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Conventional or organic cattle farming? Trade-offs between crop yield, livestock capacity, organic premiums, and government payments

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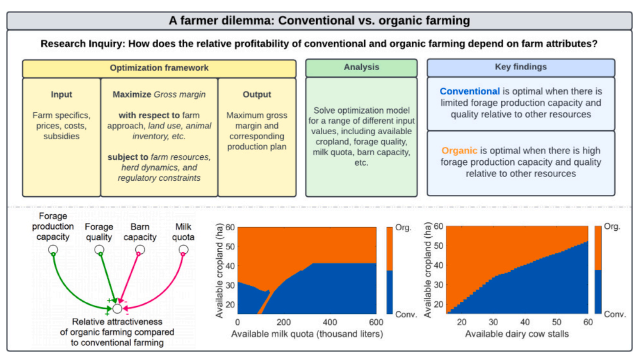
HIGHLIGHTS

- Employing a whole farm model to optimize gross margin in conventional and organic cattle systems.
- Conventional farming is superior when forage production capacity is limited in comparison to other resources.
- Organic farming is superior when forage production capacity is significant in comparison to other resources.
- Organic farming benefits more from higher forage quality than conventional farming.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: An important question for farmers is whether to run their farm conventionally or organically. This choice can significantly affect the farm's financial performance and its impact on the environment.
OBJECTIVE: The primary objective of this study is to compare the profitability of conventional and organic cattle systems and investigate how it is associated with individual farm characteristics, like forage production capacity, forage quality, milk quota, animal housing capacity, and their relative presences.
METHOD: We employ a whole farm optimization model, customized for Norwegian cattle farming. The primary goal of this model is to maximize the gross margin by optimizing decisions related to land usage and animal inventory while adhering to a set of constraints. We systematically solve more than 200,000 model instances, with varying farm characteristics.
RESULTS AND CONCLUSIONS: The results can be distilled to the following key points: If forage of good quality is readily available, but the livestock operation cannot be expanded due to animal housing and milk quota restrictions, organic may outcompete conventional farming. Otherwise, gross margin is maximized with conventional farming. These findings emphasize the crucial role of forage production capacity and quality in relation to

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available milk quota and infrastructure when considering the transition from conventional to organic farming. Extensive sensitivity analyses affirm the robustness of these conclusions. Regional regulatory factors, such as government farm payments, also play a significant role, and influence the optimal farming approach. Additionally, we show that increases in organic price premiums can markedly impact the competitiveness of organic farming, even in a system where government payments make out a significant part of the farm revenue.

SIGNIFICANCE: The model can support farmers to make informed decisions about converting to organic or conventional farming. It can also be used by policymakers to determine the level of support required to make it worthwhile for different types of farms to convert. We also show that existing government payment schemes give rise to regional differences in the incentives for organic farming in Norway. To ensure equal incentives for organic farming across the country, the organic payments would have to be regionally adjusted, in line with the other already regionally dependent government payments. This insight may be of significant interest to policymakers and other stakeholders.

1. Introduction

In agriculture, an ongoing debate is whether conventional or organic farming systems are more profitable (see e.g., Nemes, 2009; Crowder and Reganold, 2015; Reganold and Wachter, 2016; Durham and Mizik, 2021; Hirsch and Koppenberg, 2023). Researchers investigate whether the economic benefits of organic practices, such as higher product prices, lower production costs, and additional government payments for organic production, truly translate into higher farm profitability. This exploration remains complex, among other things, due to trade-offs between obtaining organic premiums and accepting diminished organic crop yields, which exert a negative influence on crop revenue and the capability to maintain livestock (Seufert et al., 2012).

Economic theory posits that, in a competitive market with low barriers of entry/conversion, conventional and organic farming should be equally profitable (Goolsbee et al., 2019). This is grounded in the belief that market dynamics, driven by incentives for entry and conversion, ought to eliminate any disparities in profitability, for example through supply-based price changes for conventional and organic products. However, the prevailing body of research that compare the profitability of conventional and organic farming tends to conclude that organic farming is, on average, more profitable (Nemes, 2009; De Ponti et al., 2012; Seufert et al., 2012; Flubacher et al., 2015; Reganold and Wachter, 2016; Krause and Machek, 2018; Smith et al., 2019; Durham and Mizik, 2021; European Commission, 2023; Hirsch and Koppenberg, 2023). This is typically credited to higher product prices, lower production costs, and/or organic farming payments, and occurs despite associated average reductions in crop yields. These findings indicate a market arena which is not characterized by, for instance, low barriers of entry/conversion, or alternatively, a market out of equilibrium, or a combination of both. Only a few studies conclude more with what could be expected from economic theory for competitive markets with low barriers of entry/conversion. For instance, studies by Flaten et al. (2019) and Hansen et al. (2021) in Norway, and Uematsu and Mishra (2012) in the United States, concluded that there were no readily apparent differences in the economic performance of conventional and organic farms.

Many of the statistical studies on the topic highlight that existing organic farms often have different attributes to conventional ones (see e.g., Hansen et al., 2021; Lakner and Breustedt, 2017; Flubacher et al., 2015). For instance, Hansen et al. (2021) noted that organic farms used more cropland than conventional ones and were localized in different regions. Thus, to ensure fair comparisons, it is important to match the two farm groups before comparison. Further insights are provided by Kerselaers et al. (2007), who explored organic conversion potential in Belgium. They found that beef cattle farms had higher economic conversion potential than dairy farms, while arable farms laid somewhere between the beef cattle farms and dairy farms. Besides the differences between farm types, they also found heterogeneity within each farm type. Notably, farms with much cropland exhibited higher economic conversion potential than their smaller counterparts. This difference was attributed to the former's ability to absorb the forage yield loss linked to organic conversion without reducing livestock. Based on this, they concluded that the economic potential of the conversion depended on the specific farm type and characteristics. Acs et al. (2007) reached similar conclusions for arable farming in the Netherlands, while also emphasizing that the costs linked to conversion from conventional to organic practices could impede profitable conversion. Allison et al. (2021), a study of optimal forage and supplement balance for grazing-based organic systems in the United States, also emphasized that the transition period could serve as a barrier to profitable conversion. The existence of conversion barriers could potentially account for the profitability disparity observed in many studies, as a higher level of profitability in organic farming would be needed to offset the conversion costs if conventional and organic farming are to be equally attractive from an economic standpoint.

Based on the reviewed literature one may conclude that organic systems appear to have an edge above conventional systems under current market and regulatory conditions, at least when one excludes conversion costs. Nevertheless, at individual farm level, it is important to recognize that the economically optimal decision hinges on farm characteristics, prevailing market conditions, and regulatory frameworks, all of which may vary across farms and time. In other words, even if organic farming is more profitable on average than conventional farming, this need not indicate that any conventional farm should convert to organic, and vice versa, as this depends on individual farm characteristics. The purpose of this study is to investigate these relationships in greater detail.

To the best of our knowledge, few studies, except from Kerselaers et al. (2007) and Acs et al. (2007), have explored how profitability in conventional and organic farming systems relate to different farm characteristics. A recent review conducted by Bang et al. (2023) underscores this gap in agricultural decision-support literature. We contribute to the debate through an exploration of the relationship between profitability of conventional and organic livestock systems, and individual farm characteristics such as the availability of cropland, animal housing capacity, milk quota, and forage quality, as well as relevant trade-offs. To achieve this, we present and apply a whole farm optimization model tailored for dairy, beef, and mixed farming operations in Norway.

Our study adds to the current literature on the comparative profitability of conventional versus organic farming. We explore how the economic choice to adopt organic practices hinges on relative availability of farm resources, as opposed to isolated availability of farm resources, which has already partly been covered. For example, we explore how the decision to adopt organic practices depends on forage production capacity relative to milk quota availability, rather than solely the available cropland. In addition, we explore how the decision depends on the forage production capacity relative to animal housing capacity. Moreover, we explore how the forage quality on the farm influences the relative profitability of the two systems, which to the best of our knowledge, has not been covered by other studies either.

The subsequent sections of the paper are structured as follows. First, in Section 2 we provide the relevant background. In Section 3, we present the materials and methods. In Section 4, we outline the results for a reference farm using Norwegian data, including a comprehensive sensitivity analysis exploring how the choice between conventional and organic approaches is influenced by farm characteristics. This section also contains the discussion of the results. In section 5, we conclude with some final remarks and suggest directions for future research.

2. Background

2.1. Norwegian dairy and beef production

Only 3.5% of Norway's total land area (excluding Svalbard and Jan Mayen islands) is cropland (NIBIO, 2022), and by most European standards Norwegian cattle farms are small-scale. In 2022, the average Norwegian farm had 26.1 ha (ha) of cropland (Statistics Norway, 2023). The average dairy farm had 31.3 dairy cows, while beef cattle farms had an average of 18.8 suckler cows (Statistics Norway, 2023). The total domestic production of milk and beef (supplied to dairy and beef plants) was 1404 million liters and 91,800 tons, respectively (Norwegian Agriculture Agency, 2024).

The main dairy breed in Norway, Norwegian Red cattle (NR), is a dual-purpose breed, bred for both milk and meat (Animalia, 2024; Geno, 2024). Many dairy farmers also fatten NR-bulls for meat production (Tine, 2023; Asheim et al., 2020). The grazing season for milk cows is short, and bulls are mostly raised intensively indoors on a ration of concentrates and silage (Asheim et al., 2020). The average milk yield per dairy cow in 2022 was 8496 kg energy corrected milk (ECM), and 39.1% of the farmers had an automatic milking system (Tine, 2023). The median slaughter age and weight for NR bulls was 545 days (about 18.2 months) and 316 kg, respectively (Tine, 2023).

Specialized beef producers in Norway make use of both British (light) and Continental (heavy) breeds (Asheim et al., 2020; Samsonstuen et al., 2019; Animalia., 2024). Common light breeds are Hereford and Aberdeen Angus, while common heavy breeds are Limousin, Simmental, and Charlois (Animalia, 2024; TYR, 2024). Specialized beef production systems in Norway are typically semi-intensive with extensive feeding (low concentrate) of suckler cows, calves and heifer progeny and intensive finishing (high concentrate) of bulls for meat production (Samsonstuen et al., 2019; Åby et al., 2012). Suckler cows are kept indoors approximately eight months per year and spend about four months per year on pasture (Samsonstuen et al., 2019).

Agricultural policies heavily shape the Norwegian farming industry. The policies are multifunctional and extensive, designed to pursue four goals. These goals include food security, agriculture throughout the country, increased value creation, and sustainable agriculture with lower emissions of greenhouse gases (Vik et al., 2019; Næringskomiteen, 2016). Norwegian dairy- and beef farmers mainly produce food for the domestic market, and to reach the goal of agriculture throughout the country, forage and grazing based livestock systems are decisive (Norwegian Government, 2024). The agricultural production conditions vary a lot across the country, and to achieve the agricultural policy goals the farmers receive substantial producer support, mostly through import tariffs and direct government payments, which vary from region to region. The structure of the direct payment scheme is so that the payment is highest for the first few cows and then declines. A milk quota system based on historical milk supplies regulates the production at the farm level, and a quota trading system makes it possible for farmers to expand while others can exit dairy farming. There are also government payments in place to support organic farming. Overall, Norwegian government support to the agriculture sector is extensive when compared to the support provided in many other countries.

2.2. Organic farming in Norway

To acquire organic premiums and payments, agricultural enterprises in Norway must undergo an approval process and accept annual inspections conducted by an organization (Debio) specially dedicated to control organic agricultural production (Ministry of Agriculture and Food, 2018). To attain approval and maintain certification, the enterprises must meet a set of conditions outlined in Norwegian regulations, which are derived from EU regulations, based on the Agreement on the European Economic Area.

Worldwide, organic regulations define organic agriculture as a chemical-free farming system, based on avoiding synthetic inputs, and relying on natural substances instead (Seufert et al., 2017). The regulations in Norway impose limitations on, for example, the use of pesticides, mineral fertilizers, and feed concentrates, as well as on the number of animals per farm relative to the available land area. Moreover, the natural needs of the animals are highlighted. For example, calves must be fed organic whole milk or organic replacers up to the age of 3 months. These regulations align with EU standards; however, they may exhibit variations when compared to regulations in other regions, such as the US.

From 1995 to 2011, driven by growing consumer interest in organic products and government support initiatives, the number of organic farms in Norway saw a significant increase. However, in recent years, despite the active efforts of the Norwegian government to encourage organic farming through targeted financial support (Ministry of Agriculture and Food, 2018), there has been a noticeable decline in the proportion of farms practicing organic agriculture (Statistics Norway, 2020). In 2011, the amount of organic agricultural land reached its peak slightly above 5%. However, by 2019, this figure had dropped to 4.2%. Due to the limited demand for organic milk and the need for a cost-efficient milk collection. Nevertheless, despite the recent decline, and regardless of its cause(s), the decision to convert from conventional to organic farming, or vice versa, remains a relevant consideration for Norwegian farmers.

3. Materials and methods

3.1. Optimization model

To explore the comparative profitability of conventional and organic farms, we have enhanced an existing whole farm optimization model, originally described, and documented by Hansen (2009). The primary purpose of the model was to explore the relationships between profitability, milk quota, milk yield per cow, slaughter age of bulls, and use of farmland. The model maximizes gross margin (GM), including conventional direct payments, by optimizing decisions related to animal composition, herd size, slaughter age of bulls and cropland utilization, all within key farming constraints concerning aspects such as available cropland, milk quota, and animal housing capacity. The model encompasses various animal breeds, notably NR and a distinction between light and heavy beef breeds, and considers multiple acreage uses, including forage and cereal crops. In a later version of the model, Engmark and Erstad (2019) updated the direct payment scheme and improved the NR herd dynamics.

Departing from the works referred to above, we modified, updated, and extended the model to account for the possibility of organic farming and its implications for forage yield, animal diet and performance, costs, prices, price premiums, and additional direct payments. The work was executed with the dual purpose of addressing our research inquiries regarding organic farming and enhancing the model's practical utility, particularly in the direction of beef production. The modifications involved reducing the available options for land use to grass growth, pasture, and rental of surplus cropland. Furthermore, to allow clear focus on cattle systems, we omitted the pre-existing inclusion of sheep. Updates included revising parameter values and direct payments. The extensions introduced the potential for organic farming through the incorporation of new variables, parameters, and structures. Moreover, we expanded the beef cattle structures and incorporated related herd dynamics, resulting in a structure that mirrors the previously established

NR cattle dynamics.

Model validation was conducted through a collaborative effort involving iterative rounds of discussions and meetings with industry experts throughout the modeling process. This diverse group included research scientists and farm advisors from prominent Norwegian agricultural entities like the dairy cooperative Tine, the meat cooperative Nortura, and the Norwegian Agricultural Advisory Service (NLR), as well as a select few farmers, with expertise on dairy production, beef production and arable crop production. These efforts were vital to make sure the model appropriately reflects the way things work in the real world and includes the important parts needed to answer our research questions. Functionality-wise, we thoroughly tested the model's performance and results, which involved successful sample runs, extreme conditions tests, and consistency tests with various solution methods.

The subsequent section offers a high-level overview of the updated model version 3 (OPTINORFARM V3). For a more detailed description of the model, we refer to Tables S1-S4 in the supplementary material.

3.2. High-level overview of the OPTINORFARM model

Fig. 1 presents a high-level overview of the updated model. The central objective is to maximize the GM, including government payments (depicted in Fig. 1 and expressed in eq. 1 in appendix Table A4). This objective is pursued through the manipulation of decision variables (depicted in Fig. 1 and expressed in eq. 2 in appendix Table A4). The decisions are guided by a series of constraints (listed in Fig. 1 and elaborated in eqs. 3–46 in appendix Table A4), ensuring that the pursuit of an increased GM remains in accordance with the practical realities of agriculture, available farm resources, and regulatory considerations.

To elaborate, the objective function includes livestock margins, farmland margins, and government payments. The livestock margin considers revenues from milk and beef sales, and costs of home-grown forage (including land preparation, use of mineral fertilizer, silage additives, seed, fuel, plastic, etc.), feed concentrates, veterinary services and medicine, insemination, and other variable costs. For practical reasons, the livestock margin also covers regionally differentiated price payments for milk and beef (paid per unit sold), and payments for grazing animals (paid per head of livestock). The farmland margin encompasses revenues generated from land rental. The government payment share of the objective function covers all relevant government payments, including potential organic payments (but, of course, excluding the government payments incorporated in the calculation of livestock margin). Note that the model does not consider opportunities for renting or leasing milk quotas, nor possibilities to purchase or sell milk quotas. As such, there is no margin contribution directly associated with the milk quota. The margin parameters used in the objective function have been calculated using 2022–2023 price, cost, and production data collected from Tine and Nortura. The government payment parameters align with the stipulations outlined in the Norwegian agricultural agreement for 2023–2024 (Norwegian Government, 2023).

The decision-making process encompasses a diverse range of factors that collectively shape the operations of the farm. This involves choices such as selecting between conventional and organic farming, decisions regarding the utilization of available cropland, selection of animal types, and the strategic management of the overall herd size.

With regards to land use, a crucial distinction is made between land allocated for feed production and land rented to external entities. Pasture is considered separately and assumed fully utilized whenever the animal forage need exceeds that provided by the pasture area. The categorization of animals is structured in a three-tiered arrangement, shown in Fig. 2. This organization primarily streamlines livestock payment calculations, while also providing a basis for practical considerations concerning herd dynamics. At the highest tier, there are dairy cows, suckler cows, and other cattle, corresponding to significant Norwegian livestock payment categories. In the intermediate tier, dairy cows contain only one subgroup, NR dairy cows. Meanwhile, suckler

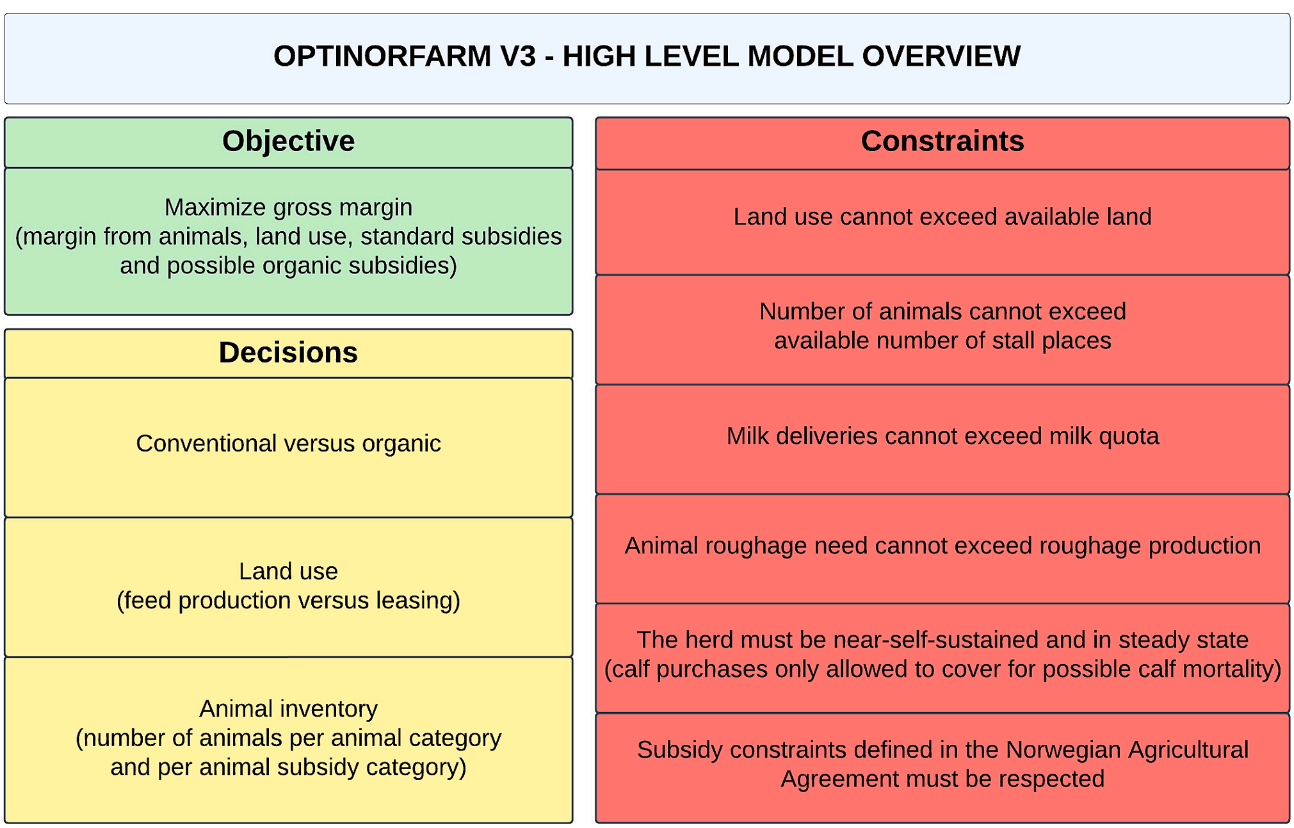

Fig. 1. High level model overview.

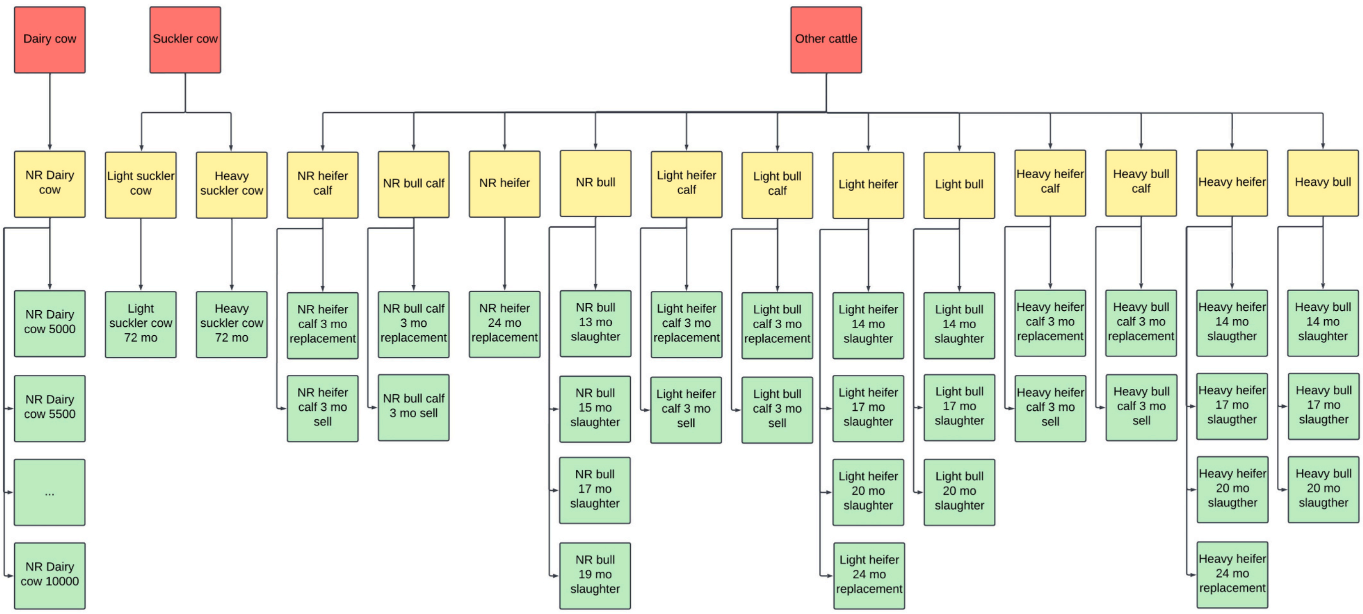

Fig. 2. Modeled animal structure.

cows are categorized into light and heavy divisions. Further categorization within the "other cattle" group leads to subgroups: NR heifer calves, NR bull calves, NR heifers, and NR bulls; light heifer calves, light bull calves, light heifers, and light bulls; and heavy heifer calves, heavy bull calves, heavy heifers, and heavy bulls. In the lowest tier, NR dairy cows are grouped according to milking intensity, ranging from 5000 kg ECM per year to 10,000 kg ECM per year. Light and heavy suckler cows each have a distinctive subgroup intended for slaughter at a given age and weight. NR, light, and heavy heifer calves and bull calves are subdivided into groups indicating whether they are intended for on-farm rearing or sale. NR heifers have a distinctive group intended for transitioning into dairy cows. Light and heavy heifers are further segmented based on age, determining whether and when they are destined for slaughter or to become suckler cows. NR, light, and heavy bulls are categorized based on the intended age of slaughter.

The decision-making process is guided by constraints that encompass factors such as available milk quota, stall places, cropland for feed production or rental, and requirements concerning self-sufficiency and sustainable operations. First, the number of dairy cows with different milking intensities cannot exceed the number of dairy cows required to fill the milk quota. Second, the number of animals in the various animal categories cannot exceed the available stall places. In relation to this, a notable differentiation is made between spaces for calves, other cattle excluding calves, and stalls designated for dairy and suckler cows. Third, the dietary needs of the animals must remain within the boundaries of the farm's forage production—a factor influenced by decisions concerning the adoption of organic farming practices and the strategic allocation of land resources. Only feed concentrate, i.e., no silage, can be obtained from outside the farm. The Nordic Feed Evaluation System (NorFor, 2023), a feed planning tool, has been leveraged to formulate the feed plans in the model. In addition to the constraints above, the number of animals is controlled in a manner that balances the inflow and outflow(s) for each group, effectively canceling each other out. This ensures a near self-sustained steady state, wherein calf acquisitions are only allowed to offset potential calf mortality.

Payment conditions stipulated by the Norwegian agricultural agreement are also incorporated as constraints in the model. These constraints encompass e.g., an upper limit on conventional government payments, limitations on government payments granted per animal, restrictions tied to government payments for dairy and beef production, conditions related to supplementary government payments for small and medium-sized farms, and boundaries on government payments pertaining to acreage and the preservation of the cultural landscape. For further details, we refer to the detailed model description in the appendix and to the Norwegian agricultural agreement (Norwegian Government, 2023).

3.3. Reference farm and computational experiments

To explore our research questions, we present a reference farm and then conduct an extensive sensitivity analysis, in which the basic data for several key input values are altered in small steps, solving thousands of numerical instances. By analyzing the results of these instances, we can compare GM under optimal conventional and organic farming and explore how the comparison respond to changes in different input values, including available cropland, forage quality, milk quota, infrastructure, and region of operation. In addition, we explore how the results respond to an increase in organic price premiums.

The reference farm represents a moderately sized dairy farm located in Jæren, Rogaland County, Norway, constructed based on statistical data from the Norwegian Farm Business Survey (NIBIO, 2023). The farm falls into specific payment regions for government payments, namely Region A for milk, Region 1 for beef, and Region 2 for forage crops (NIBIO, 2024; Norwegian Government, 2023). These regions correspond to areas in Norway with the lowest regional government payment rates (Norwegian Government, 2023). There are no regional price payments for milk and beef, and the direct payments for milk, beef production, and cattle are lower compared to less favorable regions. The farm has 28 ha of cropland, and 7 ha of pasture area. The conventional crop yield is set at 41,672 megajoules of net energy per ha per year (MJ/ha/year). The organic crop yield is assumed to be 30% lower at 29,184 MJ/ha/year, based on discussions with industry experts. The conventional and organic pasture yield is set to 60% of the conventional and organic crop yield, respectively. The forage quality is 6.3 MJ per kg of dry matter (MJ/kg DM). The farm has a milk quota of 274,000 l/year and stall places for 36 dairy cows, 56 heifers and bulls, and 18 calves. Table 1 summarizes the reference farm characteristics.

For the sensitivity analyses, we consider a range of cropland sizes, from small to large relative to other resources available at the reference farm. Additionally, we explore the effect of an increase in forage quality, from 6.3 to 6.72 MJ/kg DM. Different milk quota and infrastructure levels are also analyzed. Following this, we conduct more extensive

Table 1
Reference farm characteristics.

Input data	Reference farm
Payment region milk	A
Payment region beef	1
Payment region land	2
Cropland (ha)	28
Pasture (ha)	7
Conventional yield cropland (MJ/ha/year)	41,672
Organic yield cropland (MJ/ha/year)	29,184
Forage quality (MJ/kg DM)	6.3
Milk quota (thousand liters/year)	274
Adult cow stalls	36
Heifer and bull stalls	54
Calf stalls	18

sensitivity analyses to better understand how the choice between conventional and organic farming depends on the relative availability of different farm resources. We also explore the effect of changing the farm's region of operation. The latter is interesting because conventional government payments vary from region to region, while organic government payments are equal across all regions. This means that farms in other regions may face higher conventional payments relative to organic government payments. Also, we explore how the results respond to a 50% increase in price premiums for organic milk and beef. Table 2 provides an overview of the sensitivity analyses to be conducted.

4. Results and discussion

The analyses outlined in the preceding section encompass more than 200,000 separate model instances. Considering the computationally intensive nature of our analyses, we devised algorithms for their systematic solution, utilizing the mathematical programming language AMPL and the Gurobi solver. In the following section, we present and discuss the results.

4.1. Reference farm

To demonstrate the framework's capabilities and assess the potential benefits of adopting organic farming practices, we solve the reference model instance under a constraint that mandates conventional farming practices. Subsequently, we apply a constraint to enforce organic farming. This allows for a comparison of GM and other model results under optimal conventional and organic farming at the reference farm.

The results, summarized in Table 3, show that the optimal conventional farming approach yields a higher GM, in total 2,259,606 NOK per year, compared to the optimal organic farming approach, which generates a GM of 1,946,533 NOK per year. This suggests that the reference farm has nothing to gain from converting to organic farming. This finding is interesting, since most studies suggest that organic farming is, on average, more profitable than conventional farming (Nemes, 2009; De Ponti et al., 2012; Seufert et al., 2012; Flubacher et al., 2015; Reganold and Wachter, 2016; Krause and Machek, 2018; Smith et al., 2019; Durham and Mizik, 2021; European Commission, 2023).

The livestock and land margin contribution, which includes price and pasture payments, is higher in the conventional approach, with 1,454,710 NOK per year, compared to 1,116,210 NOK per year in the organic approach. Notably, the organic reference farm receives higher government payments, despite fewer animals. However, these higher payments are not sufficient to offset the lower livestock and land margin contribution in the organic approach.

In terms of land usage and production, both approaches allocate 28 ha or 100% of available cropland to forage production, which indicates that forage represents a limiting factor. Milk delivery is significantly higher in the conventional approach, with 270,874 l per year, compared to 174,060 l per year in the organic approach. Beef production is significantly higher in the conventional approach as well, with 10,138 kg per year, compared to 3316 kg per year in the organic approach.

The animal inventory shows that the conventional approach has a higher number of NR dairy cows producing more milk per cow. The conventional solution also includes dairy bulls reared for intensive beef production as well as specialized beef cattle, while the organic solution does not. The larger milk and beef production of the conventional livestock operation stems from its higher forage production capacity and ability to use more concentrate in the animal diet as compared to the organic livestock operation. This allows a higher number of animals. Moreover, conventional dairy cows can obtain 10,000 kg ECM per year, whereas the organic dairy cows can produce 7500 kg ECM per year only, given the available forage quality and organic limitations on the use of concentrate.

The conventional operation falls short of filling the milk quota, while

Table 2
Sensitivity analysis overview.

Parameter	Reference farm	Sensitivity	Comment
Cropland (ha)	28	[15, 15.1, 15.2, … 60]	The sensitivity analysis investigates a range from 15 to 60 ha of cropland in steps of 0.1 ha.
Forage quality (MJ/kg DM)	6.3	For each element in cropland = [15, 15.1, 15.2, … 60] solve with forage quality of 6.72	The sensitivity analysis explore the impact of higher forage quality on the preceding sensitivity analysis concerning cropland
Milk quota (thousand liters/year)	274	[0, 1, 2, … 400]	The sensitivity analysis investigates a range from 0 to 400 thousand liters per year in steps of one thousand liters.
$\begin{bmatrix}\text{Adult cow stalls}\\ \text{Heifer and bull stalls}\\ \text{Calf stalls}\end{bmatrix}$	$\begin{bmatrix}36\\54\\18\end{bmatrix}$	$\begin{bmatrix}15, 16, 17, \ldots, 60\\ 22.5, 24, 25.5, \ldots 90\\ 7.5, 8, 8.5, \ldots, 30\end{bmatrix}$	The sensitivity analysis investigates a range from 15 to 60 adult cow stalls in steps of 1, with heifer and bull stalls and calf stalls increasing proportionally by factors of 1.5 and 0.5 per adult cow stall, respectively.
Cropland (ha) versus milk quota (thousand liters/year)	28 and 274	For each element in Cropland = [15, 15.1, 15.2, … 60] solve for all elements in milk quota = [0, 1, 2, … 400]	The sensitivity analysis explores how the optimality of conventional vs. organic farming hinges on different combinations of these farm resources.
Cropland (ha) versus stall places	28 and [36, 54, 18]	For each element in Cropland = [15, 15.1, 15.2, … 60] solve for each column vector in stall places = $\begin{bmatrix}15, 16, 17, \ldots, 60\\ 22.5, 24, 25.5, \ldots 90\\ 7.5, 8, 8.5, \ldots, 30\end{bmatrix}$	The sensitivity analysis explores how the optimality of conventional vs. organic farming hinges on different combinations of these farm resources.
$\begin{bmatrix}\text{Payment region milk}\\ \text{Payment region beef}\\ \text{Payment region land}\end{bmatrix}$	$\begin{bmatrix}\text{A}\\1\\2\end{bmatrix}$	$\begin{bmatrix}D\\2\\5B\end{bmatrix}$	In the sensitivity analysis, we explore the effects in a region with higher conventional government payments.
$\begin{bmatrix}\text{Org.milk premium}\\ \text{Org.beef premium}\end{bmatrix}$	$\begin{bmatrix}0.85\ \text{NOK/liter}\\ 6.5\ \text{NOK/kg}\end{bmatrix}$	For each element in Cropland = [15, 15.1, 15.2, … 60] solve with price premiums $\begin{bmatrix}\text{Org.milk premium}\\ \text{Org.beef premium}\end{bmatrix} = \begin{bmatrix}1.275\ \text{NOK/liter}\\ 9.75\ \text{NOK/kg}\end{bmatrix}$	In the sensitivity analysis we explore how results respond to a 50% increase in organic milk and beef premiums.

Table 3
Conventional and organic results for the reference farm.

Output	Optimal conventional	Optimal Organic
Gross margin incl. government payments (NOK/Year)	2,259,606	1,946,533
Livestock and land margin contribution incl. price and pasture payments (NOK/Year)	1,454,710	1,116,210
Other payments margin contribution incl. any organic payments (NOK/Year)	804,894	830,319
Area to use for forage production (ha) [percentage of available cropland]	28 [100%]	28 [100%]
Area to rent out to external entities (ha) [percentage of available cropland]	0 [0%]	0 [0%]
Milk delivery (Liters/Year) [percentage of available milk quota]	270,874 [98.85%]	174,060 [63.53%]
Beef production (Kg/Year)	10,138	3316
Animal inventory (animals available at any given point in time, assuming continuous calving strategy)	NR dairy cow 10,000 kg = 30 NR heifer 24 mo = 26.25 NR heifer calf 3 mo = 3.75 NR bull 13 mo = 10.731 NR bull calf 3 mo = 3.219 NR bull calf 3mo sell = 0.530 Light suckler cow 72 mo = 6 Light heifer 24 mo = 2.625 Light heifer calf 3 mo = 0.375 Light heifer calf 3 mo sell = 0.375 Light bull 14 mo = 2.75 Light bull calf 3mo = 0.75	NR dairy cow 7500 kg = 25.704 NR heifer 24 mo = 22.491 NR heifer calf 3 mo = 3.213 NR bull calf 3 mo sell = 3.213

the solution proposes both a significant number of NR bulls for beef production and several specialized beef cattle. The key explanation for this is twofold. First, the reference farm can accommodate only 36 adult cows, comprising both dairy cows and suckler cows. The conventional solution involves 30 dairy cows and six light suckler cows, thereby fully utilizing the available animal housing for adult cows. Second, the government payment system in Norway involves a significant government payment for specialized beef production, amounting to 5764 NOK per suckler cow in the reference farm region, which mandates six suckler cows or more before payout. Thus, the reference farm benefits more from allocating the six adult cow spaces to suckler cows rather than acquiring additional dairy cows to fill the milking quota. While the latter option would only require a fraction of the six adult cow spaces used for suckler cows, it would eliminate the opportunity to receive the specialized beef production payment, totaling at 34,584 NOK for six suckler cows, resulting in a discrete drop in GM. Additional runs show that the six light suckler cows would be left out under circumstances where forage production capacity is reduced, while the milk quota would be filled. Contrary, given increased forage production capacity, the light breed would gradually be replaced by the heavy breed. The reason is that the heavy breed has a higher margin potential given that enough suckler cows can be acquired to get the specialized beef production payment.

The optimal conventional solution includes fattening of the most intensive bulls finished at 13 months for dairy bulls and 14 months for the light beef breed. Extending the feeding period enhances the margin per head; however, given the continuous nature of production, it is essential to consider the annual throughput. The highest annual margins are obtained by the most intensive processes.

4.2. Forage production capacity

Forage production represents a binding resource constraint in both the conventional and organic solutions for the reference farm. All available cropland is used for forage production, and all available forage is consumed by the animals. Thus, it is particularly interesting to investigate how the solutions change in response to changes in the forage production capacity. In the following, we explore how the solutions respond to both a reduction and increase in the available cropland, which together with the yield per ha determine the forage production capacity.

The reference farm has a total of 28 ha of cropland at its disposal. In Fig. 3, we analyze the GM under optimal conventional and organic farming scenarios with available cropland varying from 15 ha to 60 ha, all else equal. The conventional and organic solutions for the reference farm are represented by point A and B, respectively. The figure illustrates a noteworthy trend: as available cropland increases from 15 ha, GM of both conventional and organic farming increases. However, the marginal effect diminishes as additional cropland is dedicated to activities with lower margins. Once all avenues for livestock expansion are exhausted, the only practical use for additional cropland is rental of land, which only has a small positive impact on GM. Importantly, the impact of increased cropland declines more rapidly for conventional farming compared to organic farming. Consequently, organic farming outperforms conventional farming when available land exceeds 37.5 ha (point C). These findings align with the research of Kerselaers et al. (2007), suggesting that farms with abundant cropland are more likely to benefit from conversion to organic farming compared to those with limited cropland.

4.3. Forage quality

The analysis of the reference farm, along with the preceding sensitivity analyses, is based on a forage quality of 6.3 MJ/kg dry matter. However, through alternative management practices, Norwegian farms can achieve even higher forage quality (Randby et al., 2012). Furthermore, increased forage quality can lead to increased milk yield per dairy cow. This effect is particularly important in the context of organic dairy farming, where farmers have limited flexibility to offset lower forage quality by using more concentrate. Thus, in the following, we explore the extent to which an increased forage quality of 6.72 MJ/kg dry matter may impact the preceding results and economic attractiveness of organic farming.

When the forage quality increases from 6.3 to 6.72 MJ/kg dry matter the conventional and organic feed plans change so that animals will consume more forage and less concentrate. Moreover, it becomes possible for organic dairy cows to increase their milk maximum yield from 7500 kg ECM per year to 9000 kg ECM per year without violating restrictions on the use of concentrate.

Increased forage quality has a dual net effect on the conventional GM, and a consistent positive net effect on organic GM (Fig. 4). In the interval from 15 to approximately 30 ha of available cropland, the increase in forage quality reduces the conventional GM. The reason is that forage production, which is a constraining factor in this interval, becomes even more important when forage quality increases, as the animal diet relies more on roughage and less on concentrate. Consequently, the conventional farm cannot maintain as many animals as before. The same holds for the organic farm. However, in the organic approach, the reduction in livestock is compensated by a significant increase in milk yield per dairy cow, which results in a net positive effect on GM in the very same interval.

From 30 ha onwards, the conventional approach finally benefits from the increased forage quality. Beyond this point, the conventional

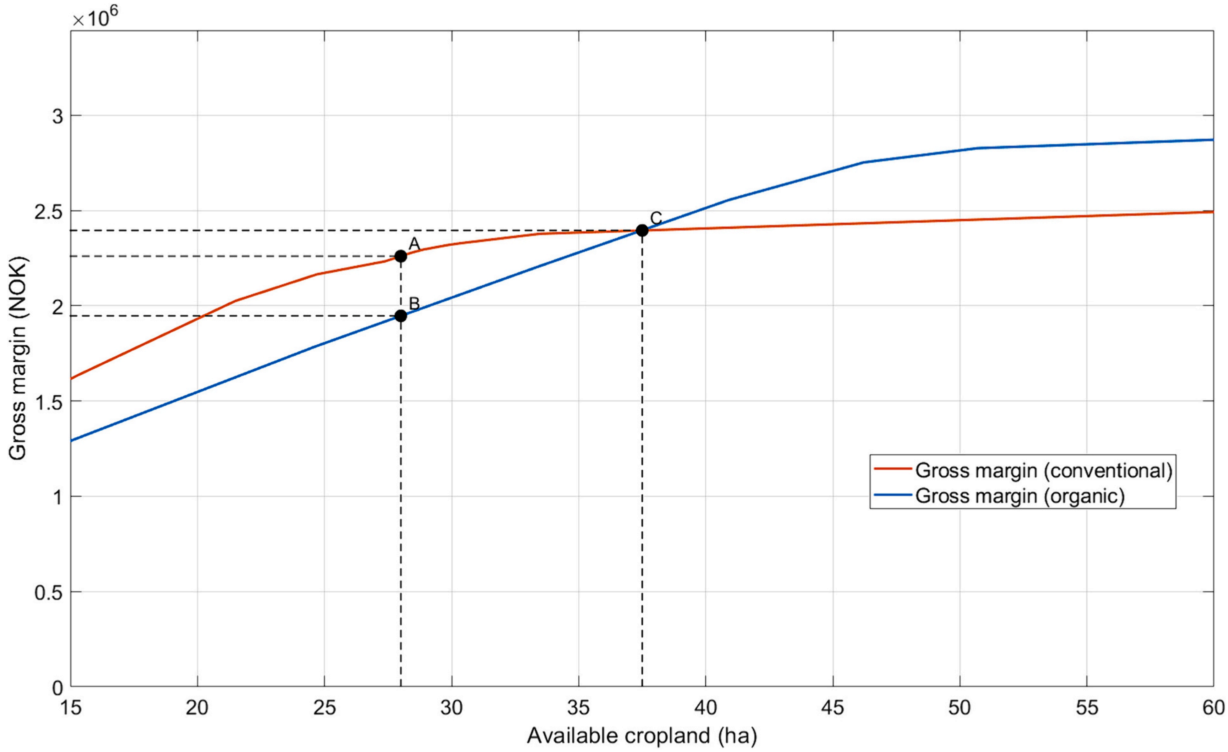

Fig. 3. Conventional and organic results for the reference farm with different availability of cropland. Point A corresponds to the conventional solution for the reference farm. Point B corresponds to the organic solution for the reference farm. Point C signals the level of available cropland at which conventional and organic operations achieve equal gross margin.

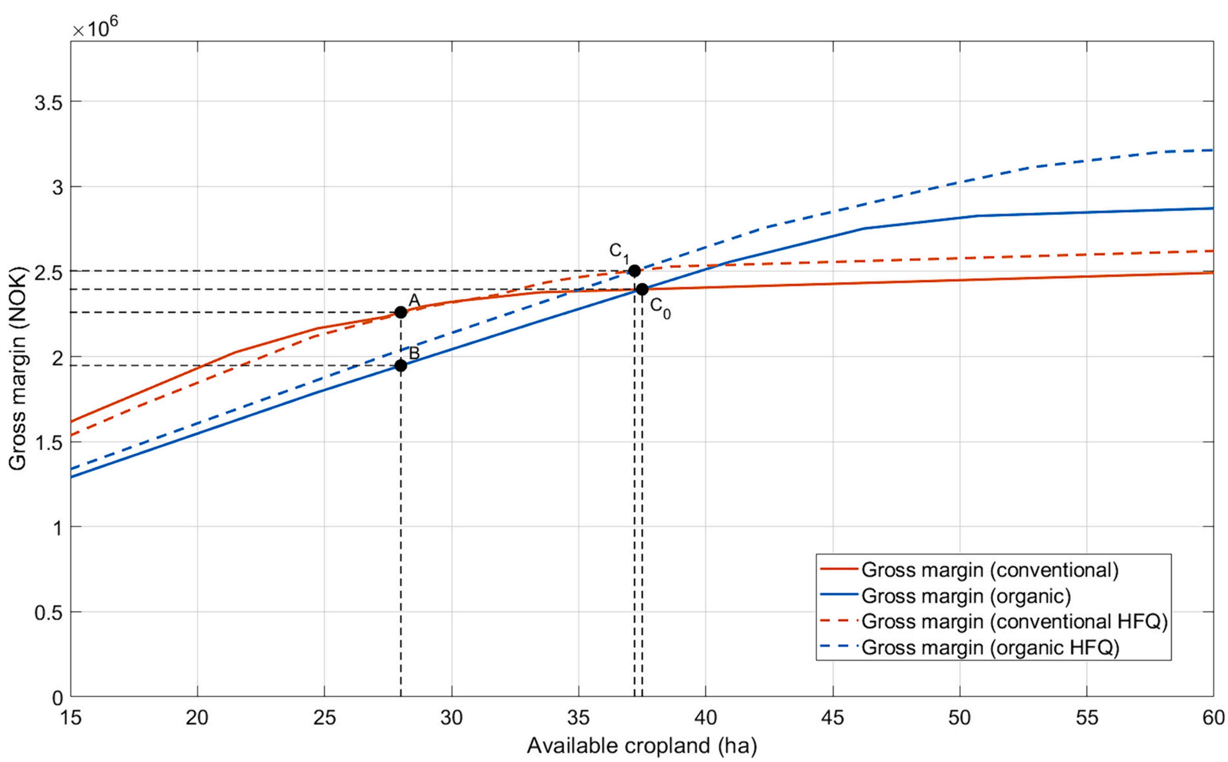

Fig. 4. Conventional and organic results for the reference farm with different availability of cropland and two different forage qualities. Point A corresponds to the conventional solution for the reference farm. Point B corresponds to the organic solution for the reference farm. Point C_0 signals the level at which conventional and organic operations achieve equal gross margin given the reference farm forage quality, while point C_1 signals the same given higher forage quality (HFQ).

approach takes greater advantage of higher forage quality through reduced forage costs compared to what it sacrifices in ability to maintain livestock. However, even extending beyond this point, the conventional approach continues to generate fewer benefits than the organic approach. Even so, the results show that the GM intersection between conventional and organic farming occurs only at slightly lower levels of available cropland compared to the scenario with lower forage quality, moving from point C_0 to C_1. In alternative scenarios, with different milk quota or stall places, the new intersection point could have shifted farther away from the initial one.

4.4. Milk quota

The preceding results and discussions suggest that the milk quota could play a role in determining whether conventional or organic farming is more economically attractive. Therefore, it is interesting to explore the impact of the milk quota in further detail.

The reference farm has a milk quota of 274,000 l per year. In Fig. 5, we compare the GMs under optimal conventional and organic farming practices across various levels of milk quota availability, ranging from zero to 400,000 l. When the milk quota is non-existent or low, both farm approaches will focus on specialized beef production. As the milk quota increases, milk production will increase relative to specialized beef production, and after a certain point, there will be no specialized beef production left. The reason for this is that dairy farming is generally more profitable than specialized beef production in both farming systems, except in some rare instances where mixed solutions are preferable, such as the situation described in Section 4.1 for the conventional farm.

The comparison in Fig. 5 reveals different trends over three different ranges of milk quota. In the initial range, from 0 to 89,000 l, conventional farming emerges as the more profitable choice, which indicates that specialized beef production using conventional methods yields higher returns compared to organic methods, although by slight margins. However, as we move into the range of 89,000 to 168,000 l (the interval between point C and D), the GM of organic farming slightly surpasses that of conventional farming. Beyond the 175,000-l mark, organic farming no longer benefits from increased milk quota availability due to limited forage resources. In contrast, conventional farming, which has a higher forage yield and can maintain a larger livestock with less dependence on roughage, can harness the advantages of an increasing milk quota until the quota reaches 325,000 l. Upon surpassing the 168,000-l threshold, conventional farming once again outperforms organic farming in terms of GM.

4.5. Infrastructure

The availability of infrastructure, particularly stall places, is another critical resource constraint that cattle farmers must consider. For instance, this factor acts as a limiting resource constraint in the conventional solution for the reference farm in Section 4.1, and in many of the solutions in sections 4.2–4.4.

The reference farm has 36 adult cow stalls, 54 heifer and bull stalls, and 18 calf stalls. In Fig. 6, we present the GM under optimal conventional and organic farming, considering the available adult cow stalls, ranging from 15 to 60. For each adult cow stall, we allocate 1.5 heifer and bull stalls and 0.5 calf stalls, while keeping all other inputs equal to the inputs for the reference farm.

In the range of 15 to 26 adult cow stalls, organic farming demonstrates a superior GM compared to conventional farming. Approximately at this point, organic farming reaches the forage constraint, which limits its ability to utilize additional stall places. Contrary, conventional farming can capitalize on extra stall places due to larger forage production capacity and lower roughage requirements in the animal diet. However, when exceeding 37 adult cow stall places the forage constraint becomes binding also in conventional farming. These results suggest that organic farming can outperform conventional farming when stall place availability is limited.

4.6. Relative resource availability

Previous analyses have highlighted several key factors which affect the competitiveness of organic versus conventional farming. First and foremost, an increase in available cropland and improved forage quality can enhance the competitiveness of organic farming, all else equal. Conversely, an increase in available milk quota and stall places can reduce the competitiveness of organic farming.

The previous analyses have also provided a clue of the

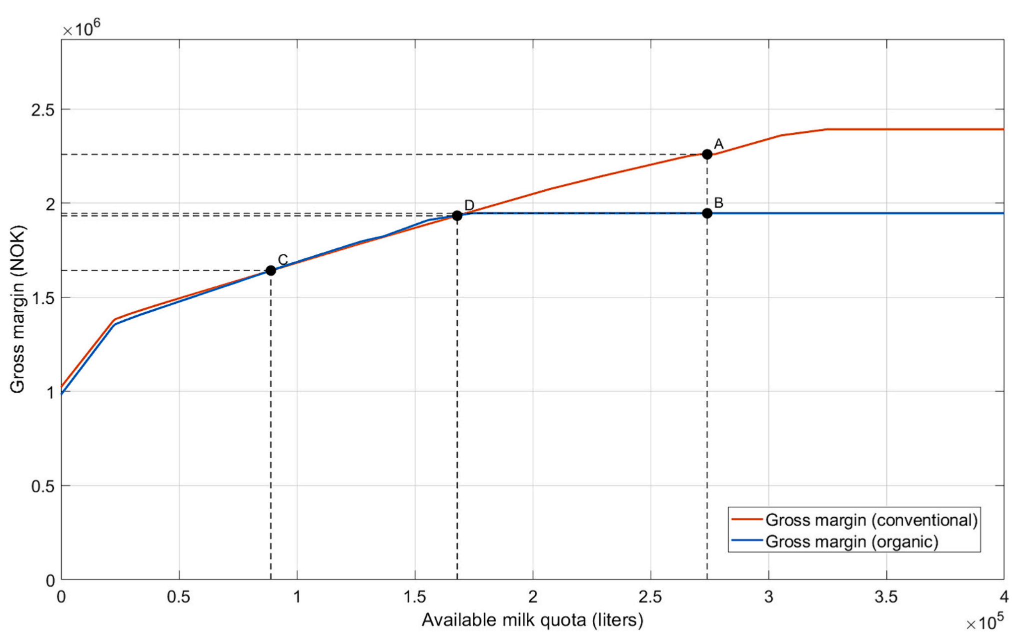

Fig. 5. Conventional and organic results for the reference farm with different milk quota availability. Point A corresponds to the conventional solution for the reference farm. Point B corresponds to the organic solution for the reference farm. Point C and D signal the levels at which conventional and organic operations achieve equal gross margin.

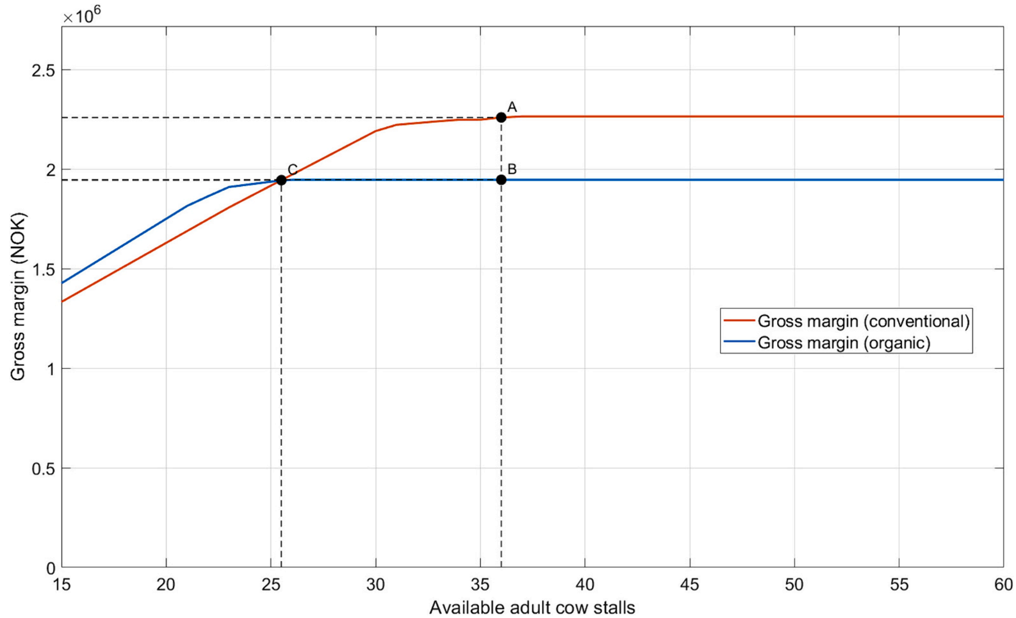

Fig. 6. Conventional and organic results for the reference farm with different cow stall place availability. Point A corresponds to the conventional solution for the reference farm. Point B corresponds to the organic solution for the reference farm. Point C signals the level at which conventional and organic operations achieve equal gross margin.

interconnectedness between these factors. For instance, the results have shown that the value of having more cropland depends on whether the milk quota is fully utilized or not. It also relies on the availability of stall places, as extra cropland does not yield significant benefits if no opportunities exist to expand livestock production. In such cases, the only practical use case of additional cropland is rental of land, which only has a small but positive effect on GM.

Naturally, the optimal decision to operate a farm organically is not solely determined by individual factors like forage production capacity, milk quota, or infrastructure. Therefore, it is interesting to analyze the relationships and accessibility of these factors in relation to one another. To this aim, we solve additional model instances where we vary more than one factor at a time, and over a broad range of values.

The results in Figs. 7 and 8 offer insights that partially overlap with Figs. 3, 5, and 6, as they should. Specifically, a vertical movement from the 'Reference farm' point in Fig. 7 corresponds to a horizontal movement in Fig. 3, while a horizontal movement from the same point corresponds to a horizontal movement in Fig. 5. Similarly, a vertical

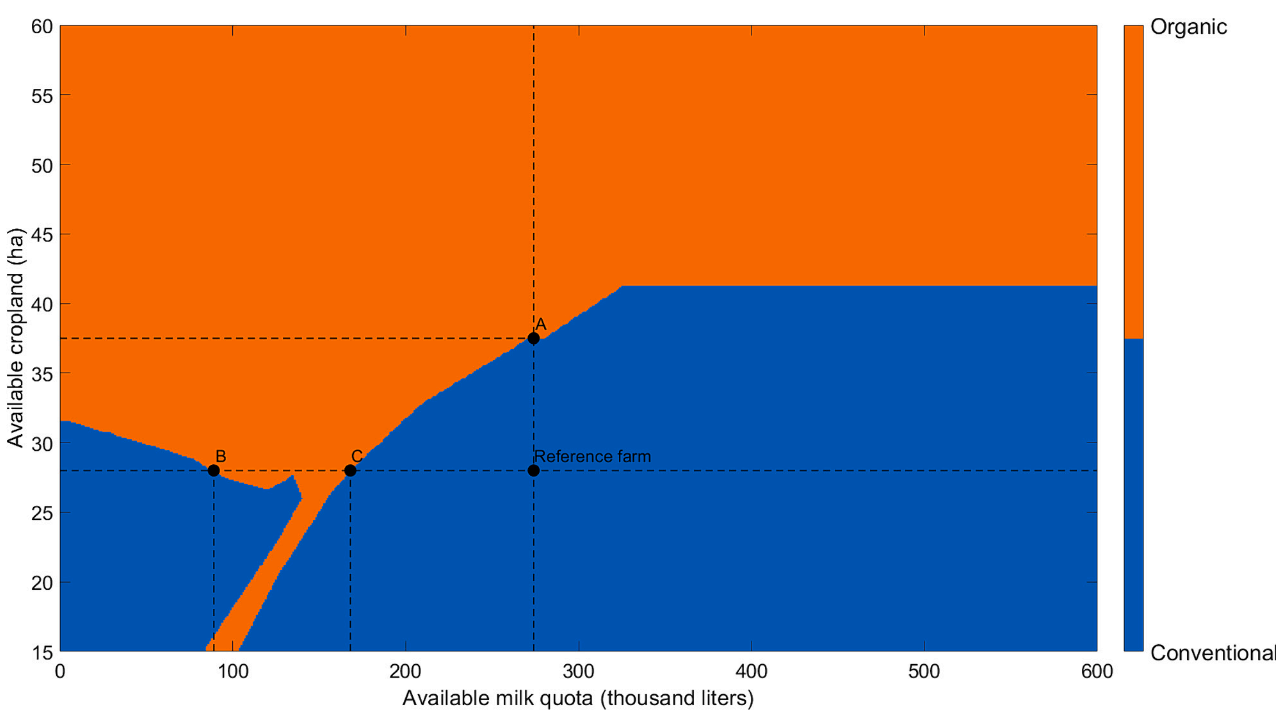

Fig. 7. Optimal farming approach with different combinations of cropland and milk quota. Blue shading indicates that conventional practices are optimal. Conversely, orange shading indicates that organic practices are optimal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

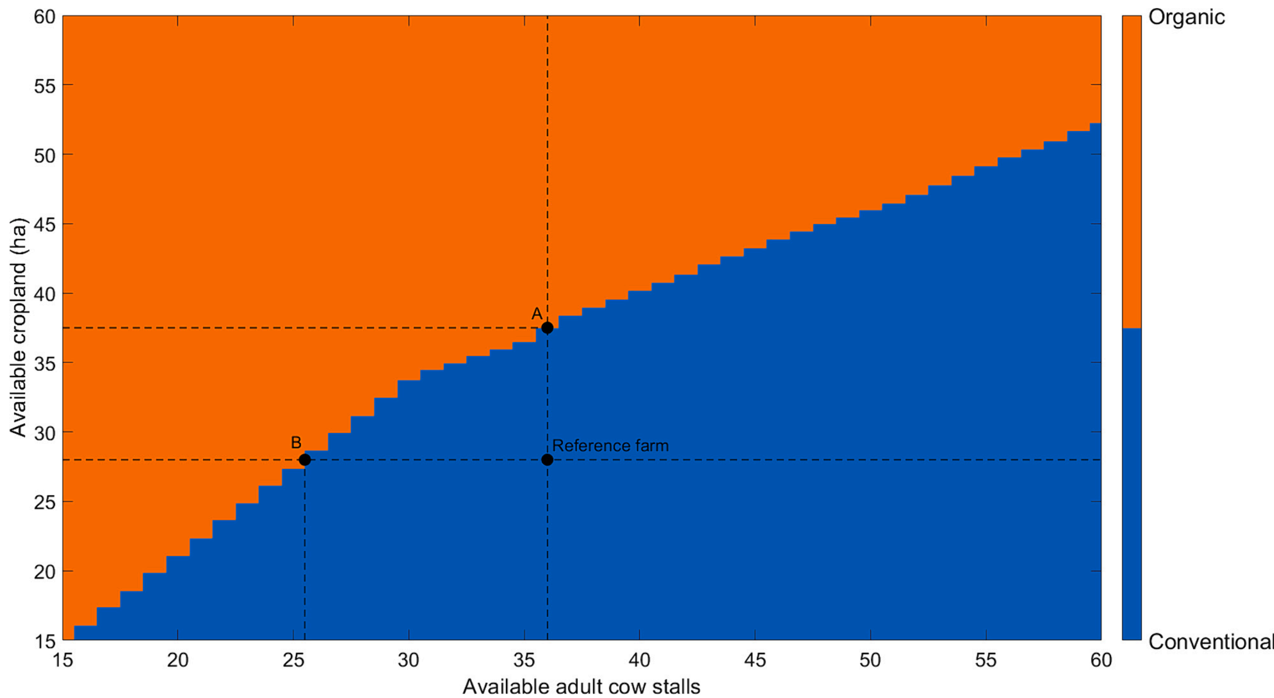

Fig. 8. Optimal farming approach for the reference farm with different combinations of available cropland and adult cow stall places. Blue shading indicates that conventional practices are optimal. Conversely, orange shading indicates that organic practices are optimal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

movement from the 'Reference farm' point in Fig. 8 corresponds to a horizontal move in Fig. 3, while a horizontal movement from the same point corresponds to a horizontal move in Fig. 6. For example, when comparing point C in Fig. 3, point A in Fig. 7, and point A in Fig. 8, it is evident that the reference farm, with a milk quota of 274 thousand liters and 36 cow stalls, would need 37.5 ha of cropland for organic farming to produce the same GM as conventional farming. Similarly, by comparing points C and D in Fig. 5 to points B and C in Fig. 7, and what happens between these points in each respective figure, it is clear that organic farming can outperform conventional practices if the farm has a milk quota between 89 thousand liters and 168 thousand liters. Likewise, by comparing point C in Fig. 6 to point B in Fig. 8, it is apparent that the reference farm would need 26 stall places for organic farming to produce the same GM as conventional farming. The consistency in the alignment of shifts in what is optimal, both vertically and horizontally, from the 'Reference farm' points in Figs. 7 and 8 with the shifts in Figs. 3, 5, and 6 serves as a numerical validation of the results presented in Figs. 7 and 8, which encompass results from more than 100,000 model runs.

Figs. 7 and 8 offer a clearer comprehension of the factors which influence the profitability of each farming approach. In cases where the milk quota is either 0 l or low, both farming approaches prioritize specialized beef production. In such scenarios, conventional farming outperforms organic farming when availability of cropland is low, while organic farming outperforms conventional when the availability of cropland is high (Fig. 7). This indicates that conventional specialized beef production is not always economically superior to its organic counterpart.

At higher quota levels, both farming approaches pivot toward more dairy-intensive production, which is generally more profitable than specialized beef production. The findings reveal that conventional dairy farming outperforms organic dairy farming when the available cropland is limited compared to the milk quota (Fig. 7). However, the organic approach may surpass the conventional approach when there is an abundance of cropland relative to the milk quota (Fig. 7).

Similar insights can be derived from the examination of available cropland in relation to available stall capacity. The results presented in Fig. 8 show that conventional farming excels when forage production capacity is restricted in comparison to available stall capacity, while organic farming has the highest GM when forage production capacity is ample relative to stall capacity.

In summary, the results outlined above can be distilled to the following key points: if forage (of good quality) is readily available, but the livestock operation can't be expanded due to animal housing and milk quota restrictions, organic may generate higher GM. But otherwise, GM is maximized with conventional.

4.7. *Region of operation*

In the presentation of the reference farm, we highlighted that the farm was situated in an area with the lowest government payments in Norway. Since many payments are higher in other regions, while organic government payments are the same across the country, it is interesting to explore how our results change if the reference farm was located elsewhere.

Table 4 shows how the results for the reference farm would change if the farm was moved from payment regions A, 1, 2 to payment regions D, 2, 5B for milk, beef, and land, respectively, like a move from the southwestern part of Norway ("Jæren") to a more northwestern location ("West"). This would trigger previously non-existing price payments of 0.85 NOK/l milk and 5.25 NOK/kg beef, as well as significant increases in direct payments for dairy production and cropland. Meanwhile, the organic payments would remain constant.

The average farm in the northwestern location is smaller than the average farm in the southern location. Moreover, the average farm in the north-western location has lower forage yield. However, for the sake of comparison, we focus on a hypothetical scenario where the reference farm moves from one location to another, and thereby on the effects of changes in regional government payments only, while leaving out changes in farm size and forage yield. Nevertheless, it is worth keeping in mind that the additional payments in the northwestern region are due to less favorable farming conditions, motivated by the Norwegian Government's goal to ensure agricultural operations throughout the

Table 4
Conventional and organic results for the reference farm with an alternative location in payment region D, 2, 5B for milk, beef, and land, respectively.

Output		Optimal conventional	Optimal Organic
Gross margin incl. government payments (NOK/Year)	Alternative location	2,695,229	2,259,952
	Reference farm	2,259,605	1,946,533
	Difference [percentage change from reference]	435,624 [+19.3%]	313,419 [+16,1%]
Livestock and land margin contribution incl. price and pasture government payments (NOK/Year)	Alternative location	1,730,520	1,281,570
	Reference farm	1,454,710	1,116,210
	Difference [percentage change from reference]	275,810 [+19%]	165,360 [+14.8%]
Other government payments margin contribution incl. Any organic government payments (NOK/Year)	Alternative location	964,714	978,379
	Reference farm	804,894	830,319
	Difference [percentage change from reference]	159,820 [+19.9%]	148,060 [+17.8%]
Area to use for forage production (ha)	Alternative location	28	28
	Reference farm	28	28
	Difference	None	None
Area to rent out to external entities (ha)	Alternative location	0	0
	Reference farm	0	0
	Difference	None	None
Milk delivery (Liters/Year)	Alternative location	270,874	174,060
	Reference farm	270,874	174,060
	Difference	None	None
Beef production (Kg/Year)	Alternative location	10,140.8	3315.75
	Reference farm	10,138.2	3315.75
	Difference	2.6	None
Animal inventory (animals available at any given point in time, assuming continuous calving strategy)	Alternative location	NR dairy cow 10,000 kg = 30 NR heifer 24 mo = 26.25 NR heifer calf 3 mo = 3.75 NR bull 13 mo = 12.5 NR bull calf 3 mo = 3.75 Light suckler cow 72 mo = 6 Light heifer 24 mo = 2.625 Light heifer calf 3 mo = 0.375 Light heifer calf 3 mo sell = 0.375 Light bull 14 mo = 1.138 Light bull calf 3mo = 0.310 Light bull calf 3mo sell = 0.440	NR dairy cow 7500 kg = 25.703 NR heifer 24 mo = 22.490 NR heifer calf 3 mo = 3.213 NR bull calf 3 mo sell = 3.213
	Reference farm	NR dairy cow 10,000 kg = 30 NR heifer 24 mo = 26.25 NR heifer calf 3 mo = 3.75 NR bull 13 mo = 10.731 NR bull calf 3 mo = 3.219 NR bull calf 3mo sell = 0.531 Light suckler cow 72 mo = 6 Light heifer 24 mo = 2.625 Light heifer calf 3 mo = 0.375 Light heifer calf 3 mo sell = 0.375 Light bull 14 mo = 2.75 Light bull calf 3mo = 0.75	NR dairy cow 7500 kg = 25.703 NR heifer 24 mo = 22.490 NR heifer calf 3 mo = 3.213 NR bull calf 3 mo sell = 3.213
	Difference	Small increase in number of NR bulls 13 mo and small decrease in number of Light heifer bull 14 mo, with corresponding changes in the number of bull calves sold and reared of each breed at the farm.	None

country.

Relocating the reference farm to the region with higher baseline payment rates amplifies the competitiveness of the conventional approach over the organic one (Table 4). This finding is as could be expected, as baseline government payments increase while organic government payments remain constant, allowing the conventional farming method to capitalize further on its higher livestock maintenance capacity. Specifically, the GM for the conventional approach, factoring in government payments, shows a significant 19% increase compared to the reference scenario at Jæren (Table 4). Conversely, the organic approach shows a lower increase of 16.1% compared to its reference scenario. Milk production and animal inventory for both the conventional and organic approaches remain equal to their respective reference scenarios.

Although our work has focused on what is optimal from farmers' perspective, we believe our findings also provide insights for policy makers. Our results shed light on how the current payment scheme in Norway appears to favor organic farming practices less in certain regions than in others. From a policy standpoint, if the government is inclined to offer consistent incentives for organic farming throughout Norway, our results suggest the organic payments should be regionally adjusted, in line with other already regionally adjusted government payments.

4.8. Organic price premiums

Organic price premiums can promote organic farming. As such, it is interesting to see how the results would respond to an increase in these premiums, for example due to a higher demand for organic products.

As of March 2023, the organic price premiums for milk and beef were 0.85 NOK/l and 6.5 NOK/kg, respectively. This translates to an organic milk price which was 14.1% higher than the conventional milk price, and organic beef prices ranging from 8.2% to 14% higher than conventional beef prices, depending on the animal category.

As could be expected, a 50% increase in these premiums increases the competitiveness of organic farming versus conventional farming, yet the increase is moderate (Fig. 9). This increase represents an organic milk price that surpasses the conventional milk price by 21%, and organic beef prices ranging from 12.3% to 21% higher than conventional beef prices. These findings highlight that organic price premiums can make organic farming competitive with conventional farming in circumstances where cropland is more limited. Although not surprising,

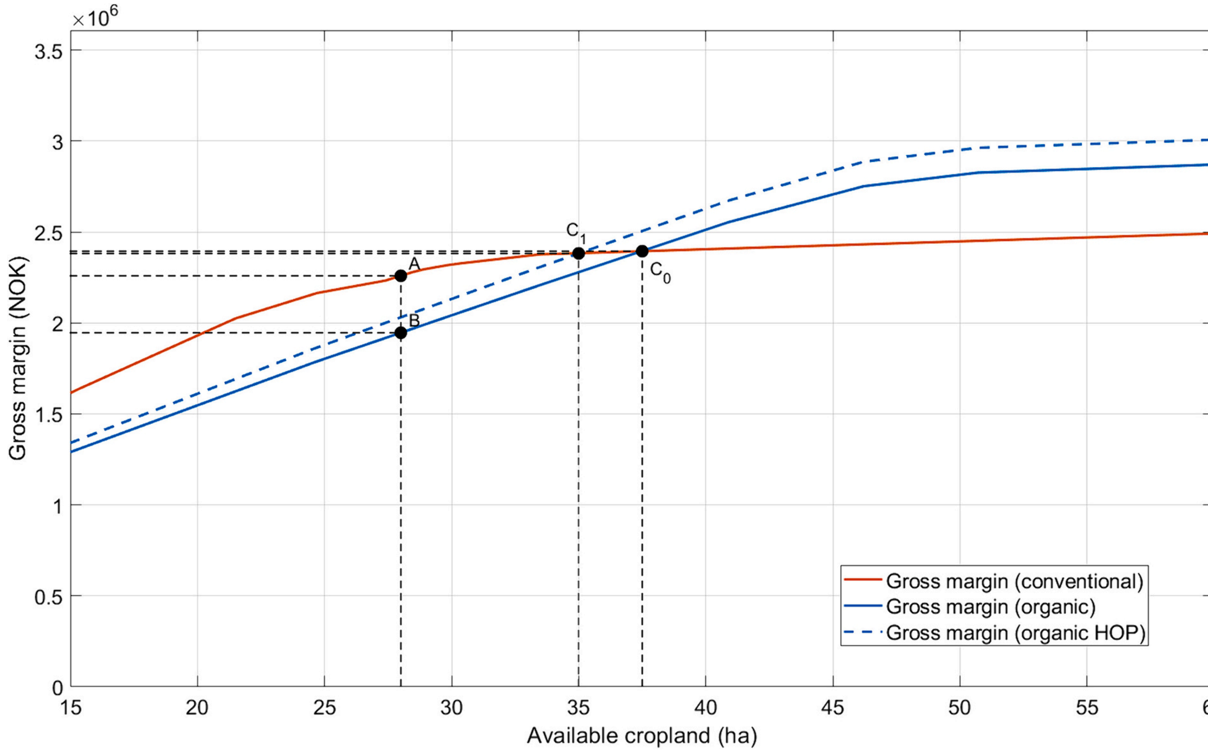

Fig. 9. Conventional and organic results for the reference farm with different availability of available cropland. 'Gross margin (organic HOP)' represents the results for the reference farm with higher organic premiums. Point A corresponds to the conventional solution for the reference farm. Point B corresponds to the organic solution for the reference farm. Point C_0 signals the level of available cropland at which conventional and organic operations are equally attractive given the current organic premiums, while point C_1 signals the same given higher organic premiums.

these results offer reassurance, suggesting that market-driven changes in organic price premiums can markedly incentivize conversion to organic farming, even in a system where government payments make out a significant part of farm revenue.

4.9. Other considerations

This study is grounded in a sophisticated model and thorough analysis. Strengths include the whole farm consideration, the inclusion of multiple cattle breeds and production systems, different slaughter ages, and feeding schemes calculated using a feed planning tool. It is crucial, however, to acknowledge that every model has its limitations, as coined by the statistician G.E.P. Box: "all models are wrong, but some are useful" (Box, 1976).

For instance, the model we employ is a steady-state model, best suited for long-term planning. The model does not account for the farm's initial conditions, or the potential costs associated with achieving the resulting optimal steady states. This limitation means that it does not consider processes like conversion from conventional to organic farming. The conversion period from conventional to organic farming systems of minimum 2 years can be financially difficult due to lack of access to premium prices, yield decreases, and conversion costs (Acs et al., 2007; Allison et al., 2021). The study by Allison et al. (2021) in the US, where no governmental organic farming payments were involved, found a fully converted organic dairy system to be more profitable than a conventional system. However, a period of twenty years was needed to justify the conversion of an existing conventional dairy to an organic dairy farm. In Norway, converting farmers receive the same rates of organic payments as existing organic farmers, in addition to area-based in-conversion payments in the first transition year to compensate for higher costs during conversion (Norwegian Government, 2023). Further research is needed to study the financial effects of the transition process under conditions with conversion support. While these factors could influence our quantitative results to some extent, we have no reasons to believe that they would fundamentally alter our qualitative findings, which emphasize the competitiveness of organic farming when there is a surplus of forage production capacity and high forage quality compared to available milk quota and stall spaces.

Furthermore, our model does not consider the possibility of purchasing milk quotas, which could lead to a larger milk quota. Additionally, it does not incorporate the possibility of expanding animal housing capacity. In cases where our model suggests that organic farming outperforms conventional farming, it is plausible that a conventional farmer might achieve higher economic gains by acquiring more milk quota or expanding their animal housing capacity instead of converting to organic farming practices. Hence, it is vital to interpret our model and its results with the awareness that unexplored opportunities for enhancing economic performance may exist beyond what is captured within the model. Nevertheless, it remains evident that the competitiveness of organic farming hinges on high forage production capacity and quality relative to other available resources like land and animal housing capacity.

In addition to the opportunities mentioned above, there exists a diverse array of promising avenues for future research. These include exploring risk factors and emissions, analyses of farm-level impacts of changes in agricultural policies, as well as delving into the realms of sequential decision-making and multi-objective optimization. Profit considerations, while no doubt important, is not always the priority for farmers (Howley, 2015), and multi-criteria approaches could better approximate behavioral responses than profit-oriented models. For the uptake of organic farming practices, non-financial reasons such as attitudes and environmental and human factors have been identified as more important than profit motives (Koesling et al., 2008; Swart et al., 2023). Policy makers hence need to consider a wide range of motivational factors beyond profit to encourage adoption of organic production – and more generally to assess farm-level impacts of policy changes.

Still, models based on profit-maximization are useful for both farm decision-making and policy recommendations as they can identify the optimal solution precisely, and farm profit is much easier to quantify in modeling than multiple non-financial factors.

5. Conclusion

In this research, we have examined the relative profitability of conventional and organic farming in the context of dairy and beef cattle systems in Norway, employing a tailored whole farm optimization model. Through an extensive series of computational experiments, we have demonstrated that the comparative profitability hinges on specific farm characteristics such as forage production capacity, forage quality, milk quota availability, and animal housing capacity, as well as their interrelationships.

Our findings suggest that when forage production capacity and quality are constrained in relation to other farm resources like available milk quota and animal housing capacity, conventional farming emerges as the superior choice in terms of GM. However, in situations where farms have access to substantial forage production capacity and forage of high quality compared to their milk quota and animal housing capacity, organic farming can outperform conventional alternatives. In other words, if forage (of good quality) is readily available, but the livestock operation cannot be expanded due to other resource constraints, such as animal housing and milk quota restrictions, organic may generate higher GM. However, in other circumstances, conventional is optimal. These insights hold substantial significance for farm advisors, farmers making informed decisions, and policy makers keen on promoting organic practices. Understanding the conditions under which organic practices become profitable not only aids in decision-making but also saves time, effort, and resources. For example, in cases where a farm's forage production capacity lags other resources, investing time, effort, and money in investigating the conversion potential may not be worthwhile.

In addition to the above, our research has revealed that the government payment system in Norway is designed such that there are regional differences in the incentives for organic farming. Organic payments remain constant across all regions in Norway, while other government payments exhibit variability contingent upon climatic factors and their influence on farming conditions. Consequently, the significance of organic payments relative to other government payments varies from one region to another, thereby contributing to regional disparities in incentives for organic farming. If the Norwegian government is interested in establishing uniform incentives for organic farming throughout the country, it is imperative that organic payments undergo regional adjustments.

Future research could introduce a temporal dimension and consider investments in increased milk quota and animal housing capacity within the model. This acknowledges the dynamic nature of farming practices and the potential to alter the availability of resources over time. In situations where organic practices prove economically superior for a specific combination of available farm resources, exploring investments in additional milk quota and animal housing capacity, rather than conversion to organic farming, could be a worthwhile avenue. An internal extension of the model to address such possibilities could provide a comprehensive framework for assessing these matters within the model itself, eliminating the need for external exploration.

Declaration of generative AI in scientific writing

During the final preparation of this work the authors used ChatGPT 3.5 (https://chat.openai.com/) to improve language, sentence structure, and grammar. The authors want to assure readers that this tool has been exclusively used for the specific purposes mentioned and no others. After using this tool, the authors carefully reviewed the AI-suggested improvements and made desirable adjustments before implementation. The authors take full responsibility for the content of the publication.

CRediT authorship contribution statement

Rasmus Bang: Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Validation, Visualization, Writing – original draft. **Bjørn Gunnar Hansen:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Mario Guajardo:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Jon Kristian Sommerseth:** Conceptualization, Data curation, Investigation, Resources, Software, Validation, Writing – review & editing. **Ola Flaten:** Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing. **Leif Jarle Asheim:** Investigation, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

Bjorn Gunnar Hansen reports a relationship with Tine SA that includes: employment. Jon Kristian Sommerseth reports a relationship with Tine SA that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103991.

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