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

Yen Pham [a,b,*], Kathryn Reardon-Smith [c], Shahbaz Mushtaq [c], Ravinesh C. Deo [d]

[a] Faculty of Health, Engineering and Sciences, University of Southern Queensland, Springfield Central, QLD 4300, Australia
[b] Department of Climate Change, Ministry of Natural Resources and Environment, Ha Noi, Viet Nam
[c] Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, QLD 4350, Australia
[d] School of Sciences, University of Southern Queensland, Springfield Central, QLD 4300, Australia

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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

* Corresponding author.
E-mail address: Yen.Pham@usq.edu.au (Y. Pham).

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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).

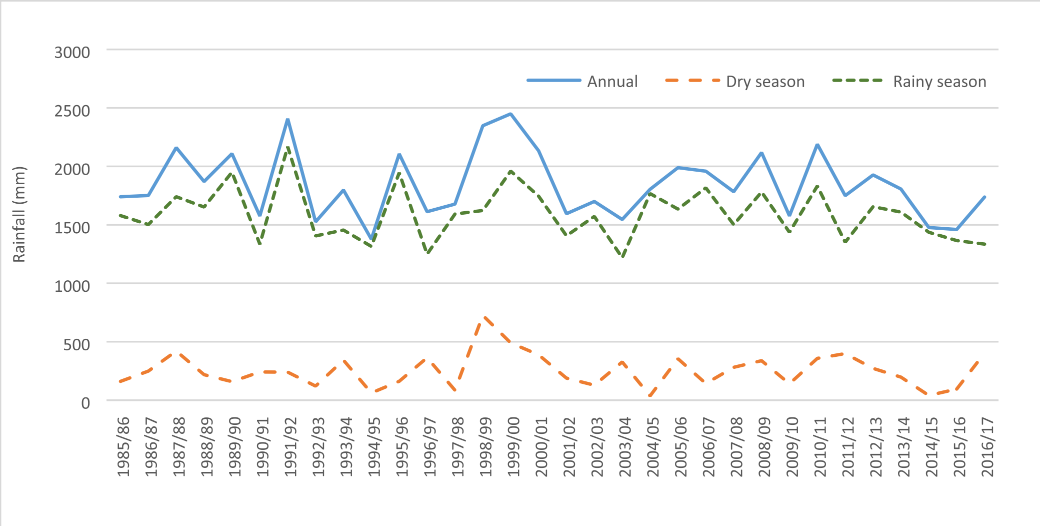
The prospect of global climate change and more frequent and severe drought events raises concern and the need for mitigation and adaptation strategies, especially when there is increasingly strong evidence in extant studies of the adverse impacts of climate change on crop yields and production and on 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 ().

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

adapted from Kim and Andersen, 2012

Table 3
An example of words-and-arrow diagrams of causal arguments ().

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

adapted from Kim and Andersen, 2012

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

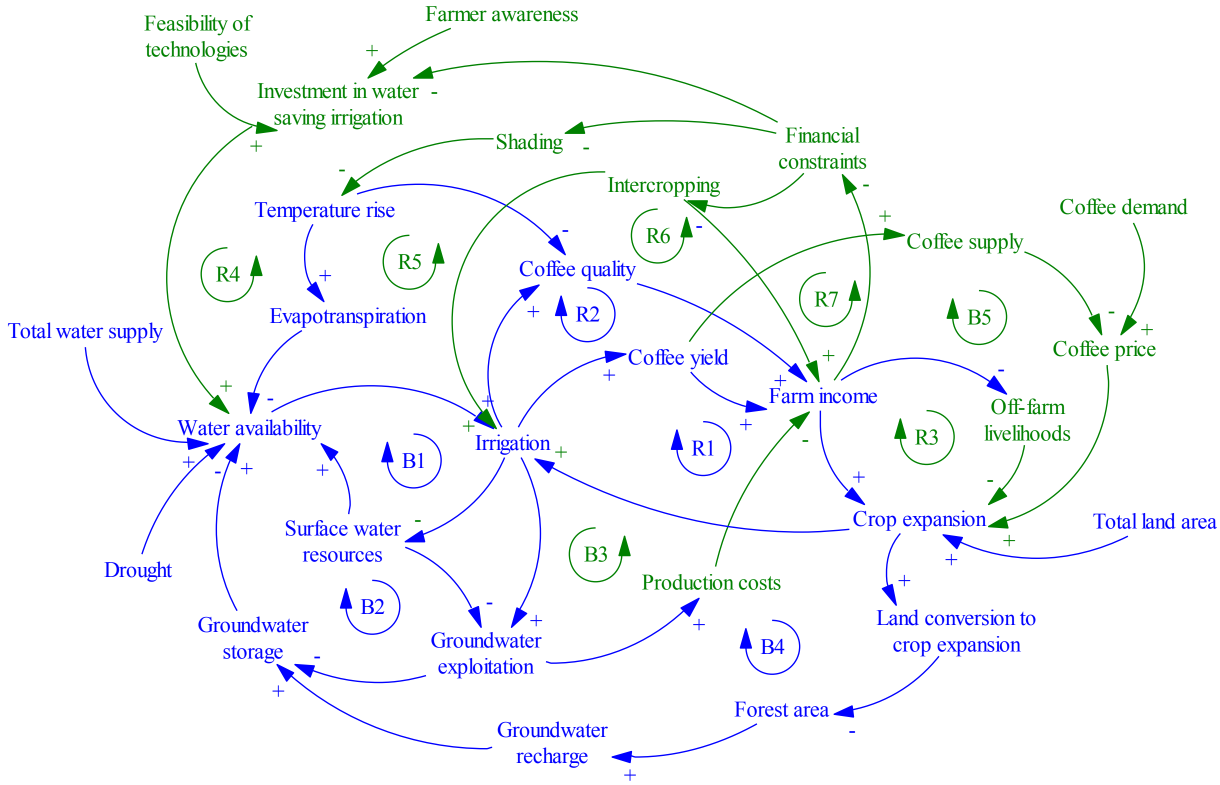


Fig. 2. Agricultural production sub-model (R: reinforcing loop, B: balancing loop, +: positive relationship, –: negative relationship, and blue colour representing overlapping variables and relationships with other sub-models). (For interpretation of the references to colour in this figure legend, the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

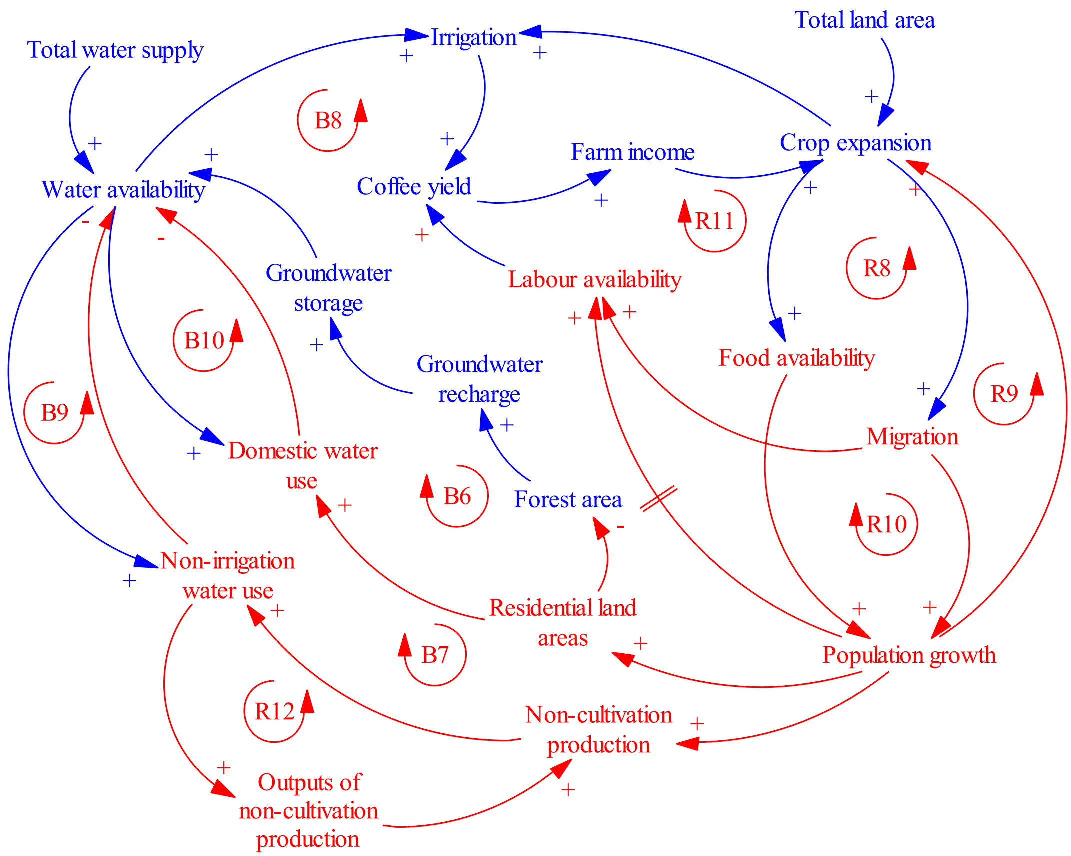


Fig. 3. Socio-economic sub-model.

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

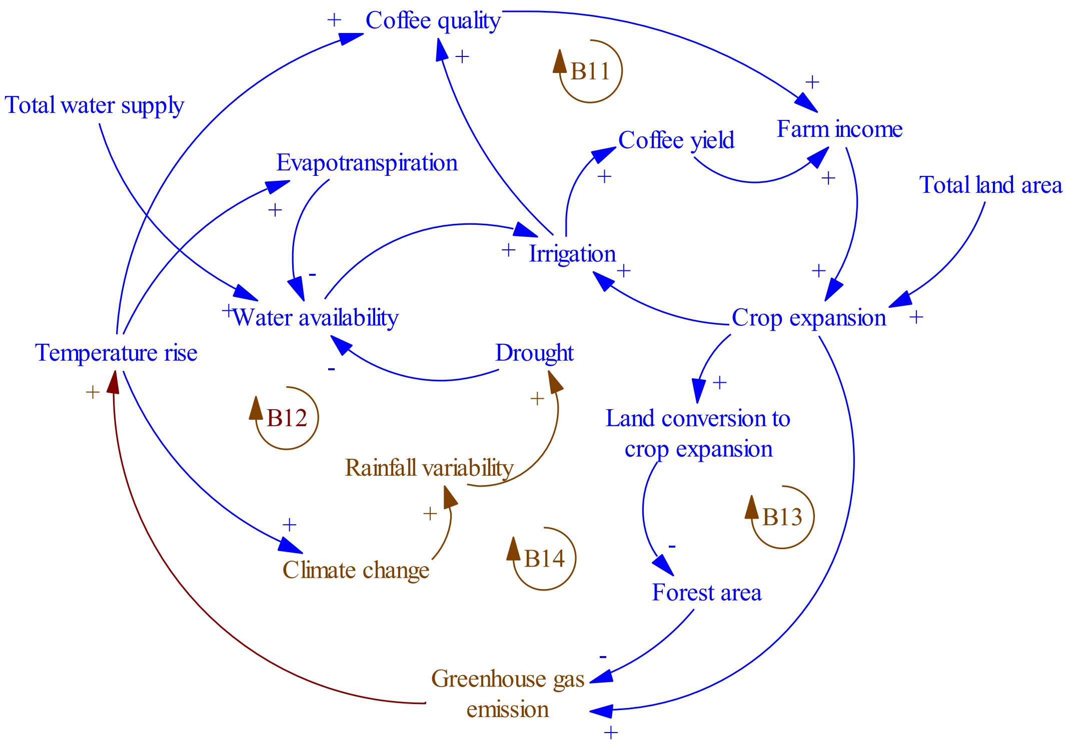


Fig. 4. Bioclimatic sub-model.

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

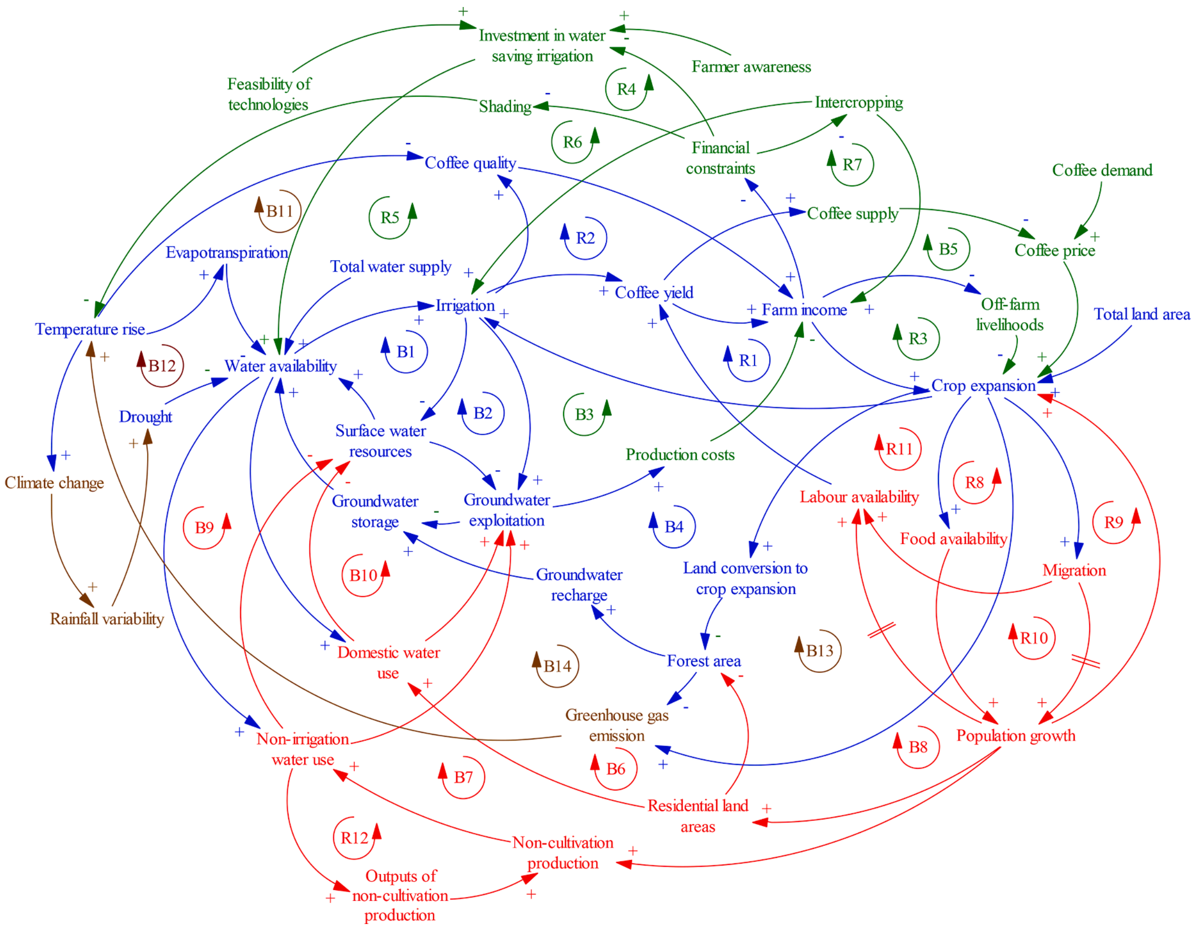


Fig. 5. The integrated causal loop model of drought impacts on coffee production in Dak Lak province, Viet Nam (green colour: agricultural production sub-model, red colour: socio-economic sub-model, brown colour: bioclimatic sub-model, blue colour: overlapping variables and relationships between sub-models). (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 immediate benefits.

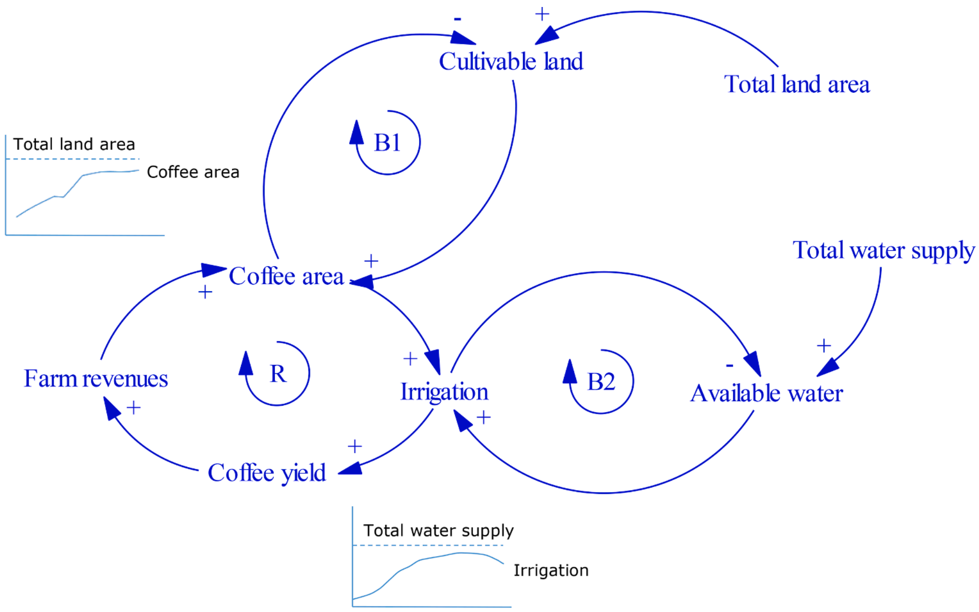


Fig. 6. *Limits to growth* – the limits of land and water resources for coffee expansion.

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.

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

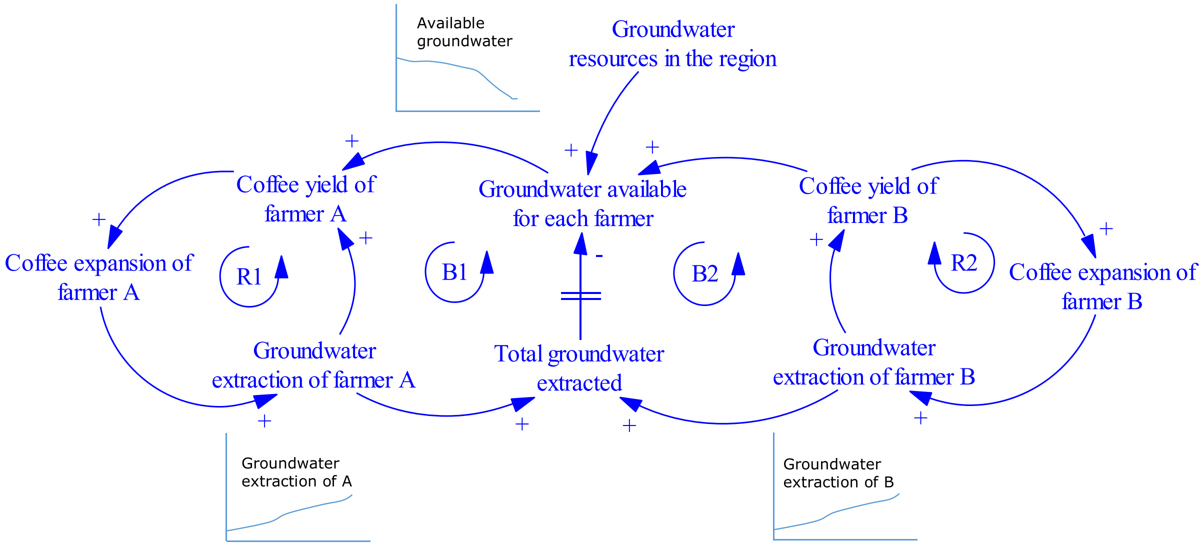


Fig. 7. *Tragedy of the commons* – the impact of groundwater over-exploitation.

(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 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).

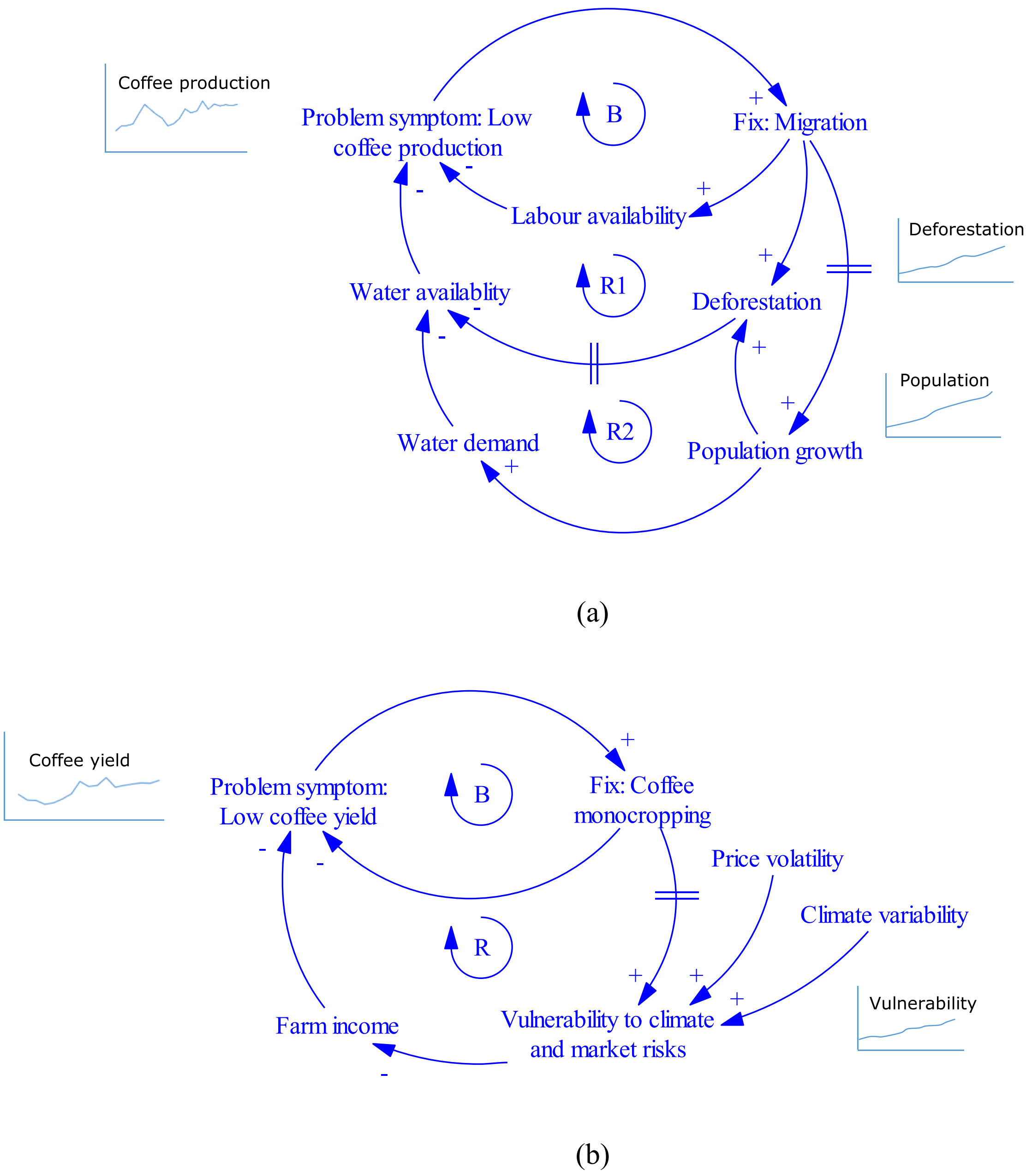


Fig. 8. *Fixes that fail* – the side effects of quick fixes aimed at improving coffee production through (a) migration program and (b) coffee monocultures.

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.

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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