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Modeling Dynamic Processes in Smallholder Dairy Value Chains in Nicaragua: A System Dynamics Approach

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ABSTRACT

In Nicaragua, the production of dairy and beef is the most important source of household income for many smallholder producers. However, erratic volumes and quality of milk limit the participation of small- and medium-scale cattle farmers into higher-value dairy value chains. This research uses a system dynamics (SD) approach to analyze the Matiguás dairy value chain in Nicaragua. The paper presents the conceptual framework of the model and highlights the dynamic processes in the value chain, with a focus on improving feeding systems to achieve higher milk productivity and increased income for producers. The model was developed using a participatory group model building (GMB) technique to jointly conceptualize and validate the model with stakeholders.

Keywords. System dynamics; value chain; group model building; dairy; Nicaragua.

1 Introduction

In Nicaragua, the production of dairy and beef is the most important source of household income for many smallholder producers. However, several factors limit the participation of small- and medium-scale cattle farmers in dairy value chains. In particular, the quantity of milk produced by small-scale farmers is usually low, characterized by high seasonal fluctuations in availability and prices, with markedly reduced production levels during the dry season, and is often of poor quality (Holman 2014; MAGFOR 2013). However, due to low milk productivity, there is potential to increase the amount of milk produced, improve milk quality, and enhance the coordination among the involved actors to meet the increasing demand for milk (INIDE-MAGFOR 2013).

Recent research on value chains has noted the utility of system dynamics (SD) modeling in agricultural and livestock systems in analyzing the *ex-ante* impacts and potential feedbacks that can arise from different policy and technical interventions within the chain (Naziri et al. 2015; Rich et al. 2011). This research develops an SD model that represents the dairy value chain in Matiguás, Nicaragua to test potential areas of improvement, with a focus on the inclusion of small- and medium-scale cattle farmers. We focus on Matiguás as it is part of the largest milk producing area in Nicaragua, the 'Via lactea', that accounts for more than 20% of national production.

Three general research objectives were identified: (i) identify and explain the dynamic processes in the dairy value chain in Matiguás, Nicaragua, (ii) identify interventions, policies, and decision-making processes, and estimate their benefits and costs in the milk value chain by asking "what-if-questions", and (iii) discuss potential strategies/policies that can strengthen the competitiveness of small- and medium-scale dairy farmers in the milk value chain. This paper focuses on the first objective, while laying the foundation for answering objective two and three in future research.

The paper first provides background information on the dairy sector in Nicaragua and Matiguás. It then provides an overview of system dynamics and group model building, which are the methodological frameworks used. This is followed by presenting the elements of the model, including a description of the different modules in the conceptual model and its feedback loops. The paper ends with concluding remarks and a strategy for policy simulation and implementation.

2 Background: the dairy value chain in Matiguás, Nicaragua

Nicaragua is the second poorest country in Latin America and the Caribbean according to the World Bank (2014) with 43% of its population considered poor and the majority of them living in rural areas. Nicaragua is a relatively small country with 6.2 million people and a GDP of US$12 billion in 2014 (ibid). It is an agricultural country, with livestock contributing 13% of the national GDP and 45% of the national value of agricultural production in 2013. The Nicaraguan government has focused on improving the sector as it can contribute to poverty reduction, food security, economic development, and ecosystem restoration (MAGFOR 2013). In 2011, 51% of livestock keepers were classified as smallholders, defined based on landholdings of up to 14 ha, while another 37% are medium-scale producers with up to 70 ha (INIDE-MAGFOR 2011). National milk production has increased over the past five years, and was estimated at between 2 and 2.3 million liters per day in in 2012, with only 25% absorbed by formal processing plants. The informal sector processes the remaining quantity of milk (Holman 2014; MAGFOR 2013). Pasteurized dairy products are looked upon as one of the most promising economic sectors due to increase in production and exports as a result of growing demand from Central America and the USA (Polvorosa 2015). Despite the increase in dairy production, the sector faces many challenges in feeding, breeding, livestock management, infrastructure, and the environment. Each aspect has national strategies implemented through numerous partners within the Nicaraguan government, research institutions, private sector, and livestock farmers (MAGFOR 2013).

The Matiguás municipality, seen in figure 1, lies in the Matagalpa region 250 km away from the capital, Managua, and has a population of 42.300, where over 80% are livestock keeping households (INIDE-MAGFOR 2013). Dual-purpose cattle systems are the most common. Approximately 60% of milk producers in Matiguás are small-scale and 20% medium-scale producers (Polvorosa and Flores 2015). Small-scale producers typically own less than 14 ha of land, about 2-20 cows, and produce about 20 liters of milk per day. Medium-scale producers own between 14 to 70 ha, and produce around 50 liters/day. In total, about 100,000 liters is produced per day and most of the milk is collected through cooperatives. The largest dairy cooperative in Nicaragua, Nicacentro, is located in Matiguás (Polvorosa 2013). Matiguás is part of the "Via lactea" (or "milky way" in English), consisting of four municipalities, where over 20% of the country's milk is produced (INIDE-MAGFOR 2013). That is the main reason for the selection of this area of study.

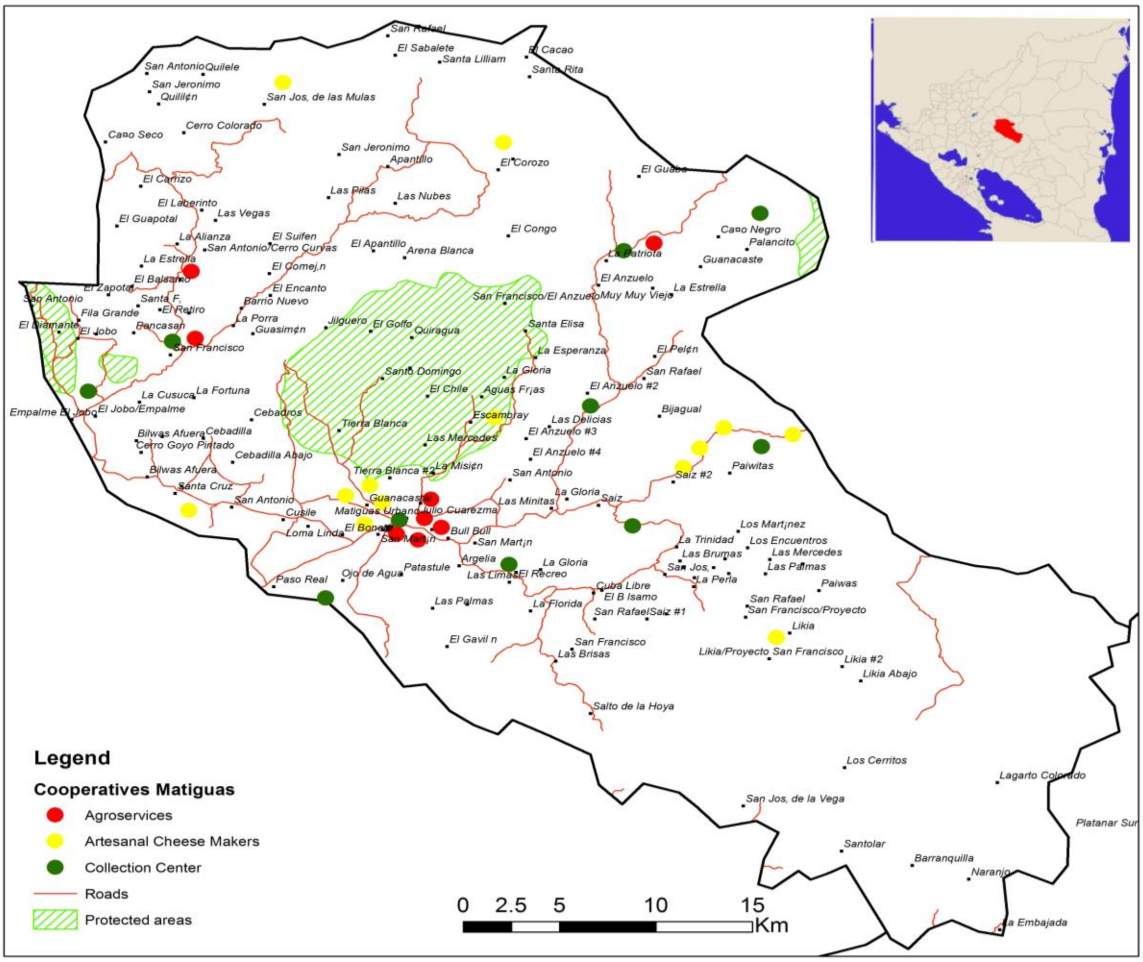

Figure 1. Map over Matiguás municipality Source: CIAT 2015

There are three main milk value chains in Matiguás highlighted in figure 2; (i) the cold milk chain where milk is collected by cooperatives and sold to the dairy industry in Managua, (ii) informal local curd processing for consumption and sale locally, and (iii) collection of milk that is processed into fresh cheese and exported to neighboring countries (Alcaldía Municipal de Matiguás 2011; Polvorosa 2013). There is competition between the chains in attracting milk suppliers (Polvorosa and Flores 2015). This research focuses on the cold milk chain. In the cold milk chain in Matiguás, five cooperatives and several private actors collect milk from more than 1000 producers in over 14 collection centers. Of those supplying collection centers, about 70% of milk producers are organized in a cooperative, whose milk is supplied to the three milk processors in Managua (Lala, Nilac, Centrolac) (Alcaldía Municipal de Matiguás 2011; Polvorosa 2013)

Several value chain analyses (VCA) of the dairy sector in Matiguás have been conducted by various institutions such as International Center for Tropical Agriculture (CIAT), HEIFER, the research and development institute Nitlapan, and Tropical Agricultural Research and Higher Education Center (CATIE). They all present a structure of the stakeholders involved, product flows (see figure 2), and identify numerous interventions to improve various areas of the chain (Flores et al. 2011; Polvorosa 2013; Velásquez and Manzanarez 2014). The Municipal government (Alcaldía Municipal de Matiguás 2011) have also made their local economic development plan which include focus on the dairy value chain.

The main challenges identified in the Matiguás dairy value chain are aligned with the national challenges. In Matiguás and 'Via lactea', there is potential to increase the amount of milk produced, improve milk quality, and enhance coordination among the involved actors. The current increase in milk production is primarily due to an increase in number of animals and using more land for livestock purposes. However, land availability is close to reaching its limits, thus forcing other strategies for increased and stable milk production. Stabilizing the volume of milk during the year and improving the productivity of animals are two of the biggest challenges, especially since there is little room to continue to expand land use for livestock purposes. There is also underutilized capacity of collection centers, especially during the dry season from January to mid-May (Alcaldía Municipal de Matiguás 2011). Despite several value chain analyses and plans, none presents any justified forecast of potential impact if any or all of the identified interventions were implemented. This suggests a need for methodologies that can better evaluate the returns to alternative investment strategies.

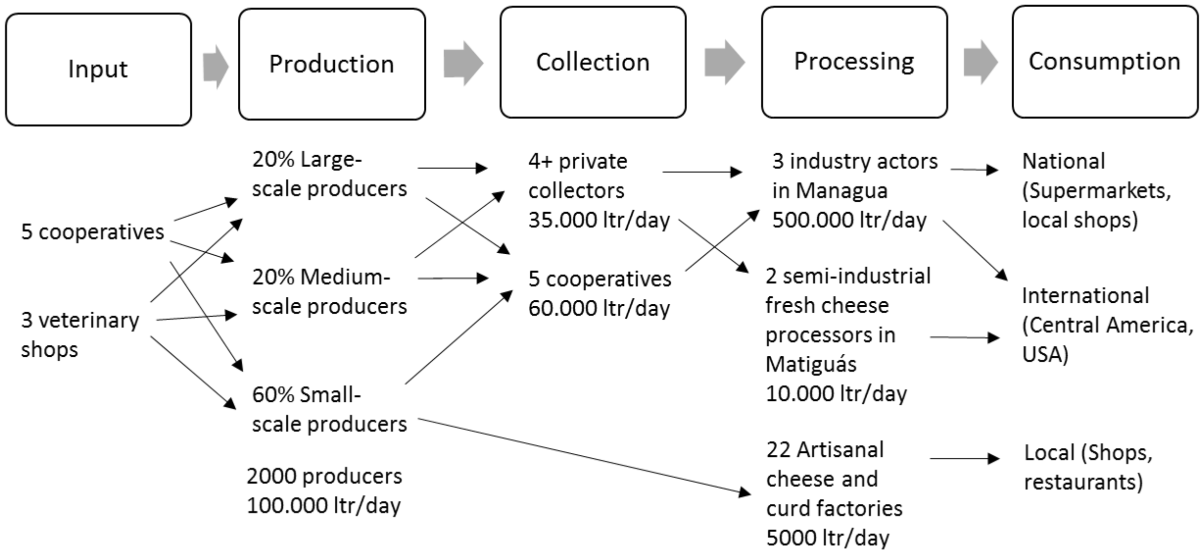

Figure 2. The Matiguás dairy value chain. Source: Modified and updated from Polvorosa and Flores (2015); Velásquez and Manzanarez (2014)

3 Methodology

Value chain analyses (VCA) provide an overview of the actors, their activities, and flows of commodities, money and information and can identify challenges and suggest interventions (Kaplinsky and Morris 2001; M4P 2008). However, an important challenge and limitation of VCA and value chain toolkits is that the results are highly qualitative. In particular, it is difficult to know or predict *ex-ante* what impact or outcomes that different interventions might have within these complex systems (Rich et al. 2011). As the introduction of new interventions will cause changes in both marketing and contextual features of the value chain, various unintended consequences or feedback mechanisms may result that could undermine or reduce the effectiveness of an intervention over time.

System dynamics methods are one means to address these gaps in value chain analysis. A system dynamics (or SD) model maps out the flows, processes, and relationships between actors that operate within a complex system. It is highly interdisciplinary and can be used as a tool to test and analyze interventions and policies (Sterman 2000). Recent research on value chains has noted the utility of this approach in agricultural and livestock systems in testing out the *ex-ante* impacts of feedbacks from different policy and technical interventions within the chain (Higgins et al. 2009; Naziri et al. 2015; Rich et al. 2011).

The central concepts in SD models are stocks, flows, and feedback loops. Stocks represent the accumulation of something, for example animals or an agricultural product. Flows, or rates of change in variables, are used to change the levels of stocks. Feedback loops are a type of circular causality where one component in the model initiates changes in another component, which further initiates changes that result in various outcomes. Feedback loops can either be positive, meaning that they are self-reinforcing, or negative which means they are self-correcting (Sterman 2000). The goal is to build an SD model that represents, in this case, a value chain and its dynamic processes. The SD model can be qualitative, also called mental maps, or quantitative which enables testing of scenarios through running simulations (Sterman 2000).

A particular advantage of system dynamics models is that they can be conceived and developed through participatory processes. In particular, many analysts use what is known as group model building, or GMB, to develop their models jointly with the participation and direct collaboration of stakeholders (Hovmand 2014; Vennix 1996). The data collection for this research was conducted in Matiguás from March to June 2015 utilizing group model building principles.

The use of GMB to develop SD models is important when it is difficult to grasp the comprehensive and complex systems involved, when there are many different alternative value chain interventions, and difficult to anticipate the possible consequences of a decision made (Vennix 1996). It is also important when there are many stakeholders involved. It is a good tool for building consensus and commitment to the final chosen strategy since all stakeholders are involved in constructing the model, testing suggested interventions and policies, and making final decisions. It can also bring together stakeholders, with very different backgrounds and focus, which often is the case in developing country settings. These people sometimes do not meet, or often meet separately, but discuss the same issues. It can uncover different attitudes and understandings among the participants during the process of making the model in the group (e.g. Olabisi 2010). This can itself create a better environment for future collaboration with a better understanding of how the different actors work, and connection among them. It can also help facilitate buy-in by stakeholders in development projects and assure sustainability after the end of a project (Hovmand et al. 2011; Vennix 1996).

A participatory SD modeling process starts with problem identification and articulation to decide on a clear purpose that guides the entire modeling process. It is important to agree on what problem to focus on, to understand why it is a problem, and to create a reference mode of the overall problem behavior. The system is then conceptualized by identifying different elements in the system and how they are related, and determining the boundary of the model. This leads to formulating dynamic hypotheses or theories about the causes of the problem. Some modeling processes focuses on qualitative conceptual models. If so, the modeling process would end here. If a quantitative approach is taken, the process continues with model formulation by estimating parameters, followed by model evaluation and testing. The model is then ready for analysis to develop policy recommendations, as well as transferring the insights to different stakeholders in the value chain. The final step is to assess the process and outcomes of the modeling exercise. (Luna-Reyes et al. 2006; Sterman 2000; Vennix 1996). The value chain stakeholders are included in the entire process, and there exists numerous ways to facilitate the participation (Hovmand 2015), which needs to be carefully considered before and during the modeling process to ensure participation of all stakeholders.

This research paid careful attention to include the various stakeholders in the complex Matiguás dairy value chain, but focused on small- and medium-scale dairy farmers. Between March and June 2015, four main group meetings were conducted with small- and medium-scale dairy farmers, dairy cooperatives, local institutions focusing on credit, research, farmers' schools, local government, and the informal dairy sector. In April 2016, a follow-up group meeting was conducted. The group meetings focused on identifying a value chain goal, problems in reaching the goal, prioritizing which problem to focus on, possible interventions, model structure, and necessary parameters and relationships for the model. In addition, reference group meetings with research institutions were organized in between focusing on verifying the model structure and data. A scoping trip was conducted before the meetings and selection of participants to have a basic understanding of the dairy value chain and its stakeholders that needed to be involved in the modeling process. Several individual interviews with cooperatives, credit institutions, and industry actors were conducted during and after the group process to complement and verify some of the information given in the group.

4.1 Model focus

The first group model building session identified the top policy goal as increasing the production of milk, both in terms of quality and quantity, to achieve higher income for the actors that are involved in the value chain. During the same session, a discussion on the problems in achieving this revealed that the deficient feeding system should be the priority focus for this SD model. We thus focus on identifying policies and investments that could enhance the quality of feeding systems in a manner that can improve milk quantity and farm income.

In Nicaragua, milk production follows a cyclical pattern due to fluctuating rainfall patterns. Low production volumes occur in the dry season, from approximately January to mid-May, with higher volumes occurring during the rainy season from mid-May to December. Approximately 65% of annual production is realized in the wet season (Polvorosa 2015). An important objective for small- and medium-scale producers in particular is to find ways to stabilize milk production during the year as a way of improving year-round market access and thus achieve more stable incomes from milk. One of four main factors pointed out to achieve this is to substitute traditional pasture with improved pasture. Other factors identified included increasing herd sizes by replacing male cattle for female cattle; ensuring sufficient labor to manage the herd, especially during milking; and introducing improved hygienic milking practices (Polvorosa 2015; Polvorosa and Flores 2015).

Using improved pasture is a common and important practice to intensify milk production. Improved pastures have positive impacts on milk production per animal and per unit area, thus reducing production costs and raising net income for livestock producers. It is also more resistant to erratic weather such as drought (Holmann et al. 2009). The percentage of farmers with improved pasture has increased in

Matiguás over the past ten years, but the proportion of land devoted to forage has declined. Several factors explain this, including new land used for livestock, and the high establishment costs of improved pasture that results in farmers only using a small portion of land to create forage banks (Polvorosa 2015).

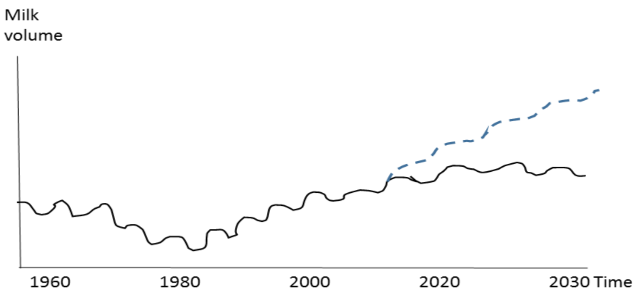

Figure 3. Milk production trends over time. Source: Developed by the authors

The first GMB session also developed a reference mode, illustrated in figure 3, which highlights the historic trends of milk production and forecasts about future trends with and without any interventions. In the 1960s, milk production was quite low, and worsened during the 1980s. Since the 1990s, there have been gradual improvements to the sector, but growth has been relatively slow. However, in the absence of interventions, limited land availability will eventually mitigate any increase in milk production. The oscillations found in figure 3 represent the annual seasonal swings in milk production during the year. The dotted line indicates predicted milk production with potential interventions that improve the feeding systems for small- and medium-scale producers. In addition to increasing milk production, the expectation is that yearly oscillations would be smaller, although natural seasonal variation will always occur. The research questions below guided the model conceptualization.

1) What feed type, or combination of feed types (traditional pasture, improved pasture, cut and carry, and concentrates), provide higher productivity of milk during the year, especially during the dry months?
2) What is the effect of changing feeding systems on the income of small- and medium-scale producers over the short-, medium- and long-term?

4.2 Model structure

We present the conceptual model developed in conjunction with stakeholders in figure 8. The model consists of four main modules: 1) herd dynamics, 2) milk processing and sales, 3) costs and revenues, and 4) feed dynamics. Each section will be explained before presenting the dynamic interactions between the different modules. The model was constructed using the model software Vensim PLE Plus[1].

Herd dynamics

The herd dynamic module consists of two stocks of calves and dairy cows, represented by the rectangular shapes in figure 4, that are mediated by biological processes of births, maturation, and exits (either by death or sales). We also consider outflows a separate bi-flow denoting the net purchasing rate of dairy cows, since farmers will decide to sell or purchase more dairy cows depending on the amount of feed per cow and the level of long-term profit (indicated by shadow variables from the other modules). If feed per cow is low over time, we assume that farmers will sell dairy cows, while if there is high home grown feed availability per cow over time, we assume they will buy high productive dairy cows to add to their herd. This decision also depends on whether realized long-term profits are higher than expected over time. If so, we assume that farmers will buy dairy cows, while negative profits relative to expectations would induce sales. There is a link from dairy cows to the birth rate to model the reproduction of animals based on the fertility rate. Fertility and death rate are influenced by feed per head.

[1] Available at: http://vensim.com/

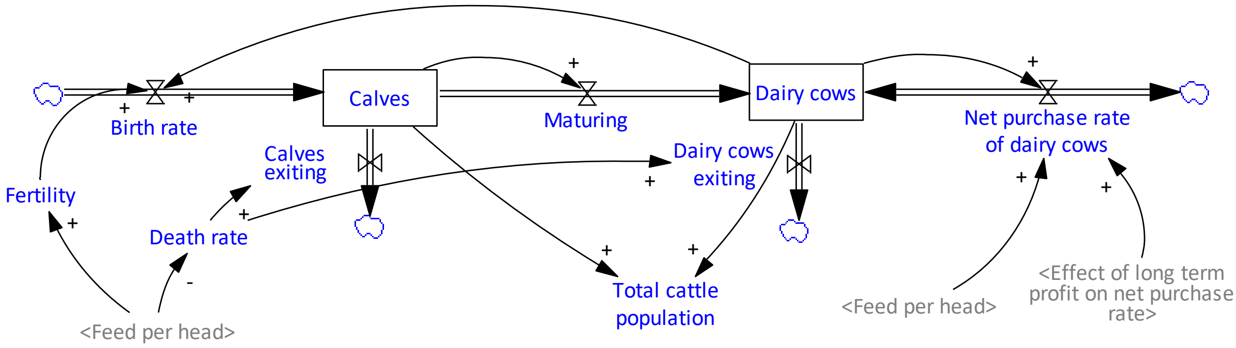

Figure 4. Herd dynamics module. Source: Developed by the authors.

Milk processing and sales

The milk flow module, shown in figure 5, illustrates the downstream activities in the dairy value chain in Matiguás municipality. We model the production of milk as influenced by the number of dairy cows and average cow productivity. Cow productivity is affected by feed per head and assumed rates of disease incidence. Producers have several options with which to supply, in addition to deciding how much milk to consume at home. In particular, farmers can choose to supply to one of the five major cooperatives, or can supply the informal sector through private milk collectors (or a combination). The cooperative supplies the five industrial processors in Managua, whose production depends on the demand for milk.

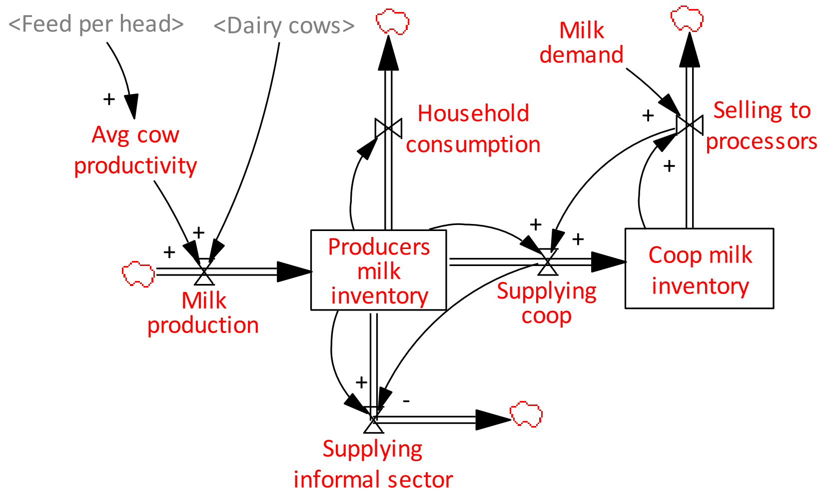

Figure 5. Milk sale and processing module. Source: Developed by the authors

Costs and revenues

The costs and revenues module, presented in figure 6, only consists of variables. The main variable is dairy farmer profit that results from revenues from milk and cow sales, and production costs. Revenues from milk sales include the total amount of milk supplied to cooperatives and informal sector multiplied by the average milk price. For simplicity, we consider only one average milk price, but in reality the milk price varies between the cooperative and the informal sector. We assume that price is an exogenous variable since it is unlikely that dairy producers in a municipality will heavily influence the milk prices set by industry actors in the capital. Even though we model prices exogenously, we assume that the milk price fluctuates seasonally. Total production costs depend on the average production cost per head of cattle and the total cattle population. For simplicity, we assume that average production costs per cattle include costs for feed production and concentrates, and other production costs such as labor, medicines, water, electricity, and so on.

Profits higher than expected induce farmers to make investments in both short-, medium- and long-term activities. In other words, we assume that different investments are endogenously determined in the model based on the level of expected profits (short-term, medium-term, long-term) and are not made independently. If profits are higher than expected in the short term, we assume that farmers invest in feeding their cattle concentrates, which is explained further below. If profits are higher than expected in the medium term, we assume that farmers will invest in improved pasture, which as discussed below changes the allocation of land towards more productive feed sources. Higher profits than expected over a longer time period leads to buying dairy cows, given that there is enough feed available to increase the herd. All of these investments occur with a delay since it takes time for farmers to make a decision, as well as completing the activity of changing their feeding system or purchasing a cow, which is indicated with a double line on the connecting arrow.

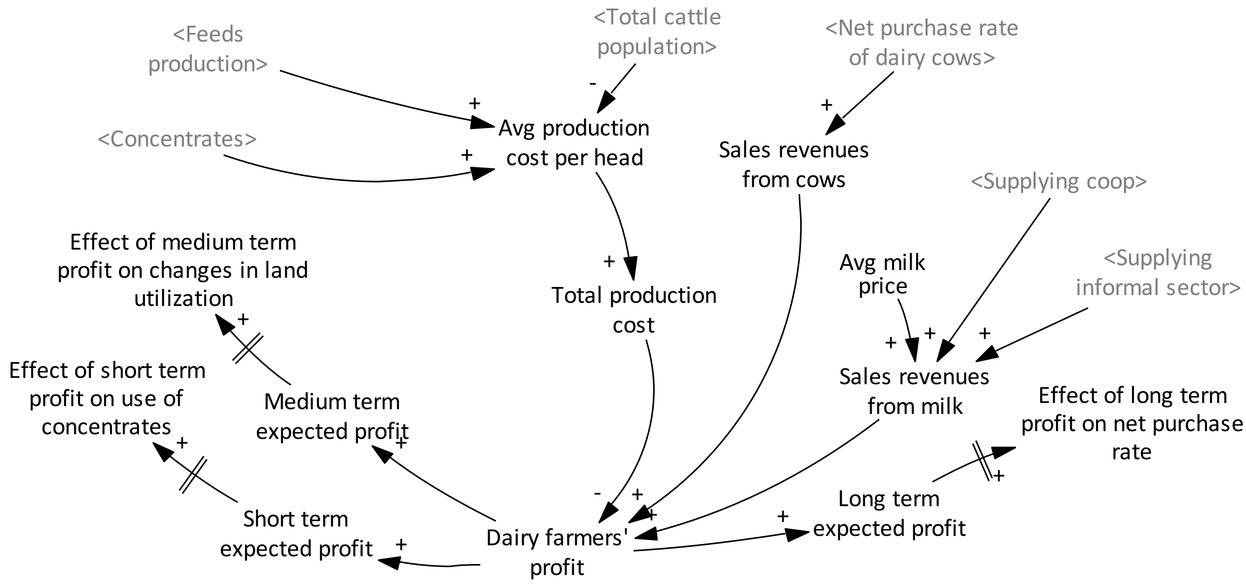

Figure 6. Cost and revenue dynamics. Source: Developed by the authors.

Feed dynamics

The feeds module consists of a stock that denotes home grown feed availability. Home grown feed availability increases through greater production and falls from the consumption of feed; these are denoted as inflows and outflows, respectively. Feed production is based on a combination of cut and carry grasses, traditional pasture, and improved pasture. We assume that the amount of land used for cut and carry grasses in this model is fixed, so that farms choose to allocate their remaining land area (also fixed in aggregate) between traditional and improved

pasture. Buying land is not included due to limited land availablility, hence our focus on intensification. We assume that each of the four feed production options have their own level of production yield (aggregated for simplicity in figure 7 as land productivity). Land productivity also depends on whether there is drought or not. The land allocation decision process depends on investments in feed, which is determined by the medium-term profitability of farmers. Changes in land utilization are also influenced by other factors. In particular, peer effects, learning, and awareness could influence perceptions and proclivities towards changing land use, although these could both happen with a delay and impose transactions costs on producers.

The reason to invest in improved feeds and concentrates is to increase the total availability of feed and thus improve average cow productivity, or the ability to keep more cows. Changing feed production adds to production costs, and whether the investment is profitable or not, depends on how much the investment in improved feeds production influences the average cow productivity. Feed per head is determined by the amount of available feed divided by the total cattle population. The use of concentrates can complement feed per head, which depends on short-term profitability.

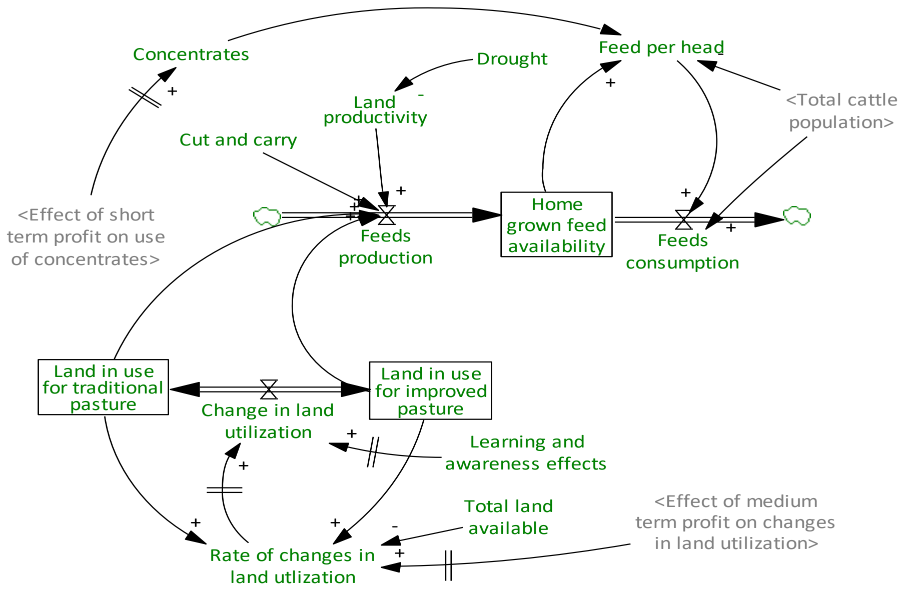

Figure 7. Feed dynamics module. Source: Developed by the authors.

4.3 Feedback loops between the four modules

The four main model modules interact through feedback loops that denote the dynamic processes in the dairy value chain. If a decision is made to invest in improved feeds, it will have implications both for herd dynamics and milk processing and sales. Following standard SD terminology, feedback loops can either be reinforcing (with exponential growth or decay) or balancing (settling on some level of stasis or equilibrium). A few of the different reinforcing and balancing feedback loops have been identified and marked with an R or B, respectively, in the conceptual model in figure 8 and are briefly explained in table 1 below.

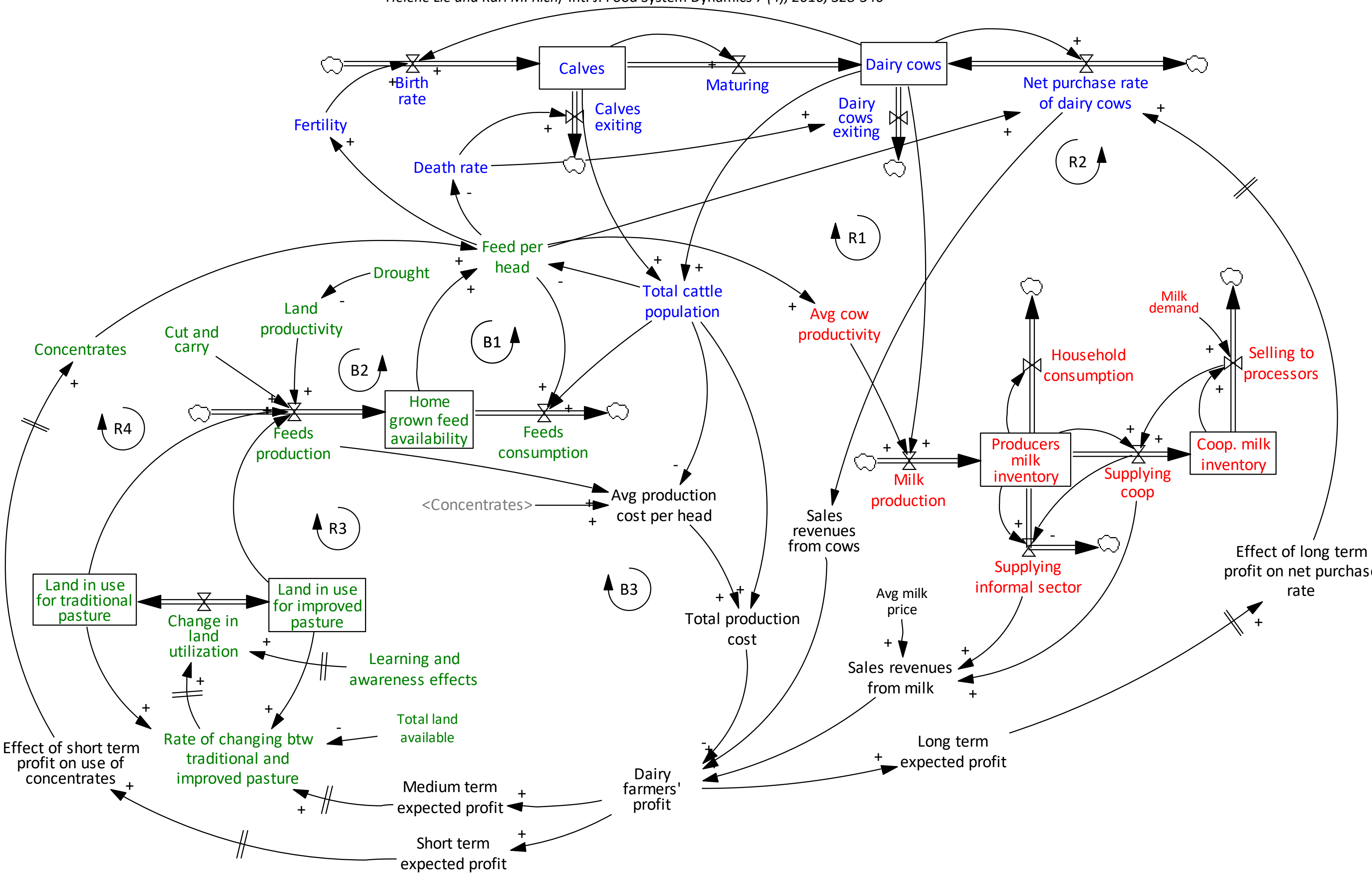

Figure 8. Conceptual SD model of the Matiguás dairy value chain. Source: Developed by the authors.

Table 1.
Overview and short explanation of feedback loops. Source: Developed by authors.

Feedback loop	Explanation
R1	This reinforcing feedback loop focuses on the relationship between increasing the number of dairy cows, which increases the amount of milk produced, thus increasing profits that are used to invest in improved feeds/concentrates, improving fertility and reducing death rates and therefore increasing the number of dairy cows.
R2	This feedback is similar to R1, but focuses on long term investments in additional dairy cows.
R3	This feedback loop focuses on the increasing land used for improved pasture, which has a positive effect on home grown feed availability leading to increasing average cow productivity, which increases milk production and milk supply. This then increases revenues and medium-term profit, allowing for investments in improved pasture that again improves feed production.
R4	This feedback loop is similar to R3 but focuses on short-term investment in the use of concentrates in the dry months, which increases the milk production and short-term farm profit.
B1	This balancing feedback loop focuses on the impact of increasing the number of dairy cows on feed use per head. More dairy cows reduce feed use per head, lowering average milk productivity and decreasing milk production. Consequently, farm profits fall, reducing investments in concentrate in the short-term and leading to dairy cow sales in the long run, which will reduce the number of cattle and increase the feeds per head.
B2	This balancing feedback loop highlights that if drought occurs, land productivity falls. This negatively affects home grown feed availability, which reduces the quantity of feed per head of cattle.
B3	This feedback loop focuses on the costs of feed production, which will increase when adopting improved pasture and/or use of concentrates. This will impact total production costs, farm profits, and subsequent investment decisions.

The four explicitly identified reinforcing feedback loops will increase milk productivity and farm profit exponentially. This growth is, however, counteracted by the various balancing loops in the model, that given biological and investment delays lead to the oscillatory behavioral patterns highlighted in figure 3. While R1 and R2 increase the number of dairy cows, this growth is balanced by B1 because if the number of dairy cows increases, the amount of feed per head will go down, leading to a reduction in milk production. Feed per head is also vulnerable to climatic changes such as drought, B2, which result in reduced land productivity. These two balancing feedback loops will slow down cow productivity and reduce the growth of milk production. That means the exponential growth in the beginning will be corrected and result in an s-shaped growth pattern.

Similarly, R3 and R4 will both result in an increase in the amount of feed per head of cattle, which positively affects cow productivity and results in the exponential growth of milk production and subsequently in farmers' profit. However, B3 counteracts and places a brake on such growth in profits, as investments in improved pasture and use of concentrate raise the average production cost per cattle and reduce profits.

With several reinforcing and balancing feedback loops, such as in this complex dairy value chain, it is difficult to predict the changes in the system and its subsequent changes in farm decisions. The effects and changes will also be different over the short-, medium- and long-term. As a consequence, transforming our qualitative structure into a quantitative SD model allows us to examine various scenarios that can be simulated over time (Sterman 2000). While some changes are easy to anticipate, other unintended consequences can also appear when running different scenarios in a quantitative model. This is an area for future work with this framework, where we will test different scenarios and hypotheses in a quantitative setting.

5 Concluding remarks

The dairy sector in Nicaragua faces several challenges, with feed availability being a crucial constraint. A system dynamics approach was taken to identify the dynamic process in the dairy value chain to be able to assess intervention options and their potential effects on milk quantity and farm income. In this paper, the conceptual system dynamics model was presented in detail including the dynamic processes between herd dynamics, milk processing and sales, costs and revenues, and feed dynamics. Future research will highlight the impact of different scenarios and hypotheses focusing on aspects such as (i) increasing the number of dairy cows, (ii) increasing the use of concentrates in the dry months, and (iii) increasing land used for improved pasture. These will support decision-making among the various stakeholders in the Matiguás dairy value chain to add value and raise incomes for stakeholders.

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