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Understanding the Impact of COVID-19 on Agriculture and Food Supply Chains: System Dynamics Modeling for the Resilience of Smallholder Farmers

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ABSTRACT

COVID-19 has caused severe agriculture and food supply chain disruptions, significantly affecting smallholder farmers who supply most of the world’s food, specifically their changes in vulnerability, resilience, and food loss and waste. Therefore, the objective of this study was to understand the complex causal and feedback relationships for this system by developing a dynamic hypothesis and causal loop diagrams utilizing the System Dynamics methodology. Results provide a roadmap for dialogue and a framework for case-specific model development and help to guide policy decisions for smallholder farmers’ survival during health crises.

Keywords: *COVID-19; Smallholder farmers; vulnerability; resilience; food loss; food waste.*

1 Introduction

The global disruptions associated with the COVID-19 pandemic have exposed weaknesses in agriculture and food (**AF**) supply chains (Stephens et al., 2020; Torero, 2020) and created a need for decision-maker action to enhance their resilience (Hobbs, 2020; IPES, 2020; Petetin, 2020; Torero and Javorcik, 2020). Agriculture and food supply chains drive the physical transformation and transportation of commodities from seed to fork (Atamer Balkan, 2019), including the flow of materials, products, financial resources, information, energy, and natural resources (Tsolakis et al., 2014). Within the context of supply chains, "resilience" can be defined as the capacity of the system to withstand disturbances and to be able to provide desirable outcomes, whereas "vulnerability" is the inability of the system to respond to disruptions without producing undesirable consequences (Brzezina et al., 2016). As this pandemic unfolds, immediate actions are needed to increase the resilience of vulnerable agriculture groups like small-scale farmers who supply most of the world's food needs (FAO, 2014; ETC Group, 2017). The emergent COVID-19 pandemic has affected AF supply chains worldwide, causing problems related to food production (Stephens et al., 2020), food loss and waste (Aldaco et al., 2020), food access (Aday and Aday, 2020), and food security (Dev and Kabir, 2020), primarily due to travel restrictions and lockdown regulations (Garnett, Doherty, and Heron, 2020; IPES, 2020; United Nations, 2020). Similarly, shifts in consumer behavior because of lifestyle disruptions and psychological stress due to the lockdown (Aldaco et al., 2020) have led to shortages or surpluses of certain goods.

Recently the FAO (2020a) reported that the pandemic is not just critical to worldwide health but also resembles a global food crisis that has varied effects on different population groups, with the most significant impact expected to be on farmers (Bruno et al., 2020). The resulting coping strategies employed by small-scale farmers can result in broader welfare implications (Haga, 2020; Galiano and Hernandez, 2008), heightening the importance of building resilience among them (Bhavani and Gopinath, 2020). The effects of the pandemic are a wake-up call to rethink current operational practices and policies (FAOb, 2020). Agriculture and food systems are complex adaptive systems with multiple stakeholders, interacting elements, and nonlinear feedback relationships (Higgins et al., 2010; Atamer Balkan, 2019; Ge et al., 2015; Orr et al., 2018). Therefore, we adopt the System Dynamics (**SD**) methodology, a formal approach to understanding and modeling complex socio-economic, managerial, or ecological systems.

Agriculture and food supply chain resilience and vulnerability have been investigated with several SD modeling studies. These studies covered supply chain resilience assessment (Spiegler et al.,2012) and understanding food system vulnerability with conceptual models (Stave and Kopainsky, 2015). Recently Armendariz et al. (2016) focused on a systemic understanding of sustainability and resilience of food systems at the urban and regional level. Others have investigated vulnerabilities, resilience, and sustainability for organic farmers (Brzezina et al., 2016), spatial group model building in urban agriculture populations (Rich et al., 2018), and subsistence farmers (Oyo and Kalema,2016). Systems studies have also highlighted the importance of endogenous structures to understand the precursors of the agricultural value chain vulnerability (Aboah et al., 2019), the effects of climate change, and the identification of adaptive mechanisms to improve food security resilience (Herrera and Kopainsky, 2019). However, no current SD studies have been applied to understanding the disruptions to AF supply chain resilience under the influence of a community health crisis (e.g., the COVID-19 pandemic). Therefore, the modeling purpose (objective) of the current study was to identify the short-term (i.e., months) and medium-term (i.e., 1-2 years) effects of immediate COVID-19 related policy actions to facilitate both input access and market access of small-scale producers, help maintain agricultural production, and suppress the increasing food loss and waste at the farm level during health crises.

2 Methods

The SD methodology utilizes qualitative and quantitative methods. It follows iterative stages of problem articulation, dynamic hypothesis formulation, model building, model testing, policy design, analysis, evaluation, and implementation (Forrester, 1961; Sterman, 2000).

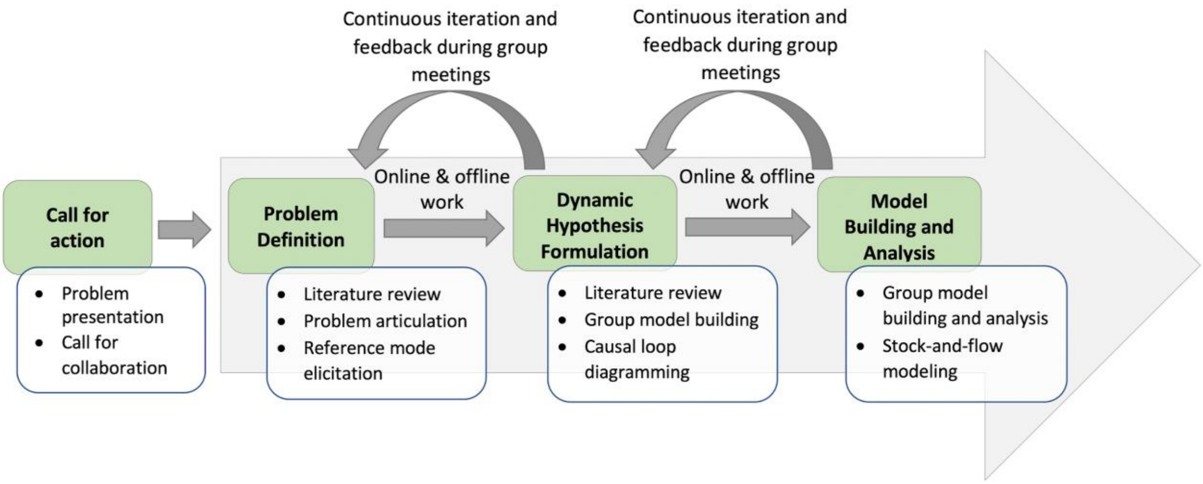

Figure 1. Summary of the modelling stages followed in the study.

The current study focused on presenting the problem definition, dynamic hypothesis formulation, and qualitative model building stages as a starting point for the further steps of quantitative model development and policy analysis (Figure 1). The COVID-19 created an additional impetus for accelerating ongoing online SD modeling (Wilkerson et al., 2020; Zimmermann et al., 2020). Our work takes the recently reported online SD modeling activities one-step-further: Consisting of a series of project meetings, model building sessions, individual and team assignments, project management activities, and eight team members from diverse countries (India, Nigeria, Philippines, Sweden, Turkey, and the US) with different perspectives on the issue. The work presented in this paper is an international, six-month-length SD modeling project which was entirely conducted using online environments.

Throughout the current study, group model building practices (Luna-Reyes et al., 2006; Hovmand et al., 2012; Anderson and Lewis, 2019) were used and adapted for online communication platforms. The current study's literature review revealed the most urgent issues regarding COVID-19 and its effects on AF supply chains, which are the restrictions on transportation, input access, and market access; shortage of farm inputs and workforce; plant shutdowns and disruptions along the production lines; closure of food markets; and changes in consumer behavior and food demand.

As the results of the problem articulation stage, smallholder farmers were selected as the main problem customers, as the beneficiaries or the victims of the consequences of the corresponding decisions (Daellenbach et al., 2012). Farming and processing communities were selected as the problem owners as the stakeholders who are dissatisfied with the current state and have some control over various aspects of the problem (Daellenbach et al., 2012).

System Dynamics models can be developed through participatory approaches and bring together stakeholders with different backgrounds (Lie and Rich, 2016). Consequently, our multidisciplinary group model building team was able to include "hard" and "soft" variables in the model boundary. For example, "hard" variables like the physical flow along the food supply chain and the financial competency of smallholder farmers, and "soft" variables like information availability and the level of cooperation within the community were considered. As the representative commodity group, the current study focused on fresh fruits and vegetables; and the variable names, causal relationships, and decision rules were defined accordingly to form a dynamic hypothesis.

As a crucial step of modeling, model validation establishes confidence in the usefulness of a model concerning its purpose (Barlas and Carpenter, 1990; Barlas, 1994). Since the current study aimed to depict the causal feedback relationships related to AF supply chain resilience from the viewpoint of small-scale farmers via a comprehensive stock-and-flow diagram, the relevant validity tests for this study were specified as Structural Assessment and Boundary Adequacy tests (Sterman, 2000). Review of model structure and assumptions were conducted through empirical evidence related to causal relationships among variables. Since our objective was to understand the effects of COVID-19 on smallholder food systems from a global perspective, the analysis relied on a diverse set of resources instead of focusing on specific cases of selected stakeholders. The stock-and-flow model was mainly constructed and validated via relevant references such as reports published by reputable international organizations (e.g., FAO, United Nations; IPES), and publications that are relevant to the relationships between the pandemic and food systems (e.g., Garnett, Doherty, and Heron, 2020; Hobbs, 2020; Petetin, 2020; Stephens et al., 2020), SD modeling (Stave and Kopainsky, 2015; Huff et al., 2015), community health during a pandemic (Demirag, 2020; Blecker et al., 2020), supply chain management (Gray, 2020; Mussell et al., 2020), and AF resource management (Burger, Warner, and Derix, 2010; Bruno et al., 2020; Galanakis, 2020; Torero, 2020). Throughout the tests, we inquired about the endogeneity and exogeneity of each variable, the consistency of the model relationships with the available knowledge about the effects of the pandemic, the level of aggregation of variables, and the decision rules along the supply chain.

3 Results

The current study resulted in a stock-and-flow diagram representing the components of the AF supply chain identified as essential to model the impacts of COVID-19 on smallholder farmers. The stock-and-flow diagram consists of nine interacting sectors: (1) Food Supply Chain, (2) Food Market, (3) Farm Finance, (4) Agricultural Inputs, (5) Labor, (6) Shelf Life, (7) Cooperation, (8) Information, and (9) Community Health. The model consists of more than 150 variables, where 15 are stocks, and 33 are flows.

The major characteristics and assumptions of the model are as follows: a) The model represents the causal relationships within a closed community (e.g., a village or city) where a certain amount of the population is engaged in AF production activities. Hence, the spread of the pandemic affects AF production, transportation, and other related operations; b) the farmers in the community are price takers rather than price makers, i.e., their production amount is not high enough to affect the exogenous market price; c) the AF supply chain in focus is assumed to represent the structures and the processes of perishable, fresh fruit, and vegetable supply chains; d) since the model focused on the effects of short-term and medium-term policy actions, the time unit of the model is assumed to be weeks where the time horizon of the model is assumed to be two years. These characteristics and assumptions resulted in explicit structures and causal loops for the nine sectors. Stylized versions of the stock-and-flow diagrams of each of the nine sectors are depicted, highlighting the number of selected key feedback loops for each sector.

3.1 Food Supply Chain

Food Supply Chain includes the physical transformation and transportation of the product from *Food Growth* to *Food Consumption* (Figure 2). During the pandemic, *Food Harvest* is severely affected due to a decrease in the *Availability of Laborers*. *Food Price at Farmers Level* is also a determinant of *Food Harvest*: If the farmers do not receive enough earnings from their products, they may decide to stop harvesting, leading to an increase in *Pre-Harvest Food Loss*. Another driver of the food loss would be insufficient storage facilities. The AF commodities can either be directly sold to consumers or put into storage (e.g., dry storage, frozen storage) depending on the product characteristics (Olafsdottir and Sverdrup, 2019).

Hence, the importance of storage facilities increases under pandemic conditions. After food is harvested, the sequence of events is assumed to be as follows: 1) The farmer(s) determine their *Desired Inventory Level* depending on their perceptions of *Food Price at Farmer Level*, 2) the products are then shipped forward as *Food at Post-Production*, as long as the partners along the supply chain have a sufficient level of *Desired Shipment Rate*. Food shipments play an important role in the market access of the farmer communities, where a farmer's assets can drive the *Transportation Capacity* (see R1 and 2 in Figure 2) or can be enhanced by cooperative structures within the community, 3) after the shipment, if the farmer still has leftover *Food Harvested*, they store it in *Farmer's Inventory* as long as *Farmer's Storage Capacity* is sufficient, and 4) if the farmer still has leftover *Food Harvested* that cannot be taken care of by their storage capacity, then it contributes to *Post-Harvest Food Loss*, in addition to food loss due to the expiration of *Shelf Life* and other external effects. Food in *Farmer's Inventory* and *Food Harvested* by the farmer community in focus is a relatively small portion of the whole market; they flow through *Food at Post-Production* with *Food from Other Sources*. *Food at Post-Production* through *Food Purchase* becomes *Food Available for Consumption*, which is affected by the *Total Population* and *Food Demand Per Capita* and *Market Accessibility of Consumers*.

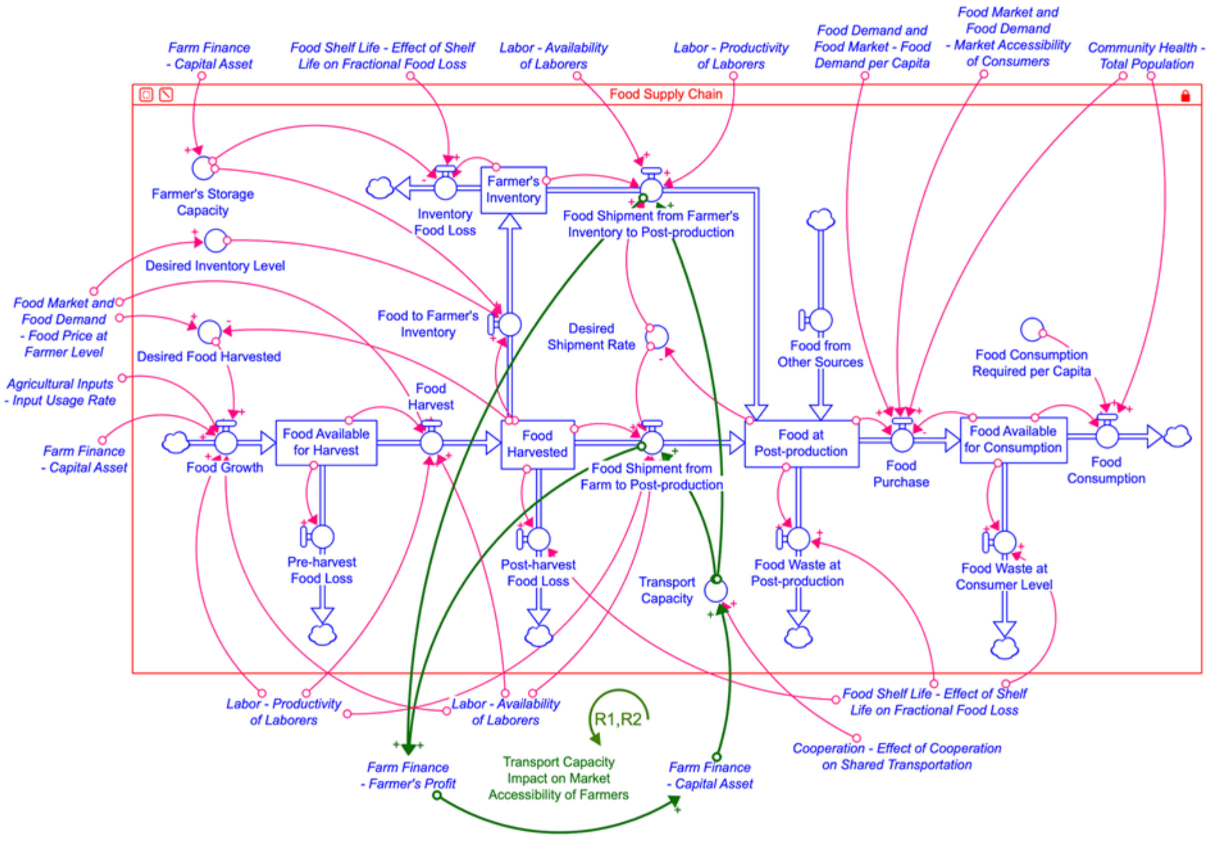

Figure 2. Stock-and-Flow Diagram of Food Supply Chain Sector.

3.2 Food Market and Food Demand

The Food Market and Food Demand sector in our model includes the major drivers of pandemic-related changes in the food market from the viewpoint of farmers and farming communities (Figure 3). For normal agriculture and food commodities, *Food Demand per Capita* is expected to change with the effects of *Disposable Income per Capita* and *Food Price at the Consumer Level*. Furthermore, with the increasing spread of the pandemic, the *Effect of Panic Buying and Hoarding* acts as another short-term effect. In contrast, the decline in consumer income is expected to generate long-term effects (Hobbs, 2020). Additionally, the *Effect of Shifts due to Food Characteristics* would be another determinant since the demand for processed food has increased and the demand for fresh products has decreased during the pandemic (CBI, 2020), shifts across product categories are expected (Hobbs, 2020).

As previously stated, *Food Price at Consumer Level* is assumed to be exogenous. Yet, the *Ratio between Food Price at Consumer Level and Farmer Level*, and hence *Food Price at Farmer Level* (i.e., producer price), is expected to fluctuate depending on the severity of the health crisis, since increasing gaps between the prices received by the farmers and the prices paid by the consumers have already been observed (Sahoo and Rath, 2020).

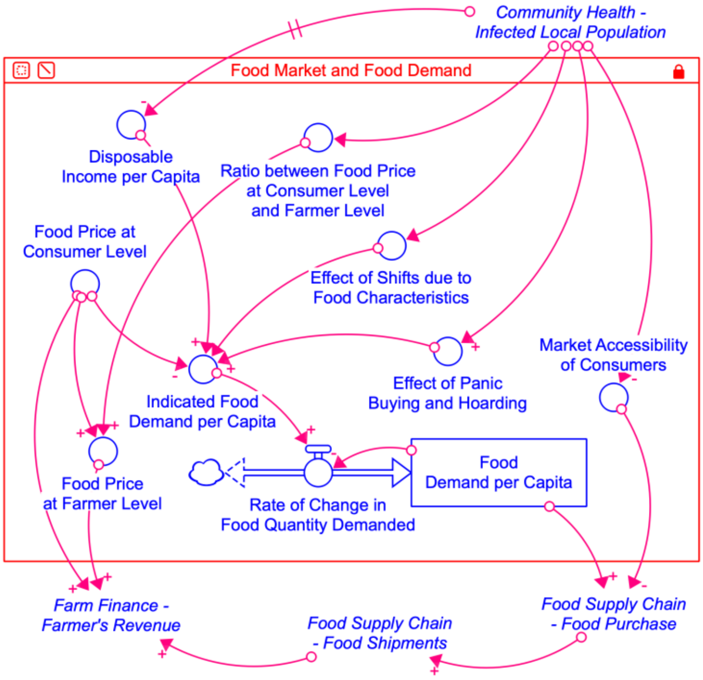

Figure 3. Stock-and-Flow Diagram of Food Demand and Food Market Sector.

3.3 Labor

Agriculture and food supply chains are labor-intensive. Labor shortages due to the lockdown effects cause several challenges and severe disruptions in the operations to a large extent (Schmidhuber and Qiao, 2020; Stephens et al., 2020). While the immediate concerns focus on the supply of farmworkers, the following considerations are about the working and living conditions of these workers (Weersink et al., 2020) (Figure 4). *The Availability of Laborers in Figure 5 can be considered an index,* representing a ratio between *Labor Available* and *Labor Required*. Considering the COVID-19 pandemic, *Restrictions on the Accessibility of Laborers* decreases *Labor Available*, and hence the *Availability of Laborers* for the agricultural operations, which is observed to be primarily affecting the harvesting and pre-sowing activities (Sahoo and Rath, 2020; Torero, 2020) as well as the food shipments (see B1, R3, and R4 in Figure 5). Depending on the changing market conditions, there is still a considerable amount of *Labor Required* driven by the farmer's *Desired Food Harvested* and *Desired Shipment Rate*. Since the *Labor Available* is low, this would lead to longer working hours and hence would create *Pressure on the Working Environment* as available laborers face a high risk of contracting and spreading the virus with a possible risk of unsanitary working conditions (see R5 in Figure 4).

As a more apparent counteracting behavior, *Restrictions on the Accessibility of Laborers* and *Safety Restrictions in the Working Environment* are expected to decrease the *Infection Rate* noticeably. The corresponding feedback loops are explicitly provided in the Community Health sector.

The Productivity of Laborers is considered a key input in the food supply chain. The implementation of lockdown measures related to COVID-19 eventually undermined capacity and the ability of the workers to produce food (Gray, 2020; Schmidhuber and Qiao, 2020). In addition, various *Effects of Pressure in the Working Environment* are becoming more apparent, primarily because of *Safety Restrictions in the Working Environment* involving the use of personal protective equipment and *Restrictions on the Accessibility of Laborers*, which ultimately affect the number of workers present in the field (Mussell et al., 2020; Blecker et al., 2020).

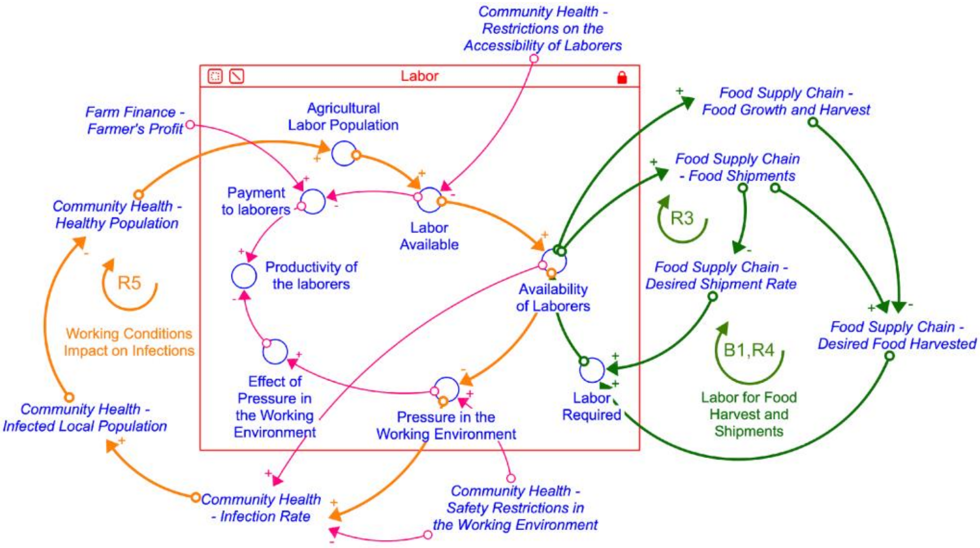

Figure 4. Stock-and-Flow Diagram of Labor Sector

3.4 Agricultural Inputs

The agricultural *Input Usage Rate* of a farm (including seeds, fertilizer, plant protection) is a crucial determinant of *Food Growth*. It thus is a determining factor to the total throughput of the food supply chain (Figure 5). In the case of large-scale shocks to the agricultural systems, such as COVID-19, inputs may be available. Still, accessibility to the farm has become delayed due to supply chain disruptions (BFAP, 2020). In many countries, agricultural practices have been declared as essential activities to society. Therefore, efforts have been made to keep borders and inland trade routes open, thereby reducing disruptions in input supply (Pais et al., 2020). In a broader context, the *Effect of Pandemic on Input Supply* is not homogenous but depends on local andregional factors. There is a risk of experiencing more widespread local or regional shortages in agricultural inputs in the coming season due to the effects of the pandemic on *Farmer's Profit* and future *Input Cost*. For instance, if pandemic induced lockdowns lead to reduced access to the market, *Farmer's Profit* is likely to fall, reducing the farmer's purchasing power and capability to acquire inputs for the next season (see R6 in Figure 5). With the general slowdown of national and international trade, *Input Cost per Unit* is likely to go up due to the pandemic. This increase will further reduce farmer's purchasing power and suppress access to agricultural inputs for the coming season(s) (Pais et al., 2020). The effects of the pandemic on agricultural productivity may not be seen until the next growing season due to the delayed impacts it may have on the availability and affordability of farming inputs.

3.5 Farm Finance

The pandemic revealed the financial fragilities of rural farming communities in many regions, mainly where farmers' income usually depends on their short-term – weekly or daily – activities (Ali et al., 2020; IFAD, 2020). The Farm Finance sector in the model consists of financial inflows, outflows, and instruments that affect the survivability of the farmer in pandemic conditions (Figure 6).

Farmers sell what they harvest, either immediately (*Food Shipment from Farm to Post-Production*) or after storing it (*Food Shipment from Farmer's Inventory to Post-Production*). Both of these flows contribute to *Farmer's Revenue*. In regular times—at least in seasons when *Fixed Costs* and *Variable Costs* might keep *Operational Expenditures* low enough to increase *Farmer's Profit* — a farm might dedicate some of that profit to *Capital Expenditure* to maintain or grow the business (increasing *Capital Assets*). Many farms, however, already have thin enough profit margins in most years that the overall concern is using *Farmer's Revenue* to maintain *Farmer's Liquidity* in the short-term. Now, of course, this concern is exacerbated by disruptions related to the COVID-19 outbreak. When revenue is not high enough to maintain the *Farmer's Liquidity*, the farmer often has to use *Credit* to maintain liquidity. Suppose there is not enough existing credit, and the farmer has *Information about Credit Programs*. In that case, the farmer might make a *Decision to Seek Additional Credit*.

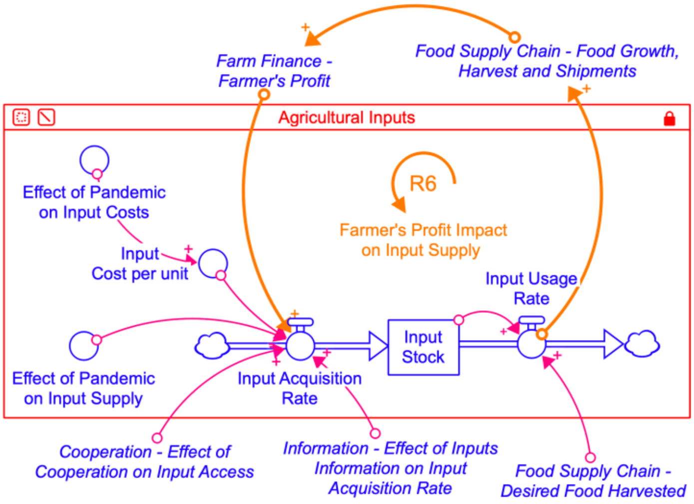

Figure 5. Stock-and-Flow Diagram of Agricultural Inputs Sector.

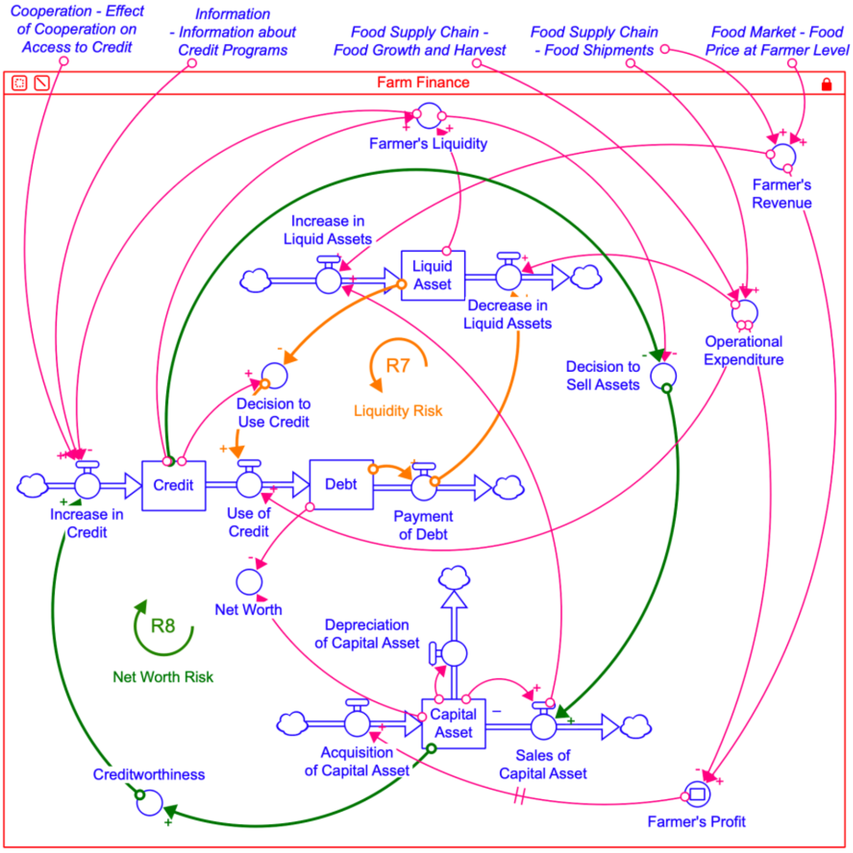

Figure 6. Stock-and-Flow Diagram of Farm Finance Sector.

This *Use of Credit* increases *Debt*, which has two serious risks: 1) *Payment of Debt* draws from existing *Liquid Assets*, there is a risk of getting stuck in a vicious cycle in which so much revenue has to go to debt payments that *Farmer's Liquidity* becomes permanently depleted (see R7 in Figure 6), and 2) When credit runs out, the farmer might need to make a *Decision to Sell Capital Assets*, which increases *Liquid Assets* in the "short term" but also decreases *Creditworthiness* and the farmer's *Net Worth* over time, potentially creating a vicious cycle that leads, essentially, to selling off the farm (see R8 in Figure 6). To prevent these risks, the farmer must find new sources of revenue when the agriculture and food supply chain is disrupted. Identification of new resources is possible if the farmer has information about where those potential sources of revenue are or if cooperation with other farmers has created new opportunities.

3.6 Food Shelf Life

Lockdowns introduced to combat the spread of the pandemic have resulted in a general slowdown of the usual food supply chain logistics and an increase in food waste and food loss due to the limited shelf life of fresh agriculture and food products (Figure 7). At the farm level, a pandemic-related decrease in the operational capacity introduces longer lag times between the point of harvest and the entry of the food into the designated cold chain. For efficiency reasons, *Food Shipments* will generally not occur until a sufficiently large batch of produce has been harvested. With more *Food Loss* at the pre-harvest and post-harvest stages, it takes a longer time than usual to fill up a batch for shipment, thus increasing the *Time to Flow from Farmer to Post-Production*. This delay increases the rate of *Shelf Life Expiring* because the food is more exposed to pests and other environmental variables, increasing its rate of degradation (Piergiovanni, 2019). Hence, the *Shelf Life Left* of each batch of harvested food starts to decline faster than usual. The overall result is an increase in *Food Loss* and *Food Waste* along the entire supply chain caused by extended time-delays (see R9 in Figure 7), particularly at the farm level where food is left exposed to the elements, waiting to enter the cold-chain for transportation to post-production.

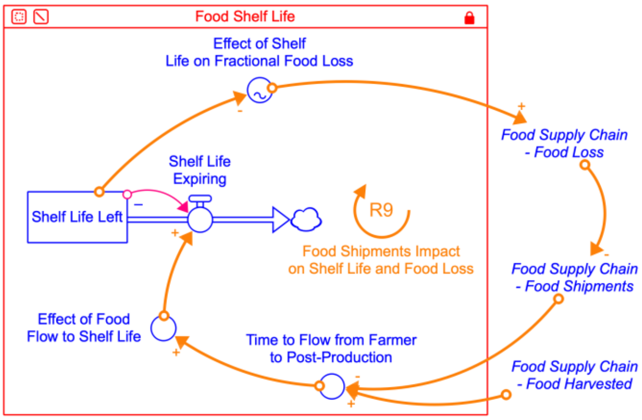

Figure 7. Stock-and-Flow Diagram of Food Shelf Life Sector.

3.7 Community Health

The Community Health sector represents the impact of disease propagation within the community (Figure 8). The *Total Population* in the model represents the consumers of food and agriculture products. A subset of *Total Population* is *Healthy Population,* which serves as the primary determinant of the available workforce in the community. A basic, three-compartment Susceptible - Infected - Recovered model represents the community health level—*Susceptible Population* changes with births, deaths, and the number of individuals that contract the disease.

The individuals in the *Infected Local Population* either recover or decease due to the infectious disease. As per the recovery rate, the *Infected Local Population* recover or become resistant to the disease. This model assumes that a fraction of the recovered population could still possibly contract the disease. Health crises render many limitations on farmers and laborers working to fulfill the food demand. If the *Infected Local Population* increases, it imposes *Restrictions on the Market Accessibility of Consumers*, *Safety Restrictions in the Working Environment*, and *Restrictions on the Accessibility of Laborers* to reduce the infection rate (see B2, B3, and B4 in Figure 8).

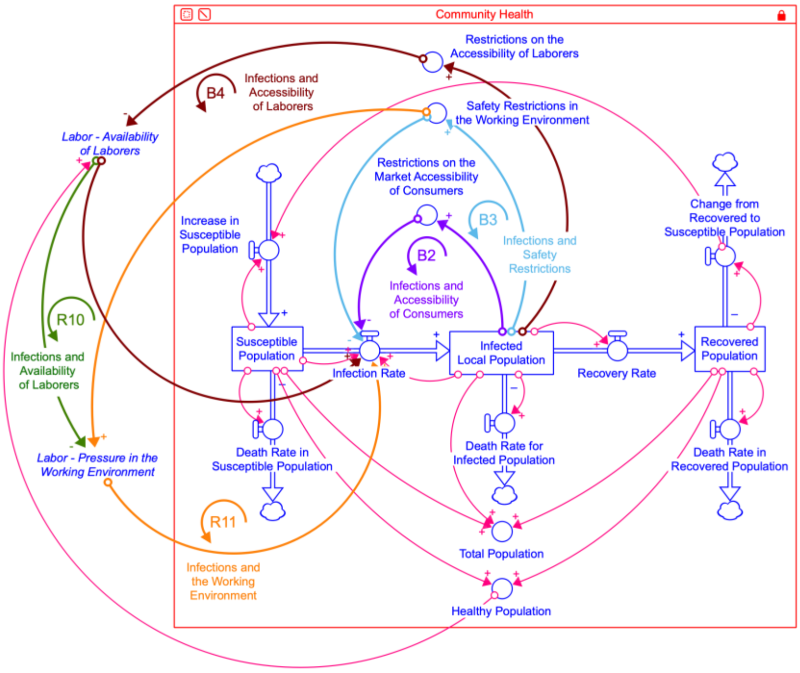

Figure 8. A Simplified Stock-and-Flow Diagram of the Community Health Sector.

On the other hand, *Restrictions on the Accessibility of Laborers* reduce the *Availability of Laborers*, which leads to a decrease in food and agricultural production capacity, and then creates excess workload on the available laborers. The extra workload increases *Pressure in the Working Environment*, which could further lead to an increase in *Infection Rate*, causing further *Restrictions on the Accessibility of Laborers* (R10 in Figure 8). Furthermore, compulsory *Safety Restrictions in the Working Environment,* such as wearing masks or any other personal protective equipment, is expected to decrease the *Infection Rate* and create additional *Pressure in the Working Environment*, which could lead to an increase in *Infection Rate* (R11 in Figure 8). In case of unethical working conditions at the farm due to relaxations in *Safety Restrictions in the Working Environment* may cause infections to rise.

3.8 Information

In building resilient food systems, learning is a key process that contributes to adaptations in dealing with changing and uncertain conditions (Mukhovi et al., 2020). As a significant determinant of learning, access to information is a central component of a farmer's capacity to reduce food loss and waste in the case of disruptive events (Figure 9). *Individual Farmer Capacity to Acquire New Information* represents any constraints on an individual farmer's ability to access new information, including *Psychosocial Constraints* (i.e., social capital, networks, and structural discrimination), as well as *Financial Status*. As mentioned in the Farm Finance section, a farmer needs information about sources of revenue and capital to identify and access these sources. But a farmer's *Financial Status* can also contribute to the level of access to information, for example, by having the means to attend knowledge-sharing convenings or subscribe to news about innovations to reduce food wastage (see R12, R13, R14, and R15 in Figure 9). Throughout every step of the food supply chain, lack of access to timely information can lead to gaps in knowledge critical to farmers' resilience, especially the smallholders. These can include *Information about Credit Programs*, *Information about Markets*, *Information about Inputs*, and *Information about Food Loss at the Farm Level*.

3.9 Cooperation

Cooperation supports the establishment of local food networks and contributes to socially sustainable food systems (Hingley et al., 2011). From the viewpoint of the farmers, cooperation represents a vital means to facilitate access to critical resources like input, credit, labor, storage, and information, access to which have been negatively impacted by the pandemic (Figure 10).

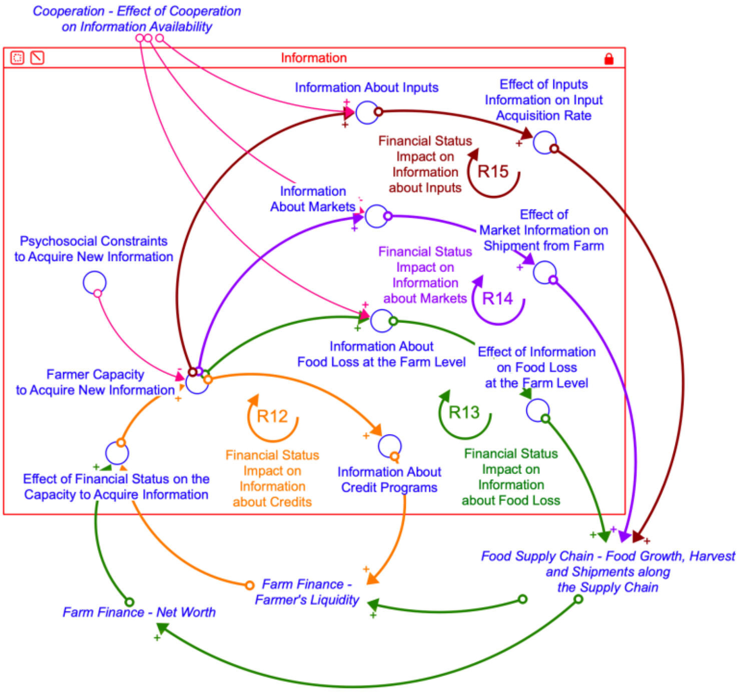

Figure 9. A Simplified Stock-and-Flow Diagram of Information Sector.

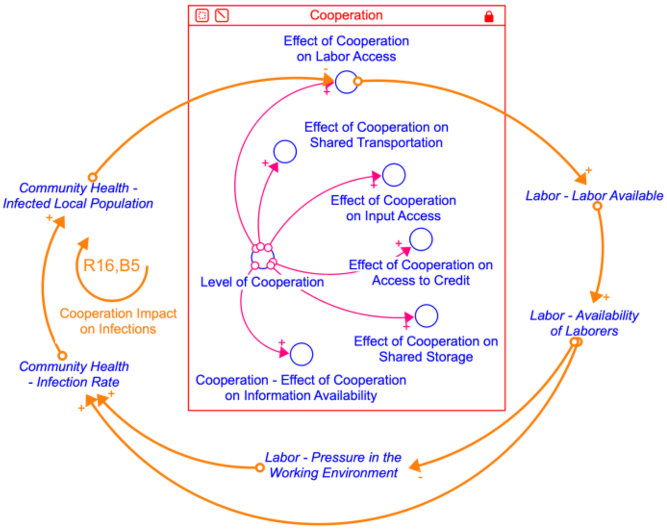

Figure 10. Stock-and-Flow Diagram of Cooperation Sector.

The pooling of resources under a cooperative structure can help farmers reduce production and supply risks. However, the health risks posed by the pandemic may lead cooperatives to become more cautious and even restrict shared labor practices. As infection increases, farming communities are less likely to cooperate in providing accessible labor resources (see B5 in Figure 10). As a counteracting behavior, the *Cooperation on Labor Access* could suppress the *Pressure in the Working Environment*, which would eventually contribute to a better level of *Community Health* (see R16 in Figure 10).

4 Discussion & Conclusion

The health problems caused by the COVID-19 pandemic have produced complex and multi-faceted impacts on economic, social, and environmental systems (Sahin et al., 2020). Consequences include significant challenges in maintaining resilient and productive agriculture and food systems during the pandemic due to its severe and adverse effects (Kumar and Chandra, 2010; Osterholm, 2005). The current study demonstrates how the SD approach can help portray the relevant interdependent systems and dominant feedback processes of agriculture and food systems, capturing the likely effects of a global pandemic (Huff et al., 2015) and identifying potential actions to promote resilience (Stave and Kopainsky, 2015) in the short-and medium-term.

The current research results suggest that the most severe effects of the pandemic for many farmers might not be observed in the short-term time horizon but the medium-term if input access or labor access remain reduced. The pandemic has made it difficult for small-scale farmers to harvest and transport goods, inputs, and laborers due to lockdown measures and travel restrictions related to COVID-19. These challenges resulted in increased food loss and food waste as food shelf life shortens (e.g., produce life) due to suboptimal handling and transportation delays. Additionally, the closure of restaurants and schools resulted in more discarded perishable food. At the same time, changes in consumer behavior significantly magnified food waste and purchases of non-perishables. These ultimately left farmers with fewer customers and less profit, affecting their ability to invest in future inputs due to a lack of capital or credit and to provide competitive wages to secure laborers. Thus, unemployment may increase, and farms may shut down.

A more troubling effect suggested by our findings is their irrecoverable coping strategies that smallholder farmers might adopt due to the pandemic. Primarily, actions such as the sale of assets to stay in business erode future productivity or, worse, lead to bankruptcy. This feedback could lead to cascading failure in the food system despite the essential function of small farms in securing food for rural and urban people. Moreover, our analysis suggests that the main impact of the pandemic on small-scale farmers is not related to how much food is produced but rather the inability of farmers to handle produce when interruptions such as exogenous shocks on the supply chain occur. Thus, post-pandemic, primary producers are exposed to the risk of lower profit margins due to the economic impacts of the pandemic coupled with reductions in demand and access to markets.

Limitations exist for the current study. No specific farmer or supply chain actor was directly involved in the modeling process since the purpose of the study was to provide a conceptual model with a global perspective instead of a specific case study. Another aspect is that many of our causal relationships are based on theory or qualitative information collected from the available resources instead of detailed quantitative analysis. As more data related to the effects of the pandemic are published by reputable resources, detailed data analysis and further tests of our dynamic hypothesis would be possible. Future research includes adapting our conceptual model to specific food categories, geographical regions, and local instances to quantify the shocks caused by the pandemic and other non-pandemic perturbations. In addition, future studies may extend the model to simulations, providing a decision support tool for policymakers, for example, in assessing the significant effects and risks posed by a pandemic in cases when labor availability collapses.

Further, this study addressed the food system resilience through the lens of “specific resilience,” that is, resilience to a specific type of shock (a global health crisis). This narrow modeling scope was motivated by the urgency to address the effects of the COVID-19 pandemic and the well-known importance of a clearly articulated problem statement in any modeling study (Martinez-Moyano and Richardson, 2013). We suggest future studies consider adding additional dimensions to our developed template and thereby approach what is described by Folke et al. (2010) as “general resilience” - generating a system capable of retaining function over a wide range of well-known and hitherto novel types of disturbances.

Our study presents a general overview of the agriculture and food supply chain resilience from the perspective of smallholder farmers and farming communities. It serves as a starting point to explore dynamic behavior and to facilitate individual and collaborative reasoning. Moreover, the resulting model structure provides the necessary framework for investigative discussions about potential leverage points that, if acted upon, can improve both input access and market access to help farmers maintain agricultural production, to suppress the increasing food loss and waste at the farm level, and thereby promote the survival of small-scale farmers.

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