Building resilient tropical commodity chains in Ghana:
The case of cocoa

A thesis

submitted in partial fulfilment of the requirement for the

Degree of Doctor of Philosophy

at

Lincoln University

by

Joshua Aboah

Lincoln University

2020

Abstract of a thesis submitted in partial fulfilment of the requirements for the PhD

Building resilient tropical commodity chains in Ghana:

The case of cocoa

by

Joshua Aboah

There has been a growing interest in resilience assessment of supply chains over the last two decades. Due to contextual differences, diverse definitions have been ascribed to resilience. Also, resilience assessment in the supply chain literature is often predicated on a fundamental assumption of infinite availability of raw materials and ignores farm-level production activities. Moreover, resilience assessment has mostly focused on individual firm-level and ignores analysis at an aggregate value chain level.

This study focuses on the cocoa value chain in Ghana. Cocoa plays an essential role in the economies of producing countries like Ghana. Hence, the government is a key stakeholder in the cocoa value chains. The consequences of potential disruptions in the cocoa value chain will be dire for producing countries like Ghana that depend on foreign exchange from cocoa exports. International companies that rely on a consistent supply of cocoa beans as raw materials for their final products will also be affected. As such, three strategies that have been espoused in the literature to build the resilience of individual firm-level and aggregate chain level are domestic market liberalisation, on-farm diversification and forward integration.

The study seeks to; *(i)* operationalise the concept of resilience for tropical commodity chains; *(ii)* identify the precursors of vulnerability in Ghana's cocoa value chain; *(iii)* evaluate *ex-ante* the effect of domestic market liberalisation on the aggregate resilience in Ghana's cocoa value chain; *(iv)* examine *ex-ante* the impact of chain actors' adaptive strategies on the aggregate resilience of Ghana's cocoa value chain.

System dynamics modelling was deployed as the principal analytical technique to achieve objectives 2, 3, and 4. For objective 1, a Citation Network Analysis was used as the primary approach to conduct a systematic literature review. A mix of primary and secondary data was used in this study. Primary data were retrieved via focus group discussions and expert elicitation. Secondary data were collated from published articles and archival data on cocoa production and trade.

Results indicate that tropical commodity chains, like most agricultural value chains, will require a farm-centric resilience assessment that considers the socioecological dimension as the primary resilience dimension, and adaptability as a central resilience element. Results also show that full liberalisation of the domestic market will enhance the resilience of the cocoa value chain at an aggregate level when; *(i)* government maintains a regulatory policy to curtail exploitation of smallholders, and *(ii)* government enacts policies that support a forward integration strategy. Moreover, the results indicate that on-farm diversification can complement the forward integration effort at the national level to build resilience in Ghana's cocoa value chain when; *(i)* farmers reinvest proceeds from on-farm diversification into farm maintenance, and *(ii)* farmers adopt good farm management practices. This study's findings suggest that a policy direction that helps to build resilience in the cocoa value chain is one that enables free cocoa trading in-country, secures world price transmission to farmers, spearheads in-country processing and supports on-farm investment.
Keywords: cocoa; resilience; vulnerability; agricultural value chains; system dynamics; Ghana

Acknowledgement

"A hundred times every day I remind myself that my inner and outer life are based on the labours of other men, living and dead and that I must exert myself in order to give in the same measure as I have received and am still receiving."

- Albert Einstein

My PhD journey can be summarised in three words in my local Ga-Dangbe language: "*Dromo*", "*Mawuhi*", and "*Mawupey*", which are the names of my three children: "*Dromo*" translates as "Grace"; it means unmerited favour and reminds me that the MFAT scholarship I obtained to pursue my PhD is one of the divine orchestrations of my life's path. Thus, my highest thanks go to God, who has given me life, the talent, and guided my path throughout my PhD journey.

"*Mawuhi*" translates as "God is good". My belief in a divinely orchestrated path acknowledges that God has put people in place to guide and support me throughout my doctoral studies. I am grateful that these people allowed themselves to be used as vessels (knowingly or unknowingly) to impact my journey. Therefore, my profound gratitude goes to my supervisors.

To Dr Mark Wilson. You have been a strong pillar and a father. You facilitated an excellent enabling environment that stimulated my creativity, and you inspired me with your words and deeds.

To Dr Karl Rich. You have been a priceless resource. Your critiques and contributions helped shape this study.

To Dr Kathryn Bicknell. You were the powerhouse of providing detailed and insightful feedback.

Sirs and Madam, I deem it a blessing and an honour to have served under your tutelages.

To my wife, Edinam, who has been an excellent sounding board for my ideas, my greatest cheerleader and motivator; and to my three children, who make me feel invincible, I am truly grateful for your sacrifices. My profound thanks go to my deceased father (James) who set this doctoral vision alive, to my mother (Hannah) who is my prayer bank, and to my siblings (Aaron, Christian, Elizabeth, Florence, Evans, and Daniel), who have always supported me throughout this journey. I would also like to express my gratitude to Dr Mike Lyne, Dr Sharon Forbes, Anne Welford, and Dr Ani Kartikasari, who have supported me in diverse ways throughout my PhD journey.

"Mawupey", which translates as "It's the Lord's doing", sums up my PhD journey. Indeed! Thus far, the Lord has helped me.

Table of Contents

Abstract of a thesis submitted in partial fulfilment of the requirements for the PhD ii

Acknowledgement vi

List of Tables x

List of Figures.. ..xi

Chapter 1 General Introduction 1

1.1 Background 1

1.2 Interest in the Concept of Resilience 2

1.3 Threats to Resilience in the Cocoa Value Chain in Ghana 3

1.4 Research Problem 4

1.5 Research Objectives 5

1.6 Relevance of the Research 7

1.7 Organisation of the Thesis.. 8

Chapter 2 Overview of the Methodology 9

2.1 Introduction 9

2.2 System Dynamics Modelling 10

2.2.1 Application of System Dynamics Modelling to the Study of Resilience 11

2.3 System Conceptualisation 13

2.4 Overview of Primary Data Collection.. 15

2.4.1 Study Area 16

2.4.2 Selecting Participants 17

2.4.3 Primary Data Collection Procedure 18

Chapter 3 Operationalising Resilience in Tropical Agricultural Value Chains............. 21

3.1 Introduction 23

3.2 Methodology 26

3.2.1 Step 1: Database Selection... 26

3.2.2 Step 2: Citation Network Analysis 27

3.2.3 Step 3: Article Selection.. 30

3.2.4 Step 4: Content Analyses 31

3.3 The Conceptualisation of Resilience for Tropical Commodity Chains 31

3.4 The Context of Tropical Commodity Chains 33

3.5 The State of Resilience for Tropical Commodity Chains.. 35

3.6 Elements of Agricultural Value Chains Resilience 36

3.6.1 Flexibility 40

3.6.2 Collaboration.. 41

3.6.3 Resourcefulness 42

3.6.4 Adaptability.. 43

3.7 Element for Aggregate Resilience in Tropical Commodity Chains 44

3.8 Indicators for Measuring Resilience in Tropical Commodity Chains 45
3.9 Conclusion.. 49
3.9.1 Limitations and Recommendations.. 50
Appendix 3.0 52
Chapter 4 Identifying the Precursors of Vulnerability in Agricultural Value Chains: A System Dynamics Approach... 64
4.1 Introduction 66
4.2 Literature Review 67
4.2.1 Limitations of Vulnerability Assessment Approaches... 68
4.2.2 Measuring Supply Chain Vulnerability 70
4.3 Methodology 72
4.3.1 System Structure of Ghana's Cocoa Value Chain 75
4.3.2 Farm-level Module... 75
4.3.3 Country-level Module... 76
4.3.4 World-level Module 76
4.4 Baseline Model.. 77
4.4.1 Vulnerability Indicators... 79
4.4.2 Data 79
4.4.3 Model Validation.. 80
4.5 Results and Discussions 82
4.5.1 Sensitivity Analyses.. 82
4.5.2 Magnitude of Effect on Vulnerability Levels – Upstream Precursors of Vulnerability........... 83
4.5.3 Duration of Vulnerability – Upstream Precursors of Vulnerability.. 84
4.5.4 Magnitude of Effect on Vulnerability Levels – Midstream Precursors of Vulnerability 84
4.5.5 Duration of Vulnerability – Midstream Precursors of Vulnerability...................................... 86
4.5.6 Ranking of Precursors of Vulnerability 87
4.6 Conclusion... 89
Appendix 4.0 92
Appendix 4.1... 95
Chapter 5 *Ex-Ante* Effect of Market Liberalisation on Aggregate Socioecological Resilience of the Cocoa Value Chain 110
5.1 Introduction 112
5.2 Methodology 113
5.2.1 Model Description 114
5.2.2 Sub-model A: Farm Management Practices 114
5.2.3 Sub-model B: On-farm Production and Processing.. 115
5.2.4 Sub-model C: In-country Trading and Processing... 116
5.2.5 Sub-model D: Cocoa Export and Price Factors.. 116

5.2.6 Sub-model E: Individual Farmer Level 118
5.2.7 Resilience Measure 119
5.2.8 Model Validation 119
5.2.9 Scenario Construction 122
5.3 Results and Discussions 124
5.3.1 Baseline Resilience Level 127
5.3.2 Effect of Policy Scenarios on Resilience Level 129
5.3.3 Practical Implication for Chain Actors 133
5.4 Conclusion 136
Appendix 5.0 138
Appendix 5.1 141
Appendix 5.2 153
Chapter 6 *Ex-ante* Impact of On-farm Diversification and Forward Integration on Agricultural Value Chain Resilience: A System Dynamics Approach 154
6.1 Introduction 156
6.2 Methodology 158
6.2.1 Conceptual Model of On-farm Diversification 158
6.2.2 Forward Integration Strategies 160
6.2.3 Model Description 161
6.2.4 Resilience Measure 165
6.2.5 Model Validation 166
6.2.6 Scenario Analyses 168
6.3 Results and Discussions 169
6.3.1 Baseline Model 172
6.3.2 Impact of Scenarios on Aggregate Resilience 173
6.3.3 Practical Implication for Chain Actors 178
6.4 Conclusion 181
6.4.1 Limitation and Future Studies 182
Appendix 6.0 183
Appendix 6.1 188
Appendix 6.2 Baseline results of selected parameters 207
Chapter 7 General Discussion and Conclusion 212
7.1 Introduction 212
7.2. Theoretical Implication of Conceptualising a Farm-centric Resilience 213
7.3 Practical Implication for Building Farm-centric Resilience 217
7.3.1 Practical Implication of Market Liberalisation in the Cocoa Value Chain 217
7.3.2 Practical Implication of Diversification and Forward Integration in the Cocoa Value Chain 221
7.4 Conclusions and Recommendations 222

7.4.1 Limitations and Future Studies ... 224
References ... 226

List of Tables

Table 1 Application of SDM for resilience assessment 12
Table 2 Description of the key issues addressed by the research articles in each cluster 32
Table 3 Different representations of nodes (vertices) and links (edges) in supply chain network research 69
Table 4 Indicators for measuring supply chain vulnerability 71
Table 5 Measures for model validity 81
Table 6 Summary of the baseline levels of vulnerability measures for three chain actors in the cocoa value chain 82
Table 7 Parameters and their counterfactual values included in sensitivity analyses 83
Table 8 Results of sensitivity analyses involving 5% and 10% adjustment of counterfactual relationships for five variables 85
Table 9 Sensitivity analyses involving 5% and 10% decrease in cocoa beans allocation for in-country processing 86
Table 10 Aggregate ranks of precursors of vulnerability 88
Table 11 Statistic measures for model behavioural validity 121
Table 12 Scenarios examined in this study 123
Table 13 Analysis of the dominant loops in the model 125
Table 14 Summary results of scenario analyses 134
Table 15 Five forward integration cases 162
Table 16 Statistic measures for model behavioural validity 167
Table 17 Scenarios examined 168
Table 18 An overview of dominant feedback loops 169
Table 19 Details of dominant loops influencing the model's dynamic behaviour 171
Table 20 The baseline levels of cocoa beans produced and processed in the value chain 173
Table 21 Impact of scenarios on the aggregate resilience 176
Table 22 Resilience impact on chain actors – Difference in Baseline level and Scenario 1, 2 & 3 179
Table 23 A comparison of three strategies recommended under a fully liberalised domestic market 220

List of Figures

Figure 1 The methodological framework 6
Figure 2 Focus group discussion with cocoa farmers at Sefwi-Wiawso in the Western North Region, Ghana 19
Figure 3 Focus group discussion with cocoa farmers at Wassa Akropong in the Western Region, Ghana 20
Figure 4 Individual interview with a cocoa farmer in Sefwi -Wiawso in the Western North Region, Ghana 20
Figure 5 A trend analysis of published articles on supply chain resilience in three databases 27
Figure 6 Top 20 journals with the highest number of peer-reviewed articles on supply chain resilience (2000-2018) 28
Figure 7 Visualisation of CNA for publications on supply chain resilience in the Web of Science database 29
Figure 8 Visualisation of CNA for publications on supply chain resilience in the Scopus database 30
Figure 9 The four steps of the CNA 33
Figure 10 Elements of supply chain resilience and their usage frequency 38
Figure 11 The conceptual framework for analysing resilience in agricultural value chains 46
Figure 12 The inverse relationship between adaptability and resilience 49
Figure 13 Framework for identifying precursors of supply chain vulnerability 73
Figure 14 Causal loop diagram highlighting the system structure of Ghana's cocoa value chain. 74
Figure 15 A comparison of model estimation and Ghana's actual cocoa production figures 81
Figure 16 Vulnerability levels for 5% and 10% adjustment of upstream precursors 85
Figure 17 Results of 5% and 10% decrease in cocoa beans allocation for in-country processing 87
Figure 18 Ranking of precursors of vulnerability based on the three criteria 90
Figure 19 A comparison of Ghana's historical cocoa production and the predicted figures 122
Figure 20 A causal loop diagram of the dominant feedback loops 126
Figure 21 Trend of the dominance level of the feedback loop 127
Figure 22 Resilience patterns of the baseline model 128
Figure 23 Resilience pattern and the effect of scenario 1 129
Figure 24 Resilience pattern and the effect of scenario 2 131
Figure 25 Resilience pattern and the effect of scenario 3 132
Figure 26 Conceptualisation of on-farm diversification 159
Figure 27 A comparison of historical and model data on cocoa beans produced in Ghana 167
Figure 28 Trend of influence of dominant loops in the SD model 170
Figure 29 Trend of the baseline resilience (FAR) level 172
Figure 30 The impact of variable diversification and cooperative forward strategies on aggregate resilience 174
Figure 31 The impact of variable-input diversification and conflicting forward integration strategies (Scenario 2) on aggregate resilience 175
Figure 32 The impact of variable-input diversification and conflicting forward integration strategies (Scenario 3) on aggregate resilience 177
Figure 33 Decomposition framework for a farm-centric resilience assessments 213

Chapter 1 General Introduction

1.1 Background

The world is increasingly interconnected due to advances in technology and globalisation. Food produced in specific regions can be accessed and consumed globally. This is true for a tropical commodity like cocoa, which is among the most consumed products in the world. Tropical commodities are agricultural commodities that are mainly grown in the tropics and subtropics but are consumed globally. They have salient attributes like the requirements for tropical ecological weather conditions and preliminary processing close to the production point, and production activities are typically not mechanised because labour is cheap relative to capital. Agricultural value chains that rely on tropical commodities are those referred to as tropical commodity chains (Talbot, 2002).

Cocoa is a tropical commodity that is globally consumed owing to the variety of products that can be produced from its beans. In terms of its production, West Africa is the hub of cocoa, accounting for over 70% of world production (ICCO, 2017; Wessel & Quist-Wessel, 2015). Cote d'Ivoire and Ghana account for approximately 40% and 20% of world production, respectively (ICCO, 2017). Cocoa contributes about 7.5 % of the GDP for Cote D'Ivoire and 3% for Ghana (Läderach et al., 2013). Much of the cocoa produced in West Africa is exported to developed countries where most of the cocoa processing companies and end-consumers of cocoa products reside. Africa, which is the largest producing continent, consumes only 3%. North America, the continent where cocoa originated from, consumes 9%. The remaining 88% is distributed among Asia and Oceania and Europe in ascending order of percentage consumption (ICCO, 2012).

Ghana is the second-largest producer of cocoa in the world (ICCO, 2017). Ghana's cocoa beans are internationally recognised as the benchmark for quality (Läderach et al., 2013). The prominent role that cocoa plays in the country's economy is well encapsulated in the national saying "*Cocoa is Ghana; Ghana is cocoa*". In Ghana, cocoa is predominantly grown on farms with an average size of four hectares (Monastyrnaya et al., 2016). Cocoa is vulnerable to diseases, pests and changes in the weather. This explains why it is one of the most researched commodities in Ghana, with most researchers focusing on farm-level production issues (Adjei-Nsiah, 2012; Anim-Kwapong & Frimpong, 2005; Kolavalli et al., 2012; Wessel & Quist-Wessel, 2015).

The importance of cocoa to Ghana's economy and rural livelihoods has driven government policy towards the sector. The cocoa sector in Ghana is partially liberalised, and private institutions (both national and international) have become key players in the cocoa value chain (Kolavalli et al., 2012). Ghana relies on foreign exchange earned from the export of cocoa beans. Private buyers, exporters and processors also depend on the efficiency and resilience of the cocoa value chain. The importance of cocoa to the Ghanaian economy, the potential threat that disruption poses to the cocoa value chain, and the ramifications for global trade of cocoa beans, lend credence to the study of resilience.

1.2 Interest in the Concept of Resilience

In this study, resilience is defined as the adaptive capacity of a system to become ready for, respond to and recover from disruptions without losing the system's primary state. Resilience has become a popular concept with researchers, business and development organisations, and governments due to increased uncertainty arising from both natural and artificial ecological, socio-economic disruptions like climatic changes, resource scarcity, and price volatility. The concept, which emerged from ecological studies, has been adopted in fields such as civil engineering, social science, food security and livelihoods, and supply chain management.

At the organisational level, building resilience involves a strategic decision-making process. This has become more prominent with globalisation because organisations are no longer restricted to doing business in one specific geographic location (Li et al., 2017; Wagner & Neshat, 2010). Organisations explore new areas for doing business; be it finding new suppliers, customers, or manufacturers (Caniato, Golini, & Kalchschmidt, 2013). Firms that operate globally seek to benefit from the potential advantages of market expansion, risk diversification, lower sourcing costs, and lower production costs associated with operating outside their original geographic location (Caniato et al., 2013). A global operation is accompanied with new challenges that did not exist when firms operated locally; organisations that are not adequately prepared, lose out. To ensure business continuity and success, organisations adopt contingency and mitigation strategies to become resilient to new challenges they may encounter as they expand their operations (Colicchia et al., 2010).

1.3 Threats to Resilience in the Cocoa Value Chain in Ghana

Disruptions in tropical commodity chains can be globalised because disruptions that occur upstream at the farm level trickle downstream to the processing and consumption levels, and vice versa. For the cocoa value chain in Ghana, interest has focused on how upstream ecological shocks like drought, disease and pest infestation, and ageing trees can affect the production of cocoa.

Previous studies have been directed at the influence of climate change on the suitability of cocoa-growing areas in West Africa (Läderach et al., 2013; Wessel & Quist-Wessel, 2015) and specifically in Ghana (Anim-Kwapong & Frimpong, 2004; Ntiamoah & Afrane, 2008). In Ghana, the age of cocoa trees is seldom monitored, and replacement of trees has been sporadically initiated and implemented by the government. According to Anim-Kwapong and Frimpong (2005), some 25% of Ghana's cocoa trees are more than 25 years old. Cocoa yields in Ghana are amongst the lowest when compared with global yields (Mahrizal et al., 2014).

Downstream shocks also influence the cocoa value chain. Cocoa production in Ghana is responsive to changes in the producer price of cocoa and production cost. The initial farmers' response to a fall in cocoa price that is insufficient to meet variable production cost is to reduce farm maintenance activities. In instances where prices do not cover the primary farm-gate processes (such as harvesting, fermenting, and drying), then farmers cease to harvest. When prices cover or exceed production costs, farmers intensify farm management practices (Anim-Kwapong & Frimpong, 2005; Quarmine et al., 2014). A 5% increase in labour decreases the profitability of cocoa production by 24% - 31% (Mahrizal et al., 2014).

A lack of young entrants into cocoa production, existing farmers switching away from cocoa production, and the rising cost of farm labour are also significant problems confronting the future of Ghana's cocoa value chain (Anim-Kwapong & Frimpong, 2005; Kongor et al., 2018). The heightened threat of disruptions imposed on the cocoa value chain in Ghana highlights the importance of finding adaptive strategies to improve resilience in the cocoa value chain.

1.4 Research Problem

The research problem that this study seeks to address pertains to the theoretical and conceptual domain of the concept of resilience, and the practical implications of strategies suggested to build resilience in Ghana's cocoa value chain. The key issues are highlighted in this section.

In recent years, the concept of resilience has received more attention in the supply chain management literature. Nonetheless, there is little congruence in its definition (Fridolin & Kurt, 2007), and most empirical studies have assessed resilience qualitatively. The resilience concept is multidimensional (Nikookar et al., 2014; Ponomarov & Holcomb, 2009). Folke et al. (2010) and Tendall et al. (2015) argued that the concept of resilience concerns interaction between people and their natural environment, necessitating an investigation of resilience from a socioecological dimension. However, little attention has been given to the comprehensive assessment of both economic and socioecological dimensions of resilience in the supply chain literature.

Although resilience has been often assessed qualitatively, there is an increased interest in the quantitative assessment of resilience. Regression and discrete-event simulation models that have been employed in the quantitative assessment of resilience have tended to neglect interactions and information feedback among chain actors. Studies that captured interactions and feedback did not extend to upstream actors at the farm level and assumed an unlimited supply of raw materials (Datta et al., 2007; Spiegler et al., 2016). Analysis of resilience that concerns upstream actors is crucial for tropical commodity chains, but such analysis is rare in the literature.

The study of disruptions in cocoa production has received some attention due to the role that environment plays in producing tropical horticultural commodities. Studies conducted to assess the vulnerabilities in the cocoa value chain have mostly focused on the potential disruption that climate change can have on cocoa production (Anim-Kwapong & Frimpong, 2004; Schroth et al., 2017). The impact of socio-economic disruptions, such as trade policies and price changes on cocoa production, has also received little attention (Quarmine et al., 2014; Wessel & Quist-Wessel, 2015). Moreover, there is no analysis on how chain actor responses to these disruptions could affect the socioecological resilience at an aggregate value chain level.

1.5 Research Objectives

The purpose of this study is to develop an analytical framework to assess the socioecological dimensions of resilience in Ghana's cocoa value chain and to examine *ex-ante* the impact of strategies that can be implemented by chain actors and policymakers to enhance resilience at an aggregate value chain level.

Specifically, the study seeks to achieve the following objectives:

i. To operationalise the concept of resilience for tropical commodity chains.

ii. To identify the precursors of vulnerability in Ghana's cocoa value chain.

iii. To evaluate *ex-ante* the effects of agricultural commodity liberalisation on the aggregate resilience in Ghana's cocoa value chain.

iv. To examine *ex-ante* the impact of chain actor adaptive strategies on the aggregate resilience of Ghana's cocoa value chain.

This study adopts system dynamics modelling (SDM) as the principal analytical approach to achieve specific objectives 2, 3 and 4 of this study. An overview of SDM is discussed in the next chapter. A network analysis of journal articles (also referred to as Citation Network Analysis) was used as an approach to achieve specific objective 1. The procedures involved in the Citation Network Analysis are extensively covered in Chapter 3. The output from objective 1 is incorporated into the SDM for objectives 3 and 4. The output from objective 2 becomes the basis for scenario construction in objectives 3 and 4. An overview of this study's analytical framework is illustrated in Figure 1.

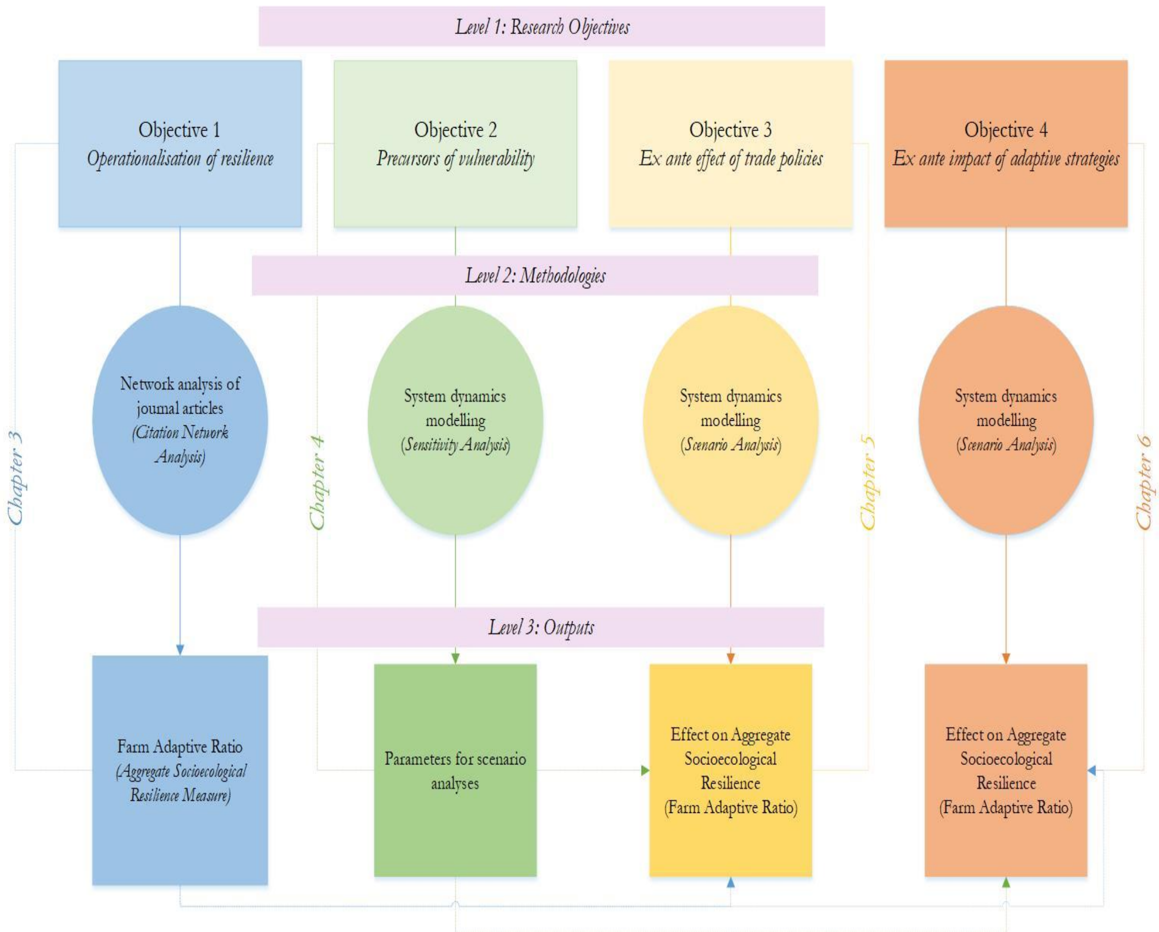


Figure 1 The methodological framework

1.6 Relevance of the Research

This study provides empirical contributions to the resilience literature in agricultural value chain management and practical guidelines for industry players in Ghana's cocoa value chain. Theoretically, this study offers a precedent for future studies on resilience by proposing an analytical framework that highlights the socioecological dimensions of resilience in agricultural value chains, especially in developing countries. This study extends the narrative on the resilience concept beyond midstream and downstream activities, by emphasising the primacy of accessible raw materials for agricultural value chain activities, which have been acknowledged by extant studies but often neglected in resilience assessment.

A decomposition and analytical framework that highlights the relevance of upstream on-farm activities are also proposed to enhance the measurability of resilience in agricultural value chains. A resilience indicator that can be adapted and applied to the resilience assessment of other agricultural value chains that do not involve heavily mechanised on-farm production activities is proposed.

From a practical perspective, this study examines adaptive strategies that are effective in enhancing the aggregate resilience of the cocoa value chain. The study recommends three strategies that can be adopted to strengthen the resilience of the cocoa value chain at an aggregate level under a fully liberalised domestic commodity market arrangement. The efficacy of the suggested strategies is compared based on pre-investment decisions, operational inhibitions, and the overarching influence on cocoa production at the national level.

Policy recommendations that the government can enact to support chain actors in order to advance an agendum to domestically add value to raw materials in the cocoa value chain are proposed in this study. Also, the study highlights crucial on-farm decisions required to enhance the resilience of the cocoa value chain at an aggregate level. In sum, this study provides result-oriented information that can become a basis for apprising the government on policies that improve resilience in the cocoa sector. The study's findings can also initiate an open discussion between the government and other stakeholders about collaboration in the cocoa value chain.

1.7 Organisation of the Thesis

This study contains seven chapters and is structured in a thesis-by-publication format. This chapter highlighted the traits that make tropical commodity chains like the cocoa value chain an ideal case for the study of resilience. The important contribution of cocoa to the economies of producing countries, and how processors and consumers consuming countries rely on the resilience of the value chain are also described in the chapter. The growing interest in resilience studies is reviewed, and a case is made for investigating and building resilience in Ghana's cocoa value chain.

Chapter 2 describes and justifies the primary analytical method adopted in this study. The general methodological framework and the primary data collection techniques that are used in this study are covered in Chapter 2. Four chapters (i.e., Chapters 3, 4, 5 and 6) that address the four research objectives are presented as journal articles. The final chapter (i.e., Chapter 7) presents a general discussion and conclusions of this study.

Chapter 2 Overview of the Methodology

2.1 Introduction

As a latent concept, resilience has been studied in different research fields. Hence, different context-specific measures have been proposed. The context of analysis determines the range of metrics that can be used to measure resilience. For instance, a 3PL (third-party logistics) firm engaged in supply distribution might logically focus on the lead time of delivery as an indicator of resilience, while a supplier will focus on quantity and quality of supplies. These indicators are easily measurable. However, in some contexts such as human livelihood and tourism, a system's state of resilience can only be described qualitatively. As a result, both qualitative and quantitative approaches have been applied to resilience analysis in the supply chain management literature.

Qualitative approaches that have been used to assess resilience provide a robust theoretical framework for quantitative analysis, and preceded much of the foundational quantitative work on resilience (Nikookar et al., 2014; Pettit et al., 2013; Tierney & Bruneau, 2007). One strength of the qualitative approach is the richness of the data that can be retrieved when assessing the resilience concept (Brusset & Teller, 2017). Holling (1973), one of the earliest proponents of a quantitative assessment of resilience, stressed the need to know precisely how much a system is misplaced under disruptions or the amplitude and period by which a system fluctuates, instead of settling for mere descriptive.

Various quantitative methods have been used to assess resilience in the supply chain management literature. Most popular among them are regression models (Brandon-Jones et al., 2014; Soni, Jain, & Kumar, 2014), discrete-event simulation models (Colicchia et al., 2010; Munoz & Dunbar, 2015; Spiegler et al., 2016) and complex nonlinear dynamic models like system dynamics and agent-based models (Li et al., 2011; Wilson, 2007). Regression models have principally been used to identify elements that explain the concept of resilience. According to Falasca et al. (2008), discrete-event simulation models have been widely used in disaster management studies because of their ability to consider uncertainty, risk, and responsiveness of the supply chain.

However, discrete-event simulation and regression models have been critiqued to be less effective for analysing a complex concept like resilience in supply chains due to the complexity in multi-echelon supply chains and the feedbacks inherent in the supply system (Datta et al., 2007; Wilson, 2007). Moreover, the resilience concept is composed of different multi-dimensional interactions (e.gs. sociotechnical and socioecological interactions), which require a technique that enables a holistic analysis. The inability of discrete-event simulation and regression models to capture feedbacks and dynamic complexity can be handled by system dynamics modelling (SDM) (Wilson, 2007), which was identified and adopted as the principal analytical approach to achieving specific objectives 2, 3 and 4 of this study.

2.2 System Dynamics Modelling

System Dynamics Modelling (SDM) is an approach to understanding complex system behaviour often aided by computer simulation (Angerhofer & Angelides, 2000). Complex systems can be represented diagrammatically in two ways: causal loop (CLD) and stock and flow diagrams (SFD) (Sterman, 2001). CLDs are used to describe the feedback structure of the system via causal links among variables (Georgiadis, Vlachos, & Iakovou, 2005; Hovmand, 2014). With the CLDs, qualitative variables and their relationships can be easily captured.

SFDs capture the structure of a dynamic system more formally. SFDs contain stocks, flows and converters. Stocks are the accumulations of things (e.gs. inventory, people, money) that describe the state of the system. Flows are the rates of change flowing in and out of the stocks, and the converters are the variables and relationships that alter the flows. Unlike CLDs that are unable to facilitate quantitative analysis of dynamics in the system (Rich, Rich & Dizyee, 2018), SFDs enables an easier translation of a system's causal relationships into differential equations that facilitate quantitative analysis (Hovmand, 2014).

One strength of SDM is its ability to capture the overall dynamics of a system (Martin & Schlüter, 2015). SDM also facilitates controlled experiments using the virtual world as a simulation canvas (Sterman, 2001), which is beneficial when adopting a proactive resilience approach, where an organisation is expected to know the strategies to adopt before the occurrence of disruptions. Rich et al. (2011) argued that complexity in decision-making processes in agricultural value chains necessitates the use of a technique that permits quantification and retains qualitative attributes of traditional value chain analyses.

2.2.1 Application of System Dynamics Modelling to the Study of Resilience

SDM has been adopted to analyse the resilience in different contexts, as shown in Table 1. Li et al. (2011) applied SDM to assess the resilience of agricultural systems to disturbances in water resources. SDM has also been deployed to assess resilience in supply chains (Li et al., 2017; Wilson, 2007). These studies revealed two attributes of SDMs: their ability to combine with other models, and their adequacy as a free-standing technique for resilience assessment. Li et al. (2011) developed an SD model to examine how future scenarios of rainfall patterns, available groundwater for irrigation, and socio-economic factors would impact agricultural food systems in the North China Plain. The model incorporated profitability, crop yield, and water resource components in the analysis. For the yield component, a Cobb-Douglas production function was incorporated into the SD model to predict crop yield.

Li et al. (2017) also integrated multi-objective optimisation in the SD model to investigate how information sharing in a three-echelon supply chain can aid in resilience. Their results showed that information sharing leads to reduced quantity and duration of the backorder, thereby enhancing supply chain resilience.

Table 1 Application of SDM for resilience assessment

Reference	*Study area*	*Context of analysis*
Li, Kou, Wang, and Yang (2020)	Beijing, China	System dynamics modelling was used to assess the dynamic structure and behaviour of urban resilience. Urban resilience is expressed as the sum of governance resilience, material and energy resilience, socio-economic resilience and infrastructure resilience.
Shao and Jin (2020)	China	System dynamics modelling was used to determine the coping ability (resilience) of the lithium supply chain to demand (for new energy vehicles) and supply (raw materials) shocks.
Hossain et al. (2020)	Switzerland	The causal loop diagram was used to identify key variables, interactions and dynamic relationship between the social and biophysical components in a coupled human and landscape model.
Zhu and Krikke (2020)	Netherlands	System dynamics modelling was applied to a 3-tiered cheese supply chain that witnesses an outbreak to determine the information that needs to be shared and the strategies that need to be applied to improve the resilience of the supply chain
Herrera and Kopainsky (2020)	Guatemala	A group model building process with farmers, local government officials, was adopted to construct two models (for each community of the study area). The models were later merged into one model. The effect of climate change on food security
Chang and Lin (2019)	Generic factory setting	Used system dynamics modelling to assess the impact of the order replenishment lead-time on a 3-echelon firms' supply chain resilience (i.e., stability of net inventory level).
Rich, Rich, and Dizyee (2018)	Christchurch, New Zealand	Combined system dynamics modelling with participatory approaches (spatial group model building) for urban and peri-urban agricultural planning
Kotir, Smith, Brown, Marshall, and Johnstone (2016)	Ghana	System dynamics modelling was used to examine the feedback and relationship between river water resource management, population and agricultural production
Gotangco et al. (2016)	Philippines	A generic system dynamics model template is adapted to quantify the impact of the flood (resulting from prolonged rainfall) on households and the local government
Joakim et al. (2016)	Vancouver, Canada	A system dynamics model-based framework was used to assess the impact of adaptation policies on social vulnerability and resilience of coastal cities
Bueno and Basurto (2009)	Gulf of California, Mexico	System dynamics modelling was used to represent the fishery population and harvest to determine the effect of disturbances in the context of marine social-ecological systems
Jewan and Heekyung (2018)	Unspecified (generic)	System dynamics was used to model the behaviour of water and energy supply in an urban system

Wilson (2007) developed two SD models to assess the impact of transportation disruption on resilience in traditional supply chains with vendor managed inventory systems. Wilson (2007) argued that multi-echelon supply chains are complex due to the inherent feedbacks among chain actors, which is ably captured by SDM technique; a claim that has been reiterated in the analysis of supply chain resilience (Spiegler, Naim, & Wikner, 2012).

2.3 System Conceptualisation

In this study, the cocoa value chain was conceptualised prior to primary data collection. One drawback of using a pre-developed (preliminary) model[1] at the onset of the model building process concerns the restriction of stakeholder participation to only commenting on already existing system structure (Rouwette et al., 2002). In contrast, participatory processes of system modelling development such as Group Model Building (GMB) offer full participation of stakeholders and promote clients' ownership of results obtained from SDM (Hovmand, 2014; Rouwette et al., 2002).

A pre-developed model was used in this study for four reasons. First, a plethora of literature on cocoa production and marketing activities that provide the information required for the model building process is readily available. Indeed, cocoa is one of the most researched crops in Ghana, and it has a dedicated research institute in Ghana. Second, the trade-off in terms of time and resources involved in the GMB process. Third, the unavailability of industry actors (processors and buyers) and government officers at strategic decision-making levels to participate in the GMB process. Fourth, the elicitation of information from a wider audience enabled the collation of vast divergent thinking from chain actors (Andersen & Richardson, 1997; Richardson, Vennix, Andersen, Rohrbaugh, & Wallace, 1989).

Although a pre-developed model was used in this study, all three cognitive tasks suggested by Rouwette et al. (2002) (viz information exploration, exploring causes of actions and evaluation)

[1] Preliminary model and pre-developed model are used interchangeably to mean the model developed before primary data collection.

were achieved. Compared with the use of a reference group in a participatory group model building, the first two cognitive tasks were performed with a broader audience to elicit information on cocoa production and marketing activities.

The preliminary model was developed using a causal loop diagram (CLD) to represent the causal links between variables in the cocoa value chain and highlight the pathways of precursors of vulnerability in the cocoa value chain. CLDs act as schemes for conveying and sharing dynamic insights (Wolstenholme, 2003). The preliminary CLD of the cocoa value chain was constructed based on published journal articles, archival data, and grey literature on cocoa production, processing, and marketing activities.

Information was elicited from chain actors via focus group discussion and individual interviews. The focus group discussion and individual interview procedures are detailed in Section 2.4.3. Information on material flow and potential disruptions were elicited at the farm level using a discussion guide for the focus group discussions and an interview guide for individual interviews. A similar procedure was followed for the individual interviews with COCOBOD officials, buyers, and in-country processors in Ghana's cocoa value chain.

The CLD was translated into a series of stock and flow diagrams to enable the quantitative analysis of resilience. Three variations of the stock and flow diagrams are presented in Chapters 4, 5 and 6. Before analysing behavioural patterns from simulated results, the model was structurally validated using two tests: empirical-direct structure and theoretical direct structure tests (Barlas, 1996). The empirical structure test was conducted by comparing the model structure with qualitative and quantitative real-world information (Barlas, 1996). Information elicited from the focus group discussions and individual interviews were used to validate the model structurally. For the theoretical direct structure test, the model structure was compared with established knowledge about the system in the literature.

2.4 Overview of Primary Data Collection

In this study, information was elicited from chain actors in their professional capacities as experts on technical issues concerning production, on-farm processing, and procurement activities in the cocoa value chain. As such, based on the exemption clause in article 6.2.3 sub-article 2 of Lincoln University Policies and Procedures for the Human Ethics Committee, no application was made for human ethics clearance. This notwithstanding, measures were taken to ensure that key human ethics concerns were addressed during this study.

(a) Before data collection

Both written and verbal consents were sought from selected participants prior to data collection. Participants were informed about the purpose of the research and assured that elicited information would be used solely for the stated purpose. Participants were assured of the confidentiality of the information provided. Participants were also informed about their ability to withdraw from the data collection process voluntarily. The contact and email address of the lead supervisor was readily available to participants who may seek to authenticate the purpose of the research.

(b) During data collection

Focus group discussions were organised in public places close to the residences of participants. Permission was sought from participants at the commencement of each session to record proceedings. Token gifts ("*Koha,*" i.e., pen and book) were given to participants as a token of appreciation for their time. Participants were also refreshed after the focus group discussion and individual interview.

A mix of primary and secondary data was used in this study. Secondary data were collected from published literature, case study reports, and actuarial records from the Ghana Statistical Service (GSS) and the Ghana Cocoa Board Authority (COCOBOD). The secondary data used in this study are highlighted in the methodology sections of their respective chapters. This overview focuses on only the primary data collected in the study. Description of where and how primary data was collected are presented in the succeeding subsections.

2.4.1 Study Area

The study area is Ghana; it is in West Africa and covers total land areas of 238,537 square kilometres (GSS, 2014). The six cocoa growing regions in Ghana in descending order concerning current production figures are Western, Western North, Ashanti, Ahafo, Central and Volta regions. Cocoa thrives well in the southern and middle belts of the country. According to the 2010 Ghana Statistical Service Population and Housing Census Report, the Western region, which is the leading cocoa-growing region, has about 37.9% of agricultural farms used for cocoa production. Ashanti and Central regions follow in descending order with 22% and 19% of agricultural farms been cocoa farms respectively (GSS, 2014).

According to Round 6 of the Ghana Living Standards Survey, the population of Ghana is estimated to be about 26.4 million people, with 13.1 million living in the urban areas (GSS, 2014). The agriculture sector employs over 70% of the entire population. It is the primary employing sector in the rural areas; 52.5% of the rural population are employed in the rural forest localities (GSS, 2014).

There are about 350,000 smallholder farmers engaged in cocoa production in Ghana (Anim-Kwapong & Frimpong, 2005). The regional analytical reports from the 2010 Ghana Statistical Service population and housing census for the six cocoa growing regions revealed that over 25% of household heads in the age group of 50-65 years are involved in cocoa production. When the age bracket is extended to 50 years and above, the national average of household head engaged in cocoa production jumps to over 40%. At the chain level, there are 27 licenced buying companies, and five major cocoa processing companies (Kolavalli et al., 2012).

2.4.2 Selecting Participants

The study population comprised the key stakeholders in Ghana's cocoa value chain. A two-step stratification of the study population in Ghana followed by a segmentation process was adopted. Segmentation of the study population helps to achieve homogeneity of participants for focus group discussions (Hennink, 2014). For the first step, the study population was stratified based on their roles in the value chain. This stratification focused on the production and on-farm processing activities as one stratum, and the procurement activities as the second stratum. Cocoa farmers were in the first stratum, and key chain actors, including licenced buying companies, COCOBOD, and processors were in the second stratum.

The second stratification step, which was based on the location of the chain actors segmented the study population based on cocoa-growing regions in Ghana. In each region, the districts producing the most cocoa were selected in consultation with the Deputy Technical Manager (Monitoring and Evaluation) at COCOBOD in Accra, Ghana. One focus group discussion was conducted in each district. The districts included Sefwi Wiawso and Wassa Akropong in the Western and Western North regions respectively, Papapse in the Oti region, Tepa and New Edubiase in the Ashanti Region, and Goaso in the Ahafo region and Assin Fosu in the Central Region.

The gatekeeper strategy (Hennink, 2014) was adopted to recruit participants for the focus group discussions. The district managers of Cocoa Health and Extension Department (CHED) in each selected district were the gatekeepers. The gatekeepers supported the data collection process by organising participants for the focus group discussions and appointing one extension officer in each district to act as a research assistant. A community-based sample of ten participants was recruited in each district. A participant size of between six and ten is recommended (Colucci, 2007; Hennink, 2014). Participants were purposively selected based on gender. Each focus group comprised of five male farmers and five female farmers. In total, six focus group discussions with farmers were conducted. Individual interviews were conducted for five non-participants of each focus group. In total, 30 individual interviews were held at the farm-level.

2.4.3 Primary Data Collection Procedure

Focus group discussion and structured individual interviews were used for primary data collection. This combination of data collection methods, where focus group discussions are conducted first can be valuable for mixed-method research (Morgan, 1996). Focus group discussions were used to elicit information from farmers at the farm level. The information covered the flow of material in the cocoa value chain and potential disruptions that can affect the cocoa value chain.

A guide for the farm-level focus group discussions covered two activity-based processes: *(i) Value chain process validation and (ii) Disruption identification.* During the value chain process validation, participants were asked to describe their pre-harvest and post-harvest practices. The discussions were facilitated by the researcher and supported by COCOBOD officials in each district. During the discussions, the facilitator confirmed issues identified during secondary data collection. The issues concerned details such as inputs and labour costs, cocoa tree productivity, and input application. The focus group discussions were tape (audio) recorded, and the facilitator took notes. The language of communication in all districts was the Twi language. The audio recordings were translated and transcribed into English.

In general, information gathered on the value chain processes were similar across all the districts. This is because all cocoa farmers received the same training from COCOBOD agricultural extension officers. However, there were some divergent views on labour cost and input application. In such situations, the average was determined. The gathered information was used to revise the pre-developed model.

During the disruption identification, participants were asked to identify and rank unforeseen disruptions that may affect the resilience of the cocoa value chain. This information was used for scenario development. Structured individual interviews were used to gather data on adaptive strategies from experts in the cocoa value chain. The experts included 30 farmers who did not participate in the focus groups, the Deputy Technical Manager (Monitoring and Evaluation) at COCOBOD, the National Deputy Director of the Produce Buying Company in Accra and the General Manager of JS cocoa Ghana (an in-country processing company), and the Project Coordinator of Cargill Kooko. Figures 2, 3 and 4 show the focus group discussion and an individual interview conducted in Sefwi-Wiawso and Wassa Akropong districts.

Figure 2 Focus group discussion with cocoa farmers at Sefwi-Wiawso in the Western North Region, Ghana

Figure 3 Focus group discussion with cocoa farmers at Wassa Akropong in the Western Region, Ghana

Figure 4 Individual interview with a cocoa farmer in Sefwi -Wiawso in the Western North Region, Ghana

Chapter 3 Operationalising Resilience in Tropical Agricultural Value Chains

If I have seen further, it is by standing on the shoulders of Giants
- *Isaac Newton*

This chapter fulfils objective one, and is based on the published journal article below:

Aboah, J. Wilson, M.J.M., Rich, K., Lyne, C.M., 2019. Operationalising resilience in tropical agricultural value chains. *Supply Chain Management: An International Journal.* 24(2) pp. 271-300. https://www.emeraldinsight.com/doi/full/10.1108/SCM-05-2018-0204

Abstract

Purpose – The analysis of the concept of resilience in supply chain management studies mostly focuses on the downstream side of the value chain and tacitly assumes an unlimited supply of raw materials. This assumption is unreasonable for agricultural value chains, as upstream disruptions clearly have a material impact on the availability of raw materials, and indeed, are a common source of supply problems. This paper aims to present a framework for the operationalisation of the concept of socioecological resilience in agricultural value chains that incorporates upstream activities.

Design/methodology/approach – A citation network analysis was adopted to review articles. A conceptual framework is then advanced to identify elements of resilience and indicators relevant to tropical agricultural value chains.

Findings – There are limited studies that assess resilience in the food chain context. Flexibility, collaboration, adaptability, and resourcefulness are key elements for assessing resilience at the individual chain actor level. However, the paper argues that adaptability is the relevant element for the assessment of resilience at an aggregate food system level because it considers the alteration of a system's state of resilience.

Practical implications – The proposed framework and propositions accommodate stakeholder interactions in the value chain and could serve as a tool to guide the assessment of resilience in agricultural value chains.

Originality/value – This paper is one of the few to extend resilience to cover the socioecological interaction aspects for supply chains that yield the raw materials needed for continuity in channel-wide value creation processes.

Keywords: adaptability; agricultural value chain; socioecological resilience

3.1 Introduction

Disruptions occur daily in various parts of the world, destabilising the normal daily activities and causing economic losses (Hosseini, Barker, & Ramirez-Marquez, 2016). More frequent occurrences of disruptions of late have aroused interest in the idea of resilience (Pettit et al., 2013; Soni et al., 2014). Resilience has become a popular concept for researchers, business, development organisations and governments because of the increased uncertainty arising from both natural and man-made disruptions (Hosseini et al., 2016).

At an organisational level, not every firm actively engages in building resilience. The concept of resilience is viewed as a strategic consideration, and this has become more prominent with the advent of globalisation, as organisations are no longer restricted to a single geographic location of operations (Wagner & Neshat, 2010). Firms that operate globally seek to benefit from the potential advantages of market expansion, risk diversification and lower sourcing and production costs associated with operating outside their original geographic location and national borders (Caniato et al., 2013; Gereffi, Humphrey, & Sturgeon, 2005). However, such global operations are accompanied by an axiomatic increase in risk and new challenges that do not always exist with local operations. Those that are not adequately prepared will inevitably suffer disruptions somewhere in their global value chain (Hohenstein et al., 2015; Jüttner & Maklan, 2011).

Food organisations like Barry Callebaut, Cadbury, Mars and Nestle, whose mainstream products hinge on raw materials derived from agricultural commodities produced in geographical-specific regions, face the problem of balancing the benefits and risks of globalisation. Globalisation does not necessarily mean that there are endless suppliers of inputs conveniently dispersed around the globe. Rather, while agricultural value chains have gone global, the source of supply is often concentrated into only a few preferential geographic areas or a few suppliers that can meet requisite standards. Therefore, risk has not really been mitigated by the dispersing of activities throughout the global value chain; rather, many commodity chains have become more vulnerable.

Commodities that are consumed globally, but grow profitably only in the tropics, are referred to as tropical commodities (Talbot, 2002). Some examples include cocoa, coffee, shea nut, cashew, and oil palm. These commodities are often of interest to policymakers in producing countries as they are major earners of foreign exchange (Talbot, 2002). Tropical commodities have idiosyncratic weather requirements that make them susceptible to ecological and climatic disruptions, and their chains are often prone to deficiencies in governance that cause socio-economic disruptions (Gereffi et al., 2005; Niforou, 2015; Talbot, 2002). As a result, the quest for resilience in tropical commodity chains transcends the actions of individual actors, and thus requires an assessment of the risks within the whole value chain. This paper defines resilience as the aggregate adaptive capacity of a system to become ready for, respond to and recover from disruptions without losing the system's primary state (i.e., raw materials that flow through the chain).

Attempts to assess resilience in supply chains usually focus on activities in the processing, manufacturing, and distribution stages of the chain (Colicchia et al., 2010; Datta et al., 2007; Munoz & Dunbar, 2015). However, the resilience of an agribusiness value chain is multidimensional. It involves interactions between people, technical systems, and the natural environment, and therefore has economic and socioecological dimensions that are upstream-focused (Folke et al., 2010). Moreover, the resilience of agricultural value chains is largely determined by upstream activities in contrast with global manufacturing and retailing chains, where resilience depends largely on downstream activities. This is because upstream disruptions are more critical in food supply chains (Pereira et al., 2014), as failures cascade down to midstream and retail actors when they do occur (Wang & Xiao, 2016).

According to Leat and Revoredo-Giha (2013), there is limited research on supply chain resilience with a focus on upstream productive activities. Indeed, their review demonstrates that articles that analyse agricultural value chains and resilience of commodity production are rare in the literature.

To address this research gap, this conceptual paper attempts to operationalise a contextual definition of resilience for agricultural value chains. In addition, it proposes a framework for a future quantitative analysis of resilience from both economic and socioecological perspectives and addresses two main objectives:

i. to conceptualise resilience in the context of tropical commodity value chains; and

ii. to propose and operationalise a conceptual model of agricultural value chain resilience.

This paper, therefore, provides two major contributions to the existing supply chain resilience literature. First, it develops a robust approach for operationalising the agricultural value chain resilience with an emphasis on upstream productive activities. This focus acknowledges the critical role that the supply of raw materials plays in the continuity of value chain processes. Indeed, the phenomenon of raw material scarcity is relevant in supply chains, but often ignored. In this regard, the paper provides a basis for extending the resilience analysis beyond the impractical assumption of infinitely available raw material. Second, the paper identifies appropriate elements of supply chain resilience. This process is based on the framework that extends the analysis of supply chain resilience from the viewpoints of individual economic units to the wider industry, thus necessitating an aggregate assessment of the system's resilience.

To achieve these objectives, literature relevant to resilience in supply chains was reviewed and synthesised to identify elements and indicators relevant for the analysis of resilience in tropical agricultural value chains. The paper concludes by highlighting the salient issues to consider when analysing resilience in these chains, identifying future research gaps and noting the limitations of the proposed framework.

3.2 Methodology

A citation network analysis (CNA) was adopted to give an objective approach for selecting research articles included in the literature review (van Eck & Waltman, 2014). The process involved four steps that are described in the subsections that follow.

3.2.1 Step 1: Database Selection

Three databases (i.e., Science Direct, Scopus and Web of Science) were initially selected based on their multidisciplinary nature. The databases were compared based on the relevance of journal sources retrieved and the number of publications on the topic of interest found from the database. For Scopus and Science Direct, "*supply chain resilience*", "*food chain resilience*", "*value chain resilience*" were used as the Boolean search strings in the article title, abstract and keywords. For the Web of Science database, the same search words were used under the topic section because the database does not permit a search based on abstract and keywords.

A preliminary search was conducted without restrictions on the timeframe. A trend analysis of the articles retrieved from the search, as shown in Figure 5, indicates that the interest in supply chain resilience heightened from the year 2000. Some of the earliest studies on supply chain resilience were conducted between 2001 and 2004 (Christopher & Peck, 2004; Jüttner, Peck, & Christopher, 2003; Sheffi, 2001). Therefore, the timeframe for the article search was set from 2000 to 2018. Inclusion criteria based on the language (articles in English) and document type (peer-reviewed articles) were applied to filter the results.

In total, 174 publications were retrieved from Science Direct. A similar search in Scopus and Web of Science yielded 453 and 684 articles, respectively. The database selection step also provided a first-hand indication of which journals contain most of the relevant publications with respect to supply chain resilience.

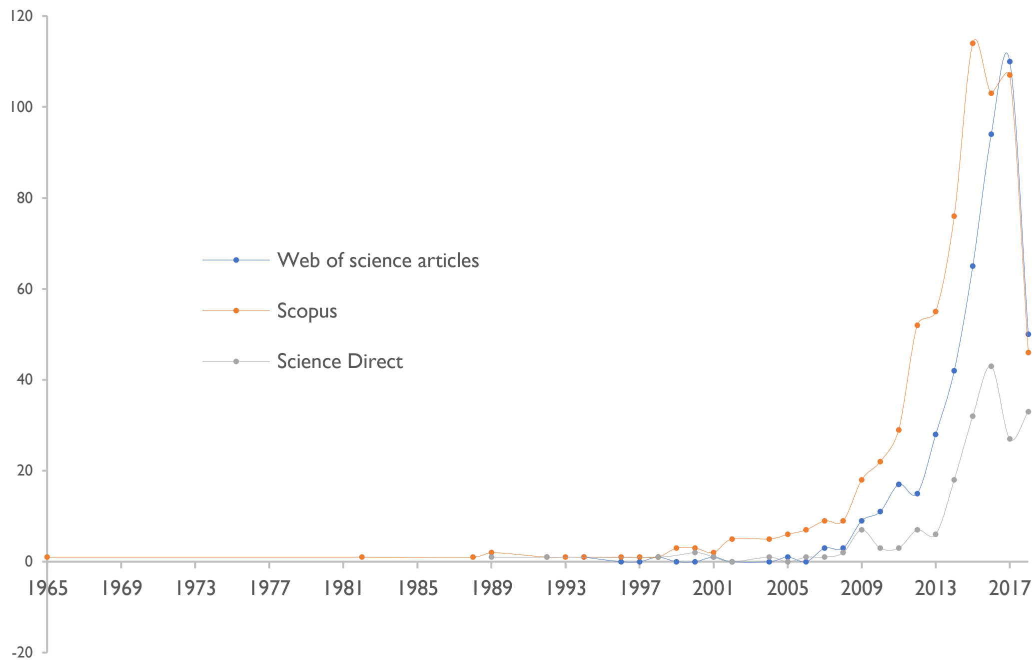


Figure 5 A trend analysis of published articles on supply chain resilience in three databases

The search also revealed the following seven journals in descending order of most publications: International Journal of Production Economics, International Journal of Production Research, Supply Chain Management: An Internal Journal, Sustainability (Switzerland), Journal of Cleaner Production, PLoS ONE and Transportation Research Part E – Logistics and Transportation Review. Figure 6 shows the top 20 journals with the highest number of peer-reviewed articles on supply chain resilience. The Web of Science and Scopus databases were selected for the citation network analysis (CNA), as they identified the largest number of papers, including 83 per cent of the articles retrieved by the Science Direct database.

3.2.2 Step 2: Citation Network Analysis

Although systematic literature reviews are comprehensive and replicable, they follow the pre-determined inclusion and exclusion criteria for article selection that can lead to a loss of important data (Weed, 2005). Rather, a CNA augments the procedure and permits a timely process that ensures that relevant publications are not ignored (van Eck & Waltman, 2014).

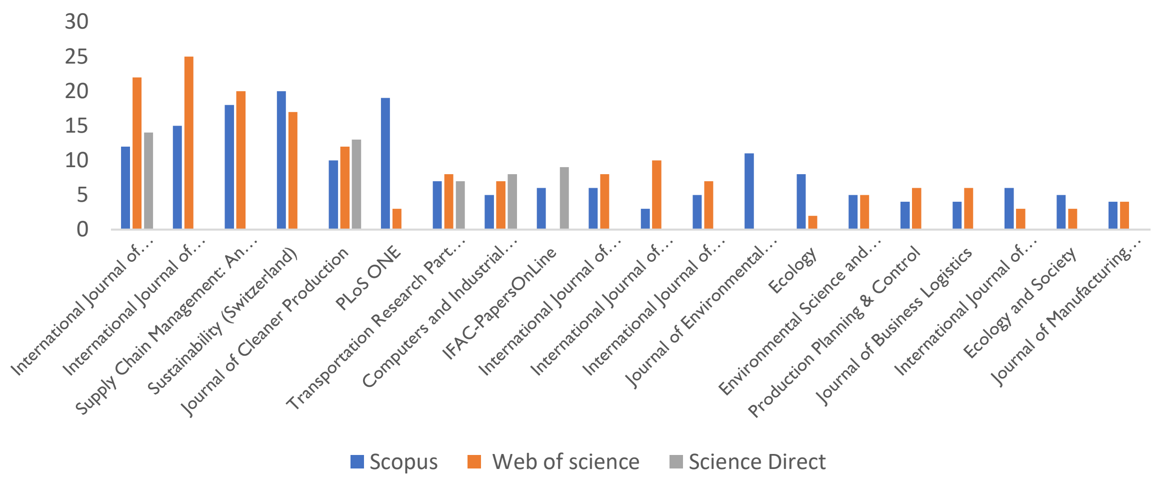


Figure 6 Top 20 journals with the highest number of peer-reviewed articles on supply chain resilience (2000-2018)

Files containing relevant information of each publication (namely, authors, title of articles, indexed keywords, abstract, publication source and referencing link, DOI and citation frequency) were extracted from the two selected databases. The Vosviewer software® was used for the CNA. The Vosviewer software® created by Nees van Eck & Waltman focus on networks involving individual publications (van Eck & Waltman, 2014). For each publication, the software uses algorithms to generate an internal citation score that represents the frequency of citation in a citation network. It also yields a link strength for each publication based on the relationships with other publications in the citation network.

The citation network fulfils two rules. First, the relations between two publications are not forward-looking, meaning that a publication with a current date can cite another publication with a later date, but not the reverse. Second, the citation network is acyclic, that is, two publications cannot cite each other (van Eck & Waltman, 2014). The CNA generates connected component and clustering, which is an analysis that groups publications into clusters based on the strength of the connection (citation relations) between the publications. The CNA also identifies core publications, which helps to eliminate publications of peripheral importance in the citation network. Core publications are publications with at least ten citation relations with other core publications (van Eck & Waltman, 2014).

The CNA was conducted for the sets of publications generated from the Web of Science and Scopus databases in Step 1. The unit of analysis was the individual article publication. The CNA depended on the strength of connection in the title, keywords, abstracts and references of publications obtained from Step 1. Recent publications were expected to have fewer citations as compared to older ones; therefore, a minimum of zero citation was set as a threshold for selecting strongly connected publications. In determining the number of publications to be included in the literature review, a threshold for the top 100 publications with the strongest connection in the CNA was set using a minimum cluster size of 10 publications. For the Web of Science database, 98 publications were grouped in eight clusters, and 99 publications in eight clusters were selected for the Scopus database. Visualisations of the CNA of publications from the two databases are presented in Figures 7 and 8. Articles shown in the same colour belong to the same cluster.

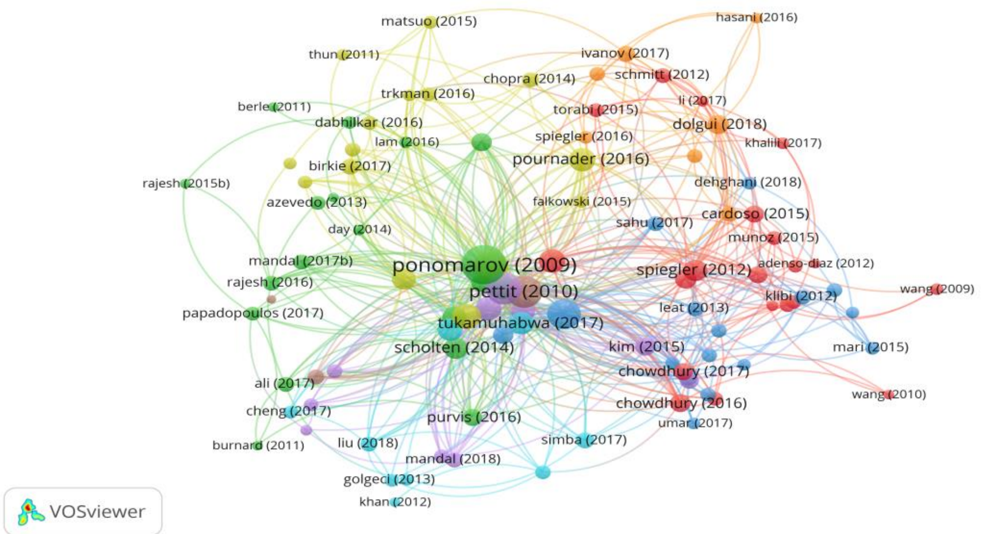


Figure 7 Visualisation of CNA for publications on supply chain resilience in the Web of Science database

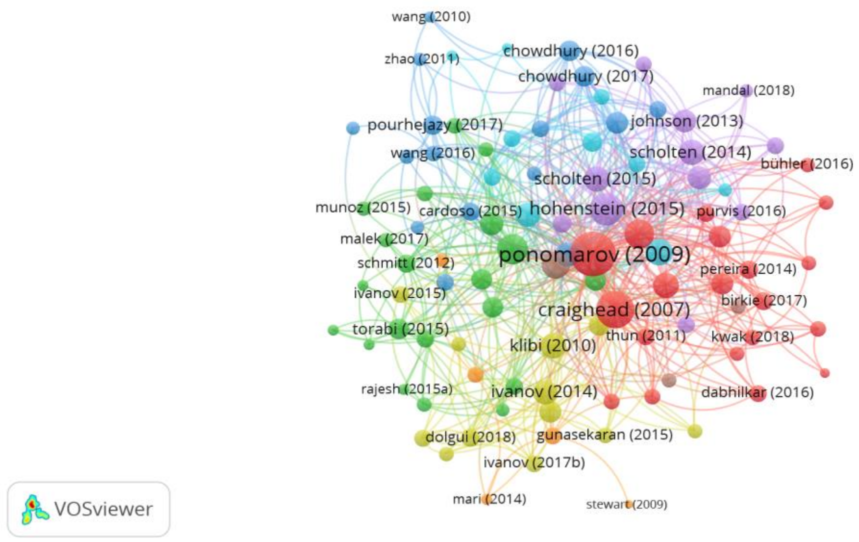


Figure 8 Visualisation of CNA for publications on supply chain resilience in the Scopus database

3.2.3 Step 3: Article Selection

All publications in the two CNAs were ranked based on their total link strength. If a publication appeared in the CNA for the Web of Science, then $X_w = 1$, else $X_w = 0$. Likewise, if a publication appeared in the CNA for Scopus, then $X_s = 1$, else $X_s = 0$. The total link strength ($Ls_{(total)}$) for a publication was estimated as:

$$Ls_{(total)} = \sum \left(Ls_{(ws)} X_{(ws)} \right) \qquad (3.1)$$

After calculating the total link strengths, duplicate publications were merged into one publication. In total, 197 publications were ranked based on their link strength. Out of these, only five publications (Agigi et al., 2016; Elleuch et al., 2016; Falkowski, 2015; Leat & Revoredo-Giha, 2013; Umar et al., 2017) focused on supply chain resilience in the context of food chains. There is no precise number of publications accepted for literature review. However, Wee and Banister (2016) recommend a threshold of 30 publications as the minimum. Therefore, 50 publications with the highest link strength were selected for content analysis. Also, four publications that focused specifically on food chains, but which were not ranked in the top 50, were included in the content analysis.

3.2.4 Step 4: Content Analyses

The following questions were explored in analysing the selected research articles: (a) *In what context was supply chain resilience examined?* (b) *How was the concept operationalised?* (c) *What indicators were used for measuring resilience?* The selected research articles were organised into eight different clusters derived from the CNA, as shown in Appendices 3.0. The commonalities in each cluster were analysed to give an overview of the key issues differentiating the research articles, as presented in Table 2. The framework of the four steps adopted in the CNA is illustrated in Figure 9.

3.3 The Conceptualisation of Resilience for Tropical Commodity Chains

A clear conceptualisation of the concept of resilience is important so that disruptions can be understood, and mitigation efforts are appropriate to deal with disturbances that affect the system (Tendall et al., 2015). Holling (1973) identified resilience as one of the two properties shaping a system's behaviour when faced with disturbance; the second is stability. Holling (1973, p. 14) defined resilience:

[. . .] "as a measure of how persistent a system is and how the system is able to absorb change and disturbance without losing the relationships between populations or stable variables."

Stability concerns the speed at which a system achieves equilibrium after disruptions. Holling (1973) further recommends the adoption of a management approach to study resilience. Subsequent definitions of resilience in management studies often refer to the system's stability and rapidity of response. Definitions of resilience proposed in the supply chain literature have been classified as either reactive or proactive (Ponomarov & Holcomb, 2009). Reactive definitions focus on a system's responses to disruptions without emphasising its preparedness (Christopher & Peck, 2004; Pettit, Fiksel, & Croxton, 2010; Rice & Caniato, 2003). Proactive definitions of resilience are those regarded as precautionary and reflect the so-called "*3Rs of resilience*": readiness, response and recovery of a system (Spiegler et al., 2016).

Table 2 Description of the key issues addressed by the research articles in each cluster

Cluster	*No. of research articles*	*Key issues addressed*
1	6	Developed conceptual frameworks for assessing supply chain resilience and exploring the relationship between the elements.
2	10	Developed indexes for measuring supply chain resilience.
3	10	Focused on downstream chain activities (esp. in manufacturing firms) and considers delivery time as a key indicator of resilience.
4	5	Concern studies on how supply chain network designs and other strategies can be used to reduce disruptions.
5	12	Explored the different elements that constitute supply chain resilience and how they influence resilience.
6	8	Highlighted the use of simulation models for assessing supply chain resilience and the role of collaboration in enhancing supply chain resilience.
7	1	Explored the use of big data retrieved from social media to enhance resilience
8	2	Examined factors that influence supply chain vulnerability and how flexibility in order fulfilment and sourcing can enhance supply chain resilience.

Resilience focuses on unforeseeable disruptions (Pettit, Fiksel, & Croxton, 2010). The uncertainty about the probability of a disruption occurring puts resilience outside the domain of risk management and gives the proactive definition precedence over the reactive definition. Within a system, organisations may view resilience practices as either an operational or strategic capability (Brusset & Teller, 2017; Munoz & Dunbar, 2015). The reactive definition of resilience presents these practices as an operational capability. In contrast, the proactive definition treats resilience as a strategic and dynamic capability that enables the firm to adapt operating activities to achieve competitive advantage (Brusset & Teller, 2017; Manning & Soon, 2016). Notwithstanding these broad definitions of supply chain resilience, the context of the analysis circumscribes the concept of resilience. Supply chain resilience will, therefore, be defined differently for different systems.

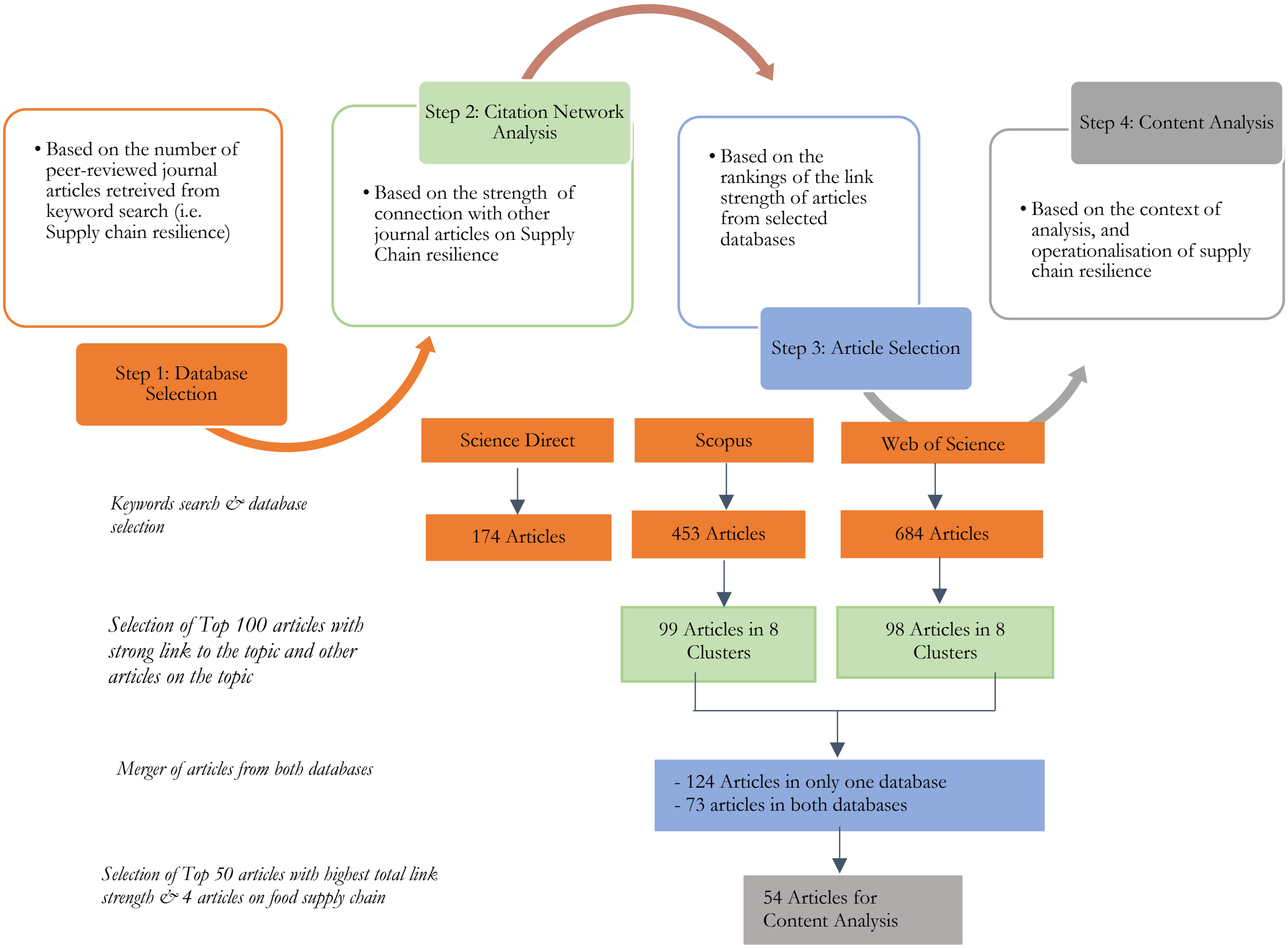


Figure 9 The four steps of the CNA

3.4 The Context of Tropical Commodity Chains

Definitions of resilience have been criticised as vague, resulting in subjective applications of the concept across different disciplines (Fridolin & Kurt, 2007). One such aspect associated with the subjective use of resilience concerns a system's state post-disturbance. While Holling's definition of resilience suggested a return to the system's initial state (Holling, 1973), other authors argue that recovery need not imply a return to the original state, but rather the achievement of a new state (Christopher & Peck, 2004; Jüttner et al., 2003). What then is the "*state*" of a supply chain or food system that must be maintained in the face of disruption? Analysis of the system's context determines the appropriate system state of resilience and should serve as a precursor for the operational definition and analysis of resilience.

The content analysis showed that, for most literature on supply chain resilience, the context of analysis relates to manufacturing, distribution, and transportation systems. These systems are regarded as sociotechnical systems (Smith & Stirling, 2010; Amir & Kant, 2018). Indeed, Amir and Kant (2018) provide a fundamental distinction between sociotechnical and socioecological systems. They argue that while sociotechnical systems capture the man–machine interactions, socioecological systems are strongly linked to man–nature interactions.

This paper posits that, in general, resilience of agricultural food systems comprises an integration of sociotechnical and socioecological aspects, with the latter being more relevant for upstream productive activities. However, the relative importance of sociotechnical resilience for upstream activities depends on the level of technology used in production activities. When production activities involve advanced technologies, as in plantation agriculture, then sociotechnical resilience becomes more relevant.

In tropical commodity chains, socioecological resilience is important for two reasons. First, upstream activities play a crucial role in agricultural value chains because the nascent outcome of these activities is a central focus for supply chain continuity. Second, production activities for tropical commodity crops like cocoa have not been easy to mechanise due to small farm size and low capital investment. The supply chain literature often neglects the socioecological aspect of resilience (Tendall et al., 2015). Rather, it focuses on downstream processing, manufacturing and distribution activities and assumes an unlimited supply of raw materials produced further up the chain (Datta et al., 2007). Such an assumption is unrealistic when the context of analysis includes upstream activities, as in the case of tropical commodity chains.

3.5 The State of Resilience for Tropical Commodity Chains

A vital aspect of resilience analysis is the identification of a system's state (Carvalho & Cruz-Machado, 2011). Indicators of a sociotechnical system's state of resilience proposed in the supply chain literature include its performance level, losses, and recovery time (the resilience triangle) (Tukamuhabwa et al., 2015); connectedness, control over structure and function (Ponomarov & Holcomb, 2009); and operations (Jüttner & Maklan, 2011).

For socioecological systems, Cumming et al. (2005) described the system's state of resilience as the identity of the system that needs to be maintained in the face of disruption. For socioecological systems like agricultural food systems, ecosystem services act as the system's state of resilience that needs to be maintained in the face of disruptions (Cumming et al., 2005). Resilient systems are those that can maintain the key attributes of ecosystem services that generate continuity in the system (Cumming et al., 2005).

Ecosystem services are the output of the interaction between human skill, technology, and nature (ecology) (Biggs, Schlüter, & Schoon, 2015). Among the three categories of ecosystem services (i.e., provisioning, regulating and cultural services), the provisioning of ecosystem services (e.g., crops, fish, timber, etc.) fits well for agricultural food systems (Biggs et al., 2015).

In tropical commodity chains, raw materials produced via upstream production activities are examples of these provisioning ecosystem services. The quantity and volumes of these raw materials flowing downstream serve as a reference point for gauging resilience levels, and these are determined by the stakeholders in their socioecological interaction (Cumming & Peterson, 2017). The notion of using the amount of inventory flowing through the supply chain as the basis for estimating resilience levels is highlighted by Torabi et al. (2016).

Further, Tendall et al. (2015) suggest three levels of enquiry for the analysis of resilience in food systems: the national or food systems level, discrete food value chain (either local or global) level and at the individual actor's level. Policymakers and governments are most interested in resilience at the national or food systems level. For industry players, resilience is of interest at the level of individual food value chains. From the individual actor's perspective, resilience is important at the level of individual firms or enterprises. A system's state of resilience may be determined at any of these levels. Results of the content analysis indicates that most supply chain resilience studies are conducted within the purview of the third, organisational, level. Yet, this paper contends that resilience in tropical commodity chains like cocoa should, in the first instance, be approached from the national food system level.

Cocoa is of national interest to the major producing countries because of its substantial contribution to the gross domestic product, 7.5 per cent and 3.4 per cent for Cote d'Ivoire and Ghana, respectively (Läderach et al., 2013). The governments of these two countries have considerable influence on the institutional environment that governs and guides actors in the value chain. They also set producer prices for the raw material (cocoa beans) traded by chain actors. This suggests analysis at the national or value chain level. Analysis at the aggregate level does not, however, prevent the inclusion of disaggregated levels of resilience for upstream actors.

In sum, the conceptualisation of resilience in agricultural food systems considers three issues. First, the context of analysis, as this determines whether the focus will be on socioecological or sociotechnical resilience. Second, the system's state of resilience, as this foundation is required to determine the levels of resilience. Lastly, the level of enquiry, as this helps to establish a threshold level of resilience. The remaining sections of this paper seek to operationalise the concept.

3.6 Elements of Agricultural Value Chains Resilience

Measures of resilience in the supply chain literature have been partially subjective and usually considered within specific context of the analysis (Tukamuhabwa et al., 2015). Indeed, much of the literature positions resilience within the context of the processing, manufacturing, and distribution of material in the value chain. As such, they adopt a sociotechnical view of the interactions between the behavioural and technical elements in determining resilience. Such views tend to be oblivious to the socioecological elements of an agricultural value chain (Tendall et al., 2015) and assume an unlimited supply of raw materials (Datta et al., 2007).

According to Jüttner and Maklan (2011), flexibility, velocity, visibility, and collaboration are the four most frequently acknowledged elements of resilience found in the supply chain literature. Christopher and Peck (2004) combined visibility and velocity as sub-components of agility. Visibility refers the ability to see the flow of inventory in real time all along the value chain, while velocity measures the total turnover of material (inventory) in a set period (Christopher & Peck, 2004). The inclusion of visibility as an element of agility has been contested and linked to the concept of inter-organisational collaboration (Ponis & Koronis, 2012). If the flow of material from one point of the value chain to another is facilitated via transactional terms between two or more chain actors, then visibility will not be a robust element.

Visibility is enhanced when a dominant actor in the value chain facilitates the distribution of information to all the others (Ponis & Koronis, 2012). Conversely, visibility can be constrained when the flow of information is siloed at each level within the chain. For instance, a processor may know the inventory in its warehouse or those in the pipeline, while information on the level of a supplier's outbound inventory may be opaque to the processor. Thus, visibility will be appropriate only when stakeholders collaborate and readily share information among themselves.

In a study that ranked different elements of resilience proposed in the supply chain literature, Ponomarov and Holcomb (2009) cited flexibility as the highest-ranked element of resilience, followed by collaboration and visibility. Alternatively, Pettit et al. (2013) presented collaboration as the highest-ranked element, followed by flexibility and adaptability. Despite these contrasting views, flexibility and collaboration have been consistently identified in the literature, and this is supported by the results of the content analysis.

From the content analysis, 20 different elements of resilience were suggested. Evidently, there is a lack of consensus concerning these elements. The content analysis revealed that the top seven elements often used for the operationalisation of supply chain resilience are flexibility, collaboration, redundancy, visibility, agility, efficiency, and adaptability. The result resonates with other findings that show collaboration, flexibility, and redundancy as the top three elements (Hohenstein et al., 2015). The different elements suggested in the supply chain literature and their usage frequencies in each cluster are illustrated in Figure 10.

The lack of consensus over the elements of resilience can be attributed to the differing contexts of analysis, the tendency to delink peripheral elements from the core ones and the interchangeability of some elements of supply chain resilience. For instance, information sharing, connectivity, coordination, integration, and visibility are regarded as components of collaboration (Ponis & Koronis, 2012; Scholten & Schilder, 2015). As such, proposing these as standalone elements of supply chain resilience reduces the concordance in literature. Indeed, these elements are often combined into one element (i.e., collaboration).

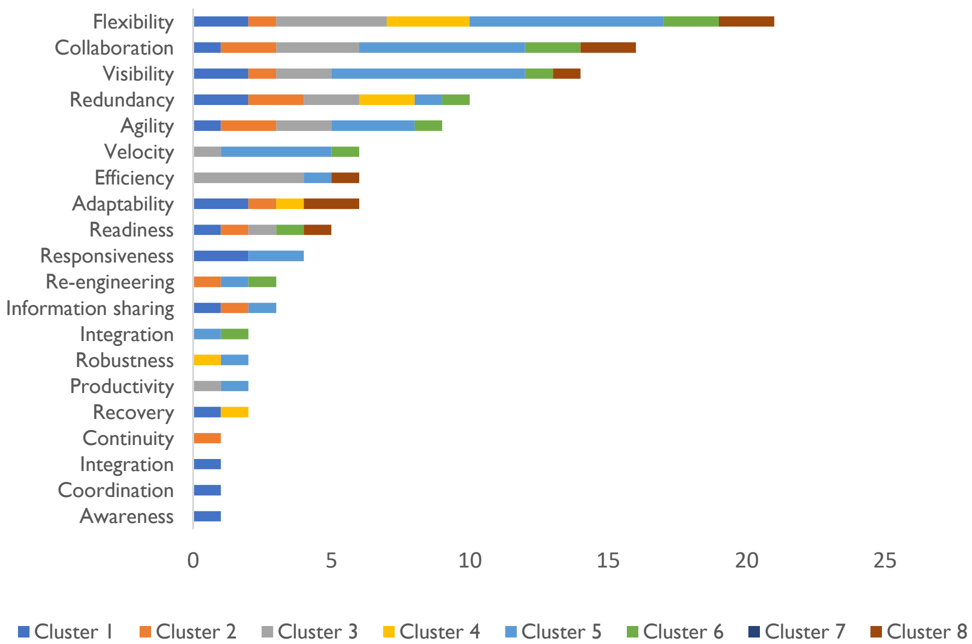


Figure 10 Elements of supply chain resilience and their usage frequency

Although most of the selected articles in the content analysis assess supply chain resilience from the sociotechnical viewpoint, transformability (i.e., the capacity of a sociotechnical system to respond to disruptions by shifting from one configuration to another), which is the central element of sociotechnical resilience (Amir & Kant, 2018), is not profound in these articles. Instead, flexibility, which is considered as a prerequisite for transformation (Amir & Kant, 2018), is the most mentioned element of resilience in the supply chain literature.

Redundancy implies building extra or surplus capacity and capabilities as a proactive measure of disruption (Sheffi & Rice, 2005). However, having extra capacity/capability does not fully explain resiliency; balancing redundancy and efficiency is a prerequisite for building supply chain resilience (Sheffi & Rice, 2005). Yet, the two elements present a dilemma for resilient supply chains; while high redundancy can potentially increase resilience, there are cost implications that lower the efficiency of a system. This paper suggests a merger of the two concepts to form an element termed "*resourcefulness*", and this is discussed in the next section.

Though velocity and visibility are among the most suggested elements of resilience (Jüttner & Maklan, 2011), they are regarded as constituents of agility (Christopher & Peck, 2004). Agility deals with responses to short-term changes in the supply chain (Eckstein et al., 2015), but resilience in tropical commodity chains suggests a long-term view for two reasons. First, the perennial nature of the tree crops that produce the raw material for long-term production suggests a need for a longer-term perspective, as actions taken today will not manifest until many years later. Second, the seasonality of raw materials that are critical for the continuity in the operations of midstream and downstream actors necessitates a strategic supply approach (Kraljic, 1983). Therefore, elements that deal with responses to long-term system changes are considered critical. Adaptability has been defined as an element that pertains to responses to long-term changes in socioecological systems (Fazey et al., 2007; Fiksel, 2003). In the following sub-sections, the suitability of these four elements: flexibility, collaboration, resourcefulness, and adaptability are discussed in the context of tropical commodity chains.

3.6.1 Flexibility

Flexibility describes how well a system responds to disruptions to ensure continuity of its operations. Flexibility and agility are often used interchangeably in the literature. Nikookar et al. (2014) defined flexibility as the speed with which a system responds to disruption; this definition has also been ascribed to agility (Christopher & Peck, 2004). Rice and Caniato (2003) described flexibility as the creation of capabilities to respond to disruptions. This definition emphasises a system's capacity to respond to disruption and resonates with later studies in the supply chain literature (Chowdhury & Quaddus, 2016).

According to Charles et al. (2010), flexibility is a precursor attribute that lays the foundation for other elements such as agility, and it is established via pre-event investment (Nikookar et al., 2014). This investment allows for the development of internal capacities through mitigation and contingency strategies like flexibility in production, contracts, procurement, and distribution (Chowdhury & Quaddus, 2016). Investments in resources and infrastructure have cost implications (Rice & Caniato, 2003; Spiegler et al., 2016). The inclusion of costs in resilience assessment is a two-edged trade-off; the cost implications involved in developing strategies that will enhance flexibility (Christopher & Peck, 2004; Datta et al., 2007; Rice & Caniato, 2003), and conversely, the costs from losses as a result of ignoring the investment (Spiegler et al., 2016). Balancing the costs involved with being flexible and the goal of achieving effectiveness when dealing with resilience is crucial (Christopher & Peck, 2004; Datta et al., 2007; Rice & Caniato, 2003) and requires astute trade-off analysis, which is often sadly neglected (Datta et al., 2007).

The effectiveness of a system's adjustment to disruptions determines the response and level of recovery, and these depend on the level of preparedness via prior investment. For instance, a distributor who has a flexible transportation system can easily dispatch replacement vehicles for those vehicles in transit that break down. Such effective adjustments facilitate good response and recovery from a disruption. For an upstream-focused tropical commodity, a flexible farm could, for instance, invest in irrigation to ensure continuous productivity even in times of rainfall shortage. So, flexibility in the context of agricultural production activities concerns the ability for a food system to build capacities via investment to respond to disruptions and safeguard appreciable levels of the raw materials needed for continuity in the value chain processes.

3.6.2 Collaboration

Collaboration is the willingness of chain actors to work together to ensure the smooth running of chain activities. It is often linked to information sharing and visibility (Ponis & Koronis, 2012; Soni et al., 2014) as means to increase the connectivity of chain actors and enable them to work effectively for their mutual benefit (Pettit et al., 2010). It concerns interactions among the socio-economic components of a system, and it is the underlying element that facilitates flexibility, velocity, and visibility (Scholten & Schilder, 2015). Collaboration is motivated by the mutual benefits attainable by all actors in a value chain, and it is undermined by self-interest seeking and short-termism.

It has been established earlier that the raw materials produced by upstream actors (i.e., provisioning ecosystem service) in tropical commodity chains are critical to ensuring continuity in the value chain processes and represent the system's state of resilience. Kraljic's purchasing portfolio matrix uses the supply risks in purchasing of such raw materials as a springboard to provide insights into the level of collaboration that chain actors can engage in (Kraljic, 1983).

From Kraljic's matrix, when the complexity of the raw material supply market is high and the importance of purchasing the raw material is also high due to its value-added profile, the commodity falls within the strategic quadrant (Kraljic, 1983). As such, the adoption of a strategic supply management approach is recommended. This involves establishing long term contractual agreements with global suppliers to secure the long-term availability of the raw materials (Kraljic, 1983).

The availability of these raw materials is naturally critical for continuous operations of actors at the midstream and downstream levels of the value chain. This dependence should stimulate midstream and downstream actors to take a greater interest in upstream production activities. However, the backward integration of these actors is impeded by the complexity (*vis-a-vis* land tenure systems, governance structure necessitating political interference and natural physical monopolies where certain goods can only be produced in certain places) involved in engaging and owning land-based production activities in tropical commodity chains. Thus, in practice, collaboration is often low.

Despite this complexity, midstream and downstream actors in tropical commodity chains have adopted certification and incentive schemes to boost on-farm productivity and ensure the availability and supply of biological raw materials (Elder, Zerriffi, & Le Billon, 2012). Hence, collaboration is the binding force that stimulates symbiotic behaviour from different chain actors and motivates chain actors to act synergistically to mitigate disruptions that occur in the system and maintain the levels of raw materials flowing through the value chain.

3.6.3 Resourcefulness

Earlier, a merger of redundancy and efficiency to form resourcefulness was suggested. Resourcefulness is defined as the ability to identify problems, establish priorities and mobilise resources to deal with disruptions (Cimellaro, Reinhorn, & Bruneau, 2010; Tierney and Bruneau, 2007), to ensure recovery of the functionality of the system (Tierney & Bruneau, 2007). Stakeholders take economic decisions to proactively prepare for disruption by developing their capacities to respond and or adapt to disruptions; such preparedness for disruption connotes investments. The capacities developed by these investments must be optimised to curtail wastes in operation. Therefore, it is important to balance the cost of investment in redundant capacities with efficiency (Scholten & Schilder, 2015). While redundancy captures pre-disruption decisions, efficiency is a post-disruption output of the latter.

Resourcefulness looks at how the decisions have resulted in maintaining the system's state of resilience. This paper focuses on upstream disruptions in socioecological systems and investments related to agricultural production. If production activities are being dominantly conducted by autonomous actors, then the decisions of these actors can severely influence resilience of tropical commodity chains. In these chains, the perennial nature of the tree crops that produce these commodities implies long-term recurring production activities that need to be efficiently managed to secure appreciable levels of productivity. Therefore, resourcefulness is defined as the prioritisation and efficient management of resources (i.e., the factors of production like land, inputs, labour) to ensure that the desired levels of productivity are not lost when the system is faced with disruption.

3.6.4 Adaptability

Adaptability is the capacity of a system to change its behaviour in response to the variation in its environment or to preserve, improve or achieve its goals (Ivanov, Sokolov, & Kaeschel, 2010). Adaptability deals with responses to long term changes in the supply chain (Fiksel, 2003). Therefore, alteration of the system structure is required for developing such capacities (Eckstein et al., 2015; Ivanov et al., 2010). Systems that are adaptive can absorb shocks and "bounce back" after disruptions. Adaptability enables systems to learn and alter their behaviour (Fazey et al., 2007) and to retain their state of resilience (Cumming et al., 2005).

In the case of socioecological interactions, the social component of the system (i.e., human) alters the structure of the system via their behaviours (Cumming et al., 2005). When resilience analysis centres on upstream activities, the food system's state of resilience is the continuity in the flow of the raw materials produced by the principal upstream actor (i.e., farmers). Thus, farmer behaviour takes primacy in determining the adaptability of the tropical commodity chain when the analysis is upstream production focused.

Indeed, in the face of disruptions, chain actors can act in a manner that is detrimental to other actors' objectives. Individual actor responses to disruptions that deviate from achieving the system's state of resilience or weaken the system's ability to preserve its state of resilience are disregarded as adaptive strategies. In effect, adaptability reinforces collaboration among chain actors and transcends individual benefits; it deals with the shared aggregate benefits in a system. In view of this, adaptability is defined as the capacity of the tropical commodity chain to absorb disruptions and maintain its state of resilience, irrespective of structural and behavioural changes in the system.

3.7 Element for Aggregate Resilience in Tropical Commodity Chains

In identifying suitable elements of resilience, this paper views resilience from economic and socioecological perspectives. Ultimately, the *raison d' être* for building resilience in a system is to reduce losses arising from disruptions. This requires either pre-disruption investments when resilience analysis takes a proactive view or post-disruption investments when resilience analysis takes a reactive stance. Elements that capture these investment decisions, which act as antecedents for other elements and represent the economic aspects of resilience, are flexibility and resourcefulness. Elements that cover the socioecological components of resilience and focus on the system's state of resilience are collaboration and adaptability. In the context of tropical commodity chains, resilience can be analysed from the viewpoint of policymakers at the national food system level or from the viewpoint of the value chain level or the individual chain actors.

The ensuing argument is presented as a basis for selecting elements suitable for analysing resilience at an aggregate level. An individual farmer's adaptive strategy in the face of disruption (e.g., switching from producing *crop A* to *crop B*) can be an economically sound decision that creates the farm system's new state of resilience (i.e., farm system X_B) and contributes to another system's aggregate state of resilience (i.e., food system Y_B). However, the same adaptive strategy is not synergetic to food system A's state of resilience, thereby reducing food system A's aggregate state of resilience (food system Y_A). Alternatively, the investment decision of the farmer to build flexibility in the farm's asset directly influences the farm system's state of resilience (i.e., farm system X_A), which in turn feeds into the system's aggregate state of resilience (i.e., food system Y_A). The same situation fits the farmer's decision to collaborate with other chain actors or efficiently utilise the inputs.

Applying this logic, when building resilience, elements that do not reinforce the system's aggregate state of resilience can be regarded as elements of an individual system's resilience. Those that do are considered as elements of the aggregate system's resilience. Therefore, when resilience analysis focuses on individual economic units in a food system, all four elements together can be used to determine resilience of the system. By contrast, when resilience analysis takes an aggregate outlook, adaptability is the key element that feeds into a system's aggregate state of resilience. An illustration of the conceptual framework for analysing supply chain resilience in agricultural food value chains is presented in Figure 11.

3.8 Indicators for Measuring Resilience in Tropical Commodity Chains

The content analysis points to two broad approaches that have been adopted to quantify supply chain resilience. The first approach determines a system's state of resilience by developing measurable indexes (Brandon-Jones et al., 2014; Nikookar et al., 2014; Tierney & Bruneau, 2007), referred to as index-based operationalisation. Examples of these indexes include the supply chain resilience index (Soni et al., 2014), aggregate resilient index (Munoz & Dunbar, 2015) and integral time absolute error (Spiegler et al., 2012). Critics of the index-based operationalisation argue that the indexes and scales used to assess the state of resilience diminish the multidimensionality of the concept, making them impractical and somewhat subjective (Datta et al., 2007).

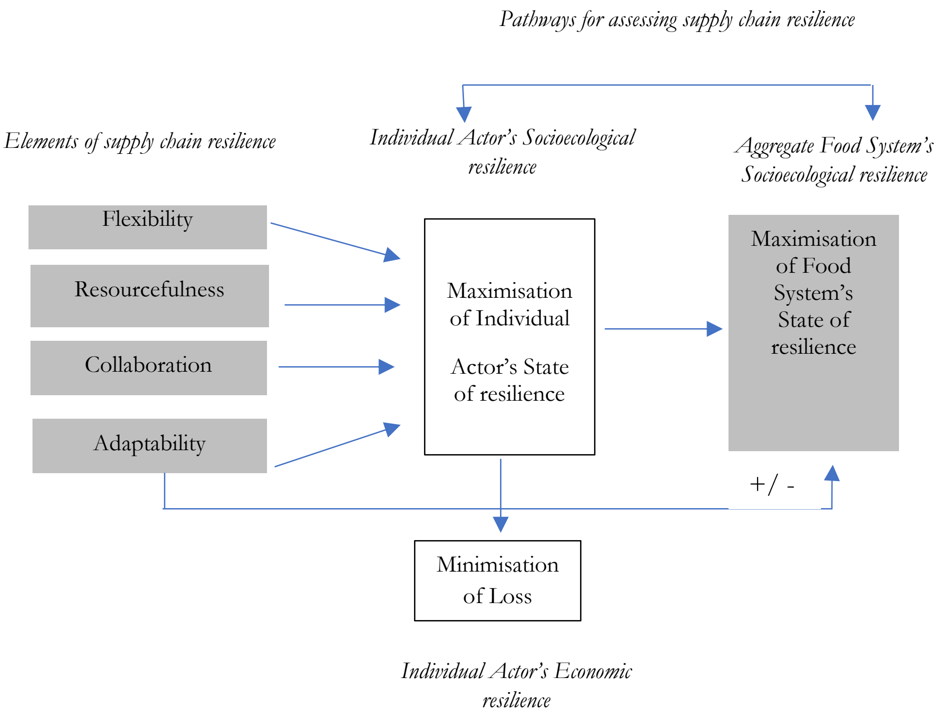


Figure 11 The conceptual framework for analysing resilience in agricultural value chains

The second approach favours performance-based operationalisation. This focuses on the system's outputs (e.g., supply lead time, cost) (Brandon-Jones et al., 2014; Spiegler et al., 2012) and construes supply chain performance measures as the state of resilience (Datta et al., 2007; Carvalho & Cruz-Machado, 201; Colicchia et al., 2010). These performance measures then become the focus of analysis as they tend to be surrogate measures because there are no established indicators for measuring the actual elements of resilience (Cumming et al., 2005). Using performance measures as indicators for resilience assessment gives industry actors verifiable metrics to manage supply chain performance (Munoz & Dunbar, 2015). In this approach, a resilient system is the one that can maintain an acceptable threshold of performance (measured) after disruptions (Falkowski, 2015).

Studies that focus on midstream and downstream actors in a value chain often use performance measures related to customer service delivery (Spiegler et al., 2012). For instance, supply lead times have been used to represent the state of resilience for production and distribution systems (Colicchia et al., 2010; Datta et al., 2007). Some suggested indicators for flexibility include lead time ratio (Carvalho et al., 2012), increased sales or reduced costs (Sheffi & Rice, 2005), stockout rate, inventory accuracy rate, percentage increase sales based on the flexibility design (Rajesh, 2016) and service delivery time (Ishfaq, 2012). For collaboration, indicators suggested in the literature include loss reduction (Chowdhury & Quaddus, 2016) and market share (Hohenstein et al., 2015). According to Ivanov and Sokolov (2013), an output performance measure is an appropriate indicator for assessing resilience.

Broadly, resilience analysis in tropical commodity chains focuses on two performance measures, socioecological and economic. The socioecological aspects focus on the minimisation of loss in a system's state of resilience. This translates into the economic aspect of resilience that focuses on the minimisation of financial loss (as illustrated in Figure 11). In a tropical commodity chain, autonomous farmers are the chain actors whose structural or behavioural changes can significantly cause a loss of the food system's aggregate state of resilience. Such autonomous actors can adapt well because they do not require mutual consent from other actors to adjust their production activities (Williamson, 1991) although peer effects may influence adaptability. Therefore, when the focus of analysis is on upstream activities, the indicator used to measure aggregate resilience in tropical commodity chains should accommodate the adaptability of each focal upstream actor (i.e., farmer) in the value chain. This means that an appropriate indicator for the aggregate resilience will capture:

- the proportion of focal upstream actors who switch-out from producing one commodity to another as an adaptation strategy to disruptions.

- the proportion of focal upstream actors who diversify part of their farms to produce other commodities as an adaptation strategy.
- the proportion that maintains the production of the same commodity despite the disruptions; and
- proportion of new entrants.

In such cases, the first two components of the indicator deal with losses in the system's aggregate state of resilience resulting from the adaptive strategies of the focal upstream actors. The third and fourth components cover the gains in the system's aggregate state of resilience resulting from the adaptive strategies used by the focal upstream actors. Thus, this paper proposes an indicator (*Farm Adaptive Ratio*) that is an offshoot of the performance measure (i.e., system's state of resilience) for measuring aggregate resilience. The Farm Adaptive Ratio (*FAR*)[2] is expressed as:

$$FAR = \frac{(LossSsoR)_{(i)}}{\mu\ (SsoR)_{(j)}} \qquad (3.2)$$

where $LossSsoR_{(i)}$ represents the loss in a system's aggregate state of resilience (i.e., the quantity of raw materials) in cropping $year_{(i)}$ resulting from adaptive strategies (i.e., switched-out farms and diversified farms), and $\mu(SsoR_{(j)})$ is a five-year average of a system's aggregate state of resilience for previous cropping years. The major tropical commodities (i.e., cocoa, coffee, cashew, and oil palm) start fruiting after an average of five years. Thus, a five-year average will capture the raw material contributions from new farm entrants and new trees. If the quantity of raw materials in cropping year(i) $SsoR_{(i)}$ is greater or equal to $\mu(SsoR_{(j)})$, then $LossSsoR_{(i)}$ is zero, else $LossSsoR_{(i)}$ is the difference between $\mu(SsoR_{(j)})$ and $SsoR_{(i)}$. The Farm Adaptive Ratio (FAR) ranges from 0 to 1. A

2 An illustration of how FAR is calculated is given below:
$Yr._{(1)}$ = 100, $Yr._{(2)}$ = 120, $Yr._{(3)}$ = 130, $Yr._{(4)}$ = 140, $Yr._{(5)}$ = 130, $Yr._{(6)}$ = 145, $Yr._{(7)}$ = 125
$LossSsoR_{(6)}$ = 0 (because the production figures for Yr 6 > Yr. 5)
$\mu(SsoR_{(6)}$ = The average of production figures from Yr 1 to Yr 5
$LossSsoR_{(7)}$ = Production figures for Yr. 7 less Yr. 6
$\mu(SsoR_{(7)}$ = The average of production figures from Yr 2 to Yr 6
$FAR_{(6)}$ = 0/124 = 0 $FAR_{(7)}$ = 20/134 = 0.149

low FAR is expected for a value chain that has more focal upstream actors absorbing disruptions through their adaptation strategies without switching from producing the commodity under review. In contrast, a high FAR is expected for a value chain that has more focal upstream actors switching from producing the commodity being analysed. Therefore, an inverse relationship exists between the FAR and resilience, as shown in Figure 12. The lower the FAR, the higher the adaptive capacity and resilience of the value chain.

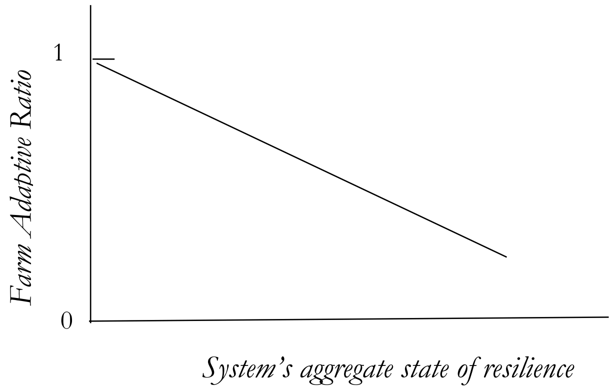


Figure 12 The inverse relationship between adaptability and resilience

3.9 Conclusion

The conceptualisation of resilience is an important step to present resilience as a calculable empirical concept, and it revolves around how the system's state of resilience is determined. The system's state can be based on performance measures and/or subjectively generated measures and indexes. This paper views the context within which resilience is assessed as a crucial influencer of the system's state of resilience. Resilience analyses in agricultural value chains that are upstream-focused highlight the relevance of socioecological interactions in determining the system's state of resilience. Therefore, conceptualisation of agricultural value chain resilience should reflect both the context of analysis and socioecological interactions that influence the system's state of resilience.

Moreover, the operationalisation of agricultural value chain resilience depends on the level at which resilience is analysed. This dictates the suitability of elements suggested for the operationalisation of resilience. The paper reveals that, while adaptability and collaboration are suitable elements for assessing socioecological resilience, flexibility and resourcefulness are critical for the analysis of the economic aspects of resilience. These are applicable when the context of analysis is an individual economic unit. However, adaptability is the suitable element for determining a system's aggregate state of resilience.

This paper contends that, when agricultural value chains are viewed as socioecological systems and resilience analysis is upstream-focused, the chain actors whose activities primarily determine the system's state of resilience are the focal actors. The behavioural changes of these focal actors in response to disruptions determine the adaptive capacity of the food system when resilience is assessed at an aggregate level.

The use of performance measures as indicators for assessing supply chain resilience gives a practical appreciation of a system's resilience level. However, they become less usable when the concept of resilience is disaggregated into its different elements. For this reason, indexes are usually constructed to capture the different components of resilience and to present a single measure of resilience. In doing so, it is argued that indicators based on performance measures are appropriate and practical measures for the assessment of resilience.

3.9.1 Limitations and Recommendations

Although the suggested conceptual framework for assessing resilience allows for trade-off analysis between the economic and socioecological dimensions of the concept, it has limitations in application. First, the framework views elements that capture responses to short-term changes in the agricultural value chain as peripheral. However, such elements can be appropriate when the context of analysis focuses on individual actors instead of the aggregate chain level. Therefore, the applicability of the proposed framework is limited to an aggregate scope of resilience analysis.

Second, by focusing on socioecological resilience, the conceptual framework assumes limited use of technology for upstream production activities. This restricts the study to primarily agricultural value chains that hinge on dispersed production activities with unsophisticated technology.

Appendix 3.0

Authors	*Link strength in Web of Science (L_w)*	*Availability in Web of Science (x)*	*Link strength in Scopus (L_s)*	*Availability in Scopus (y)*	*Total Link Strength (L_s) = $L_w X_w$ + $L_s X_s$*	*Cluster*	*Context of analysis*	*Elements for operationalisation*	*Indicators for measurement*
Ponomarov and Holcomb (2009)	*64*	*1*	*58*	*1*	*122*	*1*	*The study provides a conceptual framework for Logistics capabilities towards supply chain resilience*	*Efficiency, Cost minimisation, Timeliness, Flexibility, Agility, Information sharing, Integration, Adaptability, Maintenance and Recovery*	*Not provided*
Craighead et al. (2007)	*40*	*1*	*41*	*1*	*81*	*1*	*The study focuses on factors that contribute to the severity of supply chain disruption*	*Not applicable*	*Not applicable*
Wieland and Marcus Wallenburg (2013)	*27*	*1*	*25*	*1*	*52*	*1*	*Using the context of European Manufacturing companies, the study looks at relational competencies that enhance supply chain resilience*	*Agility, Robustness & Customer's Value*	*Agility: Speed* *Robustness & customer's value: Not provided*
Carvalho et al. (2012)	*24*	*1*	*26*	*1*	*50*	*2*	*The study assesses the resilience of a three-echelon Portuguese automotive supply chain using a simulation of different scenarios of disruptions*	*Flexibility & Redundancy*	*Flexibility: Lead time ratio* *Redundancy: Total cost (Performance measures)*
Pettit et al. (2013)	*25*	*1*	*22*	*1*	*47*	*8*	*The study develops a tool for measuring resilience from the context of manufacturing and service firms.*	*Collaboration, Flexibility in order fulfilment & sourcing, Adaptability.*	*Capability score and vulnerability score (using a Likert scale)*
Jüttner and Maklan (2011)	*43*	*1*	*0*	*0*	*43*	*5*	*The study conceptualises supply chain resilience in relation to vulnerabilities and risk management.*	*Flexibility, Velocity, Visibility and Collaboration*	*Velocity: Speed (Lead time)* *Flexibility: Effect of disruptions on cost & revenue targets.*

Pettit et al. (2010)	*43*	*1*	*0*	*0*	*43*	*8*	*The study develops a conceptual framework that explores factors that trigger supply chain disruption and the different methods that have been used to build supply chain resilience*	*Flexibility in sourcing & order fulfilment, Efficiency, Visibility, Anticipation, Collaboration, Organization, Dispersion & Adaptability*	*Not provided*

Authors	*Link strength in Web of Science (L_W)*	*Availability in Web of Science (x)*	*Link strength in Scopus (L_S)*	*Availability in Scopus (y)*	*Total Link Strength (L_s) = $L_W X_w$ + $L_S X_s$*	*Cluster*	*Context of analysis*	*Elements for operationalisation*	*Indicators for measurement*
Pournader et al. (2016)	*23*	*1*	*17*	*1*	*40*	*6*	*Develops a complex adaptive system to assess supply chain resilience for a three-tier supply chain in 9 industries (Automobile, Construction, Food Processing, IT, Machinery, Oil & Petroleum, Pharmaceutical & medical, Steel and Textile)*	*Not provided*	*Resilience to Risk ratio (Efficiency score)*
Brandon-Jones et al. (2014)	*23*	*1*	*16*	*1*	*39*	*5*	*In the context of manufacturing plants in the UK, provides a theoretical perspective of how visibility enhances the supply chain resilience and robustness.*	*Visibility*	*Likert scale*
Scholten et al. (2014)	*20*	*1*	*19*	*1*	*39*	*5*	*A conceptual study that develops a framework for investigating supply chain resilience, incorporated with disaster management.*	*Supply chain re-engineering (Efficiency), Collaboration (Visibility), Agility & Risk awareness*	*Efficiency: Output per inputs (resources); Visibility: Time; Agility (Velocity): Speed*
Scholten and Schilder (2015)	*18*	*1*	*20*	*1*	*38*	*5*	*A conceptual study (for food processing companies in the Netherlands) that narrows down on one element of resilience (i.e. collaboration) and explores how it influences supply chain resilience and establish its relationship with other elements.*	*Flexibility, Velocity, Visibility & Collaboration (information sharing, goal congruence, Decision synchronization, Incentive alignment, Resource sharing, Joint knowledge creation, communication)*	*Flexibility: No. of options to change in response to disruption & degree of difference in the options* *Velocity: Speed* *Velocity: Frequency of information sharing* *Collaboration: Not provided* *Overarching indicator: cost.*
Tukamuhabwa et al. (2015)	*37*	*1*	*0*	*1*	*37*	*3*	*Delivers a review of the different definitions of supply chain resilience, different conceptual models and theories adopted for resilience assessment*	*Flexibility, Redundancy, Collaboration & Agility*	*Flexibility: Priced using Extreme Value Theory* *Redundancy & Collaboration: not provided* *Agility: Recovery speed*

Johnson et al. (2013)	*20*	*1*	*16*	*1*	*36*	*5*	*A qualitative study that examines how the facilitatory role of three dimensions of social capital to the four elements of supply chain resilience.*	*Flexibility, velocity, visibility, and collaboration*	*Not applicable*

Authors	Link strength in Web of Science (L_w)	Availability in Web of Science (x)	Link strength in Scopus (L_s)	Availability in Scopus (y)	Total Link Strength (L_s) = $L_w X_w$ + $L_s X_s$	Cluster	Context of analysis	Elements for operationalisation	Indicators for measurement
Ambulkar et al. (2015)	19	1	14	1	33	1	A conceptual study explores factors that enhance the resilience of firms and operationalise resilience for further empirical studies.	Adaptability, Responsiveness, Awareness, Redundancy, Visibility and Coordination	A 7-point Likert scale to measure firm's ability to cope with changes arising from supply chain disruptions, ability to adapt, ability to quickly respond to the changes and situational awareness.
Colicchia et al. (2010)	16	1	17	1	33	3	An analysis of supply chain resilience in the context of an European retailer or manufacturer engaged in a global sourcing with a focus on inbound activities	Flexibility	Supply lead time is used as a proxy for resilience
Pereira et al. (2014)	21	1	10	1	31	1	An exploratory study that focuses on upstream of supply chain and explores the connection of procurement activities and the elements of resilience.	Flexibility, Redundancy, Visibility, Agility, Collaboration, Integration, Information sharing	Not applicable
Hohenstein et al. (2015)	0	0	30	1	30	5	Investigates generic elements of supply chain resilience and proposes measures for their assessment using a systematic literature review	Ex-ante disruption phase (Proactive): Collaboration, HR management, Inventory Management, Redundancy, Visibility, Post disruption phase (Reactive): Agility, Flexibility, Collaboration, HR Management, Redundancy	Performance metrics: - Customer Service, Market share and Financial performance
Liu et al. (2017)	10	1	20	1	30	6	The study explores the relationship between performance and supply chain resilience in the context of shipping industry using the resource base view as theoretical basis	Agility, Risk management culture, supply chain re-engineering, integration,	Operational performance: - customer loyalty, customer satisfaction, service level, Financial performance: - market share, and net profit before tax.
Klibi et al. (2010)	10	1	19	1	29	4	The study reviews supply chain network designs under uncertainty and how it influences performance	Flexibility, Redundancy	Not applicable

Authors	*Link strength in Web of Science (L_w)*	*Availability in Web of Science (x)*	*Link strength in Scopus (L_s)*	*Availability in Scopus (y)*	*Total Link Strength (L_s) = $L_w X_w$ + $L_s X_s$*	*Cluster*	*Context of analysis*	*Elements for operationalisation*	*Indicators for measurement*
Chowdhury and Quaddus (2016)	*15*	*1*	*13*	*1*	*28*	*3*	*Examined previous literature on the measurement of supply chain resilience and identified the elements that explain resilience in Bangladesh's apparel industry.*	*Readiness: - Disaster preparation, Flexibility, Redundancy, Visibility and Collaboration*	*Recovery time, Cost, Disruption absorption, Loss reduction*
Chowdhury and Quaddus (2017)	*15*	*1*	*13*	*1*	*28*	*3*	*A conceptual framework that uses dynamic capability theory as a basis to develop a supply chain resilience measurement instrument in the context of Bangladesh's apparel industry*	*Reflective constructs: Flexibility, Integration, Financial strength, Response and Recovery* *Formative constructs: Reserve capacity, Efficiency, market strength, Density, Complexity, Criticality*	*Supply chain performance measures: recovery time, cost, disruption absorption and ability to reduce the impact of the loss.*
Dolgui et al. (2018)	*16*	*1*	*10*	*1*	*26*	*4*	*Explored the different approaches adopted in literature for analysing the ripple effects in supply chains arising from disruptions.*	*Robustness, Redundancy (Flexibility), Recovery*	*Not applicable*
Jain et al. (2017)	*14*	*1*	*12*	*1*	*26*	*2*	*A study that develops a conceptual model to explore the relationships among different enablers of resilience identified in the literature*	*Not provided*	*Not provided*
Ivanov (2017)	*11*	*1*	*14*	*1*	*25*	*4*	*A study that reviews supply chain design and planning with disruptions and recovery*	*Not applicable*	*Not applicable*
Soni et al. (2014)	*13*	*1*	*12*	*1*	*25*	*2*	*A conceptual framework that develops a single index for measuring supply chain resilience*	*Agility, Collaboration, Information sharing, Sustainability, Visibility, Risk management culture, Adaptability*	*Supply chain resilience index*
Botes et al. (2017)	*15*	*1*	*9*	*1*	*24*	*6*	*Examines how the collaboration existing in a buyer – supplier relationship enhances resilience in the context of upstream actors in the petrochemical industry using the Kraljic matrix as theoretical base*	*Collaboration*	*Not applicable*
Pourhejazy et al. (2017)	*13*	*1*	*11*	*1*	*24*	*3*	*Assessing resilience in the context of petrochemical plants using Data Envelope Analysis method*	*Efficiency*	*Resilience score based on input usage*
Chopra and Sodhi (2014)	*10*	*1*	*13*	*1*	*23*	*4*	*This study explores the different strategies that can be used to reduce disruptions in a supply chain and analyses the relationships network connectivity and fragility*	*Not applicable*	*Not applicable*

Authors	*Link strength in Web of Science (Lw)*	*Availability in Web of Science (x)*	*Link strength in Scopus (Ls)*	*Availability in Scopus (y)*	*Total Link Strength (L_s) = L_wX_w + $L_s X_s$*	*Cluster*	*Context of analysis*	*Elements for operationalisation*	*Indicators for measurement*
Cardoso et al. (2015)	*12*	*1*	*10*	*1*	*22*	*3*	*Investigates the characteristics of resilient supply chains for a 5-echelon supply chain comprising of raw materials suppliers, plants, warehouses, final products suppliers and markets. Proposes eleven indicators for measuring supply chain resilience*	*Not provided*	*Network design: node complexity, flow complexity, density and node criticality.* *Network Centralization:* out-degree and in-degree centrality, *Coutflow and Cinflow.* *Operational measures: expected net present value, expected customer service level and investment level*
Purvis et al. (2016)	*13*	*1*	*9*	*1*	*22*	*5*	*An exploratory study that focuses on a single case of a premium drink producer in the UK but has outbound warehouses in 7 European countries and sourcing across South America. Using a qualitative analytical approach, the RALF framework is proposed for supply chain resilience assessment.*	*Robustness, Agility, Leanness and Flexibility*	*Not provided*
Bakshi and Kleindorfer (2009)	*13*	*1*	*8*	*1*	*21*	*2*	*This exploratory study focuses on a bargaining framework that two chain actors can adopt to mitigate disruptions and enhance supply chain resilience.*	*Not provided*	*Not provided*
Leat and Revoredo-Giha (2013)	*11*	*1*	*10*	*1*	*21*	*6*	*The study explores the challenges and risk associated with building resilience in the pork supply chain in Scotland. The study explores disruptions that can befall the chain and looks at how collaboration can act as an enabler to supply chain resilience*	*Collaboration*	*Not provided*
Torabi et al. (2016)	*9*	*1*	*12*	*1*	*21*	*2*	*This study focused on how manufacturers can select resilient suppliers, and proposes a model for assessing the trade-off between cost and supply chain resilience*	*Continuity*	*A resilience equation composed of* *- loss of resilience (calculated based on amount of inventory and the delivery time)* *- total amount of items (inventory) needed - allowable time for recovery.*

Authors	*Link strength in Web of Science (L_w)*	*Availability in Web of Science (x)*	*Link strength in Scopus (L_s)*	*Availability in Scopus (y)*	*Total Link Strength (L_s) = L_wX_w + $L_s X_s$*	*Cluster*	*Context of analysis*	*Elements for operationalisation*	*Indicators for measurement*
Rajesh (2016)	*10*	*1*	*10*	*1*	*20*	*5*	*A conceptual study that explores indicators that can be used to readily assess supply chain resilience using a case study of an Indian electronics manufacturing firm,*	*Flexibility, Responsiveness, Quality, Productivity and Accessibility*	*Resilience Performance Indicators – Flexibility: Stock out rate, Inventory accuracy rate, % increase in sales based on flexibility design* *Responsiveness: On time delivery ratio, Contract issue time, Contract approval time, Put-away time ratio,* *Quality measures: Quality of forecast, Testing quality, Shipping accuracy, Fill rate, Storage space utilization* *Accessibility: Dealer accessibility, Retailer accessibility, Customer accessibility*
Schmitt and Singh (2012)	*10*	*1*	*10*	*1*	*20*	*2*	*Looks at how a multi-echelon supply chain can build resilience in the face of both demand and supply disruptions in the context of a consumer-packaged goods firm that is composed of multiple products, distribution, centres and two manufacturing plants.*	*Redundancy (in terms of buffers for inventory, capacity and time)*	*Customer fill rate, Percentage of customers who are satisfied immediately from stock*
Ali et al. (2017)	*10*	*1*	*9*	*1*	*19*	*5*	*A qualitative study that looks at the elements (enablers) needed for building resilience in SMEs in Australia that deal in perishable products.*	*Proactive elements: Business certifications, Globalisation, Vertical integration, Quality management.* *Reactive elements: Responsiveness to customer needs, Responsiveness to competitor's strategies, Multi-sourcing, Collaboration*	*Not provided*

Spiegler, Naim & Wikner (2012)	*19*	*1*	*0*	*0*	*19*	*1*	*Developed a framework for assessing supply chain resilience quantitatively in a single echelon supply chain with a focus on inventory and ordering system. The study also uses an interface that considers the end consumer in the context of make-to-stock and make-to-order systems.*	*Readiness, Response, Recover*	*Integral of time multiplied by the absolute error*

Authors	*Link strength in Web of Science (L_w)*	*Availability in Web of Science (x)*	*Link strength in Scopus (L_s)*	*Availability in Scopus (y)*	*Total Link Strength (L_s) = $L_w X_w + L_s X_s$*	*Cluster*	*Context of analysis*	*Elements for operationalisation*	*Indicators for measurement*
Azadeh et al. (2013)	*9*	*1*	*8*	*1*	*17*	*6*	*A study that focuses on a fictitious 3-tiered supply chain involving a production factory, an assembling plant and a final plant. Supply chain resilience is analysed for different transportation-related disruptions, with an assumed infinite supply of raw materials to the production factory.*	*Visibility, Velocity, Redundancy and Flexibility*	*Average time in the system, Utility of resources, Number of breakdowns and the system's average cost*
Azevedo et al. (2013)	*8*	*1*	*9*	*1*	*17*	*2*	*Developed a framework that integrates greenness and resilience (Ecosilient) in supply chain within the context of an automobile supply chain.*	*Supply chain resilience behaviour. Supply chain green behaviour*	*Ecosilient index ranging from 1 to 5*
Mandal et al. (2016)	*10*	*1*	*7*	*1*	*17*	*5*	*Explored the relationship between the dominant elements of supply chain resilience and how they influence supply chain resilience in a logistic capability context.*	*Flexibility, Collaboration, Visibility, Velocity*	*Survey Likert scale*
Ivanov and Sokolov (2013)	*8*	*1*	*9*	*1*	*17*	*4*	*A conceptual study which explores the impact of disruptions on supply chain performance and highlights elements that can be systemized to enhance performance*	*Flexibility, Adaptability*	*Cost, output performance measures*
Sahu et al. (2017)	*10*	*1*	*7*	*1*	*17*	*2*	*The study develops an index for appraising resilience performance using expert opinions followed by mathematical representation in the context of manufacturing factory for automobile parts*	*Supply chain re-engineering, Supply chain collaboration, SCRM culture, agility*	*Fuzzy performance importance index*
Papadopoulos et al. (2017)	*8*	*1*	*8*	*1*	*16*	*7*	*A qualitative study that develops a theoretical framework to explore the role of big data on social*	*Not provided*	*Not provided*

							media platforms can lead to supply chain resilience and sustainability		
Vugrin et al. (2011)	*8*	*1*	*8*	*1*	*16*	*3*	*The study develops both quantitative and qualitative framework for assessing supply chain resilience in the context of disruptions caused by hurricanes in a petrochemical supply chain.*	*System Productivity, System Efficiency*	*Systemic Impact (the difference between targeted system performance level and actual performance).* *Total Recovery Effort (the number of resources used for system recovery).* *Resilience cost*

Authors	*Link strength in Web of Science (Lw)*	*Availability in Web of Science (x)*	*Link strength in Scopus (Ls)*	*Availability in Scopus (y)*	*Total Link Strength (L_s) = LwX_w + Ls X_s*	*Cluster*	*Context of analysis*	*Elements for operationalisation*	*Indicators for measurement*
Kim et al. (2015)	*15*	*1*	*0*	*0*	*15*	*5*	*A study that conceptualises supply chain disruptions and resilience for supply chain nodes and networks using a graph theory. The context focuses on supply networks of facilities and transportation.*	*Network density, the Average degree of arcs, Average walk length, Minimum and maximum walk length, Connectivity, Betweenness Centrality.*	*Supply network resilience ratio*
Mandal and Sarathy (2018)	*10*	*1*	*5*	*1*	*15*	*5*	*This study explores how communication, commitment, cooperation and trust influence supply chain resilience and performance in the context of manufacturing firms.*	*Not provided*	*Uses Likert scale obtained from respondents' answers to measure resilience*
Munoz and Dunbar (2015)	*8*	*1*	*6*	*1*	*14*	*2*	*A conceptual study that quantifies supply chain resilience as a multi-dimensional concept in the context of a fictitious 3-tiered supply chain comprising manufacturer, retailer and customer.*	*Not provided*	*Aggregate Index (Delivery performance), which is dependent on the recovery time, Impact, profile length*
Ponis and Koronis (2012)	*14*	*1*	*0*	*0*	*14*	*3*	*A conceptual study that explores the formative elements for the conceptualisation of supply chain resilience via literature review*	*Agility (Flexibility & Velocity), Redundancy, Collaboration (Visibility) and Supply chain structure*	*Not provided*
Ratick et al. (2008)	*6*	*1*	*7*	*1*	*13*	*6*	*A study that assesses how backup capacities can be used to enhance the supply chain resilience in the context of logistic facility management.*	*Flexibility*	*Cover and anti-cover distance, Solution time, Facility cost*
Ishfaq (2012)	*7*	*1*	*6*	*1*	*13*	*3*	*The study explores logistics strategies that can enhance supply chain resilience in the context of a logistics system faced with transportation disruptions.*	*Efficiency and Flexibility*	*Transportation and transfer cost, Service delivery (transportation) time*
Agigi et al. (2016)	*12*	*1*	*0*	*0*	*12*	*3*	*A qualitative study that explores the different approaches that can be used to build supply chain resilience in the context of grocery manufacturing companies*	*Redundancy and Flexibility*	*Not provided*
Falkowski (2015)	*6*	*1*	*5*	*1*	*11*	*6*	*Explores the factors that influence the resilience of upstream, and downstream actors in an agro-food supply chain using the relationship between farmer and processor in a diary chain as a case study.*	*Flexibility, Velocity, Visibility and Collaboration*	*Not provided*
(Elleuch et al., 2016)	*7*	*1*	*0*	*0*	*7*	*2*	*Developed a conceptual framework (i.e. Quality Function Deployment approach) to improve resilience in the context of food chains.*	*Redundancy and capacity for rescue, Collaboration and visibility, Efficiency), security, Integration, Recovery (REC), Organization and Customer satisfaction & quality control*	*Absolute importance of resilience capacities*

Umar et al. (2017)	*6*	*1*	*0*	*0*	*6*	*6*	*A conceptual study that explores capabilities that can be employed to enhance resilience in food chains.*	*Agility, Adaptability and Alignment* *(logistics, collaboration, sourcing, and knowledge management)*	*Not provided*

Chapter 4 Identifying the Precursors of Vulnerability in Agricultural Value Chains: A System Dynamics Approach

Look before you leap

-John Heywood (c. 1497 – c.1580)

This chapter fulfils objective two, and it is based on the published journal article below:

Aboah, J. Wilson, M.J.M, Bicknell, K. Rich, K., 2019. Identifying the Precursors of Vulnerability in Agricultural Value Chains: A System Dynamics Approach. *International Journal of Production Research*. 59:3, 683 – 701. https://doi.org/10.1080/00207543.2019.1704592

Abstract

Conventional approaches for assessing supply chain vulnerability do not capture endogenous disruptions emanating from chain actors' decisions that might increase value chain vulnerability. These approaches adopt a reactive analytical explanation of vulnerability, rather than one that considers issues of feedback effects. To address this issue, this paper adopts a system dynamics modelling approach to identify the precursors of vulnerabilities in Ghana's cocoa value chain. The paper assesses the vulnerability levels of the cocoa value chain by adjusting the baseline values of several key parameters that can be influenced by chain actors. Results of the sensitivity analyses indicate that the precursors of vulnerability situated upstream of the cocoa value chain have varying impacts on chain vulnerability, but the same magnitude of effect on the vulnerability levels of chain actors. However, precursors of vulnerability that are situated midstream of the cocoa value chain have an unequal magnitude of effect on the vulnerability levels of chain actors. Results suggest that policies governing cocoa trading can become countervailing factors that obstruct the government's call for upgrading along the cocoa value chain. The system dynamics model presented here enables a proactive assessment of vulnerability which can facilitate collaborative planning among stakeholders in the value chain.

Keywords: vulnerability; cocoa; adaptive system; value chain; disruption management

4.1 Introduction

Disruptions emanating from external sources (exogenous disruptions), both man-made and natural, highlight the vulnerabilities of a supply chain and are easily identifiable in supply chains. Perhaps more subtly, endogenous factors such as the structure of the supply chain itself also predispose systems to disruptions. The complexities of a supply chain structure increase when; more actors and tiers are added to the chain, the dispersion among these actors and tiers increases (Nakatani et al., 2018) and the interdependency of actors increases in a network (Pathak et al., 2007). Supply chains are more vulnerable to disruptions as their complexity increases (Wagner & Neshat, 2010). The first step towards mitigating disruptions is to assess a system's vulnerability (McManus et al., 2007).

Supply chain vulnerability is defined as the limitation of the supply chain to withstand disruptions (Berle, Asbjørnslett, & Rice, 2011; Nakatani et al., 2018). Other definitions link vulnerability to instability resulting from disruptions (Liu et al., 2016), interruptions in achieving key performance indicators (Thekdi & Santos, 2016; Vlajic et al., 2013), and an inability to maintain network robustness (Liu et al., 2018). In the literature, the various approaches that have been adopted to assess supply chain vulnerability are either firm-centric, or take a reactive stance, and are therefore unable to capture the decision-making behaviours that themselves alter the structure of the supply chain (Moragues-Faus, Sonnino, & Marsden, 2017).

This paper adopts system dynamics modelling (SDM) as an approach to examine the precursors of vulnerabilities in the cocoa value chain at an aggregate level, given its ability to capture the feedback between system structure and drivers of vulnerability. The vulnerability levels of three actors in the cocoa value chain – farmers, in-country processors, and the export supplier (*government*) are determined using magnitude-related and time-related performance indicators. The magnitude-related indicators capture the loss in inventory levels, and the time-related indicators consider the duration of vulnerability.

This paper offers an approach that allows for the *ex-ante* simulation of policy interventions and strategies to prevent disruptions, reduce vulnerabilities, and mitigate their impact. Results indicate that farm-level disruptions (in particular, the exodus of farmers from cocoa production) produce the highest vulnerability for processors and exporters. Also, an increase in cocoa bean exports by the government increases the vulnerability levels of local processors and farmers in the long run.

The remaining sections of the paper are as follows: Section 4.2 reviews some limitations of supply chain vulnerability assessment approaches and the indicators used for measuring supply chain vulnerability. Section 4.3 outlines the steps used in determining the precursors of vulnerability. Section 4.4 presents the results and discusses the findings, and Section 4.5 draws conclusions based on the findings and provides suggestions for future studies.

4.2 Literature Review

Disruptions expose vulnerability in a supply chain by affecting the supply chain performance. Decision-making is critical in supply chain operations when dealing with disruptions (Ivanov et al., 2016). However, some disruptions inherently stem from decisions and indecision on the part of chain actors. Due to the interconnectedness of supply chains, the impact of disruptions can extend well beyond the originating points (nodes).

Disruption from one actor can propagate and have different impacts on other actors in the supply chain (Han & Shin, 2016; Ivanov, 2017). Two distinct methods of propagation are highlighted in the supply chain literature: the bullwhip effect and the ripple effect. The former represents a high frequency/low impact disruption resulting in inventory dynamics, and the latter represents a low frequency/high impact disruption resulting in structural dynamics (Dolgui, Ivanov, & Sokolov, 2018; Ivanov, 2017).

Ivanov (2017) offers two options for modelling disruption at the structural dynamics level. The first option considers probabilities of disruption, and the second option identifies the critical elements that influence the ripple effect. This paper takes the second stance and explores the critical precursors of the vulnerability of an agricultural value chain.

4.2.1 Limitations of Vulnerability Assessment Approaches

Vulnerability assessment methodologies that view supply chains as complex networks have mostly hinged on network theories. Network analysis emphasises the topological characteristics of the supply chain that focus on the flow of physical materials from one node of the network to another (Blackhurst et al., 2018; Nakatani et al., 2018; Skeete, Zymalski, & Keyser, 2017; Wagner & Neshat, 2010). Its utility lies in its ability to capture the complexities in inter-actor relationships in the supply chain (Borgatti & Li, 2009; Kim et al., 2011), and provide a visual representation of disruption propagation in the supply chain (Blackhurst et al., 2018). However, the analytical perspective impedes an anticipatory outlook to vulnerability assessment due to the omission of dynamics that can alter the nodes, links, and structure in a network as noted in Table 3 (Moragues-Faus, Sonnino, & Marsden, 2017; Nagurney & Qiang, 2012).

Wagner and Neshat (2010) observed that vulnerabilities could be analysed at four different levels: the focal firm, the supply chain, the industry, and the economy. Previous empirical studies that have assessed vulnerabilities, however, have focused almost exclusively on the focal firm level (Blackhurst et al., 2018; Nakatani et al., 2018; Skeete, Zymalski, & Keyser, 2017; Wagner & Neshat, 2010). The firm-level focus ignores the interdependencies between firms, and the possible system impacts that disruptions associated with the focal firm will have on other actors in the chain. Vulnerability analyses at the industry and economy levels are limited in the literature.

Table 3 Different representations of nodes (vertices) and links (edges) in supply chain network research

Chain actors *(e.g. suppliers, producers, manufacturers, distributors, customers)*	**Physical facilities** *(e.g. warehouse, port, manufacturing plant, distribution centres, countries, Routers)*	**Process** *(e.g. production, shipping)*	**Material flow**	**Information flow** *(e.g. demand)*	**Capital flow**	**Routes** *(e.g. shipping transportation routes, transmission lines)*	**Network type**	**The indicator used for measuring vulnerability**	**References**
	†					†	Directed	In-degree, out-degree and all degree	Liu et al., 2018
		†	†				Directed	Market concentration (Herfindahl–Hirschman Index)	Nakatani et al., 2018
†			†	†	†		Directed	Production reduction	Skeete et al., 2017
†			†		†		Directed & Undirected	Degree centrality, Betweeness, Closeness	Kim et al., 2011
	†	†				†	Directed	Processing time and inventory levels	Blackhurst et al., 2018
†			†	†	†		Undirected	Entropy	Zeng and Xiao, 2014
†	†		†	†			Undirected	Network coefficient entropy	Li, 2014
	†		†				Directed & undirected	Out-degree centrality	Tang et al., 2016
	†					†	Directed	Total degree, betweenness centrality, beta and gamma index, average clustering coefficient	Calatayud et al., 2017
	†					†	Undirected	Network efficiency	Crucitti et al., 2004

According to Senge (1990), problematic complexities such as systemic vulnerability can be approached with three distinct foci: the event, the pattern of behaviour, and the underlying structure. Event explanation is a reactive approach. Long-term trends and their implications are unravelled using a pattern of behaviour explanation, which is responsive. The structural explanation focuses on the causes of the patterns of behaviour, and it is inherently generative (Senge, 1990 pp. 52–53). Thus, structural explanations are appropriate for dynamic complexities exhibited when the effects of a cause happen over time, and the local consequences differ across the system (Senge, 1990 pp. 71) as exhibited by disruptions emanating from decisions in supply chains. Vulnerability assessments in the empirical literature have used either event or pattern of behaviour explanations.

4.2.2 Measuring Supply Chain Vulnerability

Vulnerability assessment approaches have been context-specific in the supply chain literature. Consequently, a range of indicators has been used for measuring vulnerability. Vulnerabilities can be anticipated by examining the supply chain design, structure, and connectivity (Blackhurst et al., 2018). As a latent behaviour, vulnerability emerges from a system's structure (Wagner & Neshat, 2010), which arises from feedback and the interactions of agents (Stave & Kopainsky, 2015). Hence, studies that adopt network analysis for vulnerability assessment have suggested network structure-related indicators.

Another category of indicators that have been used for measuring vulnerability relates to supply chain performance. Vlajic et al. (2013) categorise these indicators as magnitude-related and time-related performance indicators. Magnitude-related performance indicators can be sub-divided as inventory-related performance indicators and economic-related performance indicators. Indices have also been generated from a combination of performance indicators. Table 4 shows some examples of the different categories of indicators that have been developed for measuring supply chain vulnerability.

Table 4 Indicators for measuring supply chain vulnerability

Category	*Outputs*	*Reference*
Raw materials (Inventory) - related	Average unfulfilled demand/ Number of undelivered batches	Levy, 1995; Saad & Kadirkamanathan, 2006; Wilson, 2007
	Inventory levels/ Average stock levels	Levy, 1995; Saad & Kadirkamanathan, 2006
	Number of stock-outs	
	Number of emergency orders	Saad & Kadirkamanathan, 2006
	Faulty material	
	Stock wastage	
	Quantity loss/ Stock fluctuations and goods in transit	Wilson, 2007; Saad & Kadirkamanathan, 2006
Economic-related	Costs of sourcing (increment)/ Costs (after implementation of redesign strategy)	Levy, 1995, Tomlin, 2006; Wu et al., 2007
	Economic loss	Thekdi, 2016
Time-related	Lead time	Albino et al., 1998; Wu et al., 2007
	Backorder frequency	Albino et al., 1998
	Time to reach steady state (days)	Saad & Kadirkamanathan, 2006
	Late deliveries	
	Frequency and duration of disruption in supply/ Disruption periodicity	Melnyk et al., 2009
Indexes	Herfindahl–Hirschman Index *(*HHI): the sum of squares of firms competing in the market. Ranges between 0 and 1, where 0 is when there are a large number of firms and close to 1 is when there is a monopoly	Nakatani et al., 2018
	Inoperability	Thekdi, 2016
	Time-related performance indicator (Deviation of the duration of robust range) & Magnitude-related performance indicator (the difference between available inventory and required inventory levels)	Vlajic et al., 2013
Structural (network)-related	Centrality measures (in and out-degree centrality, betweenness, node degree)	Liu et al., 2018

Most of the indicators are examinable from the purview of individual chain actors. However, assessment of vulnerability at a higher system level (industry and economy levels) (Wagner &

Neshat, 2010) requires that indicators represent a system-wide spectrum of vulnerability to highlight chain-wise distortion of activities. For the magnitude of vulnerability, inventory-related indicators offer a representation of business continuity across an entire supply chain. For instance, in the context of agricultural value chains, the loss in the levels of raw materials produced by upstream actors, and the consequential loss in inventories available to midstream actors (processors) capture the magnitude of vulnerability (Levy, 1995; Saad & Kadirkamanathan, 2006; Wilson, 2007).

Time-related indicators concern the period associated with accomplishing the inventory-related indicators. The duration of distortion in the inventory-related indicators is an example of time-related indicators that have chain-wise significance (Saad & Kadirkamanathan, 2006).

4.3 Methodology

This section presents an SDM framework to determine the precursors of vulnerability in Ghana's cocoa value chain. The cocoa value chain is an appropriate case study for exploring vulnerabilities at an industry level for three reasons. First, a wide geographical distance between major producing countries and buyers (processors and consumers) increases the spatial complexity of the chain. Second, the concentration of significant production in a few geographical location limits sourcing options for buyers. Third, the unpredictability of the political environment that dictates the economic and institutional policies and climate for chain actors.

The framework follows three steps, as shown in Figure 13. First, the system structure is developed using a series of causal loop diagrams (CLD) to highlight the feedback loops in the system. Second, the CLDs are translated into a stock and flow model to facilitate a quantitative analysis of vulnerability. Simulation results from the validated model generate the system's baseline state of vulnerability. Third, sensitivity analyses of the validated model are conducted to determine the effect of variations in key parameters (using counterfactual relationships) on the baseline state of vulnerability.

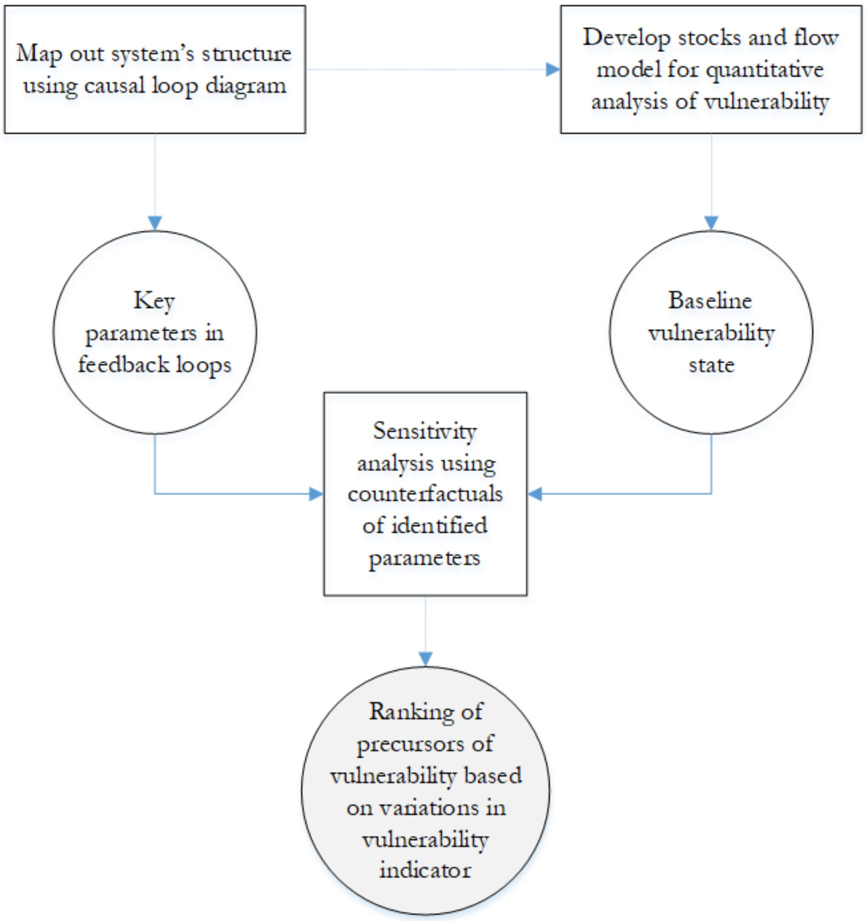


Figure 13 Framework for identifying precursors of supply chain vulnerability

Counterfactual relationships were determined by examining the causal relationships between variables in the CLD. Parameters whose counterfactuals are included in the sensitivity analyses are those that: *(i)* can be directly influenced by chain actors' decisions (farmers and government), *(ii)* directly influence production or processing activities, and *(iii)* are directly alterable in the model. Two counterfactual levels of the baseline parameters are the bases for the sensitivity analyses. A comparison of the system's state of vulnerability under varying levels of the counterfactual values illustrates the impact of disruptions associated with those key parameters. The highest-ranked variations in the vulnerability indicators help to identify the most disruptive precursors of vulnerability.

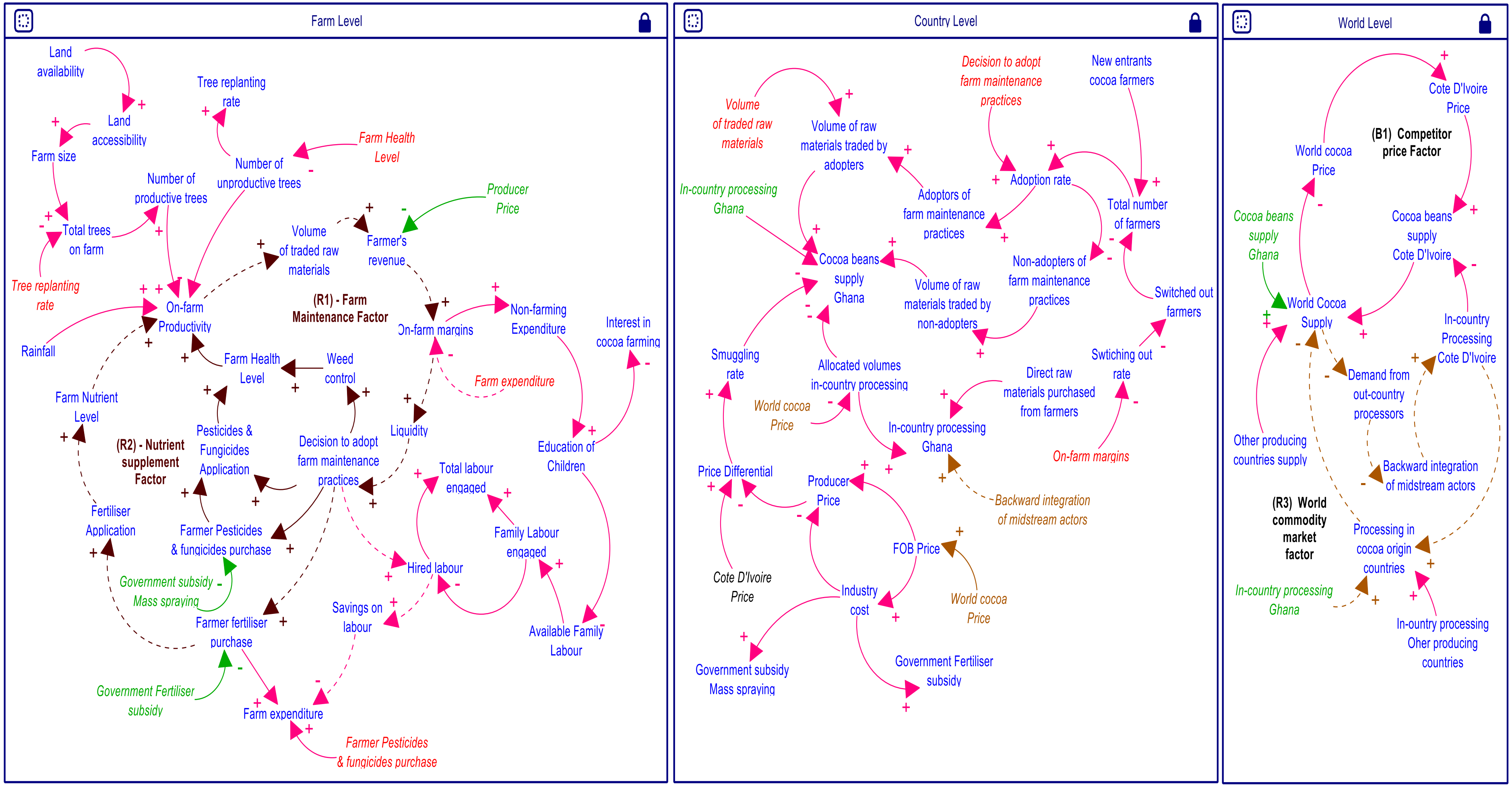


Figure 14 Causal loop diagram highlighting the system structure of Ghana's cocoa value chain

4.3.1 System Structure of Ghana's Cocoa Value Chain

The causal loop diagram (CLD) covers three boundaries (modules) – farm, country, and world levels, as shown in Figure 14. Variables that represent the interaction between the three modules are italicised and differentiated by colour. Variables coloured red, green, and brown are '*ghost*' variables of the farm, country, and world levels respectively. The paths of each feedback loop are in distinct colours and dotted lines. The Stella Architect® software was used to construct the CLD.

4.3.2 Farm-level Module

The farm-level module consists of decision and action variables that influence on-farm productivity. Two reinforcing feedback loops are highlighted at the farm-level: R1 and R2. For R1 (*nutrient supplement factor*), an increase in the farmer liquidity arising from increased revenues from cocoa beans sales causes farmers to be more willing to apply fertiliser on their farms (Wessel & Quist-Wessel, 2015). *Ceteris paribus*, increased fertiliser application causes increase in the farm nutrient level and subsequently, an increase in on-farm productivity that results in increased farmer revenue.

Similarly, for R2 (*farm maintenance factor*), positive causal relationships are established for farmer liquidity, decisions to adopt farm maintenance practices (Mahrizal, Dixon, & Popp, 2014), weed, disease and pest control, farm health level, on-farm productivity, and farmer revenues (Wessel & Quist-Wessel, 2015).

The farm-level module interacts with the country-level module via negative relationships between government subsidy on mass spraying exercises and (a) farmer purchases of fertilisers, pesticides and fungicides; (b) farm expenditures. A positive relationship between cocoa producer price and farmer revenue is another interaction between the farm-level and country-level modules. Additionally, positive causal relationships exist between individual farmer decisions to adopt farm maintenance practices, the adoption rate, and the number of adopters of farm maintenance practices at the country-level. The average volumes traded by a farmer and the aggregate volumes traded at the country level highlight another type of farm and country level interaction.

4.3.3 Country-level Module

At the country level, the supply of cocoa beans from farmers is a major driver of the volume of cocoa beans exported. The smuggling rate, the allocated percentage of cocoa for in-country processing, and the volumes of cocoa beans that processors procure directly from farmers have a negative influence on the volumes of cocoa beans supplied to the world market. The smuggling rate is dependent on the differential between producer prices in Ghana and Cote d'Ivoire, and negatively influences the volume of cocoa beans supplied from Ghana to the world market (BulÌˇr, 2002).

A positive causal relationship between Ghana's cocoa beans supply and world market supply, and the negative causal relationship between in-country processing and world market supply highlight an interaction between the country-level and the world-level modules. This interaction is situated in another reinforcing feedback loop (R3). Increases in the volume of cocoa beans processed within Ghana will reduce exports of raw cocoa beans. Because Ghana is a large player in the world market, this can be expected to increase world price. This will, in turn, incentivise cocoa processing firms operating outside origin countries to adopt backward integration to secure cocoa beans supply (Kolavalli et al., 2012); this causes a further increase in in-country processing.

4.3.4 World-level Module

The world-level module establishes a balancing feedback loop (B1) that highlights how the commodity market reacts to neutralise R3. The quantity of cocoa supplied on the world commodity market is negatively related to the percentage allocated for in-country processing. As supply from cocoa-producing countries decreases, world cocoa price increases. *Ceteris paribus*, this will cause supply from producing countries to increase, and subsequently a decrease in the volumes of cocoa beans allocated for in-country processing.

4.4 Baseline Model

The system dynamics model translates the CLD into inter-related stocks and flows capturing production, processing and trading activities at the farm, country, and world levels (*see Appendices 4.0*). An average farm size ($Farm_{size}$) of three hectares and a tree planting density ($Tree_{hec}$) of 1,100 trees/ha (Aneani et al., 2012) determine the number of cocoa trees on the farm. The total number of cocoa trees at the country level (Agg_{pd}) is determined by multiplying planting density, average farm size, and the aggregate number of cocoa farms ($Cocoa_{farm}$):

$$Agg_{pd} = Tree_{hec} * Farm_{size} * Cocoa_{farm} \qquad (4.1)$$

On-farm yields are influenced by tree maturity and the decision to engage in Good Agronomic Practices (*GAP*). Productive trees are 30 years of age and younger, while unproductive trees are trees over 30 years old (Mahrizal, Dixon, & Popp, 2014). Two classes of farmers are represented in the model: those engaged in GAPs (Adopters) and those who do not (*Non-adopters*). A productive tree for *Adopters* yields 25 cocoa pods. A triangular distribution is used to capture variability in the number of pods produced by a cocoa tree when no supplements are applied. Yield for *Adopters* is between 15 and 20 pods when no additional supplements are provided. Yield is between 10 and 15 cocoa pods for *Non-adopters*, who are assumed never to apply supplements beyond what the government subsidies provide (Mahrizal et al., 2014). Aggregate harvest for a cropping year is specified in Equation 4.2:

$$Harv_{ag} = [(P_{trees(ad)} * T_{yad}) + (P_{trees(nad)} * T_{ynad})] \qquad (4.2)$$

where $Harv_{ag}$ is the aggregate harvest, $P_{trees(ad)}$ and $P_{trees(nad)}$ are the total number of productive cocoa trees for adopters and non-adopters respectively, T_{yad} and T_{ynad} represent the average pod yield of a cocoa tree for adopters and non-adopters, respectively.

Both adoption and dis-adoption are incorporated into the farm-level module. Rates of flow between *Adopters* and *Nonadopters* are influenced by price expectations for each cocoa cropping year. More specifically, the number of farmers engaging in GAP increases when the expected price for the following cropping year exceeds the producer price of the current year. Similarly, the number of farmers who abandon GAPs increases when the price expectations are poor.

Discontentment with farm margins causes *Non-adopters* to switch out of farming cocoa altogether (Grabowski et al., 2019). Data from 17 cocoa cropping seasons (1998/99–2015) were used to calibrate the initial rate parameters (Aneani et al., 2012). A medium-term expectation of farm margins is used to represent farmer sensitivity to farm performance, which drives *Non-adopters* to exit the industry. Changes in the stocks of *Adopters* and *Non-adopters* are shown in Equations 4.3 and 4.4 respectively:

$$GAP_{adopt} = \left(Adopt_{rate} * \; Farmer_{pop}\right) - \left(\, Disadopt_{rate} * Farmer_{pop}\right) \quad (4.3)$$

$$GAP_{non-adopt} = \left(Disadopt_{rate} * \; Farmer_{pop}\right) - \left(\, Adopt_{rate} * Farmer_{pop}\right) - \; Switchout_{rate} * \; \text{Non} - \text{adopt} \quad (4.4)$$

Where $Adopt_{rate}$, $Dis\text{-}adopt_{rate}$ and $Switch\text{-}out_{rate}$ are the adopting, dis-adopting and switch-out$_{rates}$, respectively. The average farm-level harvest, arrayed by *Adopters* and *Non-adopters,* is a product function of average pod yield for a cocoa tree, the total number of cocoa trees on the farm and the weight of dried beans in a cocoa pod. The average farm-level harvest (Av_{pod} * $Farm_{size}$ * $Tree_{hec}$ * $Pod_{dweight}$) multiplied by the producer price ($Prod_{price}$) results in farm income. The difference in the farm income and total farm expenditure ($Inputs_{cost}$ + Lab_{cost}) gives the farm margin, expressed in Equation 4.5.

$$Farm_{margin} = \left[\left(AV_{pod} * \; Farm_{size} * Tree_{hec} * \; Pod_{dweight}\right) * \; Prod_{price}\right] - \left(\sum Inputs_{cost} + Lab_{cost}\right) \quad (4.5)$$

The outflow from production activities (i.e., cocoa pods) undergoes on-farm processing (fermentation and drying) into cocoa beans. On average, a cocoa pod produces 0.039 kg of dried cocoa beans (Mahrizal et al., 2014). Postharvest losses and smuggling are deducted from the total cocoa pods harvested and the total cocoa beans processed, respectively. The product of the total number of pods that undergo on-farm processing and the average weight of dried cocoa beans in a pod is the total cocoa beans produced in a cropping year.

4.4.1 Vulnerability Indicators

Following Saad and Kadirkamanathan (2006) and Vlajic et al. (2013), this paper adopts magnitude-related and time-related performance indicators to represent the state of vulnerability for three actors in the cocoa value chain: cocoa farmers, in-country processors, and the export supplier (*government*). The quantity of dried cocoa beans transacted in Ghana, processed in-country, and exported outside Ghana are used to estimate the magnitude-related performance indicators for farmers, in-country processors, and exporters, respectively. Using the magnitude-related performance indicator for each actor, vulnerability is estimated as:

$$Mag_{vul(t)} = \left[\frac{\left(Vul_{count(t)} - Vul_{base(t)}\right)}{Vul_{base(t)}}\right] * 100\% \qquad (4.6)$$

Where $Mag_{Vul(t)}$ is the vulnerability level for a specific chain actor expressed in percentages, $Vul_{base(t)}$ is the output from the baseline model, and $Vul_{count(t)}$ is the output involving the counterfactual values of key variables.

The higher the percentage loss in the quantity of cocoa beans, the more vulnerable the chain actor is. Hence, an actor is considered vulnerable when $Vul_{count(t)}$ is less than $Vul_{base(t)}$, and only negative values of this difference are used in the calculation of Mean Mag_{Vul}. The duration of vulnerability and the rise in vulnerability levels represent the time-related performance indicator.

4.4.2 Data

Data used for the analysis were retrieved from different secondary sources, collated, and stored in http://doi.org/10.5281/zenodo.2605399. Data covering midstream and downstream activities in the cocoa value chain were sourced from the International Cocoa Organisation (ICCO) annual reports on the global cocoa industry from 1998 to 2015. The availability of these reports is the decision criterion for the analytical period. Data retrieved from these reports concern world cocoa production figures, cocoa price movements and cocoa processing. Historical data drawn from 17 annual reports on the global cocoa industry with emphasis on Ghana and Cote d'Ivoire were used.

For upstream production activities, data were retrieved from published journal articles and industry sources data.

4.4.3 Model Validation

The extreme condition test was applied to confirm the model's structural validity (Barlas, 1996). The model was subjected to pre-harvest and postharvest extreme conditions by altering the farmer population and the weight of beans in a pod to zero, respectively. The pre-harvest parameter influences the number of cocoa farmers and subsequently the number of cocoa trees in the value chain, and the postharvest parameter determines the overall conversion of pods into cocoa beans. The extreme condition tests for both phases resulted in an expected division by zero error. The model results are compared to Ghana's actual cocoa production figures from 2005 to 2015 to establish the goodness of fit (Figure 15).

The model behaviour was statistically validated using the Mean Absolute Percentage Error (MAPE) and Theil U (Sterman et al., 2013), transient measures and comparative statistics (Sücüllü & Yücel, 2014). The statistical measures were analysed in R studio®. MAPE and Theil U are estimated as Equations 4.7 and 4.8 respectively.

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}[\frac{(A_t - F_t)}{A_t}] \qquad (4.7)$$

$$Theil\ U = \sum_{t=1}^{n} = [\frac{(F_t - A_t)^{1/2}}{{A_t}^{1/2}}] \qquad (4.8)$$

Where A_t and F_t represent the actual cocoa production figures and model estimation respectively. MAPE indicates the percentage error in the model prediction. The Theil U statistic has a lower bound of 0, which corresponds to a perfect forecast. A value of 1, by contrast, is consistent with a naïve (no change) extrapolation (Bliemel, 1973). Model validation results indicate a reliable percentage of the baseline model's prediction accuracy as indicated by the MAPE, Theil U and level of error between the transient measures. The model validation results indicate that the model has a 17% error in its prediction accuracy and a Theil U of less than 0.3, which is a considerable improvement over a naïve no change forecast (Table 5).

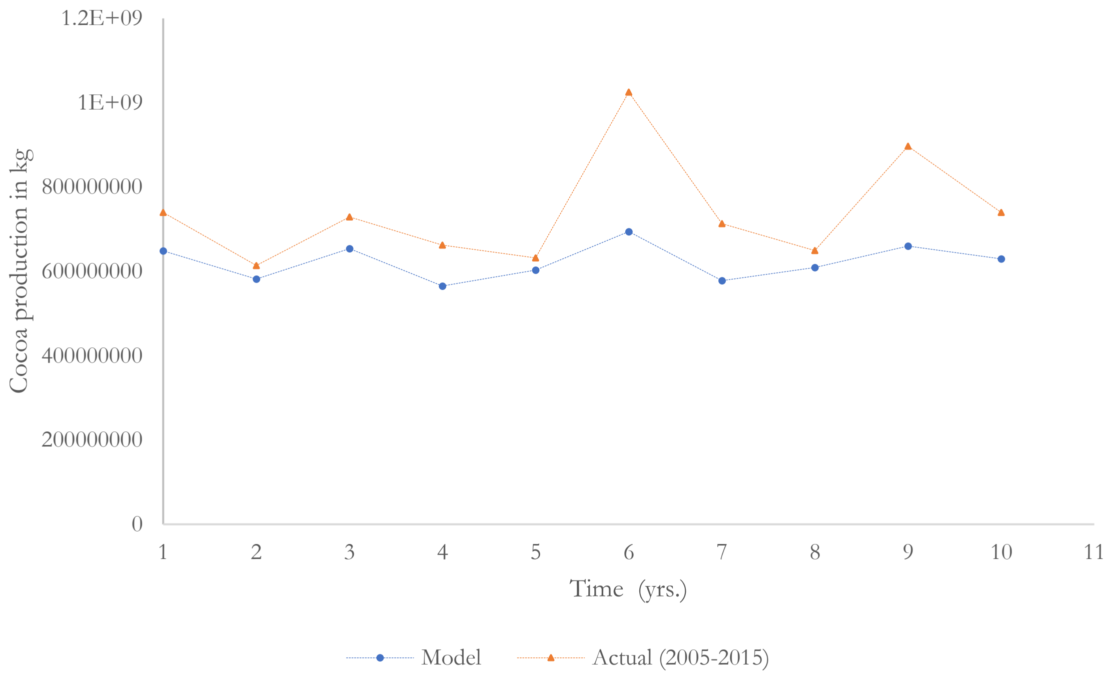


Figure 15 A comparison of model estimation and Ghana's actual cocoa production figures

Table 5 Measures for model validity

	Actual	Model	Difference	% Error
Comparative measure				
Mean (kg)	740,100,000	622,353,100	117,746,900	15.9
Comprehensive measure				
MAPE		0.168		
Theil U		0.2744		
Transient measure				
Maximum (kg)	1,025,000,000	694,361,000	330,639,000	32.3
Minimum (kg)	614,000,000	565,353,000	48,647,000	7.92

4.5 Results and Discussions

Results from the baseline model, shown in Table 6, indicate that on average, the magnitude-related performance indicator (*$Mag_{Vul(t)}$*) for cocoa farmers, in-country processors, and export supplier are 622,353 tonnes, 177,582 tonnes and 426,855 tonnes, respectively. Results of the time-related performance indicator (*TRPI*) show that on average, each chain actor experiences 1.5 years and 1.6 years of continuous losses and gains, respectively. The average continuous gains and losses mirror the trends of gains and losses in historical cocoa production in Ghana from 2000 to 2015 (ICCO, 2017). Comparatively, the baseline results indicate that cocoa farmers experience the most extended periods of continuous gains and losses. In-country processors experience the shortest periods of continuous loss. The results support current efforts to boost value addition to cocoa locally.

Table 6 Summary of the baseline levels of vulnerability measures for three chain actors in the cocoa value chain

Measures	Ghana cocoa producers	In-country processors	Exporters
Mean (kg)	622353,100	177,582,043	426,855,100
Max (kg)	694,361,000	213,560,591	516,028,395
Min (kg)	565,353,000	96704582	378,454,575
Period of gains (yrs.)	9.5	12	9
Period of losses (yrs.)	9.5	7	10
Average continuous period of losses (yrs.)	1.9	1.2	1.4
Longest continuous periods of losses (yrs.)	3.5	3	3
Average continuous period of gains (yrs.)	1.9	1.7	1.3
Longest periods of continuous gains (yrs.)	3	2.25	2

4.5.1 Sensitivity Analyses

The paper examines the effect of variations in baseline values of key parameters on the vulnerability of the cocoa value chain. A negative percentage (i.e., below 0%) signifies a vulnerable state due to the loss in the volume of cocoa beans. The paper defines precursors of vulnerability as the key parameters whose counterfactual relationship increases vulnerability levels of the cocoa value chain. Table 7 highlights the parameters and their counterfactual relationships considered in the sensitivity analyses.

The baseline values of the parameters are adjusted by 5% and 10% consistent with the counterfactual relationships. Results from the 5% and 10% adjustments in the baseline values of five parameters have the same magnitude of effect on the vulnerability levels for all three actors. However, a decrease in the cocoa beans allocated for in-country processing has a different magnitude of effects on each chain actor.

Table 7 Parameters and their counterfactual values included in sensitivity analyses

	Parameters	Counterfactual relationship	Baseline value	Counterfactual value for sensitivity analysis	
				5%	10%
Upstream (farmer decision)	Cocoa farmer population	Decreasing	371000	352450	333900
	Switching out rate	Increasing	0.015	0.0158	0.0165
	Maturity rate (cocoa trees)	Increasing	0.15	0.1575	0.165
	Smuggling rate	Increasing	0.0005	0.00053	0.00055
Midstream (government decision)	Allocated percentage for in-country processing (average)	Decreasing	0.23	0.2185	0.207
	% of FOB allocated to farmers (average)	Decreasing	0.63	0.5985	0.567

4.5.2 *Magnitude of Effect on Vulnerability Levels – Upstream Precursors of Vulnerability*

Results of the sensitivity analyses involving adjustments of upstream precursors are shown in Table 8 and Figure 16. For a 5% adjustment of baseline values, the mean vulnerability level criterion suggests that a decrease in the cocoa farmer population will result in the highest vulnerability level (i.e., 5%) for all chain actors. This implies that the volumes of cocoa beans produced by cocoa farmers, processed locally, and exported outside Ghana are projected to decrease by 5% on average when the cocoa farmer population decreases by 5%. The vulnerability level rises to −8% on average when the cocoa farmer population decreases by 10%.

Chain actors are the least vulnerable when the percentage of world cocoa price allocated to cocoa farmers decreases by 5% and 10%. The normalcy of cocoa price fluctuations can be a contributing factor to the low vulnerability levels even when the government decides to decrease the producer price. This notwithstanding, the mean vulnerability levels show that the apparent adaptive strategy that farmers use in such a situation (i.e., reduction in on-farm investments) (Mahrizal et al., 2014) makes the cocoa value chain vulnerable.

4.5.3 Duration of Vulnerability – Upstream Precursors of Vulnerability

According to the time-related performance indicators, chain actors are most vulnerable when the cocoa farmer population decreases. Conversely, chain actors experience the least prolonged periods of vulnerability when the cocoa producer price decreases by 5%. The periods of prolonged vulnerability for the chain actors increases as the tree maturity and smuggling rates increase, and the producer price decreases. However, the chain actors will experience a decrease in prolonged vulnerability levels as farmers' switching rate increases from 5% to 10%.

By contrast, the trend analyses in Figure 16 show that chain actors will face rising vulnerability levels for 10% increase relative to a 5% increase in the switching rate. Unlike the impact of a decrease in the cocoa farmer population which takes immediate effect, increasing the switching rate relies on a farmers' medium to long term decisions and directly affects only the population of less productive farmers. Of the two situations, the latter is more likely to occur in the cocoa value chain, since most farmers consider their cocoa farms as assurance for good retirement (Kos & Lensink, 2017).

4.5.4 Magnitude of Effect on Vulnerability Levels – Midstream Precursors of Vulnerability

A decrease in the percentage of cocoa beans allocated for in-country processing results in different magnitude of vulnerability for each chain actor. For both 5% and 10% adjustments, in-country processors are the most vulnerable, followed by the export supplier. Cocoa farmers are the least vulnerable when the mean vulnerability levels are considered. Table 9 and Figure 17 show the effect that a 5% and 10% decrease in the percentage of cocoa beans allocated for in-country processing has on the vulnerability levels of the three chain actors in the cocoa value chain.

Table 8 Results of sensitivity analyses involving 5% and 10% adjustment of counterfactual relationships for five variables

	Adjustment @ 5% of counterfactual relationship					Adjustment @ 10% of counterfactual relationship				
	Cocoa farmer population	Switching out rate	Maturity rate	Smuggling rate	% FOB allocation to farmers	Cocoa farmer population	Switching out rate	Maturity rate	Smuggling rate	% FOB allocation to farmers
Mean Mag. (Vul)(%)	-5.28	-3.35	-2.26	-2.14	-0.31	-8.11	-2.17	-3.46	-2.14	-2.06
Rise vulnerability levels (yr.)	10.25	5	6	5.25	4	6.25	6.25	6.25	6.50	5.50
Fall vulnerability levels (yrs.)	8.75	8.25	4.75	3.50	2.50	8	1.75	5	4.75	4
Period of vulnerability (yrs.)	20	10.75	10.75	8.75	6.5	20	8	11.25	11.25	9.25

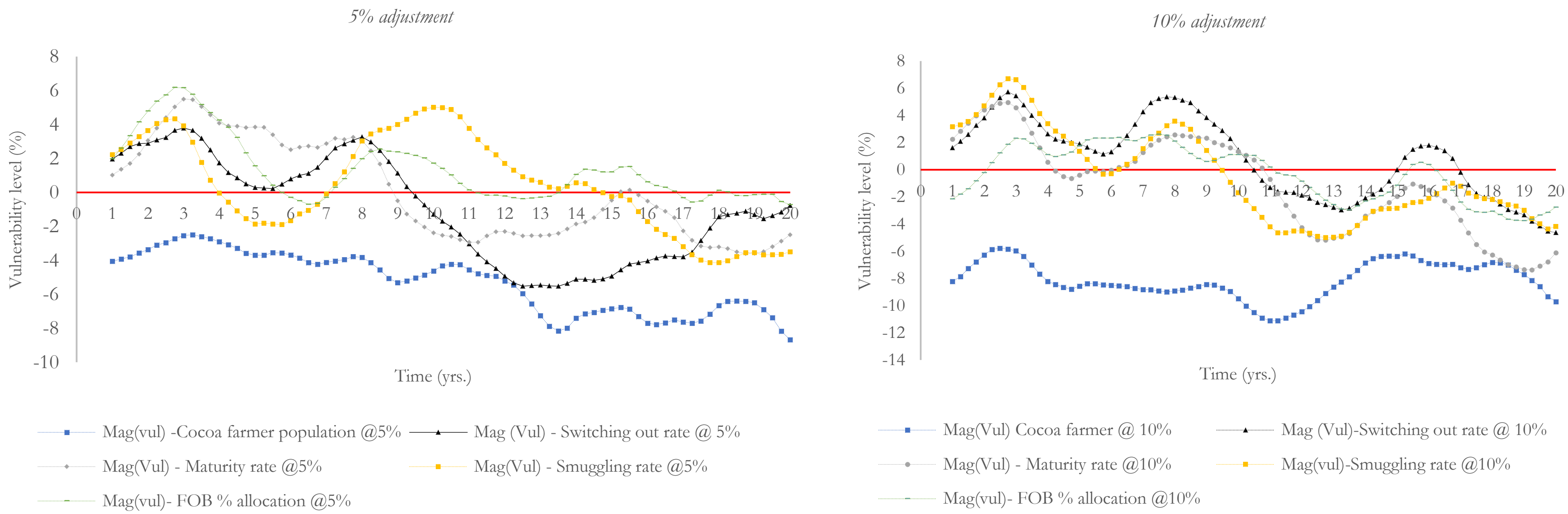


Figure 16 Vulnerability levels for 5% and 10% adjustment of upstream precursors

4.5.5 Duration of Vulnerability – Midstream Precursors of Vulnerability

Not surprisingly, in-country processors experience the most prolonged periods of vulnerability when there is a decrease in the percentage of beans allocated for in-country processing. When the 5% adjustment in the volumes of cocoa beans allocated for local processing increases to 10%, the differences in the vulnerable periods for in-country processors and the exports are 0.25 year and 1.25 years, respectively. However, cocoa farmers will experience the highest difference in the periods of vulnerability (i.e., 7 years) when the 5% decrease in allocated volumes of cocoa beans increases to 10%.

Table 9 Sensitivity analyses involving 5% and 10% decrease in cocoa beans allocation for in-country processing

	Chain actor @ 5% adjustment level			Chain actors @ 10% adjustment level		
	Cocoa producers	In-country processors	Exporters	Cocoa producers	In-country processors	Exporters
Mean Mag. (Vul)(%)	-0.48	-25.17	-2.74	-0.91	-29.50	-2.17
Rise vulnerability levels (yr.)	1.25	8.5	1.00	5.75	10.00	0.75
Fall vulnerability levels (yrs.)	2.00	6.75	2.00	4.75	10.00	1.50
Period of vulnerability (yrs.)	3.25	16.00	1.00	10.25	16.25	2.25

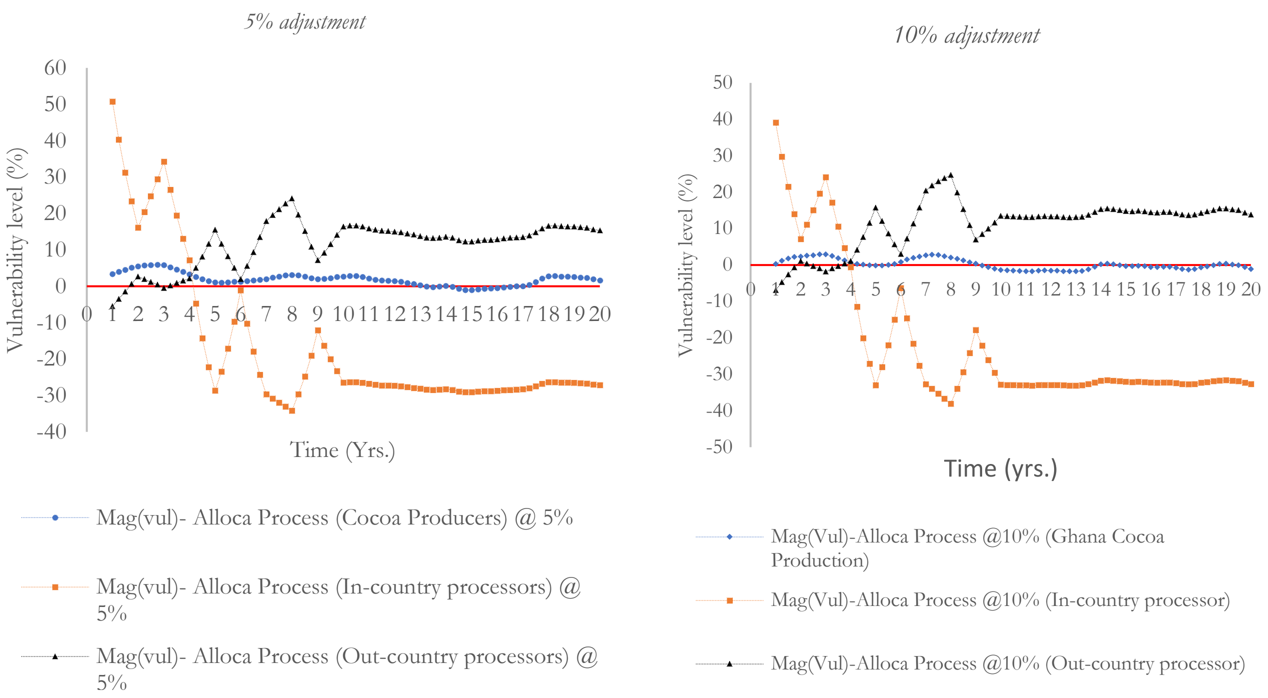


Figure 17 Results of 5% and 10% decrease in cocoa beans allocation for in-country processing[3]

4.5.6 Ranking of Precursors of Vulnerability

The precursors of vulnerability were ranked based on three metrics constructed from the magnitude-related and time-related performance indicators: the mean vulnerability level for vulnerable periods, the duration of vulnerability and the duration of a rise in vulnerability. An overall index was then formed by taking a simple average of the three vulnerability measures and used for the final ranking. Results indicate that rankings are influenced by the way that vulnerability is measured (Table 10 and Figure 18).

When the mean vulnerability level is used as a ranking criterion, a 10% decrease in the percentage of cocoa beans allocated to local processing induces the most vulnerability (a mean of −29.5% for in-country processors). This is followed by a 5% increase in the percentage of cocoa beans allocated for local processing, which results in a mean vulnerability level of −25.17% for in-country

[3] *Exporters are also referred to as out-country processors*

processors. A 10% decrease in the cocoa farmer population is the next most disruptive precursor, resulting in a mean vulnerability level of approximately −13% for all chain actors.

Table 10 Aggregate ranks of precursors of vulnerability

	Mean Mag (Vul)(%)	Periods of Rise in Vulnerability levels (years)	Period of Vulnerability (years)	Aggregate rank	Re-ranking
Cocoa farmer population @10% (all actors)	3rd	1st	1st	1.67	1st
Allocation % in-country processing @ 10% (in-country processors)	1st	3rd	2nd	2	2nd
Cocoa farmer population @5% (all actors)	4th	2nd	1st	2.33	3rd
Allocation % in-country processing @ 5% (in-country processors)	2nd	4th	3rd	3	4th
Maturity rate @10% (all actors)	5th	5th	4th	4.67	5th
Smuggling rate @10% (all actors)	7th	5th	4th	5.33	6th
Maturity rate @5% (all actors)	9th	6th	5th	6.67	7th
Switching out rate @5% (all actors)	6th	10th	5th	7	8th
Switching out rate @10% (all actors)	10th	5th	9th	8	9th
Allocation % in-country processing @ 10% (farmers)	13th	7th	6th	8.67	10th
% FOB allocation to farmers @10% (all actors)	12th	8th	7th	9	11th
Smuggling rate @5% (all actors)	11th	9th	8th	9.33	12th
Allocation % in-country processing @ 5% (Exporters)	8th	13th	13th	11.33	13th
% FOB allocation to farmers @5% (all actors)	15th	11th	10th	12	14th
Allocation % in-country processing @ 10% (Exporters)	10th	14th	12th	12	14th
Allocation % in-country processing @ 5% (farmers)	14th	12th	11th	12.33	15th

When the periods of rise in vulnerability levels is used as a ranking criterion, a 10% and 5% decrease in cocoa farmer population are the most disruptive precursors, resulting in 11 years and 10.25 years of a rise in vulnerability levels, respectively. The two are also the most disruptive precursors when the period of vulnerability is used as the ranking criterion; chain actors are vulnerable for the entire 20 years. This is followed by a 10% and 5% decrease in the percentage of cocoa beans allocated for local processing, which induces 16.25 years and 16 years of vulnerability for in-country processors, respectively.

Based on the aggregate ranking, the most disruptive precursor of vulnerability in Ghana is a decrease in the cocoa farmer population, which has the same magnitude of effect on all chain actors. This is followed by a decrease in the percentage of cocoa beans allocated for local processing, which is most disruptive to in-country processors. The tree maturity rate is the 5th most disruptive precursor of vulnerability that affects all chain actors. The aggregate ranking also suggests that cocoa farmers and export suppliers (government) are the least vulnerable when the percentage of cocoa allocated for in-country processing is decreased.

The results indicate that disruptions emanating from on-farm decisions are the most disruptive and propagate in the same magnitude to all chain actors. However, disruptions emerging from the government's decisions on cocoa bean exports is the most disruptive to local processors in Ghana, and this can have a countervailing effect on backward integration of multinationals intending to invest in local cocoa processing.

4.6 Conclusion

This paper examines the precursors of vulnerability in the cocoa value chain by considering the impact that changes in key parameters have on measures of supply chain vulnerability. The counterfactual relationships represent potential endogenous disruptions that can befall the cocoa value chain. The parameters are categorised as upstream or midstream, based on their location in the baseline model.

The findings on the effect of decreasing farmer population on vulnerability levels corroborate with government's clarion call to attract new entrants (farmers) into cocoa production (Aneani et al., 2011a), as this will maintain the cocoa farmers population and enhance the robustness of the cocoa value chain. The land tenure system (notably, sharecropping) acts as a mechanism to maintain cocoa farms (Asamoah, 2015). However, its effectiveness to curtail a decrease in farmer population depends on labour availability. The effect of decreasing the volumes of cocoa beans allocated for local processing is most disruptive to in-country processors, and farmers experience the most change in vulnerability levels when the percentage is increased from 5% to 10%.

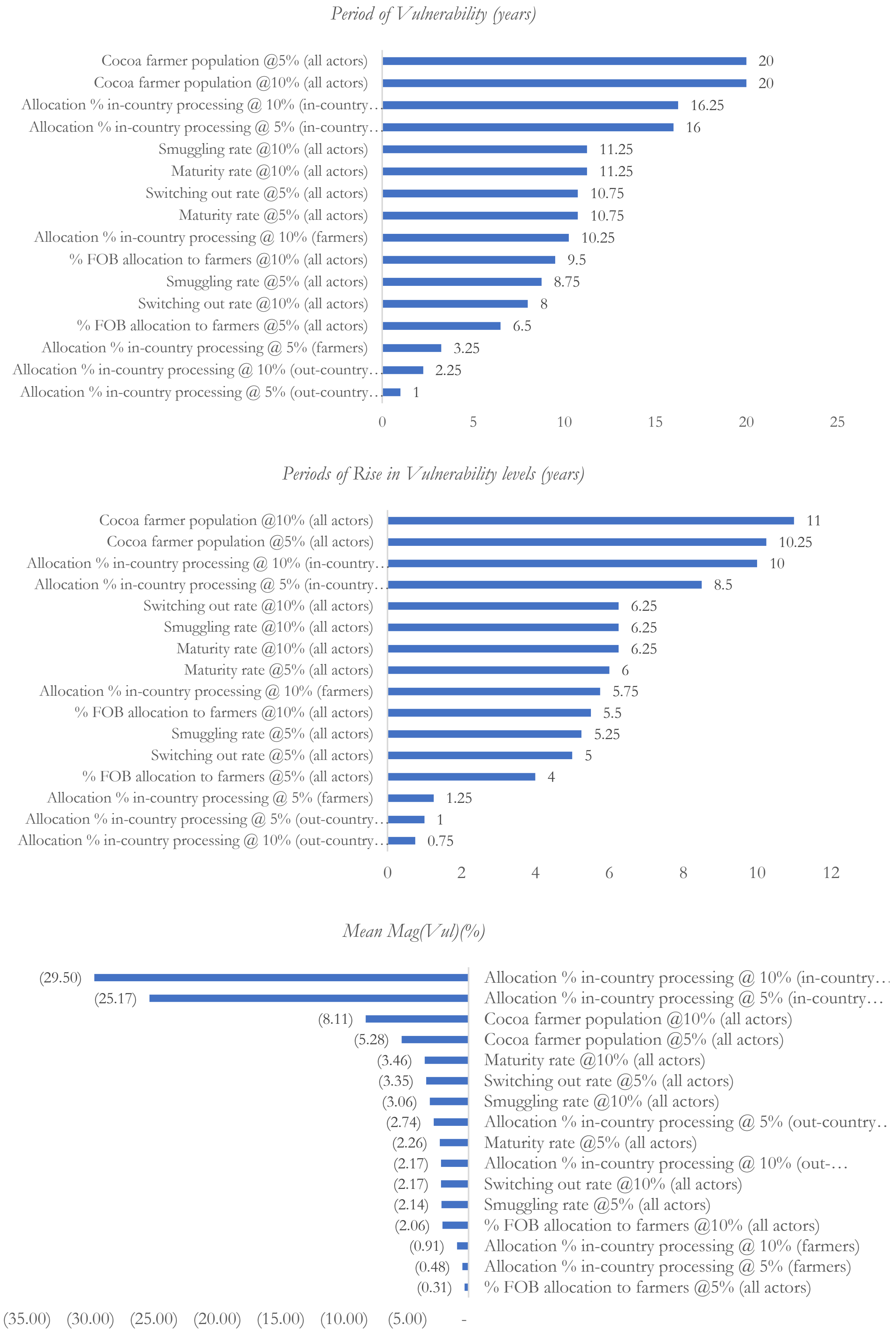


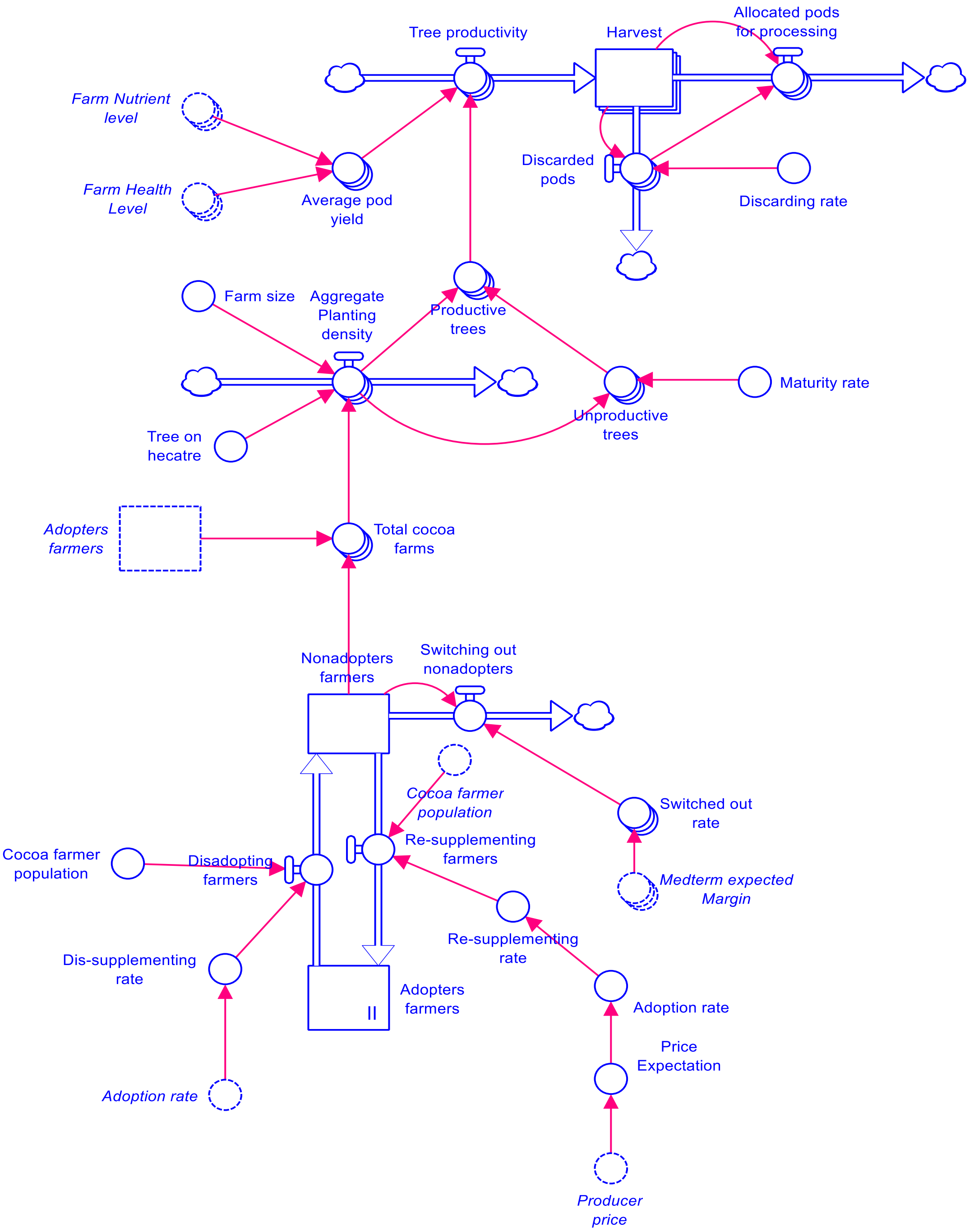
Figure 18 Ranking of precursors of vulnerability based on the three criteria

The findings suggest that precursors of vulnerability that are situated upstream of the cocoa value chain have the same magnitude of effect on the vulnerability levels for farmers, in-country processors, and exports. This is because supply-side outputs (i.e., inventory/raw material levels) are used to represent the system's state of vulnerability, and the raw material is homogenous at the different stages of the cocoa value chain. In contrast, the precursors of vulnerability that are situated midstream of the cocoa value chain have an unequal magnitude of effect on the vulnerability levels for the different chain actors.

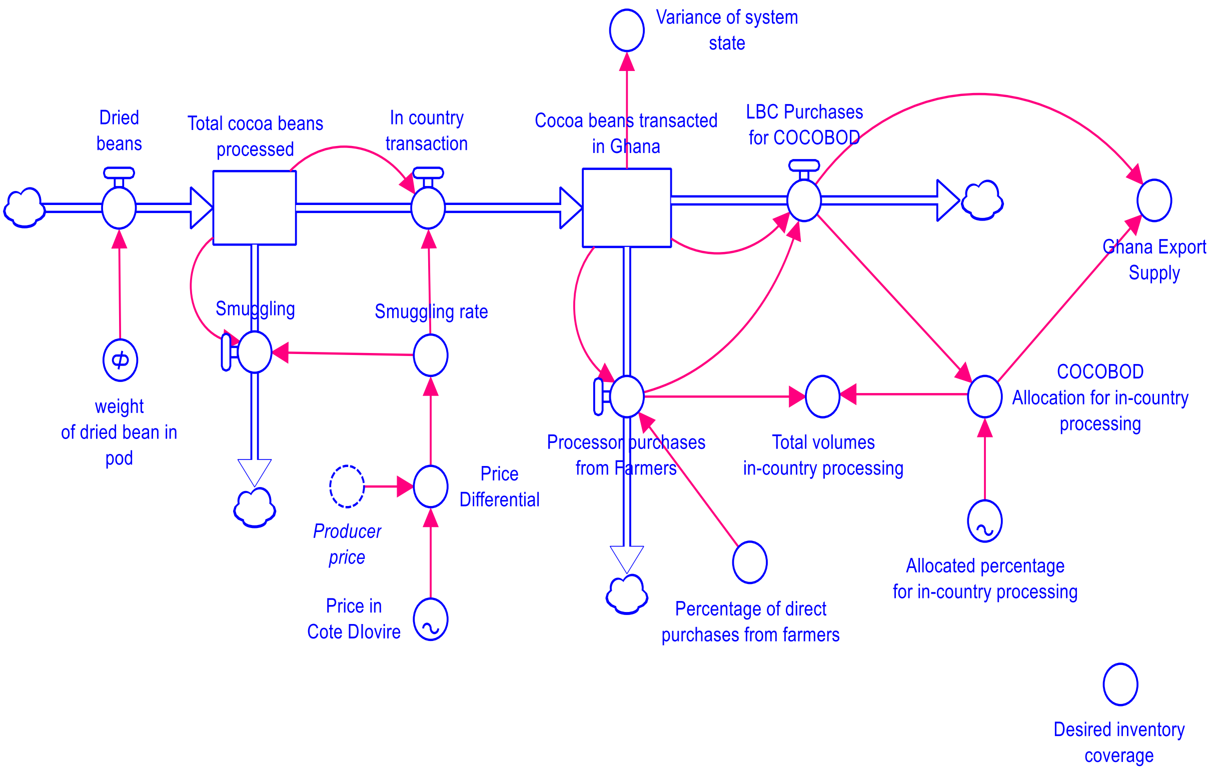
In sum, the results highlight three important management/policy implications. The first observation is that disruptions emanating from decisions at the farm level (notably, the exodus of farmers from cocoa production) initiate a ripple effect that ultimately induces the highest vulnerability (with same magnitude) on both exporters and in-country processors. The second implication is that price fluctuations do not profoundly impact the vulnerability levels of farmers, who have developed adaptive coping strategies. This is consistent with the empirical observation that price fluctuations have become a ubiquitous occurrence in Ghana's cocoa value chain. Finally, government policy direction regarding the use of cocoa bean exports as collateral for syndicated loan agreements creates an unintended consequence of increasing the vulnerability levels of local processors and farmers, particularly in the long run.

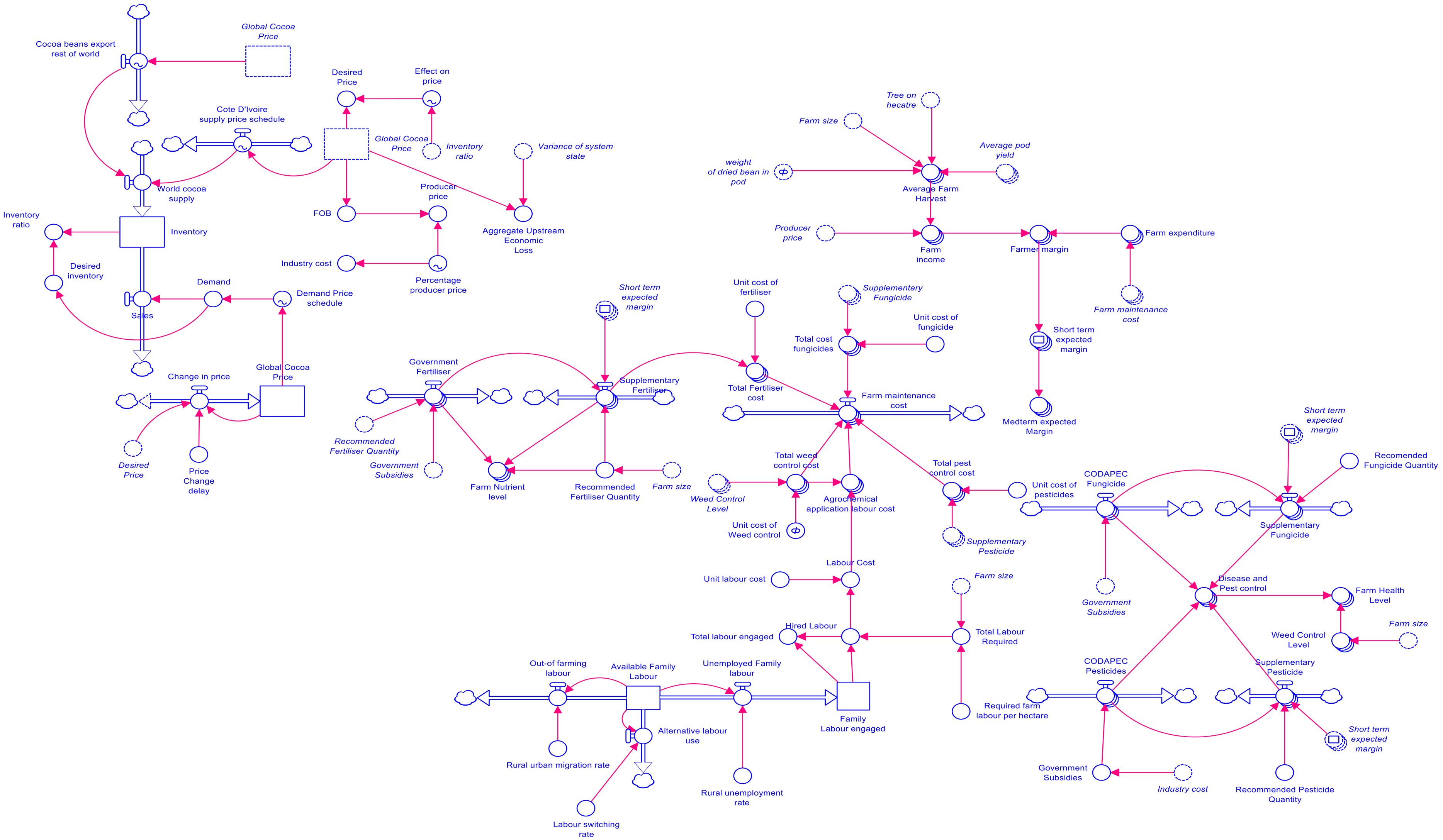
The paper demonstrates a potential reverse and non-linear cascading failure in agricultural value chains that can be further explored in future studies. In addition, scenario analyses that consider the correlation among precursors of vulnerability is a recommended area for future studies. The paper uses an unweighted average to rank the vulnerability levels of actors. Exploring how actors weigh the different types of vulnerability indicator and how it impacts on the ranking of the precursors is potential future studies.

Appendix 4.0



Tree productivity
Harvest
Allocated pods for processing
Farm Nutrient level
Farm Health Level
Average pod yield
Discarded pods
Discarding rate
Farm size
Aggregate Planting density
Productive trees
Maturity rate
Unproductive trees
Tree on hecatre
Adopters farmers
Total cocoa farms
Nonadopters farmers
Switching out nonadopters
Cocoa farmer population
Switched out rate
Cocoa farmer population
Disadopting farmers
Re-supplementing farmers
Medterm expected Margin
Dis-supplementing rate
Re-supplementing rate
Adopters farmers
Adoption rate
Price Expectation
Adoption rate
Producer price


Variance of system state
Dried beans
Total cocoa beans processed
In country transaction
Cocoa beans transacted in Ghana
LBC Purchases for COCOBOD
Ghana Export Supply
Smuggling
Smuggling rate
weight of dried bean in pod
Producer price
Price Differential
Price in Cote DIovire
Processor purchases from Farmers
Total volumes in-country processing
COCOBOD Allocation for in-country processing
Allocated percentage for in-country processing
Percentage of direct purchases from farmers
Desired inventory coverage



Cocoa beans export rest of world
Global Cocoa Price
Desired Price
Effect on price
Cote D'Ivoire supply price schedule
Global Cocoa Price
Inventory ratio
Variance of system state
World cocoa supply
Producer price
FOB
Aggregate Upstream Economic Loss
Inventory ratio
Inventory
Desired inventory
Industry cost
Percentage producer price
Demand
Demand Price schedule
Sales
Global Cocoa Price
Change in price
Desired Price
Price Change delay
Tree on hecatre
Farm size
Average pod yield
weight of dried bean in pod
Average Farm Harvest
Producer price
Farm income
Farmer margin
Farm expenditure
Farm maintenance cost
Short term expected margin
Medterm expected Margin
Short term expected margin
Unit cost of fertiliser
Supplementary Fungicide
Unit cost of fungicide
Total cost fungicides
Government Fertiliser
Supplementary Fertiliser
Total Fertiliser cost
Farm maintenance cost
Recommended Fertiliser Quantity
Government Subsidies
Farm Nutrient level
Recommended Fertiliser Quantity
Farm size
Total weed control cost
Weed Control Level
Agrochemical application labour cost
Unit cost of Weed control
Total pest control cost
Unit cost of pesticides
Supplementary Pesticide
Short term expected margin
Recomended Fungicide Quantity
CODAPEC Fungicide
Supplementary Fungicide
Government Subsidies
Disease and Pest control
Farm Health Level
Farm size
Weed Control Level
Labour Cost
Unit labour cost
Farm size
Total labour engaged
Hired Labour
Total Labour Required
Out-of farming labour
Available Family Labour
Unemployed Family labour
Family Labour engaged
Alternative labour use
Rural urban migration rate
Rural unemployment rate
Labour switching rate
Required farm labour per hectare
CODAPEC Pesticides
Supplementary Pesticide
Short term expected margin
Government Subsidies
Industry cost
Recommended Pesticide Quantity

Appendix 4.1

	Equation	Properties	Units	Documentation	Annotation
Top-Level Model:					
Adopters_farmers(t)	Adopters_farmers(t - dt) + (Readoption_farmers + Influenced_farmers - Disadopting_farmers - Switching_out_adopters) * dt	INIT Adopters_farmers = (Adoption_rate * Cocoa_Farmer_Population) + Influenced_farmers+ Readoption_farmers - Disadopting_farmers - Switching_out_adopters {farmers}			NON-NEGATIVE
Available_Family_Labour(t)	Available_Family_Labour(t - dt) + (- "Out-of_farming_labour" - Unemployed_Family_labour - Alternative_labour_use) * dt	INIT Available_Family_Labour = 28.80 * Farm_size {man days}			NON-NEGATIVE
Cocoa_beans_transacted_in_Ghana(t)	Cocoa_beans_transacted_in_Ghana(t - dt) + (In_country_transaction - Processor_purchases_from_Farmers - LBC_Purchases_for_COCOBOD) * dt	INIT Cocoa_beans_transacted_in_Ghana = In_country_transaction {kg}			NON-NEGATIVE
Cocoa_Farmer_Population(t)	Cocoa_Farmer_Population(t - dt)	INIT Cocoa_Farmer_Population = 371000{farmers}			NON-NEGATIVE
Family_Labour_engaged(t)	Family_Labour_engaged(t - dt) + (Unemployed_Family_labour) * dt	INIT Family_Labour_engaged = Unemployed_Family_labour {man days}			NON-NEGATIVE

Farm_Margin[Farmer_type](t)	Farm_Margin[Farmer_type](t - dt) + (Farm_income[Farmer_type] - Farm_Expenditure[Farmer_type]) * dt	INIT Farm_Margin[Farmer_type] = Farm_income - Farm_Expenditure {USD}	NON-NEGATIVE
Fertiliser_Aplied[Farmer_type](t)	Fertiliser_Aplied[Farmer_type](t - dt) + (Government_Fertiliser[Farmer_type] + Supplementary_Fertiliser[Farmer_type]) * dt	INIT Fertiliser_Aplied[Farmer_type] = Government_Fertiliser + Supplementary_Fertiliser	NON-NEGATIVE
Fungicide_Applied[Farmer_type](t)	Fungicide_Applied[Farmer_type](t - dt) + (CODAPEC_Fungicide[Farmer_type] + Supplementary_Fungicide[Farmer_type]) * dt	INIT Fungicide_Applied[Farmer_type] = CODAPEC_Fungicide + Supplementary_Fungicide	NON-NEGATIVE
Global_Cocoa_Price(t)	Global_Cocoa_Price(t - dt) + (Change_in_price) * dt	INIT Global_Cocoa_Price = 2200 {USD per tonne}	NON-NEGATIVE
Harvest[Farmer_type](t)	Harvest[Farmer_type](t - dt) + (Tree_productivity[Farmer_type] - Allocated_pods_for_processing[Farmer_type] - Discarded_pods[Farmer_type]) * dt	INIT Harvest[Farmer_type] = SUM(Tree_productivity) {pods}	NON-NEGATIVE
Inventory(t)	Inventory (t - dt) + (World_cocoa_supply - Sales) * dt	INIT Inventory = Desired_inventory{kg}	NON-NEGATIVE
Nonadopters_farmers(t)	Nonadopters_farmers(t - dt) + (New_nonadopters - Influenced_farmers - Switching_out_nonadopters) * dt	INIT Nonadopters_farmers = ((1-Adoption_rate) * Cocoa_Farmer_Population) - Influenced_farmers - Switching_out_nonadopters {farmers}	NON-NEGATIVE
Pesticide_Applied[Farmer_type](t)	Pesticide_Applied[Farmer_type](t - dt) + (CODAPEC_Pesticides[Farmer_type] +	INIT Pesticide_Applied[Farmer_t	NON-NEGATIVE

	Supplementary_Pesticide[Farmer_type]) * dt	ype] = CODAPEC_Pesticides+ Supplementary_Pesticide	
Switch_out_adopters(t)	Switch_out_adopters(t - dt) + (Switching_out_adopters) * dt	INIT Switch_out_adopters = Switching_out_adopters {farmers}	NON-NEGATIVE
"Switched_out_Non-adopters"(t)	"Switched_out_Non-adopters"(t - dt) + (Switching_out_nonadopters) * dt	INIT "Switched_out_Non-adopters" = Switching_out_nonadopters {farmers}	NON-NEGATIVE
Total_cocoa_beans_processed(t)	Total_cocoa_beans_processed(t - dt) + (Dried_beans - In_country_transaction - Smuggling) * dt	INIT Total_cocoa_beans_processed = Dried_beans {kg}	NON-NEGATIVE
Aggregate_Planting_density[Adopters]	Tree_on_hecatre*Farm_size*Total_cocoa_farms[Adopters] {trees}		UNIFLOW
Aggregate_Planting_density[Nonadopters]	Tree_on_hecatre*Farm_size*Total_cocoa_farms[Nonadopters] {trees}		
Allocated_pods_for_processing[Farmer_type]	Harvest-Discarded_pods {pods}	OUTFLOW PRIORITY: 2	UNIFLOW
Alternative_labour_use	Labour_switching_rate*Available_Family_Labour {man days}	OUTFLOW PRIORITY: 3	UNIFLOW
Change_in_price	(Desired_Price-Global_Cocoa_Price)/Price_Change_delay		
Cocoa_beans_export_rest_of_world	GRAPH(Global_Cocoa_Price {kg}) Points: (685, 1426000000), (824.615384615, 1.59e+09), (964.230769231, 1.64e+09), (1103.84615385, 1.92e+09), (1243.46153846, 1.98e+09),		UNIFLOW

	(1383.07692308, 2.03e+09), (1522.69230769, 2.08e+09), (1662.30769231, 2.17e+09), (1801.92307692, 2.25e+09), (1941.53846154, 2.31e+09), (2081.15384615, 2.29e+09), (2220.76923077, 2.31e+09), (2360.38461538, 2.55e+09), (2500, 2.64e+09)		
CODAPEC_Fungicide[Farmer_type]	IF(Government_Subsidies = 1) THEN 4 ELSE 0		UNIFLOW
CODAPEC_Pesticides[Farmer_type]	IF(Government_Subsidies = 1)THEN 4 ELSE 0		UNIFLOW
Cote_D'Ivoire_supply_price_schedule	GRAPH(Global_Cocoa_Price {kg}) Points: (685, 1.08e+09), (824.615384615, 1.14e+09), (964.230769231, 1174000000), (1103.84615385, 1.17e+09), (1243.46153846, 1.23e+09), (1383.07692308, 1.27e+09), (1522.69230769, 1.28e+09), (1662.30769231, 1.35e+09), (1801.92307692, 1.34e+09), (1941.53846154, 1.39e+09), (2081.15384615, 1.39e+09), (2220.76923077, 1.45e+09), (2360.38461538, 1.52e+09), (2500, 1.55e+09)		UNIFLOW
Disadopting_farmers	Disadoption_rate* Cocoa_Farmer_Population {farmers}	OUTFLOW PRIORITY: 1	UNIFLOW
Discarded_pods[Farmer_type]	Discarding_rate*Harvest {pods}	OUTFLOW PRIORITY: 1	UNIFLOW

Dried_beans	SUM(Allocated_pods_for_processing)* weight_of_dried_bean_in_pod{kg}		UNIFLOW
Farm_Expenditure[Adopters]	SMTH1(Farm_maintenance_cost[Adopters], 1) {USD}		UNIFLOW
Farm_Expenditure[Nonadopters]	SMTH1(Farm_maintenance_cost[Nonadopters], 1) {USD}		
Farm_income[Adopters]	Producer_price*(Average_Farm_Harvest[Adopters] /1000) {USD}		UNIFLOW
Farm_income[Nonadopters]	Producer_price* (Average_Farm_Harvest[Nonadopters]/1000) {USD}		
Farm_maintenance_cost[Adopters]	Total_cost_fungicides[Adopters]+Total_Fertiliser_cost[Adopters]+Total_weed_control_cost[Adopters]+Total_pest_control_cost[Adopters]+Agrochemical_application_labour_cost[Adopters] {USD}		UNIFLOW
Farm_maintenance_cost[Nonadopters]	Total_cost_fungicides[Nonadopters]+Total_Fertiliser_cost[Nonadopters]+Total_weed_control_cost[Nonadopters]+Total_pest_control_cost[Nonadopters]+Agrochemical_application_labour_cost[Nonadopters]		
Government_Fertiliser[Farmer_type]	IF(Government_Subsidies = 1) THEN (0.5*Recommended_Fertiliser_Quantity) ELSE 0		UNIFLOW
In_country_transaction	Total_cocoa_beans_processed *(1-Smuggling_rate) {kg}	OUTFLOW PRIORITY: 1	UNIFLOW
Influenced_farmers	Cocoa_Farmer_Population*Influenced_rate {farmers}	OUTFLOW PRIORITY: 1	UNIFLOW

LBC_Purchases_for_COCOBOD	Cocoa_beans_transacted_in_Ghana-Processor_purchases_from_Farmers {kg}	OUTFLOW PRIORITY: 2	UNIFLOW
New_nonadopters	Disadopting_farmers - Readoption_farmers {farmers}		UNIFLOW
"Out-of_farming_labour"	(Rural_urban_migration_rate*Available_Family_Labour) {man days}	OUTFLOW PRIORITY: 1	UNIFLOW
Processor_purchases_from_Farmers	Percentage_of_direct_purchases_from_farmers*Cocoa_beans_transacted_in_Ghana {kg}	OUTFLOW PRIORITY: 1	UNIFLOW
Readoption_farmers	("Re-adoption_rate"* Disadopting_farmers) {farmers}		UNIFLOW
Sales	Demand {kg}		UNIFLOW
Smuggling	Smuggling_rate*Total_cocoa_beans_processed {kg}	OUTFLOW PRIORITY: 2	UNIFLOW
Supplementary_Fertiliser[Adopters]	IF((Short_term_expected_margin[Adopters] > 0) AND(Government_Fertiliser < Recommended_Fertiliser_Quantity)) THEN (Recommended_Fertiliser_Quantity - Government_Fertiliser) ELSE 0		UNIFLOW
Supplementary_Fertiliser[Nonadopters]	IF((Short_term_expected_margin[Nonadopters] > 0) AND(Government_Fertiliser < Recommended_Fertiliser_Quantity)) THEN 0 ELSE 0		
Supplementary_Fungicide[Adopters]	IF((Short_term_expected_margin[Adopters] > 0) AND(CODAPEC_Fungicide < Recomended_Fungicide_Quantity)) THEN (Recomended_Fungicide_Quantity		UNIFLOW

	- CODAPEC_Fungicide) ELSE 0 {fertiliser}		
Supplementary_Fungicide[Nonadopters]	IF((Short_term_expected_margin[Nonadopters]> 0) AND(CODAPEC_Fungicide < Recomended_Fungicide_Quantity)) THEN (CODAPEC_Fungicide) ELSE 0 {fertiliser}		
Supplementary_Pesticide[Adopters]	IF(((Short_term_expected_margin[Adopters] > 0) OR (Short_term_expected_margin[Adopters] < 0)) AND(CODAPEC_Pesticides < Recommended_Pesticide_Quantity)) THEN (Recommended_Pesticide_Quantity - CODAPEC_Pesticides) ELSE 0		UNIFLOW
Supplementary_Pesticide[Nonadopters]	IF(((Short_term_expected_margin[Nonadopters]> 0) OR (Short_term_expected_margin < 0)) AND(CODAPEC_Pesticides < Recommended_Pesticide_Quantity)) THEN (CODAPEC_Pesticides) ELSE 0		
Switching_out_adopters	Cocoa_Farmer_Population*Switched_out_rate[Adopters] {farmers}	OUTFLOW PRIORITY: 2	UNIFLOW
Switching_out_nonadopters	Cocoa_Farmer_Population*Switched_out_rate[Nonadopters] {farmers}	OUTFLOW PRIORITY: 2	UNIFLOW
Tree_productivity[Adopters]	(Productive_trees[Adopters]*Average_pod_yield[Adopters]) {pods}		UNIFLOW
Tree_productivity[Nonadopters]	(Productive_trees[Nonadopters] * Average_pod_yield[Nonadopters]) {pods}		

Unemployed_Family_labour	Available_Family_Labour*Rural_unemployment_rate {man days}	OUTFLOW PRIORITY: 2	UNIFLOW
World_cocoa_supply	Ghana_Export_Supply+Cocoa_beans_export_rest_of_world+Cote_D'Ivoire_supply_price_schedule {kg}		UNIFLOW
Adoption_rate	GRAPH(Price_effect_on_adoption) Points: (0.000, 0.300), (0.200, 0.350), (0.400, 0.400), (0.600, 0.450), (0.800, 0.500), (1.000, 0.550), (1.200, 0.600), (1.400, 0.630), (1.600, 0.650), (1.800, 0.700), (2.000, 0.800)		
Aggregate_Upstream_Economic_Loss	Global_Cocoa_Price* (Variance_of_system_state/1000) {USD}		
Agrochemical_application_labour_cost[Adopters]	Labour_Cost - Total_weed_control_cost[Adopters] {USD}		
Agrochemical_application_labour_cost[Nonadopters]	Labour_Cost - Total_weed_control_cost[Nonadopters] {USD}		
"Allocated_percentage_for_in-country_processing"	GRAPH(TIME) Points: (1.00, 0.173), (2.00, 0.163), (3.00, 0.16), (4.00, 0.177), (5.00, 0.194), (6.00, 0.171), (7.00, 0.115), (8.00, 0.145), (9.00, 0.197), (10.00, 0.169), (11.00, 0.21), (12.00, 0.316), (13.00, 0.224), (14.00, 0.324), (15.00, 0.351), (16.00, 0.256), (17.00, 0.311)		
Average_Farm_Harvest[Adopters]	weight_of_dried_bean_in_pod*Farm_size*Tree_on_hecatre*Average_pod_yield[Adopters] {kg}		

Average_Farm_Harvest[Nonadopters]	weight_of_dried_bean_in_pod*Farm_size*Tree_on_hecatre*Average_pod_yield[Nonadopters] {kg}
Average_pod_yield[Adopters]	IF((Farm_Nutrient_level[Adopters]= 2) AND(Farm_Health_Level[Adopters] = 2)) THEN 25 ELSE (TRIANGULAR(15, 20, 25)) {pods}
Average_pod_yield[Nonadopters]	IF((Farm_Nutrient_level[Nonadopters]=1) AND(Farm_Health_Level[Nonadopters] =1)) THEN (TRIANGULAR(10, 14, 15)) ELSE 20{pods}
"COCOBOD_Allocation_for_in-country_processing"	LBC_Purchases_for_COCOBOD*"Allocated_percentage_for_in-country_processing" {kg}
Demand	Demand_Price_schedule {kg}
Demand_Price_schedule	GRAPH(Global_Cocoa_Price) Points: (650, 4.33e+09), (885, 4.25e+09), (1120, 3.95e+09), (1355, 3.71e+09), (1590, 3.32e+09), (1825, 3.17e+09), (2060, 3.08e+09), (2295, 2.84e+09), (2530, 2.77e+09), (2765, 2.64e+09), (3000, 2.47e+09)
Desired_inventory	Desired_inventory_coverage*Demand {kg}
Desired_inventory_coverage	1{year}
Desired_Price	Effect_on_price*Global_Cocoa_Price{USD per tonne}
Disadoption_rate	IF(SMTH1(Adoption_rate, 1) < Adoption_rate) THEN (Adoption_rate -

	SMTH1(Adoption_rate, 1)) ELSE 0 {per cent}
Discarding_rate	0.0000001{percent}
Disease_and_Pest_control	IF((Fungicide_Applied[Adopters] = 4) AND(Pesticide_Applied[Adopters] = 4)) THEN 2 ELSE 1
Effect_on_price	GRAPH(Inventory_ratio) Points: (0.000, 1.897), (0.200, 1.795), (0.400, 1.612), (0.600, 1.436), (0.800, 1.267), (1.000, 0.974), (1.200, 0.835), (1.400, 0.608), (1.600, 0.264), (1.800, 0.125), (2.000, 0.022)
Farm_Health_Level[Farmer_type]	IF((Weed_Control_Level =2) AND(Disease_and_Pest_control = 2)) THEN 2 ELSE 1
Farm_Nutrient_level[Farmer_type]	IF(Fertiliser_Aplied =Recommended_Fertiliser_Quantity) THEN 2 ELSE 1
Farm_size	3 {hectares}
FOB	Global_Cocoa_Price {USD}
Ghana_Export_Supply	LBC_Purchases_for_COCOBOD-"COCOBOD_Allocation_for_in-country_processing" {kg}
Government_Subsidies	IF(Industry_cost > 0) THEN 1 ELSE 0
Hired_Labour	Total_Labour_Required-Family_Labour_engaged {man days}
Industry_cost	GRAPH(Percentage_producer_price) Points: (0.5100, 0.0300), (0.515384615385, 0.0100), (0.530769230769, 0.0100),

	(0.546153846154, 0.0300), (0.561538461538, 0.1200), (0.576923076923, 0.0700), (0.592307692308, 0.0800), (0.607692307692, 0.1000), (0.623076923077, 0.0800), (0.638461538462, 0.0200), (0.653846153846, 0.1700), (0.669230769231, 0.1900), (0.684615384615, 0.2500), (0.7000, 0.1500)
Influenced_rate	IF(SMTH1((1-Adoption_rate), 1) < (1-Adoption_rate)) THEN ((1-Adoption_rate) - SMTH1((1-Adoption_rate), 1)) ELSE 0 {percent}
Inventory_ratio	Inventory/Desired_inventory
Labour_Cost	Hired_Labour*Unit_labour_cost {USD}
Labour_switching_rate	0.001{percent}
Maturity_rate	0.15
Medterm_expected_Margin[Adopters]	SMTHN(Short_term_expected_margin[Adopters], 5, 1) {USD}
Medterm_expected_Margin[Nonadopters]	SMTHN(Short_term_expected_margin[Nonadopters], 5, 1) {USD}
"MRI-_Ghana_Cocoa_Production"	Cocoa_beans_transacted_in_Ghana {kg}
"MRI-_In-country_Processors"	"Total_volumes_in-country_processing" {kg}
"MRI-_Exporters"	Ghana_Export_Supply {kg}
Percentage_of_direct_purchases_from_farmers	0.015{ per cent}

Percentage_producer_price	GRAPH(TIME) Points: (1.00, 0.5100), (2.00, 0.5100), (3.00, 0.5100), (4.00, 0.5100), (5.00, 0.6400), (6.00, 0.6400), (7.00, 0.6900), (8.00, 0.6400), (9.00, 0.5400), (10.00, 0.5400), (11.00, 0.5500), (12.00, 0.6900), (13.00, 0.6900)
Price_Change_delay	4{times}
Price_Differential	Producer_price - Price_in_Cote_DIovire {USD}
Price_effect_on_adoption	SMTH1(Producer_price, 1)/Producer_price
Price_in_Cote_DIovire	GRAPH(TIME {USD}) Points: (1.00, 395.25), (2.00, 677.05), (3.00, 790.54), (4.00, 430.86), (5.00, 644.11), (6.00, 638.78), (7.00, 760.14), (8.00, 652.26), (9.00, 819.36), (10.00, 1374.75), (11.00, 984.5), (12.00, 905.16), (13.00, 946.72), (14.00, 774.8), (15.00, 1078)
Producer_price	FOB * Percentage_producer_price {USD}
Productive_trees[Adopters]	Aggregate_Planting_density[Adopters] - Unproductive_trees[Adopters] {trees}
Productive_trees[Nonadopters]	Aggregate_Planting_density[Nonadopters]- Unproductive_trees[Nonadopters] {trees}
"Re-adoption_rate"	IF(SMTH1(Adoption_rate, 1) > Adoption_rate) THEN (SMTH1(Adoption_rate, 1)- Adoption_rate) ELSE 0 {per cent}
Recomended_Fungicide_Quantity	4 {times}

Recommended_Fertiliser_Quantity	7.4*Farm_size {bags}
Recommended_Pesticide_Quantity	4 {times}
Required_farm_labour_per_hectare	53.17 {man days}
Rural_unemployment_rate	0.001{percent}
Rural_urban_migration_rate	0.26{percent}
Short_term_expected_margin[Adopters]	SMTH1(Farm_Margin[Adopters], 1, 0) {USD}
Short_term_expected_margin[Nonadopters]	SMTH1(Farm_Margin[Nonadopters], 1, 0) {USD}
Smuggling_rate	IF(Price_Differential < 0) THEN 0.0005 ELSE 0 {percent}
Switched_out_rate[Adopters]	0{percent}
Switched_out_rate[Nonadopters]	IF(Medterm_expected_Margin[Nonadopters] > 0) THEN 0 ELSE 0.015 {percent}
Total_cocoa_farms[Adopters]	Adopters_farmers {farms}
Total_cocoa_farms[Nonadopters]	Nonadopters_farmers {farms}
Total_cost_fungicides[Adopters]	Supplementary_Fungicide[Adopters]*Unit_cost_of_fungicide {USD}
Total_cost_fungicides[Nonadopters]	Supplementary_Fungicide[Nonadopters]*Unit_cost_of_fungicide {USD}
Total_Fertiliser_cost[Adopters]	Supplementary_Fertiliser[Adopters]*Unit_cost_of_fertiliser {USD}
Total_Fertiliser_cost[Nonadopters]	Supplementary_Fertiliser[Nonadopters]*Unit_cost_of_fertiliser {USD}
Total_labour_engaged	Hired_Labour+Family_Labour_engaged {man days}

Total_Labour_Required	Required_farm_labour_per_hectare*Farm _size {man days}
Total_pest_control_cost[Adopters]	Supplementary_Pesticide[Adopters]*Unit_ cost_of_pesticides {USD}
Total_pest_control_cost[Nonadopte rs]	Supplementary_Pesticide[Nonadopters]*U nit_cost_of_pesticides {USD}
"Total_volumes_in- country_processing"	("COCOBOD_Allocation_for_in- country_processing")+Processor_purchase s_from_Farmers {kg}
Total_weed_control_cost[Adopters]	Weed_Control_Level[Adopters]*Unit_cost _of_Weed_control {USD}
Total_weed_control_cost[Nonadopt ers]	Weed_Control_Level[Nonadopters]*Unit_ cost_of_Weed_control {USD}
Tree_on_hecatre	1100{trees per ha}
Unit_cost_of_fertiliser	6.63{USD}
Unit_cost_of_fungicide	1.14{USD}
Unit_cost_of_pesticides	TIME{USD}
Unit_cost_of_Weed_control	2{USD}
Unit_labour_cost	7.05 {USD}
Unproductive_trees[Farmer_type]	Maturity_rate*Aggregate_Planting_density {trees}
Variance_of_system_state	IF((DELAY1(Cocoa_beans_transacted_in _Ghana, 1)) < Cocoa_beans_transacted_in_Ghana) THEN 0 ELSE (DELAY1(Cocoa_beans_transacted_in_Gh

	ana, 1)- Cocoa_beans_transacted_in_Ghana) {kg}
Weed_Control_Level[Farmer_type]	7.73*Farm_size {man days}
weight_of_dried_bean_in_pod	0.039 {kg}

Chapter 5 *Ex-Ante* Effect of Market Liberalisation on Aggregate Socioecological Resilience of the Cocoa Value Chain

"For which of you, intending to build a tower, does not sit down first and count the cost, whether he has enough to finish it" — Luke 14:28

Abstract

This paper examines *ex-ante* the effect of market liberalisation on the aggregate socioecological resilience of agricultural value chains, using Ghana's cocoa value chain as a case study. System dynamics modelling is used to simulate three policy scenarios involving two forms of domestic market liberalisation and a simultaneous increase or decrease in cocoa exports from Ghana. Results suggest that the current partially liberalised market in Ghana supports a resilient cocoa value chain, with reasonably stable cocoa production. A fully liberalised market can improve the resilience of the cocoa value chain when it is; *(i)* adopted in synchrony with the pursuit of vertical integration via in-country processing; *(ii)* accompanied with intentional interventions to boost on-farm investment and prevent farmers from switching-out of cocoa farming. The findings suggest that a move towards market liberalisation will not necessarily threaten the resilience of the supply chain of this agrarian-oriented developing economy. Practically, the paper also offers policymakers a foreknowledge of potential effects of the government's policies in Ghana's cocoa industry.

Keywords: resilience; system dynamics modelling; market liberalisation; cocoa

5.1 Introduction

Market liberalisation involves the opening of the domestic market to facilitate competition by private actors (Dhanya, 2008). In Africa's agricultural commodity market, market liberalisation has been suggested as a policy direction that can improve the welfare of producers. However, there are divergent views about market liberalisation. Opponents maintain that market liberalisation exposes farmers to increased price risk, which is often not secured owing to the possibility of changes in export supply and or demand (Gilbert & Varangis, 2003). From the viewpoint of midstream and downstream chain actors, a market liberalisation policy supports the expansion of sourcing activities because raw material availability is a critical factor for business continuity (Blengini et al., 2017). Market liberalisation dictates the flow of raw material supply at an aggregate level and indirectly influence chain actor decisions at an individual level.

Ghana's cocoa sector currently functions under a partially liberalised market. The Ghana Cocoa Board (COCOBOD) is the sole exporter of cocoa beans outside Ghana and provides input subsidies to farmers. COCOBOD also determines the percentage of; *(a)* world cocoa price that is paid to farmers and *(b)* cocoa beans allocated for in-country processing (Asante-Poku & Angelucci, 2013; Kolavalli et al., 2012; Quarmine et al., 2014). There is a call for the full liberalisation Ghana's cocoa sector (Kolavalli et al., 2012). However, there is limited empirical evidence to support this call. Moreover, the unintended consequences of such a policy have not been studied in detail.

Due to globalisation and the interconnectedness of supply chains, the effect of domestic market arrangement governing chain activities in one country can ripple through the chain and impact activities of other chain actors. The ramifications of destabilised chain activities and accompanying economic loss have generated an interest in the need for resilience (Tendall et al., 2015). The emphasis on the economic dimension of resilience ignores the socioecological dimension that concerns the raw material production and supply in the chain (Datta et al., 2007).

In the literature, two gaps in resilience assessment concern the socioecological dimension of the concept and the analytical level. Resilience is exhibited at a dual level: the individual (agent) and aggregate (network) (Levalle & Nof, 2017). The focus has mostly been on individual-level resilience, ignoring aggregate level assessment. Attention has also predominantly concentrated on socio-technical resilience because most supply chain literature does not extend to activities at the farm level, where raw material production and supply is prominent (Datta et al., 2007), which is relevant to socioecological resilience.

Derissen et al. (2011) advocate for the incorporation of resilience into the design of policy involving ecological-economic systems like the cocoa value chain. Therefore, a policy that seeks to transition Ghana's cocoa industry from a partially liberalised market to a fully liberalised market has to consider the resilience of the cocoa value chain. To this end, this paper answers two main questions: *(i)* How will the transition from a partially liberalised market to a fully liberalised market affect the aggregate resilience of the cocoa value chain? *(ii)* What are the practical implications of this transition for chain actors?

This paper aims to assess *ex-ante* the effect of domestic market liberalisation on the aggregate socioecological resilience of the cocoa value chain in Ghana. The paper provides empirical contributions to the supply chain resilience literature by exploring resilience in agricultural value chains at an aggregate level. Practically, the findings of this paper offer industry players and policymakers with knowledge of the unintended consequences of potential policies on the resilience of Ghana's cocoa value chains.

5.2 Methodology

This paper adopts system dynamics modelling (SDM) to examine *ex-ante* the effect of market liberalisation on the aggregate resilience of Ghana's cocoa value chain. The paper focuses centrally on Ghana and incorporates cocoa supply from other producing countries to the global commodity market.

5.2.1 Model Description

The stock and flow model (*see Appendix 5.0*) highlights the flow of material and information in the cocoa value chain. Data to support the development of the functional relationships and the parameter values were retrieved from different secondary sources, collated, and stored in http://doi.org/10.5281/zenodo.2605399. A summary of parameter estimates, and equations is presented in Appendix 5.1. The model is segmented into five sub-models, which are discussed in the succeeding subsections.

5.2.2 Sub-model A: Farm Management Practices

The farmer population is segregated into *adopters* and *non-adopters* of good farm management practices. The farm management practices include pest and disease control, weed control and fertiliser application. In the cocoa literature, different adoption rates for farm management practices have been reported. An average of the reported adoption rates (i.e., 0.5) is specified as the initial adoption rate at the baseline level (Aneani et al., 2011a; Kongor et al., 2018). Farmers engage in farm management practices (referred to as '*adopters*') based on their level of motivation, which is determined by farm profitability and the provision of government subsidies. Farmers are motivated when subsidies are provided or the immediate past cropping year was profitable; else, the demotivation rate rises to 1. The dis-adoption rate is estimated as:

$$\frac{Non-adopters}{(Non-adopters+Adopters)*Demotivation\ rate} \qquad (5.1)$$

The lower boundary of the reported adoption rates is used to represent the re-adoption rate. Therefore, *non-adopters* either re-adopt farm management practices at an assumed rate of 0.3 (Aneani et al., 2011a). In Ghana, cocoa production and gold mining compete for land because the two activities are often conducted in the same regions. However, cocoa farmers hardly switch-out entirely from cocoa production into gold mining (Snapir, Simms & Waine, 2017). Given the unlikelihood for cocoa farmers to switch-out from cocoa production (Knudsen, 2007; Snapir, Simms & Waine, 2017), the switch-out rate of 0.015 is assumed for *non-adopters* when the average medium-term farm profitability is less than zero.

5.2.3 Sub-model B: On-farm Production and Processing

Each farmer owns a cocoa farm with an average size of three hectares and 1100 trees per hectare (Mahrizal et al., 2014). Given that tree replanting is often government-led and seldom practised among cocoa farmers in Ghana (Kolavalli et al., 2012), the cocoa trees are simply classified as either productive or unproductive. According to Anim-Kwapong (2004), about 25% of cocoa trees on cocoa farms in Ghana are old and unproductive. However, given that COCOBOD conducted a nationwide cocoa tree replacement exercise in 2015 and that the optimal duration for tree replanting is between 5-9 years (Mahrizal et al., 2014), an optimistic view is taken by specifying the tree maturity rate in the baseline as 15%. Based on the cocoa yield estimates reported by Asare and David (2010), the yield from a cocoa tree belonging to *adopters* is specified with a triangular distribution (between 15 and 23 pods) when agrochemical inputs are applied at sub-optimal levels. At optimal agrochemical input application levels, a cocoa tree produces 25 cocoa pods (Asare and David, 2010).

The optimal agrochemical input application levels are determined based on the requisite frequency of pesticides and fungicide application, weed control and quantity of fertiliser application sanctioned by COCOBOD's Cocoa Health and Extension unit. Even without adopting farm management practices, cocoa trees can be fruitful but poor yielding (Mahrizal et al., 2014). Hence, cocoa trees belonging to *non-adopters* produce between 10 and 15 pods (Asare & David, 2010). The aggregate harvest is estimated as:

$$Harv = [(P\,Trees_{(ad)} * Ty_{ad}) + (P\,Trees_{(nad)} * Ty_{nad})] \qquad (5.2)$$

where *Harv* is the aggregate harvest, $P\ trees_{(ad)}$ and $P\ trees_{(nad)}$ are the total number of productive cocoa trees for *adopters* and *non-adopters* respectively, Ty_{ad} and Ty_{nad} represent the average pod yield of a cocoa tree for *adopters* and *non-adopters,* respectively.

5.2.4 Sub-model C: In-country Trading and Processing

Each cocoa pod produces 0.039 kg of dried cocoa beans (Asare & David, 2010; Mahrizal et al., 2014). Under the partial market liberalisation, COCOBOD via its subsidiary, the Cocoa Marketing Company is the sole exporter of cocoa beans. Historically, less than 20% of the total cocoa beans purchased by licensed buying companies are allocated for in-country processing (Kolavalli et al., 2012).

The volume of cocoa beans exported outside Ghana is estimated as the total volume of cocoa beans purchased by licensed buying companies less the allocated volume for local processing in Ghana. Historical data on the percentage of cocoa beans allocated for in-country processing (from 1998 – 2015) are incorporated in the model. Data were retrieved from the annual cocoa reports of the International Cocoa Organisation (ICCO) for the specified period. The annual reports are accessible on the organisation's website.

5.2.5 Sub-model D: Cocoa Export and Price Factors

Adopting the specification of price in Aboah et al. (2019b), the global cocoa price (G_{Price}) is modelled using an initial value of $2000 per tonne and a quarterly price change delay. Cocoa exports from cocoa-producing countries represent supply on the world market. Historical data on cocoa exports from Cote d'Ivoire from 2000/01- 2015 cocoa cropping seasons (extracted from ICCO's annual cocoa report for the specified period) are used to estimate the average cocoa exports from Cote d'Ivoire. Similarly, the historical cocoa beans supply from the rest of the producing countries from the 2000/01-2015 cropping seasons are incorporated into the model to determine the world cocoa supply. The world cocoa supply is captured as the sum of cocoa supply from Ghana, Cote d'Ivoire, and the rest of the world.

The desired inventory coverage of one year is assumed because an annual production cycle is considered in the model. The ratio of inventory to desired inventory captures the negative influence of inventory levels on price. The desired inventory is set as the demand for cocoa beans by downstream actors in a cropping year. The demand for cocoa beans is determined by the number of buyers outside cocoa-producing countries (which is represented as the non-origin processing capacity). The non-origin processing capacity is the average cocoa grindings from 2012 – 2015 cocoa cropping years of Germany, Netherlands, rest of Europe, the US, the rest of Asia and Oceania (excluding Indonesia & Malaysia).

The desired price is the product of the effect on price and the price stock, where the effect on price is determined by the relative gap between inventory on hand and the desired inventory. The effect on price is where actual price settles on. In the model, a negative linear relationship is specified graphically between the effect on price and the inventory ratio. When the desired inventory and inventory levels are equal (i.e. inventory ratio of 1), the price remains the same (i.e. effect on price is 1).

The global cocoa price translates into the net freight on board (FOB) price at the country level. Under the partial market liberalisation, COCOBOD sets the producer price to guide in-country cocoa trading activities between licensed buying companies and farmers. The producer price is determined by deducting some percentage of the net FOB price for industry, marketing, and administrative cost (Kolavalli et al., 2011; Quarmine et al., 2014). An average percentage of the net FOB price allocated for industry, marketing, and administrative cost (i.e., 19%) was estimated based on historical data on producer price from 2000/01- 2015 cocoa (Bymolt et al., 2018). Part of the industry, marketing and administrative cost is used to finance the government's subsidies to cocoa farmers (Kolavalli et al., 2011; Quarmine et al., 2014).

5.2.6 *Sub-model E: Individual Farmer Level*

The decision to adopt farm management practices is influenced by government subsidies on inputs and farm margin (Wessel & Quist-Wessel, 2015). Under the partially liberalised market arrangement, pesticide and fungicide applications are fully subsidised under the government mass spraying initiative. Therefore, no additional inputs are required when subsidies are fully provided. In instances where government subsidies are not sufficiently provided, *adopters* provide supplementary inputs (pesticides and fungicides) at recommended COCOBOD levels, but *non-adopters* do not.

Weed control is not subsidised. The frequency of weed control for adopters is estimated as a product of the average working-days spent on weed control in a cropping season and the farm size (Bymolt et al., 2018). Aneani et al. (2011a) noted a prophylactic use of herbicides among cocoa farmers. For *non-adopters*, the frequency of weed control hinges on on-farm margins from previous cropping seasons being greater than zero. Weed, pest and disease control determine the farm health level, which is differentiated at two levels: a sub-optimal level (*farm health level is 1*) and an optimal level (*farm health level is 2).*

Low fertiliser application rate has been reported (Aneani et al., 2011a; Bymolt et al., 2018; Kongor et al., 2018). Fertiliser is partly subsidised; *adopters* use extra fertiliser, which is 1.5 bags per acre, to meet the recommended requirement. Farmers apply additional inputs under the condition that the short-term expected margin exceeds the breakeven point, and the government's subsidy is less than the prescribed quantity of agrochemicals to be applied. Full fertiliser application results in a high farm nutrient level. The farm nutrient and health levels determine the number of cocoa pods produced by a cocoa tree. The cost of adopting farm management practice is the production cost in a cropping year. Farm margin is estimated as:

$$F_{margin} = [(Av_{pod} * Farm_{size} * Tree_{hec} * Pod_{dweight})\, Prod_{price}] - (\sum Inputs_{cost} + Lab_{cost}) \quad (5.3)$$

where $\sum Inputs_{cost} + Lab_{cost}$ represent the sum of input cost from supplementary fertiliser, pesticides, and fungicides applied by the farmer and the associated labour cost, and $[(Av_{pod} * Farm_{size} * Tree_{hec} * Pod_{dweight}) Prod_{price}$ is the income.

5.2.7 Resilience Measure

The model focuses on the socioecological resilience of the cocoa value chain at an aggregate level for two reasons. First, the provisioning ecosystem service produced from upstream activities (i.e., raw materials) defines the system's identity for tropical commodities like cocoa. Second, the adaptability of upstream actors to secure the output of the agricultural system (i.e., cocoa beans) guarantees continuity in the value chain (Aboah et al., 2019a).

Following Aboah et al. (2019a), the Farm Adaptive Ratio (FAR) is used as a measure for aggregate socioecological resilience level of the cocoa value chain. FAR is an index estimated as the quotient of a dividend (LossSoR) and a divisor (μ SsoR). LossSoR captures the losses in the aggregate raw material production arising from chain actors' adaptive strategies, and μ SsoR covers the trend of the system's aggregate state of resilience, estimated as [SMTHN (D_{beans}, 5, 1)]. FAR ranges from 0 to 1; with 0 being the most resilient and 1 being the least resilient. D beans is the volumes of cocoa beans produced in a cropping year

$$FAR = \text{LossSoR}/\mu\ \text{SsoR} \qquad (5.4)$$

The effect of policy scenarios is estimated as the difference between the FAR of the baseline model and FAR of the scenario model.

5.2.8 Model Validation

The inseparability of the model and its purpose induces a partial, subjective model validation process (Barlas, 1996). Although statistical significance tests are well established and used in the empirical analysis, they are inappropriate for system dynamics models because data generated by such models are cross-correlated and autocorrelated (Barlas, 1996; Senge & Forrester, 1980).

Following the logical sequence of model validation suggested by Barlas (1996), two validation tests were conducted before analysing the behavioural patterns in the simulated results. First, the empirical structure test was conducted by comparing the model structure with information retrieved from journal articles on cocoa production, processing, and trading. Information on these activities were also elicited from chain actors via focus group discussions with farmers and expert elicitation with processors and COCOBOD officers.

Second, the model was subjected to a structure-oriented behaviour test. Pre-harvest extreme-condition test was conducted by altering the farm size to zero because it influences the number of cocoa trees in the value chain. Also, the model was subjected to postharvest extreme-condition test by altering the weight of beans in a pod to zero. The first extreme condition tests resulted in a non-occurrence of production activities because no farm exists. The second test resulted in zero processed cocoa beans.

Despite the restriction of statistical significance test in SDM, a statistical significance test can serve a supplementary purpose (Senge & Forrester, 1980), by testing the prediction accuracy of system dynamic models (Barlas, 1996). Therefore, model behaviour was validated using the statistical metrics; Mean Absolute Percentage Error (MAPE) and Theil inequalities (Theil U) and comparative statistic (Sterman et al., 2013; Sücüllü & Yücel, 2014). These measures were used to compare the forecasted and real-world outcomes. The comparison is drawn between forecasted and historical data on cocoa production figures in Ghana retrieved from ICCO's annual report from 2005 - 2015. The Theil U statistic bounds between 0 and 1, where 0 means the forecast is equal to the actual data (perfect forecast), and 1 when the standard error of the model forecasts and a naïve (no change) extrapolation are the same (Bliemel, 1973). Theil U is expressed as:

$$Theil\ U = \sum_{t=1}^{n} = [\frac{(F_t - A_t)^{1/2}}{{A_t}^{1/2}}] \qquad (5.5)$$

MAPE indicates the percentage error in the model prediction, and is expressed as:

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}[\frac{(A_t - F_t)}{A_t}] \qquad (5.6)$$

Where A_t *and* F_t represent the actual cocoa production figures and model estimation respectively. The model produced MAPE of less than 30% and a Theil U less than 0.3, which indicate that the model behaviour is an acceptable replication of reality. The statistic measures and a comparative graph of the model behaviour and actual behaviour are presented in Table 11 and Figure 19, respectively.

Table 11 Statistic measures for model behavioural validity

	Actual	Model	Difference	% Error
Comparative stats				
Mean (kg)	740,100,000	821,678,200	81,578,200	11.022
Single stats				
MAPE		0.1943		
Theil U		0.2071		
Transient part				
Maximum (kg)	1,025,000,000	988,956,000	-36,044,000	3.52
Minimum (kg)	614,000,000	668,443,000	54,443,000	8.87

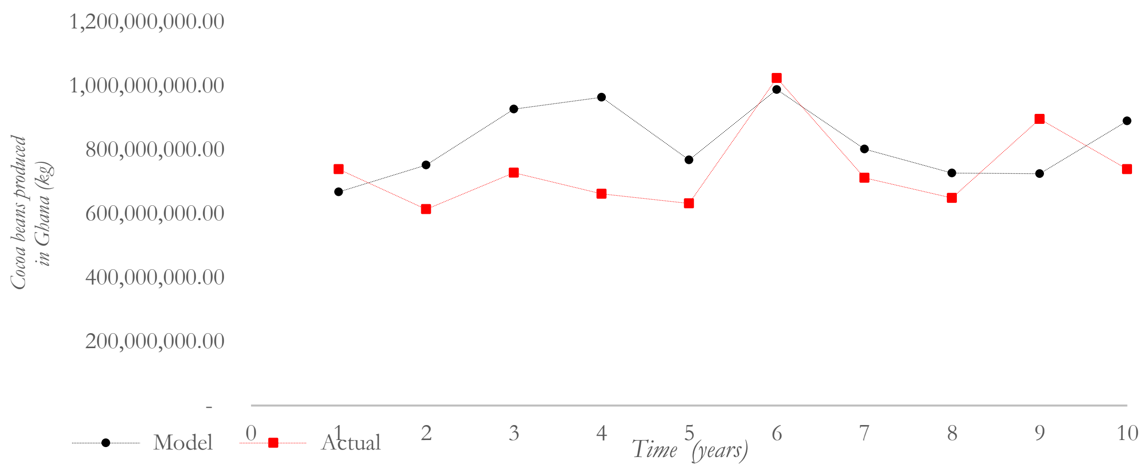


Figure 19 A comparison of Ghana's historical cocoa production and the predicted figures

5.2.9 Scenario Construction

The scenarios examined in this paper are based on an intuitive iteration by stakeholders and simulated outcome from the system dynamics (SD) model. Potential shocks were elicited from chain actors via focus group discussions with cocoa farmers in five cocoa growing regions in Ghana and individual interviews with industry experts from the Ghana Cocoa Authority. Participants of the focus group discussions were selected using a multistage sampling technique. The cocoa-growing regions are Western North, Western, Volta, Central, and Ashanti Regions. Districts with the highest cocoa production figures were selected in each cocoa-growing region. With the support from COCOBOD district officers, ten farmers were selected from the zonal areas in each district that have the highest cocoa production figures.

The counterfactual relationship of parameters in the cocoa value chain that act as precursors of vulnerability was identified from the SD model of Ghana's cocoa value chain (Aboah et al., 2019b). Volatile cocoa prices and withdrawal of government subsidies were the two shocks highlighted from the focus groups and interviews that are consistent with results obtained from the SD model. The shocks selected for scenario construction include increased cocoa beans export from Ghana, decreased percentage of cocoa beans from in-country processing in Ghana, and increased switching rate.

Two forms of market liberalisation are considered in this paper: *(i)* partially liberalised market, as is currently practised in Ghana's cocoa sector, and *(ii)* fully liberalised market. Under the partially liberalised market, the government provides farmers with input subsidies and withdraws some percentage of world cocoa prices as an industry, marketing, and administrative cost. The effect of a gradual increase in the volumes of cocoa beans exported outside Ghana as collateral for loans and the consequential decrease in allocated cocoa beans for in-country processing on aggregate resilience is examined under the partially liberalised market.

The fully liberalised market scenario involves no subsidies and full world price transmission to farmers. Under the fully liberalised market arrangement, this paper explores how the removal of the government's input subsidies and farmers' response by decreasing the adoption of farm management practices affect the aggregate resilience level. The focal parameters in each scenario are altered in two levels: 5% and 10%. Three scenarios are considered in this study. These scenarios are presented in Table 12.

Table 12 Scenarios examined in this study

Scenario	*Parameters that are changed*
Scenario 1 Collateralisation of cocoa exports in a partially liberalised domestic commodity market	Allocated percentage for in-country processing in Ghana decreases Ghana export rate increases Government subsidies are provided Producer price is FOB price less Industry cost
Scenario 2: Fully liberalised domestic commodity market	Allocated percentage for in-country processing in Ghana increases Ghana export rate decreases Government subsidies are not provided Producer price is equal to FOB price
Scenario 3: Exodus from Cocoa Farming in a fully liberalised domestic commodity market	Allocated percentage for in-country processing in Ghana increases Ghana export rate decreases Government subsidies are not provided Producer price is equal to FOB price Switching-out rate increases

5.3 Results and Discussions

Before assessing the results of the effect of market liberalisation on aggregate resilience, the key feedback loops that influence the dynamic behaviour in the model were examined. Stella Architect® software facilitates the identification and synthesis of the dominant loops driving dynamic behaviour in the model. A summary of the key feedback loops and their loop scores is presented in Table 13.

Results reveal nine significant feedback loops. Out of these, four are reinforcing loops, and five are balancing loops. Dominant feedback loops explain at least 50% of the changes in the dynamic behaviour (Schoenberg, Davidsen, & Eberlein, 2020). Results in Table 13 indicate that three feedback loops (R1, B1, and B2) explain a cumulative 95% of the changes in the model's behaviour; the reinforcing loop contributed 56% of those changes.

The dynamic behaviour generated by the model centres around the global cocoa price, demand, and supply. The dominant feedback loops are illustrated as a causal loop diagram in Figure 20. The reinforcing feedback loop (R1) shows that an increase in the demand causes global cocoa prices to increase. An increase in global cocoa prices influences supplies from cocoa-producing countries and the sales to increase. However, the presence of the balancing feedback (B5) prevents the global cocoa price from increasing in perpetuity. As the global cocoa price increase, the change between the desired price in a succeeding cropping year and the global price in the previous cropping year decrease. This, in turn, causes the global cocoa price decreases.

From the ICCO's annual cocoa reports published between 1998 and 2015, the cocoa sector has not experienced an increase in global cocoa price for more than three consecutive years. This phenomenon can be attributed to the presence of the dominant balancing loops. The balancing feedback loop (B2) shows the contribution of the increased cocoa supply on the inventory levels and ultimately, the global price.

Table 13 Analysis of the dominant loops in the model

	Feedback loop	Stocks	variables	Final loop score	Average loop score	Causal loop
1	R1	3	11	55.67%	57.51%	change in smooth (in macro) → Smoothed Input (in macro) → Demand → Sales → Inventory →Inventory ratio →Effect on price →Desired Price → Change in price → Global Cocoa Price → input (in macro)
2	B1	2	8	-34.39%	-21.69%	Desired Price → Change in price → Global Cocoa Price → Demand → Sales → Inventory → Inventory ratio → Effect on price → Desired Price
3	B2	2	8	-8.97%	-18.82%	Desired Price → Change in price → Global Cocoa Price → Cocoa beans rest of the world → World cocoa supply → Inventory →Inventory ratio →Effect on price → Desired Price
4	B3	3	11	-0.46%	-1.04%	change in smooth (in macro) →Smoothed Input (in macro) → Cote d Ivoire supply → World cocoa supply → Inventory → Inventory ratio → Effect on price → Desired Price → Change in price → Global Cocoa Price →input (in macro)
5	R2	2	8	0.29%	0.57%	Desired Price → Change in price → Global Cocoa Price → Cote d Ivoire supply → World cocoa supply → Inventory →Inventory ratio → Effect on price → Desired Price
6	R3	2	10	0.08%	0.12%	change in smooth (in macro) →Smoothed Input (in macro) → Demand →Desired inventory → Inventory ratio → Effect on price → Desired Price → Change in price → Global Cocoa Price → input (in macro)
7	B4	1	7	-0.05%	-0.09%	Desired Price → Change in price → Global Cocoa Price → Demand → Desired inventory → Inventory ratio → Effect on price→ Desired Price
8	B5	1	2	-0.05%	-0.08%	Global Cocoa Price → Change in price→ Global Cocoa Price
9	R4	1	3	0.05%	0.08%	Desired Price → Change in price → Global Cocoa Price→ Desired Price

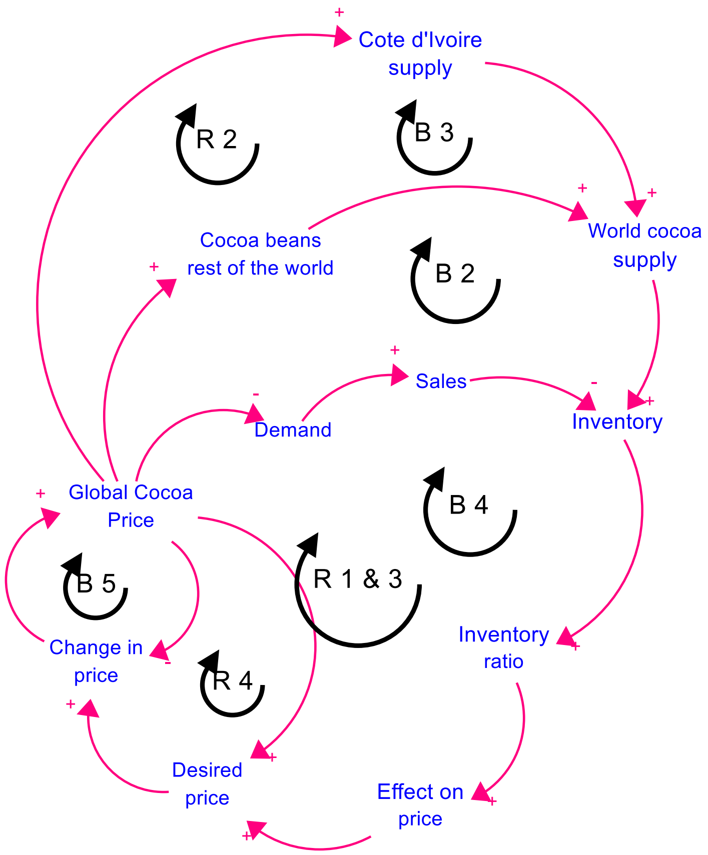


Figure 20 A causal loop diagram of the dominant feedback loops

The balancing feedback loop (B3) highlights the prominence of cocoa supply from Cote d'Ivoire as a driver of global cocoa price. B3 shows how an increase (decrease) in cocoa supply from Cote d'Ivoire influence changes in the world cocoa supply to balance and decrease (increase) the global price caused by R1. The dominant balancing feedback loops (B1 and B2) driving the dynamic behaviour affirms the significant impact of demand from downstream actors (buyers and processors outside cocoa-producing countries) to the global cocoa price.

The trend analysis in Figure 21 shows that at the onset of the simulation, B1 and B2 drive the dynamic behaviour of the model; R1 takes over the dominance after the third year. The trend shows that the periods of R1 dominance are interspersed with short period of dominance by B2. The interspersions occur in the 4th, 9th and 14th year. B1 and B2 regain dominance between the 15th and 17th year. Comparatively, the demand for cocoa beans has a higher influence than the supply.

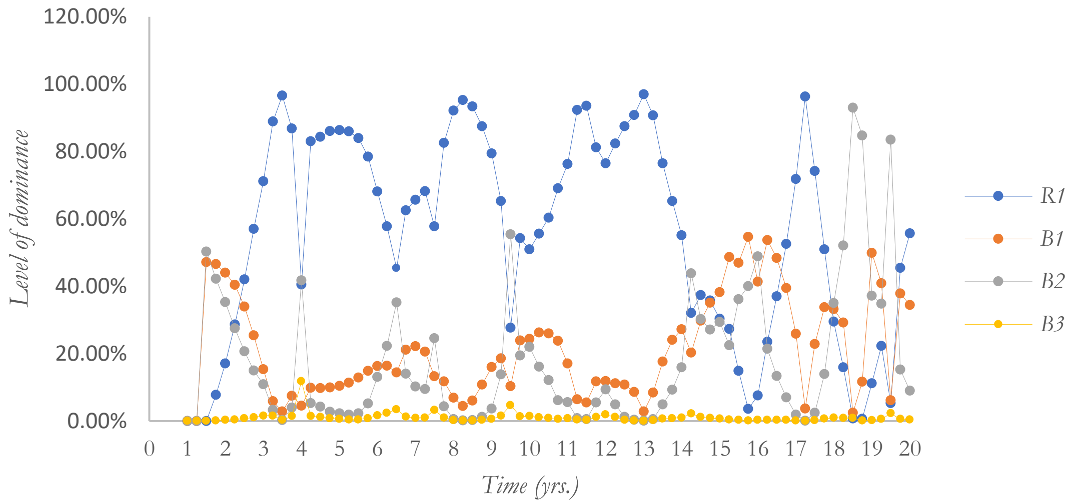


Figure 21 Trend of the dominance level of the feedback loop

5.3.1 Baseline Resilience Level

The baseline model was simulated with a primary focus on the resilience metric, Farm Adaptive Ratio (FAR). The FAR ranges from 0 to 1; closer values to 0 and 1 implying retention and loss of the system's state of resilience, respectively. The resilience state of the baseline model (Figure 22) shows a significantly stable state of socioecological resilience of Ghana's cocoa value chain. The cocoa value chain begins with a resilient state until the 13th year, and gradually loses resiliency with the peak loss being in the 15th year. The chain regains resiliency gradually until the 20th year because there is no loss in the volumes of cocoa beans produced and transacted through the chain in successive years after the peak loss.

The baseline results show that on an aggregate level, there is a loss in the raw material (cocoa beans) produced by farmers in 9.5 out of 20 years. There are gains in 9 out of 20 years and 0.75 years of stable cocoa production. Similarly, the raw materials that flow to in-country processors and exporters have the same timeframe of loss, gains and stability. Results of the baseline model suggest that the chain actors' decisions under the current partially liberalised market do not contribute significantly to the loss of resilience.

In the short-term, farmers do not switch-out from cocoa farming but resort to reducing farm maintenance costs, which causes marginal changes in the volumes of cocoa beans produced and transacted in the chain. FAR is estimated based on the volumes of cocoa beans loss for five years. Therefore, substantial losses in the cocoa beans produced are not recorded for the first twelve years. Such insubstantial losses keep the FAR reasonably stable. However, the continuous decline of aggregate cocoa bean production from the 12th to the 16th year causes a decrease in FAR between these periods. Within the same timeframe, the cocoa value chain experiences a continuous decline in global cocoa price from the 12th year to the 15th year.

A decline in global cocoa price coupled with the decreased cocoa production at the farm-level will translate into the decreased on-farm margin, decrease farm management practices and an increase in switch-out rate. However, given that the average cocoa production for the entire period is 777,779,667 kg, the highest loss in the FAR translates into only a 1.4% loss in average cocoa production figures at an aggregate level.

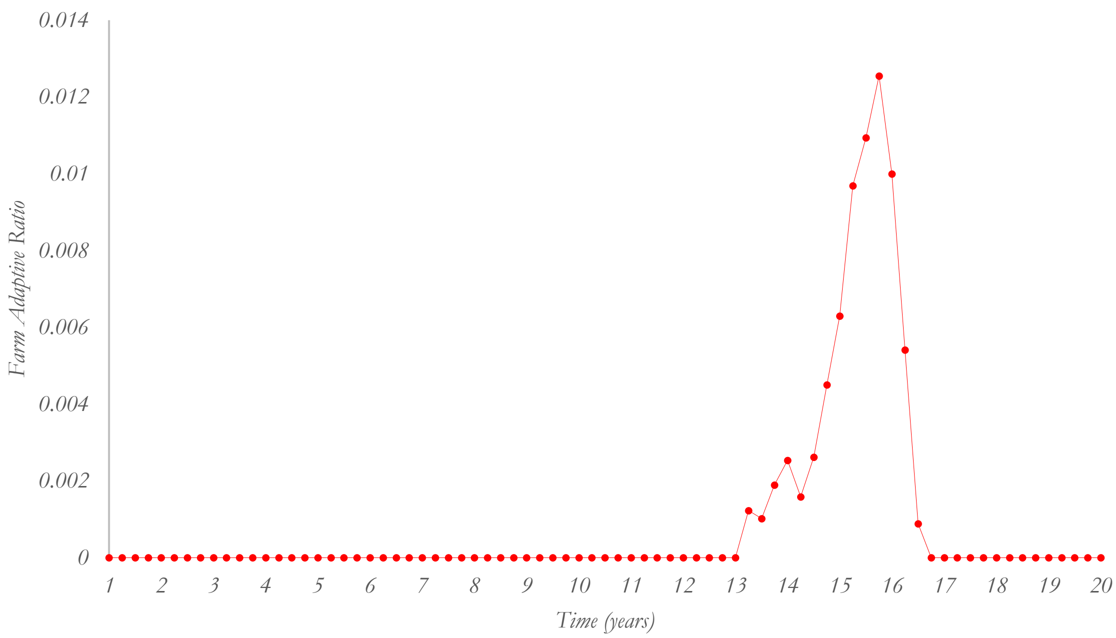


Figure 22 Resilience patterns of the baseline model

5.3.2 Effect of Policy Scenarios on Resilience Level

The resilience levels of the three policy scenarios are compared with the baseline level to determine the effect of the scenario on the aggregate resilience. Generally, the magnitude of changes in the FAR translates into unsubstantial loss and gains in aggregate cocoa production figures. Therefore, the periods of loss and gains in the FAR give a better perspective of how stable the cocoa value chain is under each scenario.

Scenario 1 *(collateralisation of cocoa exports in a partially liberalised market)* resulted in no change in the baseline resilience level, as shown in Figure 23. The top graphs in the figure represent the resilience level, and the bottom graphs represent the effect of the scenario. The graphs labelled "A" and "B" represent 5% and 10% alteration of the focal parameters, respectively. The parameter changes in the global supply from collateralisation specified in the scenario is relatively small, and the global price is relatively unresponsive to such small changes in supply.

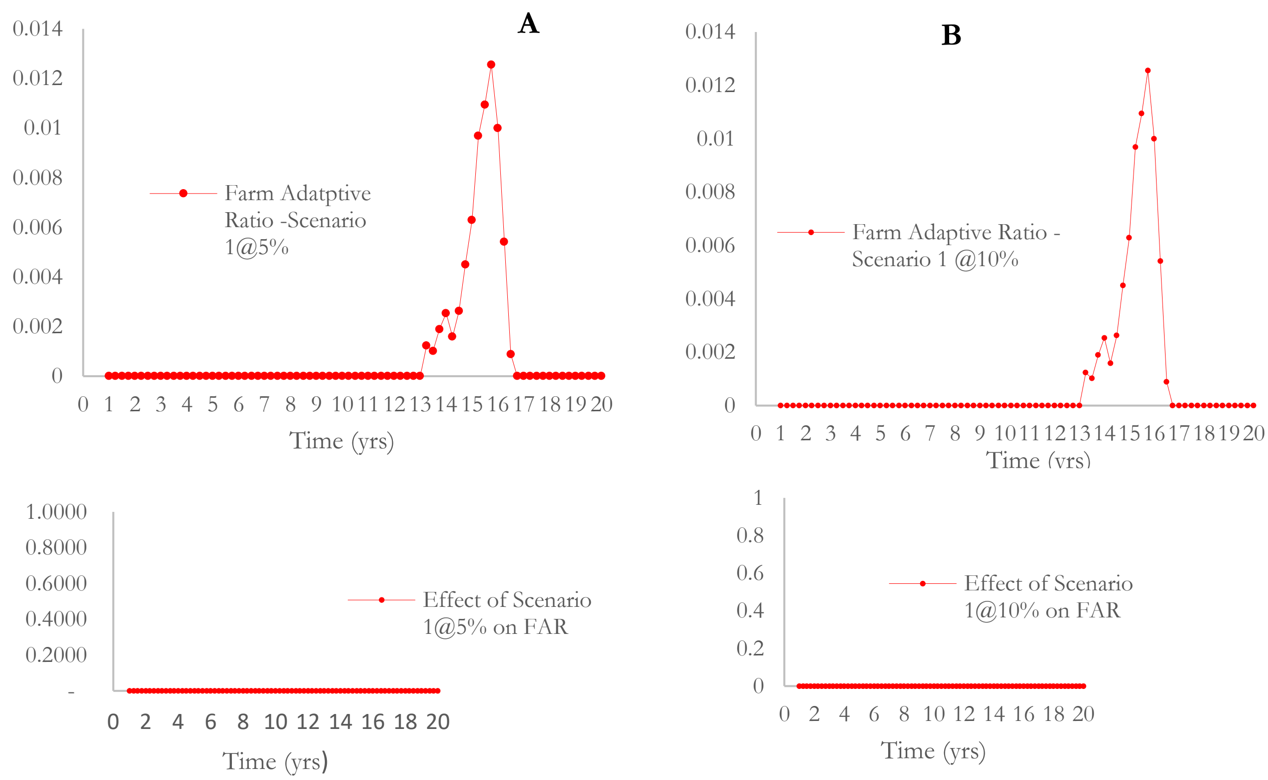


Figure 23 Resilience pattern and the effect of scenario 1

The Government of Ghana often uses export sales of cocoa beans as collateral to secure syndicated loans. The financing of the Bui hydroelectric dam project in Ghana by the Chinese government using cocoa export sales (30,000 metric tonnes per year, representing 4% of average cocoa production) over five years as a repayment mechanism is an example (Odoom, 2017). Results of scenario 1 suggest that the current percentage of annual cocoa production that the government allocates as collateral of cocoa beans exports to secure loans do not have a negative effect on the aggregate resilience of the cocoa value chain.

The recorded period of losses in the baseline translated into some gains under the fully liberalised market (scenario 2), as shown in Figure 24. The fully liberalised market also resulted in increased stability in resilience level (i.e., 15.75 years) when farmers do not switch-out from cocoa farming. Within each scenario, the transition from a lower resilience level (i.e., higher FAR) to a higher resilience level (i.e., smaller FAR) is considered as gains. Therefore, within scenario 2, the pattern of resilience shows a 2.5-year increase in resilience level; 1.75 years and 15 years loss and stability in resilience level, respectively.

Compared with the baseline level, an increased switch-out rate under a fully liberalised market results in a loss in resilience level (Figure 25). The findings corroborate with conclusions drawn by Aboah et al. (2019b) that decreasing cocoa farmer population is an important precursor of vulnerability in the cocoa value chain. The switching out of *non-adopters* may be a riddance of inefficient farmers in the cocoa value chain, which can improve the resilience of the cocoa value chain when the remaining efficient farmers increase production. However, the persistent constraint of access to farmland means that farmers switching out from cocoa production to other non-farming activities like gold mining will negatively impact the resilience of the cocoa value chain, since efficient farmers will not be able to expand their farms.

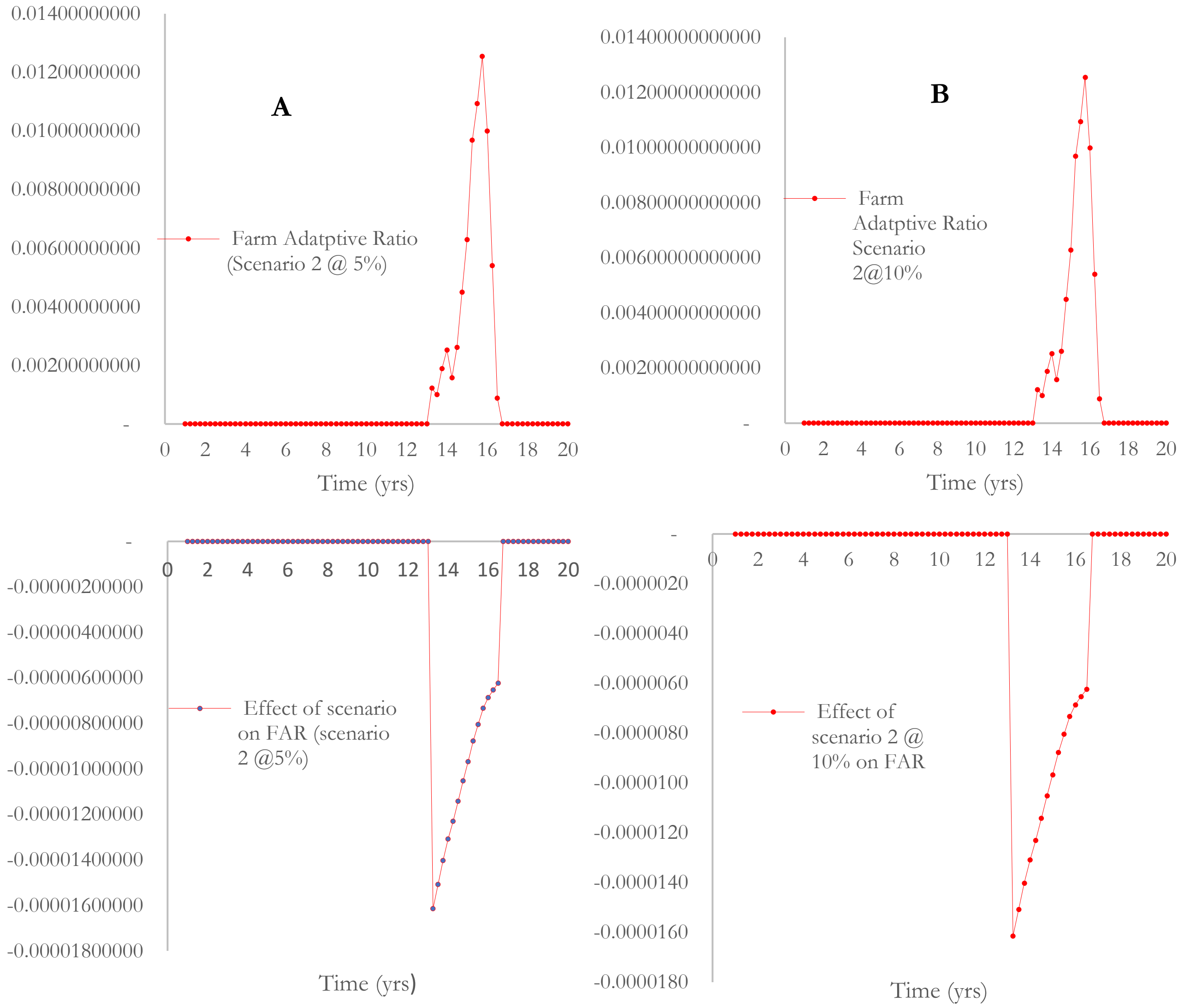


Figure 24 Resilience pattern and the effect of scenario 2

The within-scenario analysis shows that the cocoa value chain makes steady gains in the resilience level, despite the resilience level being lower than the baseline level. Given that cocoa farmers are autonomous, they can switch-out as a means of diversifying their income. Income diversification is continually being used as a risk mitigation measure by rural households in Ghana. Although at the individual producer-level switching-out from cocoa production into non-farming activities may lead to improved household income, the decision is detrimental to the cocoa value chain at an aggregate level (Aboah et al., 2019a).

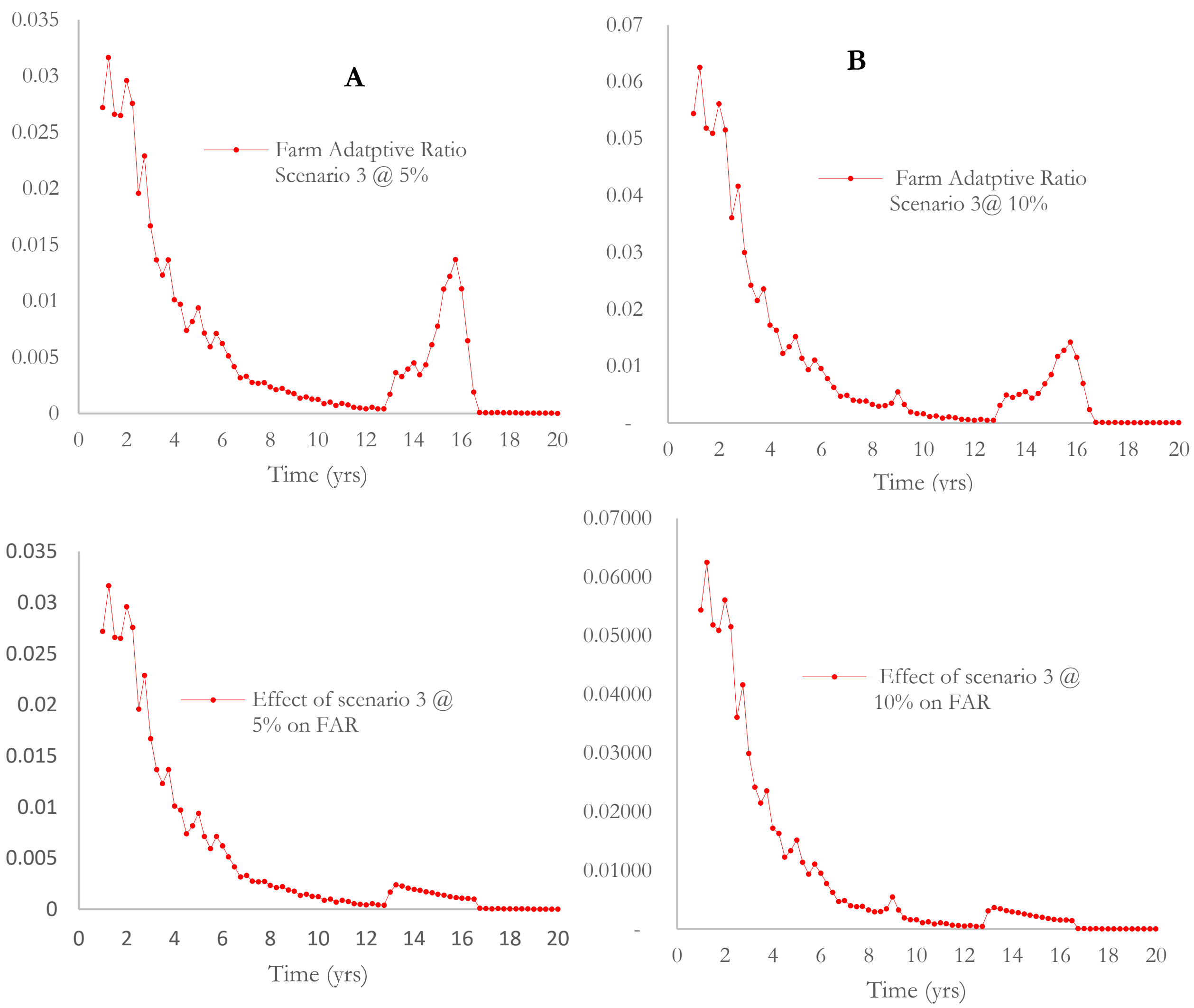


Figure 25 Resilience pattern and the effect of scenario 3

Cocoa producing regions in Ghana are also gold mining regions. Hence, there is a continuous competition between the two income generation activities, and the tendency for farmers to switch-out partially or completely from cocoa farming into gold mining or other non-farm activities exists (Hilson & Garforth, 2013; Snapir, Simms, & Waine, 2017).

The phenomenon of cocoa farmers switching-out may be linked to the informal land tenure system. Sharecropping system of cocoa production is liable to increase switch-out rate, as landowners and custodians (sometimes chiefs) can sell farmlands to small-scale miners with or without the consent of cocoa farmers (Hausermann et al., 2018). Results suggest that engagement in non-farm activities that do not lead to farmers switching-out is complementary and can sustain the resilience of the cocoa value chain (Snapir, Simms, & Waine, 2017) as evidenced by scenario 1 and 2.

5.3.3 Practical Implication for Chain Actors

Table 14 shows the detailed results of the effect of each policy scenario on raw materials flow in the cocoa value chain. The partially liberalised market (scenario 1) is characterised by a reasonably stable supply of cocoa beans from producers. Compared with the baseline level, a 5% to 10% decrease in the percentage of cocoa beans allocated for in-country processing in a partially liberalised market result in no changes in the cocoa production levels.

In-country processors are the losers under scenario 1, losing 4.6% and 9.3% of the average cocoa beans (raw materials) for a 5% and 10% decrease in the local processing allocation, respectively. Exporters are the most advantaged under such market arrangement. Results suggest that the government's strategy on collateralisation of cocoa beans exports (i.e., increasing export by $\leq$10% of cocoa production) to secure loans might not have a negative effect on cocoa production. However, the government's subsidies to cocoa farmers are crucial to sustaining farmers' interest in cocoa production.

Scenario 2 involves a transition from a partially liberalised market to the fully liberalised market. The transition involves eliminating the proportion of global cocoa price that is used for industry, marketing and administrative cost, and the government's subsidies to farmers. The fully liberalised market is characterised by short periods of fluctuations in the gains and losses of the raw materials produced at an aggregate level. The duration of loss for cocoa producers and in-country processors is 14.75 years.

Table 14 Summary results of scenario analyses

Indicator	Baseline	Scenario 1-5%	Scenario 1 -10%	Scenario 2 -5%	Scenario 2 -10%	Scenario 3 - 5%	Scenario 3 - 10%
Periods of loss in resiliency (yrs.)	2.50	-	-	-	-	19.25	19.25
Periods of gains in resiliency (yrs.)	1.75	-	-	3.50	3.50	-	-
Periods of stability in resiliency (yrs.)	15.00	19.25	19.25	15.75	15.75	-	-
Practical implication (Effect on cocoa farmers)							
Mean difference in aggregate cocoa production (kg)	13,577,591	13,577,591	13,577,591	13,577,324	13,577,324	10,895,490	8,861,248
Mean difference in aggregate cocoa production (%)		-	-	- 0.002	- 0.0020	- 19.75	- 34.74
Period of loss (yrs.)	9.50	-	-	14.75	14.75	14.75	14.75
Period of gains (yrs.)	9.00	-	-	4.50	4.50	4.50	4.50
Period of stability (yrs.)	0.75	19.25	19.25	-	-	-	-
Practical implication (Effect on in-country processor)							
Mean difference in supply (kg)	2,744,710	2,617,657	2,490,605	2,871,705	2,998,755	2,304,477	1,957,139
Mean difference in supply (%)		- 4.63	- 9.26	4.63	9.26	-16.04	- 28.69
Period of loss (yrs.)	9.50	14.75	14.75	14.75	14.75	14.75	14.75
Period of gains (yrs.)	9.00	3.75	4.50	4.50	4.50	4.50	4.50
Period of stability (yrs.)	0.75	0.75	-	-	-	-	-
Practical implication (Effect on Exporter)							
Mean difference in supply (kg)	10,832,881	10,959,933	11,086,985	10,705,618	10,578,568	8,591,012	6,904,108
Mean difference in supply (%)		1.17	2.35	- 1.17	- 2.35	- 20.70	- 36.27
Period of loss (yrs.)	9.50	3.75	3.75	14.50	14.75	18.25	18.00
Period of gains (yrs.)	9.00	14.75	14.75	4.00	3.75	0.25	0.50
Period of stability (yrs.)	0.75	0.75	0.75	0.75	0.75	0.75	0.75

However, while producers lose less than 0.01% of their baseline production level, in-country processors gain 5% and 9.3% of their baseline stock level for a 5% and 10% increase in the raw material allocation for in-country processing, respectively. On average, full liberalisation (scenario

3) results in 87% and 15% increase in the baseline farm margin level of *adopters* and *non-adopters,* respectively. Thus, although producers will lose subsidies under the full liberalisations, the producers are financially better off. Details of the differences in the farm margins for each scenario is shown in Appendix 5.2.

Exporters will be the worst affected when the government's allocation for local processing increases and the farmer switching-out rate rises under a fully liberalised market. Among the three chain actors, in-country processors are the least affected under a fully liberalised market, since the government increases the percentage of raw materials allocated for local processing.

According to Humphrey and Schmitz (2001), market liberalisation can be beneficial to developing countries if these countries can export products for which they have a comparative advantage. However, pursuing an export-oriented trade arrangement focusing on raw materials is accompanied by the trade-off of losing potential benefits attainable via value addition. Beyond the upstream end of the value chain, forward integration is a way to increase competitiveness and income for developing countries (Humphrey & Schmitz, 2001).

From the findings, presented here, it is evident that the existing partially liberalised market offers a viable form of governance of the cocoa value chain. Given the market power dynamics, the involvement of the government as a chain actor and market regulator promotes farm management practices. It prevents a transition of the cocoa value chain into a captive value chain (Gereffi, Humphrey, & Sturgeon, 2005). The government's role in determining producer price shows that the quasi-hierarchical governance of the cocoa value chain can be another form of the captive value chain. In this case, rents are captured not by a transnational cocoa-processing firm but the government. Thus, the government act as a market balancer and bottleneck (Laven, 2011).

A fully liberalised market can improve the resilience of the cocoa value chain under two conditions: *(i)* when a fully liberalised arrangement is advanced alongside the pursuit of vertical integration via in-country processing to limit the oligopsony power from buyers (processors) outside the country (Sexton et al., 2007); and *(ii)* when a fully liberalised arrangement is accompanied with intentional interventions to boost on-farm investment, improve efficiency at the farm-level and prevent farmers from switching-out of cocoa farming. However, the structure of these arrangements with an emphasis on government's role will determine the extent of liberalisation. Also, analyses of the cost implications and the benefits accruable from these arrangements are vital factors that can influence resilience.

5.4 Conclusion

This paper explored *ex-ante* the effect of three policy scenarios involving altered in-country trading regulations due to market liberalisation on the socioecological resilience of the cocoa value chain. The findings suggest that the collateralisation of cocoa beans, resulting in increased cocoa beans export by ≤ 10%, under a partially liberalised market is marked by stable aggregate socioecological resilience and cocoa production levels.

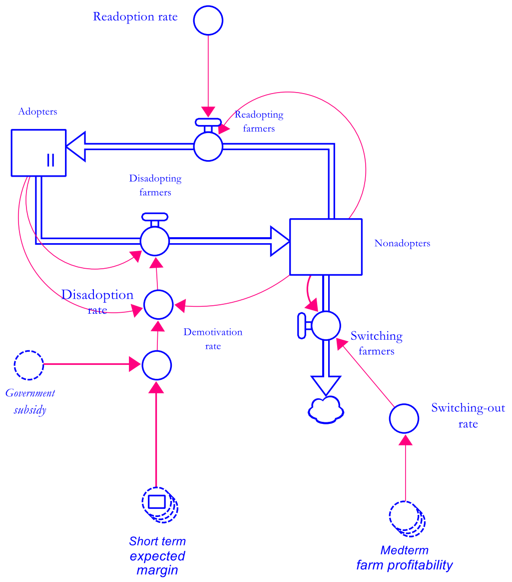
The transition from a partially liberalised market to a fully liberalised market increases the risk associated with global price fluctuations. In the quest to mitigate the risk, cocoa farmers either switch out of cocoa production or reduce their farm management expenses. These limit the average volumes of cocoa production under the fully liberalised domestic market. Hence, a fully liberalised market arrangement will reinforce aggregate resilience of the cocoa value chain when; *(i)* more cocoa farmers are efficient and practice farm management practices, and *(ii)* cocoa farmers remain in cocoa production.

Despite it being a viable arrangement, the current partially liberalised market can enhance the resilience of the cocoa value chain when the government limits the deductions on producer price for administrative and marketing purposes and provides incentives that can stimulate price competition among licensed buying companies. An exploration of the effect of tax policies on the resilience of the cocoa value chain is a potential future research.

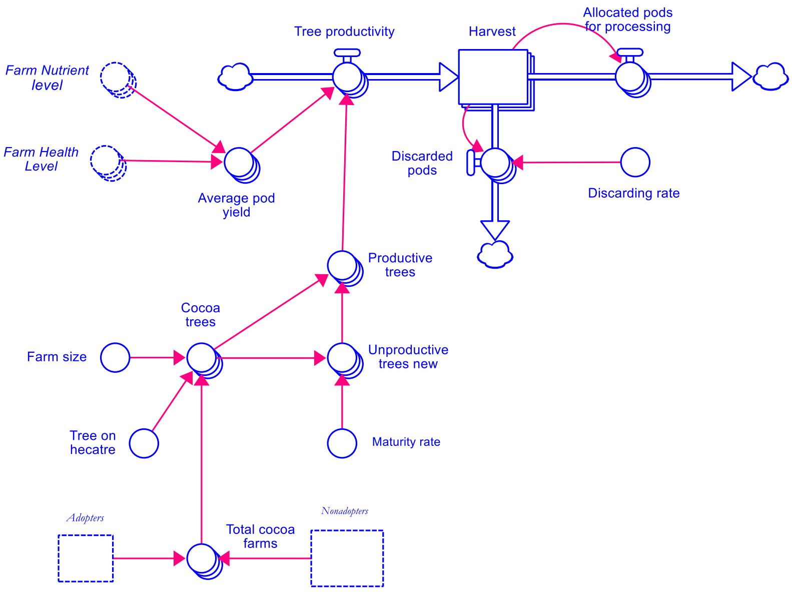
The findings show that exporters are the least affected chain actors when the government decreases raw material allocation for local processing. In-country processors and cocoa farmers are the least affected under a fully liberalised market when the government focuses on in-country cocoa processing. Thus, there is a need to harmonise the objectives of pursuing market liberalisation and forward integration of the cocoa value chain and the trade-offs of the harmonisation.

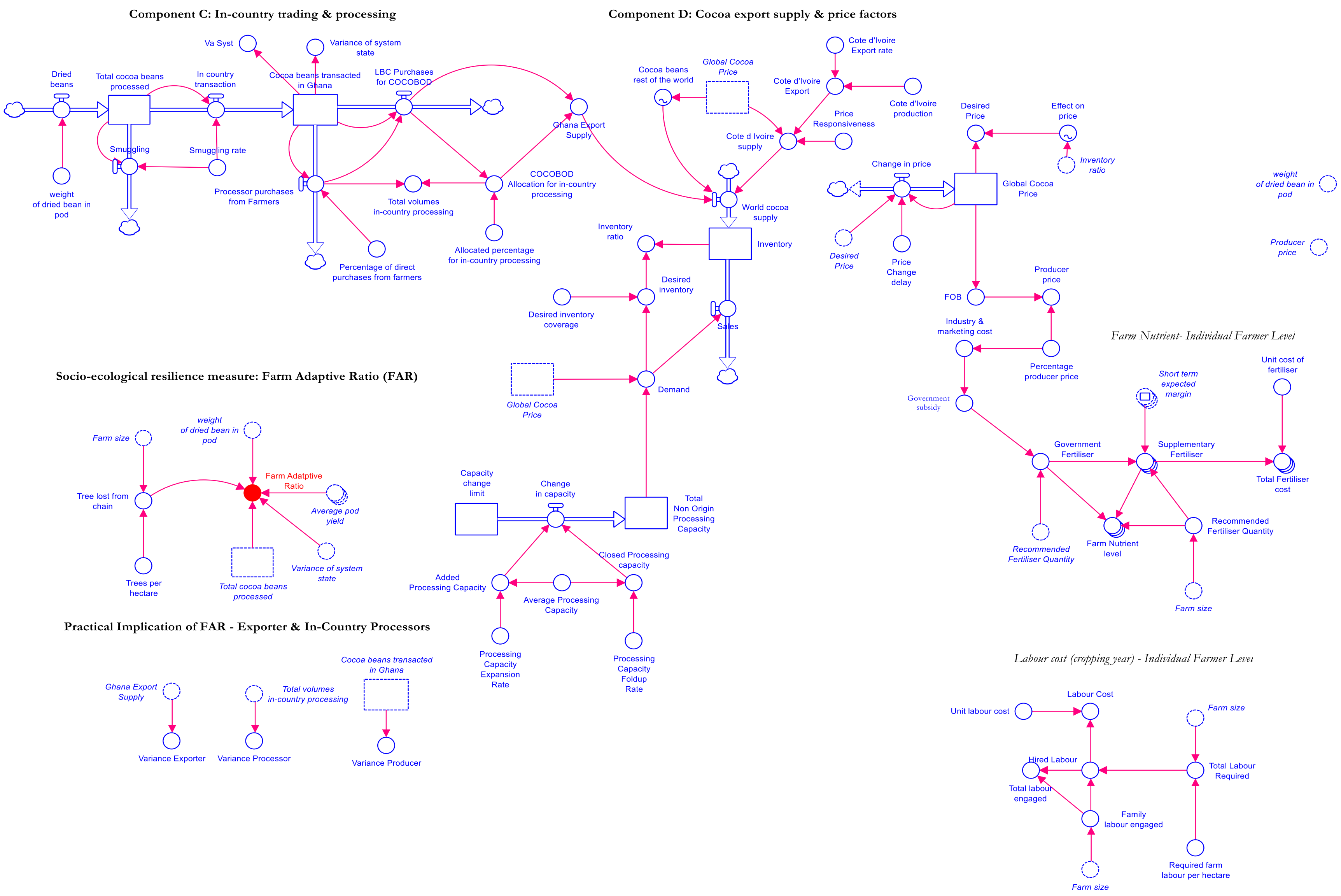
Appendix 5.0

Component A: Adoption of good agricultural practices - Aggregate level

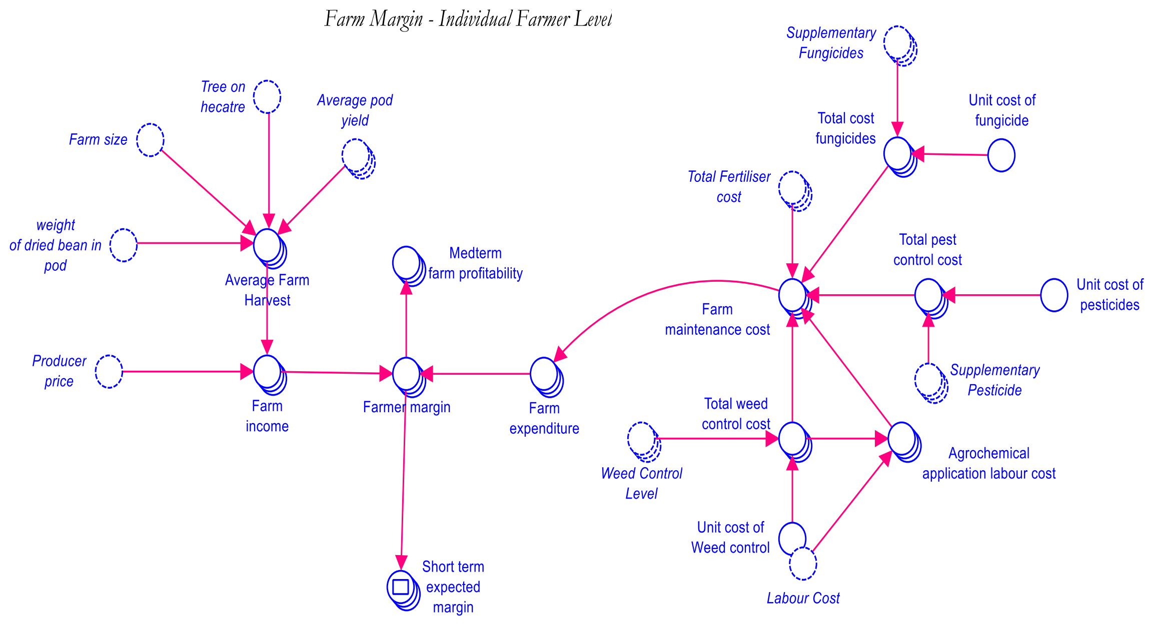


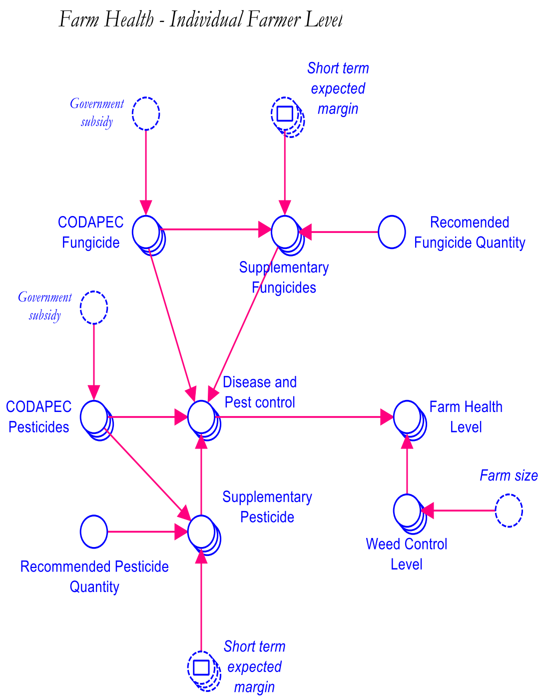
Component B: On-farm production & processing - Aggregate level




Component C: In-country trading & processing
Va Syst
Variance of system state
Dried beans
Total cocoa beans processed
In country transaction
Cocoa beans transacted in Ghana
LBC Purchases for COCOBOD
Ghana Export Supply
Smuggling
Smuggling rate
weight of dried bean in pod
Processor purchases from Farmers
Total volumes in-country processing
COCOBOD Allocation for in-country processing
Allocated percentage for in-country processing
Percentage of direct purchases from farmers
Component D: Cocoa export supply & price factors
Cote d'Ivoire Export rate
Global Cocoa Price
Cocoa beans rest of the world
Cote d'Ivoire Export
Cote d'Ivoire production
Price Responsiveness
Cote d Ivoire supply
World cocoa supply
Inventory
Inventory ratio
Desired inventory
Desired inventory coverage
Sales
Demand
Desired Price
Effect on price
Inventory ratio
Change in price
Global Cocoa Price
Desired Price
Price Change delay
FOB
Producer price
Industry & marketing cost
Percentage producer price
Government subsidy
weight of dried bean in pod
Producer price
Socio-ecological resilience measure: Farm Adaptive Ratio (FAR)
Farm size
weight of dried bean in pod
Farm Adatptive Ratio
Average pod yield
Tree lost from chain
Trees per hectare
Total cocoa beans processed
Variance of system state
Capacity change limit
Change in capacity
Total Non Origin Processing Capacity
Closed Processing capacity
Added Processing Capacity
Average Processing Capacity
Processing Capacity Expansion Rate
Processing Capacity Foldup Rate
Practical Implication of FAR - Exporter & In-Country Processors
Ghana Export Supply
Total volumes in-country processing
Cocoa beans transacted in Ghana
Variance Exporter
Variance Processor
Variance Producer
Farm Nutrient- Individual Farmer Level
Short term expected margin
Unit cost of fertiliser
Government Fertiliser
Supplementary Fertiliser
Total Fertiliser cost
Recommended Fertiliser Quantity
Farm Nutrient level
Recommended Fertiliser Quantity
Farm size
Labour cost (cropping year) - Individual Farmer Level
Labour Cost
Unit labour cost
Farm size
Hired Labour
Total labour engaged
Total Labour Required
Family labour engaged
Required farm labour per hectare
Farm size

Component E: Individual farmer level





Appendix 5.1

Equations of parameters in the SD model

Variables	Equation	Properties	Units	Annotation	Reference /Comment
Adopters(t)	Adopters (t - dt) + (Readopting_farmers - Disadopting_farmers) * dt	INIT Adopters = 228000	{farmers}	NON-NEGATIVE	Estimated based on adoption rate (Aneani et al., 2011a; Kongor et al., 2018) and farmer population. Farmer population is estimated based on the average cocoa production (from 2000-2015) and the average farm yield (Bymolt, Laven, Tyszler, 2018)
Capacity_change_limit(t)	Capacity_change_limit(t - dt) + (- Change_in_capacity) * dt	INIT Capacity_change_limit = Change_in_capacity	{kg/year}	NON-NEGATIVE	
Cocoa_beans_transacted_in_Ghana(t)	Cocoa_beans_transacted_in_Ghana(t - dt) + (In_country_transaction - Processor_purchases_from_Farmers - LBC_Purchases_for_COCOBOD) * dt	INIT Cocoa_beans_transacted_in_Ghana = In_country_transaction	{kg}	NON-NEGATIVE	
Global_Cocoa_Price(t)	Global_Cocoa_Price(t - dt) + (Change_in_price) * dt	INIT Global_Cocoa_Price = 2000	{USD/tonne}	NON-NEGATIVE	
Harvest [Farmer_type](t)	Harvest [Farmer_type](t - dt) + (Tree_productivity[Farmer_type] - Allocated_pods_for_processing[Farmer_type] - Discarded_pods[Farmer_type]) * dt	INIT Harvest [Farmer_type] = Tree_productivity	{pods}	NON-NEGATIVE	

Inventory(t)	Inventory (t - dt) + (World_cocoa_supply - Sales) * dt	INIT Inventory = Desired_inventory	{kg}	NON-NEGATIVE	
Nonadopters(t)	Nonadopters (t - dt) + (Disadopting_farmers - Readopting_farmers - Switching_farmers) * dt	INIT Nonadopters = 152000	{farmers}	NON-NEGATIVE	Estimated based on adoption rate (Aneani et al., 2011; Kongor et al., 2018) and farmer population. Farmer population is estimated based on the average cocoa production (from 2000-2015) and the average farm yield (Bymolt, Laven, Tyszler, 2018)
Total_cocoa_beans_processed(t)	Total_cocoa_beans_processed(t - dt) + (Dried_beans - In_country_transaction - Smuggling) * dt	INIT Total_cocoa_beans_processed = Dried_beans	{kg}	NON-NEGATIVE	
Total_Non_Origin_Processing_Capacity(t)	Total_Non_Origin_Processing_Capacity(t - dt) + (Change_in_capacity) * dt	INIT Total_Non_Origin_Processing_Capacity = 3452111000 + Added_Processing_Capacity - Closed_Processing_capacity	{kg}	NON-NEGATIVE	ICCO Annual Cocoa Report [+]
Allocated_pods_for_processing[Farmer_type]	Harvest	OUTFLOW PRIORITY: 1	{pods}	UNIFLOW	
Change_in_capacity	Added_Processing_Capacity - Closed_Processing_capacity		{kg/year}	UNIFLOW	
Change_in_price	(Desired_Price - Global_Cocoa_Price)/Price_Change_delay		{USD/tonnes}		

Disadopting_farmers	Adopters*Disadoption_rate		{farmers}	UNIFLOW	
Discarded_pods[Farmer_type]	Discarding_rate*Harvest	OUTFLOW PRIORITY: 2	{pods}	UNIFLOW	
Dried_beans	SUM(Allocated_pods_for_processing)*weight_of_dried_bean_in_pod		{kg}	UNIFLOW	
In_country_transaction	Total_cocoa_beans_processed *(1-Smuggling_rate)	OUTFLOW PRIORITY: 1	{kg}	UNIFLOW	
LBC_Purchases_for_COCOBOD	Cocoa_beans_transacted_in_Ghana-Processor_purchases_from_Farmers	OUTFLOW PRIORITY: 2	{kg}	UNIFLOW	
Processor_purchases_from_Farmers	Percentage_of_direct_purchases_from_farmers*Cocoa_beans_transacted_in_Ghana	OUTFLOW PRIORITY: 1	{kg}	UNIFLOW	
Readopting_farmers	Nonadopters*Readoption_rate	OUTFLOW PRIORITY: 1	{farmers}	UNIFLOW	
Sales	Demand		{kg}	UNIFLOW	ICCO Annual Cocoa Report
Smuggling	Smuggling_rate*Total_cocoa_beans_processed	OUTFLOW PRIORITY: 2	{kg}	UNIFLOW	Smuggling rate (less than 1% is assumed)
Switching_farmers	Nonadopters*"Switching-out_rate"	OUTFLOW PRIORITY: 2	{farmers}	UNIFLOW	
Tree_productivity[Adopters]	(Productive_trees[Adopters]*Average_pod_yield[Adopters])		{pods}	UNIFLOW	
Tree_productivity[Nonadopters]	(Productive_trees[Nonadopters] * Average_pod_yield[Nonadopters])		{pods}		
World_cocoa_supply	Ghana_Export_Supply+Cocoa_beans_rest_of_the_world+Cote_d_Ivoire_supply		{kg}	UNIFLOW	
Added_Processing_Capacity	Average_Processing_Capacity*Processing_Capacity_Expansion_Rate		{kg}		

Agrochemical_application_labour_cost[Adopters]	Labour_Cost -Total_weed_control_cost[Adopters]	{USD}	
Agrochemical_application_labour_cost[Nonadopters]	Labour_Cost - Total_weed_control_cost[Nonadopters]	{USD}	
"Allocated_percentage_for_in-country_processing"	0.19	{percent}	ICCO Annual Cocoa Report
Average_Farm_Harvest[Adopters]	weight_of_dried_bean_in_pod*Farm_size*Tree_on_hecatre*Average_pod_yield[Adopters]	{kg}	
Average_Farm_Harvest[Nonadopters]	weight_of_dried_bean_in_pod*Farm_size*Tree_on_hecatre*Average_pod_yield[Nonadopters]	{kg}	
Average_pod_yield[Adopters]	IF((Farm_Nutrient_level[Adopters]= 2) AND(Farm_Health_Level[Adopters] = 2)) THEN 25 ELSE (TRIANGULAR(15, 20, 23, 100))	{pods}	Asare & David, 2010
Average_pod_yield[Nonadopters]	IF((Farm_Nutrient_level[Nonadopters]=1) AND(Farm_Health_Level[Nonadopters] =1)) THEN (TRIANGULAR(10, 14, 15, 100)) ELSE 20	{pods}	Asare & David, 2010
Average_Processing_Capacity	457850000	{kg}	ICCO Annual Cocoa Report
Closed_Processing_capacity	Average_Processing_Capacity*Processing_Capacity_Foldup_Rate	{kg}	
Cocoa_beans_rest_of_the_world	GRAPH(Global_Cocoa_Price) Points: (1200, 1.48e+09), (1292.85714286, 1.58e+09), (1385.71428571, 1.76e+09), (1478.57142857, 1.91e+09), (1571.42857143, 2.05e+09), (1664.28571429, 2.26e+09), (1757.14285714, 2.35e+09), (1850, 2.46e+09), (1942.85714286,	{kg}	ICCO Annual Cocoa Report

	2.54e+09), (2035.71428571, 2.68e+09), (2128.57142857, 2.83e+09), (2221.42857143, 2.85e+09), (2314.28571429, 2.87e+09), (2407.14285714, 2.93e+09), (2500, 3e+09)		
Cocoa_trees[Adopters]	Tree_on_hecatre*Farm_size*Total_cocoa_farms[Adopters]	{trees}	
Cocoa_trees[Nonadopters]	Tree_on_hecatre*Farm_size*Total_cocoa_farms[Nonadopters]	{trees}	
"COCOBOD_Allocation_for_in-country_processing"	LBC_Purchases_for_COCOBOD*"Allocated_percentage_for_in-country_processing"	{kg}	
CODAPEC_Fungicide[Farmer_type]	IF(Government_subsidy = 1) THEN 4 ELSE (IF(Government_subsidy = 0.5)THEN 2 ELSE 0)	{times}	
CODAPEC_Pesticides[Farmer_type]	IF(Government_subsidy = 1)THEN 4 ELSE (IF(Government_subsidy = 0.5) THEN 2 ELSE 0)	{times}	
Cote_d_Ivoire_supply	((Price_Responsiveness*((SMTH1(Global_Cocoa_Price, 1)-Global_Cocoa_Price)/Global_Cocoa_Price))*Cote_d'Ivoire_Export)+Cote_d'Ivoire_Export	{kg}	
Cote_d'Ivoire_Export	Cote_d'Ivoire_production*Cote_d'Ivoire_Export_rate	{kg}	
Cote_d'Ivoire_Export_rate	0.73	{percent}	Average estimate from ICCO Annual Cocoa Report
Cote_d'Ivoire_production	1391800000	{kg}	Average estimate from ICCO Annual Cocoa Report
Demand	Total_Non_Origin_Processing_Capacity*(SMTH1(Global_Cocoa_Price, 1)/Global_Cocoa_Price)	{kg}	

Demotivation_rate	IF((Short_term_expected_margin[Adopters]> 0) OR(Government_subsidy = 1)) THEN 0 ELSE 0.5	{percent}	Assumed based on adoption rate
Desired_inventory	Desired_inventory_coverage*Demand	{kg}	
Desired_inventory_coverage	1	{year}	
Desired_Price	Effect_on_price*Global_Cocoa_Price	{USD/tonne}	
Disadoption_rate	(Nonadopters/(Nonadopters+Adopters))*Demotivation_rate	{percent}	
Discarding_rate	0.0000001	{percent}	
Disease_and_Pest_control[Farmer_type]	IF(((CODAPEC_Pesticides+Supplementary_Pesticide)= 4) AND((CODAPEC_Fungicide+Supplementary_Fungicides))= 4)THEN 2 ELSE 1		
Effect_on_price	GRAPH(Inventory_ratio) Points: (0.000, 2.000), (0.200, 1.800), (0.400, 1.600), (0.600, 1.400), (0.800, 1.200), (1.000, 1.000), (1.200, 0.800), (1.400, 0.600), (1.600, 0.400), (1.800, 0.200), (2.000, 0.050)		
Family_labour_engaged	28.80 * Farm_size	{man days}	Bymolt, Laven, Tyszler, 2018
Farm_Adatptive_Ratio	((Tree_lost_from_chain * Average_pod_yield[Adopters] * weight_of_dried_bean_in_pod) +ABS(Variance_of_system_state))/ SMTHN(Total_cocoa_beans_processed, 5, 1)		
Farm_expenditure[Adopters]	SMTH1(Farm_maintenance_cost[Adopters], 1)	{USD}	
Farm_expenditure[Nonadopters]	SMTH1(Farm_maintenance_cost[Nonadopters], 1)	{USD}	

Farm_Health_Level [Farmer_type]	IF((Weed_Control_Level =2) AND(Disease_and_Pest_control = 2)) THEN 2 ELSE 1		
Farm_income[Adopters]	(Producer_price/1000)*(Average_Farm_Harvest[Adopters])	{USD}	
Farm_income[Nonadopters]	(Producer_price/1000)* (Average_Farm_Harvest[Nonadopters])	{USD}	
Farm_maintenance_cost[Adopters]	Total_cost_fungicides[Adopters]+Total_Fertiliser_cost[Adopters]+Total_weed_control_cost[Adopters]+Total_pest_control_cost[Adopters]+Agrochemical_application_labour_cost[Adopters]	{USD}	
Farm_maintenance_cost[Nonadopters]	Total_cost_fungicides[Nonadopters]+Total_Fertiliser_cost[Nonadopters]+Total_weed_control_cost[Nonadopters]+Total_pest_control_cost[Nonadopters]+Agrochemical_application_labour_cost[Nonadopters]	{USD}	
Farm_Nutrient_level[Farmer_type]	IF((Government_Fertiliser+Supplementary_Fertiliser) =Recommended_Fertiliser_Quantity) THEN 2 ELSE 1		
Farm_size	3	{hectares}	Aneani et al., 2011a; Bymolt, Laven, Tyszler, 2018
Farmer_margin[Adopters]	SMTH1(Farm_income[Adopters], 1)-Farm_expenditure[Adopters]	{USD}	
Farmer_margin[Nonadopters]	SMTH1(Farm_income[Nonadopters], 1)-Farm_expenditure[Nonadopters]	{USD}	
FOB	Global_Cocoa_Price	{USD per tonne}	
Ghana_Export_Supply	LBC_Purchases_for_COCOBOD-"COCOBOD_Allocation_for_in-country_processing"	{kg}	

Government_Fertiliser	IF((Government_subsidy =0.5)OR(Government_subsidy >0.5)) THEN (0.5*Recommended_Fertiliser_Quantity) ELSE 0		
Government_subsidy	IF(SMTH1(Industry_&_marketing_cost, 1) > Industry_&_marketing_cost) THEN 1 ELSE 0.5		
Hired_Labour	Total_Labour_Required-Family_labour_engaged	{man days}	Bymolt, Laven, Tyszler, 2018
Industry_&_marketing_cost	1-Percentage_producer_price	{percent}	Bymolt, Laven, Tyszler, 2018
Inventory_ratio	Inventory/Desired_inventory		
Labour_Cost	Hired_Labour*Unit_labour_cost	{USD}	
Maturity_rate	0.15		Anim-Kwapong & Frimpong, 2004
Medterm_farm_profitability[Adopters]	SMTHN(Farmer_margin[Adopters], 5, 1)	{USD}	
Medterm_farm_profitability[Nonadopters]	SMTHN(Farmer_margin[Nonadopters], 5, 1)	{USD}	
Percentage_of_direct_purchases_from_farmers	0.015	{per cent}	Assumed to be less than 1% based on (Kolavalli et al., 2012)
Percentage_producer_price	0.60	{per cent}	Bymolt, Laven, Tyszler, 2018
Price_Change_delay	1	{times}	
Price_Responsiveness	0.07		
Processing_Capacity_Expansion_Rate	0	{percent}	
Processing_Capacity_Foldup_Rate	0	{per cent}	

Producer_price	FOB * Percentage_producer_price	{USD per tonne}		
Productive_trees[Adopters]	Cocoa_trees[Adopters]-Unproductive_trees_new[Adopters]	{trees}		
Productive_trees[Nonadopters]	Cocoa_trees[Nonadopters]-Unproductive_trees_new[Nonadopters]	{trees}		
Readoption_rate	0.3	{percent}		
Recomended_Fungicide_Quantity	4	{times}		
Recommended_Fertiliser_Quantity	7.4*Farm_size	{kg}		
Recommended_Pesticide_Quantity	4	{times}		
Required_farm_labour_per_hectare	53.17	{man days}		Bymolt, Laven, Tyszler, 2018
Short_term_expected_margin[Adopters]	SMTH1(Farmer_margin[Adopters], 1, 0)	{USD}	DELAY CONVERTER	
Short_term_expected_margin[Nonadopters]	SMTH1(Farmer_margin[Nonadopters], 1, 0)	{USD}		
Smuggling_rate	0.0005	{percent}		Assumed to be less than 1%. Smuggling occurs near border towns
Supplementary_Fertiliser[Adopters]	IF((Short_term_expected_margin[Adopters] > 0) AND(Government_Fertiliser < Recommended_Fertiliser_Quantity)) THEN (Recommended_Fertiliser_Quantity - Government_Fertiliser) ELSE 0	{kg}		
Supplementary_Fertiliser[Nonadopters]	0	{kg}		

Supplementary_Fungicides[Adopters]	IF((Short_term_expected_margin[Adopters] > 0) AND(CODAPEC_Fungicide < Recomended_Fungicide_Quantity)) THEN (Recomended_Fungicide_Quantity - CODAPEC_Fungicide) ELSE 0	{kg}
Supplementary_Fungicides[Nonadopters]	0	{kg}
Supplementary_Pesticide[Adopters]	IF(((Short_term_expected_margin[Adopters] > 0) AND(CODAPEC_Pesticides < Recommended_Pesticide_Quantity))) THEN(Recommended_Pesticide_Quantity - CODAPEC_Pesticides) ELSE 0	{kg}
Supplementary_Pesticide[Nonadopters]	0	{kg}
"Switching-out_rate"	IF(SMTH3(Medterm_farm_profitability[Nonadopters], 1) > 0) THEN 0 ELSE 0.015	{percent}
Total_cocoa_farms[Adopters]	Adopters	{farms}
Total_cocoa_farms[Nonadopters]	Nonadopters	{farms}
Total_cost_fungicides[Adopters]	Supplementary_Fungicides[Adopters]*Unit_cost_of_fungicide	{USD}
Total_cost_fungicides[Nonadopters]	Supplementary_Fungicides[Nonadopters]*Unit_cost_of_fungicide	{USD}
Total_Fertiliser_cost[Adopters]	Supplementary_Fertiliser[Adopters]*Unit_cost_of_fertiliser	{USD}
Total_Fertiliser_cost[Nonadopters]	Supplementary_Fertiliser[Nonadopters]*Unit_cost_of_fertiliser	{USD}

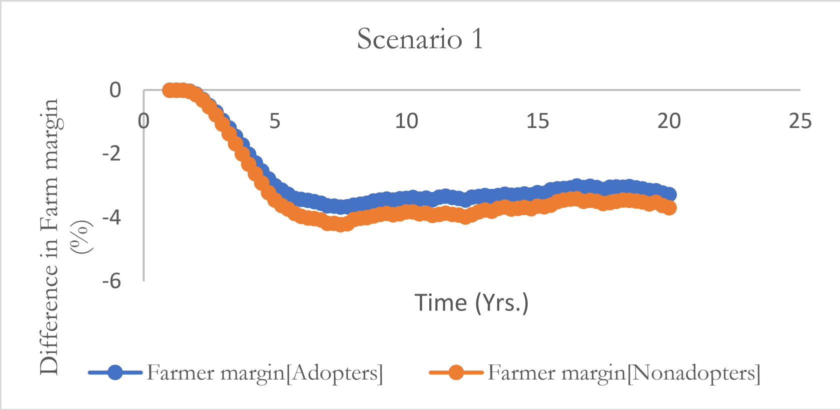
Total_labour_engaged	Hired_Labour+Family_labour_engaged	{man days}	
Total_Labour_Required	Required_farm_labour_per_hectare*Farm_size	{man days}	
Total_pest_control_cost[Adopters]	Supplementary_Pesticide[Adopters]*Unit_cost_of_pesticides	{USD}	
Total_pest_control_cost[Nonadopters]	Supplementary_Pesticide[Nonadopters]*Unit_cost_of_pesticides	{USD}	
"Total_volumes_in-country_processing"	("COCOBOD_Allocation_for_in-country_processing")+Processor_purchases_from_Farmers	{kg}	
Total_weed_control_cost[Adopters]	Weed_Control_Level[Adopters]*Unit_cost_of_Weed_control	{USD}	
Total_weed_control_cost[Nonadopters]	Weed_Control_Level[Nonadopters]*Unit_cost_of_Weed_control	{USD}	
Tree_lost_from_chain	Switching_farmers *Farm_size*Trees_per_hectare	{trees}	
Trees_per_hectare	1100	{trees}	Bymolt, Laven, Tyszler, 2018
Unit_cost_of_fertiliser	6.63	{USD}	Bymolt, Laven, Tyszler, 2018
Unit_cost_of_fungicide	1.14	{USD}	Bymolt, Laven, Tyszler, 2018
Unit_cost_of_pesticides	1.14	{USD}	Bymolt, Laven, Tyszler, 2018
Unit_cost_of_Weed_control	2	{USD}	Bymolt, Laven, Tyszler, 2018
Unit_labour_cost	7.05	{USD}	Bymolt, Laven, Tyszler, 2018

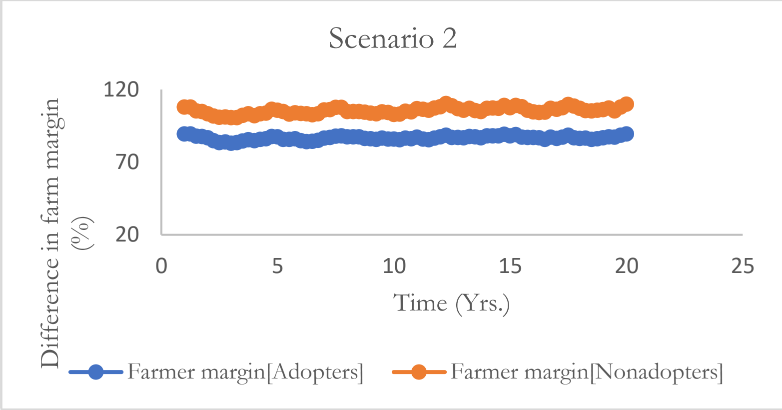
Unproductive_trees _new[Farmer_type]	Cocoa_trees*Maturity_rate	{trees}	
Va_Syst	IF((HISTORY(Cocoa_beans_transacted_in_Ghana , TIME - 1)) < Cocoa_beans_transacted_in_Ghana) THEN 0 ELSE (HISTORY(Cocoa_beans_transacted_in_Ghana, TIME - 1)- Cocoa_beans_transacted_in_Ghana)	{kg}	
Variance_Exporter	Ghana_Export_Supply-DELAY1(Ghana_Export_Supply, 1)	{kg}	
Variance_of_syste m_state	IF((DELAY1(Cocoa_beans_transacted_in_Ghana, 1)) < Cocoa_beans_transacted_in_Ghana) THEN 0 ELSE (Cocoa_beans_transacted_in_Ghana-DELAY1(Cocoa_beans_transacted_in_Ghana, 1))	{kg}	
Variance_Processor	"Total_volumes_in-country_processing"-DELAY1("Total_volumes_in-country_processing", 1)	{kg}	
Variance_Producer	(Cocoa_beans_transacted_in_Ghana-DELAY1(Cocoa_beans_transacted_in_Ghana, 1))	{kg}	
Weed_Control_Lev el[Farmer_type]	7.73*Farm_size	{man days}	
weight_of_dried_be an_in_pod	0.039	{kg}	Asare and David, 2010; Mahrizal et al., 2014

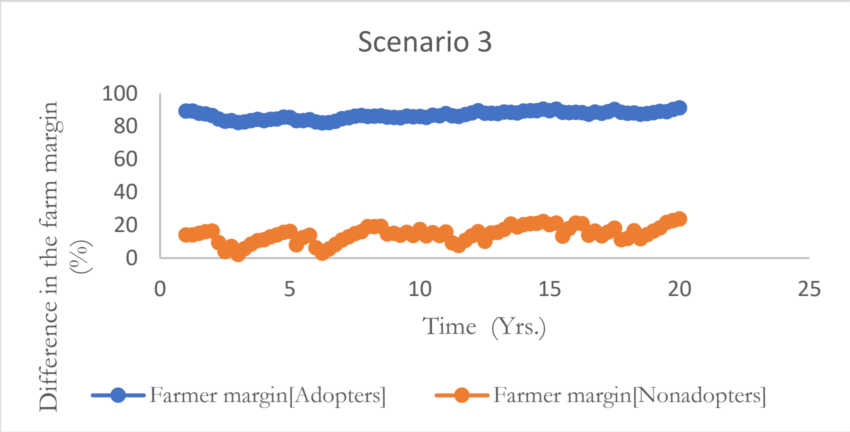
[+] Estimated based on historical data on in-country processing (from 2000 -2015). Data extracted from cocoa industry annual reports from 1997 to 2015 by the International Cocoa Organisation.https://www.icco.org/about-us/international-cocoa-agreements/cat_view/1-annual-report.html

Appendix 5.2

Differences in the farm margins for each scenario compared with the baseline







Chapter 6 *Ex-ante* Impact of On-farm Diversification and Forward Integration on Agricultural Value Chain Resilience: A System Dynamics Approach

"Divide your portion to seven, or even to eight, for you do not know what misfortune may occur on the earth."

- Ecclesiastes 11:2

This chapter fulfils objective four, and it is based on the published journal article below:

Aboah, J. Wilson, M.J.M, Bicknell, K. Rich, K., 2021. *Ex-ante* impact of on-farm diversification and forward integration on agricultural value chain resilience: A system dynamics approach. *Agricultural Systems*. 189. https://doi.org/10.1016/j.agsy.2020.103043

Abstract

This paper examines *ex-ante* the impact of on-farm diversification and forward integration strategies on agricultural value chain resilience, using Ghana's cocoa value chain as a case study. System dynamics modelling is used to explore five scenarios involving variable-input on-farm diversification pursued by cocoa farmers in Ghana and the simultaneous adoption of forward integration strategies by Ghana and Cote d'Ivoire. Results indicate that complementarity exists between on-farm diversification and a cooperative forward integration strategy. An adaptive strategy involving the simultaneous pursuit of variable-input on-farm diversification and a cooperative forward integration strategy is the most resilient strategy. Under such an adaptive strategy, in-country processors will be the most impacted if the safety stocks level during the bad years (collapse phase) of the cocoa value chain are below 25% of the average stock. The findings suggest that the cocoa value chain will be resilient when Ghana increases or retains the in-country processing level irrespective of the forward integration strategy adopted by Cote d'Ivoire.

Keywords: diversification; forward integration; value addition; resilience

6.1 Introduction

On-farm diversification has long been recognised as a strategy for attaining household resilience (Asante et al., 2018; Darnhofer, 2014; Kray et al., 2018). Compared to its opposite strategy (specialisation), diversification is regarded as more beneficial to increasing agroecosystem services. Using an income pathway, smallholders can resort to on-farm and off-farm diversification to increase resilience (Kray et al., 2018). Nonetheless, smallholders' lack of capital, coupled with limited labour and land imply that on-farm diversification will involve a trade-off between investment in existing farmed crops and the new (alternative) crops (Asante et al., 2018). Indeed, Bymolt et al. (2018) specifically recognised that further extensive studies into the benefits of diversification are required, particularly within the context of cocoa production in Ghana and Cote d'Ivoire.

Beyond the upstream end of the value chain, forward integration also referred to as an upgrading strategy (Gereffi et al., 2005), is espoused to improve the competitiveness and resilience of producers in developing countries (Gibbon, 2001; Humphrey & Schmitz, 2002; Sexton et al., 2007). The central logic of this strategy involves acquiring or adopting new actors, functions, or activities in order to reduce risk and generate higher income. Forward integration is also classified as vertical diversification that involves an extension of production activities to other activities in the value chain like processing and packaging (Aneani et al., 2011b; Barghouti et al., 2004; Kray et al., 2018).

The promotion of on-farm diversification and forward integration as adaptive strategies for increasing resilience at individual household and national levels respectively presents a compelling case for resilience studies in tropical commodity chains. This is because the complementarity or incompatibility of these strategies on agricultural value chain resilience at an aggregate level has not been examined in the literature.

Resilience in agricultural value chains can be categorised based on the decision-making unit. When the focus of resilience is on an individual or household (micro-level), then food security and nutritional diversity are generally the overarching objectives (Alinovi, Mane, & Romano, 2009; Kary et al., 2018). An aggregate resilience focuses on national (macro) food system level (Tendall et al., 2015). An individual chain actor's pursuit of resilience may not be complementary to the goals of other members in the chain. Since national policies seeking to promote productivity and food security reinforce specialisation, there is a need for a holistic approach with regards to aggregate resilience policies (Kray et al., 2018). Systems thinking approach enables a deeper understanding of the complementarities and conflicts inherent in the pursuit of individual actors' resilience juxtaposed against a chain-wise or national pursuit of resilience.

The objective of this paper, therefore, is to examine *ex-ante* the impact of the simultaneous pursuit of on-farm diversification and forward integration strategies on the resilience of the cocoa value chain at an aggregate level. The paper focuses on the cocoa value chain for three reasons. First, on-farm diversification that targets non-traditional export crops is promoted as a strategy to stabilise farm income (Aneani et al., 2011b; Bymolt et al., 2018). Second, factors like government subsidies and land tenure insecurities that are recognised as barriers to on-farm diversification (Kray et al., 2018) are present in the cocoa value chain. Third, a forward integration strategy can be pursued at an aggregate level in this context.

The next section of the paper presents a conceptual model of diversification, the forward integration strategies and a description of the system dynamics model. The results and discussions are presented in Section 6.3. Section 6.4 presents the conclusions of the findings and limitation of the study.

6.2 Methodology

This section discusses scenarios constructed based on on-farm diversification and types of forward integration strategies generated using cooperation and conflict (non-cooperation) between Ghana and Cote d'Ivoire (the two biggest global producers of cocoa). System dynamics modelling is deployed as the analytical technique to assess the impact of the scenarios on the resilience of Ghana's cocoa value chain. The first subsection presents a conceptual model of on-farm diversification. The second covers three forward integration strategies that can be engaged. The model description and validation are presented in the third subsections.

6.2.1 Conceptual Model of On-farm Diversification

On-farm diversification involving perennial export crops (like cocoa) can be viewed on a continuum, with full diversification and specialisation at the extreme ends (Asante et al., 2018). Different variants of diversification emerge when the extent of and motive for diversification are considered. Perennial export crops, by their nature, are productive for long periods (Knudsen & Agergaard, 2015), and are regarded as the most important source of income (Bymolt et al., 2018).

A farmer's motive for pursuing diversification can be either complementary or competitive to existing perennial export crops. Given that smallholders view perennial export crops as an economic assurance for retirement (Aneani et al., 2011b; Kos & Lensink, 2017), perennial crops that are the most important source of income are assumed to be the main crops, and the alternative crops are peripherals. Revenue from the diversification that supports farm maintenance activities associated with the main crop is complementary. Those that are not reinvested are considered competitive.

In the face of land availability constraints, on-farm diversification of an existing farm with perennial crop involves two main decisions (Bymolt et al., 2018): *(i)* fixed-input diversification, which involves converting a portion of the farm to an alternative crop; and *(ii)* variable-input diversification, which involves a shift of inputs and labour resources from the perennial crop to the alternative crop. Combining the extent of and motive for diversification results in these variants: Fixed-input diversification with or without plough back and variable-input diversification with or without plough back. The conceptualisation of on-farm diversification is shown in Figure 26.

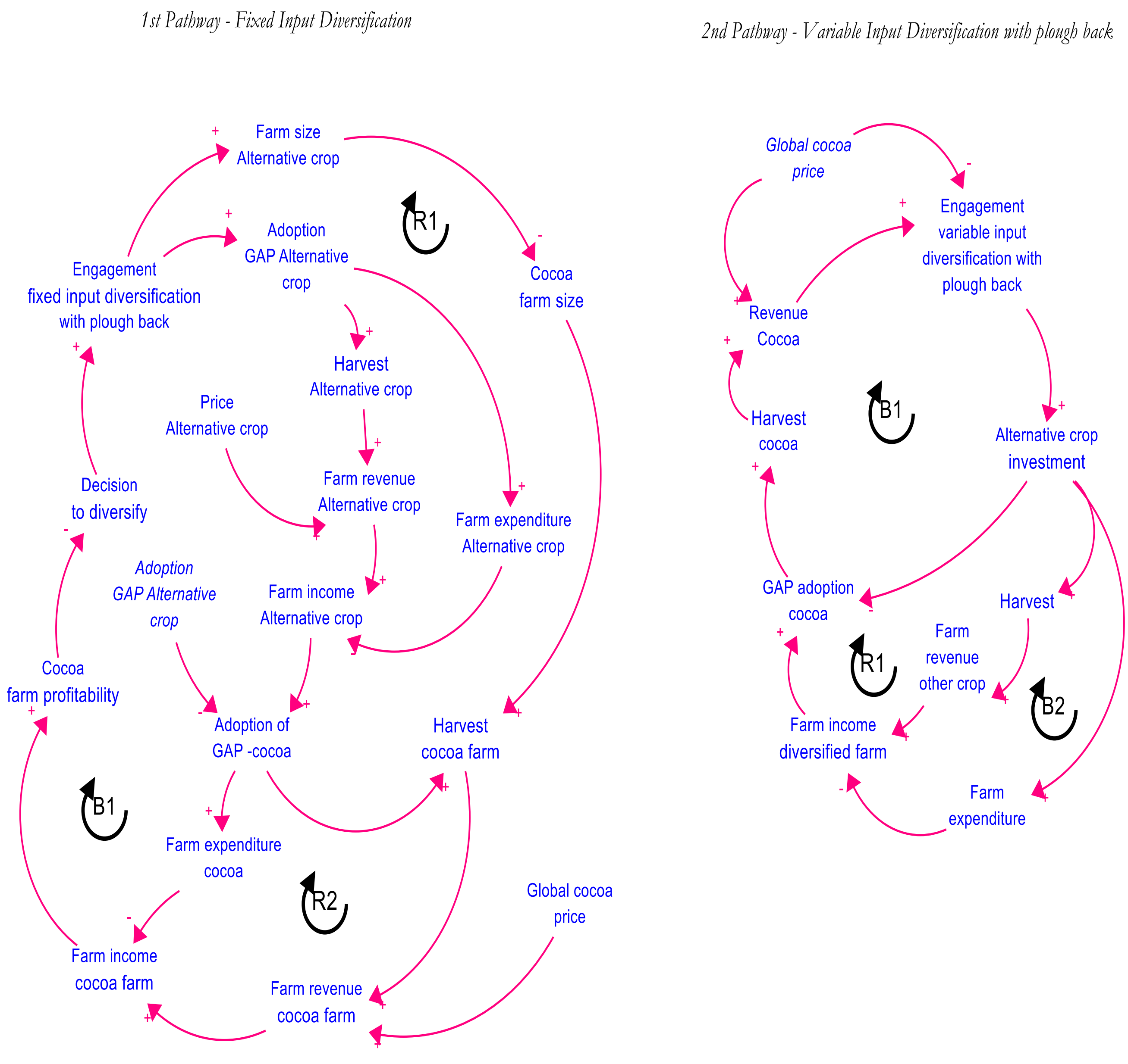


Figure 26 Conceptualisation of on-farm diversification

Variable-input diversification occurs through two pathways, as illustrated in Figure 26. The first pathway is after the alternative crop from the fixed-input diversification with plough back is established. The duration of this pathway is dependent on the type of alternative crop cultivated.

Perennial crops take a longer period to establish than annual and biannual crops. The second pathway is a short-term decision that is contingent on access to uncultivated farmland. Under variable-input diversification with plough back, the farmer diverts inputs and resources to the alternative crop when the cocoa cropping season is perceived to be unfavourable (unprofitable) or when input constraints exist. For the second pathway, the number of cocoa trees is unaffected.

This paper focuses on variable-input diversification with plough back because it is the most practised diversification form (Bymolt et al., 2018). The variable-input diversification involves the intercropping of cocoa farms with plantain. Plantain is considered as the alternative crop for three reasons. First, it is regarded as an important crop in all cocoa growing regions; the level of importance of other intercrops (like maize, cassava) is subjective to specific cocoa-growing regions (Bymolt et al., 2018). Second, plantain leaves provide shade for cocoa seedlings during the cocoa farm establishment stage, and they are used for cocoa bean fermentation process (Bymolt et al., 2018). Third, cocoa/plantain intercrop combination results in the highest crop yield and the highest increase in the farmer's net benefit from intercropping (Opoku-Ameyaw, Oppong, Acheampong, & Amoah, 2012).

6.2.2 Forward Integration Strategies

Global commodity chains can be viewed through the lens of dependency theory (Gibbon, 2001). However, the idiosyncrasies of cocoa as a tropical commodity (Talbot, 2002) require the analyst to extend the theoretical framework to include product essentiality (Jacobs, 1974). The theory of product essentiality highlights asymmetrical dependence in the supply chain. When there are few sources of supply of a commodity and an organisation needs to buy the commodity to meet its dependency, then the commodity becomes essential. Alternatively, when there are other substitutes and/or many sources of supply, then the commodity is unessential (Jacobs, 1974).

Asymmetrical dependence exists in two cases. First, when the dependency of upstream actors (*producers*) to sell exceeds the dependency of midstream or downstream actors (*buyers*) to buy. From the perspective of the buyer, such commodity is a substitute. Second, when the dependency of producers to sell is lower than the dependency of buyers to buy. From the perspective of the buyer, such a commodity is an essential commodity. In the case of an essential commodity, buyers have limited options. Hence, they attempt to mitigate their dependency, especially when the supplier also needs to sell to meet a dependency. In such a situation, the actions of buyers instigate symmetrical dependency. These actions become feedbacks to upstream actors (suppliers). From the viewpoint of the producer, the availability of more buyers lowers the dependency of upstream actors to sell; fewer buyers correspond to increased dependency to sell. An asymmetrical dependency exists when there are few buyers, i.e. small numbers bargaining.

The theory is extended in the cocoa case. Producers' ability to process raw cocoa beans (forward integration) limits their dependency. This strategy can be pursued solely or in sync with other producers. However, it is unclear whether the pursuit of a forward integration strategy will boost resilience at an aggregate level. Two plausible forward integration strategies are explored in this paper: sole and harmonised in-country processing by the two leading producers of cocoa (Ghana and Cote d'Ivoire).

Sole in-country processing and harmonised in-country processing represent conflict and cooperative behaviours respectively. A non-zero-sum game is assumed because the global cocoa price affects both countries, and there is a possibility for a win-win situation if the two countries engage in a harmonised forward integration (cooperate). Table 15 shows five cases that arise from cooperation and conflict behaviours.

6.2.3 Model Description

The flow of material and information in the cocoa value chain is presented as a stock and flow model (*see Appendix 6.0*); these are segmented into five sub-model that are discussed below. The summary of the equations in the model is presented in Appendix 6.1.

Sub-model A – Aggregate Diversification

Cocoa farmers are distinguished based on two criteria: *(i)* the diversification practices and *(ii)* adoption of good farm management practices. Based on the first criterion, the cocoa farmers are classified as *variable-input diversifiers* or *specialisers*. An average farm size *(Farm $_{size}$)* of three hectares (Aneani et al., 2012) and 1100 trees on a hectare *(Tree $_{hec}$)* (Mahrizal et al., 2014) are considered. Intercropping is typically practised in Ghana's cocoa sector (Aneani et al., 2012) using an average land size of 0.8 hectares of the farmland (Aneani et al., 2011b).

Table 15 Five forward integration cases

Cases	Description
Cooperation: Harmonise In-country processing	Both countries increase the percentage of cocoa beans allocated for in-country processing
Conflict $_{Ghana\ (Type\ I)}$: Ghana sole in-country processing	Ghana increases allocation for in-country processing; Cote d'Ivoire decreases in-country processing
Conflict $_{Ghana\ (Type\ II)}$: Ghana sole in-country processing	Ghana increases allocation for in-country processing; Cote d'Ivoire retains its in-country processing level
Conflict $_{Cote\ d'Ivoire\ (Type\ I)}$: Cote d'Ivoire sole in-country processing	Cote d'Ivoire increases allocation for in-country processing; Ghana decreases in-country processing
Conflict $_{Cote\ d'Ivoire\ (Type\ II)}$: Cote d'Ivoire sole in-country processing	Cote d'Ivoire increases allocation for in-country processing; Ghana retains in-country processing level

The cocoa trees are categorised as young unproductive, productive and old unproductive. Young cocoa trees are unproductive until the 5th year (maximum). Productive trees become unproductive after 30 years at a maturity rate of 15%. The number of young unproductive trees that become productive is predicated on the tree replanting rate, which is seldom practised by farmers in Ghana. Indeed, tree replanting exercises, which removes the unproductive trees on the farm, is mostly a government-led intervention (Mahrizal et al., 2014). Hence, the tree replanting rate is fixed at zero.

Sub-model B – On-farm Production

Based on the second criterion, cocoa farmers are classified as *adopters* and *non-adopters*. Irrespective of the diversification practices, cocoa trees for a*dopters* produce a maximum of 25 cocoa pods at optimal agronomic practice levels; at suboptimal levels, the cocoa pods produced are represented as a triangular distribution (between 15 and 23). Cocoa trees from *non-adopters* produce 20 cocoa pods. The cocoa farm harvest is estimated as:

$$Harv = [(P\ Trees_{(ad)} * Ty_{ad}) + (P\ Trees_{(nad)} * Ty_{fnad})] \qquad (6.1)$$

Harv is the aggregate harvest, *P trees(ad)* and *P trees(nad)* are the total number of productive cocoa trees for *adopters* and *non-adopters* respectively, *Ty ad* and *Tynad* represent the average pod yield of a cocoa tree for adopters and non-adopters, respectively.

The product of the average yield of 2,591 kg per hectare (Opoku-Ameyaw et al., 2012) and the size of the Alt_{farm}, gives the total yield from the diversified farm. The total harvest from an alternative crop less the proportion consumed by the farmer's household is the saleable proportion from the alternative farm. The average household size of six (Aneani et al., 2011) and a per capita consumption of plantain (Dzomeku, Dankyi, & Darkey, 2011) is used to determine the proportion of household consumption.

Sub-model C – In-country Trading and Processing

The harvested cocoa pods are processed into cocoa beans. A cocoa pod produces 0.039kg of dried cocoa beans (Mahrizal et al., 2014). Less than 1% postharvest loss and smuggling rate are assumed as a deduction from the total cocoa beans processed in the baseline model. The average percentage of total cocoa beans allocated for in-country processing (19%) is estimated based on the historical data (from 2000 – 2015). The remaining percentage of cocoa beans are exported to the world commodity market.

Sub-model D – Export and Global Price

The global cocoa price is endogenised with an initial value of $2000 per tonne and a quarterly price change delay. The global demand for cocoa beans is captured as the number of buyers represented by the processing capacity of non-origin processors. The total processing capacity of Germany, Netherlands, the rest of Europe, the US, the rest of Asia and Oceania (excluding Indonesia and Malaysia) from 2012 – 2015 cocoa cropping years is used to represent global demand. Demand increases when the processing capacity expands, either through the entry of a new processor into the global commodity market or existing processors increase processing. Demand decreases when a processing capacity folds. The baseline rates of processors entering or expanding capacity and processors' folding up is set at zero.

The supply to the world commodity market is highlighted by the cocoa supply (export) from Ghana, Cote d'Ivoire, and the rest of the producing countries. Cocoa supply from Cote d'Ivoire is estimated using historical data from 2000/01- 2015 cocoa cropping seasons; the baseline level is 73% of cocoa production in Cote d'Ivoire. The desired inventory coverage of one year is assumed. The ratio of inventory to desired inventory captures the negative influence of inventory levels on price (i.e., the effect on price).

A one-year desired inventory coverage is assumed. The global cocoa price is captured as the freight on board (FOB) price at the country level. The percentage of the FOB allocated as producer price is specified based on historical data (from 1998 – 2015 cropping years). The industry and marketing cost, which covers the cost of subsidies and freight is the remaining percentage of FOB after deducting the producer price (Kolavalli et al., 2012). The government provides full subsidy when the industry marketing and administrative cost of year $_{(t)}$ is greater than the value for year $_{(t-1)}$; half of the subsidies are given to farmers in a reverse case.

Sub-model E – Individual Farmer Level

The total cocoa production cost comprises of the following costs: fertiliser application, weed control and pest and disease control. Input subsidies provided by the government are inversely related to the quantity and amount of farm input that a farmer will apply. The total production cost for the alternative crop is 1.3% of the total cocoa production cost (Obiri et al., 2007). Cocoa farm margin is estimated as:

$$F_{margin} = \left[\left(Av_{pod} * Farm_{size} * Tree_{hec} * Pod_{dweight}\right) Prod_{price}\right] - \left(\sum Inputs_{cost} + Lab_{cost}\right) \quad (6.2)$$

where $\sum \text{Inputs}_{\text{cost}} + \text{Lab}_{\text{cost}}$ represent the sum of input cost from supplementary fertiliser, pesticides, and fungicides applied by the farmer and the associated labour cost, and $[(Av_{pod} * Farm_{size} * Tree_{hec} * Pod_{dweight}) Prod_{price}$ is the income. Farm margin from the alternative crop ($Alt\ F_{margin}$) is expressed as the revenue from the crop sales less the production cost. The total farm income ($T\ Farm_{income}$) is expressed as:

$$T\ Farm_{income} = Alt\ F_{margin} + F_{margin} \quad (6.3)$$

The total farm income determines the medium-term profitability, which has a feedback effect on the variable-input diversification rate and consequently, the farm management practice adoption.

6.2.4 Resilience Measure

From the perspective of an aggregate agricultural value chain level, the socioecological resilience is relevant for two reasons. First, the provisioning ecosystem service (raw materials) produced from upstream activities defines the system's identity and originates value chain activities. Second, farmers' adaptability is paramount to guarantee continuity in the value chain activities (Aboah et al., 2019a).

The Farm Adaptive Ratio (*FAR*) is used as a measure for aggregate value chain resilience (Aboah et al., 2019a). The *FAR* ranges from 0 to 1; 0 being the most resilient because the chain retains its system identity in the face of disruption, and 1 being the least resilient. *FAR* is estimated as:

$$FAR = \text{LossSoR}/\mu\ \text{SsoR} \quad (6.4)$$

where *LossSoR* is the loss from chain actors' adaptive strategies, and (μ SsoR) is the trend of system's aggregate state of resilience, estimated as a fifth-order exponential smoothing of cocoa beans produced. The effect of disruption scenarios is estimated as the difference between the *FAR* of the baseline model and *FAR* of the revised model.

6.2.5 Model Validation

Two phases of extreme condition test were conducted for the model structure validation. In phase 1, the pre-harvest extreme condition test was carried out by changing the farm size to zero. This resulted in a non-occurrence of production activities. In the second phase, a postharvest extreme condition test was conducted by altering the weight of beans in a pod to zero, which resulted in no processed cocoa beans. Statistical metrics; Mean Absolute Percentage Error (MAPE) and Theil inequalities (Theil U) (Sterman et al., 2013) and comparative statistic (Sücüllü & Yücel, 2014) are used for the model behaviour validation by comparing the forecasted and historical data on cocoa production figures in Ghana.

A perfect forecast (*Theil U = 0*) is attained when the forecast from the model is equal to real-world data. Theil U is 1 when the model forecast and a naïve have the same standard error (Bliemel, 1973). Theil U is expressed as:

$$Theil\ U = \sum_{t=1}^{n} = [\frac{(F_t - A_t)^{1/2}}{{A_t}^{1/2}}] \qquad (6.5)$$

The model also produced MAPE of 21% and a Theil U less than 0.2, which indicate that the model behaviour is an acceptable replication of reality. The statistic measures and a comparative graph of the model behaviour and actual behaviour are presented in Table 16 and Figure 27, respectively.

Table 16 Statistic measures for model behavioural validity

	Actual	Model	Difference	% Error
Comparative stats				
Mean (kg)	663,333,000	716,089,384	52,756,384	7.95
Single stats				
MAPE		0.185		
Theil U		0.219		
Transient part				
Maximum (kg)	1,025,000,000	938,831,000	86,169,000	8.4
Minimum (kg)	335,000,000	590,710,000	255,710,000	76.3

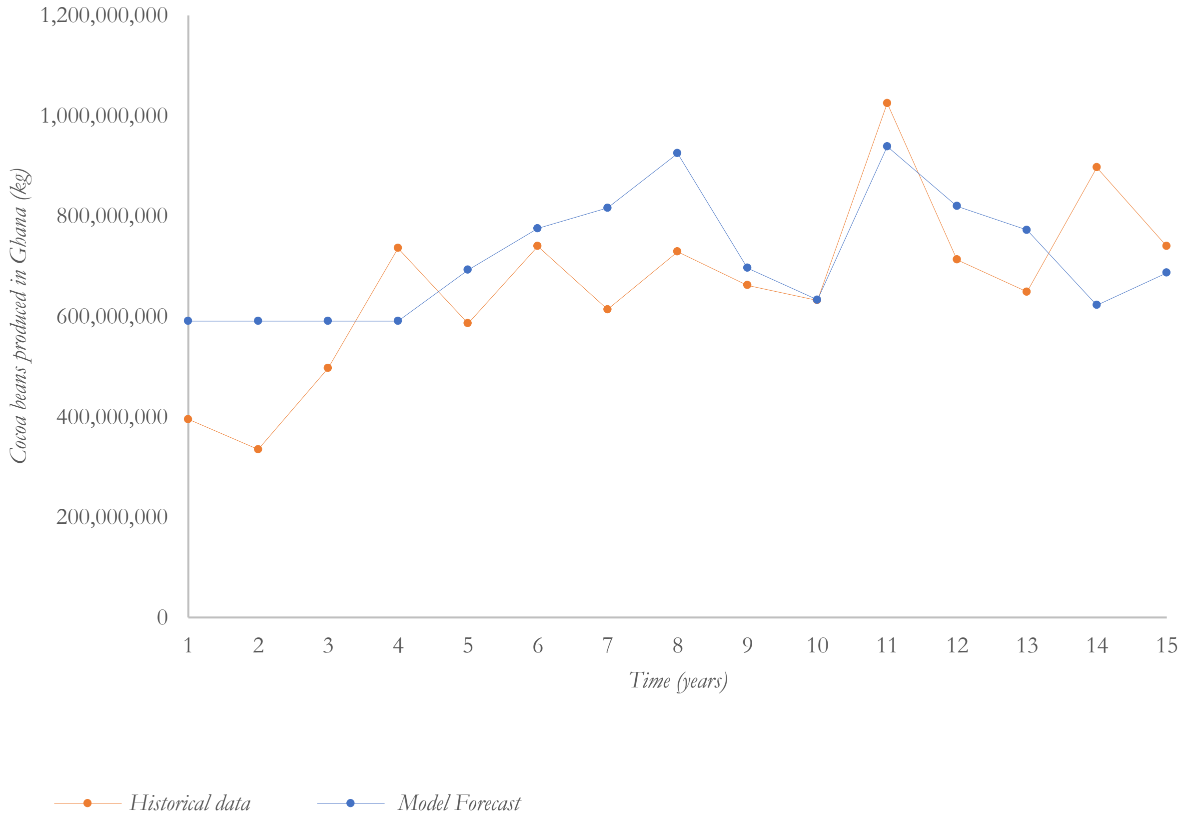


Figure 27 A comparison of historical and model data on cocoa beans produced in Ghana

6.2.6 Scenario Analyses

This study focuses on the impact of only variable-input diversification in combination with the possible forward integration strategies (one cooperation and four variants of the conflicting forward integration strategies) adopted by Ghana and Cote d'Ivoire. Details of the scenarios are highlighted in Table 17. The main parameters that are altered in the scenarios include percentage of cocoa beans allocated for in-country processing in Ghana (In-CountProc $_{(GH)}$), cocoa export rates from Cote d'Ivoire (ExpRate$_{(CI)}$), and the variable-input diversification rate at the farmer level in Ghana (VarDivRate).

Table 17 Scenarios examined

Scenarios	*Description of the scenario*	*Parameterised values (%)*
Scenario 1: Cooperation in forward integration strategy and variable-input diversification	Ghana and Cote d'Ivoire jointly decrease cocoa beans export to boost in-country processing, and there is increased variable-input diversification in Ghana	In-CountProc $_{(GH)}$= 0.2 ExpRate$_{(CI)}$ = 0.77 VarDivRate = 0.021
Scenario 2 (Type I): Conflict in forward integration strategy (*Ghana sole*) and variable-input diversification	Ghana embarks on sole in-country processing by increasing in-country processing, and there is increased variable-input diversification in Ghana. Cote d'Ivoire decreases in-country processing to increase exports.	In-CountProc $_{(GH)}$= 0.2 ExpRate$_{(CI)}$ = 0.69 VarDivRate = 0.021
Scenario 2 (Type II): Conflict in forward integration strategy (*Ghana sole*) and variable-input diversification	Ghana embarks on sole in-country processing by increasing in-country processing, and there is increased variable-input diversification in Ghana. Cote d'Ivoire maintains in-country processing levels.	In-CountProc $_{(GH)}$= 0.2 ExpRate$_{(CI)}$ = 0.73 VarDivRate = 0.021
Scenario 3 (Type I): Conflict in forward integration strategy (*Cote d'Ivoire*) and variable-input diversification	Cote d'Ivoire embarks on sole in-country processing by increasing in-country processing. Ghana decreases in-country processing to increase exports, and there is increased variable-input diversification in Ghana.	In-CountProc $_{(GH)}$= 0.18 ExpRate$_{(CI)}$ = 0.69 VarDivRate = 0.021
Scenario 3 (Type II): Conflict in forward integration strategy (*Cote d'Ivoire*) and variable-input diversification	Cote d'Ivoire embarks on sole in-country processing by increasing in-country processing. Ghana retains the in-country processing level, and there is increased variable-input diversification in Ghana	In-CountProc $_{(GH)}$= 0.19 ExpRate$_{(CI)}$ = 0.69 VarDivRate = 0.021

6.3 Results and Discussions

The feedback loops that influence the dynamic behaviour in the model were analysed using the loops that matter feature in the Stella Architecht® software. An overview of the feedbacks is presented in Table 18.

Table 18 An overview of dominant feedback loops

	Number of loops
Total feedback loops	70
Reinforcing feedback loops	29
Balancing feedback loops	41
Dominant feedback loops	
(feedback loops with an average influence of > 1%)	7
Dominant reinforcing feedback loops	1
Dominant balancing feedback loops	6

Details of the influence of each feedback loop, shown in Table 19, indicate that the one dominant reinforcing feedback loop (R1) influences on average 32% of changes in the model's dynamic behaviour. The feedback loop (R1) revolves around the global demand for cocoa beans and the global cocoa price. The most dominant balancing feedback loops (B1 and B2) revolve around cocoa harvest from farmers that adopt in farm management practices and engage in either variable-input diversification or specialisation.

Each of these balancing feedback loops influences 17% of changes in the dynamic behaviour of the model. The balancing feedback loop (B3) influences 11% of the changes in the model's dynamic behaviour and highlights the inverse relationship between demand and cocoa price. Comparing B3 and B4, the average percentage of influence in the dynamic behaviour attributable to B4 suggests that cocoa demand influences the model's dynamic behaviour more than cocoa supply. A trend analysis of the influence level of each dominant feedback loop for the entire simulation run is presented in Figure 28.

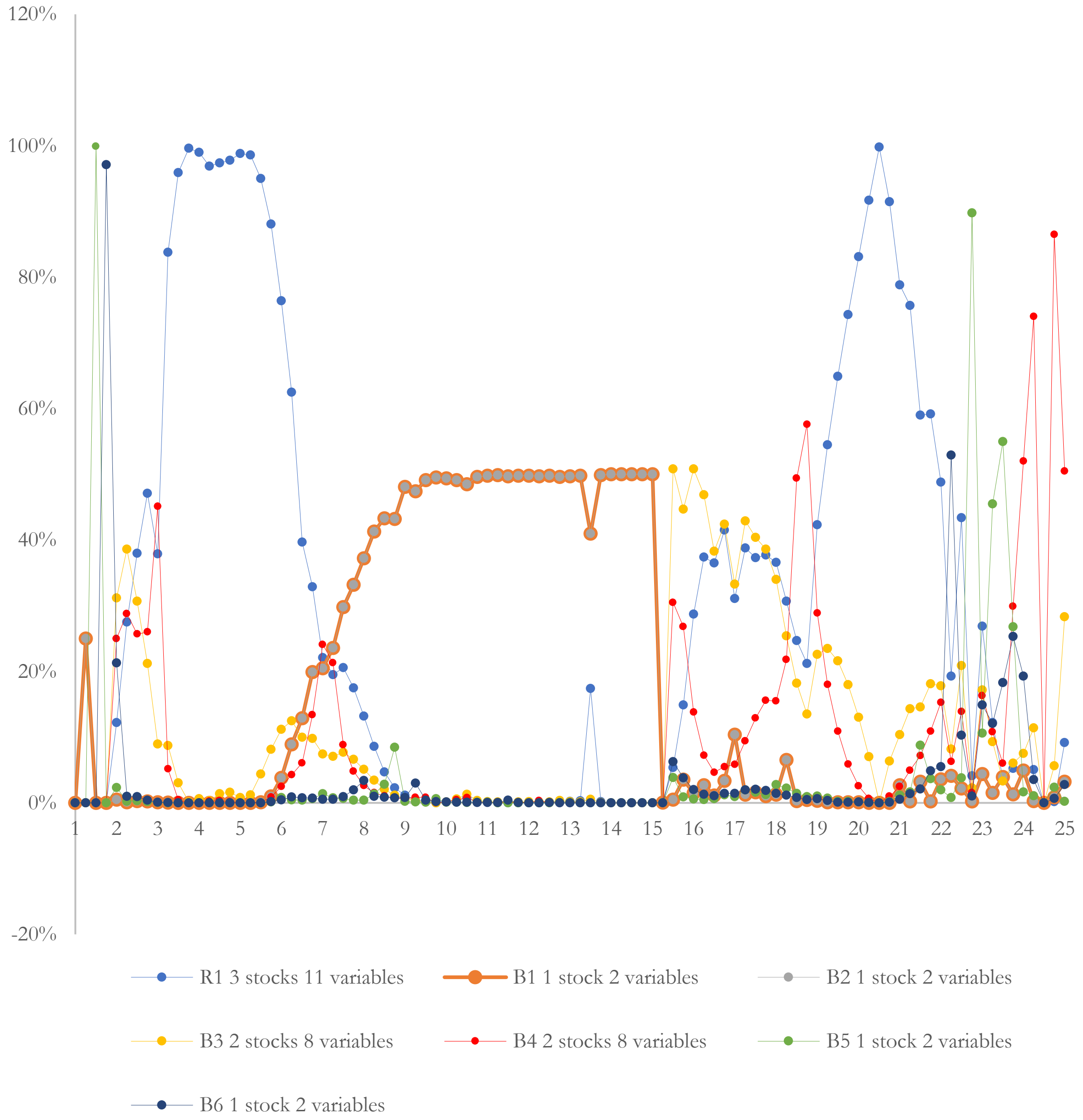


Figure 28 Trend of influence of dominant loops in the SD model

Table 19 Details of dominant loops influencing the model's dynamic behaviour

	Loop	Shown	T = 25.00 Initial	Average	Variables in the causal loop
1	R1 3 stocks 11 variables	U1	9.18%	31.86%	change in smooth (in macro) → Smoothed Input (in macro) → Demand → Sales → Inventory → Inventory ratio → Effect on price → Desired Price → Change in price → Global Cocoa Price → Demand
2	B1 1 stock 2 variables	B2	-3.22%	17.31%	Harvest [Nonadopters, Specialisers] → Allocated pods for processing [Nonadopters, Specialisers] → Harvest [Nonadopters, Specialisers]
3	B2 1 stock 2 variables	B1	-3.22%	17.31%	Harvest [Nonadopters, Variable input] → Allocated pods for processing [Nonadopters, Variable input] → Harvest [Nonadopters, Variable input]
4	B3 2 stocks 8 variables	U1	-28.28%	11.06%	Desired Price → Change in price → Global Cocoa Price → Demand → Sales → Inventory → Inventory ratio → Effect on price → Desired Price
5	B4 2 stocks 8 variables	B3	-50.52%	9.86%	Desired Price → Change in price →Global Cocoa Price → Cocoa beans rest of the world → World cocoa supply → Inventory → Inventory ratio → Effect on price→ Desired Price
6	B5 1 stock 2 variables		-0.21%	4.23%	Total cocoa beans processed → In country transaction→ Total cocoa beans processed
7	B6 1 stock 2 variables		-2.76%	3.59%	Cocoa beans transacted in Ghana → LBC Purchases for COCOBOD→ Cocoa beans transacted in Ghana

6.3.1 Baseline Model

The rise and fall of the aggregate resilience indicator, Farm Adaptive Ratio, represent loss and gain in the value chain resilience respectively over the total run period of 25 years. The baseline level of resilience, as shown in Figure 29, indicates prolonged stability (for the first 13 years), followed by a continuous loss in resilience until the 18th year. The cocoa value chain then gains resiliency continuously for five years and retains stability for the remaining three years. In total, the cocoa value chain increases resilience for a 5.5-year duration, loses resilience for 5.25 years and remains stable for 13.5 years.

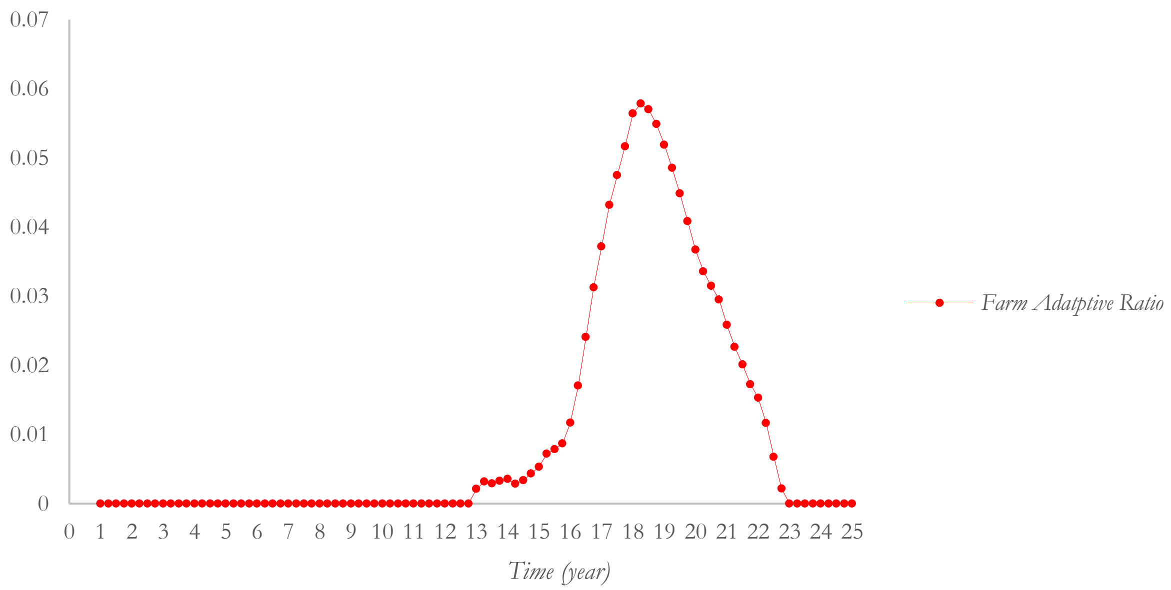


Figure 29 Trend of the baseline resilience (FAR) level

The difference in the raw materials (cocoa beans) flowing from producers to in-country processors and exporters highlight the practical implication. The baseline level of raw materials flow in the chain (presented in Table 20) shows that at the aggregate level, chain actors gain more raw materials on average in 'good' years than in 'bad' years. The baseline results show that chains actors experience the same duration of loss, gains and stability but a different magnitude of loss and gains. The equal periods of gains and loss and the differences in the magnitude of raw materials gained and lost by chain actors corroborate with the conclusions reached by Aboah et al. (2019b) regarding the propagational effect of actions from chain actors in the cocoa value chain.

Table 20 The baseline levels of cocoa beans produced and processed in the value chain

Impact on chain actors[4]	Producer	In-country processor	Exporter
Periods of gains (years)	13.25	13.25	13.25
Periods of loss (years)	10.25	10.25	10.25
Periods of stability (years)	0.75	0.75	0.75
Mean gains (kg)	19,780,852	3,998,699	15,782,153
Mean loss (kg)	-18,582,300	-3,756,412	-14,825,888

6.3.2 Impact of Scenarios on Aggregate Resilience

Scenario 1 involves variable-input diversification and cooperative forward integration strategy; scenarios 2 and 3 involve variable-input diversification and variants of conflicting forward integration strategy. The commonality in the scenarios is the variable-input diversification. Therefore, the impact of variable-input diversification is dissociated from the forward integration strategy by conducting a sensitivity analysis of only variable-input diversification. Results of the sensitivity analysis indicate that, compared to the baseline level, the cocoa value chain is reasonably stable and losses less than a year (0.75 years) of gains in resiliency when the number of cocoa farmers engaging in variable-input diversification increases.

Results of the pattern of resilience level and the impact of Scenario 1 is shown in Figure 30. Changes in the Farm Adaptive Ratio (*FAR)* that fall below zero are gains, and those above represent a loss of resilience. A 5% increase in the number of cocoa farmers that engage in variable-input diversification and the simultaneous decrease in cocoa exports from Ghana and Cote d'Ivoire at a rate of 5% results in 3.25 years loss in the baseline resilience level.

[4] When the quantity of cocoa beans produced/processed/ exported in year $_{(t+1)}$ > quantity in year (t), then a period of gain is registered. When quantities in year $_{(t+1)}$ < year $_{(t)}$, then a period of loss is registered; when the quantities in year $_{(t+1)}$ = year $_{(t)}$, then a period of stability is registered.

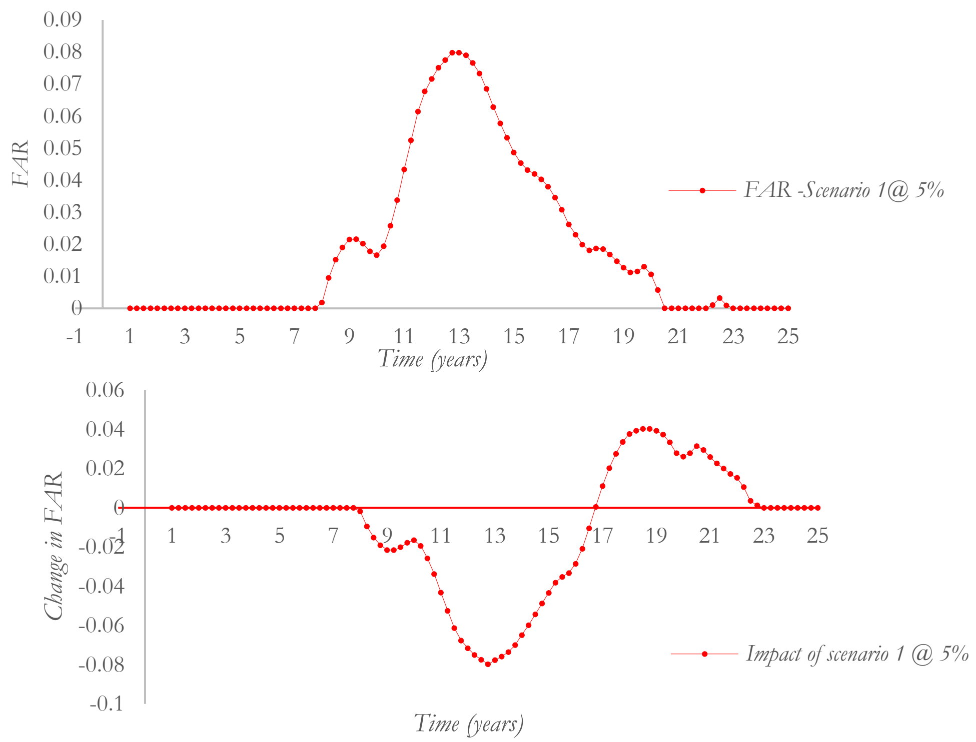


Figure 30 The impact of variable diversification and cooperative forward strategies on aggregate resilience

Two variants of scenario 2 are considered in this study. Scenario 2 (Type I) involves an increase in in-country processing in Ghana, resulting from a decrease in the percentage of cocoa beans exported outside Ghana, and the simultaneous decline in in-country processing in Cote d'Ivoire as a result of increased cocoa beans export. For scenario 2 (Type II), in-country processing in Ghana increases but in-country processing levels in Cote d'Ivoire remain unchanged. Compared with the baseline levels, scenario 2 (Type I) and scenario 2 (Type II) result in a 1.25-year loss and 1 year loss in resilience at an aggregate level, respectively. Results of the impact of scenario 2 on the baseline levels are shown in Figure 31.

Scenario 3 (Type I) deals with a decrease in in-country processing (i.e., an increase in cocoa beans export) in Ghana and decreased cocoa beans export in Cote d'Ivoire. Results of the impact of scenario 3 on the baseline levels are shown in Figure 32. Scenario 3 (Type I) results in a 6.5-year loss in resilience. However, the cocoa value chain loses resiliency for 6 years under scenario 3 (Type II).

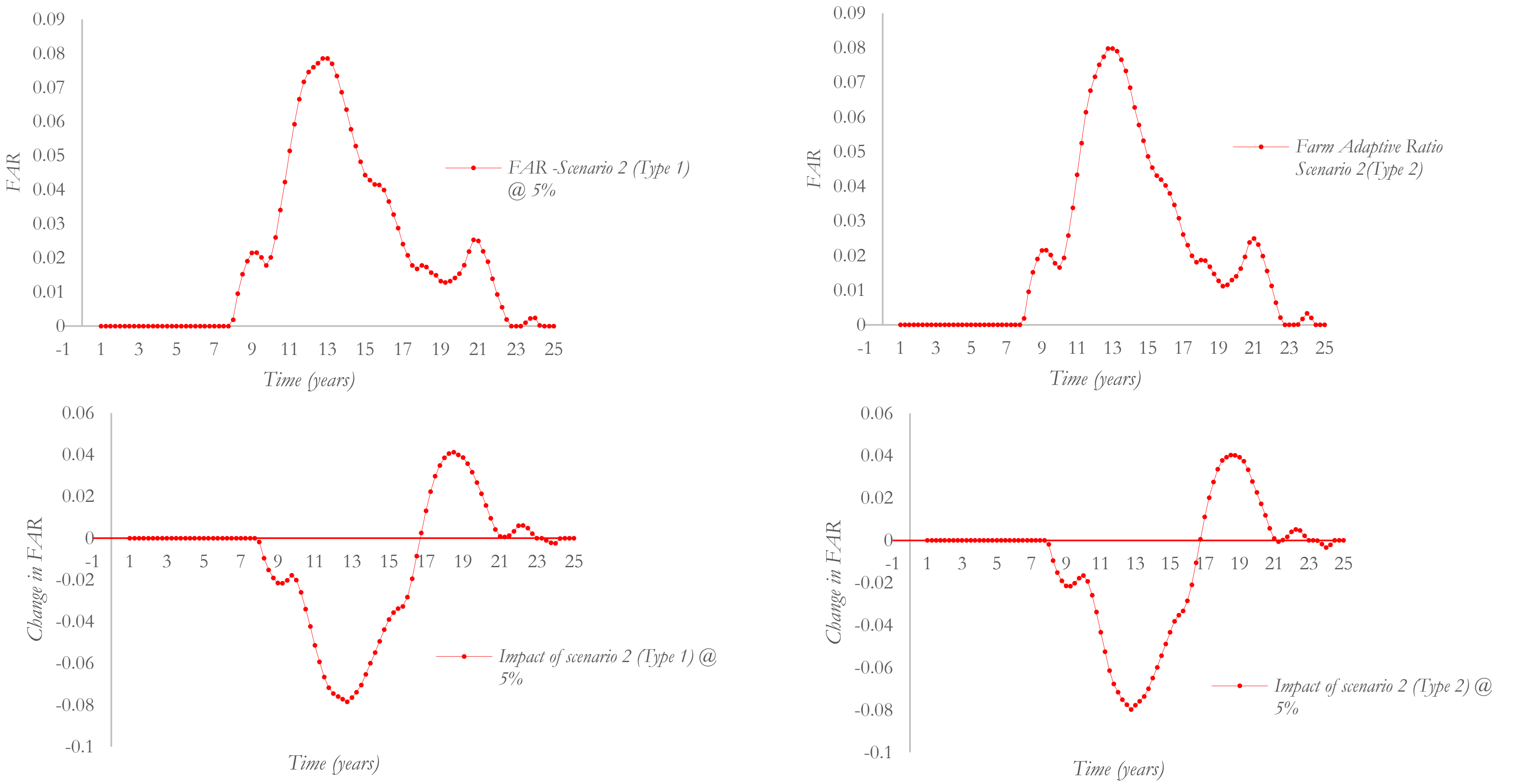


Figure 31 The impact of variable-input diversification and conflicting forward integration strategies (Scenario 2) on aggregate resilience

Between the two variants of scenario 3, the results suggest that Ghana's cocoa value chain is more resilient when the in-country processing levels are retained in response to increase in-country processing in Cote d'Ivoire than when the in-country processing levels are decreased.

When the isolated impact of variable-input diversification is factored in the total loss experienced under each scenario, the findings show that a cooperative forward integration strategy between Ghana and Cote d'Ivoire (scenario 1) contributes to a 2.5-year loss in the period of gains (good years) recorded at the baseline resilience level. An increase in or retention of the in-country processing levels in Ghana and the simultaneous decrease in in-country processing in Cote d'Ivoire (scenario 2) account for a 5-year loss in the period of gains baseline resilience level.

To validate the findings, the differences in the aggregate resilience patterns for the five scenarios are represented in the adaptive cycle of resilience theory (Rosanna & Giovanni, 2015). The changes in the baseline level represent the adaptive capacity of the cocoa value chain (Holling, 2001). Superficially, the aggregate resilience level for the baseline, scenario 1 and scenario 3 (Type II) undergo similar adaptive phases; *conservation – collapse – growth – conservation*. The baseline resilience level shows prolonged periods of conservation (13.5 years), 5.5 years in the growth phase and 5.25 years in the collapse phase.

A summary of the results of the scenario impact on resilience is presented in Table 21.

Table 21 Impact of scenarios on the aggregate resilience

	Baseline	*Scenario 1*	*Scenario 2 (Type I)*	*Scenario 2 (Type II)*	*Scenario 3 (Type I)*	*Scenario 3 (Type II)*
Period of gains (yrs.)	5.5	8.25	7.75	8	7.75	8.25
Period of loss (yrs.)	5.25	6	6.5	6.25	6.5	6
Period of stability (yrs.)	13.5	10	10	10	10	10

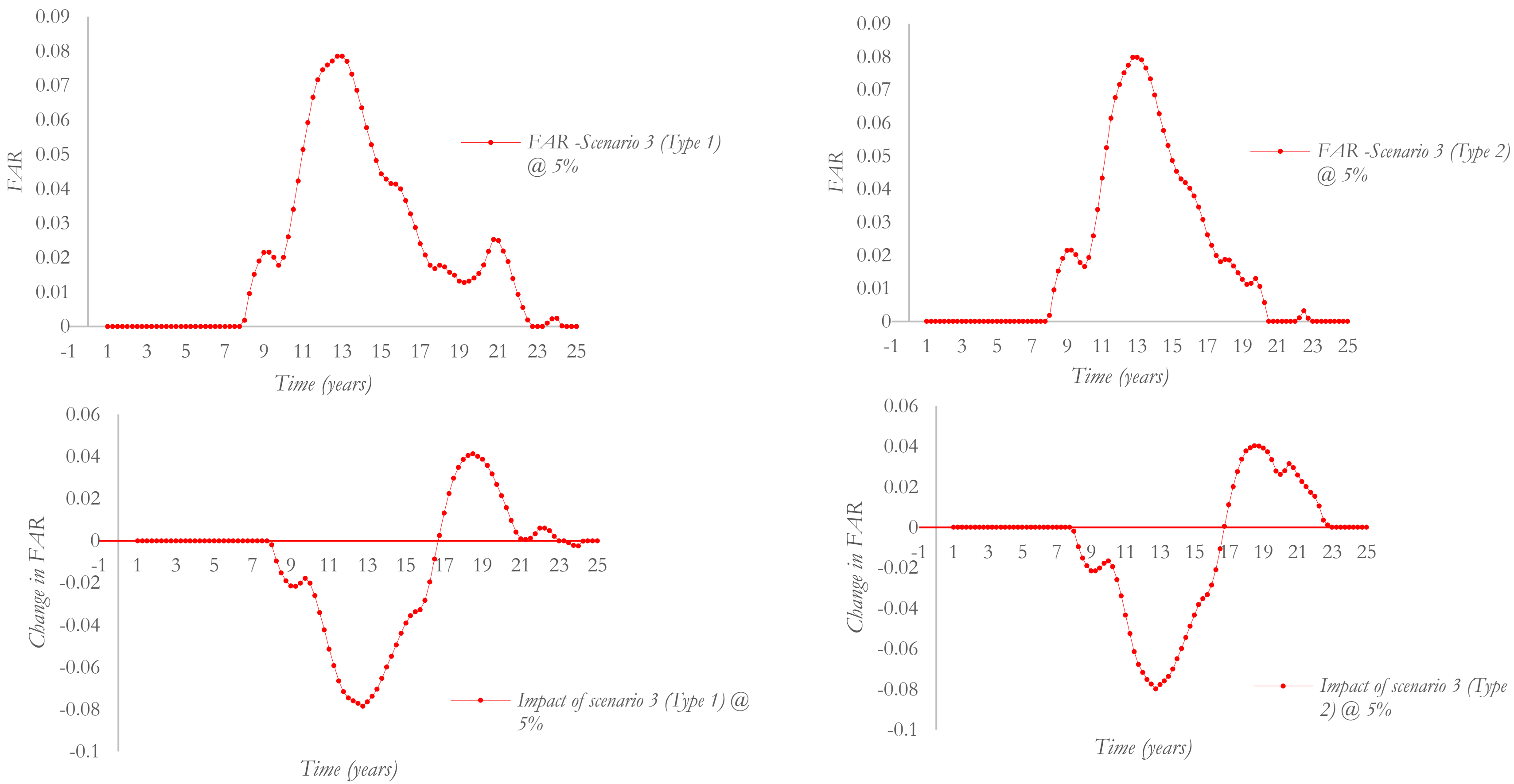


Figure 32 The impact of variable-input diversification and conflicting forward integration strategies (Scenario 3) on aggregate resilience

Under all the scenarios, the cocoa value chain remains in a conservation phase for ten years; this is relatively lower than the baseline level. Also, for all scenarios, the cocoa value chain remains in a collapse phase for a relatively longer duration compared with the baseline level. However, the cocoa value chain remains in the growth phase for a longer period for all scenarios compared with the baseline level. These results indicate that some level of complementarity accompanies the simultaneous pursuit of variable-input diversification and forward integration strategy.

According to Sundstrom and Allen (2019), systems spend the most time in the conservation and growth phases. Based on the duration in the growth phase, the cocoa value chain can adapt and retain its function the most under scenarios 1 and 3 (Type II) than scenario 2 (Types I & II) and scenario 3 (Type I). The cocoa value chain remains in the growth phase for 8.25 years under both scenarios 1 and 3 (Type II).

Comparatively, the cocoa value chain is more resilient under scenario 2 (Type I) than scenario 2 (Type II) and scenario 3 (Type I). This is because, under scenario 2 (Type I), the cocoa value chain remains in a growth phase for a relatively long period (i.e., eight years) and a collapse phase for a relatively shorter period (6.25 years). Thus, the cocoa value chain is the least resilient under scenario 3 (Type I) and scenario 2 (Type I). In sum, the findings suggest that irrespective of the forward integration adopted by Cote d'Ivoire, the aggregate resilience of Ghana's cocoa value chain will be enhanced when Ghana embarks on in-country processing or retains the in-country processing levels.

6.3.3 Practical Implication for Chain Actors

A disaggregated analysis of the impact of each scenario at the individual chain actor level expatiates the results obtained at the aggregate chain level. The difference in the volumes of raw materials (cocoa beans) flow throughout the chain between the baseline level, and each scenario (shown in Table 22) is the basis for determining the magnitude of the impact of each scenario.

Table 22 Resilience impact on chain actors – Difference in Baseline level and Scenario 1, 2 & 3

	Scenario 1			*Scenario 2*						*Scenario 3*					
	Producers	In-country processors	Exporter	Producers		In-country processors		Exporter		Producers		In-country processors		Exporter	
Good years	10	10	10	7.5 [a]	7.5 [b]	7.5 [a]	7.5 [b]	7.5 [a]	7.5 [b]	8 [a]	10 [b]	8 [a]	10 [b]	8 [a]	10 [b]
Bad years	13.5	13.5	13.5	16 [a]	16 [b]	16 [a]	16 [b]	16 [a]	16 [b]	15.5 [a]	13.5 [b]	15.5 [a]	13.5 [b]	15.5 [a]	13.5 [b]
Stable years	0.75	0.75	0.75	0.75 [a]	0.75 [b]	0.75 [a]	0.75 [b]	0.75 [a]	0.75 [b]	0.75 [a]	0.75 [b]	0.75 [a]	0.75 [b]	0.75 [a]	0.75 [b]
Mean gains (%)	10.48	15.59	9.18	19.9 [a]	19.71[b]	25.45 [a]	25.26 [b]	18.49 [a]	18.31[b]	19.38 [a]	10.48 [b]	12.53 [a]	10.48 [b]	17.99 [a]	10.48 [b]
Mean loss (%)	19.22	24.74	17.82	7.40 [a]	7.50 [b]	12.38 [a]	12.48 [b]	6.15 [a]	6.25 [b]	7.33 [a]	19.22[b]	1.17 [a]	19.22[b]	6.08 [a]	19.22[b]

[a] *Type I* [b] *Type II*

The period of gains and loss in the volumes of raw materials are considered as the 'good' and 'bad' years, respectively. Compared with the 'good' and 'bad' years of the baseline, the duration of 'good' and 'bad' years of cocoa production increases and decrease respectively for all scenarios at an aggregate level. Cocoa producers suffer the highest loss under scenario 1 and scenario 3 (Type II). The average loss in the cocoa production levels for all scenarios is 2,025 metric tonnes in the 'bad' years.

Practically, these losses may seem to be devastating at an aggregate level. However, considering the number of smallholders involved in cocoa farming in Ghana, the findings suggest that the adaptive strategies adopted under the three scenarios result in marginal changes in the production levels of individual cocoa farmers at the disaggregated levels. The results suggest that the pursuit of on-farm diversification at an individual farmer level translates into chain-level resilience when proceeds from the alternative enterprise are reinvested into cocoa production (Kray et al., 2018). Considering the relatively short duration of 'bad' years, cocoa producers are more resilient under scenario 1 and scenario 3 (Type II) than scenario 2 (Type I & II) and scenario 3 (Type I).

In-country processors earn the highest gains and loss under scenario 2 (Type I & II) and scenario 1, respectively. The gains are for a relatively short period than the loss. Given that the average safety stock held by a firm is between 10% to 20% of the average stock (Rădășanu, 2016), in-country processors will deplete their safety stocks in two consecutive 'bad' years under scenario 1.

Although the duration of loss is the lowest in scenario 1, in-country processors can use their safety stocks to maintain their normal processing levels under scenario 2 (Type I & II) and scenario 3 (Type I & II). Thus, although scenario 1 improves the aggregate resilience level, in-country processors will be the most affected in terms of the magnitude of impact during the periods of collapse or 'bad' years.

The exporter experiences the highest loss in scenario 2 (Type II) and scenario 3 (Type II). The lowest gains will be experienced under scenario 1. Indeed, lesser volumes of cocoa beans will be available on the world commodity market when Ghana and Cote d'Ivoire cooperate to increase local cocoa processing simultaneously. The highest gains are experienced under scenario 2 (Type I). Given that the exporter of cocoa beans in Ghana is technically the government, the results suggest that when there is a conflict in the forward integration strategy pursued by Ghana and Cote d'Ivoire, Ghana will benefit more when the in-country processing levels are retained or increased.

6.4 Conclusion

This paper examined *ex-ante* the impact of five scenarios involving variable-input diversification, cooperative and conflicting forward integration strategies by Ghana and Cote d'Ivoire on the aggregate resilience of Ghana's cocoa value chain. The findings indicate that complementarity exists between on-farm diversification and cooperative forward integration strategy.

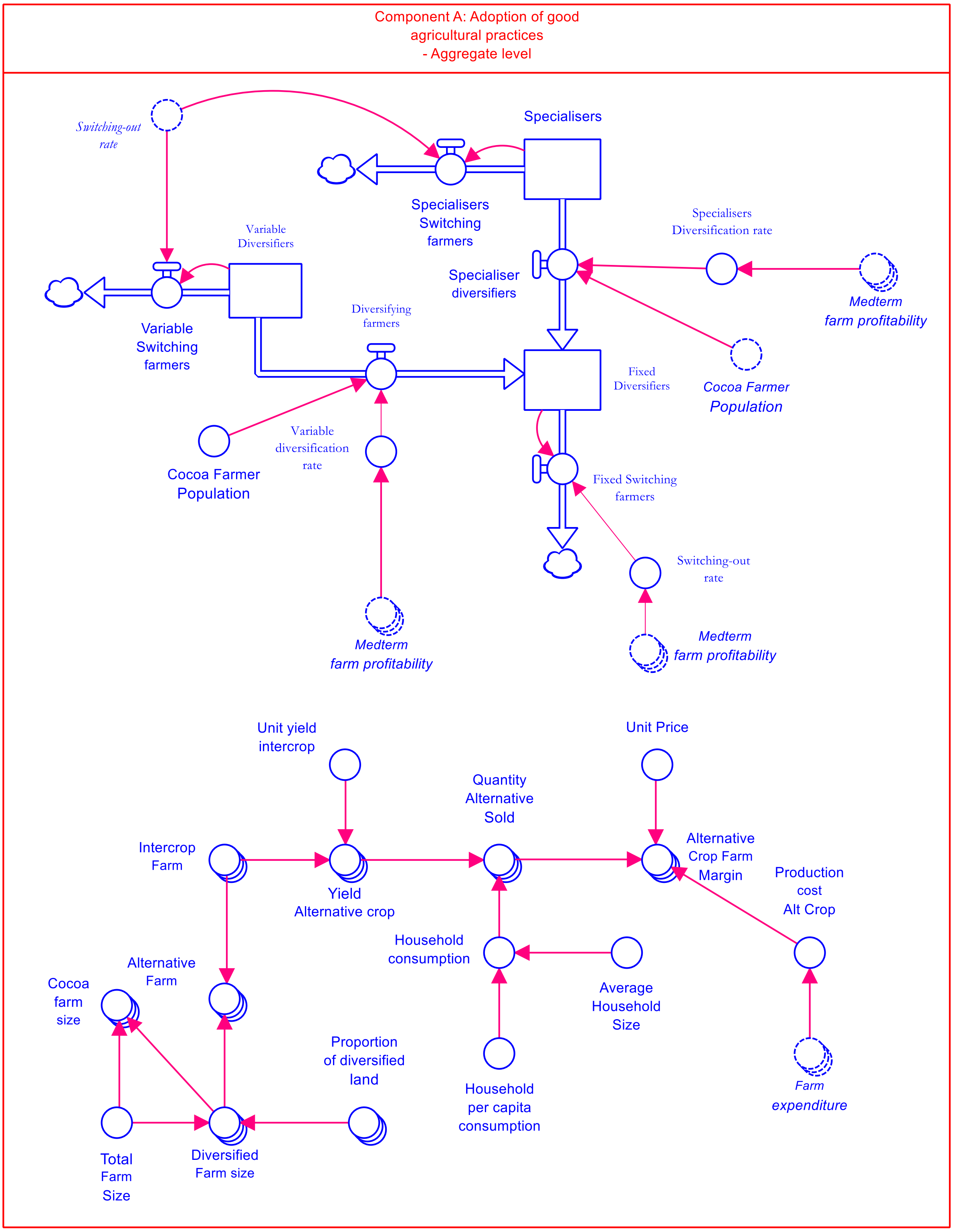
An adaptive strategy involving the simultaneous pursuit of variable-input diversification and either a cooperative forward integration or conflicting forward integration, with Ghana retaining the in-country processing levels, is the most resilient strategy. Under these strategies, the cocoa value chain undergoes four prominent phases of the adaptive cycle: *conservation – collapse – growth – conservation*; with the growth phase having the longest duration. The findings of this paper also suggest that should the intended harmonisation of forward integration strategies between Ghana and Cote d'Ivoire fail to materialise, Ghana's cocoa value chain will still be resilient when Ghana increases or retain the in-country processing levels irrespective of the forward integration strategy adopted by Cote d'Ivoire.

At an individual level, cocoa producers will not be significantly impacted when they engage in variable-input diversification, and the government increases the percentage of cocoa production allocated for in-country processing simultaneously. In the 'bad' years (collapse phase) when cocoa production levels are at their lowest, cocoa producers can rely on proceeds from the alternative enterprise. In-country processors will be the worst impacted during the 'bad' years when Ghana and Cote d'Ivoire cooperate to increase local processing. Three consecutive 'bad' years can lead to depletion of safety stocks. However, considering the relatively short period, in-country processors can withstand the cocoa value chain's collapse phase when the safety stock level is 25% of the average processing stock level.

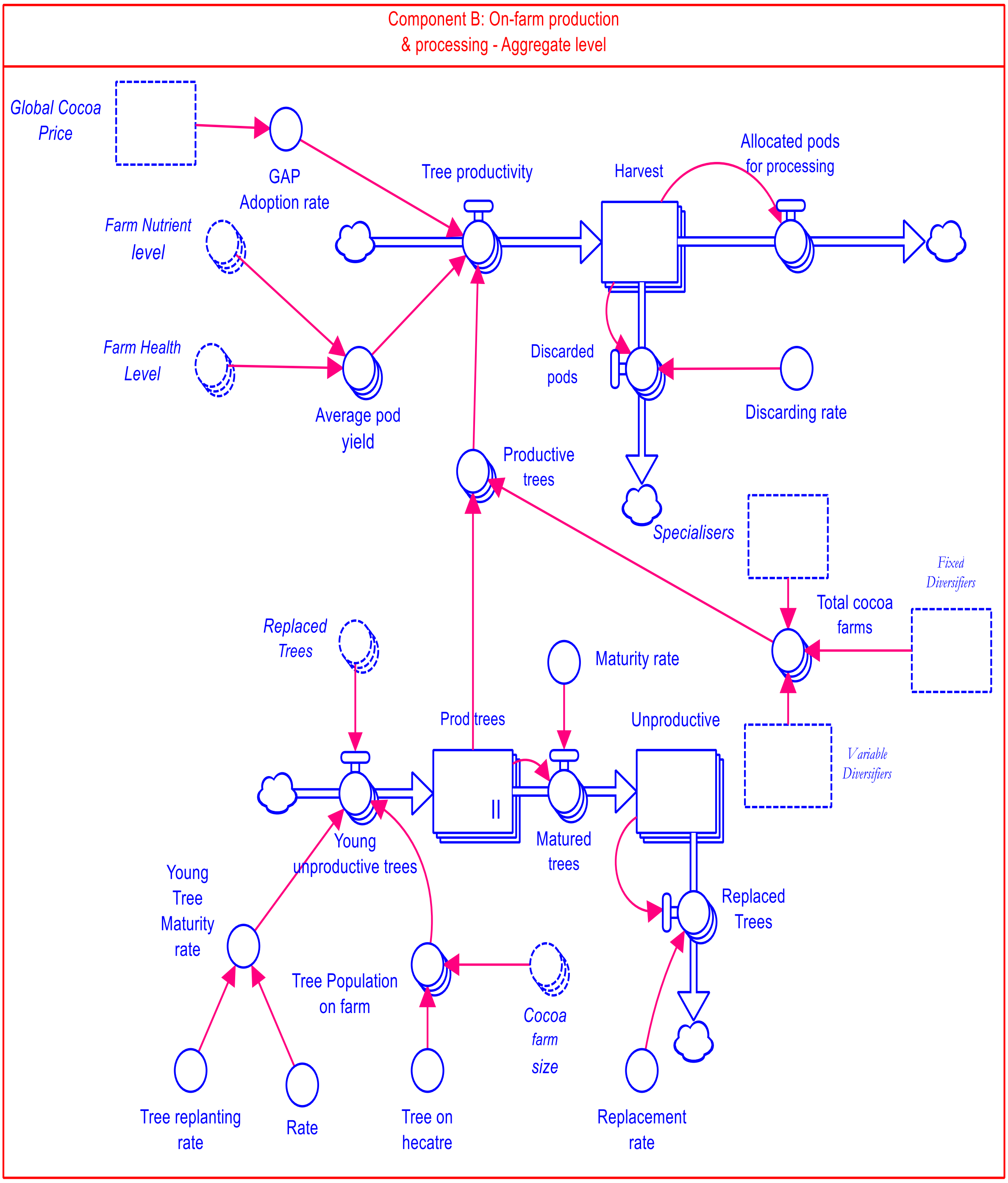
6.4.1 Limitation and Future Studies

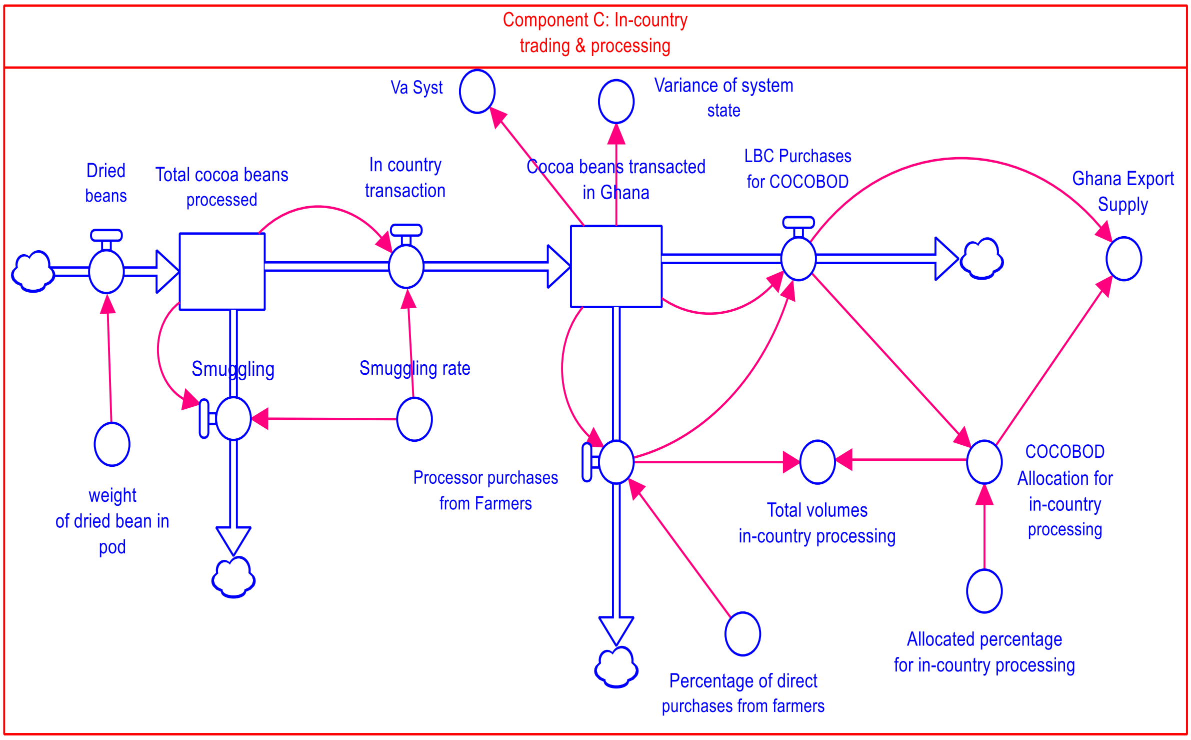
In all scenarios, the adoption of good farm management practices, that is a determinant of cocoa tree productivity, was kept at a fixed optimal and suboptimal levels. The simultaneous increase or decrease in adoption rate was not factored in these scenarios. Similarly, a possible increase in switching out rates was not considered in this study. Future studies can delve into how the fixed-input diversification impact agricultural value chain resilience at an aggregate level.

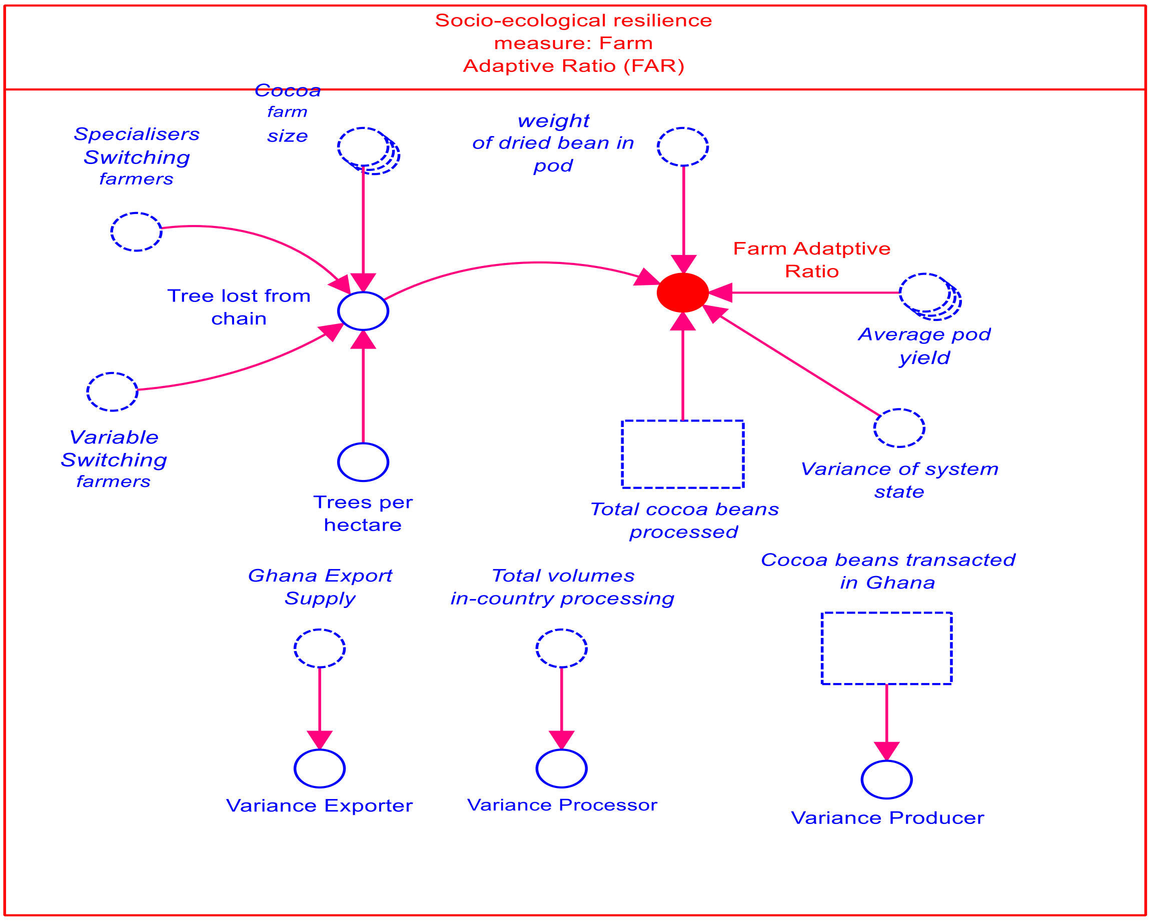
Appendix 6.0

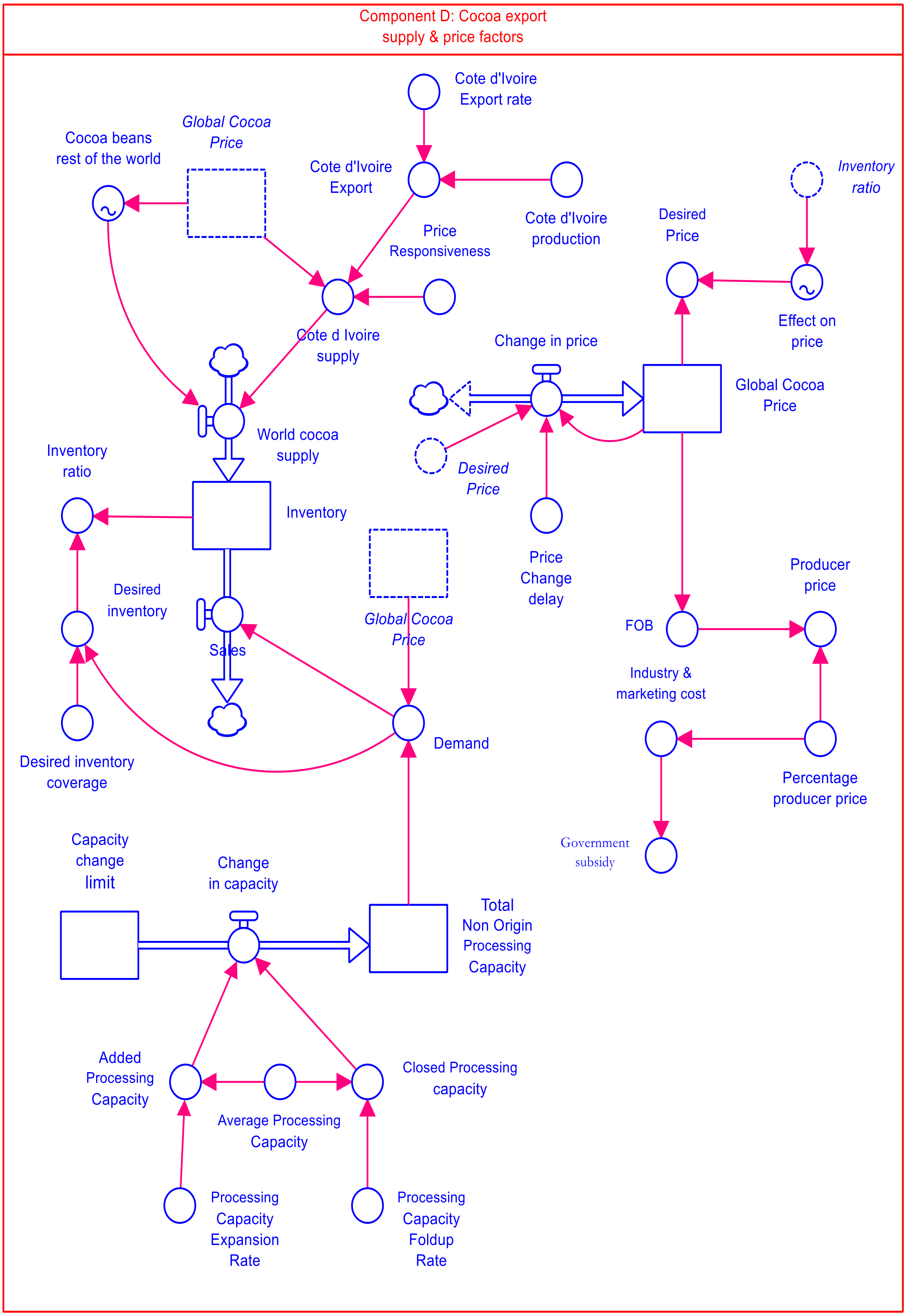


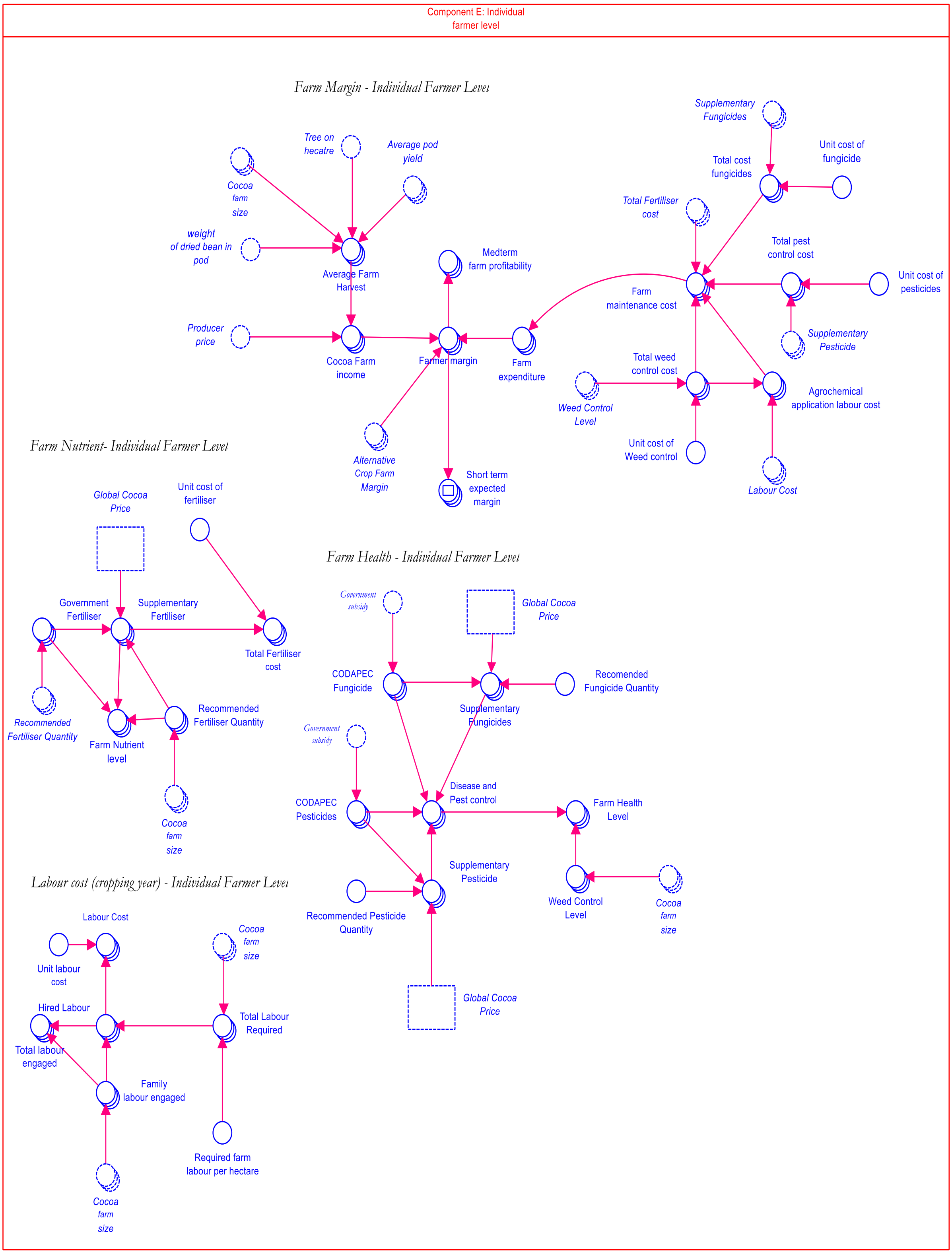
Component A: Adoption of good agricultural practices - Aggregate level
Switching-out rate
Specialisers
Specialisers Switching farmers
Variable Diversifiers
Specialisers Diversification rate
Specialiser diversifiers
Medterm farm profitability
Variable Switching farmers
Diversifying farmers
Fixed Diversifiers
Cocoa Farmer Population
Variable diversification rate
Cocoa Farmer Population
Fixed Switching farmers
Switching-out rate
Medterm farm profitability
Medterm farm profitability
Unit yield intercrop
Unit Price
Quantity Alternative Sold
Intercrop Farm
Alternative Crop Farm Margin
Production cost Alt Crop
Yield Alternative crop
Household consumption
Alternative Farm
Cocoa farm size
Average Household Size
Proportion of diversified land
Household per capita consumption
Farm expenditure
Total Farm Size
Diversified Farm size


Component B: On-farm production
& processing - Aggregate level
Global Cocoa
Price
GAP
Adoption rate
Tree productivity
Harvest
Allocated pods
for processing
Farm Nutrient
level
Farm Health
Level
Average pod
yield
Discarded
pods
Discarding rate
Productive
trees
Specialisers
Fixed
Diversifiers
Total cocoa
farms
Replaced
Trees
Maturity rate
Prod trees
Unproductive
Variable
Diversifiers
Young
unproductive trees
Matured
trees
Young
Tree
Maturity
rate
Replaced
Trees
Tree Population
on farm
Cocoa
farm
size
Tree replanting
rate
Rate
Tree on
hecatre
Replacement
rate


Component C: In-country
trading & processing
Va Syst
Variance of system
state
Dried
beans
Total cocoa beans
processed
In country
transaction
Cocoa beans transacted
in Ghana
LBC Purchases
for COCOBOD
Ghana Export
Supply
Smuggling
Smuggling rate
weight
of dried bean in
pod
Processor purchases
from Farmers
Total volumes
in-country processing
COCOBOD
Allocation for
in-country
processing
Allocated percentage
for in-country processing
Percentage of direct
purchases from farmers


Socio-ecological resilience
measure: Farm
Adaptive Ratio (FAR)
Specialisers
Switching
farmers
Cocoa
farm
size
weight
of dried bean in
pod
Farm Adatptive
Ratio
Tree lost from
chain
Average pod
yield
Variable
Switching
farmers
Trees per
hectare
Total cocoa beans
processed
Variance of system
state
Ghana Export
Supply
Total volumes
in-country processing
Cocoa beans transacted
in Ghana
Variance Exporter
Variance Processor
Variance Producer


Component D: Cocoa export supply & price factors
Cote d'Ivoire Export rate
Global Cocoa Price
Cocoa beans rest of the world
Cote d'Ivoire Export
Cote d'Ivoire production
Inventory ratio
Price Responsiveness
Desired Price
Effect on price
Cote d Ivoire supply
Change in price
Global Cocoa Price
World cocoa supply
Desired Price
Inventory ratio
Inventory
Price Change delay
Producer price
Desired inventory
Global Cocoa Price
FOB
Sales
Industry & marketing cost
Demand
Desired inventory coverage
Percentage producer price
Government subsidy
Capacity change limit
Change in capacity
Total Non Origin Processing Capacity
Added Processing Capacity
Closed Processing capacity
Average Processing Capacity
Processing Capacity Expansion Rate
Processing Capacity Foldup Rate


Component E: Individual farmer level
Farm Margin - Individual Farmer Level
Cocoa farm size
Tree on hecatre
Average pod yield
weight of dried bean in pod
Average Farm Harvest
Producer price
Cocoa Farm income
Farmer margin
Medterm farm profitability
Farm expenditure
Alternative Crop Farm Margin
Short term expected margin
Supplementary Fungicides
Total cost fungicides
Unit cost of fungicide
Total Fertiliser cost
Total pest control cost
Unit cost of pesticides
Farm maintenance cost
Supplementary Pesticide
Total weed control cost
Weed Control Level
Agrochemical application labour cost
Unit cost of Weed control
Labour Cost
Farm Nutrient- Individual Farmer Level
Global Cocoa Price
Unit cost of fertiliser
Government Fertiliser
Supplementary Fertiliser
Total Fertiliser cost
Recommended Fertiliser Quantity
Farm Nutrient level
Recommended Fertiliser Quantity
Cocoa farm size
Farm Health - Individual Farmer Level
Government subsidy
Global Cocoa Price
CODAPEC Fungicide
Supplementary Fungicides
Recomended Fungicide Quantity
Government subsidy
CODAPEC Pesticides
Disease and Pest control
Farm Health Level
Supplementary Pesticide
Recommended Pesticide Quantity
Weed Control Level
Cocoa farm size
Global Cocoa Price
Labour cost (cropping year) - Individual Farmer Level
Labour Cost
Unit labour cost
Cocoa farm size
Hired Labour
Total labour engaged
Total Labour Required
Family labour engaged
Required farm labour per hectare
Cocoa farm size

Appendix 6.1

	Equation	Properties	Units	Annotation
Capacity_change_limit(t)	Capacity_change_limit(t - dt) + (- Change_in_capacity) * dt	INIT Capacity_change_limit = Change_in_capacity	{kg/year}	NON-NEGATIVE
Cocoa_beans_transacted_in_Ghana(t)	Cocoa_beans_transacted_in_Ghana(t - dt) + (In_country_transaction - Processor_purchases_from_Farmers - LBC_Purchases_for_COCOBOD) * dt	INIT Cocoa_beans_transacted_in_Ghana = In_country_transaction	{kg}	NON-NEGATIVE
Fixed_Diversifiers(t)	Fixed_Diversifiers(t - dt) + (Diversifying_farmers + Specialiser_diversifiers - Fixed_Switching_farmers) * dt	INIT Fixed_Diversifiers = 0	{farmers}	NON-NEGATIVE
Global_Cocoa_Price(t)	Global_Cocoa_Price(t - dt) + (Change_in_price) * dt	INIT Global_Cocoa_Price = 2000	{USD/tonne}	NON-NEGATIVE
Harvest[Farmer_type, Diversification_type](t)	Harvest[Farmer_type, Diversification_type](t - dt) + (Tree_productivity[Farmer_type, Diversification_type] - Allocated_pods_for_processing[Farmer_type, Diversification_type] - Discarded_pods[Farmer_type, Diversification_type]) * dt	INIT Harvest[Farmer_type, Diversification_type] = Tree_productivity	{pods}	NON-NEGATIVE
Inventory(t)	Inventory(t - dt) + (World_cocoa_supply - Sales) * dt	INIT Inventory = Desired_inventory	{kg}	NON-NEGATIVE
Prod_trees[Diversification_type](t)	Prod_trees[Diversification_type](t - dt) + (Young_unproductive_trees[Diversification_type] - Matured_trees[Diversification_type]) * dt	INIT Prod_trees[Diversification_type] = 2805	{trees}	NON-NEGATIVE
Specialisers(t)	Specialisers(t - dt) + (- Specialiser_diversifiers - Specialisers_Switching_farmers) * dt	INIT Specialisers = 76000	{farmers}	NON-NEGATIVE
Total_cocoa_beans_processed(t)	Total_cocoa_beans_processed(t - dt) + (Dried_beans - In_country_transaction - Smuggling) * dt	INIT Total_cocoa_beans_processed = Dried_beans	{kg}	NON-NEGATIVE

Total_Non_Origin_Processing_Capacity(t)	Total_Non_Origin_Processing_Capacity(t - dt) + (Change_in_capacity) * dt	INIT Total_Non_Origin_Processing_Capacity = 3452111000 + Added_Processing_Capacity - Closed_Processing_capacity	{kg}	NON-NEGATIVE
Unproductive[Diversification_type](t)	Unproductive[Diversification_type](t - dt) + (Matured_trees[Diversification_type] - Replaced_Trees[Diversification_type]) * dt	INIT Unproductive[Diversification_type] = 495	{trees}	NON-NEGATIVE
Variable_Diversifiers(t)	Variable_Diversifiers(t - dt) + (- Diversifying_farmers - Variable_Switching_farmers) * dt	INIT Variable_Diversifiers = 304000	{farmers}	NON-NEGATIVE
Allocated_pods_for_processing[Farmer_type, Diversification_type]	Harvest	OUTFLOW PRIORITY: 1	{pods}	UNIFLOW
Change_in_capacity	Added_Processing_Capacity-Closed_Processing_capacity		{kg/year}	UNIFLOW
Change_in_price	(Desired_Price-Global_Cocoa_Price)/Price_Change_delay		{USD}	
Discarded_pods[Farmer_type, Diversification_type]	Discarding_rate*Harvest	OUTFLOW PRIORITY: 2	{pods}	UNIFLOW
Diversifying_farmers	Variable_diversification_rate*Cocoa_Farmer_Population	OUTFLOW PRIORITY: 1	{farmers}	UNIFLOW
Dried_beans	SUM(Allocated_pods_for_processing)*weight_of_dried_bean_in_pod		{kg}	UNIFLOW
Fixed_Switching_farmers	Fixed_Diversifiers*"Switching-out_rate"		{farmers}	UNIFLOW
In_country_transaction	Total_cocoa_beans_processed *(1- Smuggling_rate)	OUTFLOW PRIORITY: 1	{kg}	UNIFLOW
LBC_Purchases_for_COCOBOD	Cocoa_beans_transacted_in_Ghana-Processor_purchases_from_Farmers	OUTFLOW PRIORITY: 2	{kg}	UNIFLOW

Matured_trees[Diversification_type]	Prod_trees*Maturity_rate		{trees}	UNIFLOW
Processor_purchases_from_Farmers	Percentage_of_direct_purchases_from_farmers*Cocoa_beans_transacted_in_Ghana	OUTFLOW PRIORITY: 1	{kg}	UNIFLOW
Replaced_Trees[Diversification_type]	Unproductive*Replacement_rate		{trees}	UNIFLOW
Sales	Demand		{kg}	UNIFLOW
Smuggling	Smuggling_rate*Total_cocoa_beans_processed	OUTFLOW PRIORITY: 2	{kg}	UNIFLOW
Specialiser_diversifiers	Cocoa_Farmer_Population*Specialisers_Diversification_rate	OUTFLOW PRIORITY: 1	{farmers}	UNIFLOW
Specialisers_Switching_farmers	Specialisers*"Switching-out_rate"	OUTFLOW PRIORITY: 2	{farmers}	UNIFLOW
Tree_productivity[Adopters, Fixed_input]	Average_pod_yield[Adopters,Fixed_input]*(Productive_trees[Fixed_input]*GAP_Adoption_rate)		{pods}	UNIFLOW
Tree_productivity[Adopters, Variable_input]	Average_pod_yield[Adopters,Variable_input]*(Productive_trees[Variable_input]*GAP_Adoption_rate)		{pods}	
Tree_productivity[Adopters, Specialisers]	Average_pod_yield[Adopters,Specialisers]*(Productive_trees[Specialisers]*GAP_Adoption_rate)		{pods}	
Tree_productivity[Nonadopters, Fixed_input]	Average_pod_yield[Nonadopters,Fixed_input]*(Productive_trees[Fixed_input]*(1-GAP_Adoption_rate))		{pods}	
Tree_productivity[Nonadopters, Variable_input]	Average_pod_yield[Nonadopters,Variable_input]*(Productive_trees[Variable_input]*(1-GAP_Adoption_rate))		{pods}	
Tree_productivity[Nonadopters, Specialisers]	Average_pod_yield[Nonadopters,Specialisers]*(Productive_trees[Specialisers] *(1-GAP_Adoption_rate))		{pods}	
Variable_Switching_farmers	"Switching-out_rate"*Variable_Diversifiers	OUTFLOW PRIORITY: 2	{farmers}	UNIFLOW
World_cocoa_supply	Ghana_Export_Supply+Cocoa_beans_rest_of_the_world+Cote_d_Ivoire_supply		{kg}	UNIFLOW

Young_unproductive_trees[Diversification_type]	(Tree_Population_on_farm*Young_Tree_Maturity_rate)+Replaced_Trees	{trees}	UNIFLOW
Added_Processing_Capacity	Average_Processing_Capacity*Processing_Capacity_Expansion_Rate	{kg}	
Agrochemical_application_labour_cost[Adopters, Fixed_input]	Labour_Cost[Fixed_input] - Total_weed_control_cost[Adopters,Fixed_input]	{USD}	
Agrochemical_application_labour_cost[Adopters, Variable_input]	Labour_Cost[Variable_input] - Total_weed_control_cost[Adopters,Variable_input]	{USD}	
Agrochemical_application_labour_cost[Adopters, Specialisers]	Labour_Cost[Specialisers]- Total_weed_control_cost[Adopters,Specialisers]	{USD}	
Agrochemical_application_labour_cost[Nonadopters, Fixed_input]	Labour_Cost[Fixed_input]- Total_weed_control_cost[Nonadopters,Fixed_input]	{USD}	
Agrochemical_application_labour_cost[Nonadopters, Variable_input]	Labour_Cost[Variable_input] - Total_weed_control_cost[Nonadopters,Variable_input]	{USD}	
Agrochemical_application_labour_cost[Nonadopters, Specialisers]	Labour_Cost[Specialisers] - Total_weed_control_cost[Nonadopters,Specialisers]	{USD}	
"Allocated_percentage_for_in-country_processing"	0.19	{percent}	
Alternative_Crop_Farm_Margin[Fixed_input]	(Quantity_Alternative_Sold[Fixed_input]*Unit_Price) - Production_cost_Alt_Crop	{USD}	
Alternative_Crop_Farm_Margin[Variable_input]	(Quantity_Alternative_Sold[Variable_input]*Unit_Price) -Production_cost_Alt_Crop	{USD}	

Alternative_Crop_Farm_Margin[Specialisers]	(Quantity_Alternative_Sold[Specialisers]*Unit_Price)-Production_cost_Alt_Crop	{USD}
Alternative_Farm[Diversification_type]	Diversified_Farm_size +Intercrop_Farm	{farm}
Average_Farm_Harvest[Adopters, Fixed_input]	Tree_on_hecatre*Average_pod_yield[Adopters,Fixed_input]*weight_of_dried_bean_in_pod*Cocoa_farm_size[Fixed_input]	{pods}
Average_Farm_Harvest[Adopters, Variable_input]	Tree_on_hecatre*Average_pod_yield[Adopters,Variable_input]*weight_of_dried_bean_in_pod*Cocoa_farm_size[Variable_input]	{pods}
Average_Farm_Harvest[Adopters, Specialisers]	Tree_on_hecatre*Average_pod_yield[Adopters,Specialisers]*weight_of_dried_bean_in_pod*Cocoa_farm_size[Specialisers]	{pods}
Average_Farm_Harvest[Nonadopters, Fixed_input]	Tree_on_hecatre*Average_pod_yield[Nonadopters,Fixed_input]*weight_of_dried_bean_in_pod*Cocoa_farm_size[Fixed_input]	{pods}
Average_Farm_Harvest[Nonadopters, Variable_input]	Tree_on_hecatre*Average_pod_yield[Nonadopters,Variable_input]*weight_of_dried_bean_in_pod*Cocoa_farm_size[Variable_input]	{pods}
Average_Farm_Harvest[Nonadopters, Specialisers]	Tree_on_hecatre*Average_pod_yield[Nonadopters,Specialisers]*weight_of_dried_bean_in_pod*Cocoa_farm_size[Specialisers]	{pods}
Average_Household_Size	6	{people}
Average_pod_yield[Adopters, Fixed_input]	IF((Farm_Nutrient_level[Adopters,Fixed_input]= 2) AND(Farm_Health_Level[Adopters,Fixed_input] = 2)) THEN 25 ELSE (TRIANGULAR(15, 20, 23, 100))	{pods}
Average_pod_yield[Adopters, Variable_input]	IF((Farm_Nutrient_level[Adopters,Variable_input]= 2) AND(Farm_Health_Level[Adopters,Variable_input] = 2)) THEN 25 ELSE (TRIANGULAR(15, 20, 23, 100))	{pods}

Average_pod_yield[Adopters, Specialisers]	IF((Farm_Nutrient_level[Adopters,Specialisers]= 2) AND(Farm_Health_Level[Adopters,Specialisers] = 2)) THEN 25 ELSE (TRIANGULAR(15, 20, 23, 100))	{pods}
Average_pod_yield[Nonadopters, Fixed_input]	IF((Farm_Nutrient_level[Nonadopters,Fixed_input]=1) AND(Farm_Health_Level[Nonadopters,Fixed_input] =1)) THEN (TRIANGULAR(10, 14, 15, 100)) ELSE 20	{pods}
Average_pod_yield[Nonadopters, Variable_input]	IF((Farm_Nutrient_level[Nonadopters,Variable_input]= 1) AND(Farm_Health_Level[Nonadopters,Variable_input] =1)) THEN (TRIANGULAR(10, 14, 15, 100)) ELSE 20	{pods}
Average_pod_yield[Nonadopters, Specialisers]	IF((Farm_Nutrient_level[Nonadopters,Specialisers]=1) AND(Farm_Health_Level[Nonadopters,Specialisers]=1)) THEN (TRIANGULAR(10, 14, 15, 100)) ELSE 20	{pods}
Average_Processing_Capacity	457850000	{kg}
Closed_Processing_capacity	Average_Processing_Capacity*Processing_Capacity_Foldup_Rate	{kg}
Cocoa_beans_rest_of_the_world	GRAPH(Global_Cocoa_Price) Points: (1200, 1.48e+09), (1292.85714286, 1.58e+09), (1385.71428571, 1.76e+09), (1478.57142857, 1.91e+09), (1571.42857143, 2.05e+09), (1664.28571429, 2.26e+09), (1757.14285714, 2.35e+09), (1850, 2.46e+09), (1942.85714286, 2.54e+09), (2035.71428571, 2.68e+09), (2128.57142857, 2.83e+09), (2221.42857143, 2.85e+09), (2314.28571429, 2.87e+09), (2407.14285714, 2.93e+09), (2500, 3e+09)	{kg}
Cocoa_Farm_income[Farmer_type, Diversification_type]	(Average_Farm_Harvest/1000)*Producer_price	{USD}
Cocoa_farm_size[Fixed_input]	Total_Farm_Size-Diversified_Farm_size[Fixed_input]	{hectares}

Cocoa_farm_size[Variable_input]	Total_Farm_Size-Diversified_Farm_size[Variable_input]	{hectares}
Cocoa_farm_size[Specialisers]	Total_Farm_Size-Diversified_Farm_size[Specialisers]	{hectares}
Cocoa_Farmer_Population	380000	{farmers}
"COCOBOD_Allocation_for_in-country_processing"	LBC_Purchases_for_COCOBOD*"Allocated_percentage_for_in-country_processing"	{kg}
CODAPEC_Fungicide[Farmer_type, Diversification_type]	IF(Government_subsidy = 1) THEN 4 ELSE (IF(Government_subsidy = 0.5)THEN 2 ELSE 0)	{times}
CODAPEC_Pesticides[Farmer_type, Diversification_type]	IF(Government_subsidy = 1)THEN 4 ELSE (IF(Government_subsidy = 0.5) THEN 2 ELSE 0)	{times}
Cote_d_Ivoire_supply	((Price_Responsiveness*((SMTH1(Global_Cocoa_Price, 1)-Global_Cocoa_Price)/Global_Cocoa_Price))*Cote_d'Ivoire_Export)+Cote_d'Ivoire_Export	{kg}
Cote_d'Ivoire_Export	Cote_d'Ivoire_production*Cote_d'Ivoire_Export_rate	{kg}
Cote_d'Ivoire_Export_rate	0.73	{percent}
Cote_d'Ivoire_production	1391800000	{kg}
Demand	Total_Non_Origin_Processing_Capacity*(SMTH1(Global_Cocoa_Price, 1)/Global_Cocoa_Price)	{kg}
Desired_inventory	Desired_inventory_coverage*Demand	{kg}
Desired_inventory_coverage	1	{year}

Desired_Price	Effect_on_price*Global_Cocoa_Price	{USD per tonne}
Discarding_rate	0.0000001	{percent}
Disease_and_Pest_control[Farmer_type, Diversification_type]	IF(((CODAPEC_Pesticides+Supplementary_Pesticide) = 4) AND((CODAPEC_Fungicide+Supplementary_Fungicides))= 4)THEN 2 ELSE 1	{times}
Diversified_Farm_size[Fixed_input]	Total_Farm_Size*Proportion_of_diversified_land[Fixed_input]	{hectares}
Diversified_Farm_size[Variable_input]	Total_Farm_Size*Proportion_of_diversified_land[Variable_input]	{hectares}
Diversified_Farm_size[Specialisers]	Total_Farm_Size*Proportion_of_diversified_land[Specialisers]	{hectares}
Effect_on_price	GRAPH(Inventory_ratio) Points: (0.000, 2.000), (0.200, 1.800), (0.400, 1.600), (0.600, 1.400), (0.800, 1.200), (1.000, 1.000), (1.200, 0.800), (1.400, 0.600), (1.600, 0.400), (1.800, 0.200), (2.000, 0.050)	
Family_labour_engaged[Diversification_type]	28.80 * Cocoa_farm_size	{man days}
Farm_Adatptive_Ratio	((Tree_lost_from_chain * Average_pod_yield[Adopters,Specialisers] * weight_of_dried_bean_in_pod) +ABS(Variance_of_system_state))/ SMTHN(Total_cocoa_beans_processed, 5, 1)	
Farm_expenditure[Farmer_type, Diversification_type]	SMTH1(Farm_maintenance_cost, 1)	{USD}
Farm_Health_Level[Farmer_type, Diversification_type]	IF((Weed_Control_Level =2) AND(Disease_and_Pest_control = 2)) THEN 2 ELSE 1	

Farm_maintenance_cost [Farmer_type, Diversification_type]	Total_cost_fungicides+Total_Fertiliser_cost+Total_weed_control_cost+Total_pest_control_cost+Agrochemical_application_labour_cost	{USD}
Farm_Nutrient_level[Adopters, Fixed_input]	IF((Government_Fertiliser[Fixed_input,Adopters]+Supplementary_Fertiliser[Adopters,Fixed_input]) =Recommended_Fertiliser_Quantity[Fixed_input]) THEN 2 ELSE 1	
Farm_Nutrient_level[Adopters, Variable_input]	IF((Government_Fertiliser[Variable_input,Adopters]+Supplementary_Fertiliser[Adopters,Variable_input]) =Recommended_Fertiliser_Quantity[Variable_input]) THEN 2 ELSE 1	
Farm_Nutrient_level[Adopters, Specialisers]	IF((Government_Fertiliser[Specialisers,Adopters]+Supplementary_Fertiliser[Adopters,Specialisers]) =Recommended_Fertiliser_Quantity[Specialisers]) THEN 2 ELSE 1	
Farm_Nutrient_level[Nonadopters, Fixed_input]	IF((Government_Fertiliser[Fixed_input,Nonadopters]+ Supplementary_Fertiliser[Nonadopters,Fixed_input]) =Recommended_Fertiliser_Quantity[Fixed_input]) THEN 2 ELSE 1	
Farm_Nutrient_level[Nonadopters, Variable_input]	IF((Government_Fertiliser[Variable_input,Nonadopters]+Supplementary_Fertiliser[Nonadopters,Variable_input]) =Recommended_Fertiliser_Quantity[Variable_input]) THEN 2 ELSE 1	
Farm_Nutrient_level[Nonadopters, Specialisers]	IF((Government_Fertiliser[Specialisers,Nonadopters]+Supplementary_Fertiliser[Nonadopters,Specialisers]) =Recommended_Fertiliser_Quantity[Specialisers]) THEN 2 ELSE 1	
Farmer_margin[Farmer_type, Diversification_type]	SMTH1(Cocoa_Farm_income, 1)+Alternative_Crop_Farm_Margin[Diversification_type]-Farm_expenditure	{USD}
FOB	Global_Cocoa_Price	{USD per tonne}

GAP_Adoption_rate	IF(Global_Cocoa_Price> SMTH1(Global_Cocoa_Price, 1)) THEN 0.4 ELSE 0.6	{percent}
Ghana_Export_Supply	LBC_Purchases_for_COCOBOD- "COCOBOD_Allocation_for_in-country_processing"	{kg}
Government_Fertiliser[Fixed_input, Adopters]	IF((Government_subsidy =0.5)OR(Government_subsidy >0.5)) THEN (0.5*Recommended_Fertiliser_Quantity[Fixed_input]) ELSE 0	{kg}
Government_Fertiliser[Fixed_input, Nonadopters]	IF((Government_subsidy =0.5)OR(Government_subsidy >0.5)) THEN (0.5*Recommended_Fertiliser_Quantity[Fixed_input]) ELSE 0	{kg}
Government_Fertiliser[Variable_input, Adopters]	IF((Government_subsidy =0.5)OR(Government_subsidy >0.5)) THEN (0.5*Recommended_Fertiliser_Quantity[Variable_input]) ELSE 0	{kg}
Government_Fertiliser[Variable_input, Nonadopters]	IF((Government_subsidy =0.5)OR(Government_subsidy >0.5)) THEN (0.5*Recommended_Fertiliser_Quantity[Variable_input]) ELSE 0	{kg}
Government_Fertiliser[S pecialisers, Adopters]	IF((Government_subsidy =0.5)OR(Government_subsidy >0.5)) THEN (0.5*Recommended_Fertiliser_Quantity[Specialisers]) ELSE 0	{kg}
Government_Fertiliser[S pecialisers, Nonadopters]	IF((Government_subsidy =0.5)OR(Government_subsidy >0.5)) THEN (0.5*Recommended_Fertiliser_Quantity[Specialisers]) ELSE 0	{kg}
Government_subsidy	IF(SMTH1(Industry_&_marketing_cost, 1) > Industry_&_marketing_cost) THEN 1 ELSE 0.5	

Hired_Labour[Diversification_type]	Total_Labour_Required-Family_labour_engaged	{man days}
Household_consumption	Household_per_capita_consumption*Average_Household_Size	{kg}
Household_per_capita_consumption	101.8	{kg}
Industry_&_marketing_cost	1-Percentage_producer_price	{percent}
Intercrop_Farm[Diversification_type]	0.8	{hectares}
Inventory_ratio	Inventory/Desired_inventory	
Labour_Cost[Diversification_type]	Hired_Labour*Unit_labour_cost	{USD}
Maturity_rate	STEP(0.15, 30)	{percent}
Medterm_farm_profitability[Farmer_type, Diversification_type]	SMTHN(Farmer_margin, 5, 1)	{USD}
Percentage_of_direct_purchases_from_farmers	0.015	{percent}
Percentage_producer_price	0.60	{percent}
Price_Change_delay	1	{times}
Price_Responsiveness	0.07	
Processing_Capacity_Expansion_Rate	0	{percent}
Processing_Capacity_Foldup_Rate	0	{percent}
Producer_price	FOB * Percentage_producer_price	{USD/tonne}

Production_cost_Alt_Crop	0.13*Farm_expenditure[Adopters,Specialisers]	{USD}
Productive_trees[Fixed_input]	Prod_trees[Fixed_input]*Total_cocoa_farms[Fixed_input]	{trees}
Productive_trees[Variable_input]	Prod_trees[Variable_input]*Total_cocoa_farms[Variable_input]	{trees}
Productive_trees[Specialisers]	Prod_trees[Specialisers] *Total_cocoa_farms[Specialisers]	{trees}
Proportion_of_diversified_land[Fixed_input]	0.4	{percent}
Proportion_of_diversified_land[Variable_input]	0	{percent}
Proportion_of_diversified_land[Specialisers]	0	{percent}
Quantity_Alternative_Sold[Fixed_input]	Yield_Alternative_crop[Fixed_input]-Household_consumption	{kg}
Quantity_Alternative_Sold[Variable_input]	Yield_Alternative_crop[Variable_input]-Household_consumption	{kg}
Quantity_Alternative_Sold[Specialisers]	Yield_Alternative_crop[Specialisers]-Household_consumption	{kg}
Recomended_Fungicide_Quantity	4	{times}
Recommended_Fertiliser_Quantity[Diversification_type]	7.4*Cocoa_farm_size	{kg}
Recommended_Pesticide_Quantity	4	{times}
Replacement_rate	0	{percent}

Required_farm_labour_per_hectare	53.17	{man days}	
Short_term_expected_margin[Farmer_type, Diversification_type]	SMTH1(Farmer_margin, 1)	{USD}	DELAY CONVERTER
Smuggling_rate	0.0005	{percent}	
Specialisers_Diversification_rate	IF(Medterm_farm_profitability[Nonadopters,Specialisers] <0) THEN 0.02 ELSE 0	{percent}	
Supplementary_Fertiliser[Adopters, Fixed_input]	(Recommended_Fertiliser_Quantity[Fixed_input] - Government_Fertiliser[Fixed_input,Adopters])	{kg}	
Supplementary_Fertiliser[Adopters, Variable_input]	(Recommended_Fertiliser_Quantity[Variable_input] - Government_Fertiliser[Variable_input,Adopters])	{kg}	
Supplementary_Fertiliser[Adopters, Specialisers]	(Recommended_Fertiliser_Quantity[Specialisers] - Government_Fertiliser[Specialisers,Adopters])	{kg}	
Supplementary_Fertiliser[Nonadopters, Fixed_input]	IF((SMTH1(Global_Cocoa_Price, 1)> Global_Cocoa_Price) AND (Government_Fertiliser[Fixed_input,Nonadopters] < Recommended_Fertiliser_Quantity[Fixed_input])) THEN (Recommended_Fertiliser_Quantity[Fixed_input] - Government_Fertiliser[Fixed_input,Nonadopters]) ELSE 0	{kg}	
Supplementary_Fertiliser[Nonadopters, Variable_input]	IF((SMTH1(Global_Cocoa_Price, 1) > Global_Cocoa_Price) AND(Government_Fertiliser[Variable_input,Nonadopters] < Recommended_Fertiliser_Quantity[Variable_input])) THEN (Recommended_Fertiliser_Quantity[Variable_input] - Government_Fertiliser[Variable_input,Nonadopters]) ELSE 0	{kg}	

Supplementary_Fertiliser [Nonadopters, Specialisers]	IF((SMTH1(Global_Cocoa_Price, 1) > Global_Cocoa_Price) AND(Government_Fertiliser[Specialisers,Nonadopters] < Recommended_Fertiliser_Quantity[Specialisers])) THEN (Recommended_Fertiliser_Quantity[Specialisers] - Government_Fertiliser[Specialisers,Nonadopters]) ELSE 0	{kg}
Supplementary_Fungicides[Farmer_type, Diversification_type]	IF((SMTH1(Global_Cocoa_Price, 1)> Global_Cocoa_Price) AND(CODAPEC_Fungicide< Recomended_Fungicide_Quantity)) THEN (Recomended_Fungicide_Quantity - CODAPEC_Fungicide) ELSE 0	{kg}
Supplementary_Pesticide [Adopters, Fixed_input]	IF(SMTH1(Global_Cocoa_Price, 1) > Global_Cocoa_Price) THEN (Recommended_Pesticide_Quantity - CODAPEC_Pesticides[Adopters,Fixed_input]) ELSE 0	{times}
Supplementary_Pesticide [Adopters, Variable_input]	IF(SMTH1(Global_Cocoa_Price, 1) > Global_Cocoa_Price) THEN (Recommended_Pesticide_Quantity - CODAPEC_Pesticides[Adopters,Variable_input]) ELSE 0	{times}
Supplementary_Pesticide [Adopters, Specialisers]	IF(SMTH1(Global_Cocoa_Price, 1) > Global_Cocoa_Price) THEN (Recommended_Pesticide_Quantity- CODAPEC_Pesticides[Adopters,Specialisers]) ELSE 0	{times}
Supplementary_Pesticide [Nonadopters, Fixed_input]	0	{times}
Supplementary_Pesticide [Nonadopters, Variable_input]	0	{times}

Supplementary_Pesticide [Nonadopters, Specialisers]	0	{times}
"Switching-out_rate"	IF(((Medterm_farm_profitability[Nonadopters,Fixed_input]) > 0) OR(Medterm_farm_profitability[Nonadopters,Variable_input] >0) OR(Medterm_farm_profitability[Nonadopters,Specialisers] >0)) THEN 0 ELSE 0.015	{percent}
Total_cocoa_farms[Fixed_input]	Fixed_Diversifiers	{farms}
Total_cocoa_farms[Variable_input]	Variable_Diversifiers	{farms}
Total_cocoa_farms[Specialisers]	Specialisers	{farms}
Total_cost_fungicides[Farmer_type, Diversification_type]	Supplementary_Fungicides*Unit_cost_of_fungicide	{USD}
Total_Farm_Size	3	{hectares}
Total_Fertiliser_cost[Farmer_type, Diversification_type]	Supplementary_Fertiliser*Unit_cost_of_fertiliser	{USD}
Total_labour_engaged[Diversification_type]	Hired_Labour+Family_labour_engaged	{man days}
Total_Labour_Required[Diversification_type]	Required_farm_labour_per_hectare*Cocoa_farm_size	{man days}
Total_pest_control_cost [Farmer_type, Diversification_type]	Supplementary_Pesticide*Unit_cost_of_pesticides	{USD}

"Total_volumes_in-country_processing"	("COCOBOD_Allocation_for_in-country_processing")+Processor_purchases_from_Farmers	{kg}
Total_weed_control_cost[Farmer_type, Diversification_type]	Weed_Control_Level*Unit_cost_of_Weed_control	{USD}
Tree_lost_from_chain	(Fixed_Switching_farmers*Trees_per_hectare*Cocoa_farm_size[Fixed_input])+(Variable_Switching_farmers*Cocoa_farm_size[Variable_input]*Trees_per_hectare)+(Specialisers_Switching_farmers*Cocoa_farm_size[Specialisers]*Trees_per_hectare)	{trees}
Tree_on_hecatre	1100	{trees}
Tree_Population_on_farm[Fixed_input]	Cocoa_farm_size[Fixed_input]*Tree_on_hecatre	{trees}
Tree_Population_on_farm[Variable_input]	Cocoa_farm_size[Variable_input]*Tree_on_hecatre	{trees}
Tree_Population_on_farm[Specialisers]	Cocoa_farm_size[Specialisers]*Tree_on_hecatre	{trees}
Tree_replanting_rate	0	{percent}
Trees_per_hectare	1100	{trees}
Unit_cost_of_fertiliser	6.63	{USD}
Unit_cost_of_fungicide	1.14	{USD}
Unit_cost_of_pesticides	1.14	{USD}
Unit_cost_of_Weed_control	2	{USD}
Unit_labour_cost	7.05	{USD/man-days}
Unit_Price	0.5	{USD per kg}

Unit_yield_intercrop	2591	{kg/ hectare}
Va_Syst	IF((HISTORY(Cocoa_beans_transacted_in_Ghana, TIME - 1)) < Cocoa_beans_transacted_in_Ghana) THEN 0 ELSE (HISTORY(Cocoa_beans_transacted_in_Ghana, TIME - 1)- Cocoa_beans_transacted_in_Ghana) {kg}	
Variable_diversification_rate	IF(Medterm_farm_profitability[Nonadopters,Variable_input] <0) THEN 0.02 ELSE 0	
Variance_Exporter	Ghana_Export_Supply-DELAY1(Ghana_Export_Supply, 1)	{kg}
Variance_of_system_state	IF((DELAY1(Cocoa_beans_transacted_in_Ghana, 1)) < Cocoa_beans_transacted_in_Ghana) THEN 0 ELSE (Cocoa_beans_transacted_in_Ghana-DELAY1(Cocoa_beans_transacted_in_Ghana, 1))	{kg}
Variance_Processor	"Total_volumes_in-country_processing"-DELAY1("Total_volumes_in-country_processing", 1)	{kg}
Variance_Producer	(Cocoa_beans_transacted_in_Ghana-DELAY1(Cocoa_beans_transacted_in_Ghana, 1))	{kg}
Weed_Control_Level[Adopters, Fixed_input]	7.73*Cocoa_farm_size[Fixed_input]	{man days}
Weed_Control_Level[Adopters, Variable_input]	7.73*Cocoa_farm_size[Variable_input]	{man days}
Weed_Control_Level[Adopters, Specialisers]	7.73*Cocoa_farm_size[Specialisers]	{man days}
Weed_Control_Level[Nonadopters, Fixed_input]	7.73*Cocoa_farm_size[Fixed_input]	{man days}
Weed_Control_Level[Nonadopters, Variable_input]	7.73*Cocoa_farm_size[Variable_input]	{man days}

Weed_Control_Level[Nonadopters, Specialisers]	7.73*Cocoa_farm_size[Specialisers]	{man days}
weight_of_dried_bean_in_pod	0.039	{kg}
Yield_Alternative_crop[Fixed_input]	Intercrop_Farm[Fixed_input]*Unit_yield_intercrop	{kg}
Yield_Alternative_crop[Variable_input]	Intercrop_Farm[Variable_input]*Unit_yield_intercrop	{kg}
Yield_Alternative_crop[Specialisers]	Intercrop_Farm[Specialisers]*Unit_yield_intercrop	{kg}
Young_Tree_Maturity_rate	STEP(Tree_replanting_rate*Rate, 15)	

Total	Count	Including Array Elements
Variables	141	330
Sectors	6	
Stocks	13	27
Flows	21	47
Converters	107	256
Constants	35	39
Equations	93	264
Graphicals	2	2
Macro Variables	242	

Run Specs	
Start Time	1
Stop Time	25
DT	1/4
Fractional DT	True
Save Interval	0.25
Sim Duration	1.44
Time Units	Years
Pause Interval	0
Integration Method	Euler
Keep all variable results	True
Run By	Run
Calculate loop dominance information	True
Exhaustive Search Threshold	1000

Array Dimension	Indexed by	Elements
Aggregate_Nutrient_Level	Label (2)	GAP No_GAP
Diversification_type	Label (3)	Fixed_input Variable_input Specialisers
Farmer_type	Label (2)	Adopters Nonadopters
Pod_productivity	Label (2)	Adopters_pods Nonadopters_pods
Tree_contribution	Label (2)	Productive_trees Unproductive_trees

Appendix 6.2 Baseline results of selected parameters

Yrs.	Cocoa beans transacted in Ghana (kg)	Cocoa Farm income[Adopters, Fixed input] (USD)	Cocoa Farm income[Adopters, Variable input] (USD)	Cocoa Farm income[Adopters, Specialisers (USD)	Cocoa Farm income[Nonadopters, Fixed input] (USD)	Cocoa Farm income[Nonadopters, Variable input] (USD)	Cocoa Farm income[Nonadopters, Specialisers] (USD)
1	590,710,335	1,218	2,030	2,030	808	1,347	1,347
1.25	590,710,335	1,431	2,385	2,385	943	1,572	1,572
1.5	590,710,335	1,314	2,190	2,190	1,479	2,464	2,464
1.75	590,710,334	1,428	2,379	2,379	1,472	2,453	2,453
2	592,301,769	1,738	2,897	2,897	1,463	2,438	2,438
2.25	597,178,044	1,763	2,939	2,939	1,453	2,421	2,421
2.5	606,098,204	1,365	2,275	2,275	1,443	2,405	2,405
2.75	620,311,876	1,743	2,906	2,906	1,433	2,389	2,389
3	639,494,146	1,392	2,320	2,320	1,424	2,374	2,374
3.25	660,346,491	1,249	2,082	2,082	1,416	2,359	2,359
3.5	682,996,549	1,236	2,060	2,060	1,407	2,346	2,346
3.75	705,000,485	1,506	2,511	2,511	1,399	2,332	2,332
4	724,344,974	1,226	2,043	2,043	1,391	2,319	2,319
4.25	740,262,319	1,292	2,154	2,154	1,383	2,305	2,305
4.5	754,261,204	1,079	1,799	1,799	1,375	2,292	2,292
4.75	765,537,185	1,311	2,185	2,185	1,367	2,278	2,278
5	774,412,683	1,654	2,757	2,757	1,359	2,264	2,264
5.25	780,098,105	1,375	2,292	2,292	1,351	2,251	2,251
5.5	784,027,496	1,254	2,090	2,090	1,343	2,238	2,238

5.75	789,029,733	1,648	2,747	2,747	1,336	2,226	2,226
6	794,501,675	1,579	2,632	2,632	1,329	2,215	2,215
6.25	799,373,124	1,429	2,382	2,382	1,323	2,205	2,205
6.5	805,548,891	1,278	2,131	2,131	1,317	2,196	2,196
6.75	813,176,212	1,067	1,779	1,779	1,313	2,188	2,188
7	821,127,963	1,235	2,059	2,059	1,308	2,181	2,181
7.25	827,897,692	1,134	1,890	1,890	1,305	2,175	2,175
7.5	831,704,475	1,218	2,029	2,029	1,301	2,169	2,169
7.75	833,220,281	1,362	2,269	2,269	1,298	2,164	2,164
8	832,477,643	1,286	2,143	2,143	1,296	2,160	2,160
8.25	830,373,744	1,278	2,129	2,129	1,293	2,156	2,156
8.5	828,412,723	1,468	2,446	2,446	1,291	2,152	2,152
8.75	826,796,974	1,384	2,306	2,306	1,290	2,150	2,150
9	825,549,235	1,416	2,360	2,360	1,289	2,148	2,148
9.25	825,800,306	1,197	1,994	1,994	1,288	2,147	2,147
9.5	827,292,216	1,432	2,387	2,387	1,288	2,146	2,146
9.75	829,901,452	1,351	2,252	2,252	1,288	2,146	2,146
10	832,037,466	1,473	2,456	2,456	1,288	2,147	2,147
10.25	834,496,744	1,141	1,901	1,901	1,288	2,147	2,147
10.5	837,038,687	1,433	2,388	2,388	1,289	2,148	2,148
10.75	840,246,306	1,105	1,841	1,841	1,289	2,148	2,148
11	842,197,686	1,556	2,593	2,593	1,289	2,149	2,149

11.25	844,010,685	1,476	2,460	2,460	1,289	2,149	2,149
11.5	844,165,544	1,158	1,931	1,931	1,289	2,149	2,149
11.75	845,002,578	1,171	1,952	1,952	1,289	2,149	2,149
12	846,905,205	1,078	1,797	1,797	1,289	2,148	2,148
12.25	847,920,406	1,529	2,548	2,548	1,289	2,148	2,148
12.5	847,425,870	1,307	2,179	2,179	1,288	2,147	2,147
12.75	844,842,747	1,388	2,313	2,313	1,288	2,146	2,146
13	843,020,223	1,164	1,940	1,940	1,287	2,145	2,145
13.25	841,731,050	1,325	2,208	2,208	1,286	2,144	2,144
13.5	841,306,492	1,401	2,334	2,334	1,286	2,143	2,143
13.75	840,406,345	1,118	1,864	1,864	1,286	2,143	2,143
14	839,530,749	1,252	2,086	2,086	1,285	2,142	2,142
14.25	839,363,688	1,270	2,116	2,116	1,285	2,142	2,142
14.5	838,376,915	1,104	1,841	1,841	1,285	2,142	2,142
14.75	836,878,697	1,396	2,326	2,326	1,286	2,143	2,143
15	835,211,999	1,138	1,896	1,896	1,286	2,143	2,143
15.25	832,571,372	1,544	2,574	2,574	756	1,260	1,260
15.5	830,574,428	1,354	2,257	2,257	822	1,370	1,370
15.75	828,271,233	1,301	2,168	2,168	853	1,422	1,422
16	824,073,038	1,375	2,291	2,291	849	1,416	1,416
16.25	817,302,259	1,539	2,564	2,564	804	1,339	1,339
16.5	808,148,583	1,096	1,827	1,827	850	1,417	1,417

16.75	797,477,620	1,464	2,440	2,440	830	1,384	1,384
17	786,438,187	1,181	1,968	1,968	754	1,256	1,256
17.25	774,234,849	1,076	1,794	1,794	751	1,252	1,252
17.5	762,257,912	1,558	2,597	2,597	897	1,494	1,494
17.75	749,633,094	1,421	2,368	2,368	757	1,261	1,261
18	735,844,562	1,327	2,211	2,211	802	1,336	1,336
18.25	723,864,433	1,535	2,558	2,558	681	1,135	1,135
18.5	713,438,439	1,285	2,142	2,142	827	1,379	1,379
18.75	704,249,653	1,280	2,133	2,133	866	1,443	1,443
19	696,194,841	1,207	2,011	2,011	936	1,560	1,560
19.25	689,027,076	1,373	2,289	2,289	816	1,360	1,360
19.5	682,785,541	1,119	1,865	1,865	875	1,459	1,459
19.75	677,525,115	1,140	1,900	1,900	885	1,475	1,475
20	673,104,842	1,201	2,002	2,002	926	1,544	1,544
20.25	668,714,127	1,593	2,655	2,655	860	1,434	1,434
20.5	664,172,062	1,384	2,306	2,306	729	1,216	1,216
20.75	659,936,372	1,297	2,162	2,162	844	1,407	1,407
21	657,309,179	1,575	2,625	2,625	782	1,304	1,304
21.25	655,027,422	1,242	2,069	2,069	842	1,403	1,403
21.5	652,836,014	1,521	2,535	2,535	1,002	1,669	1,669
21.75	651,321,467	1,563	2,605	2,605	895	1,491	1,491
22	649,691,022	1,405	2,342	2,342	893	1,488	1,488

22.25	649,599,761	1,189	1,982	1,982	926	1,543	1,543
22.5	651,034,255	1,443	2,405	2,405	955	1,592	1,592
22.75	653,098,209	1,275	2,125	2,125	943	1,572	1,572
23	654,640,238	1,429	2,382	2,382	845	1,409	1,409
23.25	656,343,118	1,295	2,159	2,159	939	1,564	1,564
23.5	657,735,025	1,624	2,707	2,707	1,012	1,686	1,686
23.75	658,662,464	1,543	2,572	2,572	926	1,544	1,544
24	659,137,902	1,302	2,170	2,170	807	1,346	1,346
24.25	660,879,821	1,375	2,291	2,291	938	1,563	1,563
24.5	663,602,107	1,655	2,759	2,759	1,377	2,295	2,295
24.75	665,411,817	1,371	2,284	2,284	1,376	2,293	2,293
25	666,641,879	1,337	2,229	2,229	1,375	2,291	2,291

Chapter 7 General Discussion and Conclusion

7.1 Introduction

Resilience has become a topical subject in the supply chain literature over the last two decades (Gölgeci & Ponomarov, 2015). Different definitions have been ascribed to the concept due to contextual differences (Spiegler, Naim, & Wikner, 2012; Quinlan et al., 2016). Similarly, there is a growing interest in resilience measurement (Quinlan et al., 2016). Nevertheless, resilience assessment in the supply chain literature is often predicated on a fundamental assumption of infinite availability of raw materials and ignores farm-level production activities (Leat & Revoredo-Giha, 2013). Therefore, one pivotal research gap that this study has addressed pertains to the theoretical implication of revolving resilience assessment around farm-level production activities. A farm-centric resilience is defined as the adaptive capacity of a system (agricultural value chain) to become ready for, respond to and recover from disruptions without losing the system's primary state (raw material production levels).

Raw materials from agricultural production activities are essential for business continuity and life's sustenance (Blengini et al., 2017). Midstream and downstream chain activities depend on the continuous flow of raw materials. Consequently, to build resilience, the midstream and downstream chain actors devise measures against potential vulnerabilities emanating from their dependence on raw materials from upstream actors. These measures relay feedbacks that influence farm-level decisions and activities. This study focused on the practical implication of adopting three alternative strategies (market liberalisation, on-farm diversification, and forward integration) to mitigate vulnerability and build resilience in Ghana's cocoa value chain.

This chapter presents a two-fold discussion on; *(i)* the theoretical implication of revolving resilience assessment of agricultural value chains around the farm-level production activities; and *(ii)* the practical implication of the strategies that are espoused to deal with vulnerabilities and build resilience in the cocoa value chain.

7.2. Theoretical Implication of Conceptualising a Farm-centric Resilience

The theoretical argument advanced in this study concerns the centrality of raw materials for resilience assessment of agricultural value chains at an aggregate chain level. This study suggests that a farm-centric resilience assessment is appropriate for agricultural value chains. In Chapter 3, resilience was presented as a multidimensional and hierarchical concept that needs to be decomposed to enhance its measureability. The discussion on the decomposition framework for farm-centric resilience assessment proposed in Chapter 3 (Aboah et al., 2019a) is extended to cover other agricultural production contexts that are different from tropical commodities.

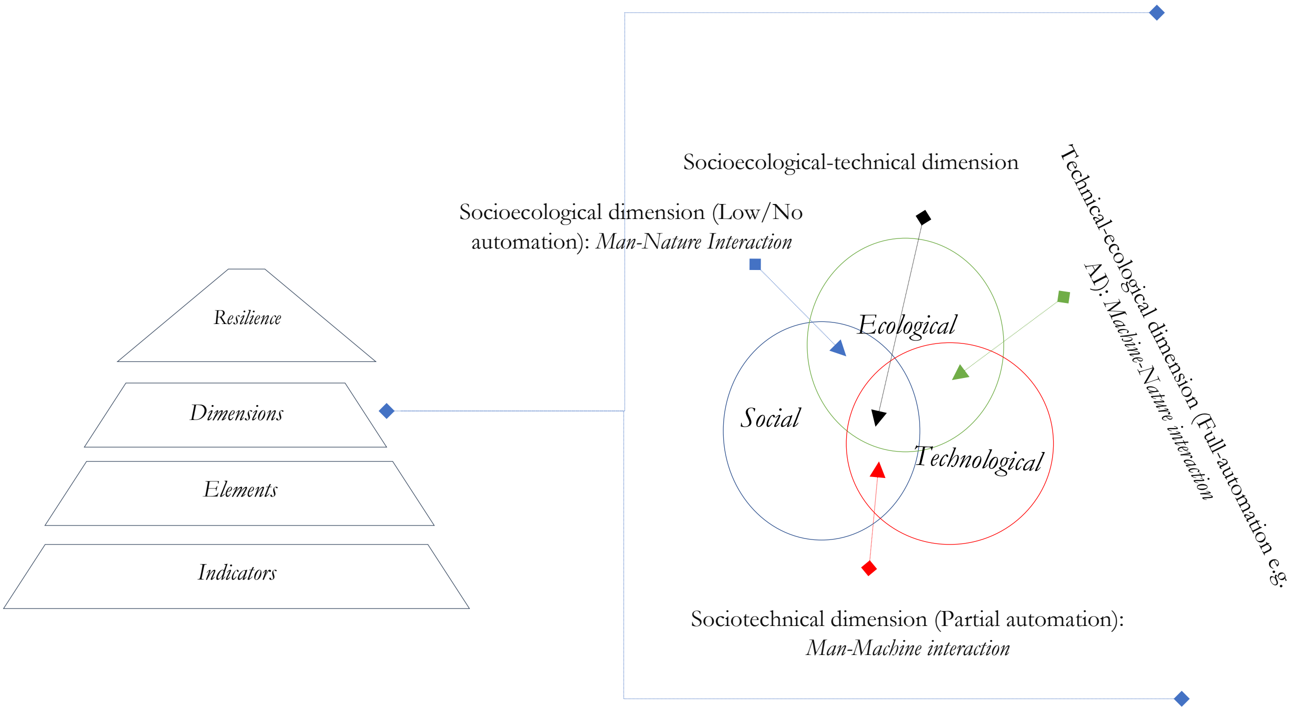


Figure 33 Decomposition framework for a farm-centric resilience assessments

The proposed decomposition framework for agricultural value chain resilience is illustrated in Figure 33. A farm-centric resilience assessment of an agricultural value chain considers a farming system as the integration of social, technological, and ecological components. The social component are the humans that apply technology (machines and equipment) to manipulate the ecological component (farm) to generate provisioning ecosystem services (raw materials) (Cabell & Oelofse, 2012; Quinlan et al., 2016). A resilience dimension results from the interaction between the components. The nature of agricultural production activities and level of technological application determine the relevance and prominence of each resilience dimension. Four dimensions of resilience are highlighted from Figure 33.

Owing to the growing interest in precision agriculture, the technological component of food systems is gaining prominence. A fully mechanised and automated agricultural production system will accentuate the technical-ecological dimension, where the use of robots and artificial intelligence are applied in agricultural production.

In most developing countries like Ghana, smallholders dominate agricultural production; therefore, the level of sophistication in the technological application at the farm-level is limited. Agricultural value chains that concern tropical commodity crops like cocoa are not easily amenable to mechanisation and are labour-intensive (Talbot, 2002). Therefore, a farm-centric decomposition of resilience focuses on the socioecological dimension. With the agricultural production systems relying heavily on rain and other forces termed as "*acts of God*" (Amir & Kant, 2018), the level of deliberate human control is limited.

In developed countries, where agricultural production is mechanised, the sociotechnical dimension becomes a relevant dimension for a farm-centric resilience decomposition. The socioecological-technical dimension highlights the interplay of the three components by emphasising the benefit from the natural environment (ecology). It involves a deliberate effort to maintain and manage an uncultivated portion of the environment as another source of ecosystem service benefits in addition to the benefits accrued from the cultivated environment (farm). Agro-ecotourism is an example of a system that can have a relevant sociotechnical-ecological dimension.

Down the agricultural value chain, the sociotechnical dimension becomes more prominent for logistics and processing activities (Amir & Kant, 2018). However, the socioecological dimension initiates the sociotechnical dimension, particularly, for agricultural value chains that have inadequate technological application at the farm-level. Therefore, the socioecological dimension becomes a more prominent and relevant decomposition of the resilience concept for the cocoa value chain at the first tier.

At the second tier, the dimension is decomposed into resilience elements. The relative importance of the elements is context dependent (Darnhofer, 2014). For an agricultural value chain that involves farming activities requiring a limited technological application, these four resilience elements are reported to be relevant for a farmer-centric resilience assessment: collaboration, adaptability, resourcefulness, and flexibility (Aboah et al., 2019a). For systems that apply a substantial amount of technology for agricultural production activities, adaptability and transformability are suggested resilience elements in addition to robustness (Meuwissen et al., 2019), buffer (Darnhofer, 2014) and persistence (Sinclair et al., 2017).

The resilience elements are not all applicable at an aggregate system level (Salomon et al., 2019). Therefore, the appropriateness of the resilience element can be analysed based on the context and level of application (individual-level or aggregate chain-level). Irrespective of the level of technological application in agricultural production, adaptability is a central resilience element. Indeed, the resilience theory accentuates a system's ability to adapt (Meuwissen et al., 2019). Adaptability concerns behavioural changes from the social component of a food system (e.g., the composition of inputs or production levels) in response to disruptions without losing the function of the farming system (Aboah et al., 2019a; Ivanov, Sokolov, & Kaeschel, 2010; Meuwissen et al., 2019).

Farm-centric resilience considers adaptive capabilities as behavioural changes in agricultural production that reinforce collaboration among chain actors (Aboah et al., 2019a). Transformability is the central resilience element for sociotechnical systems (Amir & Kant, 2018), and concerns changes in a system's internal structure (Meuwissen et al., 2019) based on man-machine interactions (Amir & Kant, 2018). Unlike Darnhofer et al. (2010) who suggested that farms transform when adaptability is not enough to absorb change, this study contends that both adaptability and transformability are resilience elements when there is high socio-technological interaction for agricultural production activities. As such, the relevant farm-centric resilience element for the cocoa value chain at an aggregate chain level is adaptability.

The foundational tier of resilience assessment is the resilience indicator. The two ways of generating resilience indicators, index-based via surrogates and performance-based operationalisation (Aboah et al., 2019a), have their pros and cons. While the index-based indicators are criticised for being impractical, the performance-based are deemed to lack depth (Quinlan et al., 2016). Although using a single index to measure resilience may restrict a deeper understanding of the inherent dynamics in a system, Quinlan et al. (2016) assert that an index that captures a historical trend of a system's state over a period overcomes this limitation. A farm-centric resilience indicator embraces the notion that raw materials are the initiator of value chain activities and determines the system's state of resilience. The level of raw materials produced acts as a static performance measure. However, generating the losses and gains in the level of raw materials produced over a period discloses the dynamics in the system.

This study proposed the *Farm Adaptive Ratio* as an index measure for adaptability to represent aggregate socioecological resilience. The index encapsulates the raw materials production levels as the central focus, and it can be adapted to suit different agricultural value chains by altering the trend duration for the losses and gains in the raw materials produced. A five-year period is suggested as adequate to capture the dynamics in a system (Darnhofer, 2014). However, the duration should highlight key changes in the life cycle of agricultural production, such as the duration before a crop matures and become productive.

7.3 Practical Implication for Building Farm-centric Resilience

One of the primary goals for assessing and managing the resilience of a system is to identify drivers of vulnerability (Blackhurst et al., 2018; Cabell & Oelofse, 2012). This is because a system's susceptibility to disruptions is the main reason for losses incurred in the supply chain (Wagner & Bode, 2006). Moreover, identifying the drivers of vulnerability can also facilitate the formulation of mitigation strategies (Wagner & Neshat, 2012).

As the vulnerability of sociotechnical systems increases, firms place more emphasis on logistics (Wagner & Neshat, 2012). This study's findings show that agricultural value chains that rely on the continuous flow of raw materials from the socioecological interaction will focus on farm-level interventions as vulnerability increases because they are the most important precursors of supply chain vulnerability (Aboah et al., 2019b). Certainly, raw materials are indispensable in almost all value chains (Mayer & Gleich, 2015). Consequently, midstream, and downstream actors become predisposed to supply-side vulnerability due to fluctuations in the raw materials produced (Neureuther & Kenyon, 2009; Vlajic, van Der Vorst, & Haijema, 2012).

The interconnectedness of the value chain implies that decisions and actions taken by midstream and downstream actors in response to supply-side vulnerabilities have a ripple effect on other chain actors (Ivanov, Sokolov, & Dolgui, 2014). As the primary raw material suppliers, farmers are affected by such demand-side vulnerabilities. Building resilience can overcome these vulnerabilities (Scholten et al., 2014). This section focuses on the practical implications of three strategies (i.e., market liberalisation, on-farm diversification, and forward integration) that have been espoused to build resilience at both individual chain actors and aggregate chain levels.

7.3.1 Practical Implication of Market Liberalisation in the Cocoa Value Chain

The failure of one chain actor to fulfil a prescribed function in the value chain process leads to a failure at the aggregate chain level (Neureuther & Kenyon, 2009; Ivanov, 2018). The inability of a farmer to produce and supply the expected levels of raw materials leads to value chain vulnerability.

Upstream vulnerabilities are highly prioritised because downstream actors tend to be dependent on the flow of raw materials from upstream actors to ensure continuity of operations (Nakatani et al., 2018; Gualandris et al., 2014).

Investing in inventory or multiple supplier-sourcing are recommended strategies to avoid or mitigate the effect of functional failure from the supply-side (Tomlin, 2006). However, the ability to secure these inventories from multiple sources is contingent on market accessibility. According to Wilcox and Abbott (2004), market liberalisation has led to backward integration (for export activities) by multinational processors, and a higher share of farmgate prices to farmers accompanied with higher susceptibility to fluctuation in the world commodity market. Market liberalisation increases access to supply and as a consequence, builds resilience (Sexton et al., 2007).

This study's findings indicate that market liberalisation will be beneficial when it is accompanied by intentional interventions to boost on-farm investment and incentivise farmers from switching-out of farming. Under a partially liberalised market arrangement, the coordination of value chain activities between farmers, midstream actors, and the parastatal marketing board lies between the spot market and relation-based alliance.

Under a partially liberalised domestic commodity market arrangement, as in the case of Ghana's cocoa value chain, farmers have an *ex-ante* control decision of who they sell to on the spot market. However, the producer price set by the parastatal marketing board provides *ex-post* control that protects farmers on the spot market. Moreover, farmers are given post-harvest specifications to meet before transactions are effected. The relation-based alliance is highlighted by the subsidised agronomic interventions at the farm-level.

A transition from a partially liberalised to a fully liberalised domestic market implies that the parastatal marketing board will relinquish all of the farm-level interventions. Therefore, the value chain will require farm-level investments to ensure sustenance of raw materials production level.

Liberalisation has led to supply chain integration; agricultural producers gain market access and also led to contract farming in some parts of Africa (Zhang & Aramyan, 2009). However, the land tenure system and farm ownership challenges could hinder collaboration between midstream actors and farmers. Recognising these potential challenges, three non-mutually exclusive routes that can help achieve vertical integration and overcome supply-side vulnerabilities under a fully liberalised domestic commodity market are suggested.

(i) A complete backward integration by midstream actors (like multinational processors) through the acquisition of a large parcel of land and engaging in plantation farming;

(ii) Quasi-backward integration by midstream actors through certification schemes and contract farming to assist farmers in expanding on-farm production.

(iii) Forward integration by farmer cooperatives and associations through the use of raw material supply in exchange for shares (equity) acquisition in local processing companies.

A comparison of the three routes is presented in Table 23. A fully liberalised market implies that the parastatal marketing board will lose its role as the lead exporter of raw materials. A price regulatory framework may be required to protect farmers from exploitation on the spot market. Additionally, a deliberate value addition effort is required to safeguard in-country processors. Ultimately, the government maintaining regulatory policies even in a fully liberalised domestic commodity market is crucial.

Table 23 A comparison of three strategies recommended under a fully liberalised domestic market

	Full backward integration	*Quasi-backward integration (contract farming)*	*Forward integration by farm cooperatives*
Chain actor engaged in integration (*integrator*)	Processor/ Buyer/ Exporter	Processor/ Buyer/ Exporter	Farmers
Level of planning	Permanent (long term) undertaking that requires strategic planning	Temporary (short term) undertaking that requires operational planning	Medium to long term undertaking that requires tactical/ strategic planning by cooperative and processors
Duration required for the strategy to be established	It takes a relatively longer duration. The strategy is established after the farm enterprise starts producing raw materials. For tropical tree crops, young plants are productive after an average of 5 years	This strategy takes the shortest duration. The integrator may reach an annual contractual agreement with farmers	This strategy will require a longer duration to establish than the quasi-backward integration
Capital requirement	The strategy is capital intensive and can result in diseconomies of scale	Comparatively, this strategy is the most liquid and least capital-intensive	This strategy is less capital intensive compared to the full backward integration strategy, but it will require contractual agreements
Ease of integration	Easier when land is available and accessible	This is the easiest. Certification schemes have been used to achieve this strategy	Relatively difficult in developing countries where the farmer cooperatives are not well organised
Technical & managerial complementarity between existing and new enterprises	Integrator may have limited knowledge on agricultural production activities. Therefore, new technical and managerial skills are required by the integrator to ensure successful integration of agricultural production activities	Knowledge on agricultural production activities is not needed but it is desirable to enable the integrator to determine the type of on-farm investment required	Knowledge on downstream activities (e.g. processing) is not needed but it is desirable
Transaction cost for raw material sourcing	Low transaction cost for integrator	High transaction cost for integrator	High transaction cost for integrator
Major impediment	Land unavailability	Moral hazards (non-compliance of contractual agreement) by farmers	No public offering by in-country processors
Influence on aggregate agricultural production level	Increases in aggregate agricultural production levels resulting from newly cultivated farms and increased farm productivity levels (achieved via on-farm investment)	Increases in aggregate agricultural production levels resulting from only increased farm productivity levels (achieved via on-farm investment)	Increases in aggregate agricultural production levels resulting from only increased farm productivity levels (achieved via on-farm investment)
Influence on farmer	Employed farmers may not be able to easily engage in off-farm work	Farmers can engage in off-farm activities	Farmers can engage in off-farm activities

7.3.2 Practical Implication of Diversification and Forward Integration in the Cocoa Value Chain

Considering that market liberalisation predisposes farmers and exporters to price and income fluctuations, on-farm diversification, and forward integration (value addition) have been promoted as adaptive strategies to build resilience at the farm and national levels respectively (Biggs, Schlüter, & Schoon, 2015; Lin, 2011). Although diversification is advocated at the farm level to improve farmers' welfare, farmers are not incentivised by the government to practice diversification. However, its opposite strategy, specification, is incentivised at the national level (Lin, 2011). This phenomenon may seem to create a contrasting effort towards resilience-building from an aggregate value chain perspective.

For building a farm-centric resilience, on-farm diversification that does not result in decreased raw material production levels will imply the availability of more raw materials for processing activities and support a forward integration agenda. The study's findings show that resilience can be achieved at an aggregate level when proceeds from on-farm variable-input diversification is re-invested into cocoa production. The findings indicate that although an increase in variable-input diversification results in losses in the volumes of raw materials produced at an aggregate level; individual farmers will experience minimal losses in cocoa production levels. The losses in the raw materials produced at an aggregate level induce increases in world cocoa prices, such that individual farmers gain higher income even with lower cocoa production levels. Moreover, the revenues obtained from on-farm diversification also contributes to higher farm margin.

At an aggregate level, resilience thinking informs policy formulation that dictates chain activities; these policies either strengthen or weaken farm resilience (Darnhofer, 2014; Sinclair et al., 2017). The pursuit of a forward integration strategy improves the aggregate resilience of the cocoa value chain. Nevertheless, a policy direction that supports forward integration (e.g., in-country processing of traditional export crops) needs to be grounded in the existing market arrangement to determine the potential strategies that midstream and downstream actors can adopt.

Some proponents of a forward integration agendum via in-country processing suggest a protectionist policy that bars raw cocoa beans exportation as a solution to boost the economy of producing countries. The efficacy of the protectionist proposition can be determined by considering the demand market and their import tariffs for processed foods. Most consumers of cocoa products are outside cocoa-producing countries; therefore, a reduction in demand will have a countervailing effect on a protectionist policy. Similarly, high tariffs that are placed on processed foods imported into cocoa consuming countries can also inhibit a protectionist forward integration policy.

A holistic forward integration policy direction will also consider the strategic location of where in-country processing is engaged. Processing that occurs in locations that are closer to raw material sources (production regions) can easily catalyse farm-level investment. In Ghana, most of the cocoa processing hubs are in the Greater Accra region, outside cocoa-growing regions. This phenomenon may have contributed to increasing rural-urban migration and the youth's low interest in cocoa farming. A policy direction that supports in-country processing at strategic cocoa-producing regions will:

(i) boost in the local rural economy by instigating job creation that will act as a source of non-farm diversification for rural households in cocoa-growing regions.

(ii) facilitate processors' direct engagement at the farm-level and stimulate on-farm investments.

7.4 Conclusions and Recommendations

This study sought to achieve the following: *(i)* operationalise the resilience concept for tropical commodity chains; *(ii)* identify the precursors of vulnerability in Ghana's cocoa value chain; *(iii)* evaluate the *ex-ante* effect of market liberalisation on aggregate resilience; *(iv)* examine the *ex-ante* impact of two adaptive strategies (diversification at the farm-level and forward integration at the national-level) on aggregate resilience.

Theoretically, this study suggests that tropical commodity chains, like most agricultural value chains in developing countries, will require a farm-centric resilience assessment that considers the following:

- *(a)* the socioecological dimension as the primary resilience dimension subject to the level of technological application in agricultural production.
- *(b)* adaptability as a central resilience element for socioecological interaction.
- *(c)* the level of raw materials produced at the farm-level as a gauge of adaptability and a primary indicator of resilience; and
- *(d)* dynamic loss and gains in the raw material produced over a period.

Being a socioecological system, agricultural value chains will rely on farm-level interventions when supply-side vulnerabilities increase because upstream vulnerabilities are the most important precursors of vulnerability. Full liberalisation of the domestic market will enhance the resilience of the cocoa value chain at an aggregate level when the government enacts.

- *(a)* a regulatory policy to ensure that the producer price for in-country transactions is in sync with the prevailing price on the global commodity market to curtail exploitation of smallholders, and
- *(b)* policies that provide an enabling environment to support forward integration strategies.

In view of the potential inhibitors associated with a protectionist forward integration policy, a systematic implementation of a fully liberalised market with a forward integration policy orientation is recommended. Two suggestions that can be substantiated in future simulation experiments are proposed.

(a) The government can incentivise multinational processors to increase the level of in-country processing at strategic cocoa-producing regions by offering tax holidays; and

(b) The government streamline policies on agricultural land tenure system in collaboration with traditional (local) chiefs to facilitate complete backward integration for multinationals.

On-farm variable-input diversification at the farm-level can complement the forward integration effort at the national level to build resilience in Ghana's cocoa value chain when

(a) farmers reinvest proceeds from on-farm diversification into farm maintenance, and

(b) farmers adopt good farm management practices.

Ghana’s cocoa industry attains resiliency when there is an increase in in-country processing. Therefore, a policy direction that helps to build resilience in the cocoa value chain is one that enables free cocoa trading in-country with a regulation to synchronise producer price with world price, spearheads in-country processing and supports on-farm investment.

7.4.1 Limitations and Future Studies

This study used the Farm Adaptive Ratio (FAR) as a proxy measure for assessing socioecological resilience. The measure considers the economic dimension of resilience as a contributory factor of the socioecological dimension of resilience. As such, its applicability is limited to the level of inventories (raw materials) that flow through an agricultural value chain.

Another limitation pertains to the nature of the focal commodity (crop). As highlighted in the study, FAR can be applied to perennial commodities like coffee, cashew, oil palm, and shea. However, it is less useful for perishable food chains where the shelf-life of produce is a crucial factor of resilience. Moreover, given the autonomy of individual chain actors in the cocoa value chain, assessment of the economic dimension of resilience is more relevant at an individual chain actor level. Therefore, FAR needs an accompanying economic measure when assessment focuses on the individual chain actor level.

The restrictiveness of the stock and flow models used for the quantitative analyses is another limitation. In the quest to achieve parsimony in the model development, the yield of cocoa trees was determined using a triangular distribution. Such estimation limits the dynamics that can be achieved in the model behaviour. Therefore, the integration of econometric models in the estimation of the cocoa tree yield will enrich the model. Also, in view of the limitation of the FAR application, a hybrid model that involves a combination of agent-based modelling and system dynamics modelling can be used to assess both resilience at both individual chain actor level and an aggregate chain level.

References

Abbesy, P., Tomlinson, P. R., & Branston, J. R. (2016). Perceptions of governance and social capital in Ghana's cocoa industry. *Journal of Rural Studies, 44*, 153-163. doi:10.1016/j.jrurstud.2016.01.015

Aboah, J., Wilson, M. M., Rich, K. M., & Lyne, M. C. (2019a). Operationalising resilience in tropical agricultural value chains. *Supply Chain Management: an international journal, 24*(2), 271-300. doi:https://doi.org/10.1108/SCM-05-2018-0204

Aboah, J., Wilson, M. M. J., Bicknell, K., & Rich, K. M. (2019b). Identifying the precursors of vulnerability in agricultural value chains: A system dynamics approach. *International Journal of Production Research*, 1-19. doi:10.1080/00207543.2019.1704592

Adjei-Nsiah, S. (2012). Climate Change and Shift in Cropping System: From Cocoa to Maize Based Cropping System in Wenchi Area of Ghana. *British Journal of Environment and Climate Change, 2*(2), 137-152. doi:10.9734/BJECC/2012/1220

Agigi, A., Niemann, W., & Kotzé, T. (2016). Supply chain design approaches for supply chain resilience: A qualitative study of South African fast-moving consumer goods grocery manufacturers. *Journal of Transport and Supply Chain Management, 10*(1), e1-e15. doi:10.4102/jtscm.v10i1.253

Albino, V., Garavelli, A. C., & Schiuma, G. (1998). Knowledge transfer and inter-firm relationships in industrial districts: the role of the leader firm. *Technovation, 19*(1), 53-63.

Ali, A., Mahfouz, A., & Arisha, A. (2017). Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic literature review. *Supply Chain Management: An International Journal, 22*(1), 16-39. doi:10.1108/SCM-06-2016-0197

Alinovi, L., Mane, E., & Romano, D. (2009) Measuring household resilience to food insecurity: application to Palestinian households. In. *EC-FAO Food Security Programme*.

Ambulkar, S., Blackhurst, J., & Grawe, S. (2015). Firm's resilience to supply chain disruptions: Scale development and empirical examination. *Journal of Operations Management, 33*, 111-122.

Amir, S., & Kant, V. (2018). Sociotechnical Resilience: A Preliminary Concept. *Risk Analysis, 38*(1), 8-16. doi:10.1111/risa.12816

Andersen, D. F., Richardson, G. P., & Vennix, J. A. M. (1997). Group model building: adding more science to the craft. *System Dynamics Review, 13*(2), 187-201. doi:10.1002/(SICI)1099-1727(199722)13:2<187::AID-SDR124>3.0.CO 2-O

Aneani, F., Anchirinah, V., Asamoah, M., & Owusu-Ansah, F. (2011a). Analysis of economic efficiency in cocoa production in Ghana. *African Journal of Food, Agriculture, Nutrition and Development, 11*(1).

Aneani, F., Anchirinah, V., Owusu-Ansah, F., & Asamoah, M. (2011b). An analysis of the extent and determinants of crop diversification by cocoa (Theobroma cacao) farmers in Ghana. *African Journal of Agricultural Research, 6*(18), 4277-4287.

Aneani, F., Anchirinah, V. M., Owusu-Ansah, F., & Asamoah, M. (2012). Adoption of Some Cocoa Production Technologies by Cocoa Farmers in Ghana. *Adoption of Some Cocoa Production Technologies by Cocoa Farmers in Ghana, 1*(1). doi:10.5539/sar.v1n1p103

Angerhofer, B. J., & Angelides, M. C. (2000). *System dynamics modelling in supply chain management: research review.* Paper presented at the Proceedings of the 32nd conference on Winter simulation.

Anim-Kwapong, G., & Frimpong, E. (2004). vulnerability and adaptation assessment under the Netherlands climate change studies assistance programme phase 2 (NCCSAP 2). *Cocoa Research Institute of Ghana, 2*, 1-30.

Asamoah, M. (2015). Utilization of cocoa farm management practices by small-scale farmers: the pressure of sociocultural factors. *Int J Innov Res Educ Sci, 2*, 17-21.

Asante-Poku, A., & Angelucci, F. (2013). *Analysis of incentives and disincentives for cocoa in Ghana: Technical notes series*. Retrieved from MAFAP, FAO Rome: http://www.fao.org/in-action/mafap/resources/detail/en/c/394343/

Asante, B. O., Villano, R. A., Patrick, I. W., & Battese, G. E. (2018). Determinants of farm diversification in integrated crop–livestock farming systems in Ghana. *33*(2), 131-149. doi:10.1017/s1742170516000545

Asare, R., & David, S. (2010). *Planting, replanting and tree diversification in cocoa systems-learning about sustainable cocoa production: a guide for participatory farmer training (No. 13)*. Horsholm: Forest & Landscape Denmark.

Azadeh, A., Atrchin, N., Salehi, V., & Shojaei, H. (2014). Modelling and improvement of supply chain with imprecise transportation delays and resilience factors. *International Journal of Logistics Research and Applications, 17*(4), 269-282. doi:10.1080/13675567.2013.846308

Azadeh, A., Raoofi, Z., & Zarrin, M. (2015). A multi-objective fuzzy linear programming model for optimization of natural gas supply chain through a greenhouse gas reduction approach. *Journal of Natural Gas Science and Engineering, 26*, 702-710. doi:10.1016/j.jngse.2015.05.039

Azaron, A., Brown, K. N., Tarim, S. A., & Modarres, M. (2008). A multi-objective stochastic programming approach for supply chain design considering risk. *International Journal of Production Economics, 116*(1), 129-138. doi:10.1016/j.ijpe.2008.08.002

Azevedo, S. G., Govindan, K., Carvalho, H., & Cruz-Machado, V. (2013). Ecosilient Index to assess the greenness and resilience of the upstream automotive supply chain. *Journal of Cleaner Production, 56*, 131-146. doi:10.1016/j.jclepro.2012.04.011

Bakshi, N., & Kleindorfer, P. (2009). Co-opetition and Investment for Supply-Chain Resilience. *Production and Operations Management, 18*(6), 583-603. doi:10.1111/j.1937-5956.2009.01031.x

Barghouti, S., Kane, S., Sorby, K., & Ali, M. (2004) Agricultural Diversification for the Poor: Guidelines for Practitioners. In. *Agriculture and Rural Development Discussion Paper 1*. 1818 H Street, N.W. Washington, D.C.: World Bank.

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review, 12*(3), 183-210. doi:10.1002/(sici)1099-1727(199623)12:3<183::Aid-sdr103>3.0.Co2-4

Berlan, A. (2013). Social sustainability in agriculture: an anthropological perspective on child labour in cocoa production in Ghana. *The Journal of Development Studies, 49*(8), 1088-1100.

Berle, Ø., Asbjørnslett, B. E., & Rice, J. B. (2011). Formal Vulnerability Assessment of a maritime transportation system. *Reliability Engineering and System Safety, 96*(6), 696-705. doi:10.1016/j.ress.2010.12.011

Biggs, R., Schlüter, M., & Schoon, M. L. (2015). An introduction to the resilience approach and principles to sustain ecosystem services in social-ecological systems. *Principles for building resilience: Sustaining ecosystem services in social–ecological systems*, 1-31.

Blackhurst, J., Rungtusanatham, M. J., Scheibe, K., & Ambulkar, S. (2018). Supply chain vulnerability assessment: A network based visualization and clustering analysis approach. *Journal of Purchasing and Supply Management, 24*(1), 21-30. doi:https://doi.org/10.1016/j.pursup.2017.10.004

Blengini, G. A., Nuss, P., Dewulf, J., Nita, V., Peirò, L. T., Vidal-Legaz, B., . . . Ciupagea, C. (2017). EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. *Resources Policy, 53*(C), 12-19. doi:10.1016/j.resourpol.2017.05.008

Bliemel, F. (1973). Theil's forecast accuracy coefficient: A clarification. *Journal of Marketing Research, 10*(4), 444-446.

Borgatti, S. P., & Li, X. (2009). On social network analysis in a supply chain context. *Journal of Supply Chain Management, 45*(2), 5-22.

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. *Futures, 38*(7), 723-739. doi:10.1016/j.futures.2005.12.002

Botes, A., Niemann, W., & Kotzé, T. (2017). Buyer-supplier collaboration and supply chain resilience: A case study in the petrochemical industry. *South African Journal of Industrial Engineering, 28*(4), 183-199. doi:10.7166/28-4-1736

Brandon-Jones, E., Squire, B., Autry, C. W., & Petersen, K. J. (2014). A Contingent Resource-Based Perspective of Supply Chain Resilience and Robustness. *Journal of Supply Chain Management, 50*(3), 55-73. doi:10.1111/jscm.12050

Brusset, X., & Teller, C. (2017). Supply chain capabilities, risks, and resilience. *International Journal of Production Economics, 184*(C), 59-68. doi:10.1016/j.ijpe.2016.09.008

Bueno, N., & Basurto, X. (2009). Resilience and collapse of artisanal fisheries: a system dynamics analysis of a shellfish fishery in the Gulf of California, Mexico. *Sustainability science, 4*(2), 139-149. doi:10.1007/s11625-009-0087-z

BulÌř, A. (2002). Can price incentive to smuggle explain the contraction of the Cocoa supply in Ghana? *Journal of African Economies, 11*(3), 413-439.

Bymolt, R., Laven, A., Tyszler, M. (2018). Chapter 10 Production and yield. In *Demystifying the cocoa sector in Ghana and Cote D'Ivoire*. Amsterdam, The Netherlands: The Royal Tropical Institute (KIT).

Cabell, J. F., & Oelofse, M. (2012). An Indicator Framework for Assessing Agroecosystem Resilience. *Ecology and society, 17*(1), 18. doi:10.5751/ES-04666-170118

Calatayud, A., Mangan, J., & Palacin, R. (2017). Vulnerability of international freight flows to shipping network disruptions: A multiplex network perspective. *Transportation Research Part E: Logistics and Transportation Review, 108*, 195-208. doi:https://doi.org/10.1016/j.tre.2017.10.015

Caniato, F., Golini, R., & Kalchschmidt, M. (2013). The effect of global supply chain configuration on the relationship between supply chain improvement programs and performance. *International Journal of Production Economics, 143*(2), 285-293. doi:10.1016/j.ijpe.2012.05.019

Cardoso, S. R., Paula Barbosa-Póvoa, A., Relvas, S., & Novais, A. Q. (2015). Resilience metrics in the assessment of complex supply-chains performance operating under demand uncertainty. *Omega, 56*, 53-73. doi:10.1016/j.omega.2015.03.008

Carvalho, H., Barroso, A. P., Machado, V. H., Azevedo, S., & Cruz-Machado, V. (2012). Supply chain redesign for resilience using simulation. *Computers & Industrial Engineering, 62*(1), 329-341. doi:10.1016/j.cie.2011.10.003

Carvalho, H., & Cruz-Machado, V. (2011). Integrating lean, agile, resilience and green paradigms in supply chain management (LARG_SCM). *Supply chain management*, 27-48.

Chang, W.-S., & Lin, Y.-T. (2019). The effect of lead-time on supply chain resilience performance. *Asia Pacific management review, 24*(4), 298-309. doi:10.1016/j.apmrv.2018.10.004

Charles, A., Lauras, M., & Van Wassenhove, L. (2010). A model to define and assess the agility of supply chains: building on humanitarian experience. *International Journal of Physical Distribution & Logistics Management, 40*(8/9), 722-741. doi:10.1108/09600031011079355

Chopra, S., & Sodhi, M. (2014). Reducing the Risk of Supply Chain Disruptions. *MIT Sloan Management Review, 55*(3), 73-80.

Chowdhury, M. M. H., & Quaddus, M. (2016). Supply chain readiness, response and recovery for resilience. *Supply Chain Management: An International Journal, 21*(6), 709-731. doi:10.1108/SCM-12-2015-0463

Chowdhury, M. M. H., & Quaddus, M. (2017). Supply chain resilience: Conceptualization and scale development using dynamic capability theory. *International Journal of Production Economics, 188*, 185-204. doi:10.1016/j.ijpe.2017.03.020

Christopher, M., & Peck, H. (2004). Building the Resilient Supply Chain. *The international journal of logistics management, 15*(2), 1-14. doi:10.1108/09574090410700275
Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. *Engineering Structures, 32*(11), 3639-3649. doi:10.1016/j.engstruct.2010.08.008
Colicchia, C., Dallari, F., & Melacini, M. (2010). Increasing supply chain resilience in a global sourcing context. *Production Planning & Control, 21*(7), 680-694. doi:10.1080/09537280903551969
Colucci, E. (2007). "Focus Groups Can Be Fun": The Use of Activity-Oriented Questions in Focus Group Discussions. *Qualitative Health Research, 17*(10), 1422-1433. doi:10.1177/1049732307308129
Craighead, C. W., Blackhurst, J., Rungtusanatham, M. J., & Handfield, R. B. (2007). The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities. *Decision sciences, 38*(1), 131-156. doi:10.1111/j.1540-5915.2007.00151.x
Crucitti, P., Latora, V., & Marchiori, M. (2004). Model for cascading failures in complex networks. *Physical Review E, 69*(4), 045104.
Cumming, G., Barnes, G., Perz, S., Schmink, M., Sieving, K., Southworth, J., . . . Holt, T. (2005). An Exploratory Framework for the Empirical Measurement of Resilience. *Ecosystems, 8*(8), 975-987. doi:10.1007/s10021-005-0129-z
Cumming, G. S., & Peterson, G. D. (2017). Unifying Research on Social–Ecological Resilience and Collapse. *Trends in Ecology & Evolution, 32*(9), 695-713. doi:10.1016/j.tree.2017.06.014
Darnhofer, I. (2014). Resilience and why it matters for farm management. *European Review of Agricultural Economics, 41*(3), 461-484. doi:10.1093/erae/jbu012
Darnhofer, I., Fairweather, J., & Moller, H. (2010). Assessing a farm's sustainability: insights from resilience thinking. *International Journal of Agricultural Sustainability, 8*(3), 186-198. doi:10.3763/ijas.2010.0480
Datta, P. P., Christopher, M., & Allen, P. (2007). Agent-based modelling of complex production/distribution systems to improve resilience. *International Journal of Logistics Research and Applications, 10*(3), 187-203. doi:10.1080/13675560701467144
Derissen, S., Quaas, M. F., & Baumgärtner, S. (2011). The relationship between resilience and sustainability of ecological-economic systems. *Ecological Economics, 70*(6), 1121-1128. doi:10.1016/j.ecolecon.2011.01.003
Dhanya, V. (2008). Liberalisation of tropical commodity market and adding-up problem: A Bound test approach. *IDEAS Working Paper Series from RePEc.*
Dizyee, K., Baker, D., & Rich, K. M. (2017). A quantitative value chain analysis of policy options for the beef sector in Botswana. *Agricultural Systems, 156*, 13-24. doi:10.1016/j.agsy.2017.05.007
Dolgui, A., Ivanov, D., & Sokolov, B. (2018). Ripple effect in the supply chain: an analysis and recent literature. *International Journal of Production Research, 56*(1-2), 414-430. doi:10.1080/00207543.2017.1387680
Domfeh, O., Ameyaw, G., Dzahini-Obiatey, H., Ollennu, L., Osei-Bonsu, K., Acheampong, K., . . . Owusu-Ansah, F. (2016). Use of Immune Crops as Barrier in the Management of Cacao Swollen Shoot Virus Disease (CSSVD)—Long-Term Assessment. *Plant Disease, 100*(9), 1889-1893.
Dzomeku, B., Dankyi, A., & Darkey, S. (2011). Socioeconomic importance of plantain cultivation in Ghana. *J. Anim. Plant Sci, 21*(2), 269-273.
Eckstein, D., Goellner, M., Blome, C., & Henke, M. (2015). The performance impact of supply chain agility and supply chain adaptability: the moderating effect of product complexity. *International Journal of Production Research, 53*(10), 3028-3046. doi:10.1080/00207543.2014.970707

Elder, S. D., Zerriffi, H., & Le Billon, P. (2012). Effects of Fair Trade Certification on Social Capital: The Case of Rwandan Coffee Producers. *World Development, 40*(11), 2355-2367. doi:10.1016/j.worlddev.2012.06.010

Elleuch, H., Dafaoui, E., El Mhamedi, A., & Chabchoub, H. (2016a). A Quality Function Deployment approach for Production Resilience improvement in Supply Chain: Case of Agrifood Industry. *IFAC PapersOnLine, 49*(31), 125-130. doi:10.1016/j.ifacol.2016.12.173

Falasca, M., Zobel, C. W., & Cook, D. (2008). *A decision support framework to assess supply chain resilience.* Paper presented at the Proceedings of the 5th International ISCRAM Conference.

Falkowski, J. (2015). Economic effects of reorganising an agro-food supply chain: some evidence from Poland. *Journal of Organizational Change Management, 28*(5), 704-723. doi:10.1108/JOCM-04-2014-0085

Fazey, I., Fazey, J. A., Fischer, J., Sherren, K., Warren, J., Noss, R. F., & Dovers, S. R. (2007). Adaptive capacity and learning to learn as leverage for social–ecological resilience. *Frontiers in Ecology and the Environment, 5*(7), 375-380. doi:10.1890/1540-9295(2007)5[375:ACALTL]2.0.CO2

Fiksel, J. (2003). Designing resilient, sustainable systems. *Environmental science & technology, 37*(23), 5330. doi:10.1021/es0344819

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and society, 15*(4). doi:10.5751/es-03610-150420

Fridolin Simon, B., & Kurt, J. (2007). Focusing the Meaning(s) of Resilience: Resilience as a Descriptive Concept and a Boundary Object. *Ecology and society, 12*(1), 23. doi:10.5751/ES-02029-120123

Gereffi, G., Humphrey, J., & Sturgeon, T. (2005). The governance of global value chains. *Review of International Political Economy, 12*(1), 78-104. doi:10.1080/09692290500049805

Gibbon, P. (2001). Upgrading primary production: a global commodity chain approach. *World Development, 29*(2), 345-363.

Gilbert, C., & Varangis, P. (2003). Globalization and International Commodity Trade with Specific Reference to the West African Cocoa Producers. *NBER Working Paper Series*, 9668. doi:10.3386/w9668

Gölgeci, I., & Ponomarov, S. Y. (2015). How does firm innovativeness enable supply chain resilience? The moderating role of supply uncertainty and interdependence. *Technology Analysis & Strategic Management, 27*(3), 267-282. doi:10.1080/09537325.2014.971003

Gotangco, C. K., See, J., Dalupang, J. P., Ortiz, M., Porio, E., Narisma, G., . . . Dator-Bercilla, J. (2016). Quantifying resilience to flooding among households and local government units using system dynamics: a case study in Metro Manila: Quantifying resilience to flooding using SD. *Journal of flood risk management, 9*(3), 196-207. doi:10.1111/jfr3.12222

Goyal, A., & Sarkar, S. (2014). The benefits and costs of financial market liberalization. *Macroeconomics and Finance in Emerging Market Economies, 7*(2), 205-207. doi:10.1080/17520843.2014.930246

Grabowski, P., Schmitt Olabisi, L., Adebiyi, J., Waldman, K., Richardson, R., Rusinamhodzi, L., & Snapp, S. (2019). Assessing adoption potential in a risky environment: The case of perennial pigeonpea. *Agricultural Systems, 171*, 89. doi:10.1016/j.agsy.2019.01.001

GSS. (2014). *Ghana Living Standards Survey Round 6 (GLSS 6) Report*. Retrieved from Accra: http://www.statsghana.gov.gh/docfiles/glss6/GLSS6_Main%20Report.pdf

Gualandris, J., & Kalchschmidt, M. (2014). A model to evaluate upstream vulnerability. *International Journal of Logistics Research and Applications, 17*(3), 249-268.

Han, J., & Shin, K. (2016). Evaluation mechanism for structural robustness of supply chain considering disruption propagation. *International Journal of Production Research, 54*(1), 135-151. doi:10.1080/00207543.2015.1047977

Hausermann, H., Ferring, D., Atosona, B., Mentz, G., Amankwah, R., Chang, A., . . . Sastri, N. (2018). Land-grabbing, land-use transformation and social differentiation: Deconstructing "small-scale" in Ghana's recent gold rush. *World Development, 108*, 103-114. doi:10.1016/j.worlddev.2018.03.014
Hearnshaw, E. J., & Wilson, M. M. (2013). A complex network approach to supply chain network theory. *International Journal of Operations & Production Management, 33*(4), 442-469.
Hennink, M. M. (2014). *Focus group discussions*: New York : Oxford University Press.
Herrera, H., & Kopainsky, B. (2020). Using system dynamics to support a participatory assessment of resilience. *Environment systems & decisions*. doi:10.1007/s10669-020-09760-5
Hilson, G., & Garforth, C. (2013). 'Everyone Now is Concentrating on the Mining': Drivers and Implications of Rural Economic Transition in the Eastern Region of Ghana. *The Journal of Development Studies, 49*(3), 348-364. doi:10.1080/00220388.2012.713469
Hohenstein, N.-O., Feisel, E., Hartmann, E., & Giunipero, L. (2015). Research on the phenomenon of supply chain resilience. *International Journal of Physical Distribution & Logistics Management, 45*(1/2), 90-117. doi:10.1108/IJPDLM-05-2013-0128
Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics, 4*, 1-23.
Holling, C. S. (2001). Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems, 4*(5), 390-405. doi:10.1007/s10021-001-0101-5
Hossain, M. S., Ramirez, J. A., Haisch, T., Speranza, C. I., Martius, O., Mayer, H., & Keiler, M. (2020). A coupled human and landscape conceptual model of risk and resilience in Swiss Alpine communities. *Sci Total Environ, 730*, 138322. doi:10.1016/j.scitotenv.2020.138322
Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. *Reliability Engineering and System Safety, 145*, 47-61. doi:10.1016/j.ress.2015.08.006
Hovmand, P. S. (2014). Group model building and community-based system dynamics process. In *Community Based System Dynamics* (pp. 17-30). New York: Springer
Humphrey, J., & Schmitz, H. (2002). How does insertion in global value chains affect upgrading in industrial clusters? *Regional Studies, 36*(9), 1017-1027.
Humphrey, J., & Schmitz*, H. (2001). Governance in global value chains. *IDS bulletin, 32*(3), 19-29.
ICCO. (2008). *Annual report for 2007/2008*. Retrieved from International Cocoa Organisation. Commonwealth House, 1-19 New Oxford Street London: https://www.icco.org/about-us/international-cocoa-agreements/cat_view/1-annual-report.html
ICCO. (2012). *Annual Report for 2011/12*. Retrieved from International Cocoa Organisation. Commonwealth House, 1-19 New Oxford Street, London: https://www.icco.org/about-us/international-cocoa-agreements/cat_view/1-annual-report.html
ICCO. (2017). *ICCO quarterly bulletin of cocoa statistics*. Retrieved from International Cocoa Organisation. Commonwealth House, 1-19 New Oxford Street, London: https://www.icco.org/about-us/international-cocoa-agreements/cat_view/1-annual-report.html
Ishfaq, R. (2012). Resilience through flexibility in transportation operations. *International Journal of Logistics Research and Applications, 15*(4), 215-229. doi:10.1080/13675567.2012.709835
Ivanov, D. (2017). Simulation-based ripple effect modelling in the supply chain. *International Journal of Production Research, 55*(7), 2083-2101. doi:10.1080/00207543.2016.1275873
Ivanov, D. (2018). Revealing interfaces of supply chain resilience and sustainability: a simulation study. *International Journal of Production Research, 56*(10), 3507. doi:10.1080/00207543.2017.1343507
Ivanov, D., & Sokolov, B. (2013). Control and system-theoretic identification of the supply chain dynamics domain for planning, analysis and adaptation of performance under

uncertainty. *European Journal of Operational Research, 224*(2), 313-323. doi:10.1016/j.ejor.2012.08.021
Ivanov, D., Sokolov, B., & Dolgui, A. (2014). The Ripple effect in supply chains: trade-off 'efficiency-flexibility-resilience'in disruption management. *International Journal of Production Research, 52*(7), 2154-2172. doi:10.1080/00207543.2016.1275873
Ivanov, D., Sokolov, B., & Kaeschel, J. (2010). A multi-structural framework for adaptive supply chain planning and operations control with structure dynamics considerations. *European Journal of Operational Research, 200*(2), 409-420. doi:10.1016/j.ejor.2009.01.002
Ivanov, D., Sokolov, B., Solovyeva, I., Dolgui, A., & Jie, F. (2016). Dynamic recovery policies for time-critical supply chains under conditions of ripple effect. *International Journal of Production Research, 54*(23), 7245-7258. doi:10.1080/00207543.2016.1161253
Jacobs, D. (1974). Dependency and vulnerability: An exchange approach to the control of organizations. *Administrative science quarterly*, 45-59.
Jain, V., Kumar, S., Soni, U., & Chandra, C. (2017). Supply chain resilience: model development and empirical analysis. *International Journal of Production Research, 55*(22), 6779-6800. doi:10.1080/00207543.2017.1349947
Jewan, R. Y. U., & Heekyung, P. (2018). Resilience assessment for interdependent water supply systems based on a system dynamics model. *WIT Transactions on Ecology and the Environment, 215*, 241. doi:10.2495/EID180221
Joakim, E. P., Mortsch, L., Oulahen, G., Harford, D., Klein, Y., Damude, K., & Tang, K. (2016). Using system dynamics to model social vulnerability and resilience to coastal hazards. *International Journal of Emergency Management, 12*(4), 366-391.
Johnson, N., Elliott, D., & Drake, P. (2013). Exploring the role of social capital in facilitating supply chain resilience. *Supply Chain Management: An International Journal, 18*(3), 324-336. doi:10.1108/SCM-06-2012-0203
Jüttner, U., & Maklan, S. (2011). Supply chain resilience in the global financial crisis: an empirical study. *Supply Chain Management: An International Journal, 16*(4), 246-259. doi:10.1108/13598541111139062
Jüttner, U., Peck, H., & Christopher, M. (2003). Supply chain risk management: outlining an agenda for future research. *International Journal of Logistics Research and Applications, 6*(4), 197-210. doi:10.1080/13675560310001627016
Kim, Y., Chen, Y.-S., & Linderman, K. (2015). Supply network disruption and resilience: A network structural perspective. *Journal of Operations Management, 33*, 43-59.
Kim, Y., Choi, T. Y., Yan, T., & Dooley, K. (2011). Structural investigation of supply networks: A social network analysis approach. *Journal of Operations Management, 29*(3), 194-211.
Klibi, W., Martel, A., & Guitouni, A. (2010). The design of robust value-creating supply chain networks: A critical review. *Eur. J. Oper. Res., 203*(2), 283-293. doi:10.1016/j.ejor.2009.06.011
Knudsen, M. H., & Agergaard, J. (2015). Ghana's cocoa frontier in transition: the role of migration and livelihood diversification. *Geografiska Annaler: Series B, Human Geography, 97*(4), 325-342.
Kolavalli, S., Vigneri, M., Maamah, H., & Poku, J. (2012). *The partially liberalized cocoa sector in Ghana: Producer price determination, quality control, and service provision*. Retrieved from Washington, D.C.: : http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/127140
Kongor, J., De Steur, H., Van de Walle, D., Gellynck, X., Afoakwa, E., Boeckx, P., & Dewettinck, K. (2018). Constraints for future cocoa production in Ghana. *An International Journal incorporating Agroforestry Forum, 92*(5), 1373-1385. doi:10.1007/s10457-017-0082-9
Kos, D., & Lensink, R. (2017). *Commitments vs Flexibility regarding take-up of pension savings accounts: A Randomised Control Trial on Cocoa Farmers in Ghana*. Paper presented at the International Symposium on Cocoa Research (ISCR, Lima, Peru.

Kotir, J. H., Smith, C., Brown, G., Marshall, N., & Johnstone, R. (2016). A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana. *Sci Total Environ, 573*, 444-457. doi:10.1016/j.scitotenv.2016.08.081

Kraljic, P. (1983). Purchasing must become supply management. *Harvard business review, 61*(5), 109-117.

Kray, H. A. H., Christine, Mikulcak, F., Giertz, Å., & Bucik, M. (2018). *Productive Diversification in African Agriculture and its Effects on Resilience and Nutrition*. Retrieved from The World Bank. Washington DC: http://documents.worldbank.org/curated/en/942331530525570280/Productive-Diversification-in-African-Agriculture-and-its-Effects-on-Resilience-and-Nutrition

Läderach, P., Martinez-Valle, A., Schroth, G., & Castro, N. (2013). Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. *Climatic change, 119*(3-4), 841-854.

Laven, A. (2011). The Ghanaian state and inclusive upgrading in the global cocoa chain. *Value chains, social inclusion and economic development: Contrasting theories and realities*, 121-147.

Leat, P., & Revoredo-Giha, C. (2013). Risk and resilience in agri-food supply chains: the case of the ASDA PorkLink supply chain in Scotland. *Supply Chain Management: An International Journal, 18*(2), 219-231. doi:10.1108/13598541311318845

Levy, D. L. (1995). International sourcing and supply chain stability. *Journal of international business studies, 26*(2), 343-360.

Li, G., Kou, C., Wang, Y., & Yang, H. (2020). System dynamics modelling for improving urban resilience in Beijing, China. *Resources, conservation and recycling, 161*, 104954. doi:10.1016/j.resconrec.2020.104954

Li, H., Liu, Z., Zheng, L., & Lei, Y. (2011). Resilience analysis for agricultural systems of north China plain based on a dynamic system model. *Scientia Agricola, 68*(1), 8-17. doi:10.1590/S0103-90162011000100002

Li, H., Pedrielli, G., Lee, L., & Chew, E. (2017). Enhancement of supply chain resilience through inter-echelon information sharing. *Flexible Services and Manufacturing Journal, 29*(2), 260-285. doi:10.1007/s10696-016-9249-3

Li, Y. (2014). Networked analysis approach of supply chain network. *Journal of Networks, 9*(3), 777.

Lin, B. B. (2011). Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change. *BioScience, 61*(3), 183-193. doi:10.1525/bio.2011.61.3.4

Liu, H., Tian, Z., Huang, A., & Yang, Z. (2018). Analysis of vulnerabilities in maritime supply chains. *Reliability Engineering & System Safety, 169*, 475-484. doi:https://doi.org/10.1016/j.ress.2017.09.018

Liu, J., Liu, F., Zhou, H., & Kong, Y. (2016). An Integrated Method of Supply Chains Vulnerability Assessment. *Scientific Programming, 2016*, <xocs:firstpage xmlns:xocs=""/>. doi:10.1155/2016/2819238

Liu, J. J. W., Reed, M., & Girard, T. A. (2017). Advancing resilience: An integrative, multi-system model of resilience. *Personality and Individual Differences, 111*, 111-118. doi:10.1016/j.paid.2017.02.007

Mahrizal, L., Nalley, L. L., Dixon, B. L., & Popp, J. S. (2014). An optimal phased replanting approach for cocoa trees with application to Ghana. *Agricultural Economics, 45*(3), 291-302. doi:10.1111/agec.12065

Mandal, S., & Sarathy, R. (2018). The Effect of Supply Chain Relationships on Resilience: Empirical Evidence from India. *Global Business Review, 19*(3_suppl), S196-S217. doi:10.1177/0972150918758094

Mandal, S., Sarathy, R., Korasiga, V. R., Bhattacharya, S., & Dastidar, S. G. (2016). Achieving supply chain resilience. *International Journal of Disaster Resilience in the Built Environment, 7*(5), 544-562. doi:10.1108/IJDRBE-04-2016-0010
Manning, L., & Soon, J. M. (2016). Building strategic resilience in the food supply chain. *British Food Journal, 118*(6), 1477-1493. doi:10.1108/BFJ-10-2015-0350
Margolis, J. T., Sullivan, K. M., Mason, S. J., & Magagnotti, M. (2018). A multi-objective optimization model for designing resilient supply chain networks. *International Journal of Production Economics, 204*, 174-185. doi:10.1016/j.ijpe.2018.06.008
Martin, R., & Schlüter, M. (2015). Combining system dynamics and agent-based modeling to analyze social-ecological interactions - an example from modeling restoration of a shallow lake. *Frontiers in Environmental Science, 3*(66). doi:10.3389/fenvs.2015.00066
Mayer, H., & Gleich, B. (2015). Measuring criticality of raw materials: An empirical approach assessing the supply risk dimension of commodity criticality. *Natural Resources, 6*(01), 56. doi:http://dx.doi.org/10.4236/nr.2015.61007
McManus, S., Seville, E., Brunsden, D., & Vargo, J. (2007). *Resilience management: a framework for assessing and improving the resilience of organisations*. Retrieved from Reslience Organisations. Christchurch, New Zealand: https://www.resorgs.org.nz/wp-content/uploads/2017/07/resilience-management-research-report-resorgs-07-01.pdf
Melnyk, S. A., Lummus, R. R., Vokurka, R. J., Burns, L. J., & Sandor, J. (2009). Mapping the future of supply chain management: a Delphi study. *International Journal of Production Research, 47*(16), 4629-4653.
Meuwissen, M. P. M., Feindt, P. H., Spiegel, A., Termeer, C. J. A. M., Mathijs, E., Mey, Y. d., . . . Vroege, W. (2019). A framework to assess the resilience of farming systems. *Agricultural Systems, 176*. doi:10.1016/j.agsy.2019.102656
Monastyrnaya, E., Joerin, J., Dawoe, E., & Six, J. (2016). *Assessing the resilience of the cocoa value chain in Ghana: Case study report*. Retrieved from Swiss Federal Institute of Technology Zurich: https://www.ethz.ch/content/dam/ethz/special-interest/usys/ias/enhancing-resilience-dam/documents/Final%20Report.%20Cocoa%20in%20Ghana.pdf
Moragues-Faus, A., Sonnino, R., & Marsden, T. (2017). Exploring European food system vulnerabilities: Towards integrated food security governance. *Environmental Science & Policy, 75*, 184-215.
Morgan, D. L. (1996). Focus groups. *Annu. Rev. Sociol., 22*, 129-152.
Morris MacLean, L. (2004). Empire of the Young: The Legacies of State Agricultural Policy on Local Capitalism and Social Support Networks in Ghana and Cte dIvoire. *Comp. Stud. Soc. Hist., 46*(3), 469-496. doi:10.1017/s0010417504000246
Munoz, A., & Dunbar, M. (2015). On the quantification of operational supply chain resilience. *International Journal of Production Research, 53*(22), 6736-6751. doi:10.1080/00207543.2015.1057296
Nagurney, A., & Qiang, Q. (2012). Fragile networks: identifying vulnerabilities and synergies in an uncertain age. *International Transactions in Operational Research, 19*(1-2), 123-160.
Nakatani, J., Tahara, K., Nakajima, K., Daigo, I., Kurishima, H., Kudoh, Y., . . . Moriguchi, Y. (2018). A graph theory-based methodology for vulnerability assessment of supply chains using the life cycle inventory database. *Omega, 75*, 165-181. doi:10.1016/j.omega.2017.03.003
Neureuther, B. D., & Kenyon, G. (2009). Mitigating Supply Chain Vulnerability. *Journal of Marketing Channels: Managing Risks and Disruptions in Global Supply Chains, 16*(3), 245-263. doi:10.1080/10466690902934532
Niforou, C. (2015). Labour Leverage in Global Value Chains: The Role of Interdependencies and Multi-level Dynamics. *Journal of business ethics, 130*(2), 301-311. doi:10.1007/s10551-014-2222-8

Nikookar, H., Takala, J., Sahebi, D., & Kantola, J. (2014). A Qualitative Approach for Assessing Resiliency in Supply Chains. *Management and production engineering review, 5*(4), 36-45. doi:10.2478/mper-2014-0034

Ntiamoah, A., & Afrane, G. (2008). Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approach. *Journal of Cleaner Production, 16*(16), 1735-1740. doi:10.1016/j.jclepro.2007.11.004

Obiri, B., Bright, G., McDonald, M., Anglaaere, L., & Cobbina, J. (2007). Financial analysis of shaded cocoa in Ghana. *An International Journal incorporating Agroforestry Forum, 71*(2), 139-149. doi:10.1007/s10457-007-9058-5

Odoom, I. (2017a). Dam In, Cocoa Out Pipes In, Oil Out: China's Engagement in Ghana's Energy Sector. *Journal of Asian and African Studies, 52*(5), 598-620. doi:10.1177/0021909615599419

Ogilvy, J. A., Schwartz,P. (1998). Plotting your scenarios. In R. R. Liam Fahey (Ed.), *Learning from the Future: Competitive Foresight Scenarios* (pp. 57-80). New York: John Wiley & Sons.

Opoku-Ameyaw, K., Oppong, F., Acheampong, K., & Amoah, F. (2012). Long term assessment of the agronomic and economic benefits of cocoa food crop intercropping in the absence of fertilizer application. *Journal of Experimental Agriculture International*, 186-197.

Opoku, I., Assuah, M., & Aneani, F. (2007). Management of black pod disease of cocoa with reduced number of fungicide application and crop sanitation. *Afr. J. Agric. Res., 2*(11), 601-604.

Papadopoulos, T., Gunasekaran, A., Dubey, R., Altay, N., Childe, S. J., & Fosso-Wamba, S. (2017). The role of Big Data in explaining disaster resilience in supply chains for sustainability. *Journal of Cleaner Production, 142*(P2), 1108-1118. doi:10.1016/j.jclepro.2016.03.059

Pathak, S. D., Day, J. M., Nair, A., Sawaya, W. J., & Kristal, M. M. (2007). Complexity and Adaptivity in Supply Networks: Building Supply Network Theory Using a Complex Adaptive Systems Perspective*. *Decision sciences, 38*(4), 547-580. doi:10.1111/j.1540-5915.2007.00170.x

Pettit, T. J., Croxton, K. L., & Fiksel, J. (2013). Ensuring Supply Chain Resilience: Development and Implementation of an Assessment Tool. *Journal of Business Logistics, 34*(1), 46-76. doi:10.1111/jbl.12009

Pettit, T. J., Fiksel, J., & Croxton, K. L. (2010). Ensuring supply chain resilience: Development of a conceptual framework. *Journal of Business Logistics, 31*(1), 1-21. doi:10.1002/j.2158-1592.2010.tb00125.x

Ponis, S., & Koronis, E. (2012). Supply Chain Resilience: Definition Of Concept And Its Formative Elements. *Journal of Applied Business Research, 28*(5), 921-929. doi:10.19030/jabr.v28i5.7234

Ponomarov, S. Y., & Holcomb, M. C. (2009). Understanding the concept of supply chain resilience. *The International Journal of Logistics Management, 20*(1), 124-143. doi:10.1108/09574090910954873

Pournader, M., Rotaru, K., Kach, A. P., & Razavi Hajiagha, S. H. (2016). An analytical model for system-wide and tier-specific assessment of resilience to supply chain risks. *Supply Chain Management: An International Journal, 21*(5), 589-609. doi:10.1108/SCM-11-2015-0430

Pourya, P., Oh Kyoung, K., Young-Tae, C., & Hyosoo, P. (2017). Evaluating Resiliency of Supply Chain Network: A Data Envelopment Analysis Approach. *Sustainability, 9*(2), 255. doi:10.3390/su9020255

Purvis, L., Spall, S., Naim, M., & Spiegler, V. (2016). Developing a resilient supply chain strategy during 'boom' and 'bust'. *Production Planning & Control: Production Systems: Successful Applications and New Challenges Part 1, 27*(7-8), 579-590. doi:10.1080/09537287.2016.1165306

Quarmine, W., Haagsma, R., van Huis, A., Sakyi-Dawson, O., Obeng-Ofori, D., & Asante, F. A. (2014). Did the price-related reforms in Ghana's cocoa sector favour farmers? *International Journal of Agricultural Sustainability, 12*(3), 248-262. doi:10.1080/14735903.2014.909639

Quinlan, A. E., Berbés-Blázquez, M., Haider, L. J., & Peterson, G. D. (2016). Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology, 53*(3), 677-687. doi:10.1111/1365-2664.12550

Rădăşanu, A. C. (2016). Inventory management, service level and safety stock. *Journal of Public Administration, Finance and Law, 5*(9), 145-153.

Rajesh, R. (2016). Forecasting supply chain resilience performance using grey prediction. *Electronic Commerce Research and Applications, 20*, 42-58. doi:10.1016/j.elerap.2016.09.006

Ratick, S., Meacham, B., & Aoyama, Y. (2008). Locating Backup Facilities to Enhance Supply Chain Disaster Resilience. *Growth and Change, 39*(4), 642.

Reyes Levalle, R., & Nof, S. Y. (2017). Resilience in supply networks: Definition, dimensions, and levels. *Annual Reviews in Control, 43*, 224-236. doi:10.1016/j.arcontrol.2017.02.003

Rice, J., & Caniato, F. (2003). Building a secure and resilient supply network. *Supply Chain Management Review, 7*(5), 22-30.

Rich, K. M., Rich, M., & Dizyee, K. (2018). Participatory systems approaches for urban and peri-urban agriculture planning: The role of system dynamics and spatial group model building. *Agricultural Systems, 160*, 110-123. doi:10.1016/j.agsy.2016.09.022

Rich, K. M., Ross, R. B., Baker, A. D., & Negassa, A. (2011). Quantifying value chain analysis in the context of livestock systems in developing countries. *Food Policy, 36*(2), 214-222. doi:10.1016/j.foodpol.2010.11.018

Richardson, G. P., Vennix, J. A., Andersen, D. F., Rohrbaugh, J., & Wallace, W. (1989). Eliciting group knowledge for model-building. In *Computer-based management of complex systems* (pp. 343-357): Springer.

Roberta Pereira, C., Christopher, M., & Lago Da Silva, A. (2014). Achieving supply chain resilience: the role of procurement. *Supply Chain Management: An International Journal, 19*(5/6), 626-642. doi:10.1108/SCM-09-2013-0346

Rosanna, S., & Giovanni, Q. (2015). Adaptive Cycle as a Tool to Select Resilient Patterns of Rural Development. *Sustainability, 7*(8), 11114-11138. doi:10.3390/su70811114

Rouwette, E. A. J. A., Vennix, J. A. M., & Mullekom, T. V. (2002). Group model building effectiveness: a review of assessment studies. *System Dynamics Review, 18*(1), 5-45. doi:10.1002/sdr.229

Saad, N. a. K., V.,. (2006). A DES approach for the contextual load modeling of supply chain system for instability analysis. *Simulation Modeling Practice & Theory, 14*, 541-563.

Sahu, A. K., Datta, S., & Mahapatra, S. S. (2017). Evaluation of performance index in resilient supply chain: a fuzzy-based approach. *Benchmarking: An International Journal, 24*(1), 118-142. doi:10.1108/BIJ-07-2015-0068

Salomon, A. K., Quinlan, A. E., Pang, G. H., Okamoto, D. K., & Vazquez-Vera, L. (2019). Measuring social-ecological resilience reveals opportunities for transforming environmental governance. *Ecology and society, 24*(3), 16. doi:10.5751/ES-11044-240316

Schmitt, A. J., & Singh, M. (2012). A quantitative analysis of disruption risk in a multi-echelon supply chain. *International Journal of Production Economics, 139*(1), 22-32. doi:10.1016/j.ijpe.2012.01.004

Schoemaker, P. (1995). Scenario Planning: A Tool for Strategic Thinking. *Sloan Management Review, 36*(2), 25.

Schoenberg, W., Davidsen, P., & Eberlein, R. (2020). Understanding model behavior using the Loops that Matter method. *System Dynamics Review*. doi:10.1002/sdr.1658

Scholten, K., & Schilder, S. (2015). The role of collaboration in supply chain resilience. *Supply Chain Management: An International Journal, 20*(4), 471-484. doi:10.1108/SCM-11-2014-0386

Scholten, K., Sharkey Scott, P., & Fynes, B. (2014). Mitigation processes – antecedents for building supply chain resilience. *Supply Chain Management: An International Journal, 19*(2), 211-228. doi:10.1108/SCM-06-2013-0191

Schroth, G., Läderach, P., Martinez-Valle, A., & Bunn, C. (2017). From site-level to regional adaptation planning for tropical commodities: cocoa in West Africa. *An International Journal Devoted to Scientific, Engineering, Socio-Economic and Policy Responses to Environmental Change, 22*(6), 903-927. doi:10.1007/s11027-016-9707-y

Senge, P. (1990). The fifth discipline. *The Art & Practice of Learning Organization. Doupleday Currence, New York.*

Senge, P. M., & Forrester, J. W. (1980). Tests for building confidence in system dynamics models. *System dynamics, TIMS studies in management sciences, 14*, 209-228.

Sexton, R. J., Sheldon, I., McCorriston, S., & Wang, H. (2007). Agricultural trade liberalization and economic development: the role of downstream market power. *Agricultural Economics, 36*(2), 253-270. doi:10.1111/j.1574-0862.2007.00203.x

Shao, L., & Jin, S. (2020). Resilience assessment of the lithium supply chain in China under impact of new energy vehicles and supply interruption. *Journal of Cleaner Production, 252*, 119624. doi:10.1016/j.jclepro.2019.119624

Sheffi, Y. (2001). Supply Chain Management under the Threat of International Terrorism. *The International Journal of Logistics Management, 12*(2), 1-11. doi:10.1108/09574090110806262

Sheffi, Y., & James B. Rice, J. (2005). A Supply Chain View of the Resilient Enterprise. *MIT Sloan Management Review, 47*(1), 41-48.

Sinclair, K., Rawluk, A., Kumar, S., & Curtis, A. (2017). Ways forward for resilience thinking: lessons from the field for those exploring social-ecological systems in agriculture and natural resource management. *Ecology and society, 22*(4), 21. doi:10.5751/ES-09705-220421

Skeete, A., Zymalski, J., & Keyser, D. (2017). Modelling Cascading Failure in Assembly Supply Chain Networks. *IIE Annual Conference. Proceedings*, 1424-1429.

Smith, A., & Stirling, A. (2010). The Politics of Social-ecological Resilience and Sustainable Socio-technical Transitions. *Ecology and society, 15*(1). doi:10.5751/ES-03218-150111

Snapir, B., Simms, D. M., & Waine, T. W. (2017). Mapping the expansion of galamsey gold mines in the cocoa growing area of Ghana using optical remote sensing. *Journal of Applied Earth Observation and Geoinformation, 58*, 225-233. doi:10.1016/j.jag.2017.02.009

Soni, U., Jain, V., & Kumar, S. (2014). Measuring supply chain resilience using a deterministic modeling approach. *Computers & Industrial Engineering, 74*(1), 11-25. doi:10.1016/j.cie.2014.04.019

Spiegler, V. L. M., Naim, M. M., & Wikner, J. (2012). A control engineering approach to the assessment of supply chain resilience. *International Journal of Production Research, 50*(21), 6162-6187. doi:10.1080/00207543.2012.710764

Spiegler, V. L. M., Potter, A. T., Naim, M. M., & Towill, D. R. (2016). The value of nonlinear control theory in investigating the underlying dynamics and resilience of a grocery supply chain. *International Journal of Production Research: Supply Chain Dynamics, Control and Disruption Management, 54*(1), 265-286. doi:10.1080/00207543.2015.1076945

Stave, K. A., & Kopainsky, B. (2015). A system dynamics approach for examining mechanisms and pathways of food supply vulnerability. *Journal of Environmental Studies and Sciences, 5*(3), 321-336.

Sterman, J. D. (2001). System Dynamics Modeling: Tools for Learning in a Complex World. *California Management Review, 43*(4), 8-25. doi:10.2307/41166098

Sterman, J. D., Fiddaman, T., Franck, T., Jones, A., McCauley, S., Rice, P., . . . Siegel, L. (2013). Management flight simulators to support climate negotiations. *Environmental Modelling and Software, 44*(C), 122-135. doi:10.1016/j.envsoft.2012.06.004

Sücüllü, C., & Yücel, G. (2014). *Behavior analysis and testing software (BATS).* Paper presented at the Proceedings of the 32nd International Conference of the System Dynamics Society.

Sundstrom, S. M., & Allen, C. R. (2019). The adaptive cycle: More than a metaphor. *Ecological Complexity, 39*. doi:10.1016/j.ecocom.2019.100767

Talbot, J. M. (2002). Tropical commodity chains, forward integration strategies and international inequality: coffee, cocoa and tea. *Review of International Political Economy, 9*(4), 701-734.

Tang, L., Jing, K., He, J., & Stanley, H. E. (2016). Complex interdependent supply chain networks: Cascading failure and robustness. *Physica A: Statistical Mechanics and its Applications, 443*, 58-69.

Tendall, D. M., Joerin, J., Kopainsky, B., Edwards, P., Shreck, A., Le, Q. B., . . . Six, J. (2015). Food system resilience: Defining the concept. *Global Food Security, 6*, 17-23. doi:10.1016/j.gfs.2015.08.001

Thekdi, S. A., & Santos, J. R. (2016). Supply Chain Vulnerability Analysis Using Scenario-Based Input-Output Modeling: Application to Port Operations. *Risk Analysis, 36*(5), 1025-1039. doi:10.1111/risa.12473

Tierney, K., & Bruneau, M. (2007). Conceptualizing and measuring resilience: A key to disaster loss reduction. *TR News*(250), 14-17.

Tomlin, B. (2006). On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management Science, 52*(5), 639-657.

Torabi, S. A., Namdar, J., Hatefi, S. M., & Jolai, F. (2016). An enhanced possibilistic programming approach for reliable closed-loop supply chain network design. *International Journal of Production Research, 54*(5), 1358-1387. doi:10.1080/00207543.2015.1070215

Tothmihaly, A. (2018). *How low is the price elasticity in the global cocoa market?* (1993-3738). Retrieved from Universität Göttingen, Research Training Group (RTG) 1666 - Global Food. Göttingen:

Tukamuhabwa, B. R., Stevenson, M., Busby, J., & Zorzini, M. (2015). Supply chain resilience: definition, review and theoretical foundations for further study. *International Journal of Production Research, 53*(18), 5592-5623. doi:10.1080/00207543.2015.1037934

Umar, M., Wilson, M., & Heyl, J. (2017). Food network resilience against natural disasters: a conceptual framework. *Sage open, 7*(3). doi:2158244017717570

van Eck, N. J., & Waltman, L. (2014). CitNetExplorer: A new software tool for analyzing and visualizing citation networks. *Journal of Informetrics, 8*(4), 802-823. doi:10.1016/j.joi.2014.07.006

Vlajic, J. V., van Der Vorst, J. G. A. J., & Haijema, R. (2012). A framework for designing robust food supply chains. *International Journal of Production Economics, 137*(1), 176-189. doi:10.1016/j.ijpe.2011.11.026

Vlajic, J. V., Van Lokven, S. W. M., Haijema, R., & Van Der Vorst, J. G. A. J. (2013). Using vulnerability performance indicators to attain food supply chain robustness. *Production Planning & Control, 24*(8-9), 785-799. doi:10.1080/09537287.2012.666869

Vugrin, E. D., Warren, D. E., & Ehlen, M. A. (2011). A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane. *Process Safety Progress, 30*(3), 280-290. doi:10.1002/prs.10437

Wagner, S. M., & Bode, C. (2006). An empirical investigation into supply chain vulnerability. *Journal of Purchasing and Supply Management, 12*(6), 301-312. doi:10.1016/j.pursup.2007.01.004

Wagner, S. M., & Neshat, N. (2010). Assessing the vulnerability of supply chains using graph theory. *International Journal of Production Economics, 126*(1), 121-129. doi:https://doi.org/10.1016/j.ijpe.2009.10.007
Wagner, S. M., & Neshat, N. (2012). A comparison of supply chain vulnerability indices for different categories of firms. *International Journal of Production Research, 50*(11), 2877-2891. doi:10.1080/00207543.2011.561540
Wang, Y., & Xiao, R. (2016). An ant colony based resilience approach to cascading failures in cluster supply network. *Physica A: Statistical Mechanics and its Applications, 462*, 150-166. doi:10.1016/j.physa.2016.06.058
Wee, B. V., & Banister, D. (2016). How to Write a Literature Review Paper? *Transport Reviews, 36*(2), 278-288. doi:10.1080/01441647.2015.1065456
Weed, M. (2005). "Meta Interpretation": A Method for the Interpretive Synthesis of Qualitative Research. *Forum: Qualitative Social Research, 6*(1).
Wessel, M., & Quist-Wessel, P. M. F. (2015). Cocoa production in West Africa, a review and analysis of recent developments. *NJAS - Wageningen Journal of Life Sciences, 74-75*, 1-7. doi:10.1016/j.njas.2015.09.001
Westhoek, H. J., van Den Berg, M., & Bakkes, J. A. (2006). Scenario development to explore the future of Europe's rural areas. *Agriculture, Ecosystems and Environment, 114*(1), 7-20. doi:10.1016/j.agee.2005.11.005
Whelan, J., Msefer, K., & Chung, C. V. (2001). *Economic supply & demand*: MIT.
Wieland, A., & Marcus Wallenburg, C. (2013). The influence of relational competencies on supply chain resilience: a relational view. *International Journal of Physical Distribution & Logistics Management, 43*(4), 300-320. doi:10.1108/IJPDLM-08-2012-0243
Wilcox, M. D., & Abbott, P. C. (2004). *Market Power and Structural Adjustment: The Case of West African Cocoa Market Liberalization*. Paper presented at the American Agricultural Economics Association 2004 Annual meeting, Denver.
Williamson, O. E. (1991). Comparative economic organization: The analysis of discrete structural alternatives. *Administrative science quarterly*, 269-296.
Wilson, M. C. (2007). The impact of transportation disruptions on supply chain performance. *Transportation Research Part E, 43*(4), 295-320. doi:10.1016/j.tre.2005.09.008
Wolstenholme, E. F. (1999). Qualitative vs quantitative modelling: the evolving balance. *Journal of the Operational Research Society, 50*(4), 422-428. doi:10.1057/palgrave.jors.2600700
Wolstenholme, E. F. (2003). Towards the definition and use of a core set of archetypal structures in system dynamics. *System Dynamics Review, 19*(1), 7-26. doi:10.1002/sdr.259
Wright, G., Cairns, G., O'Brien, F. A., & Goodwin, P. (2018). Scenario analysis to support decision making in addressing wicked problems: Pitfalls and potential. *European Journal of Operational Research*. doi:https://doi.org/10.1016/j.ejor.2018.08.035
Wu, T., Blackhurst, J., and O'Grady,P. (2007). Methodology for supply chain disruption analysis. *International Journal of Production Research, 45*(7), 1665-1682.
Zeng, Y., & Xiao, R. (2014). Modelling of cluster supply network with cascading failure spread and its vulnerability analysis. *International Journal of Production Research, 52*(23), 6938-6953. doi:10.1080/00207543.2014.917769
Zhang, X., & Aramyan, L. H. (2009). A conceptual framework for supply chain governance An application to agri-food chains in China. *China Agric. Econ. Rev., 1*(2), 136-154. doi:10.1108/17561370910927408
Zhu, Q., & Krikke, H. (2020). Managing a Sustainable and Resilient Perishable Food Supply Chain (PFSC) after an Outbreak. *Sustainability (Basel, Switzerland), 12*(12), 5004. doi:10.3390/su12125004