Forage production strategies for improved profitability in organic dairy production at high latitudes

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Abstract

The objective of this paper was to examine how cutting frequency, silage fermentation patterns and clover performance in grass-clover swards influence the use of inputs and profitability in an organic dairy system. A linear programming model was developed to compare a three-cut and a two-cut system for a model farm in Central Norway, either with restricted or extensive silage fermentation at low or high red clover (*Trifolium pratense* L.) proportion in the sward, giving 8 different silage types in all. Input-output relations incorporated into the model were derived from a meta-analysis of organic grassland field trials in Norway as well as a silage fermentation experiment, and with feed intakes and milk yields from simulations with the 'TINE Optifôr' feed ration planner in the Norfor feed evaluation system. The model maximized total gross margin of farms with 260,000 l milk quota and housing capacity for 45 cows, with separate model versions for each of the 8 silage types. Farmland availability varied from 30 to 70 ha with 40 ha as the basis. Our results suggested that farmland availability and marginal return of a competing barley crop profoundly influenced the profitability of the different silage types. A high clover proportion increased dry matter (DM) yields and was far more important for profitability than the score on the other factors considered at restricted land availabilities. Profits with the three-cut systems were always greater than those with the two-cut systems, the former being associated with greater silage intakes and improved dairy cow performances but lower DM forage yields. Three-cut systems were further favoured as land availability increased and also by a lower marginal return of barley. Although use of an acidifying silage additive improved feed intakes and milk production per cow, the practice reduced total milk production and depressed profit compared to untreated, extensively fermented silage at restrictive land availabilities. With more land available, and in particular at a low marginal return of barley, use of a silage additive was profitable.

Keywords: digestibility; cutting system; clover proportion; silage additive; milk response; linear programming

1. Introduction

At high latitudes, the grazing season is short, and dairy farmers need to feed cows indoors for up to 8-9 months, resulting in a major reliance on conserved forage crops and concentrates. These limitations result in higher input costs than in pasture-based systems and a need, also for organic farmers, to lean somewhat towards high input-output milk production systems. Such strategies require highly digestible forages and rather high proportions of concentrates in the diet. The annual energy corrected milk (ECM) yield per cow in organic production in Norway increased from 6045 kg in 2007 to 7179 kg in 2013. In the same period, concentrate feeding increased from 153 to 177 MJ Net energy lactation per 100 kg ECM produced. Although the proportion of concentrate in the diet has increased considerably, the average organic dairy ration is still predominantly forage-based. Of the total net energy intake in 2012, 41% was made up of grass-clover silage and 11% of pasture (TINE Rådgivning, 2014). Feed is generally the greatest expense for milk production and various practices in the production of forages and feeding of the herd need to be evaluated to improve profits of organic dairy systems.

The ban of synthetic nitrogen fertilisers makes legumes crucial for forage yield and quality and for profits in organic systems (Doyle and Topp, 2004). In mixed grass-clover swards cropped for silage production, the regrowths contain more clover than the spring growth (Steinshamn et al., 2016). The regrowth herbage has, therefore, usually higher crude protein (CP) concentration and lower energy value than the herbage from the first cut. Benefits of clover compared to grass in silages, such as increased feed intake and higher milk production, are well-established (Johansen et al., 2018; Steinshamn, 2010), as are difficulties with poor clover survival in the field over time and challenges with higher buffer capacity in the ensiling process (Phelan et al., 2015).

In addition to forage supplies, milk production is also highly dependent on the forage feed quality. Because dry matter (DM) digestibility and content of CP decrease with advancing crop maturity, long intervals between harvests result in decreased forage intake per cow, whereas DM forage yield per hectare increases. Farmland availability has been found to profoundly influence the profitability of harvesting grass silages at early maturity stages in non-organic dairy systems (Flaten et al., 2015). However, few studies have examined the economics of different harvesting regimes in organic dairying, which has lower forage yields, more expensive purchased feeds and organic standards that restrict the level of concentrates in the diet compared to non-organic systems.

Fermentation of silage further influences the feed value of forage by reducing voluntary intake and utilisation of digestible nutrients (Charmley, 2001). Silage additives control and direct silage fermentation and are used to stabilize and prevent losses of DM and nutrients caused by fungal and bacterial infections. Restrictedly fermented silage improves feed intake and milk production compared to extensively fermented silage (Huhtanen et al., 2007). An older study in USA, however, pointed out that the profitability of acid treatment of silage may be low (Wangsness and Muller, 1981). Mostly based on experiments from the British Isles, Steen (2004) found that application of an inoculant additive to grass before ensiling did not improve margin over feed costs. Under current conditions, it is unknown whether the improved animal performance is sufficiently large to offset the application costs and the costs of the extra silage intake by cows as a result of acid-additive treatment.

No overall assessment, or balance, has been performed of how the examined factors guide production and profitability in organic dairy production. Clearly, more knowledge is needed on the economics of forage production strategies under organic dairy management. Thus, the objective of the current study was to examine how cutting frequency, silage fermentation patterns and clover performance in grass-clover swards influence the use of inputs and profitability in an organic dairy system at varying levels of farmland availability.

2. Materials and methods

The identification of the most profitable organic dairy system involves complex modelling and an integrated whole-farm approach, within which the most efficient way of using resources in crop production are considered simultaneously with how best to use feeds, either purchased or produced on-farm, in livestock production. In this paper, we present a linear programming (LP) model we have developed to find optimal farming systems, in order to enable us to determine the most profitable practices when comparing a three-cut and a two-cut system, either with restricted fermentation through acidification or untreated, at both low or high red clover (*Trifolium pratense* L.) proportions in the sward. The eight silage types were designated 2LCNF, 2LCRF, 2HCNF, 2HCRF, 3LCNF, 3LCRF, 3HCNF, and 3HCRF, respectively, where the symbols are 2/3: 2 or 3 cuts; LC/HC: low or high clover proportion; NF/RF: natural or restricted fermentation.

The data on forage yield and quality were obtained from a meta-analysis of experiments in organically cultivated grasslands in Norway (Steinshamn et al., 2016), and the silage fermentation parameters were obtained from a silage experiment using forage from a grass-clover sward (Bakken et al., 2017). The dairy cow feed ration formulations were based on NorFor – The Nordic Feed Evaluation System (Volden et al., 2011), where marginal milk responses were adjusted according to Jensen et al. (2015a).

We evaluated the management practices at one location; Kvithamar Research Station (63°28'N, 10°54'E, altitude 30 m, 900 mm precipitation, 182 growing days,) representative of the lowland of Central Norway. In this area, farmland can be used profitably for production of both forages and grain crops.

2.1. Farm modelling - general approach

The general structure of the mathematical model takes the form of a standard primal LP problem (Hazell and Norton, 1986):

Max $Z=c'x$ subject to $Ax \leq b$, $x \geq 0$.

Here Z is the objective value at the farm level; x is the vector of levels of activities forming the combined system, to be determined; c is the vector of gross margins or costs per unit level from each activity; A is the matrix of technical coefficients showing per unit resource requirements by the activities; b is the vector of right-hand side values of fixed resources and intermediate produce balances, relating to the constraints of the model.

One version of a single-year LP model was formulated and solved for each of the eight model versions to compare the corresponding optimal production plans and profitability. The model includes common activities and constraints to organic dairy farms in Norway. Important activities are: (1) crop production; land can be used for growing either grass-clover (for pasture or silage making) or barley; (2) purchase of a variety of concentrates with different protein levels; (3) livestock production with dairy cows (replacement heifers are assumed purchased); (4) purchase, sale and application of manure; (5) field operations, such as harvesting of grain and grass and silage making of grass-clover in round bales; and (6) government farm payments.

Each model activity has its own specific vector of technical coefficients and all vectors together form the matrix A. The constraints link the different activities to the fixed assets of farmland, milk quota, housing capacity and farm labour availability. Constraints were also set up to balance the combinations of activities to accommodate rotational limitations, herd replacement, government farm payments, manure allocation, organic legislation and periodical feeding requirements in order to match feed produced or purchased with animal requirements in the forms of concentrates, silages and pasture.

The model objective is to maximize total gross margin (TGM), which includes returns from livestock and arable crop production, government farm payments and land rented out, minus variable costs of production, such as forage and arable crop costs, purchased feeds, animal purchases, variable labour and other livestock-related expenses. Fixed cost items are not included since they were assumed to be the same for all model versions. Thus, differences in profit between the model versions can be assessed by comparing their optimal TGM values.

The matrices developed each comprised some 51-63 activities linked by and subjected to 37 constraints, with the number of activities reflecting the number of feeding regimes possible. The versions of the LP model and their underlying budgets were specified in a Microsoft Excel spreadsheet and solved using the LINDO (v. 6.1) software (LINDO Systems, 2003).

2.2. Crop production

Farmland can be used either for the production of grass-clover or barley, or else rented out. The area of grass-clover is considered as partitioned into one area for grazing in the summer and one for silage production to be fed in winter. The grass-clover swards are established by under-sowing in spring barley and persist for a further three years. Barley can also be sown as a sole crop. No forage marketing activities were included. Nutrients for crop production are supplied by manure, containing 5 kg total-N/tonne, either produced on the farm or purchased from non-organic cattle farms. One constraint (measured in kg total-N) ensures that the sum of manure used on-farm or sold off-farm cannot exceed that of manure produced on-farm or purchased.

Grassland yields and feed quality for silage production, to represent the activities in ley years, were obtained from the empirical equations in the meta-analysis of data from organic grassland field experiments conducted in Norway (Steinshamn et al., 2016). We examined two-cut and three-cut systems, both cutting systems with a low (around 0.1) and a high (around 0.4) clover proportion of the annual DM yield (Table 1), which were within one standard deviation of the observed means. Details on the timing of the cuts are reported in Appendix A.1. One hundred kg total-N per ha of manure was applied annually to the grass-clover swards.

[Table 1 around here]

Annual DM grass yields in two-cut swards were 3% (LC) and 12% (HC) greater than in three-cut swards (Table 1). Two-cut swards were lower in digestibility and CP concentration, and higher in neutral detergent fibre (NDF) concentration. Annual DM yields of HC swards were 32% (two-cuts) and 23% (three-cuts) higher than LC swards. More clover had a positive effect on CP concentration and lowered NDF concentration and digestibility.

The silage crop is mown, wilted to 25% DM, and wrapped into round bales using six layers of stretch-film. With acidification, grass silage is ensiled with formic acid-based additive (GrasAAT EC, containing 590 to 650 g formic acid/kg and 160 to 200 g sodium formate/kg, Addcon Group GmbH) applied at 4 l/t fresh weight of wilted crop. DM yields of silage fed to cows are reduced by 30 % compared to Table 1, to take account of lower yield responses achieved under commercial farm conditions than in field experiments and DM losses occurring during storage and feed-out.

Other cropping activities represented are: grazed grass, spring barley production and sward establishment undersown in barley; four levels of manure application rates are modelled for each of the crop groups. Details of these cropping activities are reported in Appendix A.1.

Costs of lime are included in all cropping activities. The costs of grass silage activities also include mowing, silage additives and baling. Pasture activities include costs of topping. Grass renewal costs such as seed, cultivations and drilling are incorporated into the sward establishment activities. The barley activities include revenue from grain sales and variable costs of production such as seed, cultivations, drilling, weed harrowing, harvesting and hauling. Contractors are employed for operations such as baling, handling and spreading of lime and slurry and harvesting of barley. For field operations using farmer-owned equipment, running costs of repairs and fuel are included. Costs of manure and its application are included in separate activities for buying and selling manure.

2.3. Effects of additives on silage fermentation and quality

Acid additives are applied to herbage to induce rapid pH decline, to prevent microbial activity and to preserve water-soluble carbohydrates (WSC) and restrict protein degradation. A high rate of formic acid added to the grass-clover mixture in the silage experiment (Bakken et al., 2017) resulted in lower contents of total acids and NH_3-N and a higher content of WSC in silage, when compared with extensively fermented untreated silage (Table 1). This has also been reported in other silage fermentation studies (Huhtanen et al., 2013).

2.4. Purchased feeds

In addition to the home-produced fodder, three types of organic concentrates, with different protein levels, can be purchased for dairy cows (Natura Drøv 16, Natura Drøv 19, and Natura

Drøv Protein) and one type for calves (Natura Drøv Start). Table 2 shows prices and feed characteristics of the concentrates.

[Table 2 around here]

2.5. Livestock production

The farm livestock activities comprise management of dairy cows, including the calves. It is assumed that cows calve in autumn, with one calf per cow per year. All calves are weaned and sold at 12 weeks. This study emphasises the dairy cows, and rearing activities were not included. Replacements purchased are assumed to be down-calving heifers at 2 years of age. (In practice, organic calves for replacement are often home-reared.) The replacement rate is 40%. The herd is composed of 40% first calvers, 30% second calvers and 30% older cows.

Manure DM and N excretion per cow depend on milk yield and weight whereas the influence of dietary intake of CP on N excretion is not taken into account (see Appendix A.2.). The N content is used to determine the application rates in the crops, whereas the quantities of manure (including wastewater etc.) are used to calculate manure application costs.

2.5.1. Simulation of dairy cow performance

The software 'TINE Optifôr' (TINE Rådgiving og Medlem, Ås, Norway) of the dairy cattle feed evaluation system NorFor was used to optimize the feed ration and modelled according to predetermined feed characteristic, pre-defined restrictions (concentrate quality and quantity) and planned production levels. The output from the feed optimization was subsequently fed to the LP model. NorFor is a semi-mechanistic, static and non-additive feed evaluation system that takes into account interactions between forage and concentrate characteristics in digestion and nutrient metabolism (Volden, 2011). It predicts nutrient supply and requirements for maintenance, milk production, growth and gestation in cattle.

The model produces a ration (at a fixed feed energy level) that provides all the required nutrients at the lowest possible cost by use of SNOPT (Sparse nonlinear optimizer) (Gill et al., 2005).

The ration formulation in ‘TINE Optifôr’ involves both the selection of feed ingredients and the prediction of feed intake. Dietary fill values and animal intake capacity are applied to predict feed intake. The fill value of concentrate is considered constant, whereas the forage fill value is calculated from organic matter digestibility and NDF content. ‘TINE Optifôr’ has incorporated the relative silage index (Huhtanen et al., 2007) to take into account the negative effects on forage intake by a high content of fermentation acids and NH_3-N in silage (cf. section 2.3). Animal intake capacity depends on body weight, stage of lactation, lactation number and physical activity.

Feedstuff inputs to our ‘TINE Optifôr’ optimizations were the concentrate mixtures for dairy cows in Table 2 and the eight silage types in Table 1, with their respective feed characteristics. Optimizations were performed separately for each of the eight silage types. The proportions of first cut and regrowth silages were equal to their shares in the annual yield, and the silage diets were constant throughout the year. The reason is that organic spring growths are often high in energy and low in CP, whereas the opposite is the case for regrowths dominated by clover. Animal performance tends to improve when the cuts are offered as a mixture rather than when fed alone (Naadland et al., 2017).

Animal inputs to our feed optimizations were breed (Norwegian Red), parity and body weight (first lactation 540 kg, second lactation 570 kg and older 590 kg), body condition score at calving (3.5), and activity (loose housing). A cow’s genetic merit was fixed at a medium feed intake level for each of the age groups, and prediction of milk yield in ’TINE Optifôr’ was estimated from the total supply of NEL (minus basal energy requirements). For each silage type, we optimized the feed ration composition and feed intake for target milk production level starting from 6000 kg per cow annually (average level of the three age classes) with increasing intervals of 500 kg up to a maximum of 9000 kg. Standard milk composition of 4% fat, 3.3% protein and 4.7% lactose were used in all simulations. For some rations, it was not possible to obtain the target production level due to limitation of one or more nutrients in the silage. Cows were fed silage ad lib, where more use of concentrates was associated with increased DM and energy intake and higher production of milk, but decreased forage intake. The model were solved for 22 lactation stages (of 2 weeks) giving a 308 day lactation.

To make it possible to estimate feed rations in Norfor, cows were assumed to be fed conserved forages for the whole lactation period. Pastures were restricted to the dry period, which are not in accordance with regulations for organic production (Mattilsynet, 2014). The requirement is that rearing systems for dairy cows are to be based on maximum use of grazing pasturage according to the availability of pastures in the different periods of the year.

'TINE Optifôr' minimizes feed costs at fixed energy levels, but it does not find the profit-maximizing feeding level. In addition, the Norfor system assumes a linear milk response of 0.318 kg ECM (energy corrected milk) per MJ NEL (net energy lactation) to milk production (Volden, 2011). Diminishing marginal milk response to increased energy intake is however a well-established concept (Huhtanen et al., 2013).

Jensen et al. (2015a) have developed empirical prediction models of milk responses to increased energy intake in dairy cattle – in the perspective of the NorFor model. They estimated models for primi- and multiparous cows in early (days in milk, DIM 1 to 100) and mid stages (DIM 101 to 200) of lactation, and found multiparous cows to have higher and more nonlinear responses in milk production to increased energy intake (marginal responses from 0.34 to 0.08 kg ECM/MJ NEL in the early stage of lactation) compared to primiparous cows with more linear response (from 0.20 to 0.15) within the observation ranges of NEL intake. They also reported higher marginal milk responses to changes in energy intake in early than in mid stages of lactation. We used parameter estimates from Table 4 in Jensen et al. (2015a) to adjust the marginal milk production responses to increased NEL intake from the Optifôr simulations. The NDF-models were used for early lactation and the natural logarithm of NEL (lnNEL-models) for the rest of the lactation (included after 200 DIM).

A diminishing marginal live weight gain response to increased energy intake during the first 100 days of lactation of primiparous and multiparous cows was taken into account by estimates from Jensen et al. (2015b). Energy requirement for deposition in cows from NorFor was used for the rest of the lactation. We assumed that, by the time of the following calving, live weight differences between feeding strategies would be eliminated, estimated through adjustments in the feed requirements for the dry period.

For the dry period, net energy requirements for maintenance, gestation and live weight change adjustments were calculated using the NorFor feeding standards. Dry cows were at pasture and were supplemented with 2.5 kg concentrates daily in the last three weeks before calving.

2.5.2. Feed intake and animal performance in the whole-farm model

Nutritional requirements and milk production were modelled for each of the three age classes of the milking herd separately, that is to say first lactation, second lactation and older cows. The coefficients on feed intakes and adjusted milk production from the TINE 'Optifôr' simulations were used in the whole-farm model. Up to 7 discrete dairy activities per age class (with different feed intakes and milk yield levels) are represented in each of the eight model versions. The model may choose a linear combination of two adjacent dairy activities within an age class.

Feeding requirements per cow are specified in two distinct periods: Lactation (308 days, indoors) and dry period (57 days, outdoors). Feeding constraints (measured in kg DM) reflect periodical feed supply and animal requirement of silage in the lactation, pasture grass in the dry period and the various types of concentrates, as well as purchased feeds to the calves. The calves are fed 61 kg DM of concentrates and 44 kg DM of purchased hay, in addition to 520 l of natural milk from the cows.

The returns from the dairy activities come from sales of milk, cull cows and calves. The costs include those of minerals, AI, veterinary services and medicines, manure handling costs, interest on the capital invested in the herd and miscellaneous. Costs of purchased feeds and followers are excluded from the dairy cow activities because separate activities for buying feeds and heifers are included.

2.5. Organic legislation

Organic standards regarding use of manure, livestock housing requirements, livestock density and feeding requirements (Mattilsynet, 2014) are handled through a number of constraints. One constraint ensures that the amount of manure nitrogen applied on the holding cannot exceed 170 kg of total-N/ha of farmland used. Each category of animal requires a minimum surface area for indoor housing. The indoor space used by the herd cannot exceed the capacity of the free-stall barn. One livestock density constraint ensures that a maximum number of livestock per hectare is not exceeded.

At least 60% of the DM ration to dairy cows must be provided by forages (at least 50% in the first 3 months of the lactation). The organic feeding requirement was taken into account in the feed simulations in 'TINE Optifôr'. Calves were fed natural milk for 12 weeks.

2.6. Labour, housing requirements, prices, and other farm premises

On dairy farms, the labour requirement is fairly constant throughout the year. The labour requirements for many farm tasks are not directly allocable to specific production activities (overhead labour). The supply of family labour available for production activities, or variable labour (2500 h), is set as equal to total family labour (5000 h) less overhead labour (2500 h). The input-output coefficients for variable labour requirements, such as farmers' own field machinery operations, feed-out of silage and concentrates, milking and animal handling, are assumed to be constant per unit of each activity (NILF, 2014).

The prices of farm inputs and outputs, some of which are reproduced in Table 3, are set to reflect 2014 conditions. An hourly cost of labour input is included. Sales, variable costs and labour for forage and grain crops and livestock activities are reported in Tables S.1.-S.2.

[Table 3 around here]

Farmers are paid various premiums per livestock head and per ha of farmland, including organic farming support schemes, with rates varying according to the type of livestock or crop and in some cases with a lower rate for higher stock numbers, as shown in Table 3. Activities and constraints related to all these premiums are incorporated into the model.

The only housing constraint included is the number of cow places available (loose housing). The farm is assumed to have housing capacity for 45 dairy cows. The milk production is constrained by an annual quota of 260,000 l, similar to the average quota of organic dairy farms in Central Norway participating in TINE's efficiency analysis. It is assumed that the farm has 40 hectares of owned land available.

2.7. Parametric programming

There is wide diversity across organic dairy farms with respect to land availability compared to housing and quota resources. We investigated how profits (total gross margin; TGM) and the optimal use of inputs changed as a function of farmland availability over a rather wide range, using the parametric programming routine in Lindo Systems (2003:173-174). A TGM function examines the behaviour of the optimal value of TGM as the land resource is varied. There will be several intervals for land availability on which the TGM function is linear. The points where the slope of the TGM function changes are called breakpoints. Changes in activities in the optimal solution occur at such breakpoints.

A further case is added in order to examine the effects of a lower marginal return on the barley crop competing for the use of the same land resources as forages, generated by removing all grain area payments (*ceteris paribus*).

3. Results

3.1. Diet optimizations and milk response

Summarized feed intakes for the whole lactation from the rations found by the feed cost minimizations in 'TINE Optifôr', together with annual milk yields adjusted by the estimates from Jensen et al. (2015a) for all dairy cow activities, are reported in Table S.1. Some general patterns of relationships within and between the eight silage types in the dairy performance data are presented in Fig.1 and 2.

[Fig. 1 and 2 around here]

Within a silage type (illustrated by 3HCRF), higher yielding cows required more concentrates (higher in protein) that depressed the intake of silage (Fig. 1). Substitution rates (reduction in silage DM intake/kg DM increased concentrate intake) were in the range from 0.30 to 0.50 and increased with increasing level of concentrates. Silage and concentrate intakes and milk production increased with lactation number.

For all silage types, marginal milk responses to increased energy intakes (planned milk yield increases of 500 kg ECM in 'TINE Optifôr'; 6000 – 9000 kg ECM) decreased from 245 to 176 kg, from 341 to 178 kg, and from 307 to 159 kg for first, second and later lactations, respectively (Fig S.1). First lactation cows had the lowest marginal milk response to increased energy intake. The lower marginal response in later lactations than in the second lactation was associated with the higher energy intake and milk yield of older cows in the given intervals.

The lower content of fermentation products in RF silages decreased rumen fill. At a fixed milk yield, the intake of silage was often around 400-500 kg DM greater for RF compared to NF silages (Fig. 2). Therefore, less concentrate supplementation was needed to meet the energy requirement when using RF silages. However, more concentrates with high protein content were required to compensate the low silage protein content with the higher forage intake with RF compared to NF rations. The exception was the 2LC silage type, where the feeding strategies at lower milk yields were the same both with and without the use of silage additives. The extremely low protein content in 2LC made protein level in the feed ration the most binding constraint. The protein concentrate dominated the supplements, and the higher intake capacity of the RF silage type could not be utilized.

Intake of the LC or HC silage types was fairly similar, but LC silage required the use of supplements higher in protein content (Fig. 2). Cows fed three-cut silage often achieved higher forage intakes than those fed with two-cut silage, although seldom more than 200 kg DM silage per lactation (Fig. 2). The exception was LCNF, where the two-cut system led to higher intake of silage than the three-cut system. The small differences in silage intakes between the two- and three-cut systems were related to the lower protein concentration of two-cut silages and, therefore, the use of considerably more high protein concentrates (Drøv Protein). Drøv Protein has much higher energy content per kg DM than the other concentrate types (Table 2). Consequently, the concentrate level needed to meet the nutrient requirement was lower, resulting in higher intake of forage with the two-cut than with the three cut-systems, thus counteracting some or all of the positive effects of early cut silage on forage intake.

3.2 Optimal farm plans

Table 4 summarises optimal model results for the eight silage types at 40 ha land availability. For all silage types, the land was fully used by forage production or grain linked to grass as a compulsory cover crop in the sward establishment year. The land use patterns reflect that the combined dairy and forage activities were more profitable than barley sown as a single crop.

[Table 4 around here]

Generally, the forage supply and number of cows were highest for the HC silage types, and two cuts produced more DM in silage than three cuts. Consequently, for the LC silage types, 130 – 180 tonnes of manure were purchased and applied in addition to manure produced on-farm, whereas for the HC types manure was only purchased in the case of 3HCRF. For the other HC silage types, only manure produced on the farm was applied. The higher manure application rates for sward establishment than for pasture were related to the different shapes of their respective response curves.

The restricted forage supply did not allow the milk quota or the housing capacity to be fully used for any of the silage types (Table 4). For the silage type with most milk sold (2HCNF), some 88% of the milk quota was produced. Less than 70% of the quota was filled for the LC silage types. Where milk yield is a free variable, the marginal principle (marginal revenue = marginal costs) applies to find the optimal milk yield levels, which were low to moderate. (See Table S.4 for the calculation of changes in net profit from 6500 to 7000 kg in milk production per cow in 3HCRF.) Less extra milk was obtained in the first than in later lactations (Table S.4), lowering the optimal planned milk yield in the first lactation (Table 4).

The most striking feature of the comparative economic analyses was the great importance of a high clover proportion in the sward for farm profitability (Table 4). Silage produced was 22–34 tonnes DM/year higher for HC than for LC silage types, allowing 5–10 more cows to be kept and 26 000–52 000 l more milk to be sold. Somewhat higher costs of concentrates, also per cow and per l milk sold were, for most HC silage types (except 3RF), of minor economic importance compared to lost net margin from increased milk sales and other livestock related income sources and payments. In total, HC silage types were NOK 69 000–75 000 more profitable than comparable LC types (Table 4).

Application of silage additives was not profitable for any of the silage types (Table 4). Additives increased silage intakes per cow and less concentrates were needed (except for 2LC, as explained in Section 3.1). Since the availability of silage was limited, fewer cows were kept and milk sales were reduced by 10 000–17 000 l compared to NF. Reduced costs from less use of concentrates for the RF silage types were not sufficient to offset net income losses from the lowered milk production and the costs of applying silage additives. In total, the use of silage type 3HCNF was found to be NOK 9 500 more profitable than the comparable 3HCRF type. For the other silage type comparisons, the net profit loss of applying additives was approximately NOK 25 000, quite close to the costs of the additives.

The three-cut systems supplied less silage DM than the two-cut systems, with less than 5 tonnes DM difference for the LC silage types, and close to 14 tonnes DM difference for the HC types. The number of cows was highest for the two-cut systems (except 2LCNF). Higher digestibility of silage from the three-cut system improved animal performance and resulted in lower costs of concentrates (per cow and per l milk sold). Additional gross margin of the dairy cows (plus government farm payments – variable labour) of the two-cut systems, e.g. NOK 80 000 for 2HCRF, could not offset lower costs of concentrates (NOK 97 000) and round-baling (NOK 10 000) of the respective three-cut system, in this case 3HCRF. Profitability increased by approximately NOK 25 000 for most three-cut systems compared to two-cut systems, except for the HCNF silage type, for which it was only NOK 9000.

Altogether, the best silage type, 3HCNF, was close to NOK 110 000 more profitable than the least favourable silage type, 2LCRF.

3.3 Parametric analysis of farmland availability

The effect on the relative performance of the eight silage types of changes to the area of the farm was investigated using parametric programming, by varying the farmland constraint from 30 to 70 ha. Table 5 reports changes in activities in the optimal solution at some breakpoints, restricted to full use of milk quotas and housing capacity and the introduction of barley as a sole crop in the farm plan. Table 5 also shows the use of inputs and milk production at both 30 and 70 hectares.

[Table 5 around here]

As more land became available, forage supplies increased and more milk was produced. The lower scarcity of land for forage production decreased the cost of silage, making higher intakes of forage per cow profitable with declining optimal input of concentrates and output of milk per cow (Table 5).

The milk quota was filled only for a few of the silage types. The housing capacity became fully used for all types of silage, first for the type yielding most forage DM per ha and requiring least silage per cow, that is 2HCNF (Table 5). Barley sown as a single crop entered the optimal solutions at the same breakpoint as filling of the housing capacity or later. All additional land above that was used to grow barley supported by purchased manure, with no changes in the dairy part of the farming system. Barley, to which 150 kg total-N/ha was applied in manure, turned out to be the marginal land-user with a shadow price (marginal return) of NOK 9747 per ha.

It is not easy to extract information from a graph of the eight curves of the optimal TGM functions, but Fig. S.2 demonstrates the highest profitability of 3HCNF up to 52 ha, where adding acids to the same type (3HCRF) became most profitable. 2LCRF was always lowest in profit. In Fig. 3 (left part) the additional TGMs are presented in graphs for three silage type comparisons (NFs vs. RFs; HCs vs. LCs; and three cuts vs. two cuts).

[Fig. 3 around here]

The profitability of the NF silage types (compared to RF) increased until their housing capacity was fully used (Fig. 3i), because with limited supply of silage, the increased intake of silage with the use of additives decreased total milk production and overall farm profitability became depressed. With more land available, enough RF silages were available to take advantage of the positive effect on feed intake obtained by the use of silage additives. It was however only for 3HC that the RF silage gradually emerged as the most profitable (from 52 ha), with a maximum net gain of NOK 13 100 for 3HCRF.

All HC-LC comparisons followed the same profitability patterns (Fig. 3ii). The gains of the HC silage types increased until barley as a single crop was introduced. For the LC silage types with lower DM yields, the benefits of producing milk (having a higher shadow price of farmland than barley) continued into larger farmland areas. The advantage of the HC types thus gradually declined until barley was introduced into the LC systems. The profit advantage of the HC systems then stabilised at NOK 37 000–69 000.

Three cuts were always better than two (Fig. 3iii). Greater land availability increased the profitability of three cuts (except for LCNF). The profit advantage of three cuts surged when barley first started to be grown in the two-cut systems. Again, this was because the marginal return of producing more milk in the three-cut systems was higher than that of barley production in the two-cut systems. The opposite trend in the LCNF-comparison was because, in contrast to the other cutting comparisons, forage intake per cow with LCNF was highest for two-cut silage. When barley was grown in both of the comparable silage types, three cuts added a profit of NOK 30 000–58 000.

3.4 No grain area payments

In Fig. 3 (right part) the optimal TGM function comparisons are drawn for the land constraint varying from 30 to 70 ha, while assuming no general or organic area payments for grain crops, *ceteris paribus*. (See Fig S.3 for the total TGM functions.) Use of inputs and outputs were the same as when the grain area payments were kept, until barley started to be grown in the latter case. Thereafter, a few hectares of barley was profitable only in combination with silage types with the greatest supply of home-produced manure (2HCNF, 2HCRF, and

3HCNF), as seen in Table 5. From the breakpoints where additional land was rented out, no changes occurred in the farming system itself. More land was devoted to forages without grain area payments than with, stemming from the lower return of renting out land (NOK 3000/ha) than growing barley with grain payments (NOK 9710/ha). The lower cost of silage made it profitable to reduce the use of concentrates per cow and lower the milk yield in order to increase the intake of silage (Table 5). Input of manure in pastures also decreased. When excess land started to be rented out, no manure was applied to pastures (not shown in Table 5).

With grain area payments taken away, the silage types that first led to introducing barley with area payments, lost more profit than those using more land to produce forage for the dairy herd. The comparison curves in Fig. 3 (right part) became steeper than with barley returns maintained (Fig. 3, left part), and silage types requiring more land to produce milk gained. The decreased barley returns thus made the use of systems requiring more forage area to produce milk, that is to say the use of silage additives, low clover performance and usually three-cut systems, comparatively more attractive (Fig. 3).

With the lower marginal return of barley, all RF silage types (except for the special case of 2LC) gradually emerged as profitable, and at lowest areas for the HC types (Fig. 3, right part). The profitability of using additives was highest for 3HC. LC silage types lost less compared to HC silages at abundant land availabilities, and with natural fermentation LC types could become more profitable than HC types. The improved profits of the LC types were associated with relatively large manure applications from outside the farm, compared to no or little manure purchases for the HC types. The advantage of three-cut silages as the land constraint was relaxed, was boosted even more than with the grain area payments in place (again expect LCNF).

4. Discussion

Through the integration of output from feed optimizations in a feed evaluation system model, data from a meta-analysis of organic grass yields and fermentation parameters from a silage experiment in a whole-farm LP model, the present study has evaluated optimal resource use and profitability of different forage production options on an organic dairy farm.

Land is generally a restrictive resource under organic grassland management. At the typical land area of 40 ha, the model farm was at best able to produce 88% of the milk quota and the housing capacity was not fully used. Unused milk quotas are frequently found also in reality. Organic dairy farms in the Norwegian Farm Business Survey (NFBS) had a comparable average quota fill of 90% both in 2013 and 2014 (NIBIO, 2015).

Optimal milk sales in the models at 40 ha were below 6000 l milk per cow per year. The rather poor incremental profit from additional milk production per cow was due to the combined effect of a narrow ratio of milk price to marginal feed input costs (cost of concentrates minus reduced forage costs) and the magnitude of the marginal milk responses (see also Table S.4). The lower price premium of organic milk (+ 0.65 NOK/l milk) than the premium of organic concentrates (+ 1.10 NOK/kg feed) above their non-organic counterparts contributes to lower profitability of high milk yields under organic management. In the NFBS (NIBIO, 2015), organic milk sales were also low to moderate, with 5998 and 6148 l per cow for the years 2013 and 2014, respectively.

4.1 Clover performance

Nitrogen has the greatest effect of all nutrients on forage yield, and the ability of forage legumes to fix atmospheric nitrogen is considered as particularly attractive for organic farming systems (Doyle and Topp, 2004). The current study found that annual profits usually improved by NOK 75 000 (NOK 1875 per ha) with a high (0.40) compared to a low proportion (0.10) of clover in the sward at a restricting land area of 40 ha. High land availability and a low marginal return of barley reduced the gain of HC silage types over LC types, and in a few comparisons the LC types even performed best. The greater success of the LC types under these conditions was dependent on applications of off-farm manures.

As the importance of clover for grassland yield in organic production is well documented (Steinshamn, 2010; Steinshamn et al., 2016), it was to be expected that clover proportion also had a pronounced impact on the profitability of organic dairy production. However, the relative economic importance of clover has not previously been documented. Red clover has a relative low persistency, and leys need to be renewed relatively frequently, every third or fourth year, in order to maintain high red clover proportion (Phelan et al., 2015). In the current study, frequency of renewal was set similar among ley types.

4.2 Cutting systems

The current study always found three-cut systems to perform better than two-cut systems. A previous study of non-organic dairy systems at the same location showed less frequent cutting systems to be most profitable at (very) restricted land availabilities (Flaten et al., 2015). Producing silage of high digestibility is the key to achieving greater intakes of silage and better performance of dairy cows. However, in the previous study highly digestible silages were obtained at excessive costs, due to lower DM yields, increased cutting costs, more frequent sward renewal and the extra silage eaten that resulted in fewer cows kept and lower milk production. One factor favouring highly digestible silages in the current study is that the

DM yields of the three-cut systems were only 3 to 11% lower than in the two-cut systems, compared to a 20% reduction in Flaten et al. (2015).

With more land available, more supplies of highly digestible forages will be available, thus taking further advantage of enhanced feed intakes. In the current study, the profitability of highly digestible silage increased as more land became available, as reported in Flaten et al. (2015).

4.3. Silage additives

More milk produced per cow with the use of formic-acid treated silage compared to untreated silage, is mainly derived through changes in feed intake (Huhtanen et al. 2003). At 40 ha, in addition to the cost of applying the additive, more silage eaten per cow resulted in less milk being produced with the use of RF silage types and overall farm profitability was depressed. Other studies have also found the use of silage additives such as acids (Wangsness and Muller, 1981) or inoculants (Steen, 2004) to reduce profitability in milk production.

With more land and forage supplies available, more benefits can be reaped of the enhanced forage intake by using RF silages. With current prices, it was however only for the 3HC comparison that RF was profitable at high land availability, due to the relatively high marginal return of organic barley. With a lower opportunity cost of land, RF gradually emerged as most profitable in most comparisons. The key to profitable use of silage additives was thus a comparatively low cost of the extra silage which the cows eat as a result of the additive treatment.

A major constraint to the benefit of additives was the very low CP content of the silages. As long as the protein supply (PBV) limits the microbial protein synthesis in the rumen, the potential improvement of restrictive fermentation on metabolizable protein supply (AAT) could not be realised, except in the case of the high clover silages in the three cut system where the CP content was highest.

DM losses from silages during storage and feed-out were assumed to be the same with or without additives. Additives, such as formic acid, may reduce the losses. In a meta-analysis, Goeser et al. (2015) found that the DM losses were on average 4.45% and 3.26% in untreated silage and in silage treated with fermentation inhibiting additives, respectively. For acid-treated silages to become most profitable in the current study, at 40 ha, additional DM losses (as percentage of harvested yield) for untreated silage above 1.5% for 3HC and around 4% for the other comparisons were needed (own calculations, not shown).

Milk yield and milk fat and protein content are reduced in cows fed extensively fermented silages as compared to restricted fermented silage (Huhtanen et al., 2003). The impact of fermentation pattern is taken into account in 'TINE Optifôr', but not the impact on milk protein and fat content. We may, therefore, have underestimated some economic gains of acid treated silages.

4.4. Limitations and future research

Mathematical models are idealised representations of actual decision problems and numerical results depend on the assumptions upon which the model has been constructed, the quality of the data input and the extent of details incorporated in the model.

One weakness of the model is the inclusion of only one manure application rate in the swards. This gave no possibility to further increase grass-clover yields, particularly in swards with a low clover proportion, by applying more manure (from outside the farm). Use of manure from conventionally managed farms is controversial in organic farming (Oelofse et al., 2013).

Another application of the model developed would be to assess changes in resource use and farm profits by additional restrictions on the use of off-farm manure.

The livestock responses are based on mathematical modelling of animal processes via the Norfor system rather than observed animal performances, e.g. by experimentation. Simulations may not accurately predict feed intake and milk production. NorFor, for example, overestimates intake with increasing milk yield (Jensen et al., 2015c). Real dairy cow experiments would, however, have required huge amounts of resources and might still not have provided sufficient information to identify appropriate production practices. In meta-analysis of data from existing dairy cow experiments, it was found that cows eat on average 1.1-1.2 kg more DM and yield about 1.1-1.5 kg more milk when fed on grass/red clover-based diets compared with grass-based diets (Johansen et al., 2018; Steinshamn, 2010). Higher DM intake on clover than on grass is likely due to higher rumen digestion and passage rate despite lower OM digestibility. In the current study, DM intake on high clover silage may have been underestimated, as the fibre digestion rate of high clover silage was calculated, based on chemical analysis, to be lower or similar to low clover silages. However, a positive effect of higher silage intake and milk production on high clover diets could have been offset by limited silage availability.

The untreated silage used in the models of the current study were well preserved (Bakken et al. 2017) under favourable harvesting conditions, which is in line with Finnish studies (Huuskonen et al., 2017). Baling of forages without additives is, however, more susceptible to difficult ensiling conditions (due to crop or weather factors), increasing risks of poor silage fermentation and subsequent lower feeding value of silage as compared to ensiling with acid-based additives. Unpredictable weather conditions and variation in crop DM and WSC concentration as well as epiphytic flora, are important factors to evaluate in the risk management of ensiling and in making decisions on silage additives (Huhtanen et al., 2013). Furthermore, variations between years in the timeliness of harvest and in the yield and quality of forages were not considered. Modelling of these various risks and adaptive strategies to cope with them would have made the model too complex for the main tasks at hand. There is, however, potential scope to extend the model developed to allow for some of these uncertainties.

Despite these limitations, the current model has proved robust enough to generate essential and logically sound understandings of the system.

5. Conclusions

We have compared the use of inputs and profitability of cutting frequency, fermentation patterns and clover performance in grass-clover swards in an organic dairy system at varying levels of land availability. The factor that had the most positive influence on profitability, due to higher forage yields and more milk produced, was the proportion of clover in the sward. Three-cut systems were always more profitable than two-cut systems. Cutting systems producing silages that result in increased intake of silage per cow, generally three-cut systems, performed relatively best at higher land availability and with a low marginal return of crops competing for the same land resources. Many organic farms will not have enough land at their disposal to make a profit from increasing intake of silage and improved cow performance by the use of formic-acid treated silage, since total milk production is reduced compared to untreated silage. With more land available, and particularly at a low marginal return of competing crops, use of a silage additive was profitable.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found online at:

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Appendix A. Supplementary material

A.1. Details of cropping activities

Silage – times of cutting and seed mixture

The timing of first cut and the regrowth periods after the first cut, were chosen to represent standard practice in Central Norway, using mean daily temperature data (2006-2010) at Kvithamar Research Station. The first cut was taken at the early booting stage and inflorescence fully emergence of timothy in the three and two cut systems respectively, which in the selected period was June 7 and 18. The second cut was taken 600 and 1000°C accumulated mean daily temperature after the first cut in the three and two cuts system, respectively, which was July 20 and August 23. The third cut was taken 680°C accumulated temperature after the second cut in the three- cut system, September 4.

For swards intended for cutting, seed mixtures of timothy (*Phleum pratense* L.), meadow fescue (*Festuca pratensis* Huds.) and red clover (*Trifolium pratense* L.) are used.

Grazed grass

Pastures are re-seeded every 4th year with seed mixtures of timothy, meadow fescue, smooth-stalked meadow grass (*Poa pratensis* L.), red clover and white clover (*Trifolium repens* L.). Pastures are topped throughout the grazing season to maintain pasture quality.

Spring barley

Spring barley production is modelled according to regional production standards, i.e., conventional cultivation for seedbed preparation, sown at 200 kg/ha, and mechanical weed control (weed harrowing). It is assumed that the only outlet for barley is to sell it, since a price subsidy on domestic grains used in the off-farm processing industry has encouraged farmers to pass their grain through the grain marketing system instead of using it as home-produced concentrates.

Sward establishment

The swards are established in the spring after ploughing and conventional cultivation for seedbed preparation. Seeding rates are 25 kg/ha for silage leys and 30 kg/ha for pasture. Grass is undersown in barley. The cover crop is sown at 150 kg per hectare. Barley is combined harvested and sold; no grass is harvested in the seeding year after sowing under a cover crop.

Yield responses to increasing applications of manure

Other crop yields than swards for cutting are subject to diminishing marginal returns to input of manure. Four levels of manure applications with associated yields are distinguished in the model with ranges of from 0 to 150 kg total-N per ha for pasture and from 50 to 200 kg total-N/ha for sward establishment and barley activities (Table 1). A maximum of two adjacent rates of manure application can be chosen in the optimisation process.

Table 1
Annual yields of pasture and barley at different manure application rates.

	Application of manure (kg total-N/ha)				
	0	50	100	150	200
Pasture (kg DM/ha)	2410	2960	3100	3180	–
Barley (sward est.) (kg/ha)[a]	–	1836	2372	2700	2835
Barley (kg/ha)[b]	–	2219	2754	3105	3249

Source: Flaten and Lien (2009) adjusted to field conditions at Kvithamar Research Station.
[a] Straw is sold for baling (no net value).
[b] Straw is incorporated into the soil.

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A.2. Manure Production Estimates

Equations used to calculate manure (including urine) and nutrient excretion of dairy cows (kg per cow per year) are based on Karlengen et al. (2012):

$\textit{Manure DM Excretion} = 633.104 + 0.415 \times MY + 0.690 \times BW$ (Equation 1.15)

$\textit{Total Nitrogen Excretion} = 39.148 + 0.00798 \times MY + 0.0433 \times BW$ (Equation 1.5),

where MY is milk yield (kg ECM/year) and BW is body weight (kg).

A dairy cow diet lower in crude protein (CP) concentration reduces N excretions (Lee et al., 2012). The most complex Norwegian regression equation (1.4) for calculating total N excretion by dairy cows includes CP content in roughage and CP content in concentrates as explanatory variables (Karlengen et al. 2012). Several feeding strategies in this study use the high protein concentrate Natura Drøv Protein (447 g CP per kg DM) as the single supplement. The protein concentrate has a much higher CP concentration than that of the concentrates used in the construction sample of Equation 1.4 (140 to 230 g CP per kg DM). Extrapolation of Equation 1.4 was found to be useless. The simpler regression equation (1.5) not including dietary CP levels were therefore used. Total N intake in the diets is according to animal requirements, and there is no overfeeding of protein.

Dry matter content in manure is 9% (Nesheim et al., 2011).

Manure from calves is added, in total 500 kg of wet manure excretion and 2.5 kg of nitrogen excretion per calf (Karlengen et al., 2012).

Washing water (300 l per lactation month) and 10% addition to the wet manure excretion due to wastewater and bedding material are added (Nesheim et al., 2011).

Manure indoor is produced for 11 months (indoor feeding period plus half of the grazing period).

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Table S.1. Annual milk production, feed intake, sales, variable costs and variable labour requirement in the dairy cow activities

Activity[a]	Milk yield (kg/year)	Lactation (kg DM/cow)				Dry period (kg DM/head)		Sales (NOK/head)[b]	VC (NOK/head)[c]	Labour (h/head)
		Silage	Natura 16	Natura 19	Natura protein	Grass	Concentrates			
2 cuts, low clover, natural fermentation										
C2LNP_60	5597	4070	0	0	610	445	44	31588	4201	31
C2LN2_60	6258	4273	0	0	761	533	44	34674	4239	32
C2LNM_60	6767	4371	0	0	811	510	44	37406	4268	33
C2LNP_65	5844	4163	0	0	721	432	44	32864	4212	31
C2LN2_65	6605	4278	0	0	931	507	44	36471	4256	33
C2LNM_65	7086	4375	0	0	974	488	44	39054	4283	34
C2LNP_70	6074	4040	273	0	772	421	44	34056	4236	32
C2LN2_70	6913	4140	372	0	914	484	44	38067	4284	34
C2LNM_70	7369	4242	360	0	959	470	44	40521	4309	35
C2LNP_75	6289	3909	422	0	924	409	44	35171	4248	32
C2LN2_75	7186	4036	564	0	1016	462	44	39477	4300	34
C2LNM_75	7618	4133	558	0	1072	450	44	41808	4325	35
C2LNP_80	6491	3715	707	0	1018	399	44	36213	4262	33
C2LN2_80	7424	3851	757	0	1176	445	44	40711	4313	35
C2LNM_80	7834	4033	564	0	1317	436	44	42925	4333	36
2 cuts, low clover, restricted fermentation										
C2LRP_60	5597	4070	0	0	610	445	44	31588	4201	31
C2LR2_60	6258	4273	0	0	761	533	44	34674	4239	32
C2LRM_60	6767	4371	0	0	811	510	44	37406	4268	33
C2LRP_65	5844	4163	0	0	721	432	44	32864	4212	31
C2LR2_65	6605	4278	0	0	931	507	44	36471	4256	33
C2LRM_65	7086	4375	0	0	974	488	44	39054	4283	34
C2LRP_70	6074	4040	273	0	772	421	44	34056	4236	32
C2LR2_70	6913	4140	372	0	914	484	44	38067	4284	34
C2LRM_70	7369	4242	360	0	959	470	44	40521	4309	35
C2LRP_75	6289	3984	130	0	1090	411	44	35171	4239	32
C2LR2_75	7187	4109	205	0	1236	469	44	39483	4290	34
C2LRM_75	7616	4217	217	0	1299	453	44	41800	4315	35
C2LRP_80	6491	3950	223	0	1229	399	44	36214	4250	33
C2LR2_80	7427	4062	322	0	1364	446	44	40725	4304	35

Activity	Milk yield	Silage	Natura 16	Natura 19	Natura P	Grass	Concentrates	Sales	VC	Labour
C2LRM_80	7828	4128	407	0	1400	433	44	42896	4329	36
C2LRP_85	6679	3801	440	0	1348	389	44	37189	4264	33
C2LR2_85	7634	3956	428	0	1545	429	44	41798	4315	35
C2LRM_85	8012	4069	417	0	1592	425	44	43846	4337	36
2 cuts, high clover, natural fermentation										
C2HNP_60	5597	3900	0	1080	0	445	44	31588	4229	31
C2HN2_60	6258	3987	0	1361	0	533	44	34674	4267	32
C2HNM_60	6767	4102	0	1414	0	510	44	37406	4296	33
C2HNP_65	5845	3846	0	1105	187	432	44	32870	4234	31
C2HN2_65	6607	3942	0	1337	226	506	44	36483	4278	33
C2HNM_65	7087	4074	0	1249	329	487	44	39062	4303	34
C2HNP_70	6076	3673	0	1462	187	420	44	34066	4247	32
C2HN2_70	6917	3826	0	1447	387	483	44	38088	4290	34
C2HNM_70	7370	3935	0	1476	411	467	44	40525	4316	35
2 cuts, high clover, restricted fermentation										
C2HRP_60	5597	4316	0	0	574	445	44	31588	4188	31
C2HR2_60	6258	4471	0	0	779	525	44	34674	4226	32
C2HRM_60	6767	4564	0	0	830	505	44	37406	4255	33
C2HRP_65	5846	4210	0	302	580	432	44	32874	4213	31
C2HR2_65	6606	4312	0	469	665	506	44	36477	4260	33
C2HRM_65	7087	4389	0	554	662	487	44	39061	4289	34
C2HRP_70	6077	4061	0	497	699	420	44	34071	4227	32
C2HR2_70	6916	4199	0	558	847	483	44	38083	4274	34
C2HRM_70	7370	4318	0	590	861	467	44	40527	4300	35
C2HRP_75	6293	3905	0	766	764	409	44	35187	4241	32
C2HR2_75	7189	4027	0	902	862	462	44	39495	4291	34
C2HRM_75	7618	4036	0	930	947	450	44	41811	4316	35
3 cuts, low clover, natural fermentation										
C3LNP_60	5597	3822	0	807	0	444	44	31588	4224	31
C3LN2_60	6258	4011	0	1007	0	532	44	34674	4263	32
C3LNM_60	6767	4160	0	1022	0	509	44	37406	4292	33
C3LNP_65	5842	3853	0	990	0	432	44	32854	4236	31
C3LN2_65	6600	3993	0	1228	0	506	44	36443	4279	33
C3LNM_65	7080	4139	0	1233	0	487	44	39025	4307	34

Activity	Milk yield	Silage	Natura 16	Natura 19	Natura P	Grass	Concentrates	Sales	VC	Labour
C3LNP_70	6071	3835	0	1220	0	420	44	34039	4247	32
C3LN2_70	6905	3949	0	1468	0	483	44	38025	4294	34
C3LNM_70	7359	4048	0	1530	0	467	44	40468	4320	35
C3LNP_75	6285	3854	0	1146	219	409	44	35148	4251	32
C3LN2_75	7176	3957	0	1314	297	462	44	39427	4299	34
C3LNM_75	7605	4072	0	1354	297	450	44	41740	4324	35
C3LNP_80	6486	3676	0	1445	277	399	44	36189	4260	33
C3LN2_80	7414	3835	0	1487	419	445	44	40657	4309	35
C3LNM_80	7820	3949	0	1519	426	436	44	42853	4333	36
3 cuts, low clover, restricted fermentation										
C3LRP_60	5597	4216	0	0	368	444	44	31588	4183	31
C3LR2_60	6258	4476	0	0	487	529	44	34674	4222	32
C3LRM_60	6767	4607	0	0	540	503	44	37406	4251	33
C3LRP_65	5842	4298	0	0	461	432	44	32857	4195	31
C3LR2_65	6599	4503	0	0	614	506	44	36440	4238	33
C3LRM_65	7074	4619	0	0	662	487	44	38994	4265	34
C3LRP_70	6073	4358	0	0	588	420	44	34050	4206	32
C3LR2_70	6906	4521	0	0	762	483	44	38030	4253	34
C3LRM_70	7354	4493	0	0	887	474	44	40441	4279	35
C3LRP_75	6289	4262	0	320	582	409	44	35166	4231	32
C3LR2_75	7179	4375	0	499	643	462	44	39440	4284	34
C3LRM_75	7602	4387	0	507	742	451	44	41727	4307	35
C3LRP_80	6490	4136	0	501	708	399	44	36208	4243	33
C3LR2_80	7417	4267	0	674	761	445	44	40675	4296	35
C3LRM_80	7818	4368	0	735	753	436	44	42844	4321	36
C3LRP_85	6678	3930	0	839	764	389	44	37183	4256	33
C3LR2_85	7624	4091	0	901	884	430	44	41746	4308	35
C3LRM_85	8004	4214	0	965	852	426	44	43809	4331	36
C3LRP_90	6854	3820	0	832	1028	380	44	38094	4262	33
C3LR2_90	7802	3983	0	835	1194	419	44	42667	4312	36
C3LRM_90	8163	4160	0	802	1216	417	44	44631	4333	36
3 cuts, high clover, natural fermentation										
C3HNP_60	5597	3745	1036	0	0	450	44	31588	4219	31
C3HN2_60	6258	3959	1233	0	0	536	44	34674	4258	32

Activity	Milk yield	Silage	Natura 16	Natura 19	Natura P	Grass	Concentrates	Sales	VC	Labour
C3HNM_60	6767	4127	1254	0	0	509	44	37406	4286	33
C3HNP_65	5845	3844	1205	0	0	432	44	32872	4231	31
C3HN2_65	6607	3939	1489	0	0	506	44	36479	4274	33
C3HNM_65	7085	4077	1513	0	0	487	44	39048	4302	34
C3HNP_70	6075	3841	1301	0	99	421	44	34063	4239	32
C3HN2_70	6914	3876	1600	0	134	483	44	38073	4285	34
C3HNM_70	7366	4027	1616	0	135	467	44	40504	4311	35
3 cuts, high clover, restricted fermentation										
C3HRP_60	5597	4454	364	0	0	445	44	31588	4219	31
C3HR2_60	6258	4506	689	0	0	533	44	34674	4258	32
C3HRM_60	6767	4590	774	0	0	510	44	37406	4286	33
C3HRP_65	5846	4358	686	0	0	432	44	32874	4231	31
C3HR2_65	6609	4407	1014	0	0	506	44	36490	4274	33
C3HRM_65	7088	4493	1087	0	0	487	44	39063	4302	34
C3HRP_70	6077	4127	1129	0	0	420	44	34071	4242	32
C3HR2_70	6919	4236	1406	0	0	483	44	38095	4289	34
C3HRM_70	7371	4349	1455	0	0	467	44	40529	4315	35
C3HRP_75	6293	3940	1372	0	123	409	44	35187	4248	32
C3HR2_75	7192	4088	1503	0	206	462	44	39508	4296	34
C3HRM_75	7619	4223	1533	0	206	450	44	41813	4321	35
C3HRP_80	6494	3809	1452	0	329	399	44	36230	4253	33
C3HR2_80	7430	3959	1578	0	419	445	44	40742	4303	35
C3HRM_80	7835	4101	1595	0	420	436	44	42931	4327	36

[a] Abbreviations in the 'Activity' column: C2/C3: 2 or 3 cuts; L/H: low or high clover proportion; F/R: natural or restricted fermentation; P/2/M: first lactation, second lactation, or older cows; 60, 65, …, 90 refers to the predicted milk yields (in 100 kg) in TINE 'Optifôr', from 6000 to 9000 kg milk produced annually per average cow in the herd..

[b] Sales of milk, cull cows, and calves.

[c] Minerals, AI, veterinary services and medicines, manure handling costs, interest on the capital invested in the herd and miscellaneous.

Table S.2.
Summary of sales, variable costs and variable labour requirements in the forage and grain crop activities.

Activity	Crop sales (NOK/ha)	Variable costs (NOK/ha)	Labour (h/ha)
Seeding year (50 kg N/ha)	6132	5895	7.9
Seeding year (100 kg N/ha)	7921	5965	7.9
Seeding year (150 kg N/ha)	9018	6007	7.9
Seeding year (200 kg N/ha)	9469	6025	7.9
Barley (50 kg N/ha)	7410	4253	6.9
Barley (100 kg N/ha)	9198	4323	6.9
Barley (150 kg N/ha)	10371	4369	6.9
Barley (200 kg N/ha)	10852	4387	6.9
Silage (2LCNF)		5397	1.4
Silage (2LCRF)		6361	1.4
Silage (2HCNF)		6979	1.4
Silage (2HCRF)		8254	1.4
Silage (3LCNF)		5391	2.1
Silage (3LCRF)		6323	2.1
Silage (3HCNF)		6448	2.1
Silage (3HCRF)		7588	2.1
Pasture (0 kg N/ha)		514	3.0
Pasture (50 kg N/ha)		514	3.0
Pasture (100 kg N/ha)		514	3.0
Pasture (150 kg N/ha)		514	3.0

Abbreviations: 2/3: 2 or 3 cuts; LC/HC: low or high clover proportion; NF/RF: natural or restricted fermentation.
Cost of manure and its application are excluded from the forage and grain crop production activities.
Variable costs for sward establishment activities in pasture are NOK 380 per ha higher than for silage (shown), due to the higher seed rate.

Table S.3.
Net change in profit (NOK per cow) by a switch from 6500 to 7000 kg per cow planned milk production for the three age classes (3 cuts, high clover, restricted fermentation). Forty ha of land, 260 000 l milk quota and 45 cow places.

		Physical change (/cow)			Monetary change (NOK/cow)		
	Price[a]	1. calver	2. calver	Older	1. calver	2. calver	Older
Added revenue							
Milk (l sold)	5.45	220	295	269	1197	1606	1466
Manure (kg N)	16.00	1.8	2.5	2.3	19	25	23
A. Change in revenue					1216	1631	1488
Added costs							
Concentrates (kg DM)[b]	5.17	443	392	368	2289	2029	1904
Labour (h)	150	0.39	0.62	0.59	58	93	88
Reduced costs							
Silage (kg DM)	4.15	-231	-171	-144	-959	-711	-597
Pasture (kg DM)	5.56	-12	-23	-20	-66	-130	-110
B. Net change in costs					1322	1280	1286
Net change in profit (A – B)					-106	350	202

[a] Shadow prices for manure, silage and pasture.
[b] Formel Drøv Natura 16.

Fig. S.1.
Actual marginal milk response for the three age classes at increased predicted milk yield in 'TINE Optifôr' (intervals of 500 kg milk). Total lactation. Based on Jensen et al. (2015a).

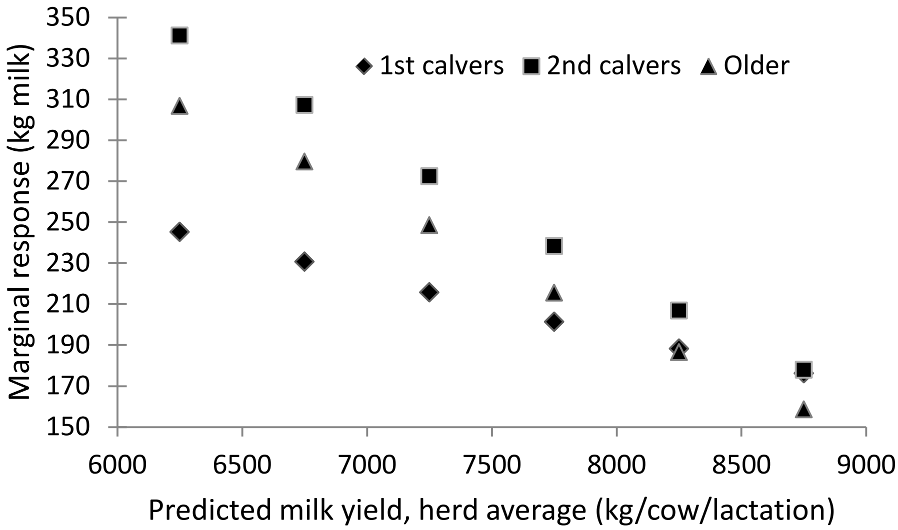


Fig. S.2. Optimal TGM functions at land constraint (30-70 ha) with 260 000 l milk quota and 45 cow places.

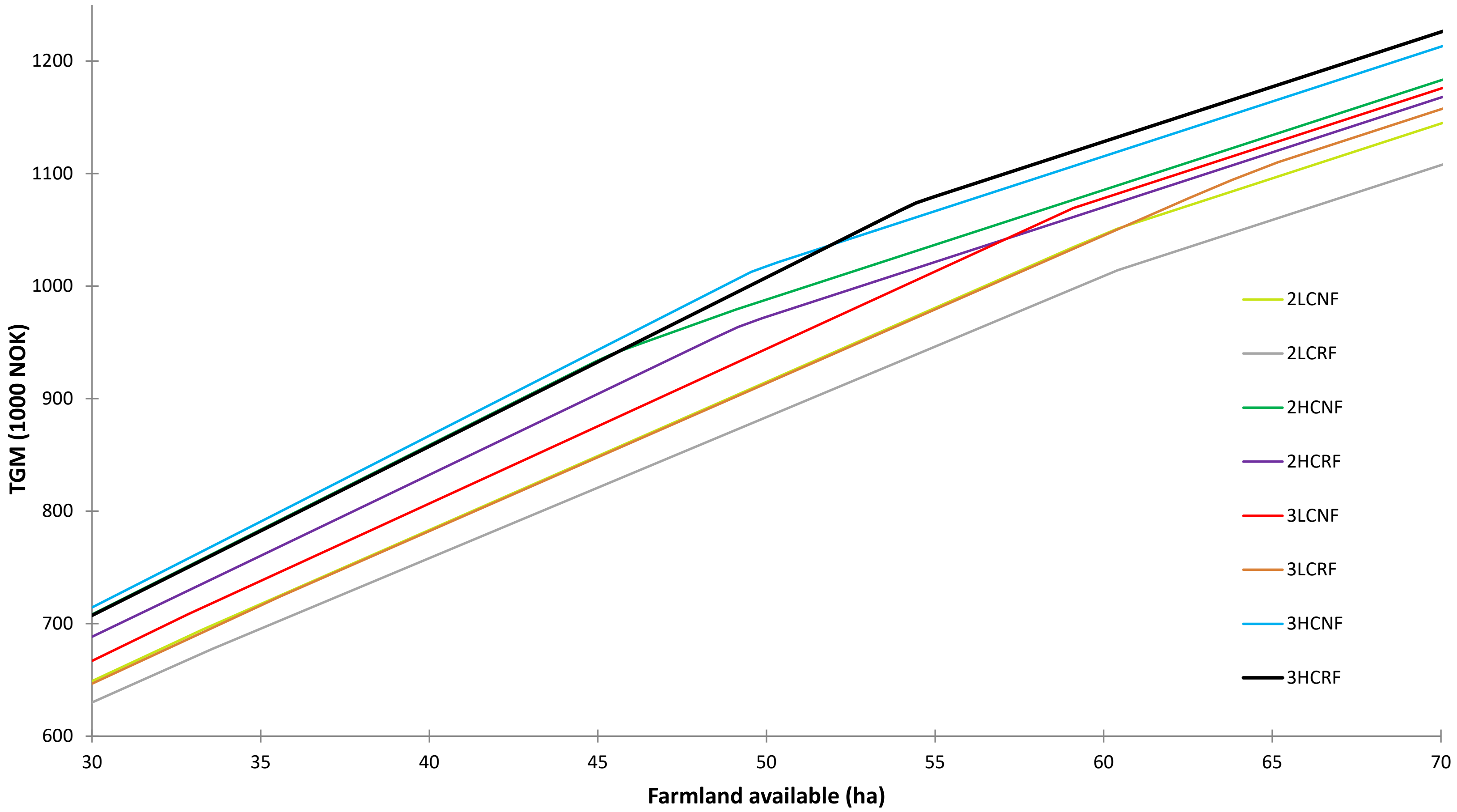
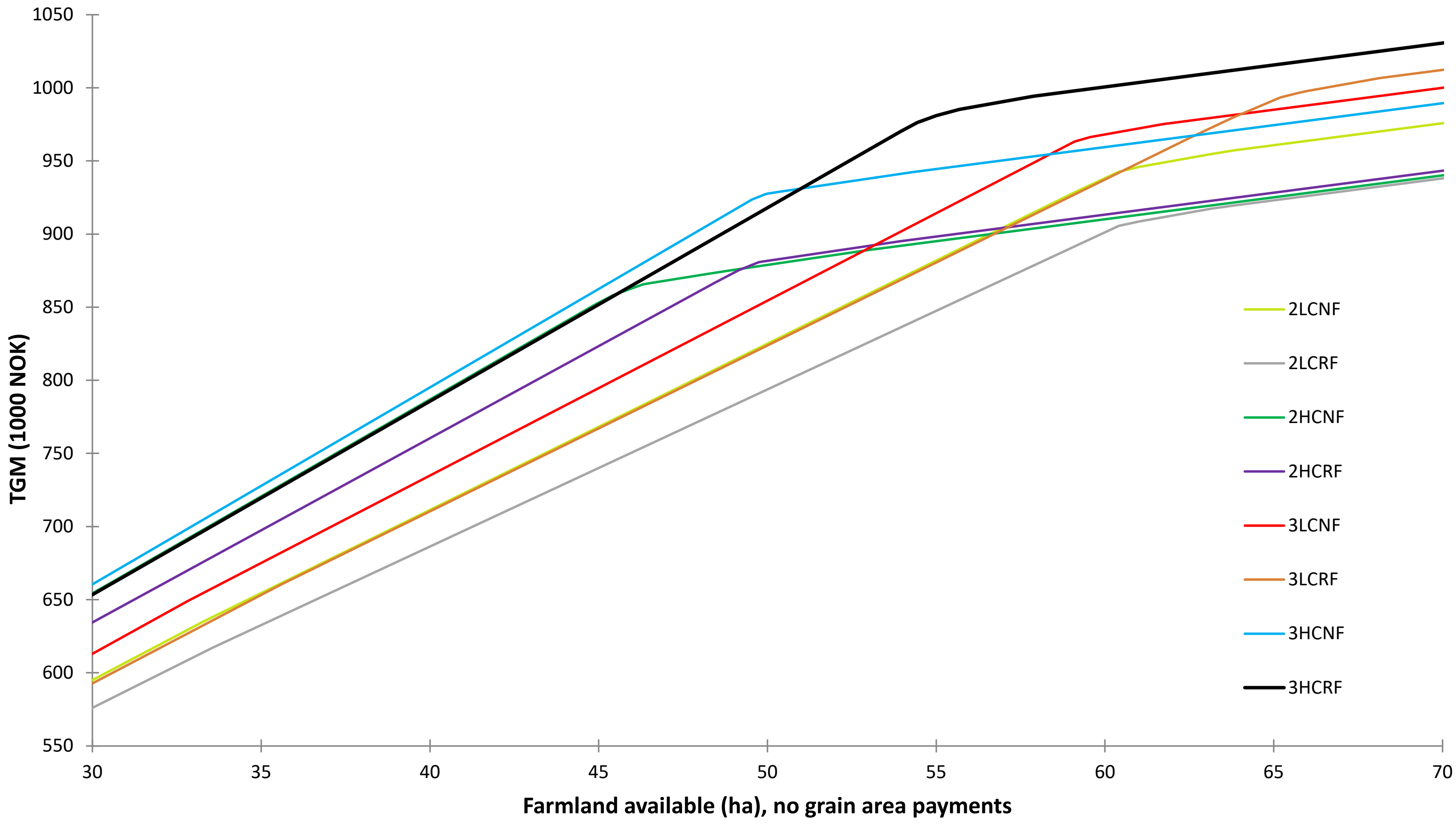
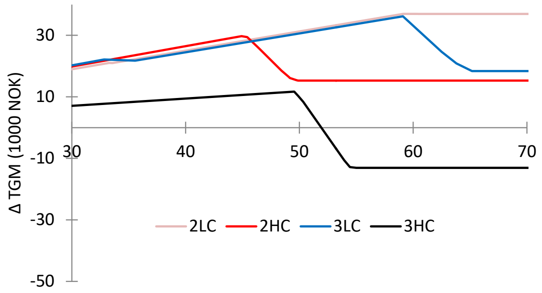
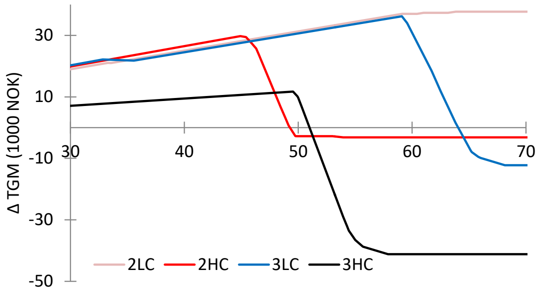


Fig. S.3. Optimal TGM functions at land constraint (30-70 ha) with 260 000 l milk quota and 45 cow places. No grain area payments.

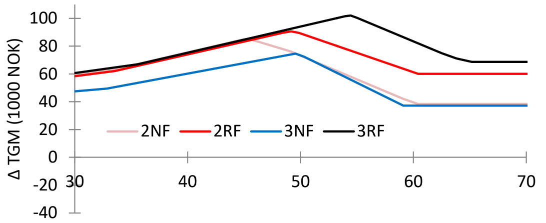


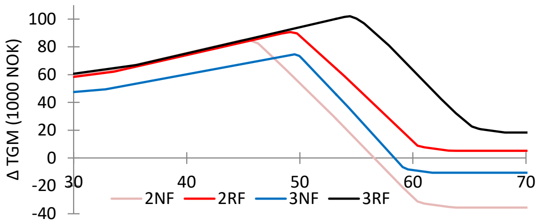
i. Natural - restricted fermentation



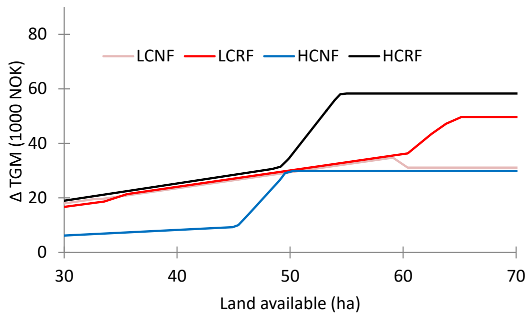


ii. High clover - low clover





iii. 3 cuts - 2 cuts



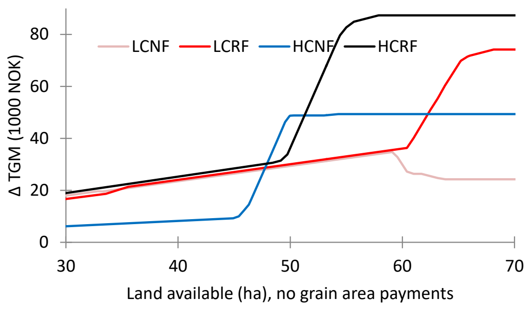


Table 1

Annual DM yields (sum of all cuts) and chemical composition (weighted averages of the cuts) of grass-clover silages not treated (natural fermentation) or treated with formic acid (restricted fermentation) according to number of cuts and clover performance.

	Natural fermentation				Restricted fermentation			
	2 cuts		3 cuts		2 cuts		3 cuts	
	LC[a]	HC[a]	LC	HC	LC	HC	LC	HC
Yield (kg DM/ha)[b]	7010	9270	6780	8290	7010	9270	6780	8290
Clover proportion in DM yield[b]	0.09	0.38	0.07	0.41	0.09	0.38	0.07	0.41
DM (g/kg)	250	250	250	250	250	250	250	250
Composition of silage								
IVOMD (% of DM)[c]	72.0	69.9	74.9	74.1	72.0	69.9	74.9	74.1
CP (g/kg DM)[d]	91.3	115.2	122.8	143.3	91.3	115.2	122.8	143.3
Soluble CP (g/kg CP)[e]	553	545	529	529	471	464	451	451
NDF (g/kg DM)[f]	540	498	500	458	540	498	500	458
pdNDF (g/kg NDF)[g]	879	838	898	855	879	838	898	855
kdNDF (%/h)[h]	3.9	3.4	4.2	4.0	3.9	3.4	4.2	4.0
NH_3-N (g/kg total N)[e]	57.6	56.7	54.9	54.9	33.9	33.7	33.4	33.4
TAF (g/kg DM)[e,i]	124.5	127.5	133.3	133.4	50.6	52.9	57.4	57.5
Water-soluble carbohydrates (g/kg DM)[e]	24.5	22.3	18.2	18.1	144.2	137.0	123.2	122.9

[a]Acronyms: LC is low and HC is high clover proportion.

[b] From the meta-analysis published by Steinshamn et al. (2016). Commercial DM yields harvested are reduced by 20%. An additional 10% of the DM yields reported in Table 1 is lost during storage and feed-out.

[c] IVOMD is in vitro organic dry matter digestibility, estimated from IVDMD according to Mcleod and Minson (1974). The IVDMD was determined from equation in Steinshamn et al. (2016).

[d] CP is crude protein determined from equation in Steinshamn et al. (2016).

[e] From the ensiling experiment published by Bakken et al. (2017).

[f] NDF is neutral detergent fibre determined from equation in Steinshamn et al. (2016).

[g] pdNDF is potentially degradable NDF fibre determined from equation in Steinshamn et al. (2014).

[h] kdNDF is the degradation rate of potentially degradable NDF calculated according to Volden (2011).

[i] Total fermentation acids (TAF) = lactic acid + acetic acid + propionic acid + butyric acid.

Table 2
Prices and feed characteristics of the purchased concentrate mixtures.

	Price (NOK/kg)	NEL (MJ/kg DM)	CP (g/kg DM)	AAT (g/kg DM)	PBV (g/kg DM)
Natura drøv 16	4.50	7.46	179	117	0
Natura drøv 19	4.90	7.69	214	132	22
Natura drøv Protein	6.78	9.36	447	198	201
Natura drøv Start	4.86	7.38	224	120	43

Notes: Commercially available concentrates produced by Felleskjøpet, Norway. Price per kg feed, 870 g DM/kg feed.
NEL = Net energy lactation; AAT = Amino acids absorbed in the small intestine; PBV = protein balance in rumen.

Table 3
Economic parameters, prices, and government farm payments.

Parameter	Value (NOK)	Parameter	Value (NOK)
Receipts		*Livestock expenses*	
Milk[a]	5.45/l	Purchase of heifer	14 000/head
Culled young cows[a,b]	44.31/kg CW	Miscellaneous, cows[d]	3510/head
Culled cows[a,b]	43.81/kg CW	Hay to calves, organic	4.00/kg
Calf value (12 weeks old)	3378/head	*Other expenses*	
Barley[a]	3.34/kg	Seeds, organic grass silage	76/kg
Manure, sold	40/t	Seeds, organic pasture	76/kg
Land, rent out	3000/ha	Seeds, organic barley	6.40/kg
Governmental payments		Silage additive	10.75/l
Grassland	3010/ha	Diesel	8.00/l
Grain	3780/ha	Lime[d]	0.60/kg
Dairy cow, 1-16	4028/head	Manure, purchased[e]	80/t
Dairy cow, 17-25	2072/head	Contract charge,	
Dairy cow, 26-50	1000/head	manure handling	30/t
Dairy cow, structural 1-5	25 000/head	Custom baling, incl.	
Vacation payment[c]	3522/cow	wrapping and transport	175/bale
Grassland, organic	250/ha	Contract charge,	
Grain, organic	3000/ha	combining grain	1500/ha
Dairy cow, organic	2800/head	Cost of labour	150/h

Source: NILF (2014). Exchange rates in 2014 was NOK 100 = € 11.97.

[a] Organic price premiums are included: Milk (NOK 0.65/kg), culled cows (NOK 2.75/kg CW, carcass weight), barley (NOK 0.95/kg, 15% water).

[b] Young cows are cows culled before second lactation. Carcass weights are 250 kg for first calvers, 270 kg for second calvers, and 285 kg for older cows.

[c] Maximum payment is NOK 73 500.

[d] Includes minerals, AI, veterinary services and medicines, dairy supplies, interest on breeding herd, etc.

[e] Cost of purchased lime and manure includes material, hauling it to the field and application. Limestone is applied at an average rate of 300 kg/ha/year.

Table 4

Model solutions and financial results for the eight silage types at 40 ha land available, 260 000 l milk quota and 45 cow places.

	2LCNF	2LCRF	2HCNF	2HCRF	3LCNF	3LCRF	3HCNF	3HCRF
Land use								
Ley for grass silage (ha)	25.4	25.4	24.0	24.4	25.3	25.8	24.5	24.8
Pasture (ha)	4.6	4.6	6.0	5.6	4.7	4.2	5.5	5.2
Ley establishment (ha)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Barley (ha)	0	0	0	0	0	0	0	0
Manure to pasture (kg N/ha)	50	50	100	81	50	50	68	50
Manure to ley establishment (kg N/ha)	150	150	174	150	150	150	150	150
Silage produced (t DM/year)	124.7	124.5	155.8	158.0	120.0	122.2	142.0	144.1
Purchase of manure (t/year)	135.1	144.8	0.0	0.0	128.4	181.8	0.0	54.1
Livestock								
Dairy cows (head)	30.0	29.8	40.1	37.2	30.5	28.1	36.3	33.4
Milk sold (1000 l/year)	175.9	172.1	227.8	211.1	175.7	166.4	209.9	192.8
Milk sold (l/cow/year)[a]	5854	5776	5684	5680	5770	5917	5776	5779
Milk yield (1./2./older)[b]	65/75/70	65/70/70	60/70/70	60/75/65	65/70/70	65/75/75	65/70/70	65/70/70
Concentrates total (t DM/year)	37.9	35.0	66.2	45.6	42.6	28.3	59.3	41.3
− Natura 16	8.3	6.5	0.0	0.0	0.0	0.0	52.6	37.8
− Natura 19	0.0	0.0	52.5	16.2	39.4	8.5	0.0	0.0
− Natura Protein	26.5	25.3	9.6	25.5	0.0	16.9	2.9	0.0
− Natura calf	1.8	1.8	2.4	2.3	1.9	1.7	2.2	2.0
− Dry period[c]	1.3	1.3	1.7	1.6	1.3	1.2	1.6	1.5
Financial results (1000 NOK)								
Gross output	1747.9	1724.9	2123.8	2004.7	1750.7	1678.5	1990.0	1870.4
Milk sales	957.7	937.1	1240.2	1149.7	956.9	905.9	1142.6	1050.0
Cull cow and calves	149.1	147.8	198.8	184.4	151.1	139.5	180.3	165.6
Grain sales	90.2	90.2	92.3	90.2	90.2	90.2	90.2	90.2
Government farm payments	550.9	549.8	592.5	580.4	552.6	542.9	577.0	564.7
Costs	964.8	966.8	1265.1	1172.5	944.1	896.3	1123.1	1012.9
Seed, lime, plastic wrap, machinery	200.1	200.0	231.6	233.6	199.4	203.7	221.4	223.5
Silage additives	0.0	24.5	0.0	31.1	0.0	24.0	0.0	28.3
Concentrates	266.9	248.7	393.6	312.1	240.0	195.7	316.0	215.1
Purchase of livestock	168.3	166.9	224.4	208.2	170.6	157.5	203.4	186.9
Manure purchased	10.8	11.6	0.0	0.0	10.3	14.5	0.0	4.3

Miscellaneous	124.9	123.7	166.8	153.8	126.9	114.4	151.2	138.9
Variable labour	193.7	191.5	248.7	233.7	196.9	186.5	231.1	215.9
Gross margin	783.2	758.1	858.7	832.2	806.7	782.2	866.9	857.5
Marginal analysis								
Cost of silage (NOK/kg DM)[d]	3.93	3.96	3.44	3.63	4.26	4.28	4.00	4.15

Abbreviations: 2/3: 2 or 3 cuts; LC/HC: low or high clover proportion; NF/RF: natural or restricted fermentation.

[a] The unsold milk includes milk fed to calves (520 l per cow) and 2% waste of the original production (colostrum milk, penicillin milk etc.). The density of milk is 1.031 kg /l.

[b] Optimal milk yields (in 100 kg) for each of the age classes (1st calvers/2nd calvers/older) based on the 'TINE Optifôr' predictions of milk produced. Marginal milk responses and actual production were adjusted according to Jensen et al. (2015a).

[c] Same quantities of purchased hay (in kg DM) to calves.

[d] The shadow (dual) price of the silage constraint showing the real cost of silage made up of the variable costs of the crop and the net opportunity costs of the fixed resources required by the crop.

Table 5

Breakpoints (in ha) and optimal solutions for cases with: a) with grain area payments, b) without grain area payments. Land is constrained (30-70 ha), the milk quota is 260 000 l, and 45 dairy cow places.

	2LCNF	2LCRF	2HCNF	2HCRF	3LCNF	3LCRF	3HCNF	3HCRF
a. Grain area payments								
Milk quota filled (ha)[a]	59.1; 60.4	–	–	–	–	62.5	–	53.9; 54.0
Housing capacity used (ha)	60.4	60.4	44.9	48.4	59.1	65.2	49.5	53.9
Barley introduced (ha)	60.4	60.4	45.4	49.7	59.1	65.2	49.9	55.0
Dairy cows (head)[b]	22.5; 45.0	22.4; 45.0	30.1; 45.0	27.9; 45.0	22.8; 45.0	21.1; 45.0	27.3; 45.0	25.0; 45.0
Milk sold (1000 l/year)[b]	132; 260	129; 260	171; 252	158; 248	132; 260	125; 260	157; 256	145; 252
Milk sold (l/cow/year)[b]	5854; 5776	5776; 5776	5684; 5603	5680; 5514	5770; 5770	5917; 5777	5775; 5696	5778; 5603
Purchase of manure (t/year)[b]	101; 506	109; 506	0; 627	0; 603	96; 517	136; 470	0; 590	0; 558
Concentrates (t DM/year)[b]	28.4; 52.8	26.2; 52.8	49.7; 70.2	34.2; 46.8	32.0; 63.0	21.2; 35.9	44.5; 70.2	31.0; 44.9
Silage (t DM/year)[b]	93.5; 188.1	93.4; 188.1	116.9; 176.8	118.5; 195.1	90.0; 177.3	91.7; 198.8	106.5; 176.6	108.1; 198.0
Cost of silage (NOK/kg DM)[b,c]	4.15; 3.00	4.18; 3.20	3.43; 2.51	3.63; 2.71	4.48; 3.13	4.40; 3.32	4.00; 2.74	4.15; 2.94
b. No grain area payments								
Milk quota filled (ha)[a]	59.1; 60.4	–	–	–	–	62.5; 65.2	–	53.9; 54.0
Housing capacity used (ha)	60.4	60.4	44.9	48.4	59.1	65.2	49.5	53.9
Barley introduced (ha)[e]	–	–	46.5	49.8	–	–	50.0	–
Land rented out (ha)	63.8	63.8	53.0	54.0	61.7	68.1	54.3	57.9
Milk sold (1000 l/year)[d]	252.3	252.3	244.0	248.1	256.1	260.0	256.3	248.2
Milk sold (l/cow/year)[d]	5607	5607	5423	5514	5690	5777	5696	5515
Purchase of manure (t/year)[d]	202	202	0	0	151	291	0	73
Concentrates (t DM/year)[d]	43.4	43.4	64.3	46.8	59.0	34.5	70.2	39.6
Silage (t DM/year)[d]	191.8	191.8	178.8	195.1	178.6	201.9	176.6	200.3
Cost of silage (NOK/kg DM)[c,d]	1.66	1.86	1.43	1.63	1.73	1.93	1.53	1.80

Abbreviations: 2/3: 2 or 3 cuts; LC/HC: low or high clover proportion; NF/RF: natural or restricted fermentation.

[a] For 2LCNF, 3LCRF, and 3HCRF the quota is filled in the land availability interval shown. (Milk yield per cow decreases as land availability improves.)

[b] First numbers are values at 30 ha; second numbers are values at 70 ha.

[c] See note d in Table 5.

[d] Optimal solution from the breakpoint where additional land is rented out to 70 ha.

[e] Areas of barley are at maximum 4.3 ha, 1.5 ha and 2.2 ha in 2HCNF, 2HCRF, and 3HCNF, respectively.