The potential value of seasonal climate forecasts in agricultural decision-making

- *case of forage-based dairy production in Vestland, Norway*

June 2023

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THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE MASTER OF PHILOSOPHY IN SYSTEM DYNAMICS

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Acknowledgements

I would like to express my gratitude to Professor Birgit Kopainsky, my supervisor, and Manuel Hempel, my co-supervisor, for their valuable advice and helpful guidance. I am truly grateful for their generosity with their time and their high promptness in answering my numerous questions.

I am also deeply thankful for the support I received from my friends and family. Their unconditional love and belief in me have been the driving force behind my achievements. I owe a special debt of gratitude to Khaoula Lasfar, whose unwavering support and motivation have been instrumental in every step of my journey, inspiring me to become a better person. From the moment I landed in Norway, I was extremely fortunate to meet Yasmina Mehelleb, whose company was delightful and an encounter I will never forget. Furthermore, I want to extend my thanks to my newfound friend, Steffen Sjåstad. Our wonderful conversations and endless cups of tea have helped me find solace and joy during my time in Bergen, allowing me to truly appreciate and savour every moment.

To all my classmates, thank you for making this learning experience more enjoyable and rewarding. I am grateful for the opportunity to exchange ideas, study together, and engage in meaningful and light-hearted discussions.

This is for the harmony of 💙 💚 💜

CHAPTER 1 | INTRODUCTION

1.1 | GENERAL BACKGROUND

From historical times, farmers have always coped with uncertainty and weather unpredictability. They are compelled to constantly adjust and adapt to changing circumstances in order to remain in the farming business and make a living out of it. Yet, as natural hazards become more pronounced, uncertainty is higher than ever before, extreme weather events occur more frequently, and related costs are becoming exuberant. Consequently, the challenges that farmers are facing are multiplying consistently. This calls upon an accelerated adaptation of the farming practices and decision-making, and hence the need to take full advantages of all available information/technology that support farmers' adaptative responses.

In this context, **climate services** have attracted a lot of interest and are being hailed as an important component of the adaptation strategy (FAO- 2018). They are tools that convey climate information regarding how average conditions, mainly temperature and rainfall, might evolve in the future. Their main objective is to reduce the adverse socioeconomic consequences of climate variability (Nicholls 1999), by assisting decision-making and future planning (Hewitt, C., Mason, S., & Walland, D. (2012), Vaughan, C. & Dessai 2014). To that end, their usefulness derives from the capability of allowing for better plans, either by preparing for climate events, preventing worse damages and reducing losses, or even taking advantage of the opportunities that the climate event may potentially offer (ibid 2012, 2014).

***Box 1*: Definition of Climate Services**

> ***Climate services*** can be defined as the provision of climate information with the objective to assist decision-making (Hewitt, Mason, and Walland 2012). The provision involves the generation of the information by climate scientists and experts, its transformation into products such as projections, forecasts, information, trends, economic analysis, and assessments (European Commission 2015), its dissemination to the end-users as well as the monitoring and evaluation of the entire process performance (Vaughan and Dessai 2014). These services are typically developed by national meteorological agencies, climate research institutes, and other organisations specialising in the study of climate science. They may operate at different scales (international, national, regional, or local) and across diverse sectors whether public, semi-public or private. On the users' side, they can be sought by governments and policymakers, businesses and industries, the health sector and NGOs. Essentially any entity or individual that employs climate information to make decisions can exploit these services.

Based on this definition (Box 1), there is no doubt that climate information is very useful. Nevertheless, its full usability has not been fully achieved, leading to suboptimal decision-making (Lemos and Morehouse 2005, Hewitt et al. 2017). In fact, the connection between providers and prospective users of climate information has been a research topic in the climate literature. In many cases, it has been proven weak or nonexistent (Brasseur and Gallardo 2016, Vaughan and Dessai 2014). The main recurring underlying barriers are poor access, insufficient awareness of their existence or value, the highly technical language used, their probabilistic nature, and differences in values and interests (McNie 2007*,* Power, Plummer, and Alford 2007, Vaughan and Dessai 2014).

In an attempt to overcome these barriers and bridge the gap, the ***co-production[1] of climate services*** has prominently emerged in the last decade and a half (Bremer et al. 2021). It is an approach that prones an iterative dialogue between providers and users, with the objective to tailor the climate information to the users' needs (Lemos and Morehouse 2005, Brasseur and Gallardo 2016). It advocates for the involvement and engagement of all stakeholders in every stage of the process, as well as their collaboration to design, develop and evaluate the climate product. This approach allows therefore to build a trusting relationship and credibility, which renders the integration of the climate information in the decision-making process more likely to succeed.

1.2 | THE STARTING POINT

The theme of this master thesis falls within the framework of an ongoing project led by NORCE in the Climate Futures center[2], which works on co-producing climate services for sustainable food production within the Norwegian agricultural sector. This project serves as a pilot project and was motivated by the dry summer of 2018 where extreme climatic conditions have posed significant challenges across all levels of food production (Climate Futures, 2022 Annual Report). The forecasts produced for July 2018 from a June perspective showed « a high probability for high positive temperature anomalies as well as high negative precipitation anomalies, indicating a very warm and dry July» (ibid, 2022). Therefore, the pilot project investigates, inter alia, the question of whether and how the agricultural decision-makers would have utilised this information if it had been available at the time.

Investigating this question is of utmost importance, considering that the future of Norway's climate until 2100 is foreseen to be largely characterised by weather variability and extreme events (NCCS 2017[3]). Predictions indicate a significant increase in precipitation by 18%, leading to more frequent and severe episodes of heavy rainfall, larger and more common floods, and twice as many days with heavy precipitation. Additionally, brief periods of intense rainfall, lasting less than a day, could increase by approximately 30%. While some benefits

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[1] The first uses of the concept of co-production date back to late 1970 in the field of public services administration (Vincent et al. 2018)

[2] Climate Futures is a Centre for Research-based Innovation funded by the Research Council of Norway in 2020. Its primary objective is to foster collaboration among companies, public organisations, and research groups across various sectors and disciplines to tackle challenges related to climate risk. Source: https://www.climatefutures.no/en/about/

[3] The Norwegian Centre for Climate services report n1/2017, Climate in Norway 2100- a knowledge base for climate adaptation. (The next update is to be released in 2024)

can be expected from the rise in the levels of temperature, mainly a longer growing season, these advantages will be counterbalanced by the wetter climate conditions and the limited number of consecutive dry days. These conditions can cause problems such as "increased compaction, delayed sowing and harvesting, failure to combat fungal diseases and weeds, high risk of erosion and occurrence of floods, increase in runoff and loss of nutrients (phosphorus)" (NIBIO report n°20, April 2016).

***Box 2*: Seasonal climate forecast versus weather forecast**

The climate product covered by this project is sub-seasonal to seasonal climate forecasts (referred thereafter to as S2SF), which provide forecasts looking 4 weeks to 3 months ahead and are updated on a weekly/monthly basis. S2SF are to be distinguished from weather forecasts. The latter provides short-term predictions, up to 10-14 days into the future and describes the state of the atmosphere at a given place and time (Vaughan, C. & Dessai 2014). They are de facto deterministic by nature, indicating precise details such as the exact level of temperature in the next few days. Conversely, S2SF cover longer timescales ranging from sub-season to centuries. They are presented in a relativised manner, meaning that they present the probabilities for certain parameters (e.g. temperature or precipitation) to be above or below the historical average (referred to as the "normal" or climatology). These forecasts are typically presented in coloured maps (Figure 1), with the shading indicating possible outcomes (below-normal, near-normal, or above-normal) as well as the corresponding probabilities of occurrence at each point.

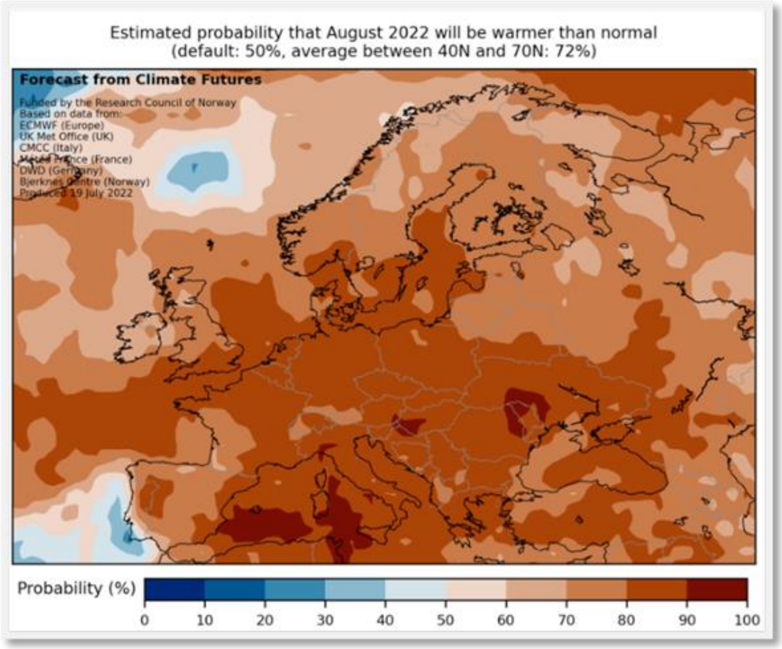

Figure 1: Example of a seasonal climate forecasts map (source: Climate Futures- NORCE)

The initial idea of my thesis was sarked by the following rationale: Assuming that the co-production efforts yield their desired objectives, meaning that the seasonal forecasts are adequately and largely communicated and that the relevant end-users - primarily farmers- are able to comprehend this type of probabilistic information, what would be the outcomes resulting from decisions based on seasonal forecasts? Will such climate information enable farmers to make optimal choices and decisions? or rather *"offer no more than an entertainment value"*[4] where producing changes is not possible? My thesis will therefore investigate the potential value of seasonal climate forecasts in the case of Norwegian forage-based dairy farming using system dynamics. It will be a model-based hypothesis testing of whether the seasonal climate forecasts lead to improved outcomes.

1.3 | FRAMING THE PROBLEM

The experience of the dry summer in 2018 alluded to a dynamic interconnected problem. The agricultural sector witnessed crop failures, shortages in livestock feed, the need for harsh adjustment of livestock (slaughtering) and financial losses. Simultaneously, the dairy industry which represents the primary demand before reaching the end-consumer, had to intervene to prevent any disruption in the dairy supply chain. The state also provided substantial compensation to preserve the economic viability of the affected farmers.

One noteworthy aspect that emerged from the crisis was the intricate dynamics between crop and forage management and livestock management. The adverse climate conditions caused crops to fail, leading to shortages in feed availability and stress on existing stocks. Farmers were confronted with difficult trade-offs, having to decide whether to secure and purchase feed from elsewhere or adjust their herd size. Financial considerations heavily influenced this decision-making process. Additionally, the dairy industry had a vested interest in farmers maintaining their cows instead of culling them, as doing so would have disrupted the milk supply. This was particularly crucial considering that building up the cow stock entails a significant delay. The substantial compensations provided by the government. which weighted on the state budget, raises concerns about whether a potential next crisis will be compensated accordingly. There is uncertainty about whether the same level of financial support would be available in a future crisis.

Defining the problem of my thesis started from **delineating the term "value"** and how to assess the value of a probabilistic information. By common sense, there are two main ways to determine the value of an information: either by comparing the outcomes of a group that has access to that information to a group that doesn't, or by comparing the outcomes of a decision made with and without that information. In climate studies, there is a tendency to estimate the value of seasonal forecasts following the latter. Bruno Soares, Daly, and Dessai (2018) provide several examples of studies which conceptualised the value of S2SF (either theoretically or empirically) by comparing the expected or observed outcomes resulting from a decision made with the use of S2SF to the expected outcome of the same decision made without the S2SF.

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[4] The expression has been used by John Maunder in his review of the book R. W. Katz and A. H. Murphy, Economic Value of Weather and Climate Forecasts, *Climatic Change* 45, no. 3/4 (2000): 601–6, https://doi.org/10.1023/A:1005617405583.

Similarly, I have deemed this approach more suitable in the context of this thesis. First, there are no documented users of seasonal forecasts in Norway, so proper group testing is not an alternative. It is worth noting that the Climate Futures pilot project conducted a series of focus groups during the second half of 2022, where participants (from different agricultural sectors[5]) were provided with climate information. However, considering the farmers involved in these focus groups seems to me premature. No full agricultural year has been elapsed since their participation in the workshops, hence no history of concrete decision-making practices. This has also been reflected in the post-evaluation of the workshops, where most narratives of the participants revolved around the potential value of S2SF in terms of improved decision-making in the future.

Unpacking the decision-making process became my next step in the process of better defining the problem. In order to investigate how the seasonal forecasts can be potentially transformed to a support for decision-making, I needed first to capture the process of decision-making and the type of decisions that this climate information can be used and inform. The literature is very rich with regard to knowledge about farming systems, the kind of decisions made by farmers, the determining factors and even estimates of the impact of climate uncertainty and variability. It was therefore easy to identify generic static decision-making prototypes, for instance, whether or not to apply fertilisers in response to uncertainty about rain, or whether or not to purchase supplementary feed in response to uncertainty about harvested yield. However, it was challenging to dynamically organise and interconnect all this information. Referring to the same example, the decision to apply fertiliser is based on last years' experiences of applying fertilisers, constrained by many factors like money availability, impacted by future expectations… The relative importance of factors differs from one case to another and depends on their utility and the satisfaction they brought to farmers.

To contain this complexity and present a coherent and systematic story of all these interacting factors, I decided to conduct a system dynamic participatory modelling. This approach allows for capturing farmers' mental model and realistically representing the system in which they operate. It allows to set the system boundary and identify the variables to include, as well as gain knowledge about how farmers process information based on their experience. More importantly, it provides a direct way to collect data on where seasonal forecasts could potentially be useful and how they fit into the matrix of all pertinent information used in decision-making.

I felt that narrowing down the thesis to one specific agricultural activity and calibrating my model on an actual farm would yield a more transparent and targeted model (for the simple reason that growing fruit trees is a sector that is exposed to climate variability in a different way than beekeeping, where it is possible to relocate beehives while the placement of trees is fixed). The second argument is related to Norway's heterogeneous

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[5] Fruit farmers (Gartnerhallen); Beekeepers (NORCE) · Berry farmers (Gartnerhallen); Fodder producers at Vestlandet (Statsforvalteren i Vestlandet); Fodder extension service advisers at Østlandet (Norsk Landbruksrådgiving); Agricultural governmental consultants (Statsforvalteren); and Grain extension service advisers (Norsk Landbruksrådgiving). Source: Climate Futures, 2022 Annual Report

geography with dispersed topography and climate, which present unique challenges across regions and municipalities. Therefore, I opted to study forage-dairying farming since it is the backbone of Norwegian agriculture, measured both in production worth and importance for farmers' livelihood and regional rural settlement (Jervell and Borgen 2000). Besides, it is the most widespread agricultural activity as the cold climate and the relatively short growing season make the lands primarily utilised and economically appropriate for forage-based animal production (Arnoldussen et al., 2014).

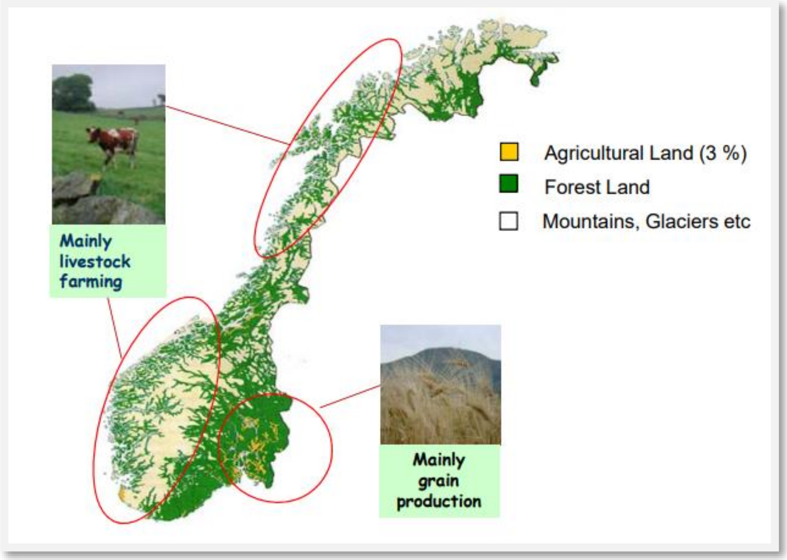

Figure 2: Topography map of Norway (Source: the Norwegian Ministry of Agriculture and Food)

The agricultural lands account only for 3% of the total land area, as the country's topography is scattered and divided by mountains, fjords, lakes and forests.

From a climate perspective, taking the average for the entire country or a whole region is not relevant. The Southwestern coastal parts of the country, for instance, experience the highest levels of rainfall compared to regions located about 50 km further inland, which receive less than a tenth of this amount. Likewise, during the dry summer of 2018, the average temperature for the whole of Norway was recorded to be 1.8°C above normal. However, in the eastern parts, the temperature reached around 4°C above normal (Meteorological Institute).

Given these variations and the reasons mentioned earlier, I intend to narrow down the thesis to a specific farm. The farm-level choice rather than a municipality or county level can be justified by the following example. Let's consider the scenario of two farms situated in close proximity but at different latitude levels. Farm A experiences an average temperature of 3 degrees, while Farm B records an average temperature of 6 degrees. Calculating the mean temperature of the two farms yields 4.5 degrees, which suggests that no crop growth occurred (as plants typically require a minimum of 5 degrees for growth), while in reality, Farm B did record some level of growth. The second reason pertains to the decision formation delays which are case-specific and vary from one farmer to another (e.g. the week of mowing or of applying fertilisers). The model considers different time lags between inputs and outcomes of the decision-making process, and the farm case study enabled the parameterization of these lags.

1.4 | RESEARCH OBJECTIVES AND QUESTIONS

The overall objective of this thesis is to investigate the potential value of seasonal climate forecasts in the context of the forage-based dairy farming system. To that end, the following research questions will be answered:

> **RQ1: What is the dynamic structure governing the decision-making process in the forage-based dairy farming system? And where the seasonal climate forecasts (S2SF) can be useful?**
>
> **RQ2: How does this dynamic structure contribute to the generation of the system's behaviour?**
>
> **RQ3: How does the integration of the S2SF impact the outcomes/behaviour of this dynamic structure?**

1.5 | METHODOLOGY AND PROCESS

System dynamics (SD) modelling was chosen as the overall methodology to answer the research questions. It is a methodological approach that is well-suited for similar cases and has proven to be useful in addressing issues in the field of agriculture (Turner et al. 2016, Kopainsky et al., 2017). This is because farmers are involved in a complex system, characterised by continuous change, uncertainty, and delays. It's a system that comprises adjustments of the biophysical sphere and technology sector alongside all the economic and socio-political considerations (Eriksen et al., 2015; Nightingale et al., 2022). All these components are interconnected, oftentimes by non-linear relationships, and are governed by feedbacks. The system dynamics approach, grounded in the feedback-based theory and non-linear dynamics, enables, therefore, the analysis of how these different components interact with one another and allows to study of the changing relationships under different scenarios/chocs.

Given the nature of the thesis and the project overseeing it, it was natural to involve farmers in the modelling process. Those are the primary stakeholders concerned with the problem as well as the end-users of the seasonal climate forecasts. The involvement of relevant stakeholders in the SD modelling process has been acknowledged since the earliest work in SD. J. Forrester (the father of system dynamics) has emphasized that stakeholders' mental models serve as a valuable source of information to build a model and that the incorporation of their perception and understanding of the system results in a more comprehensive and inclusive system (Vennix 1999).

The modelling process has followed the steps outlined by Sterman (2000), generally employed in the field of system dynamics. These steps include 1/ Problem articulation/Boundary selection [chapter 2- section 1], 2/ Formulation of dynamic hypothesis [chapter 2- section 2], 3/ Formulation of a simulation model [chapter 3-

section 1], 4/ Testing and validation [chapter 3- section 2], 5/ Simulation results and findings [chapter 4] and 6/ conclusion and discussion [chapter 5].

The first two steps, which are qualitative in nature, were attained by conducting system mappings with farmers and through a literature review on the topic. The workshops allowed us to reach a consensus about the problem and mutually determine its boundaries and main variables. They also enabled me to gain knowledge about links and relationships, resulting in a visual map of all important cause-and-effect relationships governing the forage-based dairy system. The latter, known as a causal loop diagram (CLD) in the SD literature, framed the dynamic hypothesis and offered an initial explanation of the endogenous feedback structure composing the farming decisions.

The CLD formed the framework for developing the quantitative simulating model. The running model comprises several parameters which needed to be estimated either because of lacking data or because the data is case-specific. Therefore, the data collection process involved gathering information from both primary and secondary sources, including numerical data (hard data) as well as soft variables such as expectations and perceptions. The collection of primary data was conducted through a structured interview with one of the farmers who participated in the mapping workshop. Consequently, the simulation model is **parameterised on the farm belonging to our interviewee (see box 3)**.

***Box 3*: Information card of the interviewee's farm**

- Location: Førde Commune, Vestland
- Weather input retrieved from Hovlandsdal weather station.
- Total Land Area: 350 decares, the equivalent of 35 hectares (18 hectares owned, 17 hectares rented)
- Livestock: 35 cows
- Milk Quota: 300.000 litres per year

Previously, the farm had 40 cows with a milk quota of 350.000 litres. Due to challenges in managing the larger quota, the decision was made to downsize the number of cows by 5.

In terms of ethical considerations for handling the primary data obtained through workshops and interviews, ethical guidelines were followed diligently as part of the NORCE-Climate futures project (approved by the Norsk Senter for Froskningsdata).

Moving forward, the next step entailed conducting a series of tests following standard procedures for system dynamics model validation. Both direct structure tests and behavioural tests were conducted to build confidence in the model. The final step involved analysing the simulation results and running alternative scenarios to provide answers to the research questions.

CHAPTER 2 | DYNAMIC HYPOTHESIS

2.1 | SYSTEM MAPPINGS OUTCOMES

The system mapping workshops were carried out by my co-supervisor and I. The conduct of these sessions has followed pre-defined scripts for facilitating Group Model Buildings, which are available in the online handbook "Scriptapedia" ***https://en.wikibooks.org/wiki/Scriptapedia*** (the full scripts used in the workshops are presented in Appendix A, which is attached to this thesis).

A total of 11 farmers from Førde and Voss[6] participated in the workshops. The selection of the participants was delegated to two different gatekeepers: Statsforvalteren[7] and Fylkeskommunen[8]. Both are partners of the Climate Futures projects and have a close relationship with the farmers, making it easier to select a representative sample with sufficient heterogeneity. The diversification of gatekeepers intends also to mitigate potential selection biases and ensure that there is no hidden agenda in participant selection.

The workshops began with a brief presentation of the seasonal forecasts and the type of information they convey. This was followed by an introduction to system mapping and finally a description of the desired outcomes by the end of our gathering. With regard to system mapping, a feedback process (see Figure 3) was presented to illustrate a generic process of decision-making where a farmer exploits all available information (past and present) to form expectations about the next agricultural season. Social and psychological considerations (risk aversions, stress, the memory of climate occurrences, cultural beliefs….) are also mentioned to not omit qualitative factors or social constraints that the farmers have to cope with to achieve economic goals. The decision-making process involves constantly updating and adjusting the future plan until its execution. The results of the executed plan then become part of the past available information, feeding into future decision-making cycles.

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[6] Førde and Voss are towns located in the county of Vestland.

[7] The County Governor is the chief representative of the King and Government, and works to ensure that decisions of the Parliament and Government are implemented correctly at the regional level. Source: https://www.statsforvalteren.no/en/

[8] The County Council is the democratically elected body that provides a wide range of public welfare services. Source: https://www.vestlandfylke.no/om-oss/english/

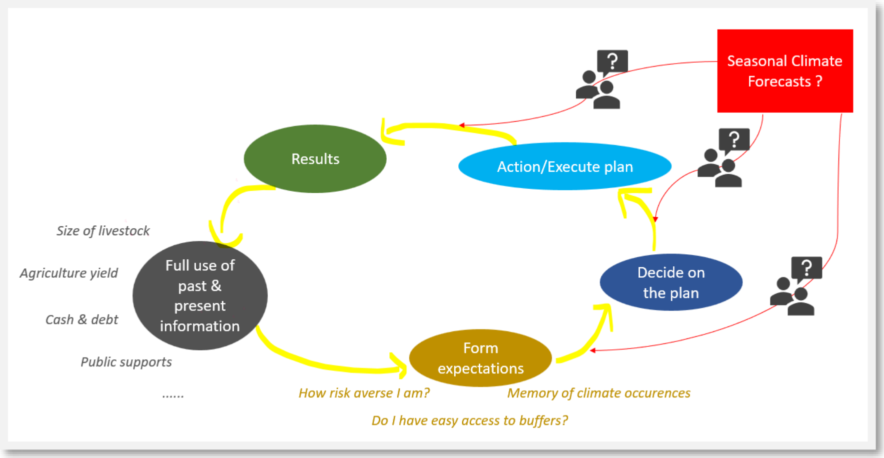


Figure 3: Typical decision-making process

After closing the decision-making process loop (Figure 3), seasonal climate forecasts have been mentioned to avoid the session leaning towards mapping the whole system- with the participants listing all kinds of decisions taken within their farming practice. The goal has been reiterated to focus the discussion on decisions where S2SF can be potentially useful and employ the mapping session to structure the problem.

The final mappings produced during the workshops can be found in Appendix A. The narrative of the problem as well as the final causal loop diagram are presented in greater detail in the subsequent section. Globally, four major clusters have emerged: crop management, livestock management, fertilisers use and economic considerations. The variables listed by the participants helped establish the boundary of the system, determining which variables to integrate endogenously (within the model) and which to include exogenously.

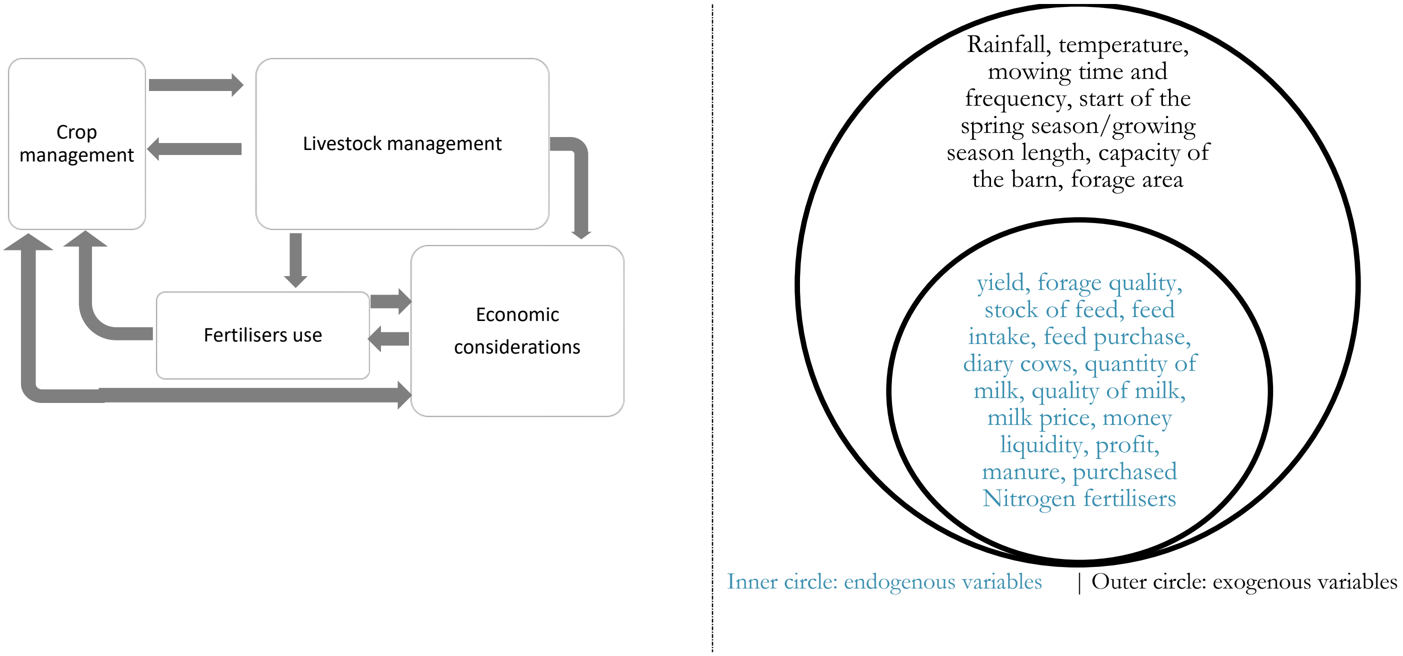


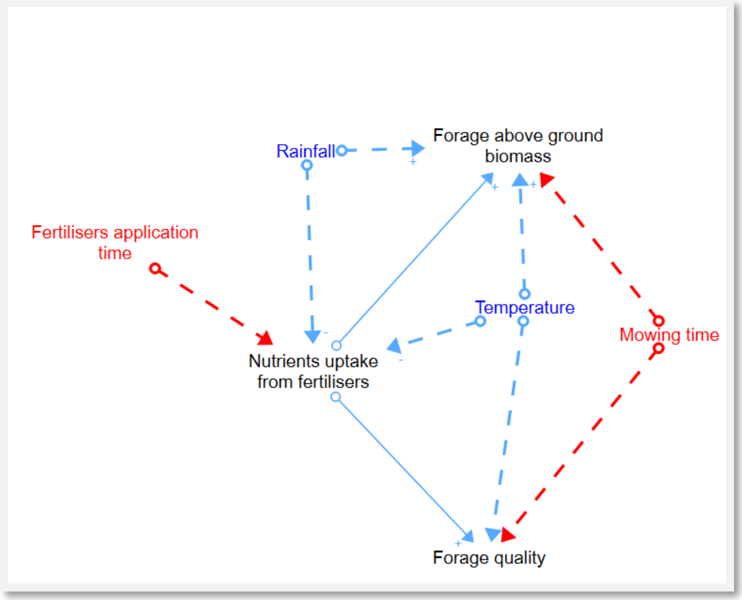
Figure 4: Boundary chart of the system

2.2 | CAUSAL LOOP DIAGRAM: the narrative of the problem

The CLD was developed based on the system mapping obtained during the workshops. It underwent iterative improvement after additional understandings gained through literature as well as insights emerging while building the simulating model.

Forage quality and quantity (also referred to as forage above-ground biomass) were identified as important variables and constituted the centre point around which the mappings were expanded. For the participants, producing enough and high-quality forage is key to ensure the great performance of dairy cows. They distinguish however between factors they can manipulate and others beyond their control. Weather conditions (rainfall and temperature) are imposed, but the timing of mowing, the timing of applying fertilizers and how much to apply fall within their management decisions.

Deciding on the timing of mowing, which is one of the most important management decisions in dairy farming (O. Flaten et al., 2015 2019), implies a trade-off between higher quantity and higher quality. Cutting the forage at an early maturity stage allows it to reach a higher quality but at the expense of lower yields. Farmers need therefore to assess whether gains from higher quality outweigh the limited quantity of the forage in terms of underlying costs and livestock performance. The second set of challenges is related to the weather conditions around the mowing time window. The mowing can't happen under rainy conditions and mowing wet forage poses many challenges. To mention a few, wet forage tends to lose nutrients during the harvesting process, compromises the fermentation process, requires drying which is time and energy-consuming and is more difficult to handle due to its heavier and stickier nature. F**armers constantly face the dilemma of whether to mow now or wait and risk the possibility of encountering a week of rain or even several consecutive weeks of rain.**



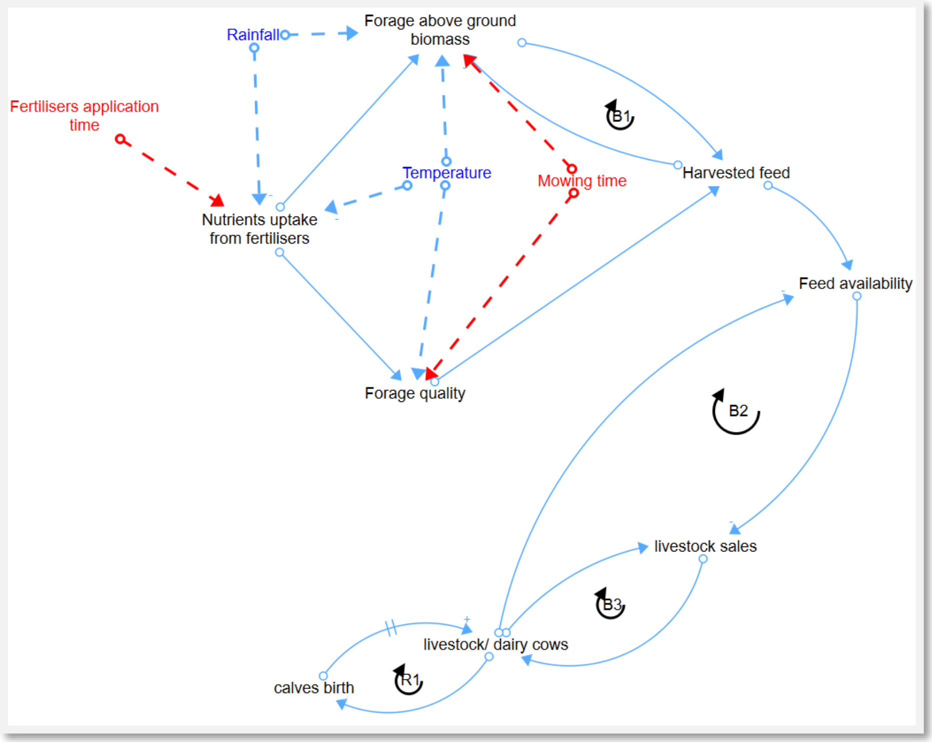
An arrow ↷ indicates the direction of the causal relationship (A is affecting B and not the other way around). The use of the + or – signs denotes the polarity of the relationship. + signifies that both sides are evolving in the same direction (for instance an increase in A induces an increase in B), while – indicates a change in the opposite direction (an increase in A causes a decrease in B). I have employed dashed lines to separate exogenous variables that do not belong to any feedback loop. These variables are categorized using the colours blue and red, with blue representing factors that are beyond the farmers' control, and red representing factors that are within their decision-making sphere.

Figure 5: CLD Forage quality and quantity (above-ground biomass)

With regards to fertilization, farmers need to adhere to standard guidelines, such as applying fertilizers in the spring when the accumulated degree days (the sum of daily temperatures above 0 degrees from January 1st) reach around 200 (Oregon State University, 2019). However, farmers need to meticulously evaluate any potential risk of loss due to weather conditions. Heavy rainfall can result in nutrient leaching, while high temperatures and dry conditions can exacerbate the risk of fertilizer evaporation. Furthermore, frozen soil poses a challenge as it becomes less permeable, impeding the penetration and absorption of nutrients. **Farmers must strike a balance between ensuring adequate nutrients for their forage for a better yield and quality and minimizing the potential risk of nutrient loss.**

Both forage quality and forage quantity are positively linked to the harvested feed. As the harvested feed increases, the above-ground biomass is depleted (B1). A higher quantity of harvested feed replenishes the availability of feed. This increased availability enables the retention of livestock on the farm, reducing the need for livestock sales. Nevertheless, as the size of livestock grows, their feed intake also increases, leading to the depletion of feed availability (B2). B3 represents a minor balancing loop where an increase in "livestock sales" causes a reduction in livestock. In turn, a smaller size of livestock leads to diminished sales.

The feed availability balancing loops B2 & B3 control the reinforcing loop of livestock reproduction (R1), according to which: more cows give birth to more calves which mature through a long aging chain to become cows again.



The letter B is used to indicate a loop which is balancing in nature while the letter R refers to a reinforcing one.

Figure 6: CLD: B1 – B2 – B3 – R1

The relationship between harvested feed and feed orders is inversely correlated. As the quantity of harvested feed increases, the requirement for ordering additional feed decreases. The decision to purchase feed is guided by financial considerations (B4). When there is a greater amount of cash liquidity, there is a capacity to acquire more feed. However, this increased purchasing of feed leads to higher costs, subsequently reducing the available cash liquidity. The stock of cash liquidity also impacts the costs in the sense that higher cash liquidity increases the capacity to spend. This link closes loop B5.

Increased feed orders contribute to greater feed availability, which enables to maintain the size of the livestock, as explained earlier. However, larger livestock comes with higher maintenance costs, resulting in a reduction in cash liquidity. With diminished cash liquidity, there is a decrease in the ability to purchase feed (B6).

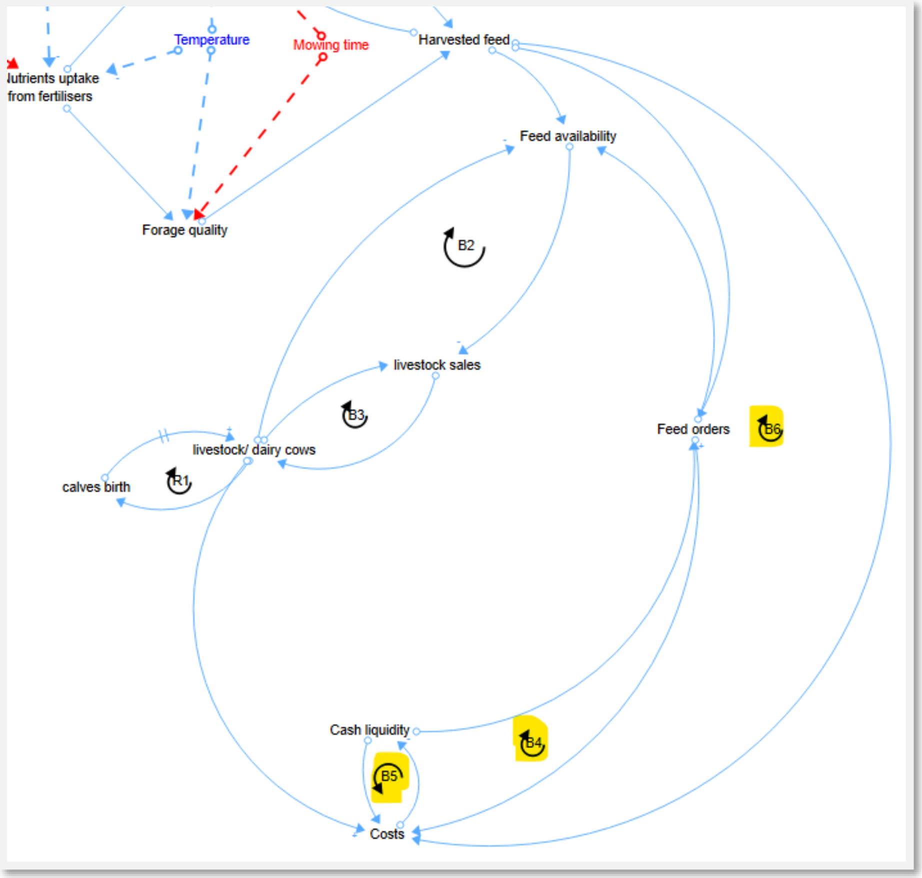


Figure 7: CLD: B4- B5-B6

Nutrients from fertilisers are supplied by manure and supplemented by purchased fertilisers. The participants mentioned the use of Nitrogen because livestock manure, although rich in phosphate and potassium, contains very low rates of nitrogen. The model will therefore only consider inputting nitrogen nutrients because it is the most critical and has the most significant impact on financials.

The quantity of manure increases with the size of livestock: the bigger the size of livestock, the more they produce manure (R2). As the quantity of manure increases, the need for supplementing the forage with purchased fertilisers decreases. The decision to purchase fertilisers responds to a financial logic (B7): When there is a higher amount of cash liquidity, more fertilizers can be bought, resulting in increased costs and in turn a reduction in cash liquidity.

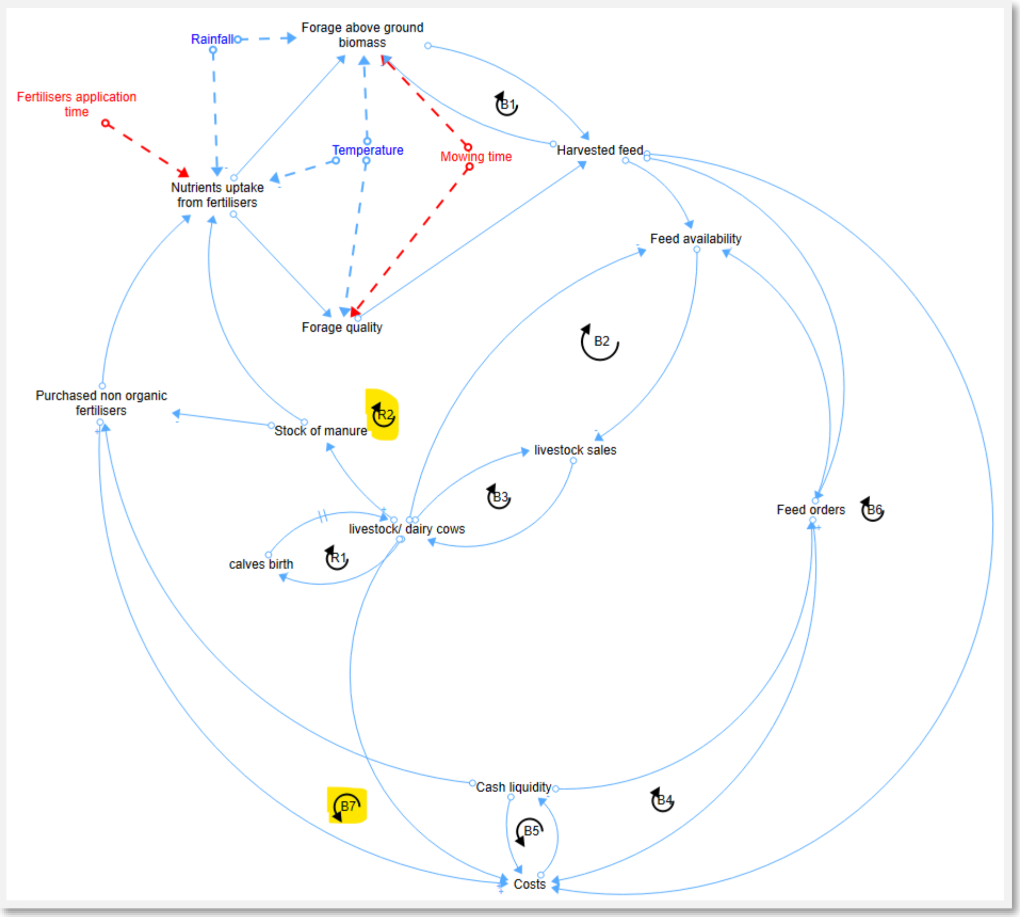
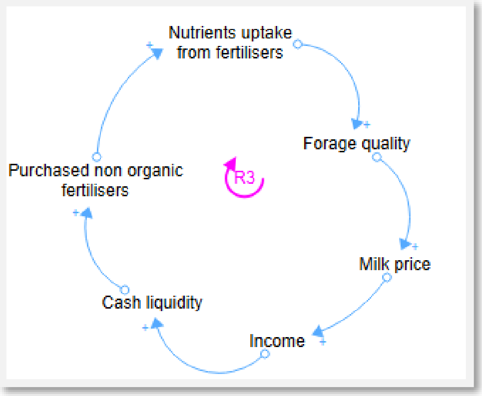


Figure 8: CLD: B7-R2

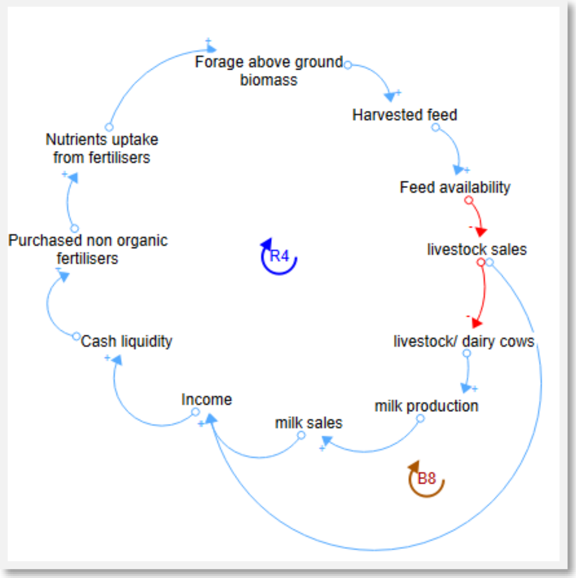
Milk sales are determined by the level of production as well as the milk price. Milk production increases with the size of the livestock, in particular the number of dairy cows, and also with feed availability. The latter controls the productivity of the cows, where limited feed availability leads to lower milk yield per cow. As for the price, it is impacted positively by the quality of forage because cows that are fed high-quality forage produce milk that is rich in nutrients and which is sold at a higher price.

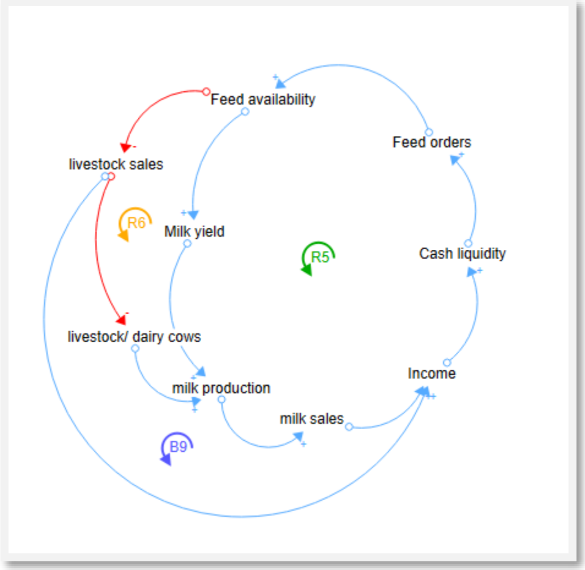
The increased sales of milk contribute to higher income, leading to the accumulation of cash liquidity. The route from cash liquidity to feeding back to milk sales takes 4 reinforcing paths. Livestock sales and livestock/dairy cows are interconnected through the balancing loop (B3). This means that, ceteris paribus, any higher gains from livestock sales counteract milk sales, as the size of livestock diminished.



The first path covers the purchase of fertilizers, which positively impact the quality of milk. This quality improvement is directly linked to milk price.

The same reinforcing behaviour involves the purchase of fertilizers but through its impact on above-ground biomass, which affects the availability of feed. Since livestock sales are directly related to income, the balancing loop is closed.





The third path is through feed orders, which directly affect both the availability of feed and milk production by influencing milk yield. The fourth path, similar to the third, relies on feed orders to influence feed availability, but this time it affects milk production through the size of livestock/the dairy cows. Since livestock sales are directly related to income, the balancing loop is closed.

Figure 9: CLD: R4-R5-R6 -B8 -B9

The last link to consider within the entire CLD is the cost associated with feed harvesting. As the amount of harvested feed increases, so does the subsequent cost. This leads to a decrease in cash liquidity and this information connects to all feedback loops mentioned earlier.

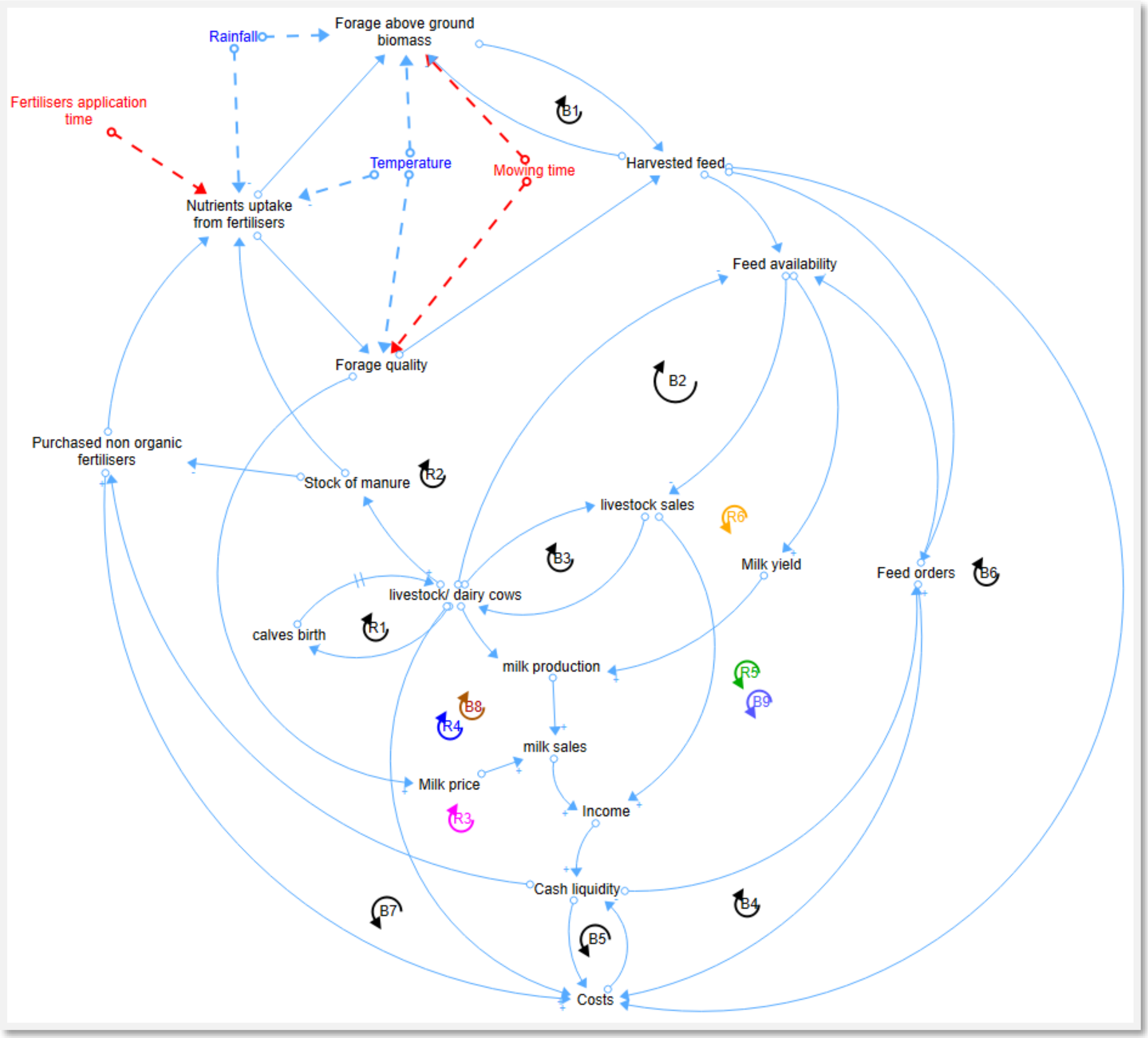


Figure 10: Complete CLD

CHAPTER 3 |MODEL STRUCTURE & VALIDATION

3.1 | MODEL STRUCTURE

This section will present the stock and flow structure of every sector of the model and the corresponding feedback loops. The complete model structure, including all equations and parameter values, can be found in Appendix C attached to this thesis.

Forage sector

The forage sector models the dynamics of **the above-ground biomass** measured in kg per ha and **the quality of the forage** which represents the percentage of the forage biomass that can be digested by the livestock made up of carbohydrates, proteins and lipids.

The forage above-ground biomass regenerates through a natural growth process impacted by rainfall and temperature and is boosted by nutrients coming from fertilisers. Similar to what Gerber (2016) has employed, a Mitscherlich-Baule equation has been used to capture these three levels of detail:

$$\textbf{Eq 1: } Y = A \times (1 - 10^{-\alpha_1 \times f_1}) \times (1 - 10^{-\alpha_2 \times f_2}) \times (1 - 10^{-\alpha_3 \times f_3})$$

where Y is the forage above-ground biomass; A is the yield plateau representing the maximum yield under perfect factor availability; α_n are estimated response coefficients and fn represents the three determining factors (rainfall, temperature and nutrients). All the effects have been delayed by 6 weeks as the response of the plants is not instantaneous (Godde et al. 2019). The coefficients are obtained through optimisation to fit historical data.

The harvesting rate depletes completely the forage above-ground biomass when time equals the timing of mowing.

The weekly temperature has been converted to growing degree weeks (GDW), which is close to the concept of growing degree-days (GDD) widely used to determine and describe the growth of plants (Mcmaster 1997). The inflow calculates the positive difference between the weekly temperature and the base temperature which represents the threshold above which forage growth can happen. This difference is then accumulated in the stock of "accumulated GDW", to track the maturity stages and the length of the growing season during a year. The outflow simply sets the stock to 0 to account for the beginning of a new year (minor balancing loop).

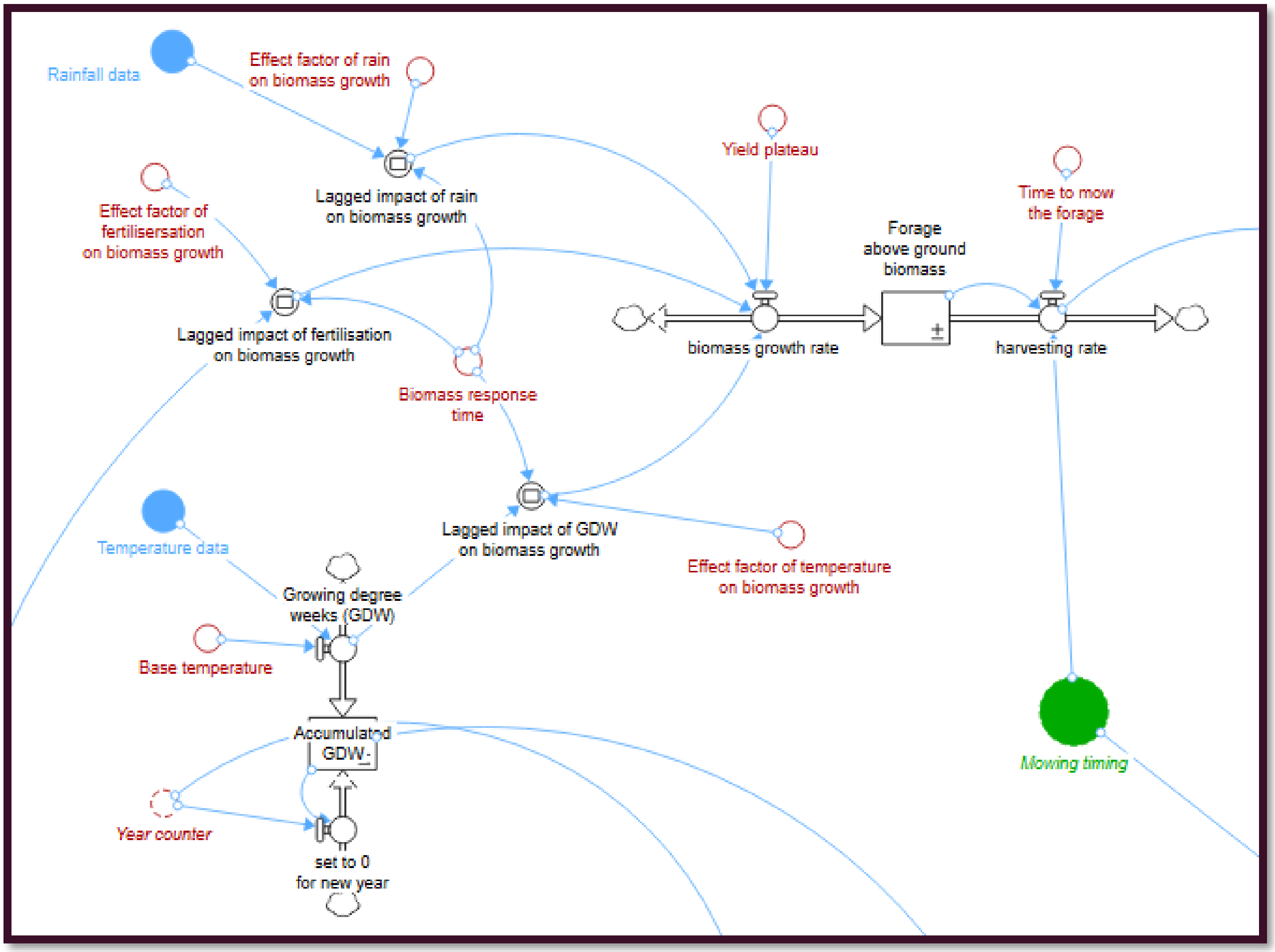


Figure 11: Model structure: Forage sector – Above-ground biomass

The forage quality is modelled to be varying with fertilisation and growing degree days. This is rather a simplistic assumption but considered sufficient given the scope of this thesis. Referring to the farmers' workshop mappings, only temperature and fertilisers were listed as variables impacting the forage quality. The "quality growth rate" equation is also formulated as an S-shaped logistic equation with one determining factor fertilisation:

Eq 2: $\mathbf{Z = B \times (1 - 10^{-\beta \times f_1})}$

where Z is the quality of the forage, B is the maximum reference quality growth, β is an estimated effect parameter and f_1 represents the nutrients coming from fertilisers. The effect of fertilisation has been delayed by 6 weeks as the response of the plants is not instantaneous.

The conditional statement in the quality growth is formulated to reset the quality of the forage to the average value after the mowing has occurred. This means that after the forage has been cut, its quality is immediately restored to a predetermined level. The recovery converter enables this quick adjustment by closing the gap almost immediately, with the adjustment time being equal to the time step used in the simulation (minor balancing loop).

The quality declines with forage maturity (Fariaszewska et al. 2020). As a consequence, for each week that goes beyond the optimal degree days, the quality level will decrease by a fraction (minor balancing loop).

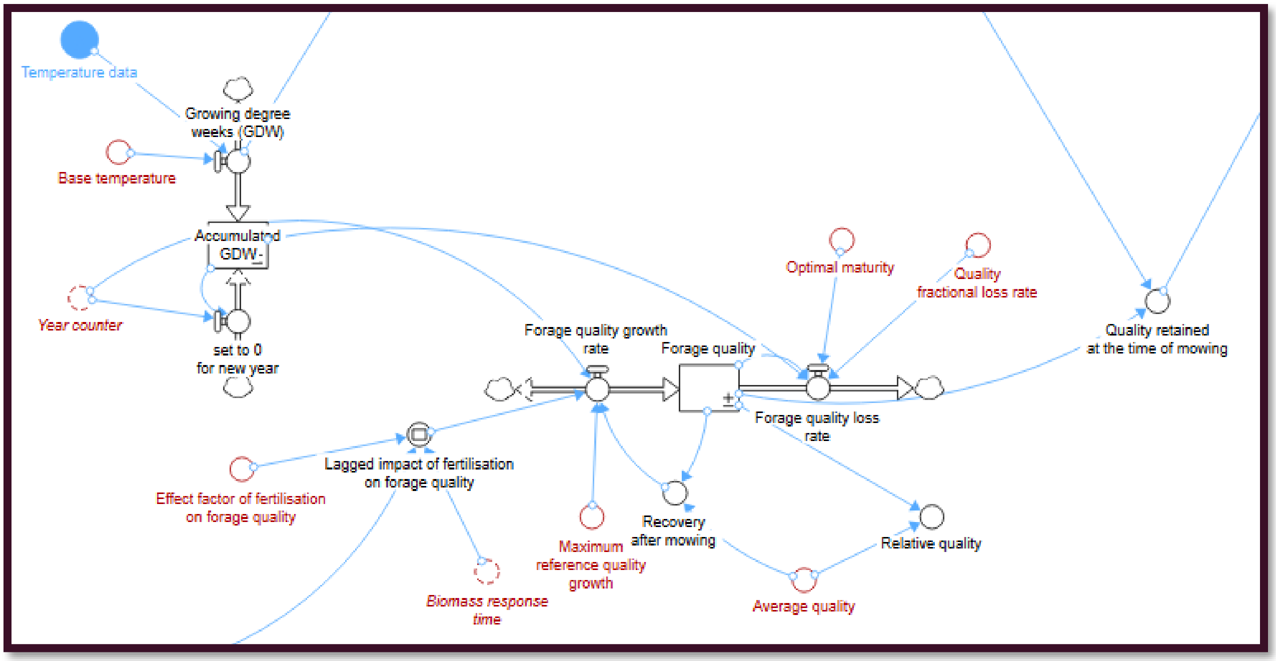


Figure 12: Model structure: Forage sector – Forage quality

The timing of mowing determines the quality of the forage, which in turn informs about the energy concentration of the forage. The conversion to energy content is computed straightforwardly by multiplying the quality by the gross energy content. For instance, if the level of quality is 50%, the equivalent energy content is half of that of the gross energy.

The total harvested rate (taking into account the whole forage area) together with the retained quality at the time of harvest indicate the total harvest feed in terms of energy contents that will replenish the feed stock.

Nutrients for forage are supplied by manure produced on the farm and by purchased fertilisers. The stock of fertiliser nutrients accumulates through the manure applied every week and the nutrients coming from purchased fertilisers. It is completely depleted when it is time to apply fertilisers (minor balancing loop). Two simplistic assumptions are made, the first one is that the amount of produced manure per animal does not change with feed intake and the second is that the manure is not commercialised. The purchase of fertilisers is governed by the decision rule to close the discrepancy between the desired nutrient uptake and the level of nutrients contained in manure (B10).[9] This is however constrained by cash availability and the effect function "effect of cash on purchased fertilisers" ensures that this logic (Balancing loop B7 in Figure 8).

The "fertilisers retention" is activated when weather conditions are not suitable for proper retention of the fertilisers at the time of applying fertilisers. Heavy rain causes the runoff of the fertilizers from the soil while high temperature or frozen soil results in their evaporation (see the full model documentation in Appendix C for parameter values).

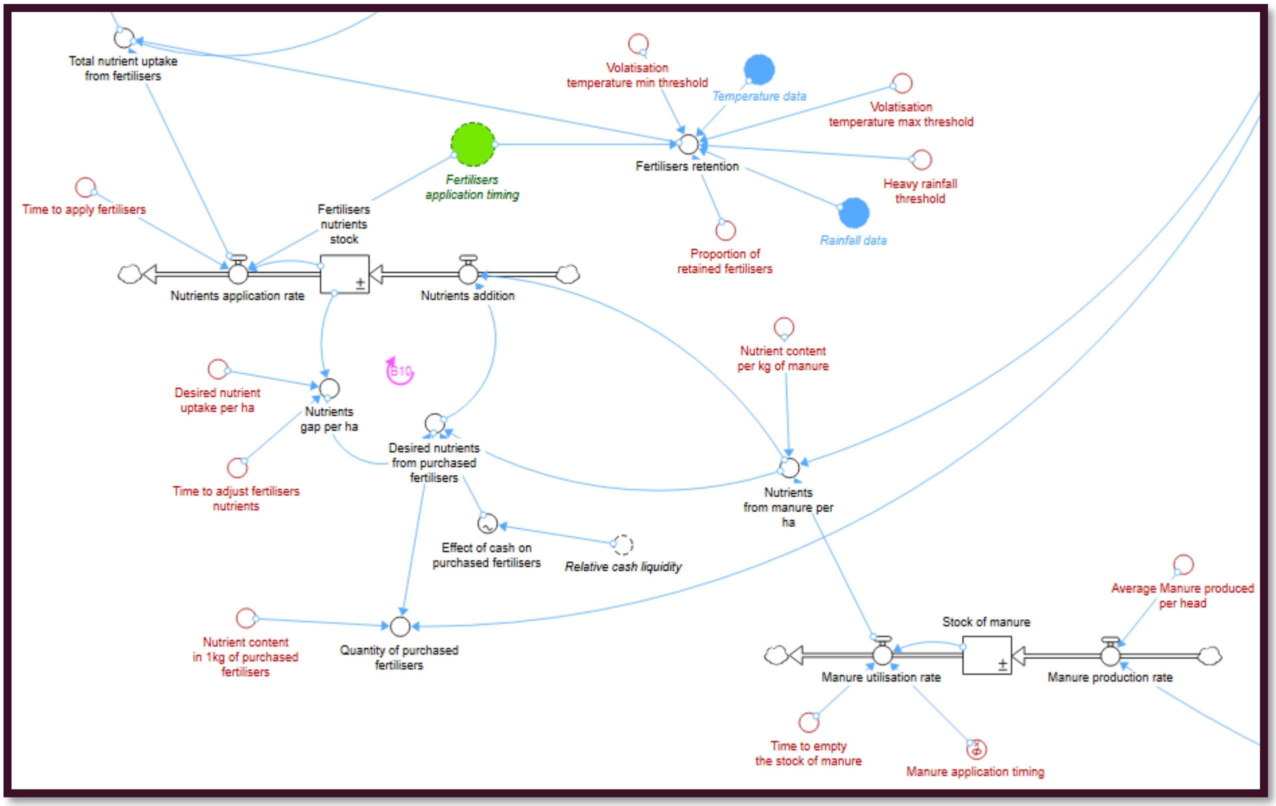


Figure 13: Model structure: Forage sector – Fertilisers

Stock of feed sector

The stock of feed holds a crucial role in the running of a dairy farm, and like any type of inventory management, it is a complex dynamic task. In the model, only two flows are impacting the stock of feed and no spoilage or expiration have been assumed. The stock accumulates the replenishment rate which included the harvested feed and the feed orders and is reduced by the livestock intake rate.

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[9] It should be noted that the gap equation does not take into consideration the application rate (the outflow). This is because the objective is not to maintain the stock of fertilizer nutrients at the desired level, but rather to reach that level for the agricultural purpose and repeat in the following years.

The feed stockout loop (B11) regulates the livestock intake rate as the stock of feed changes. Ample levels of feed stock increase the maximum feed intake rate and this allows the livestock intake rate to meet the desired feed intake. Inversely, if the stock is insufficient, the livestock intake rate drops below the desired rate and will even fall to zero if the stock is empty. Such dynamics are captured by the fulfilment ratio which represents the fraction of desired intake rate that is fulfilled and is a table function of the ratio of the maximum feed intake rate and the desired feed intake.

The maximum feed intake rate is determined by the stock level and the minimum time required for ordering and transporting feed. This minimum parameter can vary from less than a week if the order is placed from a neighbouring farm or a close farm shop to several weeks if there is a need to import from another country.

The feed stock control loop (B12) aims to bring the stock of feed in line with a desired level. The desired level depends on the expected livestock intake rate and the desired stock coverage. The latter includes two components: a base coverage which is equal to the minimum time for ordering and transportation, and a safety coverage chosen to ensure a certain supply of feed intake. The level of safety coverage can be determined by various factors including the risk aversion of the farmer and the event of any serious disruptions. In normal practice, the safety stock tends to cover one year's worth of consumption/intake (this fact has been confirmed by the interview data). However, following a storage crisis, farmers tend to adopt a more risk-averse approach and maintain higher levels of coverage. As the memory fades away and the normal conditions prevail, the safety coverage returns to normal levels (Beitnes, Kopainsky, and Potthoff 2022).

The desired replenishment rate is governed by the decision rule to adjust the feed stock to its desired level, but only in the case of stock shortage (hence the use of the fuzzy Max in the equation). The desired feed orders constitute then the difference between the desired replenishment rate and the total harvested feed. Not all desired orders can be fulfilled as they are limited by cash availability.

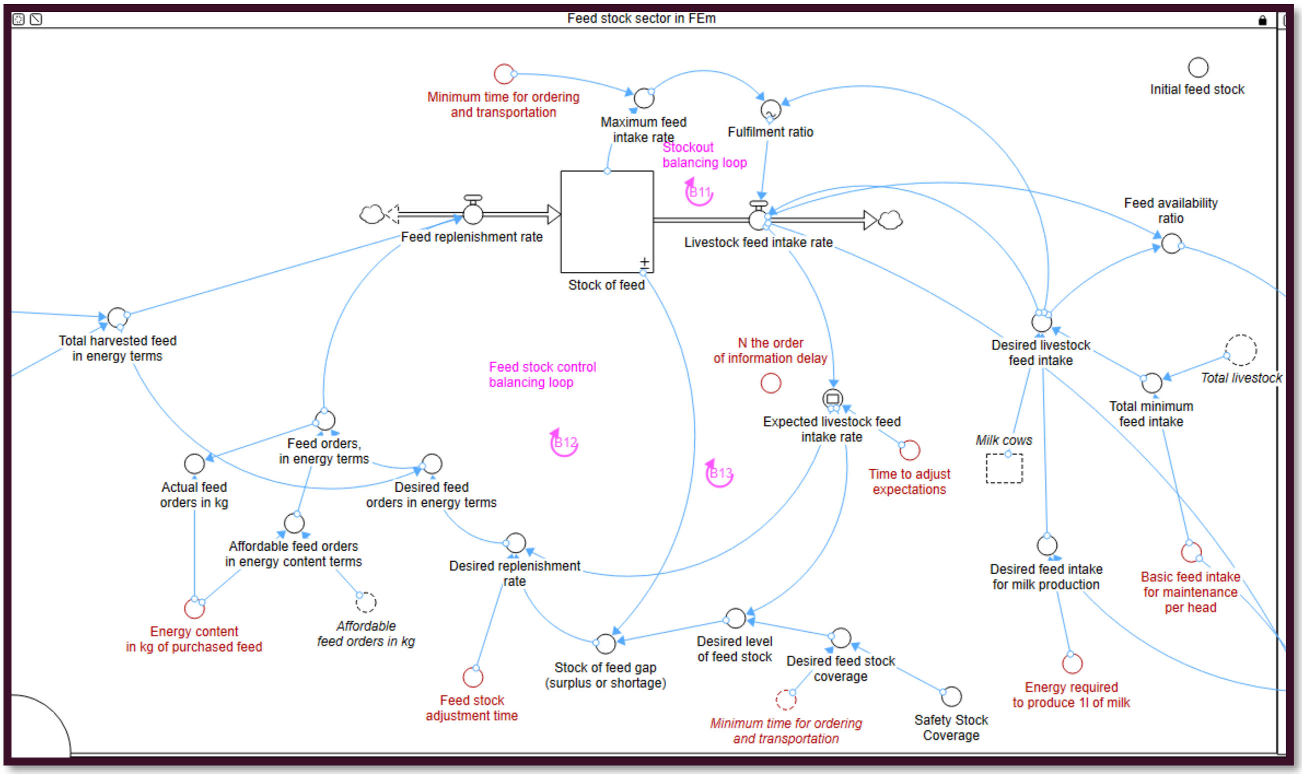

Figure 14: Model structure: Stock of feed sector

Livestock sector

The livestock sector captures the aging chain of the cattle population as well as herd management decisions. The cattle population is structured as female cattle and male cattle and is divided into different cohorts depending on their maturity. The death rates are represented to account for any natural loss at different livestock classes, for instance, due to diseases, and are determined by a fixed mortality fraction. This latter is age-dependent, assumed to be higher among young calves since they are more vulnerable to health issues compared to adult cattle.

It is assumed that a cow calves every year in the middle of November week 46 (Flaten, Bakken, and Randby 2015) and gives birth to one calf (Livestock reproduction reinforcing loop R1). For simplicity, the probability of the calf being male or female is set to 50%. Based on this sex ratio, the stock of newborns splits into a stock of female calves and a stock of male calves. All calves are weaned for 24 weeks, the minimum period they are supposed to stay with their mothers after which they either continue their transition in the aging chain or are sold. The female weaned calves are considered heifers when they reach the mating and conception age. Once they give birth to their first offspring, they join the stock of milk cows. During their productive life, the cows go through a repetitive cycle of lactation and drying off. The residency time of the cows on the farm is determined by their productive life as well as feed availability. The productive life of a cow depends on factors such as biological aspects, breed, and profitability considerations. However, in cases of feed shortage, some cows may have to be sold before completing their productive life because the farm cannot adequately feed them (balancing loop B3).

Besides feed availability, the management of the cow stock is controlled by two other factors. The carrying capacity of the farm which allows a maximum of one cow per hectare (Statsforvalteren) and the milk quota. The adjustment of the cow stock is carried by an indirect control of the stock of heifers. This setting resembles a generic stock management structure in a supply chain (Sterman,2000 chapter 17), where the main stock is the milk cows and heifers are the supply line. The adjustment covers the:

- replacing the losses from natural deaths, normal sales at the end of the productive life and emergency sales;
- closing the gap between the target and the current level of the cow stock. The target level is determined by considering the discrepancy between the cumulative milk delivered throughout the year and the annual milk quota. It takes into consideration the milk yield, recognizing that a higher milk yield allows a smaller number of cows to produce the same quantity of milk. Additionally, the statement mentions that the milk gap is capped by the maximum adjustment allowed by the carrying capacity. The carrying capacity, which is influenced by the available forage area, sets the limit on the number of animals the farm can sustainably accommodate. (Cow stock control loop B13)
- adjusting the heifers (the supply line control loop B14). According to Sterman (2000), the supply line adjustment is a sophisticated exercise and assumes a high degree of rationality, it must therefore depend on empirical investigation of the decision-making process. The desired level of heifers has been therefore calibrated to reproduce historical data.

The sum of these elements might be negative in extreme cases. For instance, in case of a significant drop in the milk quota, the cow stock would be in a large surplus compared to the desired level. To ensure that the equation formulation for "cow replacement rate" is robust and does not display a negative value, a MAX function has been used.

> **Eq 3:** Cow replacement rate = MIN (Weaned female calves//DT, MAX (0, Expected cow exits+ Adjustment of heifers in the supply line + MAX (0, Cow adjustment rate))]. The MIN function prevents withdrawing from the "Weaned female calves" when the stock is empty. The remaining female calves that are not needed for replacement are sold.

Given that dairy production is the primary focus of the farm, all male calves are sold once they are weaned. Insemination is widely used in the reproduction of livestock, especially since raising a bull is a heavy investment. This observation was confirmed during the interview.

To sum up the whole livestock, the calculations have been anchored on cows using average weight data. A heifer is equivalent to 0.75 cows while a calve is equal to 0.42 cows.

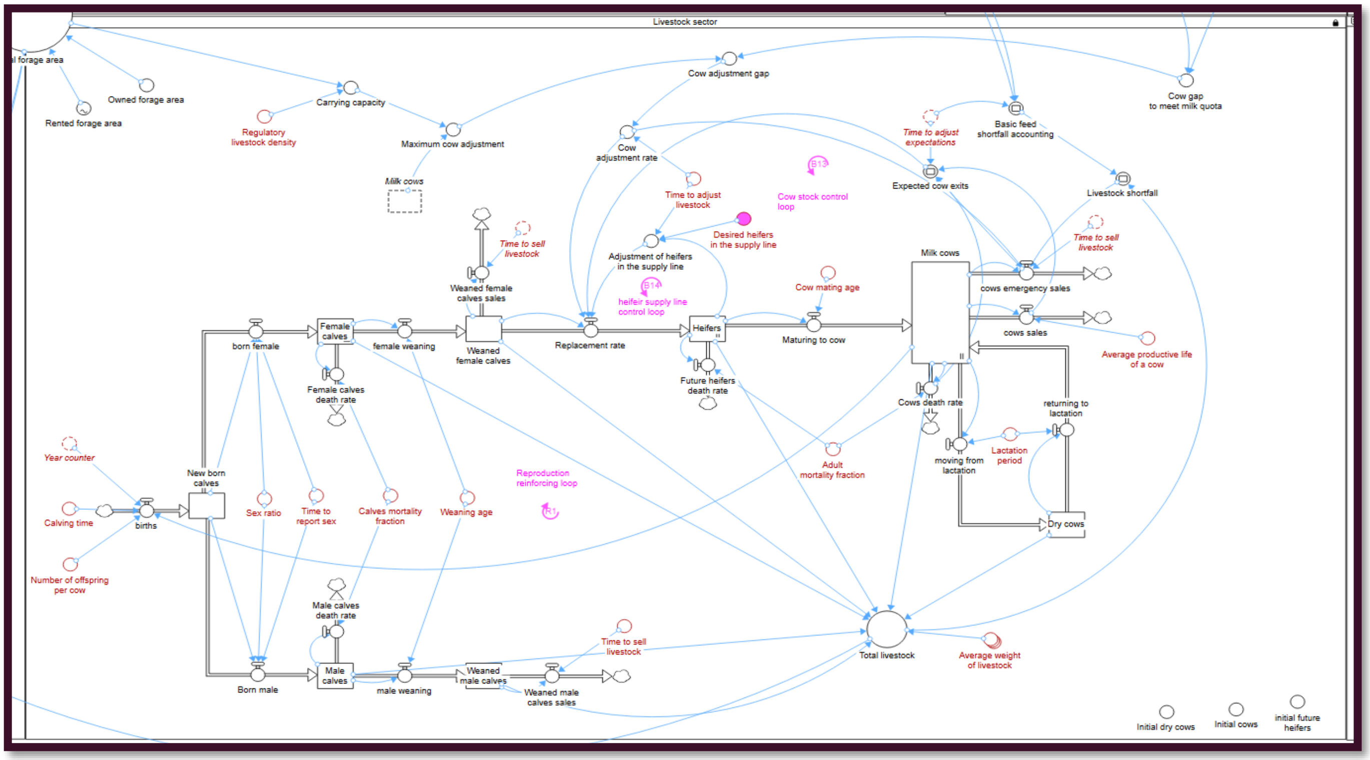

Figure 15: Model structure: Livestock sector

Milk production sector

In Norway, the milk production is regulated by a quota system. Every farm possesses its quota which sets the annual amount of milk litters it can sell at full price. The allocation of quotas takes into consideration the farm size as well as any disadvantages related to geographic location and varies over time to ensure that the milk production is adapted to the needs of markets (landbruksdirektoratet). Quotas can be traded either in the private market or by the government but their transfer is restricted within the same county (Jervell and Borgen 2000). In the context of this thesis, it has been assumed that the farmers aim to fully utilise their quota with no possibility of selling or renting any quota surplus.

The milk production rate increases with the number of cows as well as the milk yield per cow. The milk yield is impacted by changes in feed ratio as well as other productivity factors that can be related to milking or efficiency practices. Part of the effect of feed availability on milk yield is derived from the calculations performed in the new Nordic feed evaluation system Norfôr Plan. According to this system, the level of feed given to the cow is positively and linearly linked to the yield with a coefficient of around 0.32. This implies that a 10% decrease in the rate of feed intake compared to the desired intake will result in a 3.2% decrease in milk yield. Adapted to the model logic that is based on relative value rather than absolute, the effect factor of feed availability takes the following shape (Figure 16). It assumes that as the feed ratio (feed intake relative to the desired intake) drops below 50%, the milk yield quickly approaches zero because the feed intake is insufficient for the cow's sustenance and survival and the effect factor of feed availability grows linearly. Beyond the 50% feed ratio, the effect factor slowly plateaus towards 1 (there is a biological limit to how much a cow can be fed and produce milk). This implies that the incremental gain in milk yield becomes smaller as the feed ratio approaches 1. At a feed ratio of 1, the potential maximum yield is reached, and the marginal gain is close to zero.

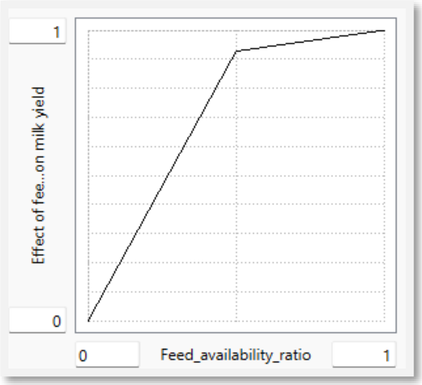

Figure 16: The effect of feed availability on milk yield

Not all produced milk is delivered to the market as a portion is consumed internally to feed the calves. The volume of milk fed to calves per day amounts to approximately 10% of their body weight (College of Veterinary Medicine, Cornell University). The stock of cumulative milk delivered, as the name implies, accumulates the weekly delivery rate and will be compared to the annual quota both in terms of gaps in litres and in terms of a utilisation ratio.

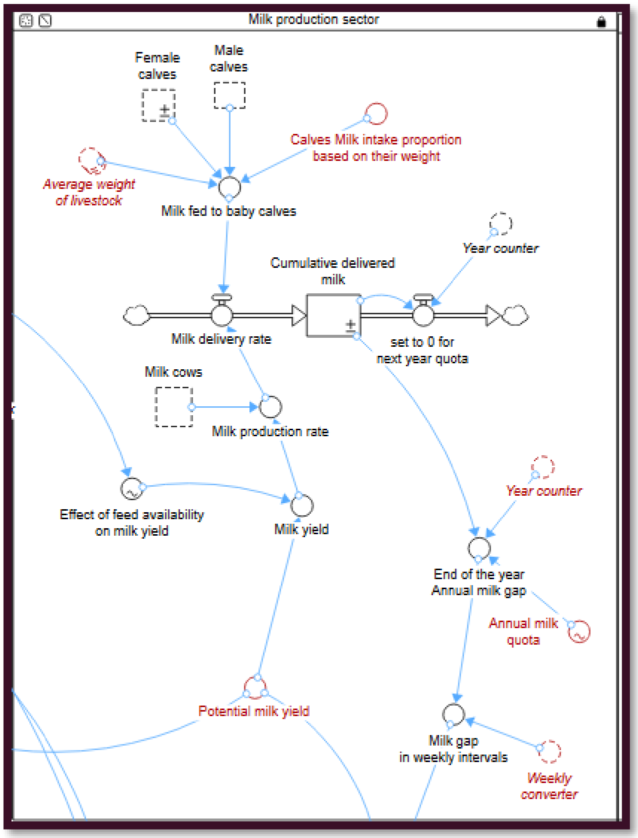

Figure 17: Model structure: Milk production sector

Finance sector

The finance sector captures the cash liquidity dynamics of the farm by modelling main income sources and expenditures. The structure used is similar to the one presented by Herrera et al. 2022 but with more detailed information on both income and expenditures. The income of the farm is made up of income from milk production, income from livestock sales, production/price support and extraordinary compensation.

The revenues from milk are determined by the rate of milk delivery and the milk price. The price changes depending on the level of quality of the forage. Cows that are fed high-quality forage produce milk that is rich in nutrients and contains higher fat and which is sold at a higher price than the base price. The income from the livestock is calculated by summing the returns from sales (voluntary and emergency sales) at different cohorts of the livestock, discounted by two factors: the average carcass weight and the respective unit price of meat.

Part of the income also comes from direct payments that the farmers receive from the State as support for every hectare of forage harvested and head of livestock. Norway stands out among OECD countries for providing the highest level of support to agricultural producers. Despite agricultural reforms being implemented in many countries, the primary agricultural sector in Norway remains strongly protected from global markets (OECD, The agricultural policy environment in Norway). Additionally, farmers receive extraordinary climate compensation in the event of climate-related production failure (Statsforvalteren). The subsidy scheme calculation is determined by comparing the actual crop yield with the normal yield, where the normal yield is specified by regulations (in this case, it is 540[10] FEm/daa[11]). Compensation is provided only if the decline in yield exceeds 30%. In such cases, the subsidy covers 70% of the loss, and the rate of compensation is 4.43 Nok per FEm[12].

On the expenditure side, the livestock maintenance expenditure is determined by the livestock size and the cost of keeping every head on the farm, excluding feed expenses. This includes barn upkeep, energy costs, and pay for workers…. Similarly, the harvesting expenditure changes with the total harvest and the cost it takes to harvest one kilogram of feed, covering the mowing, baling, and preservation costs…. As for fertilisers, the expenditure is determined by the price of fertilisers and the "quantity of purchased fertilisers". To ensure robustness, the equation formulas for the above-mentioned expenditures include a MIN function with "available cash to spend". This is to make sure that the cash liquidity is not depleted by more than what is left in it. The remaining cash, calculated by subtracting the expenditures from the available cash, sets the number

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[10] https://lovdata.no/dokument/SF/forskrift/2018-08-01-1215/KAPITTEL_5#%C2%A714

[11] The yield measurement is presented in food units (FEm) per decare. A decare is equivalent to 0.10 hectares.

[12] https://lovdata.no/dokument/SF/forskrift/2018-08-01-1215#KAPITTEL_2

of affordable feed orders given the price of feed. The actual feed orders are however regulated by the decision rule explained in the feed stock sector.

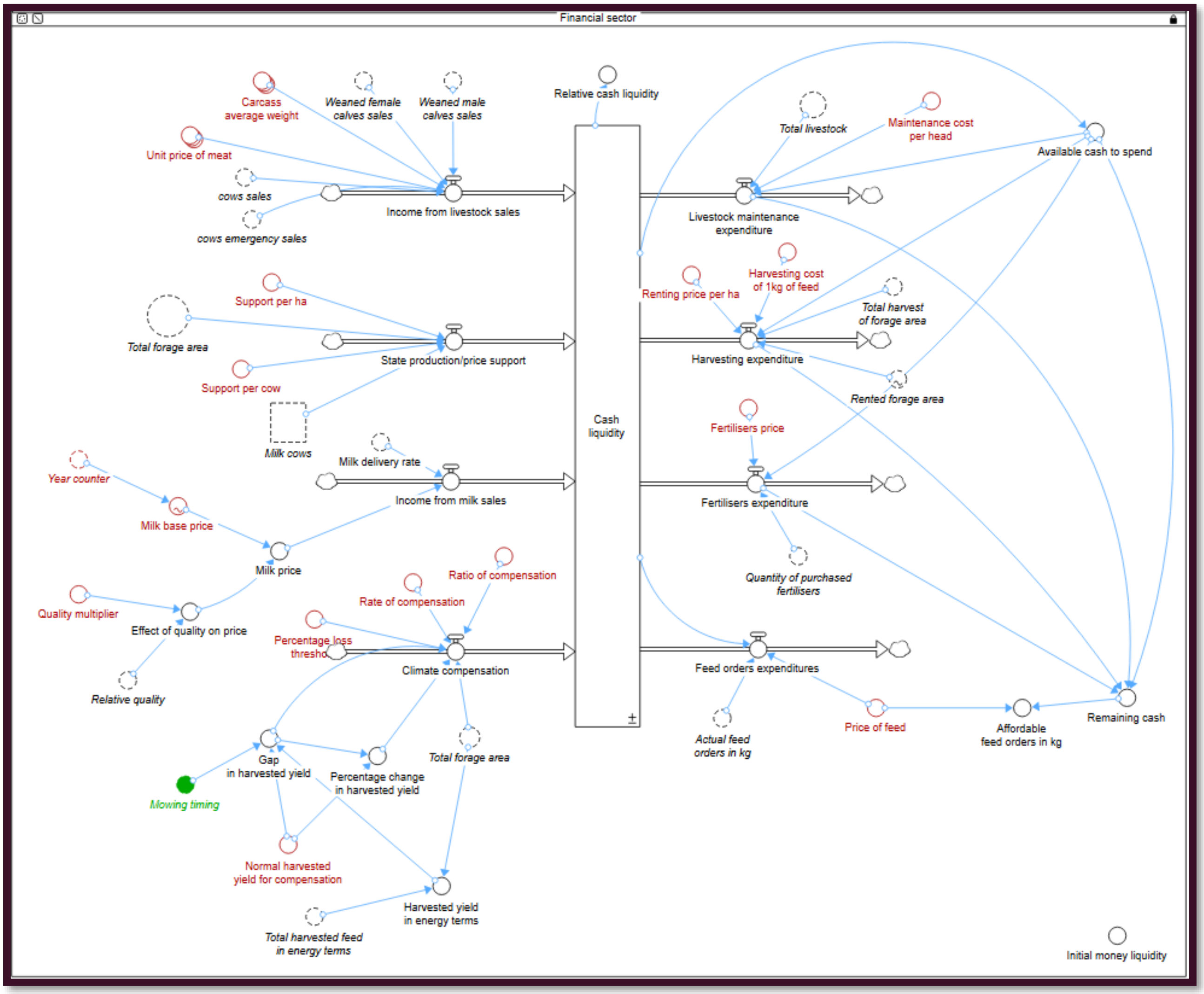


Figure 18: Model structure: Finance sector

The highlighted variables in green on the different figures indicate specific points where seasonal forecasts can be utilised. These areas are the timing of mowing and the timing of fertilisers' application and will be used as focal points for conducting testing and experimentation in the future.

Model settings

The chosen period for the model's simulation is from 2017 to 2022, which serves the purpose of calibrating the model to historical data and conducting a retrospective analysis. By considering a 6-year time horizon, the model effectively incorporates short and medium-term fluctuations. It runs weekly and allows to capture the effects of seasonal climate variability and aligns with the frequency of information provided by seasonal forecasts.

Euler's method has been selected as the integration method for the simulation due to its capability to handle discontinuous events within the model, unlike other higher-order methods which are sensitive to discontinuity. When higher-order methods (Runge-Kutta 2 and fourth-order Runge-Kutta) are used, distinct behaviours are observed in the stocks of the forage sector and this can be attributed to the presence of variables that displays step and pulse shapes, like the timing of mowing or the timing of applying fertilizers.

The model incorporates a combination of fast and slow dynamics, with certain variables responding quickly to changes while others change at a slower rate. For example, milk yield adjusts rapidly to variations in feed intake, whereas the stock of milk cows changes much slower. To ensure that the time constants governing these dynamics do not differ significantly, **the time step** is set to 1, matching the shortest time constants in the model. This value, DT, is considered a suitable estimate and ensures sufficient accuracy in the numerical integration process. It is important to note that the model results are highly sensitive to the selection of DT, which should always be equal to the shortest time constants in the model (time of mowing, time of applying fertilizers, and time to empty the manure stock). Failure to align the time step with these short time constants can lead to implausible behaviour in the above-ground biomass, such as continuous growth without reaching a plateau or even negative values.

3.2 | MODEL VALIDATION

Validation of model structure

Structure, parameters, extreme conditions, dimensional consistency & boundary-adequacy tests

This first group of tests assesses the validity of the model structure by verifying its conformity with the real system (Forrester & Senge, 1980). It is carried out for each component of the model to ensure that every equation and relationship is logical and correct (displaying behaviours in line with the feedback polarity) and that the variables and parameters have real-world equivalents and are set to plausible values.

Thorough verifications have been carried out during the development of the model. Some sectors were formulated by drawing upon previously validated models related to similar topics (e.g. the forage sector) while the feed stock and livestock sectors were formulated by replicating generic stock management structures outlined in chapters 17 and 18 of Sterman (2000). In other cases, equations and relationships were identified in the literature and translated into a stock and flow structure. This was specifically the case for the finance sector, particularly regarding climate compensations. Expert judgment was also employed in the structure validity process. This was necessary to address certain uncertainties regarding how feed availability impacts livestock, and whether the impact cut across all cohorts symmetrically or asymmetrically. The interview revealed that in the case of feed shortage, milk cows, especially the oldest and most problematic ones, are the only ones to be sold. **The model can therefore be judged to successfully have undergone structure verification.**

Concerning the parameters validation tests, the confidence in their numerical validity varies across the model. It is strongest when real primary or secondary sources are utilised, fairly strong for parameters calibrated from the model and weaker when the latter is set arbitrarily based on judgment. It was not feasible to parameterize the model using a single source or a comprehensive dataset. Instead, the model incorporated a fusion of heterogeneous and potentially incompatible data from multiple sources. For example, information on the desired nutrient levels of forage was sourced from a UK reference, while average manure production per animal was obtained from Canadian statistics. It should be noted that these data sources will be subject to further scrutiny during sensitivity testing, and any significant deviations in model behaviour will be duly reported. The same applies to parameters for which data was unavailable and I had to rely on my assumptions, a sensitivity test was conducted to enhance confidence in their validity (e.g., time to adjust expectations). I tried to address these data gaps through the interview, however, it was challenging to gather data related to information delays, like expected variables, perceived variables, and time to adjust expectations. I managed nonetheless to gather valuable insights and fill in other missing information, such as the desired level of stock feed and all adjustment times for material variables. For certain parameters, such as effect factors and initial stock values, experimental simulations were carried out to explore parameter values that resulted in the most plausible behaviours. The model is documented following the guidelines of Rahmandad & Sterman (2012) and provides a comprehensive description of all variables within the model, including their definitions and data sources (see Appendix C attached to this thesis).

Extreme conditions testing was conducted to ensure that the model behaves realistically when stressed by extreme conditions. This involved a careful examination of the model equations and robustly formulating them. To address potential issues, the fuzzy MIN function was employed in outflows to effectively shut down the flow if the stock reaches zero. This also guarantees that the stocks remain nonnegative. Additionally, the use of the MAX function was implemented to control some inflows, ensuring that they remain positive. As mentioned before, desired levels/goal targets might be set lower than the actual stock levels, resulting in a negative gap in the inflow.

The model also fulfils **dimensional consistency** requirements across the model and no cheat converters have been used to force units' consistently. The software Stella automatically verifies that the dimensions of variables and parameters are consistent across the model. It failed however to check the units when logistic equations are used due.

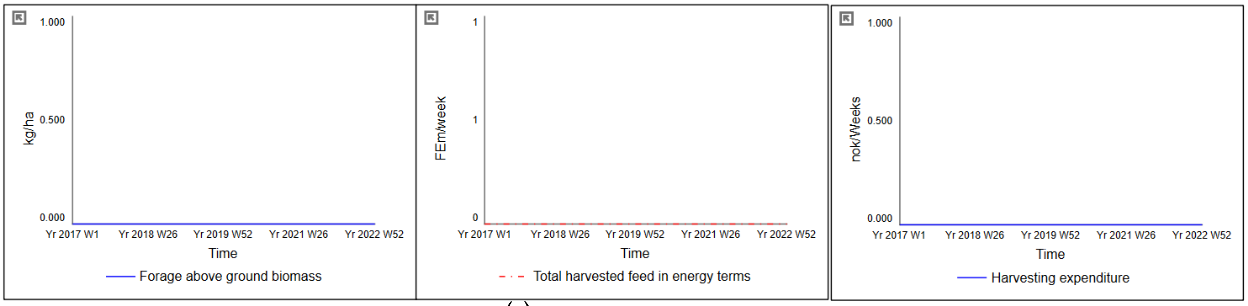
Regarding **the boundary adequacy test**, it can be judged appropriate given that the model boundary emerged from the system mapping of the farmers. It is also deemed adequate to address and answer the thesis research questions.

Tests of model behaviour:

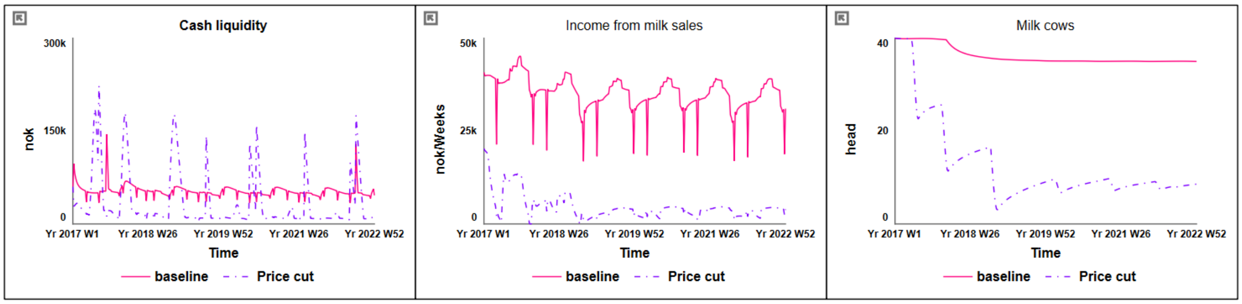
Indirect extreme conditions, behaviour-sensitivity & behaviour-reproduction tests

This second set of tests examines the adequacy of the model structure by analysing the behaviour it produces (Forrester & Senge, 1980). It also incorporates extreme conditions testing, but this time through an assessment of the entire model rather than an evaluation of each equation independently. **The model exhibited plausible responses when exposed to extreme values, both at the upper and lower ends of most parameters and exogenous inputs.** For illustrative purposes, Figure 19 demonstrates how the system responded to the expected behaviour under two highly unlikely scenarios: the absence of recorded rainfall and a 50% cut in the milk price. In the case of the absence of rain, it is expected that there would be no biomass growth, no harvesting of feed and no associated costs. As anticipated, the system responded accordingly.

Similarly, a reduction in milk price is anticipated to lead to lower sales income and reduced cash liquidity. This financial decline is also expected to have a significant impact on the livestock sector. The subsequent simulation results confirm these expectations, as milk income decreased and the milk cow stock experienced a significant decline, with the number of cows dropping from 35 to less than 9. The drop in cash liquidity was moderate since fewer milk cows meant lower maintenance costs which alleviate the burden on the cash stock. Overall, these figures exemplify how the model's structure remained robust under extreme conditions, producing plausible outcomes when exposed to extreme values.



(a)



(b)

Figure 18: Main simulation behaviours under testing with nor rain (a) and with a 50% reduction in milk price (b)

Additionally, **the model has undergone extensive parametric sensitivity testing.** A total of 24 parameters have been varied across a relatively wide and realistic range of values, distributed uniformly, to study the model responses to these changes. Appendix B presents the exhaustive list of conducted sensitivity tests. Globally, the findings can be divided into three distinct categories:

(1) Parameters shown to be insensitive: the system is unaffected by changes in their assumed values;

(2) Parameters for which change in assumptions results in changes in numerical values. In this particular category, the specific findings hold little significance as the primary purpose of the model is to assess the value of seasonal forecasts. Consequently, the analysis will primarily focus on comparative evaluations, examining the gaps and disparities between the base run and alternative runs, rather than absolute terms or precise numerical levels.

One example of a parameter that displays numerical sensitivity is the biomass plateau. It is unsurprising that modifying its value, either upward or downward, influences the behaviour of the system. As the parameter serves as a ceiling and foundation upon which other effects occur, it is expected that the system's behaviour inherently slides up and down. Another example involves adjusting the aggressiveness of the fractional loss rate of quality. Doing so affects the rate at which quality deteriorates and activates more the minor balancing loop. However, by maintaining the value at a realistic assumed level, we can conduct comparative analyses without being overly concerned about the precise value of the parameter.

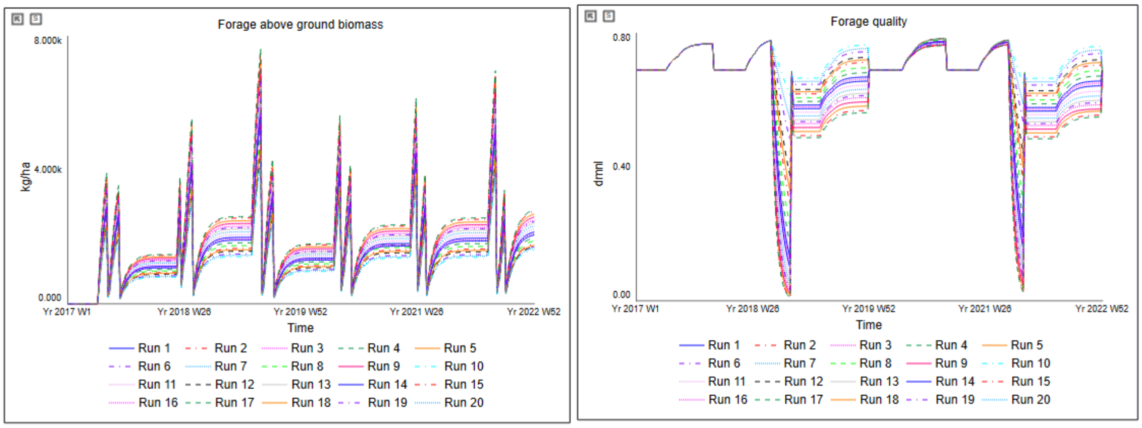


Figure 190: Example of numerical sensitivity analysis results for biomass plateau and quality fractional loss rate

(3) The last category encompasses the parameters for which changes exhibit behaviour mode sensitivity.

Within this category, several parameters have been identified that have been assumed constant but are volatile and vary in real-life situations. Examples include the various costs involved, such as the price of feed, fertilizers, and livestock maintenance costs. When these costs experience significant and abrupt increases, it poses a financial challenge that ripples throughout the entire system. Let's consider the scenario of a sharp rise in maintenance costs due to increased energy prices. This, in turn, reduces the available cash liquidity for purchasing fertilizers and feed. As a consequence, the harvest yield decrease, leading to a shortage of feed to sustain the livestock and there is no capacity to buy supplementary feed. Ultimately, this leads to a rapid depletion of the cow stock and a drop in the milk yield (two factors that determine the milk sales incomes).

In addition to cost-related parameters, the model also demonstrates sensitivity to the minimum time to order and transport supplementary feed. When the latter extends from a mere week, representing a convenient purchase from a neighbouring farm or a local supplier to months due to the necessity of importing from another country, it causes a capacity constraint that hinders fulfilling the livestock intake. Consequently, a majority of the livestock must be sold off to mitigate the lack of adequate feed supply. The process of rebuilding the livestock population occurs gradually as the harvest replenishes the stock allowing for the retention of calves.

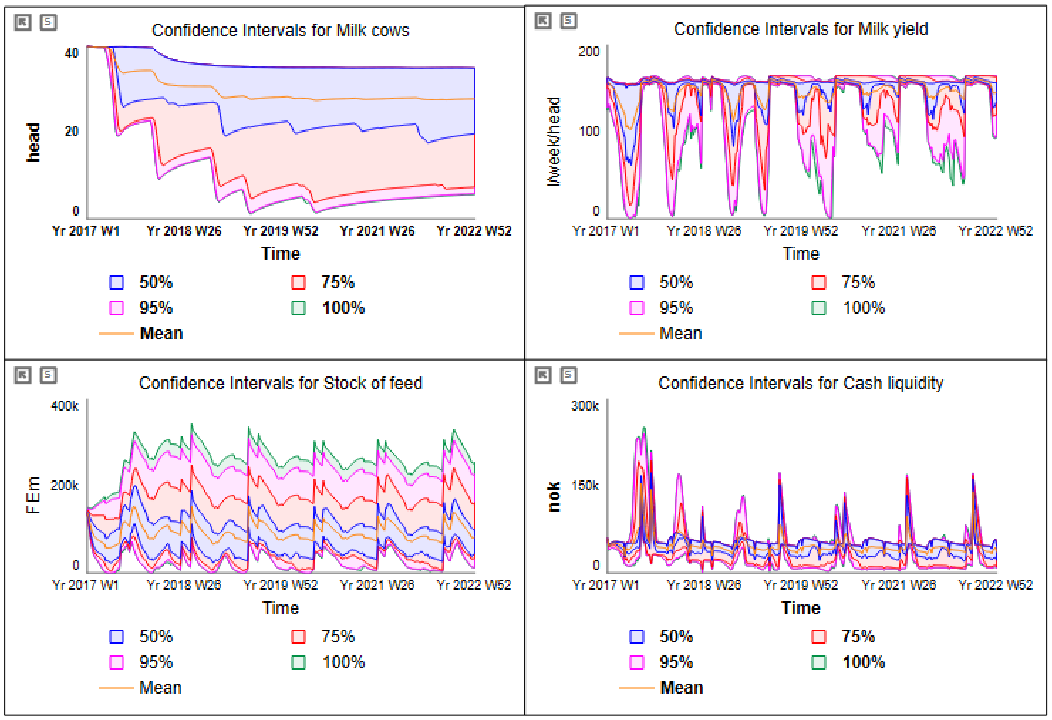


Figure 20: Example of behaviour sensitivity analysis results for maintenance cost and minimum time to order & transportation

The penultimate stage of behaviour validation involves performing behaviour reproduction testing, which should be conducted only when there is a high level of confidence in the results obtained from preceding tests. Its objective is to evaluate the degree of similarity between the behaviour generated by the model and the observed behaviour of the real system when available.

The above-ground biomass of forage exhibits a globally consistent behavioural trend and shape pattern that closely resembles real data observed in forage agriculture[13]. Both graphs exhibit a characteristic bell-shaped curve with a dip in the middle. The interpretation of these graphs is as follows: the initial phase represents a period of growth where the biomass increases due to the rise in the temperature among other factors. The subsequent decline in biomass is a result of the first mowing, which involves cutting the forage and reducing the overall biomass level. The extent of this reduction varies between farms, depending on the proportion of forage that is mowed. The biomass then continues to grow until the second cut. Typically, after the second cut, the biomass surpasses its plateau phase as the forage matures, senesces, and begins to decline. The width of the

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[13] It is important to take into account specific details when comparing the two graphs. In Figure 22, graph (a) represents the model-generated behaviour, depicting the development of above-ground biomass of forage from week 17 of 2017 until week 39 of the same year. On the other hand, graph (b) displays actual biomass development (both underground and above-ground) using data extracted from the Agriculture and Horticulture Development Board (AHDB, UK) spanning from week 1 to week 39 of the year 2022.

curve may vary, which can be ascribed to differences in the length of the growing seasons. In Norway, where the growing season is generally shorter, the curve is narrower.

It is important to note that the model-generated behaviour is smoothed out and does not display small fluctuations along the curb. This can be attributed to other influencing factors that are omitted (for instance, the model considers the weekly average of rainfall without accounting for the effects of rainfall distribution. Similarly, the average temperature is modelled without considering the variance around the mean or the minimum and maximum temperatures, the effect of hail….). In any case, SD modelling does not aim to replicate real data point by point; instead to provide insights into the general trends, patterns, and feedback mechanisms.

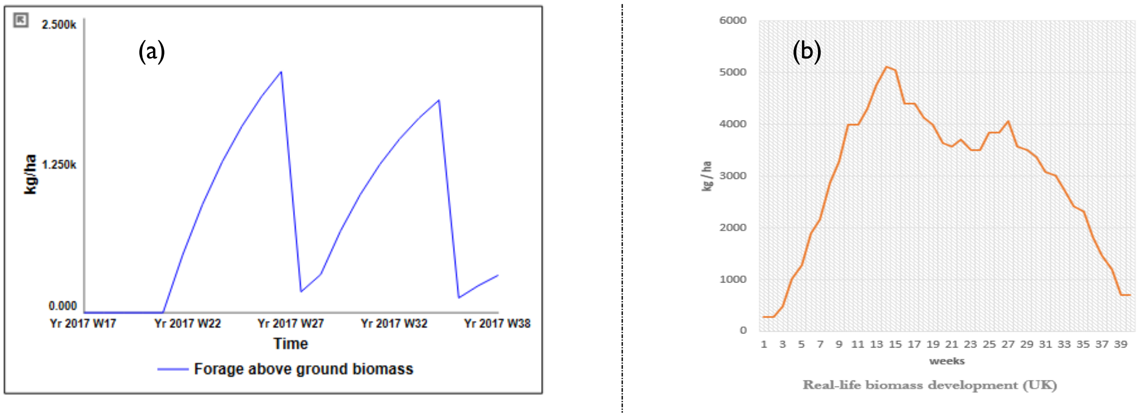


Figure 21: Biomass behaviour comparison (sources: Model & AHDB-UK)

The comparison between the data obtained from the farm case and the parametrized model has revealed notable discrepancies. Specifically, the analysis of the total energy content of the harvest demonstrates significant variations, particularly in the years 2018 and 2022. The model's results indicate a dry and unfavourable season as documented in the existing literature (the dry summer of 2018), whereas the farm under examination appears to have performed well during those periods. Another instance of contrasting outcomes is observed in the year 2022, wherein the farm experienced an exceptionally low yield of 50 FEm per hectare, in stark contrast to the average of 204 FEm/ha recorded over the past five years. One can speculate that certain exceptional factors, such as crop failure or a deliberate decision not to fully harvest during the second cut, influenced this outcome and which are beyond the boundary of this model.

The reproduction of the forage-quality data was challenging and can be judged as not strongly valid. The model was able to replicate the general trend for about half of the data points. This difficulty arises partially from the inherent nature of the quality data, which was based on subjective perceptions provided by the interviewee. The latter was asked to grade the forage quality on a scale of 1 to 5, with 5 representing the highest quality.

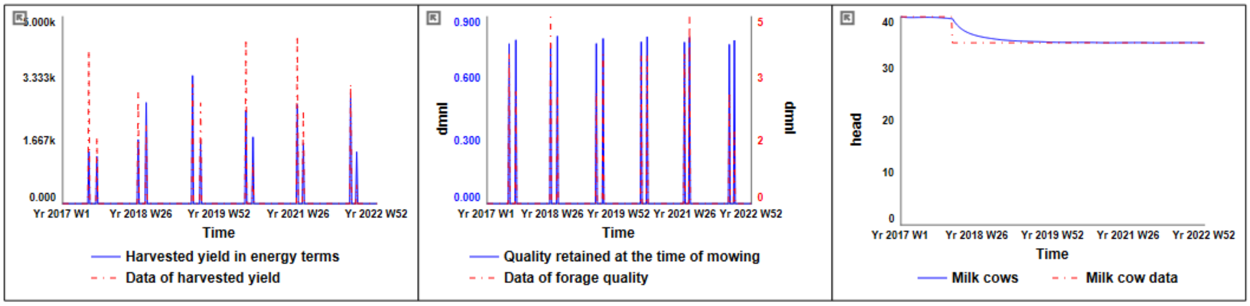


Figure 223: Behaviour comparison between model results and case study data

Lastly, the system effectively replicated the milk cow stock, even when subjected to granulated point-by-point comparisons. It accurately simulated the shift from a quota of 350 000 litres in 2017 to 300 000 litres in 2018, resulting in a decrease in the cow stock from 40 to 35. This can be attributed to the structure of the livestock sector with is controlled by balancing loops and well-defined goals/targets. Furthermore, there is only one interaction point with the other sectors through the emergency sales which is active solely during feed shortages.

In conclusion, the generated behaviours of the model aligned and, in some cases, coincide with real-life data or data collected through the interview. However, there were instances where it couldn't capture the complexities of certain stocks entirely. This limitation is not a significant concern since the primary purpose of the model was to facilitate comparative testing with various potential scenarios.

CHAPTER 4 |SIMULATION RESULTS & FINDINGS

4.1 | ANALYSING THE SIMULATION BEHAVIOURS

In this section, I will present the simulation results while addressing the second research question which asked: How does this dynamic structure contribute to the generation of the system's behaviour? (RQ2).

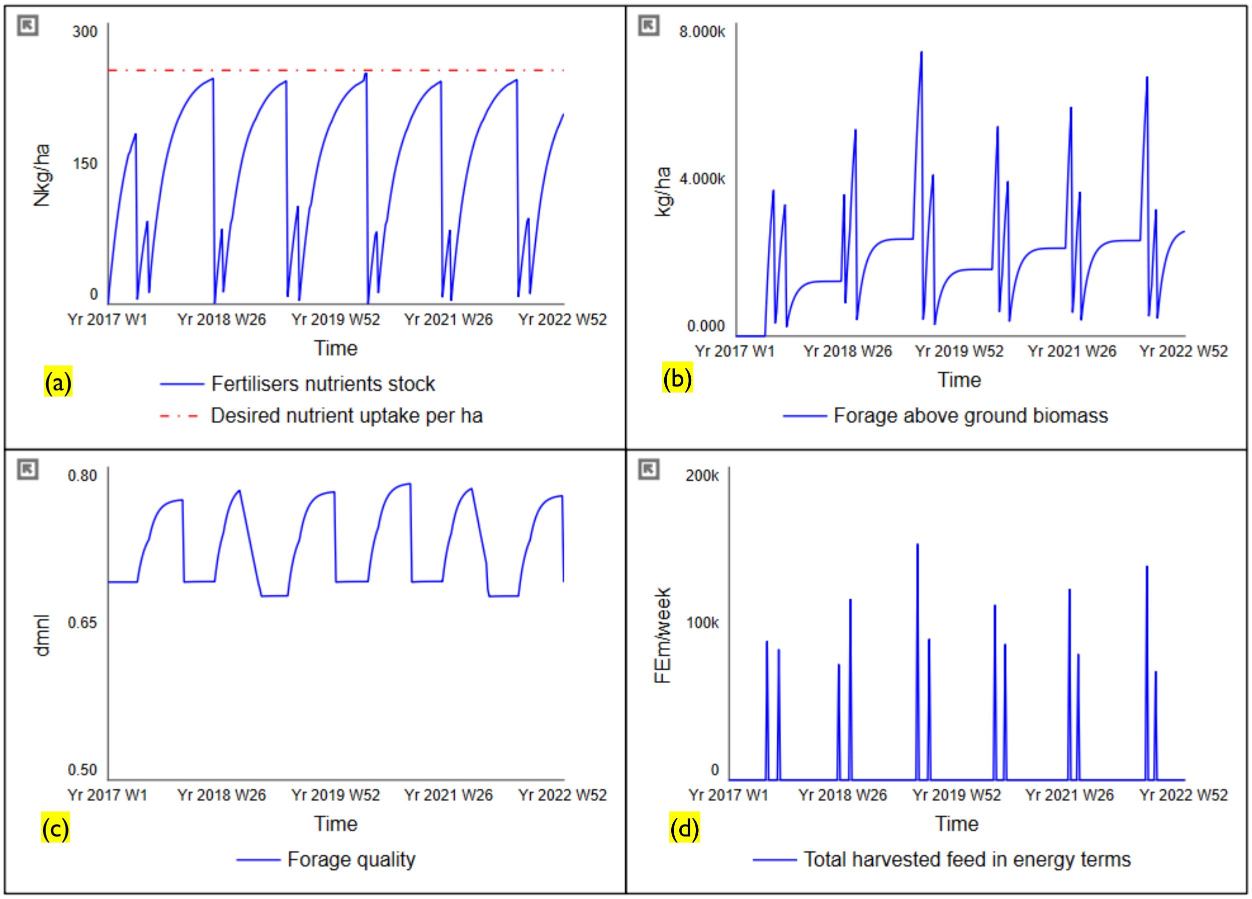
The decision-making structure of dairy farming comprises 4 sub-management decisions: Forage farming, Feed stock management, Cow stock and milk production management and Finances. These sub-decisions are interrelated and dependent on one another. Sometimes, optimising the management of one subsystem may impose some constraints on the other and even hinder the functionality of the whole aggregate system. The dynamics of these interdependencies and trade-offs will be explained using the model results and considering the earlier established feedback story.

Management of forage farming

The management of forage farming includes managing the stock of manure, which accumulates as a result of livestock production. The stock depletes when the farmer decides to apply it to the field. In the case of the farm being studied, this application occurs twice a year, in early May and early July. This pattern of application explains the sawtooth behaviour (Figure 24a), where the stock of manure fluctuates between a complete depletion and a high accumulation level twice every year. The second application, which takes place in early July, is typically smaller in quantity and this aligns with general fertilizing practices, where the application of fertilizers tends to decrease with each subsequent cut (even for a 3 or 4 cutting systems).

The application of manure adds nutrients to the soil, but it is not sufficient to meet the desired amount required for proper soil replenishment. The gap that needs to be filled is done by purchasing fertilizers, a decision governed by the balancing (B10) with the interplay of the cash availability loop (B7). In this baseline simulation, cash liquidity does not pose any grave problems as it remains within a comfortable range allowing the fertilisers nutrients stock to approach the desired level. This situation is not surprising in the Norwegian context, where access to liquidity is not a serious concern, as confirmed by the interviewee. Cash is typically available from agricultural incomes or other non-farming activities. In more challenging situations, farmers can also receive informal support from business partners, fellow farmers, assistance from public local entities, or even emergency liquidity credit from the bank. The availability of cash has therefore a neutral effect, allowing all desired orders to be fulfilled. This can be observed in Figure 24a, where the stock of fertilizer nutrients consistently approaches the desired level of 250 kg of nitrogen per hectare.

Fertilisers are the only endogenized element influencing the forage biomass and the quality, with rainfall and temperature being exogenous inputs to the model. Analysing the simulation results by the development of these three factors reveals the following insights: The spikes observed in the growth patterns of both the biomass and the quality are attributed to the boosting effect of fertilizers, which appears after a response time lag of 6 weeks. Since the desired nutrient levels from fertilizers are consistently approached almost every year, the year-on-year variations in levels are caused predominantly by disparities in rainfall and cumulative temperature. This distinction becomes evident when examining the year 2017, where the low biomass level can be attributed to inadequate rainfall and limited temperature, impeding the extension of the growing season (the green line and circle in Figure 24 e & f). Similarly, in 2018, the prolonged period of low levels of precipitation (indicated by the red circle) caused the growth of the forage to be very limited. Concerning the forage quality, it can be seen how the warm summer of 2018 resulted in activating the loss balancing loop, leading to a subsequent loss in quality. Taking together the evolution of the biomass level and its quality, the total harvest (graph d) presented in terms of energy it supplies to the livestock was very low during the challenging years 2017 and 2018 but a rebound in the following years.



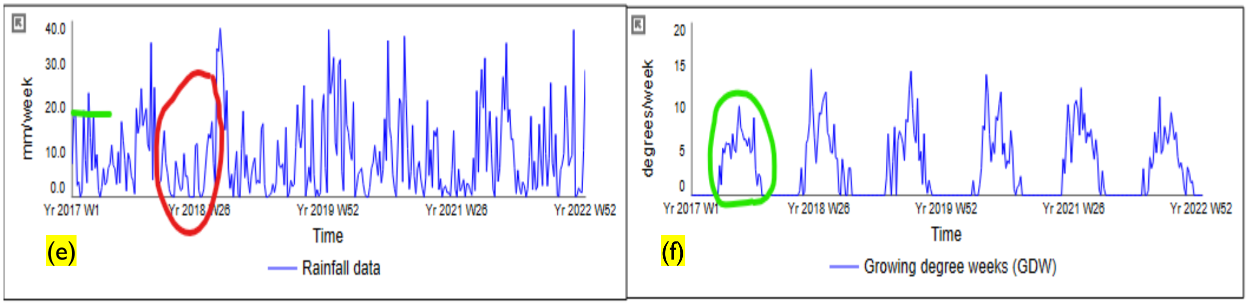
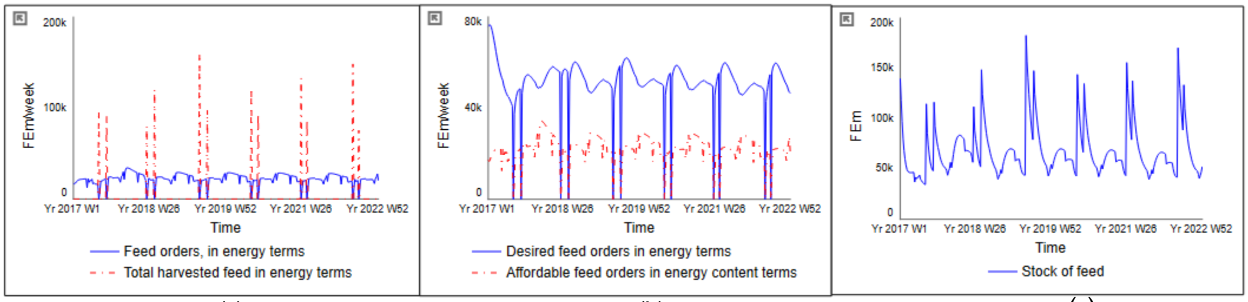


Figure 234: Main simulation results in the forage sector

Management of feed stock

The stock of feed exhibits a cyclical behaviour characterized by refilling to peak levels after each harvest and gradually decreasing throughout the year due to livestock intakes (Figure 25a). Besides the harvest, the stock of feed is replenished by feed orders. The decision of how much to buy is governed by the requirement to maintain the stock level at a coverage level of at least one year's worth of consumption. The structure is then regulated by three negative feedback loops (the stockout loop B11 and feed stock control loops B12 and B13) that adjust the replenishment rate through feed orders to align the stock level with the desired target.

Figure 25b illustrates how the feed orders exhibit a counter-cyclical pattern compared to the harvested feed. They reach their highest levels before the new harvest, coinciding with the end of the previous agricultural year and the depletion of the stock. Once the new harvest is obtained, feed orders diminish and subsequently stabilize at moderate levels. The interplay of affordability becomes crucial in this context. The purchase of feed is constrained by the remain of cash after covering maintenance costs, harvest expenses, and fertilizers expenditure. Figure 25c demonstrates that the desired feed orders are not fully met, and only what is financially affordable is used to replenish the stock.



(a) (b) (c)

Figure 25: Main simulation results in the feed stock sector

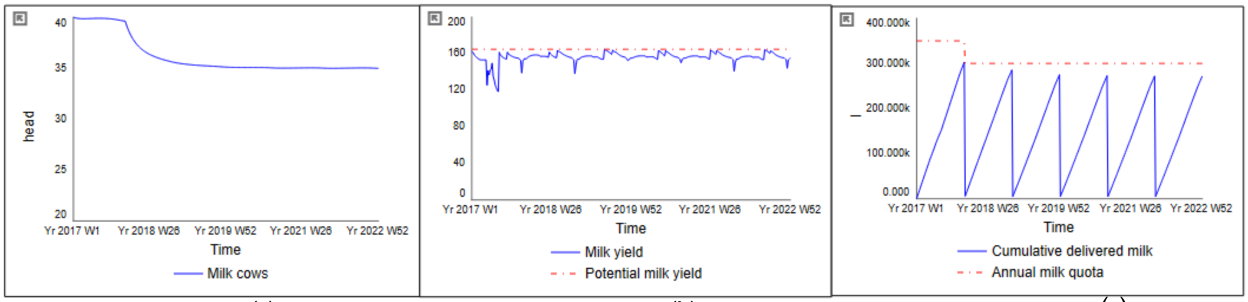
Management of livestock and milk production

The management of livestock primarily revolves around replacing heifers to maintain the desired number of cows, enabling the farm to fully utilise the allocated milk quota. This decision-making process considers various metrics. Firstly, it involves assessing existing rates, which encompass natural deaths, regular sales of unproductive cows which were milked for 6 years, and emergency sales in exceptional circumstances such as feed shortages and/or in our specific case, the reduction of the milk quota from 350.000 litres per year to 300.000 litres per year between the year 2017 and 2018. This reduction necessitates a corresponding decrease in the number of cows from 40 to 35.

Another important aspect taken into consideration is the reproduction process and the time required for maturation within the age chain. This information helps determine the targeted level of heifers necessary for maintaining the desired cow level. It allows for determining the number of weaned calves to be retained on the farm, allowing them to mature and eventually replace the discarded cows. In the model, a desired level of 13 heifers, which was subsequently reduced by two heads following the transition to the new milk quota, yield stability of the cow population at 35, starting from 2019 (as can be observed in Figure 26a).

The milk production is influenced by the change in the number of cows as well as their milk yield which evolves endogenously in the system. The simulation results indicate that there have been instances where the yield dropped below the potential level of 160 litres per week (Figure 25b). This decline is caused by the decrease in the availability of feed. For example, in late 2017, the cows were only fed around 60% of the desired consumption due to a low level of feed stock resulting from a challenging harvest and limited cash available to order the necessary supplementary feeds. Consequently, the cows were not as productive as they could have been, producing approximately 10 litres of milk less than their potential.

The outlook over the full year is positive as the cumulative production is closely aligned with the milk quota, indicating a high utilisation rate (Figure 25c). There are variations from year to year, primarily influenced by the fluctuating cow yield, which is impacted by feed availability. To a less extent, the year-on-year variations are also due to the change in the milk consumption on the farm to feed the calves.



(a) (b) (c)

Figure 246: Main simulation results in the livestock and milk production sectors

Management of finance

The simulation results in the finance sector can be read and analysed similarly to a balance sheet. On the income side (Figure 27a), the primary source of revenues comes from milk sales, which is expected as the farm's main activity is dairy production. On average, these revenues amount to around 30.000 NOK per week. However, twice a year, during the Easter and Christmas periods, the revenues decrease by half due to the pricing policy of Tine, offering less than 3,5 NOK per litre. The second source of income comes from the sales of livestock. These revenues display a cyclical behaviour, which aligns with the dynamics of livestock reproduction. The sales of calves typically occur after they have reached six months of age, which is the legal period for separating them from their mothers.

The support from the state is stable in the simulation and is determined based on two factors: the number of cows and the area harvested for forage. According to the statistics from the previous year, farmers received a premium of 3300 NOK per hectare of harvested area and 4290 NOK per cow. These premiums vary from year to year but have been assumed to be fixed in the mode. The cash flow includes entries from climate compensations in case of bad harvest, therefore occasional by nature. They only occur if there is a significant drop in the harvested yield compared to the normal value specified by the regulation. As mentioned in Chapter 3, if the drop exceeds 30%, the compensation will cover 70% of the loss. The simulation indicates three episodes of compensations in 2017, 2018 and 2022 which amount to over 100 thousand NOK each.

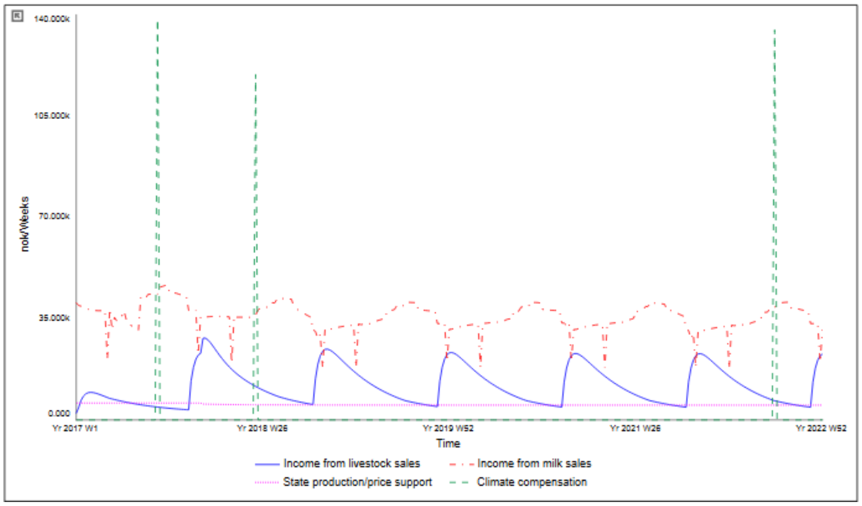


Figure 257(a): Main simulation results in the financial sector- income side

On the expenditure side (Figure 27b), the feed expenses are the main costs weighing on the budget, reaching a maximum of 87.500 Nok in 2022 for a single order. They display a behaviour over time that answers the dynamics happening in the sector of stock of feed but also put a limit to the latter dynamics through the affordability balancing B4. The next significant expenses are the livestock maintenance costs, which have been assumed to be approximately 200 NOK per cow per week.

This assumption reflects relatively moderate labour and energy costs. In contrast, the harvesting expenditure is not spread out throughout the year as it is only accounted for during the period of the harvest. There is however a recurring cost included in the harvesting expenditure associated with the rent of 17 hectares of forage land, priced at 1960 NOK per hectare per year. Lastly, there are the costs of fertilizers, which increase prior to the time of applying fertilisers, occurring twice every year but fading away afterwards until the next harvesting season. They are relatively not significant due to the moderate price of fertilisers assumed in the simulation (5,6 NOK per kilogram of Nitrogen/urea). The low level of fertilizer costs is also attributed to the assumption of the land is of good quality, requiring only 250 kilograms of nutrients from fertilizers (Nitrogen).

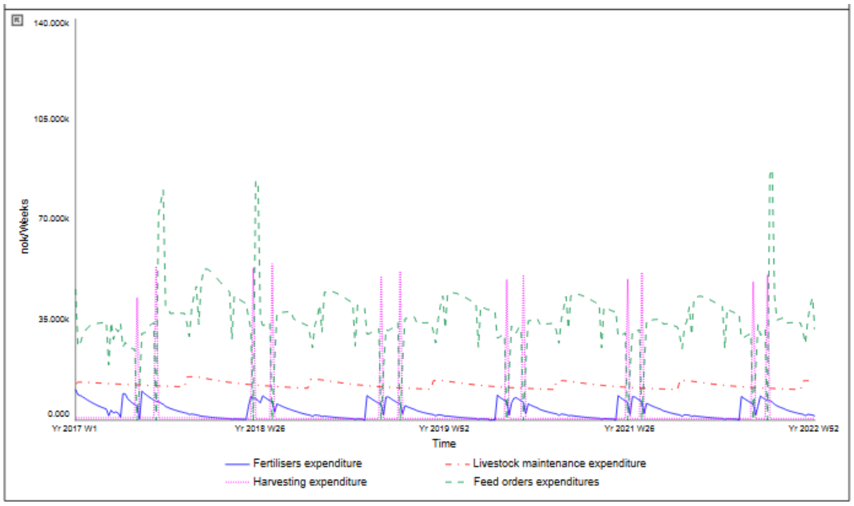


Figure 267(b): Main simulation results in the financial sector- expenditure side

Taken together and in an overall assessment, the cash liquidity exhibited fluctuations within a comfortable range. It experienced sharp drops in some weeks (mostly before the harvest season) but without reaching a point of complete depletion.

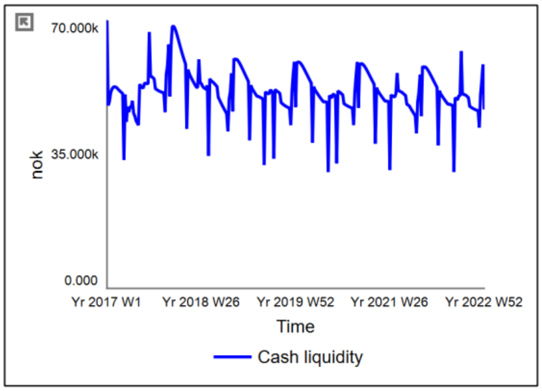


Figure 278: Main simulation results in the financial sector- cash liquidity stock

4.2 | TESTING THE VALUE OF THE SEASONAL CLIMATE FORECASTS

This section will answer the fourth research question which asks How does the integration of the S2SF impact the outcomes/behaviour of this dynamic structure? (RQ3)

To assess the potential of seasonal forecasts and illustrate empirically their value, I compared the baseline simulation results that integrate the past decisions regarding the mowing timings and fertilisers' application timing with 6 other alternative simulation experiments. In these experiments I shifted the timings by one and two weeks and forward them by up to 4 weeks. The rationale behind this is that if a couple of weeks' deviation yields a significant change in outcomes, then the forecasts bring valuable information and also it allows to quantifiably investigate their value. In what follows, I will only present the findings of a few experiments to highlight the most interesting outcomes (the exhaustive list of results for all 6 experiments for all years are presented in Appendix D).

Value in terms of harvest gain (quantity & quality)

The first outcome that is examined is the harvested yield in terms of energy contents both during the first mowing and the second mowing. It is observed that in certain years, the timing gap did not produce a notable change in the outcomes. However, in other instances, the temporal variation resulted in significant fluctuations in levels. For instance, as depicted in Figure 29, a shift from the actual week of the first cut in 2017 demonstrated both gains and losses. These findings indicate that the mowing occurred prematurely, as delaying the harvest by several weeks would have led to gains of up to 200 FEm per hectare. That being said, the actual harvest week is not the worst choice, as mowing two weeks or even one week earlier would have resulted in a loss of approximately 400 FEm/ha and 200 FEm/ha respectively.

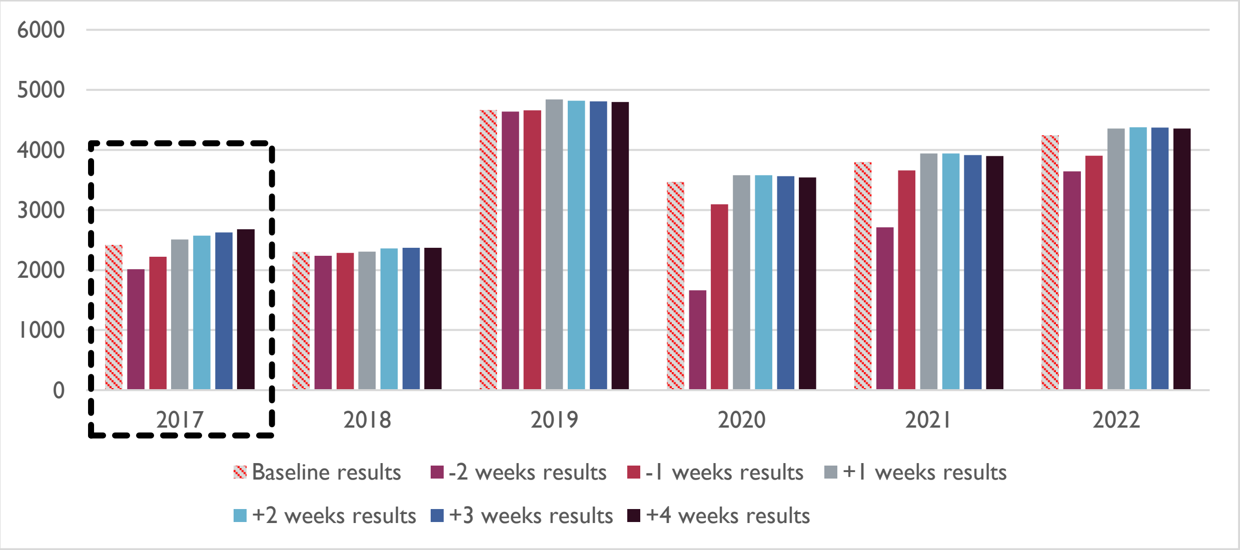


Figure 2928: Simulations values of harvested feed for the different experiments

Regarding the forage quality, the analysis reveals that the timing gap results also in variations in values. The year 2017 stands out as particularly noteworthy, as the results confirm that the initial harvest was conducted prematurely. If the harvest had occurred three to four weeks later than the actual week, a significant improvement of up to 0,3 percentage points in quality could have been achieved (see Figure 29a). Another significant finding pertains to the year 2021, where the data indicates that an earlier harvest by two weeks would have resulted in a decrease in quality by 3,6 percentage points, reducing from 82,5% to 78,9% (Figure 30).

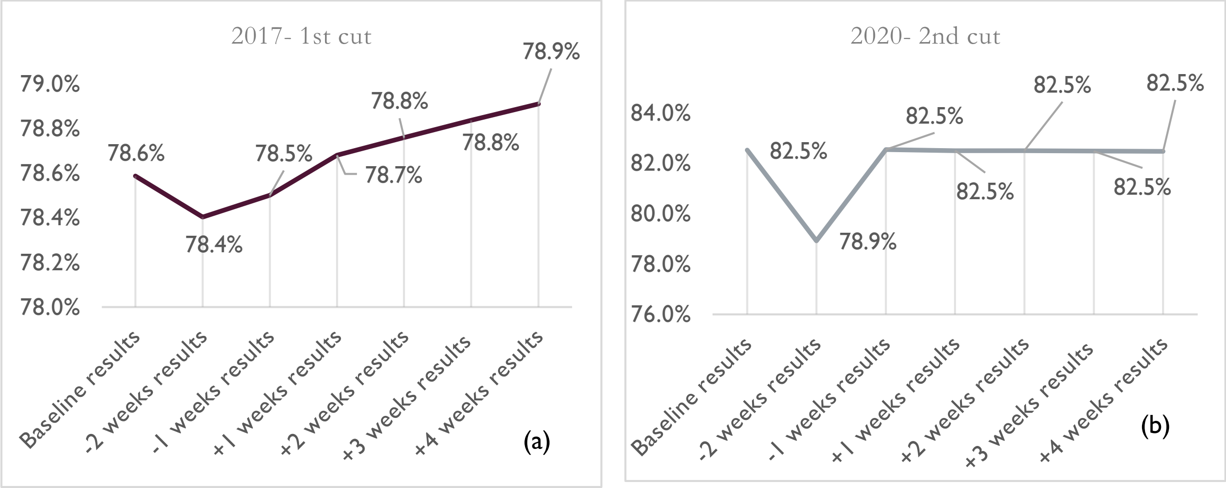


Figure 290: Simulations values of forage quality for the different experiments

The potential gains per hectare, if extrapolated to cover the entire forage area, would have played a significant role in replenishing the feed stock and reducing the need for additional feed orders. As a result, it would alleviate pressure on the budget, providing more flexibility in preparing for the next season. This includes purchasing desired fertilisers and establishing buffers to account for any eventual increases in costs. The subsequent section will delve into the exploration of potential monetary benefits.

Value in terms of profitability

To analyse the potential gains or losses that could have been incurred in terms of profitability, I have consolidated the expenses associated with feed orders and fertilizer purchases over the entire year, instead of examining them weekly according to the model frequency. The results are presented in Figure 30, showcasing the changes relative to the baseline simulation results. Negative values indicate a reduction in potential expenditure by a certain percentage compared to the baseline simulation results (and vice-versa). This approach of presenting the results in terms of gaps rather than absolute values is justified by the sensitivity of the model to certain assumptions and parameters pertaining to costs.

One of the significant findings is observed in the year 2017, where a delay of three or four weeks in the harvest would have resulted in cost savings of up to 7,5% compared to the actual expenses. On the other hand, if the harvest happens to be one or two weeks earlier, it would have caused the costs to increase by 8% and 9,7%, respectively. Another noteworthy finding relates to the year 2020, where an earlier harvest by two weeks would have had substantial consequences, resulting in a significant increase in the costs of about 18%.

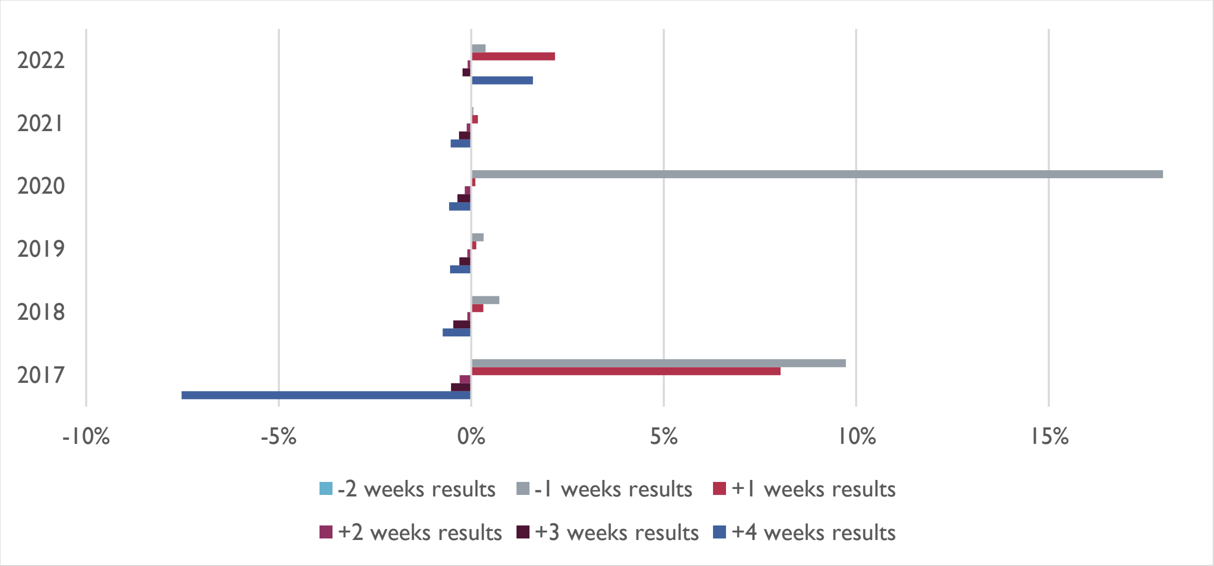


Figure 31: Simulations values of feed and fertilisers expenditures changes for the different experiments

Value in terms of state's compensation

The final metric to consider is the climate compensation that farmers can receive if their harvested yield falls below the normal yield. As mentioned in the previous section (4.1), in the baseline results, there were three instances of climate compensation: in 2017, 2018, and 2022. In 2017, a delay of three to four weeks in the harvest would have eliminated the need for compensation, resulting in a saving of 138,617 NOK for the state. In 2018, the compensation could not have been avoided due to the prolonged heatwave experienced throughout the 7 weeks covered in the experiments. However, if the harvest had been delayed, the level of compensation could have been reduced. Lastly, in 2022, the baseline scenario yielded the lowest level of compensation, as all experiments resulted in higher compensation levels at different levels.

Outcome	**Baseline results**	-2 weeks results	-1 weeks results	+1 weeks results	+2 weeks results	+3 weeks results	+4 weeks results
2017	**138 617**	321 999	290 383	132 347	127 605	0	0
Change		*183 381*	*151 766*	*-6 271*	*-1 1013*	*-138 617*	*-138 617*
2018	**119 373**	126 094	120 754	118 845	112 750	111 473	111 685
Change		*6 722*	*1 382*	*-528*	*-6 623*	*-7 900*	*-7 687*
2019	**0**	0	0	0	0	0	0
Change		-	-	-	-	-	-
2020	**0**	0	374204	0	0	0	0
Change		*374204*	-	-	-	-	-
2021	**0**	0	0	0	0	0	0
Change		-	-	-	-	-	-
2022	**134818**	136459	189231	135006	137008	187434	139564
Change		*1642*	*54413*	*189*	*2190*	*52617*	*4746*

Figure 32: Simulations values of climate compensation for the different experiments

CHAPTER 5 | CONCLUSION & DISCUSSION

This thesis attempted to close a knowledge gap concerning the potential value of climate seasonal forecasts in the Norwegian context by examining the decision-making process on a more frequent and dynamic basis using a realistic dairy farm model in Vestland, Norway. The findings of this thesis indicate that there is a measurable value in utilising seasonal forecasts to maximize yield and quality, reduce costs, and minimize financial implications for the state. The following chapter will synthesise again the answers to the research questions before presenting some reflections on the findings.

5.1 | ANSWERS TO RESEARCH QUESTIONS

1. The first research question aimed to identify the dynamic structure governing the decision-making process in the forage-based dairy farming system as well as where the seasonal climate forecasts (S2SF) can be useful. A participatory mapping workshop with farmers was conducted to identify the types of decisions made and how these are interconnected. The same setting was used to identify where exactly can the seasonal climate forecasts be useful. Chapter 3 extensively covers the intertwined decision-making process undertaken by farmers, which includes important choices at the forefront in the harvesting/mowing and fertilisers' application timings. The latter directly impacts both the quantity and quality of the harvest. However, it is not a straightforward decision, as it involves unpredictable elements and a trade-off between maximizing biomass or achieving higher quality. On one hand, allowing the forage to grow for a longer period enhances biomass density, but on the other hand, prolonged maturity adversely affects its quality. Considering these aspects, seasonal forecasts emerge as a valuable resource to aid and better guide in selecting the optimal combination (quantity/quality) for the highest harvest outcomes.

   Another important decision concerns the replenishment of the feed stock, which is governed by the need to ensure a sufficient feed supply for the livestock until the next harvest. Financial capacities play a significant role in determining the feasibility of the latter decision. In a scenario where the harvest season turned out to be challenging, it becomes necessary to purchase a higher quantity of supplementary feed. Failure to do so leads to downsizing the livestock and hurts the cows' milk yield, and, in fine, impacts the income from milk sales. This financial strain limits the ability to purchase additional feed and cover fertiliser expenses for the next season. Consequently, the decision regarding fertilisers' application is affected. The inability to apply the desired amount of fertilisers leads to lower forage quality and lower yield (the loop is closed). It is worth noting that in such challenging years, the state compensation helped compensate for some of the losses, making it less burdensome for farmers.

2. In light of this dynamic structure, the farm in the case study has undergone the following main developments (answer to the second research question RQ2: How does this dynamic structure contribute to the generation of the system's behaviour?).

   The evolution of the harvest is influenced by the dynamics of fertilizers (the only endogenized factor) as well as the patterns of rainfall and temperature. In our case, the application of fertilizers was consistent and approached the desired levels due to the farm's comfortable financial situation. Therefore, the observed dynamics can be attributed to natural factors. The notable episodes that are worth mentioning were observed in the years 2017 and 2018. In 2017, the growing season was characterized by below-average precipitation and a colder growing season, thus significantly impacting the harvest. The year 2018 experienced a prolonged period of low precipitation levels and consecutive weeks of warm weather which ultimately resulted in a decrease in forage quality.

   The behaviour over time of the feed stock displays a cyclical pattern, with annual peaks observed after harvesting and subsequent depletion throughout the year. Feed orders act as a counter-cyclical factor to ensure a stable supply of feed to the livestock. However, this objective was not always realised because of insufficient cash availability. The situation did not reach a critical point where significant emergency sales were required, but the yield of dairy cows was still affected during certain periods. The outlook over the full year is positive as the cumulative production is closely aligned with the milk quota, indicating a high utilisation rate.

   Regarding the evolution of the cow, their number decreased from 40 to 35 following a reduction in the milk quota. As for cash liquidity, it displayed fluctuations within a favourable range. There were notable decreases during certain weeks, particularly prior to the harvest season, but it did not reach a state of complete depletion.

3. Finally, to assess the potential value of seasonal forecasts, simulation experiments were conducted comparing baseline results with 6 alternative scenarios. The experiments involved shifting mowing and fertilizer application timings by one to two weeks, as well as forward shifting them by up to four weeks. The findings of selected experiments can be summarized as follows:

   - Regarding the harvested yield, the timing variations resulted in notable fluctuations in certain years. For instance, delaying the first cut by several weeks in 2017 could have led to gains of up to 200 FEm per hectare. On the contrary, mowing two weeks or one week earlier would have resulted in losses of approximately 400 FEm/ha and 200 FEm/ha, respectively.
   - In terms of forage quality, delaying the harvest by three to four weeks in 2017, could have improved quality by up to 0.3 percentage points. On the other hand, in 2021, an earlier harvest by two weeks would have decreased quality by 3.6 percentage points. This suggests that the optimal week of harvest was chosen by the farmer in 2021.

- On the monetary aspects, savings of up to 7.5% in terms of total costs (all types) could have been achieved in 2017 with a delay of three to four weeks in the harvest. Conversely, an earlier harvest by one or two weeks would have increased costs by 8% and 9.7%, respectively. In the year 2020, an earlier harvest by two weeks would have led to a significant cost rise of about 18%, indicating that the actual harvesting and fertilisers' application timings were good decisions.
- Concerning the state climate compensation received by farmers, Delaying the harvest in 2017 could have eliminated the need for compensation, resulting in savings of 138,617 NOK for the state. In 2018, compensation was unavoidable in all experiments due to the prolonged heatwave. Nevertheless, delaying the harvest could have reduced the compensation levels. In 2022, the baseline scenario yielded the lowest level of compensation compared to the alternative experiments.

5.2 | LIMITATIONS AND FUTURE DIRECTIONS

There are several limitations to the work done in this thesis. First, it focuses only on the quantitative analysis of the values of the seasonal forecast and demands further investigation to cover the qualitative aspect of non-quantifiable values, such as a sense of control, and reduced stress in dealing with unpredictability. Second, the thesis omitted some dynamics like the presence of outfields which are a source of feed and could act as a buffer. According to Beitnes, Kopainsky, and Potthoff 2022, "*the availability of outfield resources was central to tackling the Summer 2018 drought. The grazing conditions in the mountains were, according to the farmers, surprisingly good during the summer, and the autumn rain provided fresh grass*." In more advanced future works, there is potential for the incorporation of this variable, as further efforts are required to accurately assess and model the growing conditions in the outfields. We should acknowledge that no model can fully incorporate all the complexities of farming, and the developed model is for a specific purpose and under certain assumptions. However, this model can be expanded further to include soft dynamics and other structures. Moreover, for future works, it would be insightful to cover the implementation part, as this work's findings are conditioned by the adoption and large diffusion of the forecasts among farmers.

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