested land (D'haeze et al., 2005a; Meyfroidt et al., 2013). Currently, the total coffee area is approximately 200, 000 ha, which exceeds the 2017 provincial plan for sustainable coffee production for 2020–2030 b y 20,000 ha. We examined a scenario that restricts the total area of arable land for coffee to slightly lower than 190,000 ha, a 10% decrease of the current area of arable land.

- *Water-saving irrigation (S3):* Stakeholders contributing to the study on the impacts of drought on coffee production in Dak Lak Province reported in Pham et al. (2020) emphasised the importance of water-saving irrigation measures, which could reduce labour and energy costs for coffee smallholder farmers. Application of approximately 1200 L of water per coffee plant per year was recommended to maintain a 4 tonnes/hectare coffee yield (Amarasinghe et al., 2015); this is considerably less than the normal irrigation amount currently applied by farmers, indicating that there are potential water savings to be made. Following this, we simulated a scenario where the normal irrigation amount per hectare of coffee is reduced by 25% compared with the current amount as presented in Table 1.

- *Reservoir increase (S4):* Based on the results of the sensitivity analysis, and given the distinct seasonal climatic characteristics of the region where rainfall in the rainy season accounts for more than 85% of total annual rainfall, this scenario reflects a 10% increase in surface water storage capacity. This investigates the impact of increasing the storage capacity of reservoirs in the region to supply more water in the dry season for domestic, agricultural and industrial water use. The results of the sensitivity analysis indicate that the fraction for groundwater withdrawal is also a major influencing parameter. However, while groundwater levels fluctuate significantly between seasons and are often very low or depleted in the dry season (CHYN, 2015; Pham et al., 2020), intervention scenarios for groundwater are not considered in this study.

- *Best-case scenario (S5):* A combination of the above-mentioned scenarios, where the total arable land for coffee production and the irrigation water amount per hectare of coffee are minimized by 10% and 25%, respectively, while surface water storage capacity is increased by 10% was also simulated.

- *Worst-case scenario (S6):* A scenario where the total arable land and the normal irrigation amount per hectare of coffee are both increased by 10% and no strict control measures are enforced, which is likely to occur under the current circumstances, is also simulated to represent the worst-case among all simulation scenarios of the model.

3. Results and discussion

3.1. Model testing

The results of structural tests indicated that the developed simulation model can reproduce rational behaviour. Specifically, the model did not violate the conservation of matter test with stocks remaining positive even under extreme conditions and any changes in stock equating to the net flow. In the extreme condition tests, the behaviour of the model was evaluated in response to extreme values for precipitation and population-related parameters. Test results show that the trends of all stocks behave logically with population, coffee area and production falling towards 0, indicating that the model performs well even under extreme conditions and can be reliably used for policy design and evaluation.

Fig. 4 represented the results of behaviour replication tests performed by a comparison between model simulation outputs and historical data. Generally, model results have the same trend as historical data. Discrepancy coefficients (U) of key variables are within the range of a good-to-average model, *i.e.,* between 0.4 and 0.7 (Barlas, 1989). These values are not quite close to 0 (perfect predictions), possibly due to uncertainties related to the model structure when not all relationships have been captured or attributed to assumptions generated for model parameters and graphical functions when data were not available. For example, in 2009 there was a decline in coffee production; which is likely due to an increase in the area of aging trees as well as the consequences of a typhoon that caused a loss in coffee cherries (IPSARD, 2009). Our model, which was restricted by the availability of empirical data and understanding of the relationships between coffee production and factors other than irrigation, including coffee varieties, fertiliser inputs, and cultivation and harvest practices and techniques, has yet to capture such influences. Nonetheless, the goal of system dynamics models is to enhance our understanding about the behaviour over time of the system under different conditions rather than to generate precisely simulated values of the model variables (Sterman, 2000).

3.2. Sensitivity analysis

Sensitivity analysis was conducted to identify which parameters are most likely to influence the behaviour of the model. Since the aim of the

Table 2
Policy scenarios for coffee production in Dak Lak.

Policy parameters	Base-case and intervention scenarios with the percentage of change compared to the base-case					
	S1 Base-case (No intervention)	S2 Land control	S3 Saving irrigation	S4 Reservoir increase	S5 Best-case	S6 Worst-case
Total arable land	209,799 ha	−10%	0%	0%	−10%	+10%
Normal coffee irrigation per ha	2500 m^3/ha	0%	−25%	0%	−25%	+10%
Surface water storage capacity	$1.85.10^9$ m^3/year	0%	0%	+10%	+10%	0%

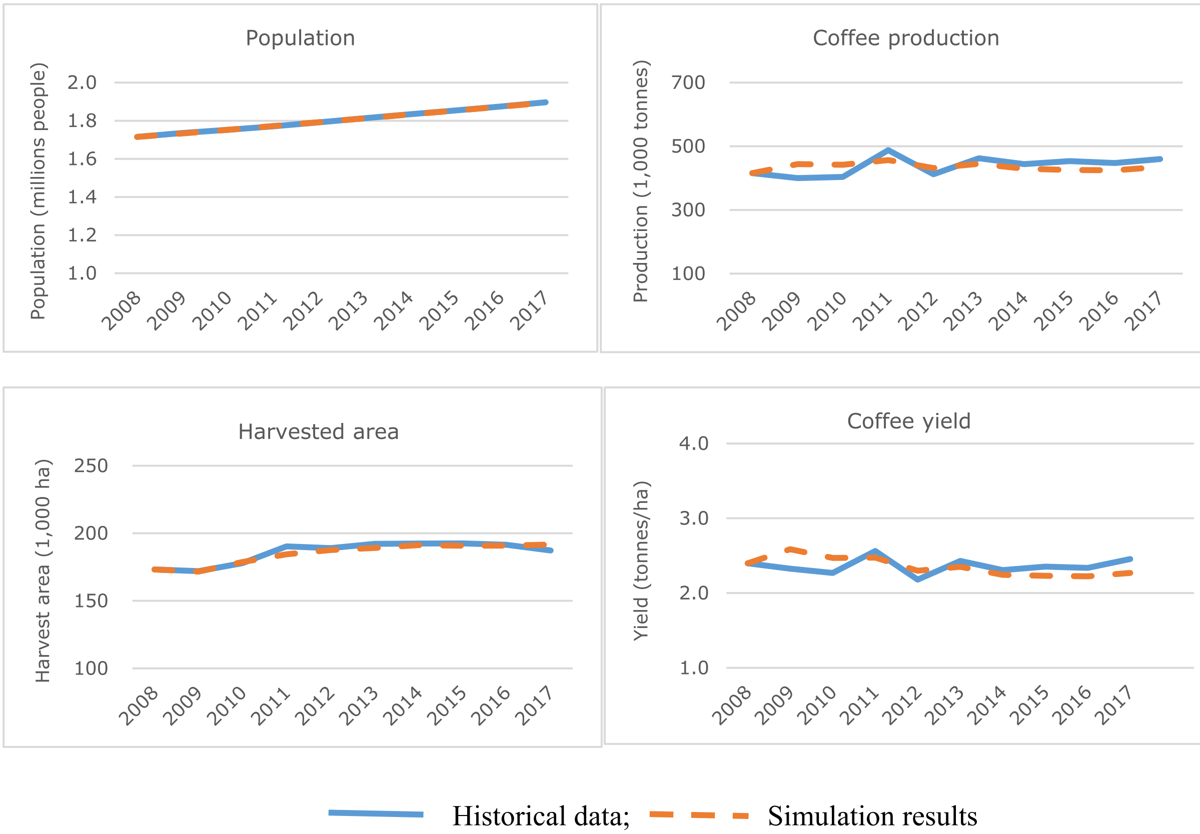

Fig. 4. A comparison of the behaviour of simulation outputs with historical data for population, coffee production, harvested area and yield.

model is to investigate how coffee production behaves under drought and water availability conditions, the percentage of change in coffee production and harvested coffee area were evaluated in response to changes in selected model parameters. Results indicate that coffee production and harvested coffee area are most sensitive to changes in the irrigation amount per hectare of coffee and the total area of arable land available for coffee, while the fraction of groundwater withdrawal, groundwater recharge rate, precipitation and reservoir capacity are also likely to have substantial impacts (Figure S.1 in Supplementary material). Variations in the values of other auxiliary variables that were assumed to be constants are insignificant to the model behaviour. Changes in the dynamics of the model in response to variations in model parameters of up to 15% indicate low-to-moderate sensitivity of the model (Maani and Cavana, 2007). This implies that no single model parameter could, on its own, considerably change the dynamics of the system that the model represents and provides significant implications for the design of policy scenarios in the following step.

3.3. Policy scenario analysis

The simulation results of the base-case or business-as-usual (BAU) and policy intervention scenarios are presented in Fig. 5. For the BAU scenario, coffee production and yield decrease in years when drought conditions occurred such as 2012 and 2016. Under this scenario, coffee production and harvested area are predicted to plateau around 2040 at approximately 435 thousand tonnes and 195 thousand hectares, respectively, leading to a peak in coffee yield at the same time of 2.23 tonnes/hectare. This is associated with a peak in surface and groundwater availability, which in the model determines the maximum irrigation water amount available for coffee.

Key variables of the model exhibit the "limits to growth" behaviour in all scenarios as the system reaches the carrying capacity of land and water resources, with the exception of population which will most likely continue to grow exponentially over the simulation period, resulting in increasing domestic and industrial water demands. This upward tendency will likely contribute to increasing water shortages in the region in the future, affecting coffee cultivation, with coffee production and yield quickly reaching their peaks within the simulation time.

Under 'normal rainfall' conditions, when total annual rainfall equals average annual rainfall, the maximum growth in coffee production and yield is expected to occur under the S5 scenario – reaching approximately 474 thousand tonnes and 2.64 tonnes/hectare, respectively, by 2050 – when a combination of policies including land-use control, water-saving irrigation and increased reservoir storage is enforced (Table 3). Individual scenarios on water-saving irrigation (S3) followed by restrictions on the total land area available for coffee expansion (S2) result in lower volumes of coffee production compared to S5 but better outputs compared to the BAU scenario. Conversely, for yield, better results are achieved in S2 followed by S3, as the harvested coffee area is more restricted under S2 than S3, causing lower yield values. The adoption of water-saving irrigation practices is unlikely to reduce coffee yields but will result in overall improved outcomes. This result confirms previous findings in the literature (Amarasinghe et al., 2015) associated with improved coffee yields under water-saving irrigation regimes compared to existing practices applied by many farmers. Apart from optimised irrigation achieved through changes in irrigation practices, advanced technologies including drip irrigation and water harvesting (Baca et al., 2014; Perdona and Soratto, 2015) can also be applied to reduce water usage in coffee production systems in the region.

In relation to the land-use control scenario, setting restrictions on the total area of arable land available for coffee cultivation is likely to generate improved values for coffee production compared to the BAU scenario. Stabilising the coffee area (Ahmad, 2001) is likely to minimize further adverse consequences on the environment, including deforestation (De Koninck, 1999) and subsequent groundwater depletion (Ahmad, 2001; D'haeze et al., 2005b), as well as water resource

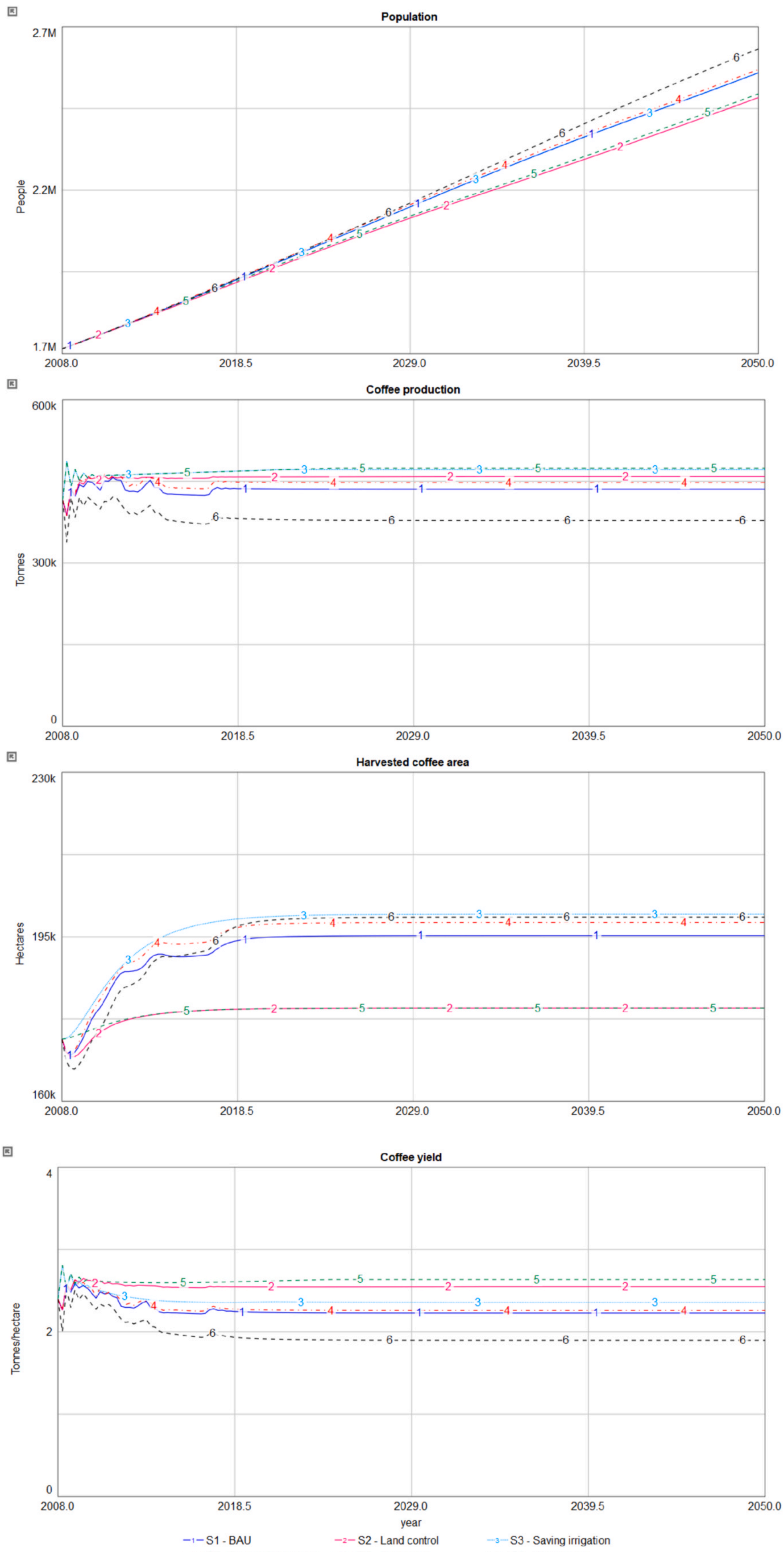

Fig. 5. Behaviour of key variables under the base-case and different policy scenarios under 'normal rainfall' conditions.

Table 3
Values of key variables by 2050 under base-case and policy scenarios under different rainfall conditions.

	S1 Base-case (No intervention)	S2 Land control	S3 Saving irrigation	S4 Reservoir increase	S5 Best-case	S6 Worst-case
Coffee production (tonnes)						
Normal rainfall	435,403	458,551	471,177	447,440	474,110	378,001
Low rainfall	421,982	455,271	470,104	434,019	473,913	364,470
High rainfall	455,117	459,451	472,788	457,765	474,110	396,214
Harvested coffee area (hectares)						
Normal rainfall	195,276	179,828	199,809	198,060	179,828	199,193
Low rainfall	192,172	179,828	199,809	194,956	179,828	194,192
High rainfall	199,809	179,828	199,809	199,809	179,828	204,834
Coffee yield (tonnes/hectare)						
Normal rainfall	2.230	2.550	2.358	2.259	2.636	1.898
Low rainfall	2.196	2.532	2.353	2.226	2.635	1.877
High rainfall	2.278	2.555	2.366	2.291	2.636	1.934

over-exploitation and consequent water scarcity (Pham et al., 2020).

An increase in surface water storage capacity (S4) will likely drive an increase in coffee production and yield over the BAU scenario; however, the production system is likely to be less influenced by reservoir expansion for surface water storage compared to land-use control and water-saving irrigation measures. This is also reflected in the results of the sensitivity analysis when the expansion of reservoirs is likely to cause minor changes in coffee production.

Although an increase in harvested coffee area is expected to occur under the worst-case scenario (S6), this is unlikely to lead to a similar increase in coffee production and yield. This is because, when both the total area of arable land and the irrigation amount for coffee increase, the total coffee area and the harvested area will be maximised, but the actual irrigation amount per hectare of coffee will fall over time due to water shortages, causing a decline in coffee production.

Similarly, under low and high rainfall conditions, maximum growth in coffee yield is expected to occur under the S5 scenario, followed by S2 and S3 while the least growth will most likely occur under S6. This again emphasises the significance of land-use controls to limit coffee expansion and the adoption of water-saving irrigation practices, which in combination will likely maximise the benefits for current coffee farmers in the region. On the other hand, uncontrolled land-use enabling expansion in the proportion of the total area of arable land used for coffee cultivation by 10%, and irrigation practices that increase water usage by 10% will most likely result in a considerable reduction in coffee productivity in the region compared to the current situation. Without policy interventions, even with increasing rainfall, coffee yield is expected to only slightly increase over the BAU scenario. In the worst-case scenario (S6), when both land and water resources are exploited to the highest levels, coffee production and yield are likely to plummet under any rainfall conditions. It should be noted that for all rainfall conditions, there are likely just small variations in the values of coffee yield under the same scenario. These results suggest that rainfall, including drought conditions, might not be the most significant variable influencing coffee yield and that non-climatic factors associated with land and water use dynamics might be of more importance. It is these key drivers that appear to profoundly impact coffee cultivation in the case study region, representing the greater variation in the value of coffee outputs among different intervention scenarios for these drivers.

It is noteworthy that the best-case scenario (S5) will likely produce relatively similar outcomes for both coffee production and yield (Table 3), reaching approximately 474,000 tonnes and 2.64 tonnes/hectare, respectively, by 2050 under any rainfall conditions. The S3 scenario with the adoption of water-saving irrigation practices might result in better coffee production outcomes than the S2 scenario representing land-use controls; however S3 on its own may also result in increased water availability enabling more coffee area to be irrigated and harvested. Consequently, the S3 scenario is likely to generate lower yields than S2 over time. These findings have substantial implications for decisions about whether it is more beneficial, in the long term, to allow coffee production to achieve the highest volume over the greatest area of total arable land (S3), or to reach the lower volume over a restricted land area available for coffee cultivation (S2). The best-case scenario (S5) will likely enable highest production over a restricted cultivated area which will be more economically and ecologically sustainable in the long term. On the contrary, uncontrolled exploitation of land and water resources (S6) will most likely result in negative outcomes for coffee production compared to the current situation, as the system will likely soon collapse once these critical natural resources reach their 'limits to growth'.

Overall, the best scenario with a combination of land-use control and water-saving irrigation measures appears to produce the greatest benefit to coffee production in the region. Economically, optimal irrigation practices will also help to reduce labour, fuel and energy costs associated with water exploitation, particularly in Dak Lak where widespread groundwater withdrawal prevails. This result plays an essential part in confirming the significance of water-saving irrigation practices, contributing to encouraging irrigation practice change among coffee farmers and water efficiency irrigation technology adoption in coffee production systems in Viet Nam.

In terms of land-use change for coffee production, strict enforcement including forest protection is required to increase the effectiveness of land-use control measures. Substitute livelihoods should be provided to those who live on the edge of the forest (Pham et al., 2020) and fragile areas (Ahmad, 2001) that are unsuitable for coffee cultivation to minimize further deforestation, water resource depletion and unsustainable agricultural development in the region.

4. Study limitations

While the model presented in this study has advantages in predicting future trends in the absence of high-quality data, a number of limitations require consideration prior to applying the model results to a broader context. The model generally captures key feedback loops in the causal loop model presented in Pham et al. (2020) about the dynamics of drought impacting coffee production in Dak Lak; however, not all feedback loops were included. Specifically, the model does not capture the complexity of the groundwater system and its interrelationships with deforestation which has prevailed in the region.

The model also relies on an assumption that farmers have only one land-use choice, following the provincial sustainable coffee production plan, which does not account for the presence of other crops through adaptation measures such as crop diversification. While research on the potential synergies and trade-offs of intercropping and shading practices in coffee farms is being investigated, it would be more beneficial to integrate this application into broader system dynamics models.

The modelling of coffee production dynamics presented here does not include other factors influencing coffee production, such as coffee varieties, fertilisers, production costs and cultivation techniques, and the complexity inherent in rainfall variability. While detailed climate change scenarios for the case study area only provide the percentage of change over decades, the model relies on limited data on the average value of annual rainfall, resulting in relatively linear outputs over time. Application of detailed climate change scenarios with rainfall data at time scales lesser than decades would likely provide improved inputs for the system dynamics model and thus enhance projected outputs.

Addressing the above shortcomings will require intensive data and additional empirical work. Nonetheless, our study's aim was to design a model to improve understanding of the long-term dynamics of the coffee production system in response to various scenarios given changing conditions, rather than focus on accurate prediction outputs of system variables, which is the core nature of system dynamics modelling (Barlas, 1989; Sterman, 2000).

5. Conclusions

This study presents an approach based on a whole-of-system view to understand the dynamics of drought impacts on agricultural development using a case study in a coffee production system in Viet Nam. A detailed investigation of the feedback interactions between the system components enables the key dynamics influencing coffee production and the effects of changes on system behaviour to be identified. The test results of the output of the system dynamic model verified its ability to satisfactorily reproduce the historical behaviour of the system it represents. It is noteworthy to recognize that, while drought is one of the factors impacting coffee production, it is not the most decisive factor determining the sustainability of coffee production. Our model results indicate that water- and land-use drivers and their interactions with ecological and socio-economic factors play a more significant role and that it is this dynamic that drives sustainable coffee production in the region. Drought conditions might exacerbate problems related to water scarcity for irrigation under the current circumstance but their impacts could be substantially minimized through applying a set of policy interventions including land-use control and the adoption of water-saving irrigation practices with an option of increasing surface water storage capacity. The best-case scenario that allows coffee outputs to reach the potential maximum which most benefits coffee farmers in the region is a strategy that combines all of these policies, while the worst will likely be the case when exploitation of land and water resources continue to increase beyond current levels.

While the model findings add insight into designing management strategies, a number of issues should be considered before applying the model results to a broader context. Owing to data limitations, the model parameterization depends on a range of assumptions. No model can perfectly represent reality, but additional empirical research that could improve these assumptions will most likely enhance modelling accuracy. The model does not account for the detailed dynamics of the water resource sector, particularly the complexity of groundwater and its interrelationships with vegetation cover changes as a result of coffee cultivation, the effects of shading and intercropping on coffee farms, and other technical factors influencing coffee production. It is also noteworthy to acknowledge that farmers might have more land-use choice than coffee alone; thus, future work is required to investigate the impacts of adaptation measures, such as crop diversification through intercropping and shading, on the efficiency of coffee cultivation, which is encouraged in the provincial sustainable agricultural production plans. Within our current study, it must be acknowledged that addressing these issues would involve an inclusion of a wider and more detailed system dynamics model with additional sectors, requiring access to high quality empirical data or assumptions based on more extensive stakeholder engagement. While this will undoubtedly be advantageous for decision-making on sustainable crop production, it is imperative to undertake proactive measures to address problems associated with land and water resource use that are most likely to dominate in the near future in order to ensure the viability of agricultural production and to protect the livelihoods of the people reliant on that, and to balance with socio-economic development in general.

CRediT author statement

Yen Pham: Conceptualization, Methodology, Formal Analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Kathryn** Reardon-Smith and Ravinesh C. Deo: Conceptualization, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112790.

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Supplementary material

"Evaluating management strategies for sustainable crop production under changing climate conditions: a system dynamics approach"

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Number of tables: 2

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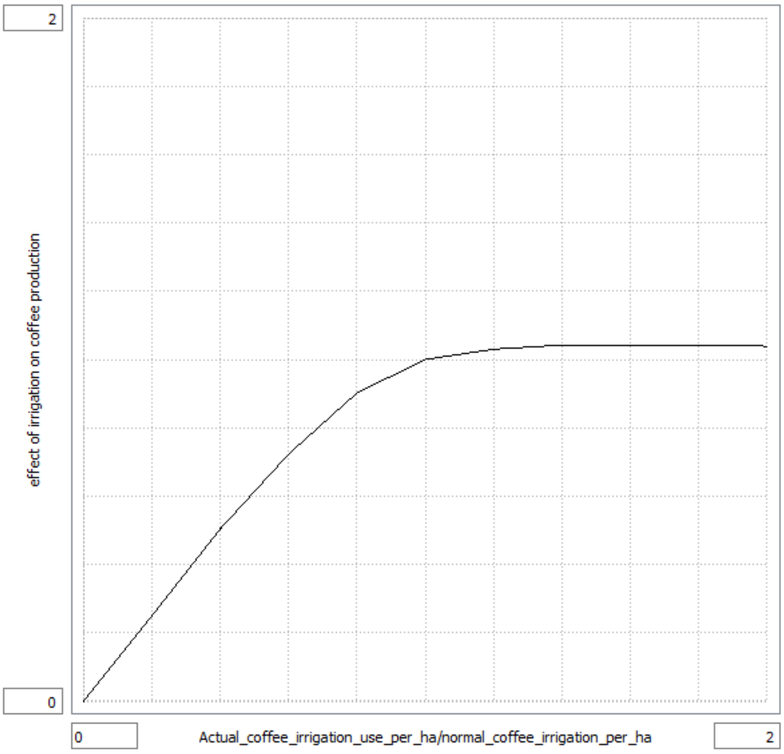
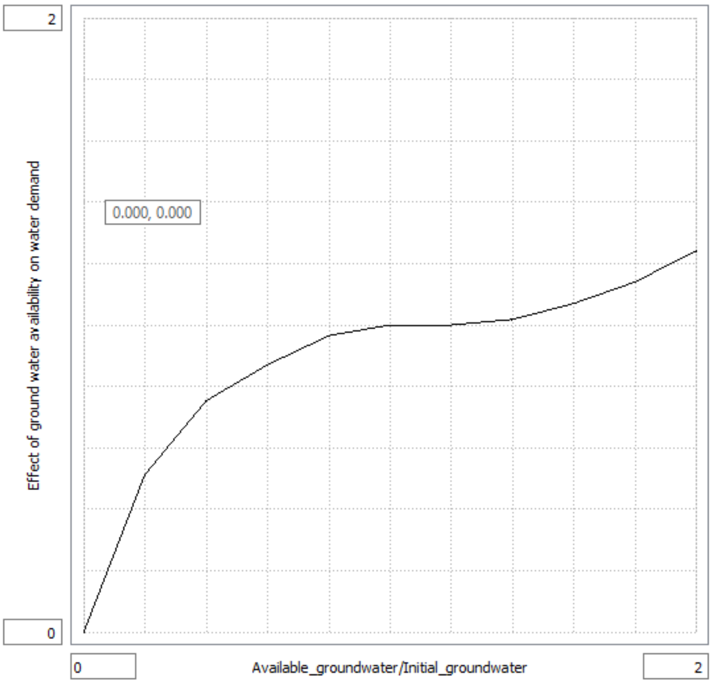
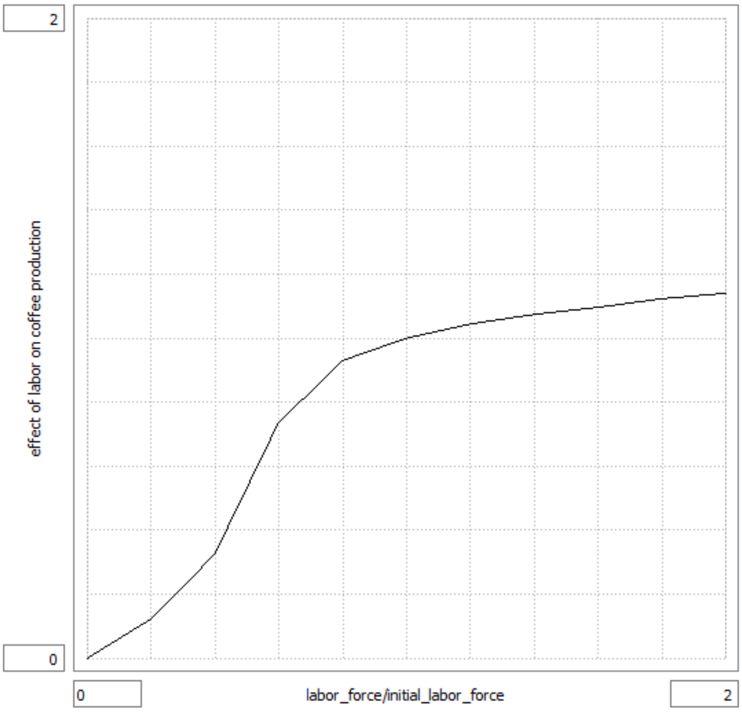
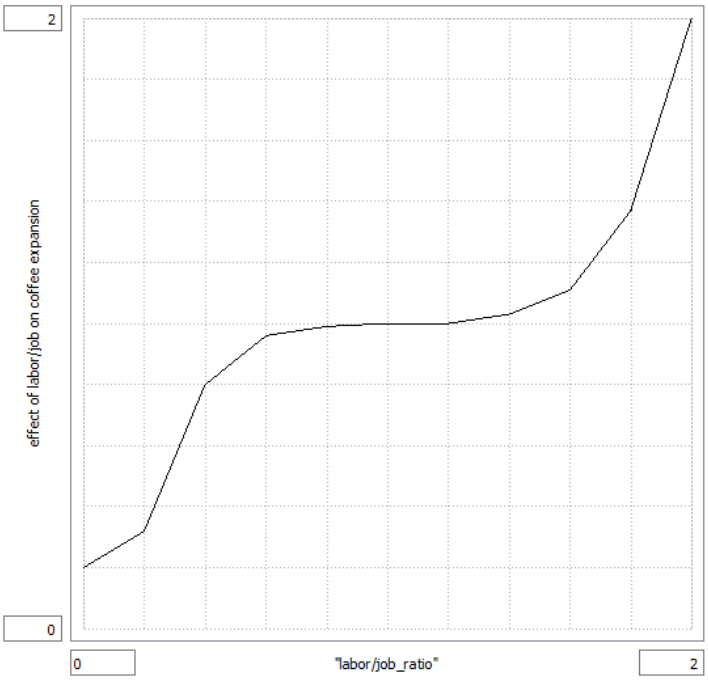
Table S.1. Key dimensionless multipliers used in the model based on assumptions

Variable	**Value**
Effect of irrigation on coffee production	
Effect of ground water availability on water demand	

Effect of labour on coffee production	
Effect of labour/job on coffee expansion	

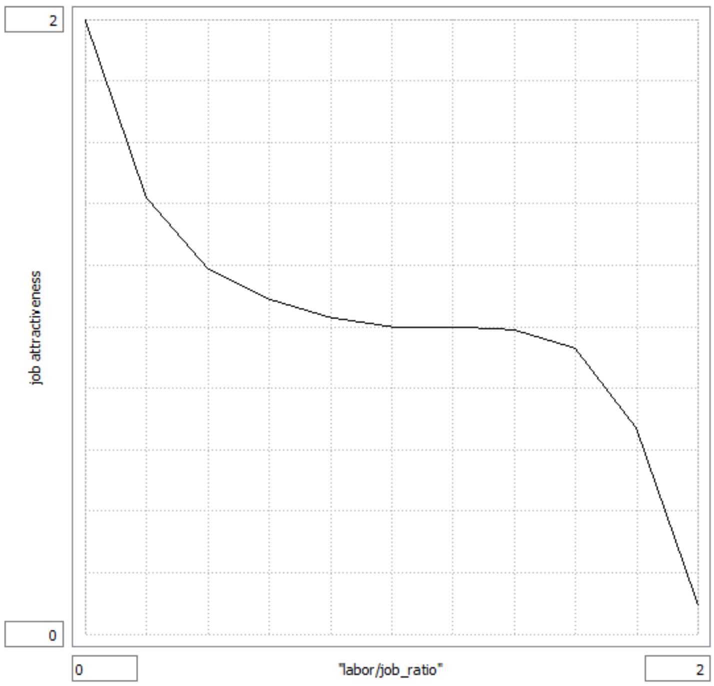
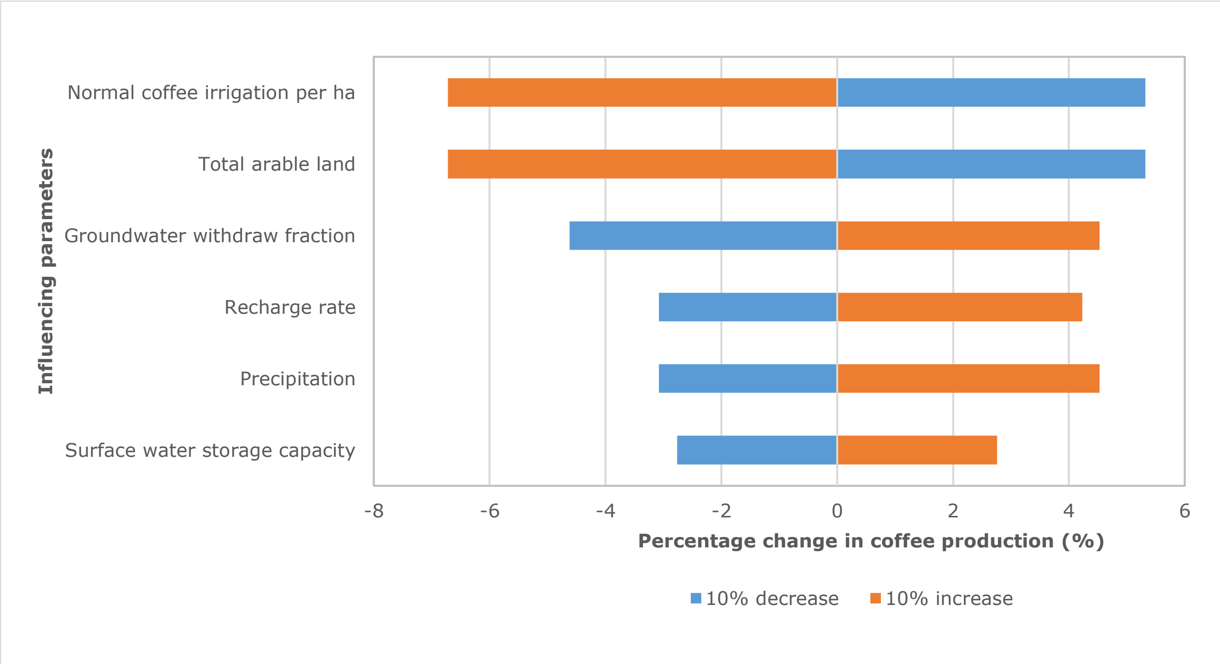
Job attractiveness	

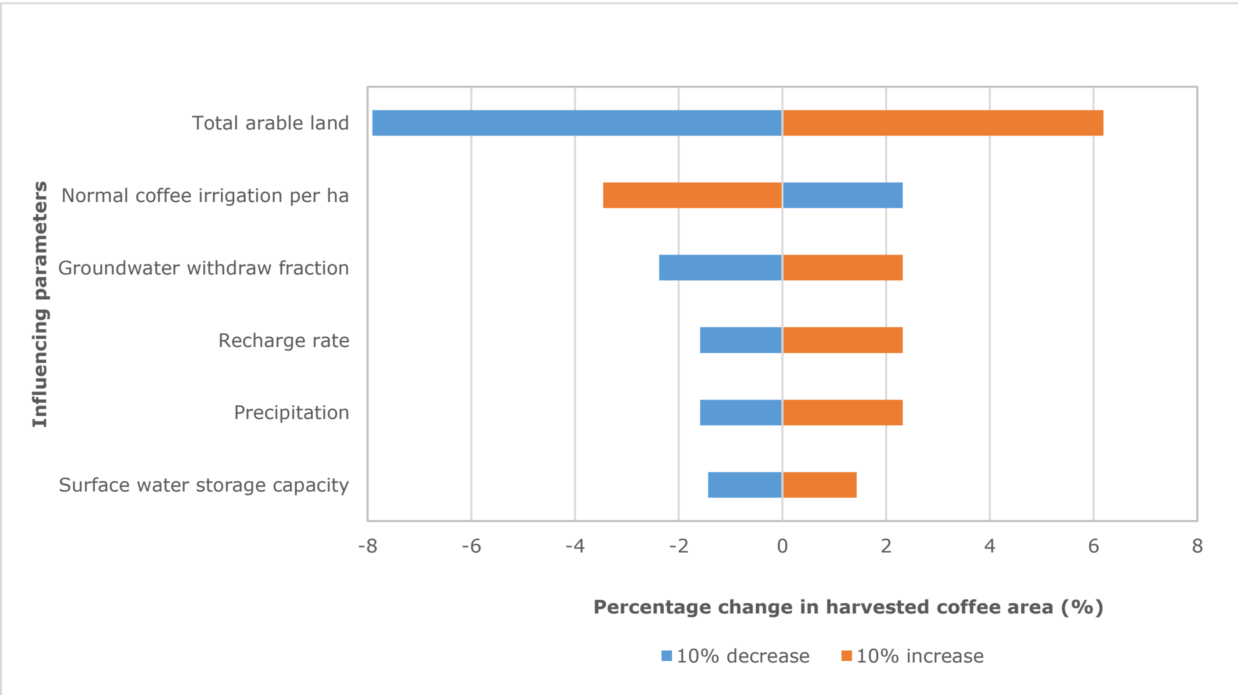
Table S.2. The total and harvested area of coffee in Dak Lak Province from 2008 to 2017

(Source: Department of Agriculture and Rural Development of Dak Lak Province, Viet Nam)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Total coffee area	182,434	181,960	190,765	200,193	202,022	202,503	203,746	203,357	203,737	204,808
Harvested area	173,233	171,977	177,890	190,329	189,091	192,193	192,471	192,534	191,483	187,280



(a)



(b)

Fig. S.1. Results of sensitivity analysis for (a) coffee production and (b) harvested coffee area (Only parameters causing more than 1% change in coffee production and harvested area are presented)

Chapter 7. Synthesis and conclusions

Chapter overview

The impacts of drought on agricultural production are generated from the interactions between bioclimatic drivers and ecological processes and socio-economic dynamics. While numerous studies focus on drought impacts in agricultural systems, little effort has been made to consider the complexity, uncertainty and multiple dimensions of the interrelationships of drought-related factors impacting crop production. To fill this knowledge gap, this research aims to make a fundamental research contribution by developing an effective decision-support tool – an integrated conceptual and simulation model – that incorporates both qualitative and quantitative data to enable the identification of the underlying ecological and socio-economic feedback mechanisms that drive the impacts of drought on crop production.

The purpose of this chapter is to synthesise the key findings and conclusions that address the study's research questions. The chapter outlines the outcomes produced from the five stages of research conducted, discusses the limitations and makes suggestions for future research. Finally, the implications of this study and its broader contribution to the field are also examined.

7.1. Key findings in response to research questions

The central aim of this research is to support decision-making on drought management for sustainable coffee production in Dak Lak Province, Viet Nam, which was achieved through addressing three specific research questions. The following section outlines the key findings in relation to each of these questions.

Research question 1: What are the potential drought-related direct and indirect impacts on coffee production?

A systematic quantitative analysis of the academic literature was undertaken to obtain comprehensive understanding of the current state of knowledge of the bioclimatic drivers that influence the sustainability of coffee production (as discussed in Chapter 4). This review enabled the identification of direct and indirect climate-driven impacts, particularly those of drought on coffee production, which addressed the first objective of this research project and forms a core basis to achieve the next objectives. Key findings of the systematic quantitative literature review include:

- Climate-driven impacts on coffee production include direct (i.e. changes in yield or productivity or in bio-climatically optimal areas for coffee growing) and indirect (i.e. changes in coffee quality or in pest/disease distribution or pollination activities) impacts, which increase production costs and affect farmers' income and livelihoods and the whole coffee industry.
- Most of the current literature has focussed on the impacts of climate change and climate variability with limited research on drought, and on the suitability of coffee cultivation areas with less consideration to the impact on coffee yield or production.
- Mostly negative impacts of climate change reported in current studies were due to losses of areas suitable for coffee cultivation, reductions in coffee yield or production, and increases in pest and disease distribution.
- Lack of the integration of socio-economic dynamics and the rationale and effectiveness of proposed adaptation measures (e.g. irrigation and efficient water use, agro-forestry, application of new coffee varieties, and diversification of new cropping patterns or livelihood alternatives) in addressing climate-driven impacts on coffee production. These gaps are similar to those identified in relevant research on other crops, as discussed in Chapter 2 of this research.

In response to Research question 1, the systematic quantitative literature review provided significant inputs for the subsequent model development phase of the research, specifically potential climate-driven influences on coffee production, including direct (e.g. reductions in coffee yield and productivity) and indirect (e.g. declines in coffee quality, increases in production costs, and outmigration in coffee-growing farms due to drought) impacts. The review also enabled the identification of possible drought-related drivers influencing coffee production that were analysed in the current literature. These consist of, but are not limited to, climate change, rainfall variability, rising temperatures and evapotranspiration, population growth, and coffee prices. Response measures discussed in the review, including shading, intercropping and irrigation, were significant variables for the formulation of the model in the next steps. Finally, some of the interrelationships between climatic and non-climatic factors driving coffee production, such as the interactions between temperature rise, shading, and coffee yield and quality, were also explored, forming the basis for achieving Objective 2 of this research.

<u>Research question 2</u>*: What are the causal dynamics that drive the impacts of drought on coffee production that have been observed in the case study region?*

The second stage of this research was to achieve Objective 2, which was to identify climatic and non-climatic factors associated with drought and capture the underlying drivers, and their interactions and feedback structures that influence coffee production and the livelihoods of coffee farm households in the case study area.

An intensive stakeholder consultation was conducted in Viet Nam with interviews of 60 experts and farmers involving in drought management and/or coffee production. The results of these interviews, along with secondary data from different sources and inputs from the systematic quantitative literature review, primarily contributed to the development of the causal loop model on the impacts of drought on coffee production. The model indicated that the current drought and water shortage situation in Dak Lak Province might not be solely attributed to changes in precipitation patterns but result from the complex interactions between climatic drivers, ecological processes, and agricultural production and other socio-economic development activities. Growing demand for irrigation driven by increasing areas of farmland, particularly driven by uncontrollable coffee expansion, and inefficient irrigation practices are likely major factors driving water scarcity in the region, followed by deforestation and rising water demand from socio-economic development activities fuelled by population growth in the region.

By applying causal loop modelling grounded in a systems thinking approach, the complex interactions between climatic and ecological processes and socio-economic dynamics were analysed. It is worth noting here that the interrelationships and feedback mechanisms between these processes are likely to influence the sustainability of coffee production, and that without appropriate intervention measures, water scarcity is likely to occur before a meteorological drought event.

Several leverage points were identified from an analysis of the model and its system archetypes (e.g. *limits to growth*, *tragedy of the commons*, and *fixes that fail* archetypes, as discussed in Chapter 5). These involve strategies that control deforestation and coffee expansion and more importantly, measures that improve water use efficiency, including water saving irrigation practices and technologies, and the resilience of Robusta coffee monocrop farms to a changing climate, such as shading and intercropping.

<u>Research question 3</u>*: How could these dynamics influence coffee production over time and what are the implications to support decision-making on drought management for sustainable coffee production in the case study region?*

To quantify the causal dynamics that were identified in the conceptual model of the system, the next stage of the research was to design a system dynamics simulation model. This stage addressed Objective 3 of the research, which was to construct a model to evaluate alternative policy intervention scenarios to support effective decision-making on drought responses for sustainable coffee production.

A stock-and-flow simulation model was built to simulate feedback loops over a period of more than 40 years, from 2008-2050. The model included more than 100 variables with six stocks, 16 flows and 86 converters, and 70 equations and 12 graphical functions (as specified in Chapter 6 and Appendix B). Model testing, conducted over a 10-year period indicated that the model was able to satisfactorily represent the structure of the system it represents and that the behaviours of the model are in line with the observed patterns generated from historical data. The results of sensitivity analysis demonstrated that irrigation-related variables and the total area of arable land for coffee were the parameters that most likely influence the dynamics of the system.

Simulation of the business-as-usual scenario (Scenario 1) showed that coffee production and yield decline in drought years, as expected. The simulation results of this scenario also indicated that coffee yield is expected to plateau around 2040 at 2.23 tonnes/hectare due to a peak in water availability, following which the irrigation water amount available for coffee is predicted to decrease.

To identify the implications of the model outputs for decision-making, the last stage of the research focused on policy scenario analysis and evaluation. Results of this stage demonstrated that maximum growth in coffee production and coffee yield in Dak Lak Province will likely occur under Scenario 5, when a combination of policies on land-use control (a restriction of less than 190,000 ha of total area for coffee cultivation), water-saving irrigation (application of an irrigation amount of less than 1,875 m^3/ha) and increased reservoir storage (a 10% increase in surface water storage capacity) is enforced. This scenario appears to produce the greatest benefits to coffee production in the region, under different rainfall conditions, including drought when rainfall drops by 15% compared to the annual average value. Analysis of simulation results also indicated that solely adopting either water-saving irrigation measures (Scenario 3) or, to a lesser extent, land-use controls (Scenario 2), might result in improved coffee production outcomes under any of the rainfall conditions simulated in the model. An expansion in the surface water storage capacity (Scenario 4) will also likely drive an increase in coffee production and yield; however, the system is likely to be less sensitive to the influence of reservoir expansion for surface water storage compared to land-use controls and water-saving irrigation. On the other hand, uncontrolled land-use enabling coffee expansion, and inefficient irrigation practices will most likely lead to substantial declines in coffee production over time compared to the current situation. Without policy interventions, even with increasing rainfall, coffee yield will likely only slightly increase under Scenario 1 to 2.28 tonnes/hectare; while under drought conditions, it is expected to drop to 2.20 tonnes/hectare by 2050. In the worst-case scenario (Scenario 6), when both land and water resources are exploited to the highest levels, coffee yield is likely to plummet to 1.93 and 1.88 tonnes/hectare under high and low rainfall conditions, respectively.

It is noteworthy that for all rainfall conditions, there are likely just small variations in the values of coffee yield under the same scenario. These results suggest that rainfall, including drought conditions, will likely not be the variable most influencing coffee yield, and that non-climatic factors associated with land and water use dynamics are likely to be more significant. It is these key drivers that appear to profoundly impact coffee cultivation in the case study region, representing the greater variations in the values of coffee outputs among the different intervention scenarios for these drivers.

Generally, these model outputs have substantial implications for decision-making about whether it is more beneficial, in the long term, to allow coffee production to achieve the highest volume over the greatest area of total arable land, or to reach the lower volume over a restricted land area available for coffee cultivation. The best strategies with a combination of both land-use controls and efficient water-use irrigation, however, will likely generate both environmental and social-economic benefits by reducing production expenditures and protecting water, land and forest resources, and maintain sustainable and viable outcomes for coffee production in the region.

7.2. Limitations and recommendations for future research

In spite of the significant findings and contributions to knowledge as presented throughout this thesis, a number of limitations exist within this research, providing a future pathway for further investigation. Firstly, the research design was somewhat constrained by the boundaries established within its scope and aims. The model was built based on the hypotheses derived from the mental models of a moderate number of stakeholders, which could potentially be subjective. A number of exogenous factors were not captured in this study, given the stakeholders primarily focused on the direct impacts of drought on coffee production. Such factors include, but are not limited to, those related to the political dimensions and coffee market forces driving the expansion of coffee. In a future study, an expanded consultation process engaging additional stakeholders might result in a more comprehensive model which will likely capture other processes relevant to the problem under investigation. Involving stakeholders including decision-makers, representatives from local authorities and researchers in policy scenario planning and validation through expert consultations would enhance the robustness of the model outcomes to meet management's objectives and strategies. Further consideration given to this issue in future research will help to improve the breadth of the model developed and presented in this research.

It is construed that the system dynamics simulation model was not used to generate precise predictions of the future behaviour of the system, but to explore and evaluate the long-term trends, particularly the impact over time of management decisions, to enable and inform more comprehensive policy-making. Additionally, owing to data limitations, which is common for case studies in developing nations, the prescribed model does not consider the detailed dynamics of a number of processes occurring within the system, for example, the complexity of the groundwater system. A more in-depth future model with additional sectors and a greater variety of datasets might improve the comprehensiveness and accuracy of the model.

Within this investigation, several assumptions that have not been empirically tested were made to capture the processes where data were not available, which might limit the accuracy of the model simulation. While empirical data, particularly at local levels, remain limited, critical evaluation of the qualitative assumptions with the participation of different stakeholders might help to verify the model's findings and improve its accuracy.

To enable the application of the system dynamic model in this research as a practical decision-support tool, it would be useful to initiate an implementation and evaluation phase (Maani and Cavana 2007), including better communication of the model outcomes and insights of the proposed policy intervention scenarios to different stakeholders, and facilitation of interactive learning and assessment.

7.3. Research contributions

The research findings described throughout this thesis demonstrate the significant value to be realised by applying a systems framework in problem-solving, particularly addressing the complexity, uncertainty and multi-dimensionality of natural resource-related issues (e.g. water availability) under a changing climate. Through investigating the system as a whole or the interactions between its constituent parts, this approach is able to explore the key dynamics that drive the behaviour of the system, which is not commonly taken into account in traditional linear approaches. Specifically, the findings presented in this thesis suggest that drought is an important factor but not likely a key driver impacting coffee cultivation. In the case of Dak Lak Province in Viet Nam, the key dynamics influencing the coffee production system are the interactions between land- and water-use related drivers. To address water scarcity for irrigation, it is imperative to adopt appropriate intervention measures that target efficient use and management of both water and land resources. While research that applies a systems approach to investigate the impacts of climate change and drought on crop production remains limited, this thesis has demonstrated the successful application of this modelling methodology in generating improved understanding of the multi-disciplinary aspects of climate-driven impacts on the agricultural sector and the potential for addressing these through an evaluation of various intervention scenarios.

Secondly, a decision-support tool generated from the model developed in this research adds significant value to the policy-making process. It first provides relevant stakeholders with a more explicit theory of what – apart from the drought factor – is driving water shortages for coffee production, through the use of causal loop diagrams. This conceptualisation greatly depends on stakeholder consultation, which enables the exploration of causal relationships and archetype behaviours that influence the dynamics of the system. The systems mapping process also allows identification of leverage points that might be adopted to address the unintended consequences of policy and management decisions and the persistent problems under investigation. The system dynamics simulation model has the ability to simulate hypotheses about the problem, i.e. the behaviour over time of the whole system at different time scales, thus further reducing uncertainty and improving understanding of the problem.

Further, a variety of alternative intervention scenarios can also be reproduced in the model to explore their effectiveness and/or consequences on the trajectory of the system. Since all of the system's components are interconnected and their interactions, represented in feedback loops, are simulated, the model will enable comprehensive evaluation and comparison of the effects of policy measures on key drivers (e.g. crop yield) over time. Thus, it will be able to predict the long-term impact, and importantly, improve decision-making on sustainable crop production, given changing climatic, ecological and socio-economic settings.

Despite the underlying limitations, which might be addressed in future research, this project has nonetheless made notable contributions, particularly in applying system dynamics modelling for drought management with relevant findings for sustainable agricultural development. These contributions not only benefit the coffee production system in Viet Nam but also other regions where drought impacts are affecting the livelihoods of many farmers and the sustainability of agricultural production, and where appropriate policy interventions could enable effective risk management to optimise the productivity and revenue for stakeholders.

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Appendices

Appendix A. Human ethics approval letter

OFFICE OF RESEARCH
Human Research Ethics Committee
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UNIVERSITY OF SOUTHERN QUEENSLAND

21 June 2018

Ms Yen Hoang Pham

Dear Yen Hoang

The USQ Human Research Ethics Committee has recently reviewed your responses to the conditions placed upon the ethical approval for the project outlined below. Your proposal is now deemed to meet the requirements of the *National Statement on Ethical Conduct in Human Research (2007)* and full ethical approval has been granted.

Approval No.	H18REA118
Project Title	Systems thinking and system dynamics approaches to address drought impacts on coffee production in Dak Lak Province, Vietnam.
Approval date	21 June 2018
Expiry date	21 June 2021
Status	**Approved with standard conditions**

The standard conditions of this approval are:

(a) responsibly conduct the project strictly in accordance with the proposal submitted and granted ethics approval, including any amendments made to the proposal;
(b) advise the University (email: ResearchIntegrity@usq.edu.au) immediately of any complaint pertaining to the conduct of the research or any other issues in relation to the project which may warrant review of the ethical approval of the project;
(c) promptly report any adverse events or unexpected outcomes to the University (email: ResearchIntegrity@usq.edu.au) and take prompt action to deal with any unexpected risks;
(d) make submission for any amendments to the project and obtain approval prior to implementing such changes;
(e) provide a progress 'milestone report' when requested and at least for every year of approval;
(f) provide a final 'milestone report' when the project is complete;
(g) promptly advise the University if the project has been discontinued, using a final 'milestone report'.

For (d) to (g) forms are available on the USQ ethics website:

https://www.usq.edu.au/current-students/academic/higher-degree-by-research-students/conducting-research/human-ethics/forms-resources

Please note that failure to comply with the conditions of approval and the *National Statement (2007)*, may result in withdrawal of approval for the project.

Yours sincerely,

Mrs Nikita Kok
Ethics Officer

Appendix B. Equations of the stock-and-flow model

Variable	Stella equations*	Unit
Actual coffee groundwater demand	0.6 * Coffee area * Actual coffee groundwater demand per ha	cubic meter/year
Actual coffee groundwater demand per ha	Normal coffee water demand per ha * Effect of groundwater availability on coffee water demand	cubic meter/ha/year
Actual coffee irrigation groundwater use	0.75 * Groundwater consumption	cubic meter/year
Actual coffee irrigation surface water use	0.1 * Surface water consumption	cubic meter/year
Actual coffee irrigation use per ha	(Actual coffee irrigation groundwater use + Actual coffee irrigation surface water use)/Coffee area	cubic meter/ha/year
Actual coffee surface water demand	0.4 * Coffee area * Actual coffee surface water demand per ha	cubic meter/year
Actual coffee surface water demand per ha	Normal coffee water demand per ha * Effect of surface water availability on coffee water demand	cubic meter/ha/year
Actual domestic and industrial groundwater demand	Population * Actual domestic and industrial groundwater demand per capita	cubic meter/year
Actual domestic and industrial groundwater demand per capita	Normal domestic and industrial groundwater demand per capita * Effect of ground water availability on water demand	cubic meter/person/year
Actual domestic and industrial surface water demand	Actual surface water demand per capita * Population	cubic meter/year
Actual irrigation groundwater demand	1.2 * Actual coffee groundwater demand	cubic meter/year
Actual irrigation surface water demand	6.5 * Actual coffee surface water demand	cubic meter/year
Actual surface water demand per capita	Normal domestic and industrial surface water demand per capita * Effect of surface water availability on water demand	cubic meter/person/year
Available groundwater (t)	Available groundwater (t - dt) + (Groundwater inflow - Groundwater consumption - Groundwater overflow - Evaporation) * dt	cubic meter
Available surface water (t)	Available surface water (t - dt) + (Surface water inflow + Return flow - Surface water consumption - Overflow - Evapotranspiration) * dt	cubic meter
Available water per person	(Available groundwater + Available surface water)/Population	cubic meter/person

Birth	Population * Birth rate	people/year
Change in coffee area	IF Predicted minus coffee area>Total arable land minus coffee area THEN Total arable land minus coffee area/Delay in coffee area change ELSE Predicted minus coffee area/Delay in coffee area change	hectare/year
Change in coffee production	Predicted minus perceived coffee production/Delay in coffee production change	tonnes/year
Change in harvest area	Predicted minus perceived harvest area/Delay in harvest change	people/year
Coffee area (t)	Coffee area (t - dt) + (Change in coffee area) * dt	hectares
Coffee farm jobs	Coffee area * Jobs per ha of coffee	jobs
Coffee harvest area (t)	Coffee harvest area (t - dt) + (Change in harvest area) * dt	hectares
Coffee production (t)	Coffee production (t - dt) + (change in coffee production) * dt	tonnes
Coffee yield	Coffee production/Coffee harvest area	tonnes/ha
Death	Population * Death rate	people/year
Emigration	Population * Emigration rate	people/year
Emigration rate	Initial emigration rate * Effect of water available on emigration rate	%/year
Evaporation	Available groundwater * Evaporation rate	cubic meter/year
Evapotranspiration	Available surface water * Evapotranspiration rate	cubic meter/year
Gross income	Coffee production * Coffee price	VND/ha
Groundwater consumption	MIN (Groundwater demand, Groundwater withdrawal capacity)	cubic meter/year
Groundwater demand	Actual irrigation groundwater demand + Actual domestic and industrial groundwater demand	cubic meter/year
Groundwater inflow	Total recharge	cubic meter/year
Groundwater netflow	Groundwater inflow-Groundwater consumption-Evaporation	cubic meter/year
Groundwater overflow	MAX (((Available groundwater + Groundwater netflow)-Groundwater storage capacity), 0)	cubic meter/year
Immigration	Population * Immigration rate modified by available jobs	people/year
Immigration rate modified by available jobs	Immigration rate * Job attractiveness	%/year

Initial gross income	Coffee price * Initial coffee production	VND/ha
Initial water available per person	(Initial groundwater + Initial surface water)/Initial population	
Labour force	0.52 * Population	people
"Labour/Job ratio"	Labour force/Coffee farm jobs	
Groundwater withdrawal capacity	IF (Groundwater inflow > Available groundwater) THEN (Groundwater inflow * Allowable groundwater withdrawal fraction) ELSE (Available groundwater * Allowable groundwater withdrawal fraction)	
Normal coffee water demand per ha	2500	cubic meter/ha/year
Normal domestic and industrial groundwater demand per capita	45.06e6/1715100	cubic meter/year
Normal domestic and industrial surface water demand per capita	321e6/1715100	cubic meter/year
Normal harvest	Coffee area/Harvest delay	
Normal production	455000	
Population (t)	Population (t - dt) + (Immigration + Birth - Death - Emigration) * dt	people
Predicted coffee area	Coffee area * DELAY ("Effect of labour/job on coffee expansion", 1) * DELAY (Effect of income on coffee area, 1)	hectares
Predicted minus coffee area	Predicted coffee area-Coffee area	hectares
Predicted minus perceived coffee production	Suggested coffee production-Coffee production	tonnes
Predicted minus perceived harvest area	Suggested harvest area-Coffee harvest area	hectares
Return flow	Total recharge to rivers	cubic meter/year
Suggested coffee production	Normal production * MIN (Effect of irrigation on coffee production, Effect of labour on coffee production)	tonnes
Suggested harvest area	Normal harvest * Effect of irrigation on harvest area	hectares
Surface water consumption	IF Available surface water< Surface water demand THEN Available surface water ELSE Surface water demand	cubic meter/year
Surface water demand	Actual domestic and industrial surface water demand + Actual irrigation surface water demand	cubic meter/year

Surface water inflow	Total surface flow	cubic meter/year
Surface water netflow	Surface water inflow + Return flow-Evapotranspiration-Surface water consumption	cubic meter/year
Surface water overflow	MAX (((Available surface water + Surface water netflow)-Surface water storage capacity), 0)	cubic meter/year
Total arable land minus coffee area	Total arable land-Coffee area	hectares
Total recharge	Actual recharge rate * (Rainfall/1000) * Total surface area	cubic meter/year
Total recharge to rivers	Actual return flow rate * (Rainfall/1000) * Total surface area	cubic meter/year
Total surface area	13158e6	square meter
Total surface flow	Actual surface flow rate * (Rainfall/1000) * Total surface area	cubic meter/year