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International Journal of Production Research

ISSN: 0020-7543 (Print) 1366-588X (Online) Journal homepage: https://www.tandfonline.com/loi/tprs20

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International Journal of Production Research, 2019
https://doi.org/10.1080/00207543.2019.1704592

Identifying the precursors of vulnerability in agricultural value chains: A system dynamics approach

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(*Received 21 March 2019; accepted 4 December 2019*)

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

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 and 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, and 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 and 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, and 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,

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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 2 reviews some limitations of supply chain vulnerability assessment approaches and the indicators used for measuring supply chain vulnerability. Section 3 outlines the steps used in determining the precursors of vulnerability. Section 4 presents the results and discusses the findings, and Section 5 draws conclusions based on the findings and provides suggestions for future studies.

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 and 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, and 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.

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, and Keyser 2017; Wagner and Neshat 2010). Its utility lies in its ability to capture the complexities in inter-actor relationships in the supply chain (Borgatti and 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 1 (Moragues-Faus, Sonnino, and Marsden 2017; Nagurney and 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, and Keyser 2017; Wagner and 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.

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 (see Senge 1990, 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 (see Senge 1990, 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.

System dynamics modelling (SDM) can overcome the limitations of other vulnerability assessment approaches by offering a structural explanation (Dolgui, Ivanov, and Sokolov 2018; Senge 1990) and highlighting: (i) the decision-making behaviours in the supply chain (Blackhurst et al. 2018) and (ii) multi-level interdependencies of chain actors (Hearnshaw and Wilson 2013). However, SDM has not been widely applied to vulnerability assessment (Spiegler et al. 2016) due to complications of monitoring nodal activity and collecting data beyond the focal firm level (Blackhurst et al. 2018).

Table 1. 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, Zymalski, and Keyser (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, Mangan, and Palacin (2017)
	†					†	Undirected	Network efficiency	Crucitti, Latora, and Marchiori (2004)

Table 2. Indicators for measuring supply chain vulnerability.

Category	Outputs	Reference
Raw materials (Inventory) – related	Average unfulfilled demand/ Number of undelivered batches	Levy (1995); Saad and Kadirkamanathan (2006); Wilson (2007)
	Inventory levels/ Average stock levels	Levy (1995); Saad and Kadirkamanathan (2006)
	Number of stock-outs	Saad and Kadirkamanathan (2006)
	Number of emergency orders	
	Faulty material	
	Stock wastage	
	Quantity loss/ Stock fluctuations and goods in transit	Wilson (2007); Saad and Kadirkamanathan (2006)
Economic-related	Costs of sourcing (increment)/ Costs (after implementation of redesign strategy)	Levy (1995), Tomlin (2006); Wu, Blackhurst, and O'Grady (2007)
	Economic loss	Thekdi and Santos (2016)
Time-related	Lead time	Albino, Garavelli, and Schiuma (1998); Wu, Blackhurst, and O'Grady (2007)
	Backorder frequency	Albino, Garavelli, and Schiuma (1998)
	Time to reach steady state (days)	Saad and Kadirkamanathan (2006)
	Late deliveries	
	Frequency and duration of disruption in supply/Disruption periodicity	Melnyk et al. (2009)
Indexes	Herfindahl–Hirschman Index (HHI)	Nakatani et al. (2018)
	Inoperability	Thekdi and Santos (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, between ness, node degree)	Liu et al. (2018)

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 and Neshat 2010), which arises from feedback and the interactions of agents (Stave and 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 2 shows some examples of the different categories of indicators that have been developed for measuring supply chain vulnerability.

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 and Neshat 2010) requires that indicators represent a system-wide spectrum of vulnerability to highlight chainwise 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 and 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 chainwise significance (Saad and Kadirkamanathan 2006).

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

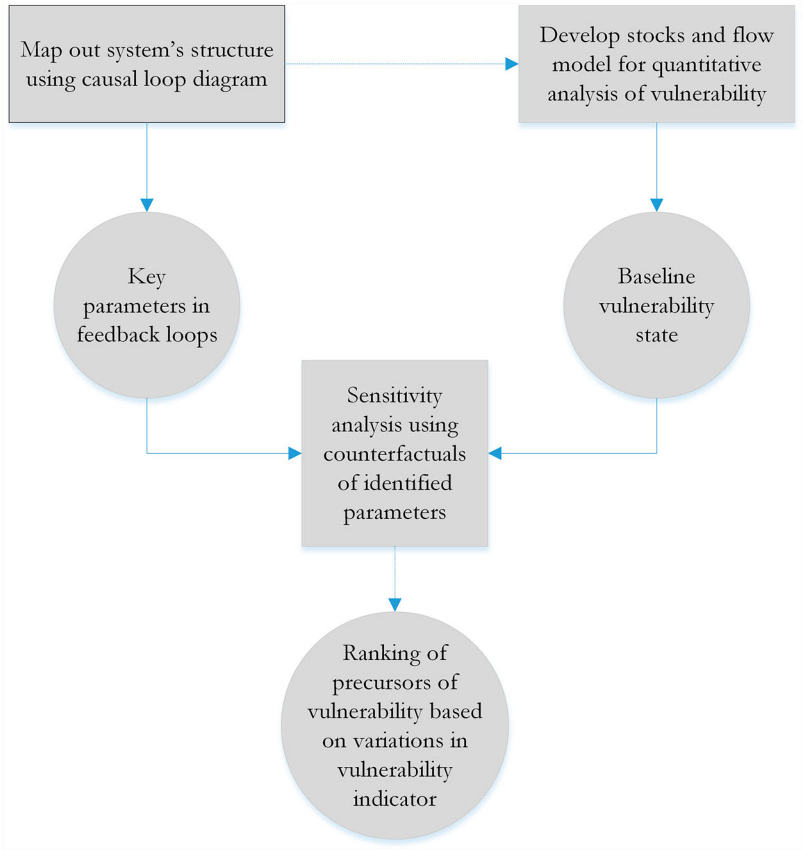

Figure 1. Framework for identifying precursors of supply chain vulnerability.

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 locations 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 1. 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. 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.

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 2. 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.

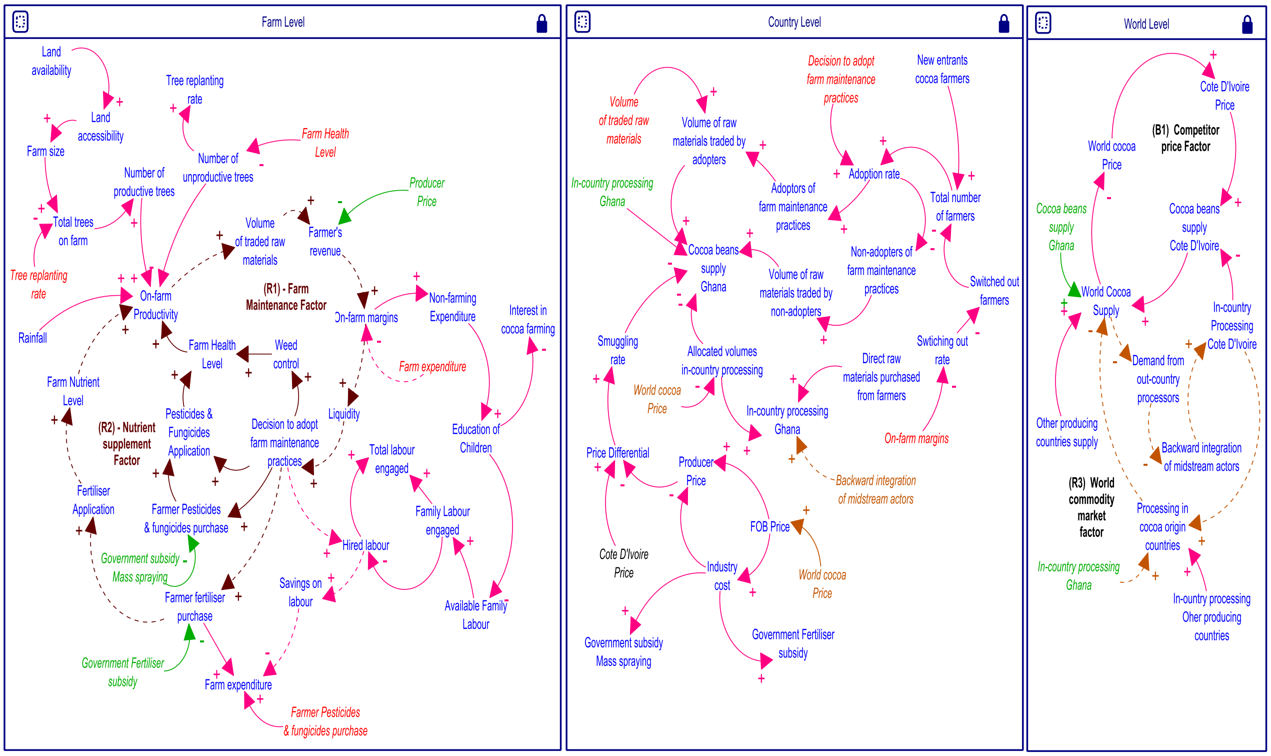

Figure 2. Causal loop diagram highlighting the system structure of Ghana's cocoa value chain.

3.1.1. *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 and Quist-Wessel 2015). *Ceteris paribus*, increased fertiliser application causes increases 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 (Nalley, Dixon, and Popp 2014), weed, disease and pest control, farm health level, on-farm productivity and farmer revenues (Wessel and 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.

3.1.2. *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 (BulÌř 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.

3.1.3. 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.

3.2. 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). An average farm size ($\mathrm{Farm_{size}}$) of three hectares and a tree planting density ($\mathrm{Tree_{hec}}$) 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 ($\mathrm{Agg_{pd}}$) is determined by multiplying planting density, average farm size, and the aggregate number of cocoa farms ($\mathrm{Cocoa_{farm}}$):

$$\mathrm{Agg_{pd}} = \mathrm{Tree_{hec}} * \mathrm{Farm_{size}} * \mathrm{Cocoa_{farm}} \tag{1}$$

On-farm yields are influenced by tree maturity and the decision to engage in Good Agricultural Practices (GAP). Productive trees are 30 years of age and younger, while unproductive trees are trees over 30 years old (Nalley, Dixon, and Popp 2014). Two classes of farmers are represented in the model: those engage 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 (Nalley, Dixon, and Popp 2014). Aggregate harvest for a cropping year is specified in Equation (2):

$$\mathrm{Harv_{ag}} = [(P_{\mathrm{trees\ (ad)}} * Ty_{\mathrm{ad}}) + (P_{\mathrm{trees\ (nad)}} * Ty_{\mathrm{nad}})] \tag{2}$$

where $\mathrm{Harv_{ag}}$ is the aggregate harvest, $P_{\mathrm{trees(ad)}}$ and $P_{\mathrm{trees(nad)}}$ 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.

Both adoption and dis-adoption are incorporated into the farm-level module. Rates of flow between *Adopters* and *Non-adopters* 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 3 and 4 respectively:

$$\mathrm{GAP_{adopt}} = (\mathrm{Adopt_{rate}} * \mathrm{Farmer_{pop}}) - (\mathrm{Dis} - \mathrm{adopt_{rate}} * \mathrm{Farmer_{pop}}) \tag{3}$$

$$\mathrm{GAP_{non\text{-}adopt}} = (\mathrm{Dis} - \mathrm{adopt_{rate}} * \mathrm{Farmer_{pop}}) - (\mathrm{Adopt_{rate}} * \mathrm{Farmer_{pop}}) - \mathrm{Switch} - \mathrm{out_{rate}} * \mathrm{Non} - \mathrm{Adopt} \tag{4}$$

Where $\mathrm{Adopt_{rate}}$, $\mathrm{Dis\text{-}adopt_{rate}}$ and $\mathrm{Switch\text{-}out_{rate}}$ 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 ($\mathrm{Av_{pod}} * \mathrm{Farm_{size}} * \mathrm{Tree_{hec}} * \mathrm{Pod_{dweight}}$) multiplied by the producer price ($\mathrm{Prod_{price}}$) results in farm income. The difference in the farm income and total farm expenditure ($\sum \mathrm{Inputs_{cost}} + \mathrm{Lab_{cost}}$) gives the farm margin, expressed in

Equation (5).

$$F_{\text{margin}} = [(\text{Av}_{\text{pod}} * \text{Farm}_{\text{size}} * \text{Tree}_{\text{hec}} * \text{Pod}_{\text{dweight}}) * \ \text{Prod}_{\text{price}}] - \left(\sum \text{Inputs}_{\text{cost}} + \text{Lab}_{\text{cost}}\right) \tag{5}$$

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 0.0033 kg of dried cocoa beans (Nalley, Dixon, and Popp 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.

3.2.1. *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 out-country processors respectively. Using the magnitude-related performance indicator for each actor, vulnerability is estimated as:

$$\text{Mag}_{\text{Vul}\,(t)} = \left[\frac{(\text{Vul}_{\text{count}\,(t)} - \text{Vul}_{\text{base}(t)})}{\text{Vul}_{\text{base}(t)}}\right] * 100\% \tag{6}$$

Where $\text{Mag}_{\text{Vul}(t)}$ is the vulnerability level for a specific chain actor expressed in percentages, $\text{Vul}_{\text{base}(t)}$ is the output from the baseline model, and $\text{Vul}_{\text{count}(t)}$ 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 $\text{Vul}_{\text{count}(t)}$ is less than $\text{Vul}_{\text{base}(t)}$, 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.

3.2.2. *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.

3.2.3. *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 3).

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 and Yücel 2014). The statistical measures were analysed in R studio®. MAPE and Theil U are estimated as Equations 7 and 8 respectively.

$$\text{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\left[\frac{(A_t - F_t)}{A_t}\right] \tag{7}$$

$$\text{Theil U} = \sum_{t=1}^{n} = 1\left[\frac{(F_t - A_t)^1/2}{A_t{}^1/2}\right] \tag{8}$$

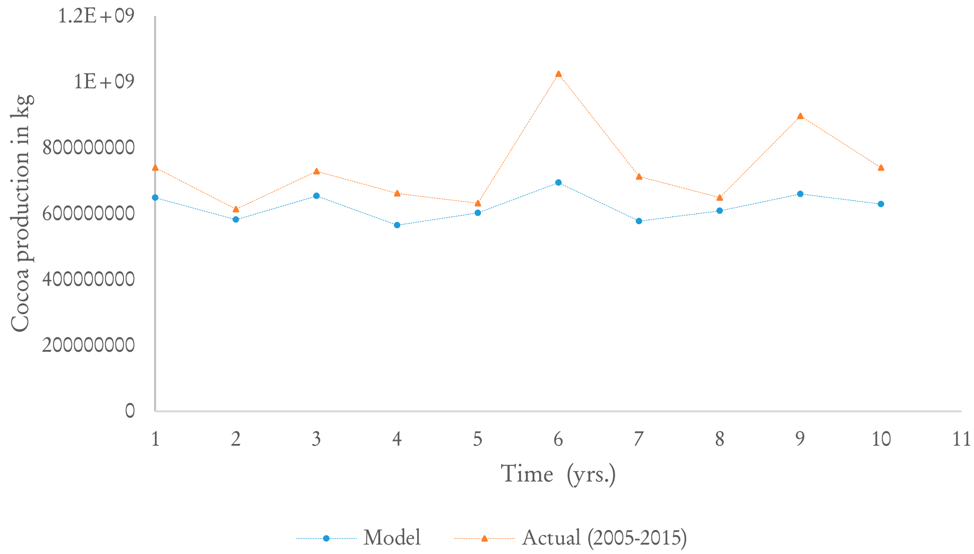

Figure 3. A comparison of model estimation and Ghana's actual cocoa production figures.

Table 3. Measures for model validity.

	Actual	Model	Difference	% Error
Comparative measure				
Mean (kg)	740,100,000	622,353,100	60,154,300	0.16
Comprehensive measure				
MAPE		0.168		
Theil U		0.2744		
Transient measure				
Maximum (kg)	1,025,000,000	694,361,000	330,639,000	0.323
Minimum (kg)	614,000,000	565,353,000	48,647,000	0.079

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 3).

4. Results and discussions

Results from the baseline model, shown in Table 4, indicate that on average, the magnitude-related performance indicator (MRPI) 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.

4.1. 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

Table 4. Baseline levels of vulnerability measures.

Measures	Ghana cocoa producers	In-country processors	Out-country processors
Mean (kg)	622353,100	177,582,043.11	426,855,100.89
Max (kg)	694,361,000	213,560,591.04	516,028,395.54
Min (kg)	565,353,000	96704582.21	378,454,575.33
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

Table 5. 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

levels of the cocoa value chain. Table 5 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.

4.1.1. Magnitude of effect on vulnerability levels – upstream precursors of vulnerability

Results of the sensitivity analyses involving adjustments of upstream precursors are shown in Table 6 and Figure 4. 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) (Nalley, Dixon, and Popp 2014) makes the cocoa value chain vulnerable.

4.1.2. 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

Table 6. Results of sensitivity analyses.

	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)(%)[a]	– 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

[a]Mean vulnerability level is estimated for only vulnerable periods.

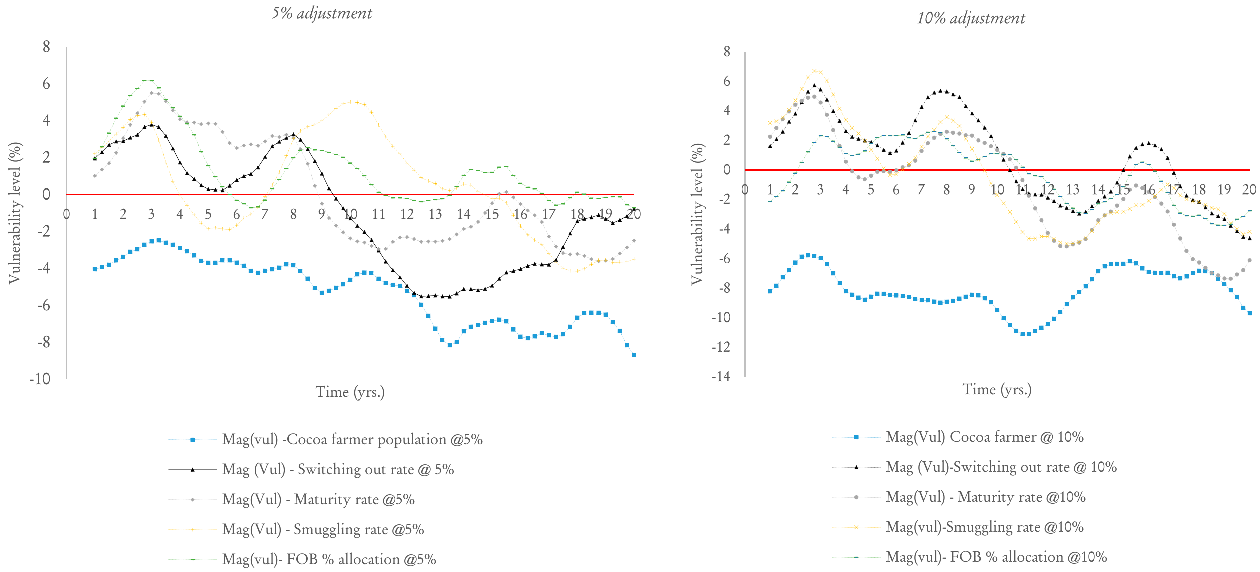

Figure 4. Vulnerability levels for 5% and 10% adjustment of upstream precursors.

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 4 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 and Lensink 2017).

4.1.3. 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 7 and Figure 5 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.

4.1.4. 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

Table 7. 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	Processors out-country	Cocoa producers	In-country processors	Processors out-country
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

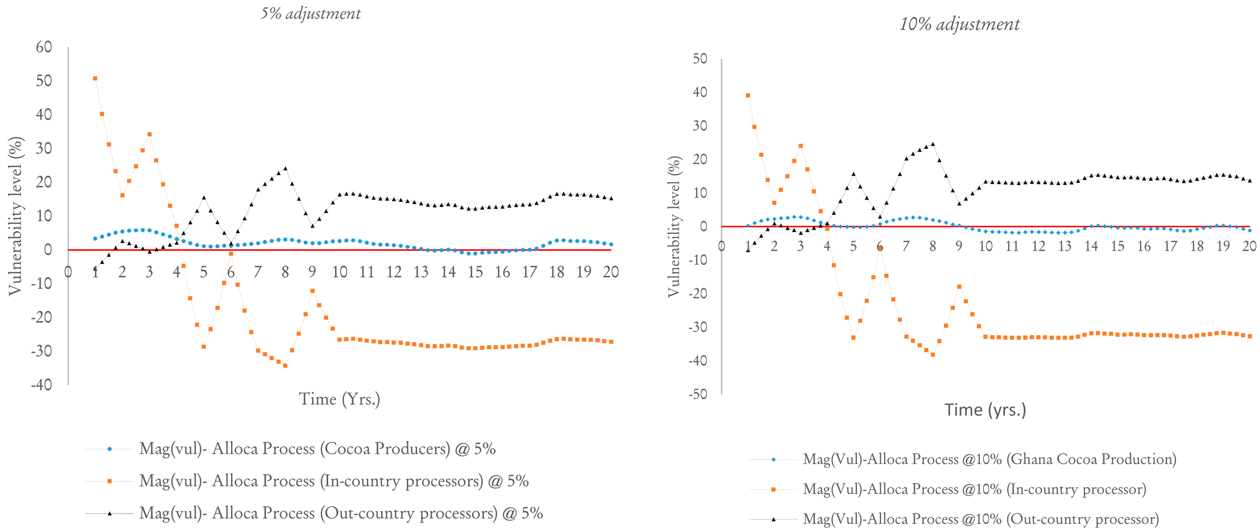

Figure 5. Results of 5% and 10% decrease in cocoa beans allocation for in-country processing.

the export supplier 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%.

4.2. 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 8 and Figure 6).

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 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.

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.

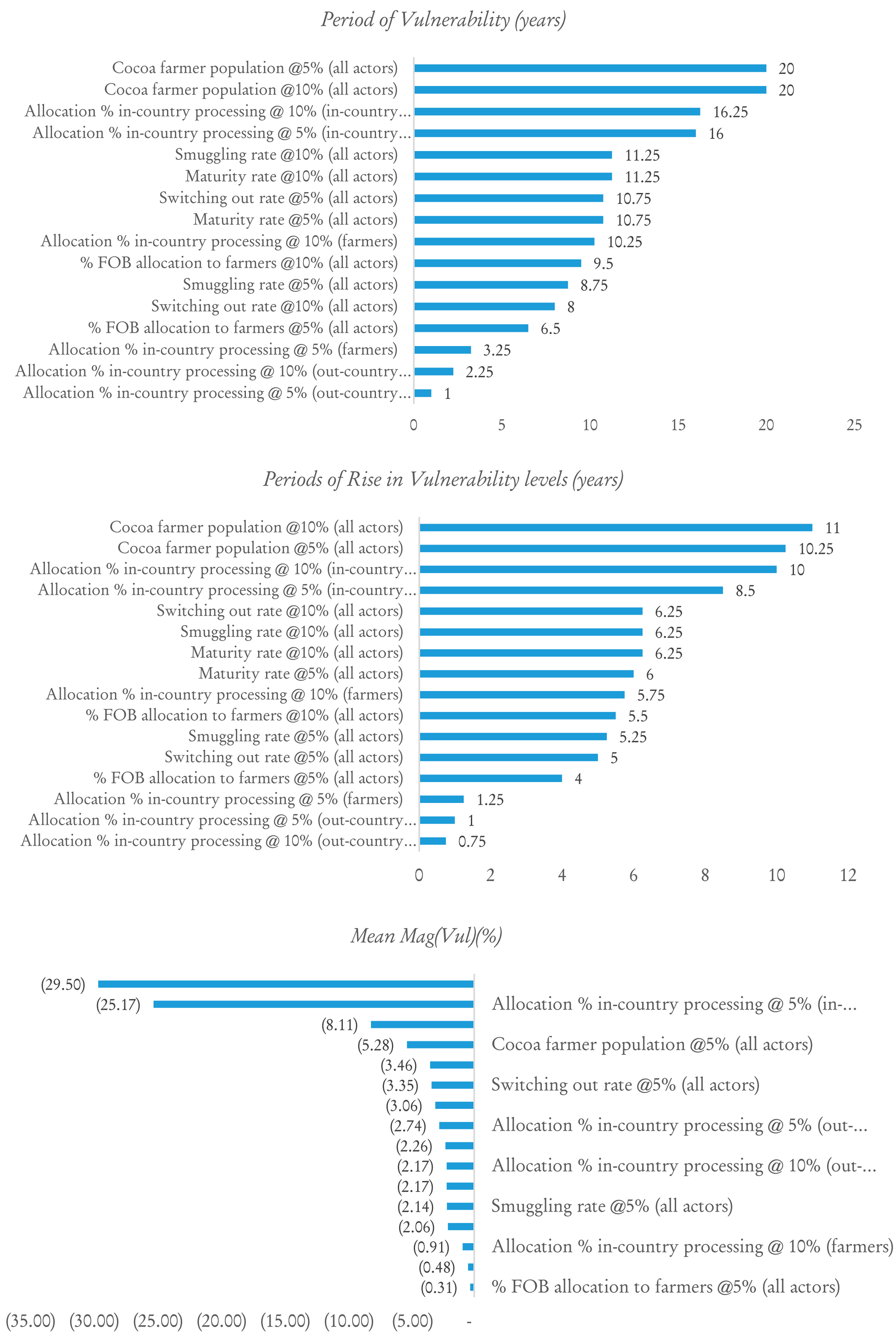

Figure 6. Ranking of precursors of vulnerability based on the three criteria.

Table 8. 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	1.6666667	1st
Allocation % in-country processing @ 10% (in-country processors)	1st	3rd	2nd	2	2nd
Cocoa farmer population @5% (all actors)	4th	2nd	1st	2.3333333	3rd
Allocation % in-country processing @ 5% (in-country processors)	2nd	4th	3rd	3	4th
Maturity rate @10% (all actors)	5th	5th	4th	4.6666667	5th
Smuggling rate @10% (all actors)	7th	5th	4th	5.3333333	6th
Maturity rate @5% (all actors)	9th	6th	5th	6.6666667	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	8.6666667	10th
% FOB allocation to farmers @10% (all actors)	12th	8th	7th	9	11th
Smuggling rate @5% (all actors)	11th	9th	8th	9.3333333	12th
Allocation % in-country processing @ 5% (out-country processors)	8th	13th	13th	11.333333	13th
% FOB allocation to farmers @5% (all actors)	15th	11th	10th	12	14th
Allocation % in-country processing @ 10% (out-country processors)	10th	14th	12th	12	14th
Allocation % in-country processing @ 5% (farmers)	14th	12th	11th	12.333333	15th

5. 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. 2011), 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%.

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 export supplier. 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 take into account 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.

Disclosure statement

No potential conflict of interest was reported by the authors.

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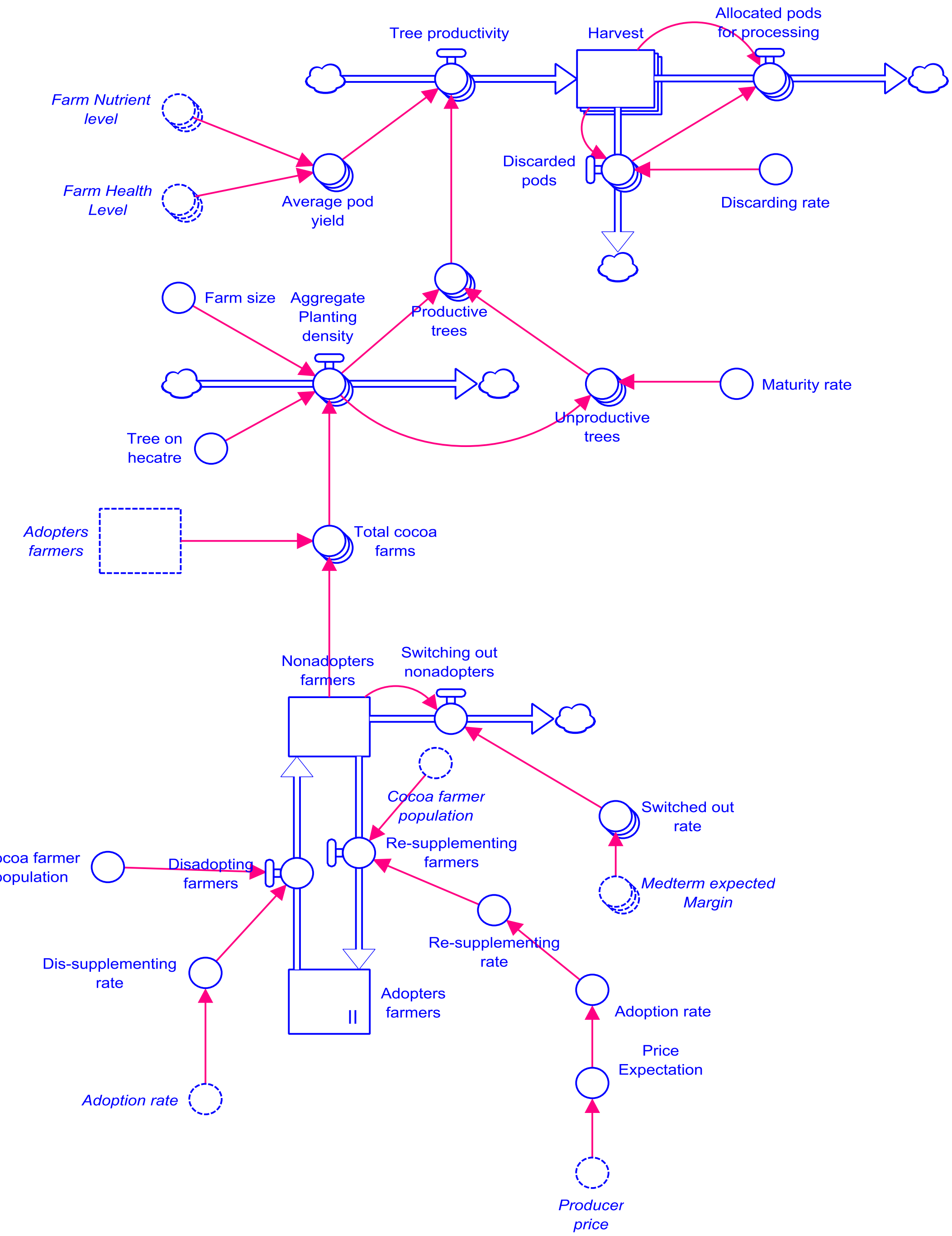
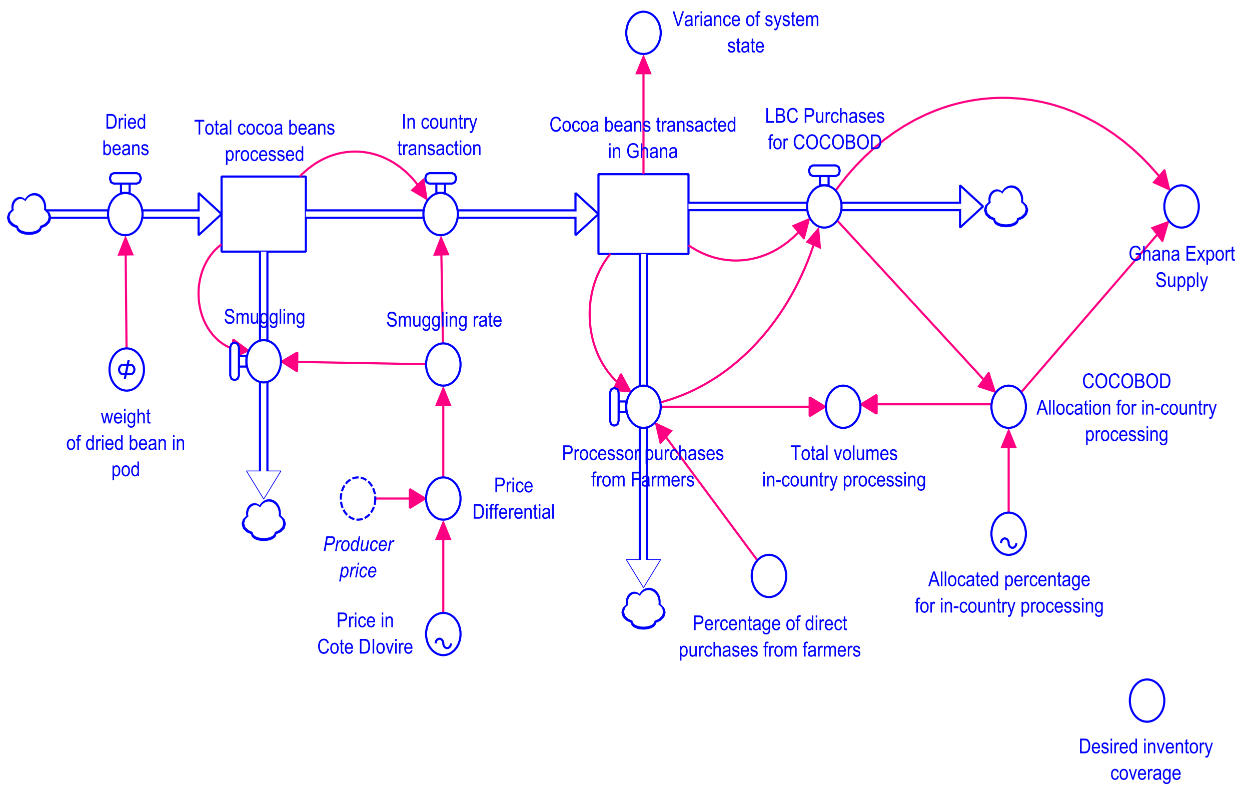
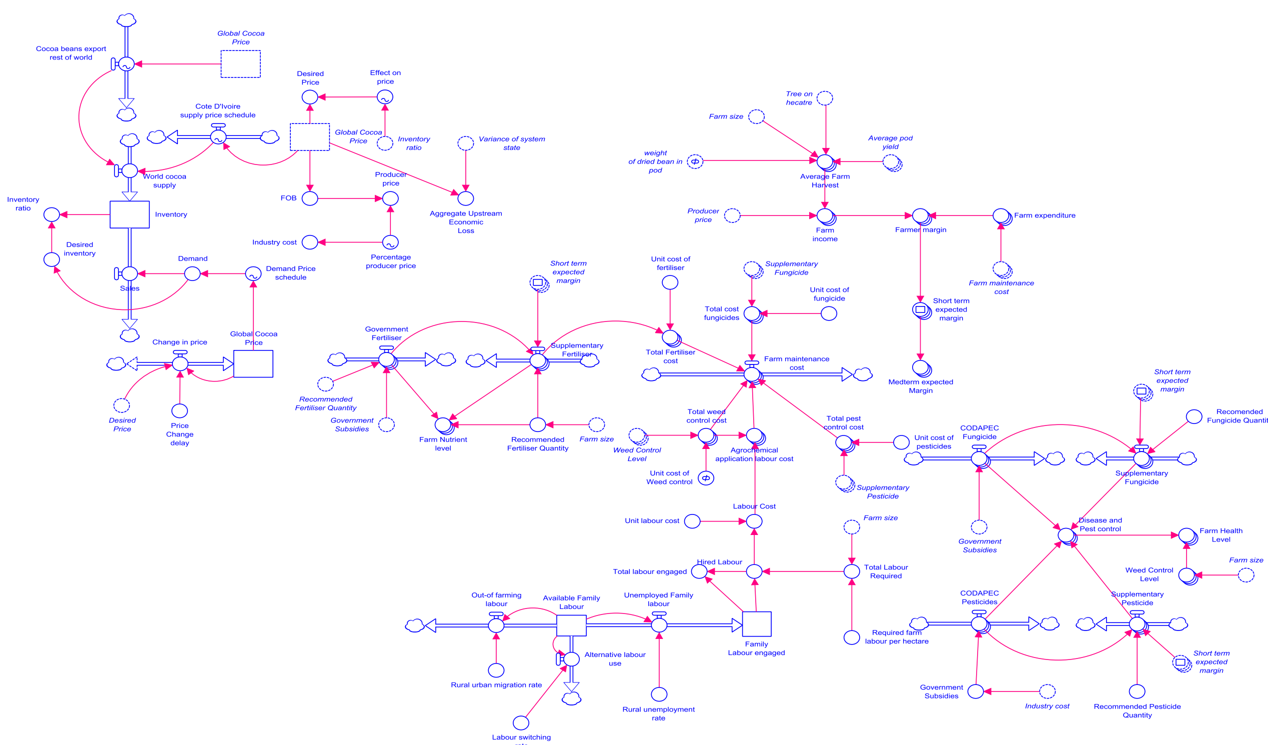
Appendices


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
Re-supplementing farmers
Cocoa farmer population
Disadopting farmers
Medterm expected Margin
Re-supplementing rate
Dis-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
COCOBOD Allocation for in-country processing
Processor purchases from Farmers
Total volumes in-country processing
Price Differential
Producer price
Price in Cote DIovire
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
Inventory ratio
Variance of system state
World cocoa supply
Producer price
Inventory
FOB
Aggregate Upstream Economic Loss
Desired inventory
Industry cost
Demand
Demand Price schedule
Percentage producer price
Sales
Change in price
Price Change delay
Government Fertiliser
Supplementary Fertiliser
Recommended Fertiliser Quantity
Government Subsidies
Farm Nutrient level
Farm size
Tree on hecatre
Average pod yield
Average Farm Harvest
Farm income
Farmer margin
Farm expenditure
Farm maintenance cost
Short term expected margin
Medterm expected Margin
Unit cost of fertiliser
Supplementary Fungicide
Unit cost of fungicide
Total cost fungicides
Total Fertiliser cost
Total weed control cost
Agrochemical application labour cost
Total pest control cost
Weed Control Level
Unit cost of Weed control
Supplementary Pesticide
Unit cost of pesticides
CODAPEC Fungicide
Recomended Fungicide Quantity
Disease and Pest control
Farm Health Level
Labour Cost
Unit labour cost
Hired Labour
Total labour engaged
Total Labour Required
Required farm labour per hectare
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
CODAPEC Pesticide
Supplementary Pesticide
Government Subsidies
Industry cost
Recommended Pesticide Quantity