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Timing of the outfield grazing season and finishing of lambs: A whole-farm modelling study of forage-based sheep production systems in Norway

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ABSTRACT

Norwegian sheep production is based on the use of free outfield grazing resources in the mountains and forests in summer. Lamb prices are strongest at the beginning of the slaughter season in August and then begin to gradually decline, reaching a lower plateau in mid-October. Seasonal pricing provides incentives to get slaughter lambs to market early. The objective of this study was to examine how outfield summer pasture quality, time of collection from the outfields, and inclusion of annual forage crops in the diet of finishing lambs influence optimal farm plans and profitability in Norwegian forage-based sheep production systems at varying levels of farmland availability (varying from 15 to 25 ha with 20 ha as the basis). A linear programming model was developed for sheep production systems in the mountainous areas of Southern Norway. Input-output relationships incorporated into the model included data from field experiments with grasses for annual and perennial use, observed performance of lambs and ewes at pastures, a feed planning tool for the indoor season, and expert judgements. The model maximised total gross margin of farms with a housing capacity of 200 ewes. The results suggested that with more land available, drafting older and heavier lambs for slaughter was profitable. The lighter lambs at weaning were usually drafted much later and at the same or heavier carcass weights than the heavy lambs at weaning because of seasonal pricing. Higher quality outfield summer pastures increased lamb live weights at weaning. Annual profits improved considerably with rich summer pastures compared to poor summer pastures. Early collection was always less profitable than normal time of collection because greater prices for lambs sold could not offset losses from the additional feed costs incurred and a possibly smaller flock. Speeding up the growth rate of finishing lambs by offering annual forage crops in addition to grazed grass was usually more profitable than grass only. Only for rich summer pastures and normal time of collection at low land availability was use of annual forage crops unprofitable.

1. Introduction

Grassland or rangeland-based sheep farming systems across the world represent sustainable alternatives to large-scale intensive systems (Dumont et al., 2013). Where sheep grazing is removed, there can be shrub encroachment, which can lead to loss of elements of landscape and biodiversity (Dýrmundsson, 2006). Since the demand for land suitable for human-edible crop production is small, sheep also contribute to food supplies without triggering the feed-food competition (Mottet et al., 2017).

At high latitudes, the grazing season is short. Housing and indoor feeding of the sheep is required throughout the winter in Nordic and Alpine regions (Dýrmundsson, 2006). In Norway, mating, pregnancy, and lambing of the seasonal sheep breeders coincide with the indoor period. The flock is let out on infield spring pastures when lambs are a few days to a couple of weeks old (Vatn, 2009). Norwegian agriculture distinguishes between “infield” and “outfield” pastures (Strand et al., 2019). The infields are pastures on cultivated and fenced farmland. The infield land may be used as pasture in the spring and in the autumn, but also to harvest and conserve forage crops to be used in the indoor period. The outfields are unmanaged and unfenced pastures in forest and mountain areas. Free-roaming sheep graze the outfields in the summer, and they are inspected at least once a week. Lambs are weaned after collection from the outfields in autumn and are slaughtered directly or after a finishing period on the same farm. At slaughter of lambs, average carcass weight is ~ 19.5 kg at an average age of 155–160 days, but weight and age vary considerably (Animalia, 2016–2018). The breeding stock stays in the autumn pastures until they are housed again in late

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autumn. More than 45 % of the Norwegian land area consists of outfields suitable for grazing. Currently, only 40 % of the grazing resources in the outfields are used to feed livestock (Strand et al., 2019). In summer, nearly two million ewes and lambs from approximately 14,000 farms graze in the outfields (Statistics Norway, 2021). Average flock size in 2021 was 70 ewes, however, around 55 % of the ewes were found on farms with more than 100 ewes.

Meat makes up almost 90 % of total sheep market returns in Norway. The remainder comes from wool. However, more than 60 % of the total revenues from sheep farming are government farm payments. Nevertheless, profitability in Norwegian sheep production is low (Flaten, 2017) and there is a continued need to evaluate various farm practices to improve profit.

The seasonal nature of sheep reproduction in temperate regions results in significant variation in the quantity of lamb reaching the market throughout the year (Chemineau et al., 2007). Consequently, lamb prices follow a strong, consistent pattern from season to season. In Norway, prices are strongest in August and then begin to gradually decline, reaching a lower plateau in mid-October. Adjustments to the dynamics of seasonal trends are an important component of successful sheep farming. However, the influence of seasonal pricing on optimal crop and livestock management has not been addressed in previous studies of sheep production systems that depend on outfield grazing in summer.

The producer can increase returns from finishing lambs by selling when prices are high. Use of forages with high feed value can provide lambs with better growth rates (De Brito et al., 2017), and fast growth rates get lambs to market early. Factors that promote lamb growth rates include high grazing quality of the outfield summer pastures (Lind et al., 2020), the use of annual forage crops (grasses, legumes, or brassicas) or concentrates to speed up the growth rate of finishing lambs after weaning (De Brito et al., 2017; Todnem and Lunnan, 2017), and a shortened outfield grazing season that is replaced with feed options for better growth of finishing lambs. With a shortened outfield period, more feed will be required from costlier home-grown feeds, and the flock may have to be smaller. The use of annual forage crops in combination with offering grazed grass to improve lamb growth allows more lambs to be finished earlier at better prices with less maintenance feed. However, the establishment costs of annual forage crops must be recovered in a single year, whereas the costs of perennial forage crops are spread over several years. To date, no study has examined the relative profitability of outfield summer pasture quality and early versus normal collection times and how these management strategies influence optimal whole-farm systems. In addition, whether using annual forage crops in addition to grazed grass for finishing lambs is financially justifiable, and at what weight lambs on different diets should be drafted when considering seasonal and qualitative aspects, is unclear.

Simple budgeting techniques, such as gross margin analysis, complete budgets, and partial budgets, are the most widely used aids to developing improved farming systems (Nuthall, 2011). These techniques are cheap and quick but may fail to capture important aspects, such as biological interactions between enterprises and the application of the opportunity cost concept for limited available resources. An alternative is detailed whole-farm optimisation modelling. Identification of the most profitable sheep production system involves complex modelling and an integrated whole-farm approach, within which the most efficient way of using resources in forage production (and outfields in the Norwegian context) is considered simultaneously with how best to use feeds, either purchased or produced on-farm, in livestock production. Optimisation models are often based on linear programming (LP, Janssen and van Ittersum, 2007), also for exploring factors to improve sheep farming systems (Fisher, 2001; Thompson et al., 2016; Young et al., 2020) or to study policy impacts (Vosough Ahmadi et al., 2015; Asheim et al., 2020). Skonhoft et al. (2010) analysed the economics of sheep farming based on outfield grazing in summer within an optimal control framework, however, these tools are better used for part-farm problems than whole-farm approaches (Nuthall, 2011). No existing models were suitable for the issues to be examined in this study.

The objective of the present study was to examine how outfield summer pasture quality, time of collection from the outfields, and inclusion of annual forage crops in the diets of finishing lambs influence optimal farm plans and profitability in Norwegian forage-based sheep production systems at varying levels of farmland availability. An LP model was developed to better understand the impact of resource availability and the role of constraints on the farm business. The model was not developed to predict actual farmer responses, but rather to unravel the complexity of the farming system and explore patterns, where the normative farm goal is to maximise profit.

2. Materials and methods

The constructed LP model enabled us to evaluate management practices in specialised sheep production systems in Norway. Fig. 1 represents the choices and decisions the farmer is faced with for the modelled farming system: allocation of available farmland resources for forage crops, herd size, types of animals to be sold, livestock feed requirement satisfaction, and time of collection from the outfields, influenced by prices of farm inputs and outputs and government payments. These choices are interdependent. The model objective is to maximise profit subject to available farm resources (land, labour, housing) and other restrictions.

2.1. Study areas

Sheep in Norway are released into a wide range of summer grazing environments. These outfield areas differ in soil and climatic conditions, affecting the growth rates of the lambs. In any case, sheep have free access to outfields in the summer, and no supplementary feeds is provided.

In this study, two typical outfield environments in the Nord-Østerdalen region located in the mountainous areas of Southern Norway were studied. The outfield areas, reaching from 700 to 1500 m above sea level (masl), have similar climates but different soil fertility. The Spekedalen study area (62°08'N, 11°20'E) has bedrocks dominated by sparagmite, an arkosic nutrient-poor sandstone, and the sheep pasture quality is generally poor ("poor pasture" area). In the Bratthøa study area (62°32'N, 10°44'E), the bedrock is dominated by base-rich phyllite,

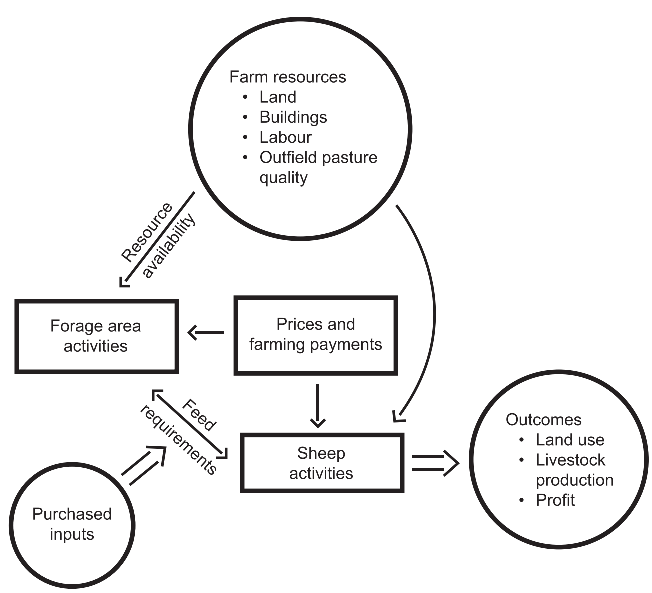

Fig. 1. Conceptual diagram showing the main features of a sheep farming system. Outfield pasture quality and time of collection from outfields influence forage and livestock activities.

resulting in richer vegetation ("rich pasture" area). The difference in soil fertility is reflected in mean lamb autumn live weights (LWs; 1993–2013) of 47 kg in the rich pasture area and only 40 kg in the poor pasture area (Jørgensen et al., 2018).

Infield farmland has the same quality regardless of the outfield grazing opportunities. Considerable farmland areas in the Nord-Østerdalen region are located at ~ 500 masl, representative of the mountainous areas of Southern Norway. In this area, farmland can only be used profitably to produce forage crops.

2.2. Farm modelling – general approach

The LP models optimise farm activities to maximise the value of the objective function (Z) at the farm level with respect to a set of fixed farm constraints. The general structure of the mathematical models is shown in Table 1 and takes the form of a standard primal LP problem (Hazell and Norton, 1986):

$$\text{Max } Z = c'X \text{ subject to } AX \leq b, X \geq 0$$

where a prime superscript indicates a row vector. X is the vector of the 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 that give amounts of inputs and outputs for a unit of each activity; and b is the vector of right-hand side values or constraints. One version of a single-year steady-state LP model was formulated and solved for each of the two areas (rich and poor summer pastures) to find the optimal production plans and farm profit.

The matrices comprised up to 104 activities linked by, and subjected to, 48 constraints. The group of activities, based on common sheep practices in the area, are shown at the top of Table 1: (1) forage production for on-farm use, land can be used for growing grass from temporary leys or annual forage crops for grazing and silage; (2) hiring out land; (3) purchase of a variety of concentrates; (4) sheep production, including mature ewes, rearing of ewe lambs, and finishing of slaughter lambs on different diets and drafted for slaughter at different carcass weights (CWs), with separate activities for early and normal time for collecting the flock from the outfield; (5) government farm payments; (6) feed out of feeds; and (7) labour supply.

Each model activity has its 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, housing capacity, and farm labour availability (Table 1). Constraints were also set to balance the combinations of activities to accommodate forage crop rotations, herd replacement control of the steady-state flock and lamb balances (which reconcile the sources and uses of each class of livestock), government farm payments, and periodic feeding requirements to match feed produced or purchased with animal requirements. There are four distinct periods of the year: (1) winter/indoors from October 16 to May 20 with conserved feeds; (2) spring from May 20 to June 14 with infield grazing; (3) summer from June 14 to September 6 with outfield grazing for normal time of collection and 2 weeks earlier (August 23) for early collection; and (4) autumn until October 15 with infield grazing.

The model objective is to maximise the total gross margin (TGM), which includes returns from livestock production, government farm payments, and land rented out (only if land has become surplus to the availability of other fixed resources), minus variable costs of production, such as forage crop costs, purchased feeds, variable labour, and other livestock-related expenses. Fixed cost items are not included because they are 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 versions of the LP model and their underlying budgets were specified in a Microsoft Excel spreadsheet and solved using LINDO (v. 6.1) software (LINDO Systems, 2003). In the following sections,

Table 1
General structure of the linear programming models.

	Activities (X) – columns									
				Sheep production (head)						
	Forages (ha)	Land hire out (ha)	Purchase of feed (unit)	Ewes	Finishing lambs	Replacers	Farming payments (ha/head)	Feed out	Labour supply (h)	Right-hand side (b)
	(13)[a]	(1)	(4)	(4)	(64)[b]	(4)	(9)	(4)	(1)	
Objective function	Costs	Revenue	Costs	Gross margins	Gross margins		Revenues		Cost	Max $Z = c'X$
Constraints										
Farmland (1)[a]	1	1								$\leq$ Land available
Crop rotation (4)	$\pm A$									≤ 0
Housing (1)				1						$\leq$ Ewe places available
Replacement control (2)				$\pm A$						≤ 0
Lamb balances (8)				$-A$	$+A$	$+A$				≤ 0
Transfer, ewe lambs (2)				1		-1				≤ 0
Size of lambs for replacement (2)						$\pm A$				$= 0$
Farming payments (11)	$-A$			$-A$	$-A$		$+A$			≤ 0
Feeding requirements (11)	$-A$		$-A$	$+A$	$+A$	$+A$				≤ 0
Feed out (4)				$+A$	$+A$	$+A$		-1		≤ 0
Labour transfer (1)	$+A$			$+A$	$+A$	$+A$		$+A$	-1	≤ 0
Labour (1)									1	$\leq$ Labour available

Revenues, gross margins, and costs comprise the c's. A are the technical coefficients that relates activities to constraints. b, c, and A are fixed real constants, and X are real numbers to be determined.

[a] Numerals in parentheses refer to numbers of rows and columns in the matrix.

[b] Maximum number is 64. The actual number of activities is lower (rich pastures 52; poor pastures 60) because some target weights are achieved before collection from summer pastures or that male lambs should be slaughtered no later than three weeks before the mating season starts.

different parts of the LP model will be given greater detail.

2.3. Production of forage crops and purchased feeds

Farmland can be used to grow grass from temporary ley or annual forage crops for grazing and conservation as silage, or else rented out. How much land occupied by different activities is considered in the optimisation process. No forage marketing activities are included. Nutrients for forage production can be supplied by manure produced on the farm and purchased fertilisers. In addition to the home-grown forage, a variety of concentrates can be purchased (Table 2).

Sheep production systems rely on pastures, and forage yields are divided into grass produced for spring grazing, autumn grazing, and mowing for silage to be fed during the winter period. Early collection of the flock from the summer pastures requires earlier mowing to produce enough pasture grass throughout the autumn grazing period. Thus, separate activities of early and normal collection are needed for forage systems that include autumn grazing.

The swards of temporary leys are established in the spring after ploughing and conventional cultivation for seedbed preparation (drag, tine harrow, roll) without a cover crop and persist for another 3 years. The seed mixture contains timothy (*Phleum pratense*), meadow fescue (*Festuca pratensis* Huds.), and red clover (*Trifolium pratense* L.) sown at 30 kg/ha. The fields are mowed (one cut) and conserved as silage during the seeding year. The sward establishment year represents one activity.

Commonly used combinations of grazing and silage production in later sward years are represented by separate activities: grass used only for mowing (two cuts); grass used for mowing (two cuts) with aftermath grazing; and grass used for spring pasture and mowing (one cut) with aftermath grazing. Roughly 200 kg N/ha is applied annually to the swards. Details on the use of all fertiliser types are given in Table S4.

Annual forage crops were restricted to a combination of Italian ryegrass (L. *multiflorum* var. *italicum*) and Westerwolds ryegrass (L. *multiflorum* var. *westerwoldicum*), which are often used for grazing in Norway (Steinshamn et al., 2016). In Norway, both Westerwolds and Italian ryegrass types behave as annual crops. Annual ryegrasses are sown for a maximum of 3 subsequent years in a 50:50 mixture of Italian ryegrass and Westerwolds ryegrass at a seeding rate of 450 kg/ha. Annual ryegrasses are established either in early summer after spring grazing of an old grass sward (conventional tillage with ploughing) or in early spring if annual ryegrass follows annual ryegrass (tillage operations: disc harrow, tine harrow, and roller).

Annual ryegrasses are represented by three activities for each of early and normal time of collection: 1) grass used for spring pasture, summer-sown with ryegrass, mowing (one cut) with aftermath grazing; and 2 and 3) spring-sown ryegrass used for mowing (two cuts) with aftermath grazing (separate for the two possible years). Constraints are included to ensure that the area of temporary leys (establishment year included) is at least 4-times the area of summer-sown ryegrasses, the area of first-year spring-sown ryegrasses does not exceed the area of summer-sown ryegrasses, and the area of second-year spring-sown ryegrasses does not exceed the area of first-year spring-sown ryegrasses.

Yield and energy values of the forage crops, representing the forage activities in the model, were obtained from field experiments with grasses for annual and perennial use in 2012 and 2013 (Todnem and Lunnan, 2017) and supplemented with expert judgements. Fig. 2 shows the resulting yields (expressed in FUm, where 1 FUm is equal to 6900 kJ net energy for lactation) of the different forage crop activities. Dry matter (DM) yields and energy concentration of the grasses are presented in Table S1. The field experiments were conducted at representative locations in the mountain region of Southern Norway: Løken Research Station (61°8'N, 9°8'E, 520 masl) and Tynset in Nord-Østerdalen (62°16'N, 10°49'E, 550 masl).

The grass to be harvested is conditioned at mowing, wilted, and raked before harvesting. The DM content of the wilted grass and annual ryegrass silage is 30 % and 25 %, respectively. The grass silage is preserved with a formic acid-based additive applied at 4 l/t fresh weight of wilted crop before ensiling. The annual ryegrass silage is not treated with additives. All silage is wrapped into round bales (800 kg/bale).

The costs of plant nutrients (including fertiliser application), lime, mowing, raking, silage additives, and baling are included in all forage crop activities. Costs of one topping are added to the temporary ley activities with spring pasture. Renewal costs, such as seed, cultivation, drilling, and spraying, are incorporated into the sward establishment activity and the annual ryegrass activities. Contractors are employed for operations such as baling, spraying, and spreading of lime. For field operations using farmer-owned equipment, the running costs of repairs and fuel are included.

2.4. Sheep production

The livestock activities comprise the management of mature ewes, rearing of ewe lambs, and finishing of slaughter lambs. The dominant breed in Norway, the cross-bred prolific Norwegian White Sheep (NWS), is used. Ewes lamb in April-May, represented by May 5 in the model. Age at first lambing is 1 year. Annually, 1.43 and 2.07 lambs are reared per yearling ewe and mature ewe, respectively (see Table S5 for more details about prolificacy and lamb mortality). Each year, 25 % of the ewes are replaced by ewe lambs raised on the farm, and 2 % of the ewes are lost annually. Ewes are culled after the summer season.

Table 2
Prices and feed characteristics of the commercial concentrate mixtures produced by Felleskjøpet, Norway.

	Price (NOK/kg)	Energy value (FUm[a]/kg DM)	NDF (g/kg DM)	AAT (g/kg DM)	PBV (g/kg DM)
Formel sheep	4.18	1.05	230	120	5
Formel sheep extra	4.40	1.15	170	146	-9
Formel lamb	3.93	0.98	290	109	-5

Price per kg feed, 870 g DM/kg feed.
FUm = feed unit milk; NDF = neutral detergent fibre; AAT = amino acids absorbed in the small intestine; PBV = protein balance in rumen.
[a] FUm = 6900 kJ NEl, where NE1 is the net energy for lactation (Sundstøl and Ekern, 1992). FUm is equivalent to the net energy of 1 kg of barley with 86 % DM.
Source: NIBIO (2017). Exchange rates in 2017 were NOK 100 = $ 12.09 = € 10.76 = £ 9.43.

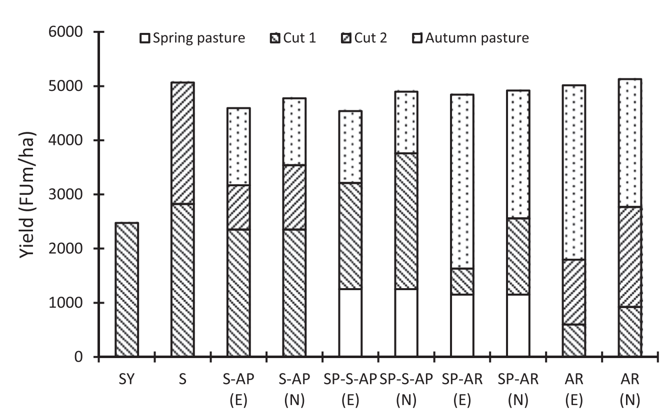

Fig. 2. Annual yields (expressed in FUm/ha) for temporary ley and annual ryegrass under different management regimes. Abbreviations: SY: seeding year (sward establishment); SP: spring pasture (ley); S: silage (ley); AP: autumn pasture (ley); AR: annual ryegrass; E: early time of collecting sheep; N: normal time of collecting sheep.
Sources: Todnem and Lunnan (2017) and expert judgements.

2.4.1. Ewes and replacers

Feeding requirements for mature ewes and replacement lambs are specified in the four distinct periods of the year: winter, spring grazing, outfield summer grazing, and autumn grazing. A feed planning tool from the Norwegian meat cooperative (Nortura sauefôring) was used to determine winter feed rations based on energy requirements and forage intake capacities. Energy requirements are calculated for maintenance, growth, change in body condition score, pregnancy, and lactation. Parity, body weight, body condition score, prolificacy, and the intended growth rates of new-born lambs and replacement ewes influence the energy required. Feed requirements are estimated for three periods: start of the winter season to late gestation (8 weeks before lambing), late gestation to lambing, and lambing to spring grazing. For each period, the tool estimates the intake of the major feed energy source, silage, fed ad lib. Finally, the tool proposes the composition and amount of concentrates that must be fed with the silage to cover periodic feed requirements for energy, protein, and fibre content. The tool uses the net energy in the lactation system as a guideline for nutritional requirements, whereas protein requirements are expressed in amino acids absorbed in the small intestine and protein balance in the rumen.

The pasture rations in spring and autumn are based on grass grazing alone (no annual ryegrasses). In the spring, the daily net energy required (in FUm) by each ewe is $0.033 \times LW^{0.75}$ for maintenance and 0.316 FUm/100 g lamb growth for lactation (Sundstøl and Ekern, 1992). The LWs of replacement and mature ewes are 75 kg and 90 kg, respectively. Lamb daily growth rates from lambing to the end of the spring pasture season were set to the registered mean growth rates of NWS lambs in the spring period in the Norwegian Sheep Recording System over 3 years (Animalia, 2016–2018). Lambs are weaned immediately after collection from the summer pastures. After weaning, only maintenance is required for the ewes.

In the outfield summer grazing period, energy required for maintenance (and growth of the yearlings) were calculated for all ewes. Net energy required for growth and maintenance of lambs were estimated (see Section 2.4.2 for growth rates). The net energy requirement for lamb growth (FUm/kg) is $0.362 + 0.0522 \times LW$ for male lambs and $0.304 + 0.0652 \times LW$ for female lambs (McDonald et al., 2011). All feed requirements were added and calculated per ewe with lambs included.

Feeding constraints (expressed as FUm) reflect periodic feed supply and animal requirements for silage in winter, pasture grass in the two separate grazing periods, and the various types of concentrates to be used in winter. Feed from the outfields is a free resource, and a constraint registers the feed requirements in the outfield season. The forage and concentrate needs of replacement ewes and mature ewes (included lambs until weaning) in various periods are summarised in Fig. 3.

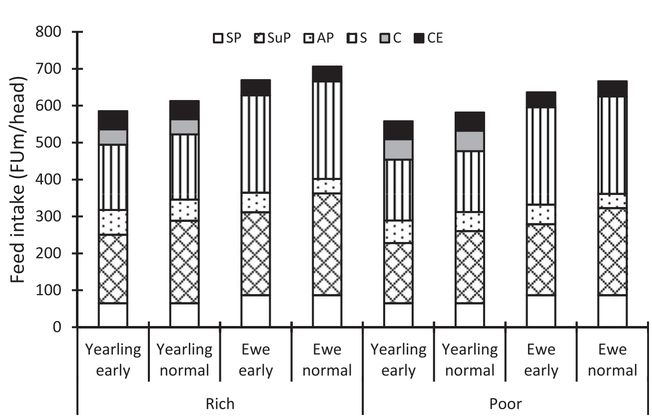

Fig. 3. Annual intake of various feeds (expressed in FUm) by summer pasture quality and time of collection (early or normal) for replacement ewes (yearlings) and mature ewes. Autumn pasture intake for yearlings is in the year of birth. Abbreviations: SP: spring pasture; SuP: summer pasture; AP: autumn pasture; S: silage; C: concentrates sheep, CE: concentrates sheep extra.

The returns from the ewe activities come from the sale of cull ewes, wool, and the nutrient value of manure. Finishing lambs are transferred to separate activities. The costs include minerals, veterinary services and medicine, manure application (minus fertiliser application costs replaced), interest on the capital invested in the herd, and miscellaneous. Costs of purchased feeds are excluded from the ewe activities because separate activities for buying feeds are included.

2.4.2. Lamb growth in summer

Lamb growth on summer pastures varies and depends primarily on factors affecting available forage quality (Lind et al., 2020). Based on weight records from flocks in the two study areas (Jørgensen et al., 2018), the average LW for lambs collected from mountain pasture September 6 was set to 44 kg for the rich summer pasture and 38 kg for the poor summer pasture. Towards the end of the outfield grazing period, lamb growth rates decrease (Lunnan and Todnem, 2011). Eines (2012) recorded the LWs of NWS lambs throughout the summer grazing season in the two study areas. The reduction in weight gain was highest in the rich pasture area. These estimates and a previous study from another mountainous area in Southern Norway (Nedkvitne and Garmo, 1986) were used to work out periodic lamb growth rates in the summer season. Table 3 summarises the performance from birth to the normal date of collection for the average lamb in the two study areas.

Male lambs grow faster than female lambs (Fourie et al., 1970). Lamb growth is also influenced by many other characteristics of the lambs and ewes and disease events. Thus, lamb autumn LWs within a flock vary and will influence plans to finish slaughter lambs. We classified lambs at weaning into four categories: “heavy female”, “heavy male”, “light female”, and “light male”. Real autumn LWs of NWS lambs over 3 years (2014–2016) from a flock in the Nord-Østerdalen region were used to calculate relative lamb LWs for the four lamb categories. Table S2 shows the resulting lamb LWs at early and normal time of collection in the two study areas. Based on data from the same flock, two-thirds of the replacement ewes originate from the “heavy female” category.

2.4.3. Finishing of lambs

Except for ewe lambs retained for breeding, all lambs are sold for slaughter. Weaned lambs can be sold directly for slaughter or can be carried to heavier weights (changing the grading and pricing) by prolonging the period of feeding. In the model, the CWs of the slaughter lamb activities start at 16.1 kg and increase at 2-kg intervals up to a maximum of 22 kg. Dressing percentages (CW divided by LW immediately preslaughter multiplied by 100) are 40 % for male lambs and 42 % for female lambs (Avdem, 2018). Some target weights are not obtainable due to a higher LW at collection or too low weight towards the end of the slaughter season (Tables S6–S7).

Finishing lambs are fed grass only or a mixture of annual ryegrasses and grass (70:30 mixture on a FUm basis) until October 15. Thereafter,

Table 3
Average performance of lambs.

	Rich pasture	Poor pasture
Birth weight May 5, kg[a]	5.0	5.0
ADG to June 14, 40 days, g/d[a]	332	332
LW June 14, kg	18.3	18.3
ADG to August 23, 70 days, g/d[b]	316	240
LW August 23, kg	40.4	35.1
ADG to September 6, 14 days, g/d[b]	256	210
LW September 6, kg[c]	44.0	38.0

ADG = average daily gain, LW = live weight.

[a] Mean for the NWS breed from the Norwegian Sheep Recording System (2015–2017), Animalia (2016–2018).

[b] Based on Nedkvitne and Garmo (1986) and Eines (2012).

[c] Autumn weight records from sheep flocks in the study areas.

the quantity and quality of available fresh grass decreases, and grass silage and concentrate supplementation (0.5 kg/d) are fed outdoors. Lambs grow faster on a mixture of grass and annual ryegrasses than on grass only and grow slowest on the silage/concentrates diet. Estimates under Norwegian conditions (Avdem, 2018) were used to calculate the growth rates of finishing lambs by type of diet and gender (Table 4) independent of weight at weaning. Energy is required for maintenance and growth. Replacement lambs are offered grass only in the autumn pasture period, and they have the same growth rates and energy requirements as female lambs for slaughter.

Heavier lambs yield carcasses with higher conformation and fatness scores, and carcasses of female lambs are fatter than those of male lambs (Fourie et al., 1970). The grading of slaughter lambs in Norway is described in Appendix A1. The carcass characteristics and grading of lambs from 16.1 to 22 kg CW by sex are summarised in Table S3.

The feeding constraints of the finishing lambs and replacement ewes pertain to net energy (FUm) in pasture grass and annual ryegrasses in the autumn, and silage and concentrates (Formel lamb) in the winter period, specified in the same constraints as the requirements for ewes (where applicable).

The returns from the finishing lamb activities include the sales of meat and wool. Costs are included in separate activities.

2.5. Labour, housing, and land requirements

The workload on sheep farms fluctuates throughout the year. Lambs are born under surveillance and intensive care, and lambing is the time of the indisputably highest labour demand. Winter is the least labour-intensive period. There are data difficulties involved in incorporating seasonal labour requirements and it adds considerable size to the model. However, most sheep farms are part-time operations that are integrated with off-farm work. Sheep farmers deal with seasonal labour peaks by working longer hours, help from other family members during the busy seasons, and by having flexibility in off-farm work. If required, some casual labour can also be hired. We found it sufficient to include only one labour constraint for the whole year (Nuthall, 2011:289).

The labour requirements for many farm tasks are not directly allocable to specific production activities (overhead labour). The supply of labour available for production activities, or variable labour (1500 h), is set to an upper limit on labour input (3000 h) less overhead labour (1500 h). The input-output coefficients for variable labour requirements, such as farmers' own field machinery operations, feed-out of silage and concentrates, lambing, and animal handling, are assumed to be constant per unit of each activity (NIBIO, 2017). An identical hourly cost for all variable labour input is included, regardless of whether own or casual labour is used.

The farm has 20 ha of cultivated land available, and it has a housing capacity of 200 ewes, corresponding to the same stocking rate as in standard gross margin budgets (NIBIO, 2017).

Table 4
Growth rates of finishing lambs by gender on autumn pasture diets and a later silage/concentrate diet.

	ADG (g/d)	
	Male	Female
Until October 15		
Annual ryegrasses + grass[a]	410	380
Grass only	280	250
After October 15		
Silage + concentrates[b]	170	140

[a] Mixed in a 70:30 ratio on FUm basis.
[b] 0.5 kg/d of Formel Lamb.
Source: Avdem (2018).

2.6. Prices and government payments

The prices of farm inputs and outputs, some of which are reproduced in Table 5, reflect 2017 conditions. The price of lambs varies with the time of year. Fig. 4 shows the base price received by farmers for a standard slaughter lamb throughout the season. The predetermined prices are strongest in August and then gradually decline, reaching the lower plateau in mid-October. Premiums and penalties for all weights, conformations, and fat classes are also included in the final slaughter lamb prices (Table S3). Sales, variable costs, and labour input of all forage crop and livestock activities are reported in Tables S4–S7.

Farmers are paid various premiums per livestock head and per hectare of farmland, with rates varying according to the type of livestock or crop, and in some cases with a lower rate for higher stock numbers (Table 5). Activities and constraints related to these premiums are incorporated into the model.

2.7. Model validation

Validation is the determination of whether a model adequately reproduces reported behaviour (Doole and Pannell, 2013). Important components to consider are structure, inputs, and outputs. Matters of model structure and input data have been addressed in Sections 2.1–2.6 and was dealt with initially during the early stages of the modelling process, cf. Fig. 1 in Doole and Pannell (2013). These matters were also

Table 5
Prices and government farm payments.

Item	Value (NOK)	Item	Value (NOK)
Receipts		*Expenses*	
Cull ewe[a]	18.71/kg CW	Variable costs, ewe[b]	449/ewe
Wool, ewe	40.80/kg	Seeds, grass	64/kg
Wool, lamb	46.70/kg	Seeds, annual ryegrass	27/kg
Manure, nutrient value[c]	120/t	Herbicide (MCPA + Express)	100/ha
Land, rent out	2250/ha	Silage additive	10.7/l
Governmental payments		Diesel	8.00/l
Forages	3950/ha	Lime[d]	0.70/kg
Ewe, 1–126[e]	868/head	Fertiliser (NPK 18-3-15)	3.84/kg
Ewe, > 127[e]	194/head	Fertiliser (NPK 25-2-6)	3.20/kg
Lamb, slaughter premium[f]	532/head	Spreading of manure	30/t
Grazing payment[g]	40/head	Spraying	250/ha
Outfield grazing payment[g]	185/head	Raking	250/ha
Vacation payment[e,h]	408/head	Custom baling[i]	195/bale
		Cost of labour	150/h

[a] Data from the Norwegian Sheep Recording System. Basis and regional government payment per kg carcass weight (CW) of NOK 2.70 and NOK 7.35, respectively, are included.
[b] For details, see Table S5.
[c] Value based on what it would cost to provide the same quantities of plant nutrients from fertilisers. Manure production in the indoor season is 0.7 t/ewe.
[d] Cost of lime includes material, hauling it to the field, and application. Limestone is applied at an average annual rate of 600 kg/ha.
[e] Number of sheep as of March 1. Sheep must be born the previous year or earlier.
[f] Lambs in conformation class O+ or better (in the EUROP grid system) qualify for the slaughter premium.
[g] All sheep. At least 12 weeks and 5 weeks of grazing is required for the general grazing and outfield grazing payment, respectively. The outfield grazing payment is calculated based on a weighted average of the number of animals released (70 %) and the number of animals collected (30 %).
[h] Maximum payment is NOK 74,200.
[i] Wrapping and transport of bales included. NOK 5 per bale in addition to grass silage bales due to use of silage additive.
Sources: NIBIO (2017) and industry sources. Exchange rates in 2017 were NOK 100 = $ 12.09 = € 10.76 = £ 9.43.

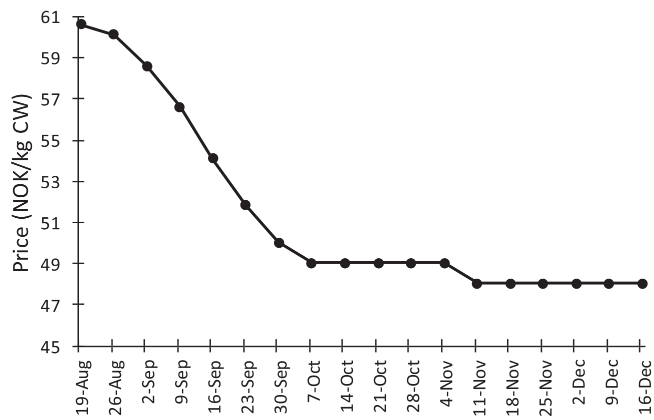

Fig. 4. Seasonal variation in the base price received by farmers for slaughter lambs in 2017 (weekly changes). Lamb in conformation class R, 16.1–23 kg carcass weight (CW). Basis and regional government payment per kg CW of NOK 3.9–4.9 and NOK 7.35, respectively, are included.
Source: Nortura (2017).

revisited in the cycle of model construction, validation and use as greater precision was sought. The performance of the models was repeatedly tested and verified as functional relationships and constraints were adjusted until we were satisfied with the models' performance. Opinions of farmers in the area, farm advisors, and agricultural researchers were sought in the verification and validation process of the models. The model structure was found to capture important aspects of the real farming systems and input data was consistent with reported or expected values.

Output validation is difficult and rarely achieved in the optimisation of complex farming system models (Doole and Pannell, 2013). We used the more subjective and intuitive approach of "sensibility" testing (Robertson et al., 2012). In this approach, model output is tested against expert opinion and common sense and the credibility of the model evaluated against its ability to mimic reality. Models are always an approximation of the real world. The models were however deemed credible and fit for purpose of providing a reasonable representation of the systems under study.

2.8. *Model runs*

In each study area, the model was first run under a standard, least-restrictive situation where all activities were included. Both early and normal time of collection consequently competed in the same run of the model to see which of them was preferred or if a mix of the two times of collection was optimal. The inclusion of both times of collection in the model is termed *flexible* time of collection. Next, the annual ryegrass activities were excluded to examine effects on production and profitability. Finally, the two situations (with or without annual ryegrasses) were repeated for each study area by excluding the normal time of collection activities to find the best options that only included early time of collection. In total, therefore, eight situations were analysed.

2.9. *Parametric programming*

There is wide diversity across sheep farms concerning land availability compared to housing resources, and land availability is important in determining the optimal decision. To improve understanding of the systems behaviour, we investigated how profit (i.e., TGM) and the optimal use of inputs changed as a function of farmland availability over a rather broad range using the parametric programming routine in LINDO Systems (2003:173–174). A TGM function examines the behaviour of the optimal TGM as the land resource varies. There will be several intervals for land availability with 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.

3. Results

3.1. *Optimal farm production plans*

The outputs of the model at the basis using 20 ha of land for all eight situations are presented in Table 6. All land was used for forage production, except for grass only after a flexible collection time in both study areas. In these two situations, some land was rented out. Annual ryegrasses were included in the optimal crop plans.

A total of 6500–8400 kg of meat, or 35– 42 kg/ewe, was produced in the different farm situations (Table 6). Around 650–730 FUm of feed was required per ewe, corresponding to 17.5–19.0 FUm per kg meat. Infield pasture grass constituted approximately 25 %, outfield summer pasture 34 %, silage 34 %, and concentrates 8 % of the feed ration for normally collected flocks. Producing 1 kg of meat required 1.27–1.65 FUm of concentrates. Early collection, poor summer pastures, and use of grass only in finishing the lambs decreased production of meat and increased the use of forages and concentrates per kg of meat produced.

Normal collection was always used if the time of collection was flexible, and the flock size was restricted by the housing capacity of 200 ewes. The increased infield feed requirements did not allow the housing capacity to be fully used for any of the early collection situations.

Optimal lamb finishing strategies varied for different situations. Generally, the lighter lambs from poor summer pastures were retained longer and obtained lower prices. The average CWs were nevertheless 1–2 kg less than those from rich summer pastures. Lambs from grass only diets were usually drafted earlier and at lower CWs than the ryegrass-fed lambs.

More home-grown feed was available at the flexible (i.e., normal) time of collection and lambs from normally collected flocks were drafted at higher average weights (1.2–1.6 kg CW) than those from the early collected flocks, though later in the season at lower average prices.

At flexible (i.e., normal) time of collection, most heavy lambs at weaning were drafted for slaughter at lower or similar weights than lambs in the light-weight categories (Table 7). This apparent anomaly was caused by seasonal pricing. Declining prices at the start of the season (Fig. 4) also applied to the weight previously added. For the heavy lamb categories, the negative return effects more than offset the gains in feeding, and it was worthwhile to terminate production quickly after collection (Table 7). Most lambs in the light-weight categories were carried to heavier weights by prolonging the period of feeding into the flatter price curve. Under constant prices, it pays to extend the finishing period for as long as returns for the extra meat added cover the additional opportunity costs of producing it. The growth rates were lower with the silage/concentrate diet than the autumn pastures; coupled with an increased cost of the diet, this resulted in quick termination of the finishing phase after grazing was phased out in mid-October (Table 7).

3.2. *Economic evaluation of the optimal production plans*

Normal time of collection in rich summer pastures with the inclusion of annual ryegrasses in the diet of finishing lambs was most profitable (Table 6). The use of rich summer pastures was NOK 44,200 (or NOK 221 per ewe) more profitable than the comparable use of poor summer pastures, mainly associated with higher gross output from lamb sales. The advantage of rich summer pastures was even greater for flocks using grass only.

Early collection was always less profitable than normal collection (Table 6). The total output of meat was ~ 1000 kg less in the early collected flocks, partly because of the lighter weights of the lambs sold. In addition, the additional home-grown feed required to provide autumn

Table 6
Model solutions and financial results for different summer pasture qualities, times of collection (flexible[a] or early), and diets for finishing of lambs with 20 ha of available land and a housing capacity of 200 ewes.

	Rich summer pastures				Poor summer pastures			
	Flexible		Early		Flexible		Early	
	AR-G	GO	AR-G	GO	AR-G	GO	AR-G	GO
Land use (in ha)								
Grass silage	2.35	1.73	3.44	2.81	2.27	0.63	3.40	2.58
Silage - pasture	0.00	0.00	0.00	0.00	0.00	1.28	0.00	0.19
Pasture - silage - pasture	10.61	12.99	10.07	12.19	10.28	12.99	10.01	12.22
Pasture - annual ryegrass	2.59	–	1.98	–	2.95	–	2.12	–
Annual ryegrass	0.13	–	0.00	–	0.31	–	0.00	–
Sward establishment	4.32	4.91	4.51	5.00	4.19	4.97	4.47	5.00
Land rented out	0.00	0.37	0.00	0.00	0.00	0.13	0.00	0.00
Livestock								
No. of ewes[b]	200	200	183	188	200	200	184	188
No. of lambs slaughtered	332	332	304	312	332	332	306	312
Outputs								
Lamb (kg CW)	6855	6499	5885	5582	6253	5895	5401	5051
Mutton (kg CW)	1532	1532	1402	1437	1532	1532	1409	1441
Meat total (kg CW)	8386	8031	7287	7019	7785	7427	6810	6492
Meat total (kg/ewe)	41.9	40.2	39.8	37.4	38.9	37.1	37.0	34.5
Wool (kg)	1024	1024	937	960	1024	1024	942	963
Average lamb carcass value (NOK/kg)	57.51	58.53	61.03	61.14	56.78	56.20	59.27	58.29
Average lamb carcass weight (kg)	20.6	19.6	19.4	17.9	18.8	17.8	17.7	16.2
Average slaughter date	23-Sep	21-Sep	9-Sep	5-Sep	26-Sep	26-Sep	12-Sep	8-Sep
Feed requirements								
Grass demand spring (FUm/flock)	16,242	16,242	14,865	15,234	16,242	16,242	14,945	15,278
Outfield grass demand (FUm/flock)	52,752	52,752	39,539	40,520	45,315	45,315	34,179	34,941
Grass demand autumn, ewes (FUm/flock)	8707	8707	10,671	10,935	8426	8426	10,394	10,626
Grass demand autumn, lambs (FUm/flock)[c]	9821	6259	9081	5274	10,993	7966	9719	5907
Silage demand, ewes (FUm/flock)	48,459	48,459	44,353	45,453	47,862	47,862	44,040	45,023
Silage demand, lambs (FUm/flock)	0	380	0	0	101	174	0	0
Concentrate demand, ewes (FUm/flock)	10,675	10,675	9771	10,013	11,364	11,364	10,457	10,690
Concentrate demand, lambs (FUm/flock)	0	229	0	0	69	139	0	0
Total (FUm/flock)	146,656	143,703	128,280	127,429	140,372	137,487	123,733	122,465
Total (FUm/ewe)	733	719	701	679	702	687	672	651
Concentrates (FUm/ewe)	53.4	54.5	53.4	53.4	57.2	57.5	56.8	56.8
Concentrates (FUm/kg CW)	1.27	1.36	1.34	1.43	1.47	1.55	1.54	1.65
Financial results (1000 NOK)								
Gross output	1100.8	1086.4	1026.1	1018.8	1061.7	1037.7	989.3	973.3
Finished lambs	424.1	410.3	386.6	369.3	385.0	361.3	347.6	322.6
Wool	44.0	44.0	40.3	41.3	44.0	44.0	40.5	41.4
Culled ewes	28.7	28.7	26.2	26.9	28.7	28.7	26.4	27.0
Government farm payments	587.3	585.8	557.7	565.6	587.3	586.8	559.4	566.6
Manure	16.7	16.7	15.3	15.7	16.7	16.7	15.4	15.7
Land rented out	0.0	0.8	0.0	0.0	0.0	0.3	0.0	0.0
Costs	538.9	532.9	502.9	506.8	543.9	537.8	508.3	511.4
Concentrates	53.5	54.5	49.0	50.2	56.9	57.2	52.0	53.2
Forage inputs	173.6	169.0	166.7	165.5	173.5	168.8	166.5	164.9
Vet & Med	25.0	25.0	22.9	23.4	25.0	25.0	23.0	23.5
Misc.	54.8	54.8	50.2	51.4	54.8	54.8	50.5	51.6
Variable labour	231.9	229.6	214.1	216.2	233.7	232.0	216.3	218.2
Gross margin	561.9	553.5	523.3	512.1	517.7	499.9	481.0	461.9

AR-G = annual ryegrasses + grazed grass; GO = grass only; CW = carcass weight.
[a] Normal time of collection was always more profitable than early collection.
[b] Replacement ewes included.
[c] Annual ryegrasses included.

grazing for the early collected flock caused fewer ewes to be kept. The higher price received for the early collected lambs, because they came to market earlier, offset only some of the lower meat production. All these differences resulted in losses of roughly NOK 40,000 with early compared to normal collection.

Annual grasses increase establishment costs associated with seeds, fuel, machinery, and labour compared to perennial grasses, as reflected in the higher cost of forage inputs in the alternatives involving annual ryegrasses in Table 6. However, the use of annual ryegrasses increases lamb growth rates. In all situations, the finishing period was the same as for grass only or prolonged, but with production of heavier lambs. Grass only resulted in a loss of approximately NOK 10,000 compared to the inclusion of annual ryegrasses with rich summer pastures, and close to NOK 20,000 with poor summer pastures. The greater importance of annual ryegrasses in poor summer pastures compared to rich summer pastures was related to the need for a longer lamb finishing period. Feed then became a more limiting factor of production.

3.3. Effect of changes in farmland availability

The effect on relative performance in the eight situations of changes to the area of the farm was investigated using parametric programming by varying the farmland constraint from 15 to 25 ha. Table S8 reports changes in activities in the optimal solution at selected breakpoints, the number of ewes at 15 ha, and optimal CWs of all lamb categories with both 15 and 25 ha.

For farms with surplus of land to the availability of other fixed resources (that is, more forages available than needed to feed the flock),

Table 7
Optimal carcass weight (CW) and slaughter date for finishing lambs at different times of collection and diets for finishing lambs by summer pasture quality, weight category, and sex with 20 ha of available land and a housing capacity of 200 ewes.

	Flexible				Early			
	AR-G		GO		AR-G		GO	
	CW (kg)	Date	CW (kg)	Date	CW (kg)	Date	CW (kg)	Date
Rich summer pasture								
Light, female	22.0	15-Oct	20.0	16-Oct	18.0	14-Sep	16.1	07-Sep
Light, male	20.1	28-Sep	18.0	21-Sep	19.4	18-Sep	16.1	01-Sep
Heavy, female	20.0	11-Sep	20.0	13-Sep	20.0	07-Sep	19.8	12-Sep
Heavy, male	20.5	06-Sep	20.5	06-Sep	20.0	31-Aug	20.0	03-Sep
Poor summer pasture								
Light, female	20.0	17-Oct	18.0	19-Oct	16.1	14-Sep	16.1	25-Sep
Light, male	19.2	06-Oct	18.0	10-Oct	18.0	22-Sep	16.1	19-Sep
Heavy, female	18.0	15-Sep	16.7	06-Sep	18.0	09-Sep	16.1	30-Aug
Heavy, male	18.0	08-Sep	18.0	09-Sep	18.4	05-Sep	16.3	23-Aug

AR-G = annual ryegrasses + grazed grass; GO = grass only.

the real cost of producing grazed autumn grass was NOK 0.32–0.63/FUm and grazed annual ryegrass NOK ~ 1.20/FUm compared to NOK 1.30–1.60/FUm for spring grass, NOK 2.43/FUm for home-grown silage and more than NOK 4.00/FUm for purchased concentrates (Appendix A2, Tables A2.2 and A2.5). Shortage of land increased the real (opportunity) costs of producing forage crops.

As more land became available, forage supplies increased, and more ewes were kept (Table S8). Until the building was used at full capacity, lamb slaughter weights were unchanged.[1] When the housing constraint became binding, the behaviour of the system changed. All feed from additional land was used to feed slaughter lambs. Less shortage of land and lowered cost of the forage crops made it profitable to carry lambs to heavier weights by prolonging the feeding period, in some cases also into the period of silage/concentrate feeding. The CWs of the lighter lambs at weaning responded most to changes in land availability. The slaughter weights of the heavy lambs at weaning could be constant or little weight added with increasing land availability because the strongly declining lamb prices through the early season "locked-in" the optimal finishing weight for these lambs.

Profitability was always highest in rich summer pastures at normal time of collection (Fig. 5). In Fig. 6, the additional TGMs are presented in graphs for three comparisons: rich vs. poor summer pastures, flexible vs. early collection, and inclusion of annual ryegrasses vs. grass only.

The profitability of rich summer pasture situations compared to poor

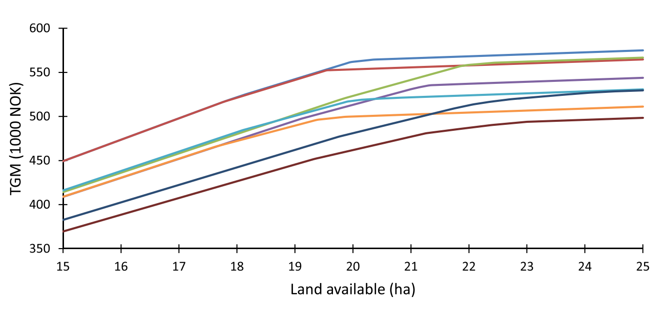

Fig. 5. Estimated total gross margin to modelled sheep farming system across farm situations, 15–25 ha of land and a housing capacity of 200 ewes. Abbreviations: R: rich summer pastures; P: poor summer pastures; F: flexible time of collecting sheep; E: early time of collecting sheep; A: annual ryegrasses + grass; G: grass only.

[1] The exception was for flexible time of collection in rich summer pastures, where annual ryegrasses was not introduced until 17.8 ha (Table S8).

summer pastures increased until their housing capacity was fully used (Fig. 6a). The smaller lambs weaned in the poor summer pastures required more feed in the finishing phase and, with more land available, the differences slightly decreased. However, rich summer pastures were always considerably more profitable than the poor summer pastures.

All comparisons of flexible and early collection followed the same profitability pattern (Fig. 6b). The gains of normal collection increased until the maximum vacation payment was reached (at 182 ewes). Thereafter, the additional gain decreased slightly up to fully used housing capacity. As early collection required more feed and land resources, the benefits of adding more ewes continued into larger farmland areas than for normal collection. Yet, the relatively greater competitiveness of early collection with more land available could not preclude normal collection as the most profitable option. For poor summer pasture farms with small restrictions in land availability, the higher price received for early collected lambs with rapid growth in the finishing phase by use of annual ryegrasses almost offset the additional costs (Table S8). Furthermore, the slower growth rate of lambs in the last 14 days of the summer season in the poor summer pastures compared to the rich pastures (Table 3) contributed to early collection being relatively less unattractive for poor summer pastures.

The use of annual ryegrasses in addition to grazed grass to ensure more rapid growth of lambs was usually more profitable than feeding grass only (Fig. 6c). The exception was for rich summer pastures and normal time of collection at land availabilities below 17.8 ha (Table S8), associated with a much lower opportunity cost of grazed grass (0.25 NOK/FUm) compared to annual ryegrasses (2.64 NOK/FUm, Appendix A2, Tables A2.2 and A2.3). Greater land availability increased the profitability of annual ryegrasses. Annual ryegrasses were most economically important for systems requiring most home-grown feed to produce more meat, that is, the use of poor summer pastures and early collection.

4. Discussion

The present study evaluated optimal strategies around the timing of the outfield grazing season and finishing of slaughter lambs in forage-based sheep production systems. The whole-farm LP model represents the predominant production systems of sheep farming in mountainous areas of Norway.

Since lambing is concentrated in spring, the nutritional requirements are high in the relatively short period of grazing on infield and outfield pastures (40 % of the year). In total, close to 60 % of the feed consumed by the flock was provided by pastures (Table 6). The large share of feeds from outfield summer pastures (~ 35 %) preserves biodiversity (Dumont et al., 2013). Some 8 % of the flock requirements were supplied by concentrates, consistent with feed budget estimates of the small ruminant meat sector in Western Europe (Mottet et al. 2017; Table SI 9).

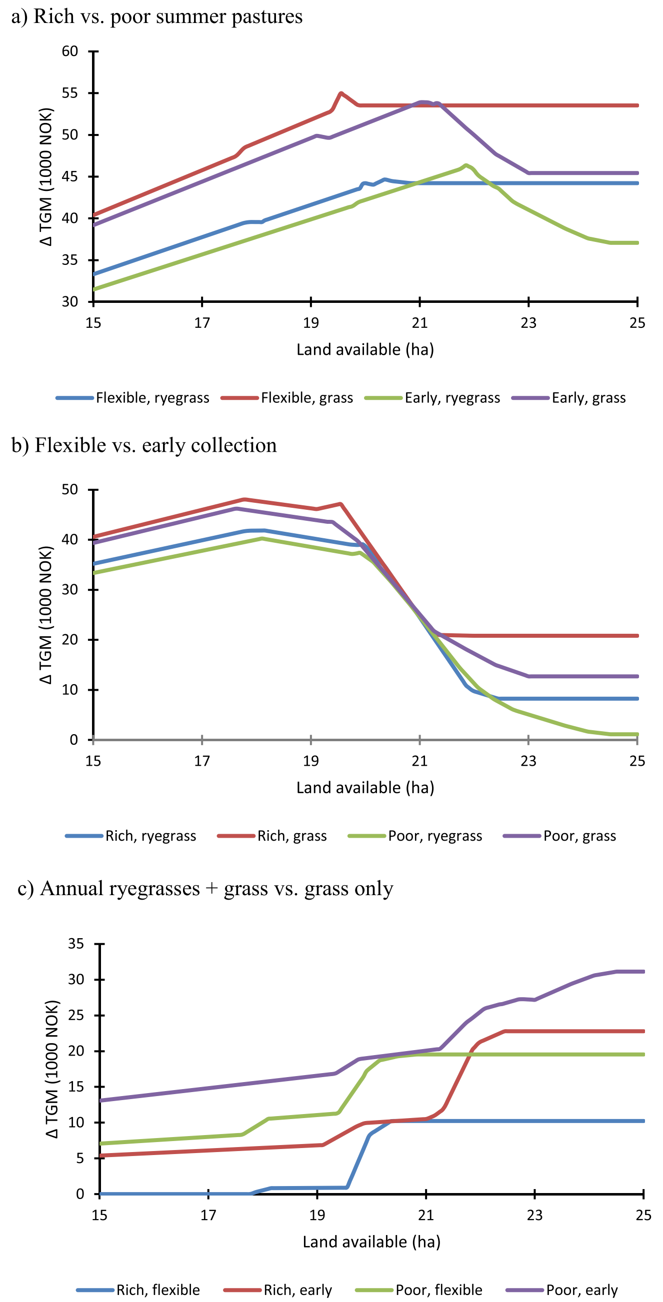

Fig. 6. Additional total gross margin (TGM) for rich vs. poor summer pastures (a), flexible vs. early collection (b), and annual ryegrasses + grass vs. grass only for finishing of slaughter lambs (c). Land is 15–25 ha with a housing capacity of 200 ewes.

Our estimates of 1.3–1.7 FUm (or 1.4–1.8 kg) concentrates per kg meat produced concurs with Bohan et al. (2018) who reported 1.6–2.0 kg concentrates per kg meat from an Irish sheep modelling study.

Various government farm payments contributed more than half of the gross outputs (Table 6). Gross margins would have been negative without the government payments, with no amount available to pay fixed costs or to provide returns to equity capital, unpaid labour, and management. Policy measures are needed to support the provision of socially preferable farming systems that are uncompetitive in the market.

For farms where land is not a limited available resource, this study found low real costs of producing grazed and conserved grass compared to purchased concentrates. This result corroborates findings from an Irish study (Finnernan et al., 2010) pointing out that home-grown forage crops, particularly grazed grass, can be low-cost feed. As land is generally considered a restrictive resource in forage-based livestock systems (McInerney, 2000), this cheapness may be more illusory than real if its production is evaluated in terms of foregone alternative opportunities. High real costs of forages at strict land and feed supply availabilities made it unprofitable to carry finishing lambs to heavier weights. As the land availability increased and real costs of forages decreased, drafting lambs for slaughter at heavier weights by prolonging the feeding period was profitable.

The light lamb categories at weaning were usually drafted at the same or heavier CWs than the heavy lamb categories. This apparent anomaly was caused by seasonal pricing, as declining prices at the start of the season affected the heavy weight categories negatively, whereas the lighter lambs were carried to heavier weights and more constant prices. These findings follow discussions in Barnard and Nix (1979; Ch. 10) of how seasonal pricing influences the optimal rate of feeding and the finishing period of temporary livestock.

4.1. *Summer pasture quality*

Having outfield summer pastures of higher quality improves the growth rate of lambs (Lind et al., 2020). The current study found that heavier lambs weaned from rich summer pastures were drafted earlier, obtaining higher lamb prices, and their optimal average CWs were still greater than those from the poorer summer pastures. Annual profits improved with rich summer pastures compared to poor summer pastures. High land availability, early collection, and use of annual ryegrasses reduced the gain from high-quality pastures, but rich summer pastures always performed the best. Numerical illustrations in Skonhoft et al. (2010) did also indicate higher lamb slaughter weights in better quality summer pastures, however, under assumptions of limiting grazing resources in summer and a constant lamb price.

Summer pasture quality was expected to have a great impact on farm profit. However, the actual gain from higher quality summer pasture has not been documented previously. Estimates of the economic value of outfields of various quality as feed resources can also be utilised in the governance and management of these land areas. This is related to the emerging multiple land-use patterns in outfields, where traditional agricultural land uses are threatened by consumption activities, such as second home development, tourism, and recreation (Short, 2008).

4.2. *Time of collection*

The greater profit with normal time of collection compared to early collection was not surprising, as the use of outfield pastures in late summer is essentially free of cost. On the other hand, early collection is associated with extra costs for the additional feed supplies needed to provide grazing for both lambs and ewes. Lambs from early collected flocks generated greater average prices because they came to market earlier, either drafted directly after collection or by higher growth rates on cultivated pastures than on late-summer outfields. The additional income did not offset the greater feed costs and the losses from a reduced flock size associated with early collection. For farms rich in land resources using poor summer pastures that included annual ryegrasses for finishing lambs, early collection was an almost equally profitable option as normal collection, which is attributed to relatively low real costs of home-grown forages and low lamb growth rates in the late-season outfield pastures.

We found no other studies comparing the profitability of early and normal collection systems in the literature. However, the seasonal aspects of early and mid-season lambing systems have been examined in Ireland (Bohan et al., 2016). Interestingly, the Irish lambing study also found early systems to be less profitable because lambs sold earlier for greater prices could not offset the increased feed costs.

4.3. Finishing of lambs

Finishing lambs by offering high-quality annual ryegrasses in addition to grass pastures produces higher growth rates than grazing grass only. Lambs with faster growth rates can produce heavier CWs or can be drafted earlier at a better price and require less feed for maintenance, allowing more feed to be available for the ewes. Costs of producing annual ryegrasses are however higher. In the current study, the opportunity costs of producing autumn pasture grass were cheaper than annual ryegrasses, especially at low land availabilities (Tables A2.2 and A2.5). Accordingly, for rich summer pastures and normal time of collection at low land availabilities feeding grass only to the finishing lambs gave the highest profit (see Table A2.3 for an example). In other situations, the higher costs of producing annual ryegrasses did not offset the gains of including it in the diet of finishing lambs.

No comparable studies have been found in the literature. However, our results can be associated with the discussion in Barnard and Nix (1979:86); they stated that it is preferable to feed intensively to speed up the production process if pasture grass is relatively costly compared to the feed offered to add weight (annual ryegrasses). If costs of grass are relatively low, it may be better to feed for a lower daily gain (over a longer period). Also, Thompson et al. (2016) have demonstrated interactions and trade-offs between feed supply and lamb growth rates and highlighted that increasing the lamb LW gain does not necessarily increase farm profit.

Several sheep farmers do not produce annual forage crops. Farmers' lack of familiarity with the crops, knowledge or perceptions of low profitability may hinder adoption. There may also be farm-specific practical problems of growing annual ryegrasses such as: site-specific conditions (steep or stony fields or small plots less suitable for cultivation of annual crops), good management is needed for high utilisation, labour considerations (included additional harvesting periods), and rotational challenges.

4.4. Limitations and future research

The research questions examined in this study were initiated by farmers in the study area (having rich as well as poor summer pastures). They needed guidance on the most profitable time to collect sheep from the outfields and how these management strategies influenced the whole-farm system. The optimisation framework is free to consider all strategies without human preconceptions or prejudices, and it puts biological information in an economic framework. This is particularly useful in situations where the complexity of an issue makes it difficult to identify the optimal solution. Numerical results however 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 cannot fully represent all the complexities of variable interactions, constraints and farming objectives when faced with decisions problems in livestock systems. Optimisation, then, should be regarded as a tool of conceptualisation and analysis rather than as a principle yielding the philosophically correct solution (Luenberger and Ye, 2016).

Some of the crop and livestock responses were based on expert judgments or feed planning tools rather than observed performances, e.g., by controlled experiments. Experiments would, however, have required huge amounts of resources and might still not have provided sufficient information to identify appropriate production practices since research may be carried out under conditions that are different from those met by farmers.

Sheep are kept under a wide range of socio-economic, environmental, and climatic conditions, and grass growth patterns differ. The farm model presented here represents the characteristics of a sheep production system with summer outfield grazing. Generalising the specific findings to other sheep production systems can be problematic.

The model can be extended in several ways. An interesting direction is to include activities that finish lambs on a predominantly concentrate diet after weaning to increase performance. De Brito et al. (2017) accurately pointed out that supplementation may not be economically justified due to the high cost, but where shortage of land is a major problem, the purchase of concentrates may offer a solution to improve profits (cf. the very high real cost of forage with low land availability). Another extension of the model is to include the smaller short-tailed Nordic spælsau breed in addition to the NWS to compare the profitability of breeds under different production circumstances. The impacts of policy changes on farm management and profit can also be examined.

The deterministic modelling framework overlooks variations between years in, for example, the yield and quality of forages, lamb growth rates at various stages, and the rate of decline in outfield pasture quality in the late season. Appropriate tactical responses to seasonal conditions can improve farm profits (Pannell et al., 2000). In practice, these aspects are critical to farmer success in grazing systems (Nuthall, 2012). Management strategies to cope with shortages or surpluses of feed (inter- or intra-year) or feeding of finishing lambs under various autumn live weight outcomes, for example, can be obtained through the use discrete stochastic programming (DSP; Hazell and Norton, 1986: 104–106). However, considerations of tactical responses to risk are outside the scope of this study, DSP models are data and labour intensive, and the model has proven robust enough to generate essential and logically sound understandings of the system.

5. Conclusions

This study compared optimal farm plans and the profitability of variation in outfield summer pasture quality, time of collection from the outfields, and inclusion of annual ryegrasses versus grass only in the diets of finishing lambs in Norwegian forage-based sheep production systems at varying levels of farmland availability. Better quality of the outfield summer pastures had a positive influence on profitability, due to higher lamb growth rates and heavier LWs at weaning. Early collected flocks sold lambs for greater prices but were less profitable compared to normal collection because of the additional feed costs incurred and possible losses from having a smaller flock. Speeding up the growth rate of finishing lambs by offering annual ryegrasses in addition to grazed grass was generally more profitable than grass only. The exception was rich summer pastures and normal time of collection at low land availability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.smallrumres.2022.106892.

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