J. Dairy Sci. 103:10898–10916
https://doi.org/10.3168/jds.2020-18157

Development of a linear programming model for the optimal allocation of nutritional resources in a dairy herd

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ABSTRACT

A linear programming model that selects the optimal cropping plan and feeds allocation for diets to minimize the whole dairy farm feed costs was developed. The model was virtually applied on 29 high-yielding Holstein-Friesian herds, confined, total mixed ration dairy farms. The average herd size was 313.2 ± 144.1 lactating cows and the average land size was 152.2 ± 92.5 ha. Farm characteristics such as herd structure, nutritional grouping strategies, feed consumption, cropping plan, intrinsic farm limitations (e.g., silage and hay storage availability, water for irrigation, manure storage) and on farm produced forage costs of production were collected from each farm for the year 2017. Actual feeding strategies, land availability, herd structure, crop production costs and yields, and milk and feed market prices for the year 2017 were used as model inputs. Through optimization, the feeding system was kept equal to the actual farm practice. The linear program formulated diets for each animal group to respect actual herd dry matter intake and fulfill actual consumption of crude protein, rumen-degradable and rumen-undegradable fractions of crude protein, net energy for lactation, neutral detergent fiber, acid detergent fiber, forage neutral detergent fiber, and nonfiber carbohydrate. Production levels and herd composition were considered to remain constant as the nutritional requirement would remain unchanged. The objective function was set to minimize the whole-farm feed costs including cash crop sales as income, and crop production costs and purchased feed costs as expenses. Optimization improved income over feed costs by reducing herd feed costs by 7.8 ± 6.4%, from baseline to optimized scenario, the improved was explained by lower feed costs per kilogram of milk produced due to a higher feed self-sufficiency and higher income from cash crop. In particular, the model suggested to maximize, starting from baseline to optimized scenario, the net energy for lactation (+8.5 ± 6.3%) and crude protein (+3.6 ± 3.1%) produced on farm, whereas total feed cost (€/100 kg of milk) was greater in the baseline (20.4 ± 2.3) than the optimized scenario (19.0 ± 1.9), resulting in a 6.7% feed cost reduction with a range between 0.49% and 21.6%. This meant €109 ± 96.9 greater net return per cow per year. The implementation of the proposed linear programming model for the optimal allocation of the nutritional resources and crops in a dairy herd has the potential to reduce feed cost of diets and improve the farm feed self-sufficiency.

Key words: income over feed cost, animal modeling, feed efficiency, optimization, cropping plan

INTRODUCTION

The economic objective of a dairy farm is generally to maximize net economic returns (de Ondarza and Tricarico, 2017), and feed cost is an important factor affecting farm profitability, representing more than 40% of dairy farms' variable cost (Ishler et al., 2009). Further, volatility in milk and feed prices has increased since the mid-1980s and represents one of the main economic challenges dairy farmers face (Valvekar et al., 2010). Borreani et al. (2013) stated that there is an increase in market exposure of protein supplementation due to a strong increase in soybean price volatility (Lehuger et al., 2009), and consequently a high uncertainty of concentrate costs. Further, several issues related to climate change such as persistent drought conditions in summer (Camnasio and Becciu, 2011), aflatoxin contamination of crops during the growing season (Battilani et al., 2016), or new and more aggressive corn pests (Boriani et al., 2006; Ciosi et al., 2008) are additional challenges farmers consider while making decisions about crop plans. Several researchers have pointed out the critical need of designing specific optimization tools for making appropriate decisions on crop plans in dairy farms (O'Kiely et al., 1997; Shalloo

Received January 5, 2020.
Accepted July 1, 2020.
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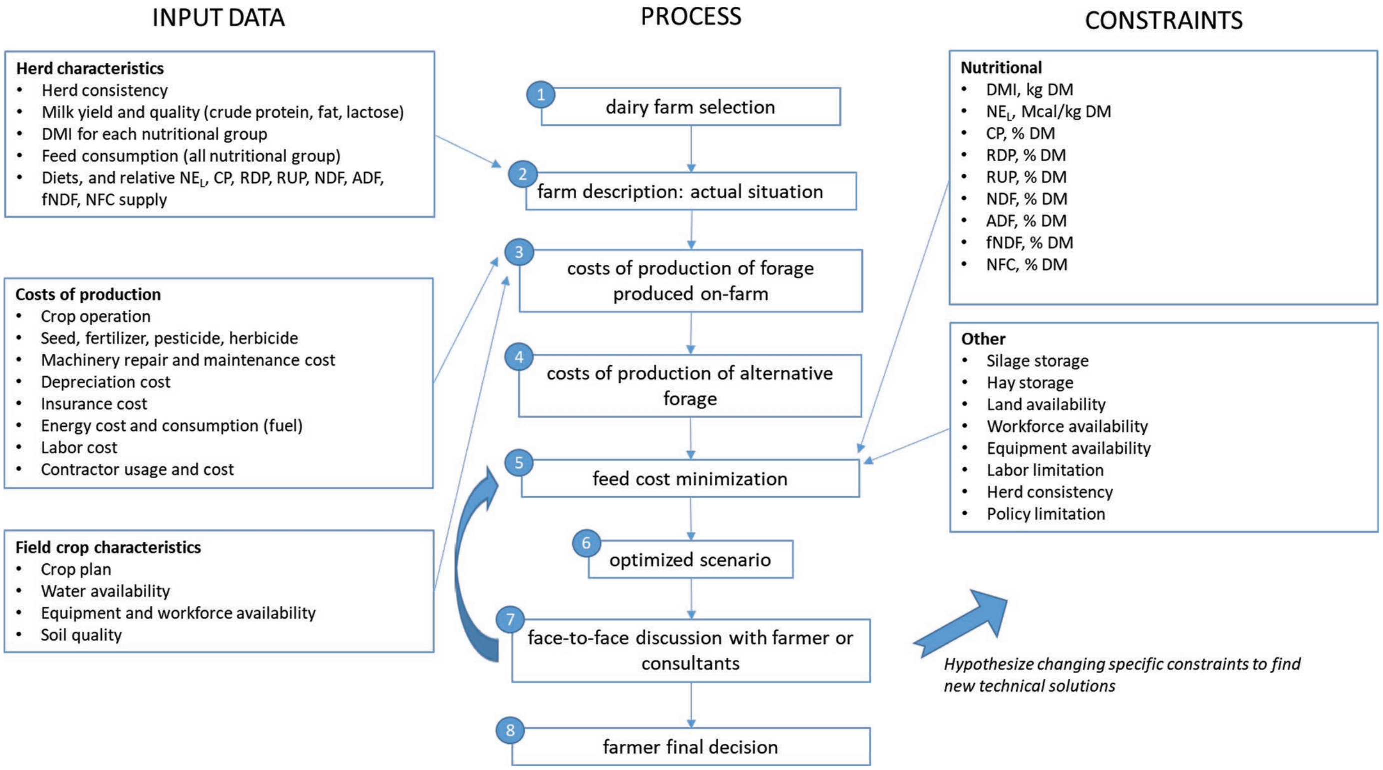

Figure 1. Linear program optimization model framework for finding the minimum whole-farm feed costs. fNDF = NDF from forage.

et al., 2004). The decision in selecting certain crops inevitably interacts with many other farm productive factors (i.e., farm size, soil type, water for irrigation, equipment availability, crop rotations, environmental impact, and worker organization) as discussed by Dury et al. (2012). Cropping plan selection models are used to support farmers, policy makers, and other stakeholders in defining strategies to allocate resources more efficiently or design policy options to anticipate their effects (Dury et al., 2010; Dury, 2011). Among these, linear programming optimization (**LPO**) models have often been used for strategic decisions on cropping plans at the farm level (Sharifi and van Keulen, 1994; Vayssières et al., 2009; Dogliotti et al., 2010). These models find the best combination between land availability and crops by solving static and deterministic problems under specific farms' constraints (Dury et al., 2012). However, to the best of our knowledge, these models have not been developed to concomitantly optimize the cropping plan and feedstuff allocation in different diets. Consequently, our objective was to develop and test an LPO-based model to maximize farm income over feed cost (**IOFC**), through crop and feeding plan optimizations in high-yielding, confined, and TMR dairy farm systems considering actual homegrown feed production cost, specific farm constraints, and cash crop usage.

MATERIALS AND METHODS

The assessment is organized according to the framework presented in Figure 1. After description and evaluation of the farm's baseline situation, the optimized scenario is developed with an LPO that has minimum feed costs as its objective function and the optimal cropping and feeding plans as the final outcome. The IOFC that included milk sold and cash crops sales as income and crops production costs as well as purchased feed costs as expenses was used as an indicator of farm profitability.

The annual data of herd composition, nutritional grouping strategies, feed consumption, cropping plan choices, intrinsic farm limitations (i.e., irrigation water, land, workforce, machinery, and silage storage availability), and forage cost of production were collected in 2017 from 29 selected dairy farms located in the Po Valley (Italy). On each farm, the feed self-sufficiency, in terms of total home-produced energy (Mcal) and CP as the percentage of animal diet (% of DM per yr), was calculated.

Farm Selection

The farms were purposefully selected based on the previous knowledge that they recorded high-quality data (Bellingeri et al., 2019). All herds were composed of Holstein-Friesian cows, which were housed in freestall barns, fed TMR, had no access to pasture, and were high yielding. In general, farms had a unique diet for lactating cows, a single diet for dry cows, and 2 diets for heifers from weaning to first calving. A total of 14 crops were available for the farms to grow: corn grain, corn silage first seeding, corn silage second seeding, high-moisture ear corn, high-moisture ear corn second seeding, alfalfa hay, ryegrass hay, perennial grass hay, small-grain silage, mixed-crop silage, sorghum silage first seeding, sorghum silage second seeding, soybean grain first seeding, and soybean grain second seeding. Farms were not growing all of the crops listed above at the time of the study. Hence, the cost of production for crops not grown in 2017 in a farm was estimated based on the current farm agronomic practices and data from the overall sample of farms.

LPO Model Overview

The whole-farm optimization model can be stated as follows:

$$\begin{aligned}&\text{Minimize: } Z = \mathbf{C}'\mathbf{X}\\&\text{Subject to: } \mathbf{AX} >,\ =,\ \text{or} < \mathbf{B}\\&\mathbf{X} > 0,\end{aligned} \quad [1]$$

where Z = minimum whole-farm feed costs. The whole IOFC calculation included milk and cash crop sales as income and crop production costs and purchased feed costs as expenses (€/d); $\mathbf{C}'$ = 1 × n vector of objective function coefficient (e.g., price of milk and feeds); $\mathbf{A}$ = $m \times n$ matrix of technical coefficients [e.g., DMI, NE_L, CP, RDP, RUP, NDF, ADF, forage NDF (**fNDF**), NFC, and crop yield]; $\mathbf{B}$ = $m \times 1$ vector of constraints (e.g., DMI, NE_L, CP, RDP, RUP, NDF, ADF, fNDF, NFC, total crop hectares, first seeding crop hectares, second seeding crop hectares, specific crop hectares limitation, silage storage capacity, hay storage capacity, and feed inclusion level in the diets); and $\mathbf{X}$ = $n \times 1$ vector of variables (e.g., feed consumption and crop hectares).

The LPO model was developed using the General Algebraic Modeling System (**GAMS**) with the GAMS/CPLEX solver (GAMS Development Corporation, 2013, Washington, DC). The optimization model has the following components: cropland with yields and cost of production, cropland characteristics, economic variables, farm storage and facilities capacity, herd consistency and performance, animal feed, nutrients, and market feed availability and prices. Each component has constraints (Table 1) and equations as explained below. On each farm, given a determined production level and relative nutritional supplies to match each nutritional group, the model formulates optimized diets, the relative cropping plan, and the amount of feeds to purchase from the market with the goal of maximizing the whole-farm IOFC while considering specific farm constraints. For the crop plan, the model can select between producing forage for farm usage or cultivate cash crops to sell in the market. In this study, the only crop allowed as cash crop was corn grain in first seeding. The model formulated diets for each animal group. Nutrient content in the diet had to meet the actual farm nutritional management strategies. The nutrient allocation strategy followed a standard least-cost optimization linear programming approach (Wang et al., 2000; Fox et al., 2004).

Animal Feed and Nutrients

In the optimized scenario, DMI and dietary nutritional supplies were kept equal to the actual farm nutritional level (DMI_{act} and $Nutrient_{act}$, respectively). The model required an input of milk production, which was used to calculate milk income and IOFC. Production levels were considered to remain constant as the nutritional supplies remained unchanged between the baseline situation and the optimized scenario. With respect to the feeds used in the baseline situation (F_{iact}), that are available for formulation of diets, the ingredients (i.e., either used or did not use homegrown crops, purchased feed, and cash crop in baseline situation) and subsequent feed allocations could change between the baseline situation and the optimized scenario.

$$F_{ij}MIN \le F_{ij} \le F_{ij}MAX, \quad [2]$$

where F_{ij} is the ith feed supply from the jth diet, and $F_{ij}MIN$ and $F_{ij}MAX$ represent the lower and upper constraints expressed as kilograms of DM/animal per day, respectively. In the baseline scenario, $F_{ij}MIN$ (F_{iact} × 0.995) and $F_{ij}MAX$ (F_{iact} × 1.005) represent the lower and upper constraints expressed as kilograms per day. In the optimized scenarios, these constraints were not adopted, thus permitting the LPO to introduce new feeds not used in baseline diets.

$$DMI_jMIN \le DMI_j \le DMI_jMAX, \quad [3]$$

where DMI is from the jth diet, and DMI_jMIN and DMI_jMAX represent the lower (DMI_{act} × 0.995) and upper (DMI_{act} × 1.005) constraints expressed as kilograms of DM/animal per day.

Table 1. Abbreviations and constraints used in the whole-farm nutrient optimization model

Lower constraint[1]	Name	Upper constraint[1]	Unit	Description
DMI_jMIN	DMI_j	DMI_jMAX	kg of DM/d	DMI from *j*th diet, lower and upper constraints
$Nutrient_j$MIN	$Nutrient_j$	$Nutrient_j$MAX		Nutrient from the *j*th diet, lower and upper constraints
NE_{Lj}MIN	NE_{Lj}	NE_{Lj}MAX	Mcal/kg	NE_L concentration from *j*th diet, lower and upper constraints
CP_jMIN	CP_j	CP_jMAX	% of DM	CP from *j*th diet, lower and upper constraints
RDP_jMIN	RDP_j	RDP_jMAX	% of DM	RDP from *j*th diet, lower and upper constraints
RUP_jMIN	RUP_j	RUP_jMAX	% of DM	RUP from *j*th diet, lower and upper constraints
NDF_jMIN	NDF_j	NDF_jMAX	% of DM	NDF from *j*th diet, lower and upper constraints
ADF_jMIN	ADF_j	ADF_jMAX	% of DM	ADF from *j*th diet, lower and upper constraints
$fNDF_j$MIN	$fNDF_j$	$fNDF_j$MAX	% of DM	NDF from forages from *j*th diet, lower and upper constraints
NFC_jMIN	NFC_j	NFC_jMAX	% of DM	NFC from *j*th diet, lower and upper constraints
	F_i€		€/t	Price of the *i*th feed
	G_j		n	Animal number in the *j*th group
F_{ij}MIN	F_{ij}	F_{ij}MAX	kg/d	The *i*th feed supply from the *j*th diet, lower and upper constraints used only in baseline scenario
	TF€		€/yr	Whole-herd feed expense
	TF_i		t/yr	The *i*th annual herd feed requirement
HF_iBUYMIN	HF_iBUY	HF_iBUYMAX	t/yr	Purchased portion of the *i*th annual herd feed requirement
	TL		ha	Total farm land hectares
	TL_iY_i		t/ha	Crop production from land *i* grown for crop first seeding *i* and second seeding *g*[2]
	$L1st_z$		ha	Total land first seeding for a first seeding crop *z*[3]
	$L1stA2nd_f$		ha	Total land first seeding allowing a first seeding allowing a second crop *f*[4]
	$L2nd_g$		ha	Total land second seeding for a second seeding crop *g*
L_iMIN	L_i	L_iMAX	ha	Hectares of land grown for the *i*th feed, lower and upper constraints used only in baseline scenario
	Y_i		t/yr	The *i*th annual crop yield
	YHa_i		t of DM/ha	The *i*th annual crop yield as t of DM per hectare
	$TSSC_i$	$TSSC_i$MAX	t of DM/yr	Total silage storage capacity considering land *i* grown for ensiled crop *i*
	$THSC_i$	$THSC_i$MAX	t of DM/yr	Total hay storage capacity considering land *i* grown for hay crop *i*
	Milk		€/yr	Annual milk income
	CP_i		€/ha	Cost of production as € per hectare for crop *i*
	$CPDM_i$		€/t of DM	Cost of production as € per t of DM for crop *i*
	P_i		€/t of DM	Market price of the *i*th feed
	CC		€/yr	Cash crops net income
	IOFC		€/yr	Income over feed cost

[1]MIN and MAX refer to lower (actual value × 0.995) and upper (actual value × 1.005) constraints.

[2]First seeding crop *g* as corn silage first seeding, corn grain, high-moisture ear corn first seeding, alfalfa hay, perennial grass hay, soybean grain first seeding, and sorghum silage first seeding.

[3]First seeding crop allowing a second seeding crop *z* as small-grain silage, mixed-crop silage, and ryegrass hay.

[4]Second seeding crop *f*: corn silage second seeding, high-moisture ear corn second seeding, sorghum silage second seeding, and soybean grain second seeding.

$$\text{Nutrient}_j\text{MIN} \leq \text{Nutrient}_j \leq \text{Nutrient}_j\text{MAX}, \quad [4]$$

where Nutrient is a general term to refer to the following nutrient categories (NE_L, NDF, fNDF, ADF, CP, RDP, RUP, and NFC) from the jth diet, and $\text{Nutrient}_j\text{MIN}$ and $\text{Nutrient}_j\text{MAX}$ represent the lower ($\text{Nutrient}_{act} \times 0.995$) and upper ($\text{Nutrient}_{act} \times 1.005$) constraints expressed as % of Nutrient/kg of DM.

Cropland

The focus of the agronomic-cropland component of the model was to find the best allocation between cash crops and crops to feed the herd, given the constraint of available land and the productivity expected on that land. Below are the equations and constraints used in the cropland component of the model.

$$\text{TL} = \sum\nolimits_{z=1}^{Z} \text{L1st}_z + \sum\nolimits_{f=1}^{F} \text{L1stA2nd}_f, \quad [5]$$

where TL are the total farm lands in hectares, L1st_z the hectares of crops in first seeding grown for the crop z, and L1stA2nd_f the hectares of land in first seeding allowing a second crop f in the same year. The terms Z and F refer to the number of first seeding crop and first seeding crop allowing a second crop, respectively.

$$\sum\nolimits_{f=1}^{F} \text{L1stA2nd}_f = \sum\nolimits_{g=1}^{G} \text{L2nd}_g, \quad [6]$$

where L2nd_g are the sum of the hectares of second seeding crop. The term G refers to the number of second seeding crop.

$$\text{TL}_i\text{Y}_i = \sum\nolimits_{i=1}^{I} \text{L}_i \times \text{Y}_i, \quad [7]$$

where TL_iY_i are the total t of DM produced on land i (L_i) growing crop i. The term I refers to the number of first and second seeding crops.

$$\text{TF}_i = 365 \times \sum\nolimits_{n=1}^{N} (\text{F}_{ij} \times \text{G}_j), \quad [8]$$

where TF_i is the total annual feed supply, F_{ij} is the ith feed supply from the jth diet, and G_j is the animal number in the jth group. The term N refers to the number of animal groups.

$$\text{TF}_i\text{BUYMIN} \leq \text{TF}_i\text{BUY} \leq \text{TF}_i\text{BUYMAX}, \quad [9]$$

where TF_iBUY is the purchased portion of the ith feed, expressed as a percentage of the annual whole-herd requirement, and TF_iBUYMIN is the lower and TF_iBUYMAX the upper requirement.

$$\text{YHa}_i = \text{Y}_i/\text{L}_i, \quad [10]$$

where YHa_i is the annual crop yield for the crop i, expressed as t of DM/hectare, obtained by the total yield for the crop i (Y_i) expressed as t of DM and the relative cultivated area for the crop i (L_i) expressed in hectares.

$$\text{CPDM}_i = \text{CP}_i/\text{YHa}_i/\text{L}_i, \quad [11]$$

where CPDM_i is the cost of production as € per t of DM for crop i, obtained by the total cost of production for the crop i (CP_i), expressed as €, the relative annual crop yield for the crop i, expressed as t of DM per hectare, and the relative cultivated area for the crop i (L_i) expressed in hectares.

Economic Variables

$$\text{TF€} = \sum\nolimits_{i=1} \text{TF}_i \times \text{F}_i \ , \quad [12]$$

where TF€ is the total feed cost for all of the i feeds, considering total annual feed supply TF for the feed i and the relative feed price F, for the feed i.

$$\text{CC} = \sum\nolimits_{i=1} (\text{Y}_i \times \text{P}_i) - (\text{L}_i \times \text{CP}_i), \quad [13]$$

where CC is the cash crop net income, obtained by the yield as t of DM of the crop i and the relative market price P for the crop i, minus all of the cost of production of the crop i, obtained as the amount of land cultivated (L) for the crop i, and the relative cost of production expressed as € per hectare (CP) for the crop i.

$$\text{IOFC} = \text{Milk} - \text{TF€}, \quad [14]$$

where IOFC is the income over feed cost, expressed as € per year, and was obtained by calculating the difference between total annual milk income (Milk) expressed as € per year and the total feed cost to feed the herd (TF€) expressed as € per year. For each dairy farm, the Milk was obtained from the farm balance sheet because it is farm specific. It included the payment for both milk volume and milk quality, the latter based on fat, protein, SCC, and in some cases casein and urea contents too. The total annual milk revenue was assumed to be constant in each farm between baseline situation and optimized scenarios.

$$\text{WIOFC} = \text{IOFC} + \text{CC}, \quad [15]$$

where WIOFC is the whole-farm income over feed cost, expressed as € per year, and was obtained by the sum of IOFC and CC, and expressed as € per year.

Harvested Crop Production and Storage Capacity

$$\mathrm{TSSC}_i = \sum\nolimits_{i=1}^{m} (\mathrm{L}_i \times \mathrm{Y}_i), \quad [16]$$

where TSSC is the total silage production, considering land i grown for ensiled crop i, m are all of the crops grown on farm that require silage storages to be stored and were expressed as t per year. For all silage, a 10% decrease in harvested versus stored forage was considered for fermentation loss.

$$\mathrm{TSSC}_i \leq \mathrm{TSSC}_i\mathrm{MAX}, \quad [17]$$

where $\mathrm{TSSC}_i\mathrm{MAX}$ is the actual silage storage capacity of each farm, expressed as t per year.

$$\mathrm{THSC}_i = \sum\nolimits_{i=1}^{n} (\mathrm{L}_i \times \mathrm{Y}_i)^2, \quad [18]$$

where THSC is the total hay production, considering land i grown for hay crop i, n are all of the crops grown on farm that require hay storages to be stored and were expressed as t per year. For hay, a 3% decrease in harvested versus stored forage was considered for take into account DM loss.

$$\mathrm{THSC}_i \leq \mathrm{THSC}_i\mathrm{MAX}, \quad [19]$$

where $\mathrm{THSC}_i\mathrm{MAX}$ is the actual hay storage capacity of each farm, expressed as t per year.

Feed Costs

The farm could purchase feed ingredients from the market following prices obtained (CLAL, 2018; Advisory in Dairy and Food Products) plus transportation costs. These prices were the same for all farms that were studied. At the end, the market purchase prices (€/t of DM) were as follows: 100 for straw, 232 for corn grain, 142 for corn silage, 222 for legume hay, 155 for grass hay, 404 for soybean meal, 250 for sunflower meal, 355 for whole cottonseed, 233 for molasses, and 1,000 for rumen-protected fat. Feed sale prices for cash crop were the same as the market purchase prices. The costs of homegrown crops were calculated according to Bellingeri et al. (2019). Mineral and vitamin supplementation was considered constant between the baseline situation and optimized scenario. Composition of feed ingredients were assumed to be equal to values reported into NRC (2001) feed tables (Tables 15.1 and 15.2) and they were used consistently in all scenarios.

Assumptions

For simplicity, the model considered the herd size and structure, and group DMI to remain unchanged throughout the simulation. Also, the meat sold off the farm was not considered in the economic analysis because farm-level data on it were not available. Finally, the analysis was made for a calendar year and thus we assumed these farms carried no feed inventory (purchased and homegrown) to the next calendar year, and all surplus feed was sold (Tedeschi et al., 2000).

Statistical Analysis

The cluster analysis is a multivariate statistical technique commonly used to group n subjects (i.e., dairy farms) into k groups (i.e., clusters), when no a priori grouping information is available (Härdle and Simar, 2012). As a result, dairy farms that are grouped in the same cluster could be considered similar for specific farm characteristics, whereas there is heterogeneity across clusters. In this study, the hierarchical cluster analysis considered the following variables to create farm groups: land usage (first and second seeding), relative cropping plan, herd composition and performance (milk yield and components), energy and protein self-sufficiency, and economic variables such as milk price, and feed costs and IOFC. The analysis used the unweighted pair group mean with the arithmetic averages (UPGMA) method by the CLUSTER procedure of SAS (version 9.4, 2016, SAS Institute Inc., Cary, NC). Then, the obtained clusters grouping different dairy farms were descriptively presented (arithmetic mean ± SD) for farm characteristic or yield and cost of homegrown forage. Differences in cropping plans between baseline and optimized scenario among clusters were analyzed in agreement with a completely randomized design in which the main tested effect was the cluster. Significance was declared at $P < 0.05$.

RESULTS

As described in Table 2, cluster 1 could be described as dairy farms characterized by having a high stocking rate (4.09 cows/ha, when the average of all of the farms was 3.65 cows/ha). Cluster 2 included dairy farms with low incidence of double cropping strategies (i.e., only 21.2% of the land). Cluster 3 can be described as dairy farms having a low stocking rate (3.2 cows/ha) but with high usage of double cropping (i.e., 33% of the land).

Cluster 4 included a small group of perennial grass-based dairy farms with a high stocking rate (3.91 cows/ha) and high usage of double cropping strategies (33% of the land) considering the high proportions of perennial grasses in the crop plan (37.5% of the crop plan). Among the cropping plan strategies, cluster 1 had the greatest usage of corn grain as cash crop, whereas cluster 3 had the highest land area dedicated to corn grain. Corn silage in the first seeding was used in clusters 1 and 2 with a higher degree than cluster 3, whereas it was not used in cluster 4. Inversely, corn silage in the second seeding was used at a higher inclusion rate in the crop plan in cluster 3. High-moisture ear corn in the first seeding was used at the highest inclusion rate in clusters 1 and 2. On the other hand, high-moisture ear corn second seeding was not used in most of the farms that were considered. Further, alfalfa had the highest proportion among the crop plan in cluster 3, whereas its minimum usage was found to be typical among clusters 1 and 3. Small-grain silages were used at high proportions in cluster 1, at an intermediate level in cluster 2 and 3, and not at all in cluster 4. Ryegrass usage had the highest proportions in the crop plan among cluster 4, whereas it was used at an intermediate level in clusters 1 and 3, and not used in cluster 2. Average size of farms was 152.2 ± 94.6 ha with 313.2 ± 144.2 lactating cows, producing 32.7 ± 2.2 kg of milk/cow per d. Among the herd composition differences in the clusters considered, cluster 2 had the biggest farms, clusters 1 and 3 had dairy farm characterized by a slightly less number of lactating cows, whereas cluster 4 was made up of a group of small farms. The performance of milk yield and components was found to be similar among the clusters considered: the same pattern was found for milk price, which was slightly higher for farms in cluster 4. A different pattern was found for IOFC, where cluster 4 had the highest IOFC (€8.35 ± 1.04 per lactating cow), cluster 2 had among all farms an average IOFC (€7.85 ± 1.27 per lactating cow), cluster 3 had an average IOFC (€7.73 ± 1.24 per lactating cow), whereas cluster 1 had the lowest IOFC (€7.56 ± 1.55 per lactating cow). The feed cost was the lowest in cluster 2 (€19 ± 1 per 100 kg of milk), whereas it was the highest in cluster 4 (€22 ± 4 per 100 kg of milk), with an intermediate value for cluster 1 and 3. Feed self-sufficiency, calculated for both energy and protein, has been expressed as a percentage of the total nutritional requirement of the whole herd. These variables were found to be the highest in cluster 3 with a feed self-sufficiency of 60.2 ± 10.3% for energy and 43.3 ± 6.9% for protein; cluster 4 had the lowest feed self-sufficiency, with values of 36.4 ± 8.7% for energy and 29.1 ± 1.0% for protein, whereas cluster 1 and 2 showed intermediate values.

In Table 3, DMI, NE_L, and dietary nutritional characteristics of different cow groups were reported as the average for each cluster. The nutritional traits in the dry cow diets did not show important differences among clusters, except for DMI, which was highest in cluster 2 (i.e., 13.20 kg of DM/d) and lowest in cluster 4 (i.e., 11.60 kg of DM/d). Similar trends can be found for heifer diets, where the nutritional variables considered did not show important differences among clusters, except for DMI, which was highest in cluster 3 (i.e., 9.40 kg of DM/d) and lowest in cluster 1 (i.e., 8.55 kg of DM/d). The nutritional variables in the lactating cow diets showed important differences among clusters. In particular, the highest energy content was found in cluster 1 (i.e., 1.70 ± 0.03 Mcal of NE_L/kg) and the lowest in cluster 4 (i.e., 1.66 ± 0.02 Mcal of NE_L/kg), with very similar RDP and RUP contents. Nutritional indicators of fiber content (NDF and fNDF) showed the highest levels in cluster 4 (37.6 ± 3.98% DM and 31.7 ± 4.51% DM, respectively), whereas the lowest NDF level was found in cluster 1, being 35.0 ± 2.92% DM. The NFC content was very similar in the first 3 clusters (41.0 ± 4.21, 41.0 ± 2.91, and 40.5 ± 3.11% DM, respectively, for clusters 1, 2, and 3), whereas a lower level was found in cluster 4 (38.9 ± 1.68% DM).

The data in Table 4 present the average yields of different crops as well as the associated costs of production and market prices of purchased feeds. As expected, the greatest yields were reported for corn and sorghum silages of either the first or second seedings. The lowest yield was reported for soybean grains, particularly as second seeding (i.e., 3.2 and 2.8 t of DM/ha, respectively). There was not a great difference in the yield performance among farms (CV $\leq$ 10%). The average cost of production among the farms studied was highest for soybeans in the second and first seeding (i.e., €473.25 and €417.8/t of DM), whereas it was the lowest for small-grain silage and corn silage first seeding (i.e., €105.9 and €110.6/t of DM). Among dairy farms, moderate differences were observed in production costs; the coefficient of variation associated with cost of production was higher than 25% for perennial grass hay and soybean grain first seeding and lower than 15% for corn grain, corn silage, and high-moisture corn, both first and second seeding. Market prices for the purchased feeds used in the diets are presented as the average for the entire 2017 year. On average, as expected, the highest prices were for soybean meal and whole cottonseed and the lowest price was for ryegrass.

The differences within dairy farms in crop plan, feed cost per 100 kg of milk, NE_L and CP self-sufficiency, and IOFC between the baseline situation and optimized scenario are shown in Table 5. After the cluster analysis, 4 clusters were identified. The dedicated land

Table 2. Descriptive statistics (arithmetic mean ± SD) of farm characteristics of studied farms (n = 29) and clusters of farms

		Cluster[1]				
Variable	Unit	1 (n = 7)	2 (n = 11)	3 (n = 9)	4 (n = 2)	Mean (n = 29)
Land						
Land first seeding	ha	143.5 ± 80.4	163.2 ± 85.8	165 ± 102.7	65 ± 10	152.2 ± 92.5
Land second seeding	ha	42.6 ± 27.8	34.7 ± 23.7	54.5 ± 28.2	21.5 ± 3.5	41.8 ± 27.8
Crop plan						
Corn grain as cash crop	% total land[2]	6.38 ± 10.1	1.54 ± 4.87	0.16 ± 0.47	0 ± 0	2.17 ± 6.3
Corn grain	% total land	1.87 ± 2.2	7.79 ± 8.97	7.62 ± 6.92	3.0 ± 3.0	5.98 ± 7.34
Corn silage first seeding	% total land	19.64 ± 6.27	19.38 ± 6.99	9.93 ± 7.39	0 ± 0	15.17 ± 10.04
Corn silage second seeding	% total land	18.37 ± 10.69	13.98 ± 6.99	22.41 ± 7.90	12.33 ± 12.53	17.54 ± 9.5
High-moisture ear corn first seeding	% total land	10.01 ± 12.32	12.33 ± 13.18	6.22 ± 5.76	7.53 ± 7.53	9.51 ± 11.1
High-moisture ear corn second seeding	% total land	2.99 ± 7.32	1.5 ± 4.74	0.69 ± 1.94	0 ± 0	1.50 ± 4.85
Alfalfa hay	% total land	8.97 ± 8.98	16.67 ± 7.51	18.12 ± 2.46	11.5 ± 11.5	14.9 ± 8.1
Small-grain silage	% total land	12.34 ± 8.63	4.67 ± 6.5	3.41 ± 4.14	0 ± 0	5.81 ± 7.36
Ryegrass hay	% total land	8.24 ± 9.3	0.35 ± 1.09	19.95 ± 10.24	24.83 ± 24.83	10.02 ± 11.65
Perennial grass hay	% total land	0 ± 0	4.61 ± 9.31	1.43 ± 3.04	28.31 ± 28.31	4.14 ± 9.28
Soybean grain first seeding	% total land	4.99 ± 9.68	1.99 ± 3.5	2.20 ± 4.16	0 ± 0	2.64 ± 5.89
Soybean grain second seeding	% total land	0.3 ± 0.73	1.13 ± 1.93	3.44 ± 4.93	12.5 ± 12.5	2.43 ± 5.38
Sorghum silage first seeding	% total land	2.79 ± 4.62	0.93 ± 2.93	0 ± 0	0 ± 0	1.03 ± 3.10
Sorghum silage second seeding	% total land	1.14 ± 2.8	0.83 ± 2.19	0.62 ± 1.75	0 ± 0	0.78 ± 2.18
Mixed-crop silages	% total land	1.97 ± 3.17	12.42 ± 7.1	3.80 ± 3.03	0 ± 0	6.37 ± 6.92
Herd composition						
Lactating cows	n	312.8 ± 92.3	343.3 ± 108.3	302.3 ± 166.4	162.7 ± 28.3	313.2 ± 144.1
Dry cows	n	48.5 ± 13.4	53.3 ± 17.3	47.34 ± 25.12	26.7 ± 3.4	48.8 ± 21.9
Heifers	n	318.1 ± 85.5	366.9 ± 110	366 ± 224.6	162.2 ± 21.8	347.7 ± 172.8
Herd performance						
Milk fat content	%	3.80 ± 0.1	3.89 ± 0.12	3.82 ± 0.13	3.93 ± 0.08	3.85 ± 0.12
Milk protein content	%	3.37 ± 0.07	3.39 ± 0.04	3.39 ± 0.08	3.40 ± 0.02	3.39 ± 0.07
ECM[3]	kg/d	34.72 ± 2.44	34.72 ± 1.92	34.61 ± 2.45	35.88 ± 3.8	35.4 ± 2.86
Economics						
Milk price	€ per 100 kg of milk	38.7 ± 2.7	39 ± 2.5	38.1 ± 2.2	41.5 ± 3.0	38.8 ± 2.7
IOFC[4]	€/lactating cow per d	7.56 ± 1.55	7.85 ± 1.27	7.73 ± 1.24	8.35 ± 1.04	6.02 ± 1.5
Feed cost	€ per 100 kg of milk	21 ± 2	19 ± 1	20 ± 2	22 ± 4	20.4 ± 2.3
NE_L self-sufficiency[5]	% herd used level	49.2 ± 10.7	57.1 ± 7.5	60.2 ± 10.3	36.4 ± 8.7	53.9 ± 11.8
CP self-sufficiency[6]	% herd used level	31.4 ± 6.6	39.3 ± 5.5	43.3 ± 6.9	29.1 ± 1	37.4 ± 8

[1]Cluster 1 = dairy farms characterized by having a high stocking rate (4.09 cows per hectare; the average of all of the farms was 3.65 cows per hectare) and a medium level of land addressed to double cropping (i.e., 31.3% of the land; the average of all of the farms considered was 30.2% of the land). In cluster 2, dairy farms were grouped with low incidence of double cropping strategies (i.e., 22.1% of the land). Cluster 3 = dairy farms having a low stocking rate (3.2 cows per hectare) but with high usage of double cropping usage (i.e., 38.6% of the land). Cluster 4 = a small group of perennial grass-based dairy farms with a high stocking rate (3.91 cows per hectare) and high usage on double cropping strategies (33% of the land).

[2]% total land means the sum of the land used for a single crop and the land used for 2 crops within the same year.

[3]ECM = [12.82 × fat yield (kg)] + [7.13 × protein yield (kg)] + [0.323 × milk yield (kg)]. Calculated in agreement with Batistel et al. (2017).

[4]Whole-farm IOFC = milk income over feed cost of the herd plus extra income from cash crops.

[5]As percentage of actual herd energy consumed level (% Mcal).

[6]As percentage of actual herd protein consumed level (% CP).

Table 3. Descriptive statistics (arithmetic mean ± SD) of DMI (kg of DM/d), NE_L, Mcal/kg of DM), and nutritional characteristics (% DM) of studied farms (n = 29) and clusters of farms

Cluster[1]	Category	DMI	NE_L	CP	fNDF[2]	NDF	ADF	NFC
1	Dry cows	12.1 ± 1.05	1.29 ± 0.03	12.62 ± 0.75	49.3 ± 3.41	51.7 ± 3.51	33.6 ± 2.21	27.6 ± 3.15
1	Heifers	8.55 ± 1.21	1.32 ± 0.09	13.63 ± 1.12	49.7 ± 3.88	53.3 ± 3.28	34.2 ± 2.17	27.1 ± 4.18
1	Lactating cows	23.11 ± 1.87	1.70 ± 0.03	16.57 ± 0.47	29.6 ± 2.61	35.0 ± 2.92	22.0 ± 2.01	41.0 ± 4.21
2	Dry cows	13.20 ± 0.98	1.29 ± 0.05	13.46 ± 0.64	52.4 ± 4.14	55.6 ± 3.71	35.2 ± 3.01	26.7 ± 2.17
2	Heifers	9.20 ± 0.86	1.31 ± 0.04	14.04 ± 0.62	49.8 ± 3.71	54.1 ± 3.91	34.4 ± 3.17	26.9 ± 3.17
2	Lactating cows	23.34 ± 1.02	1.69 ± 0.02	16.31 ± 0.35	28.3 ± 1.51	35.4 ± 2.93	22.1 ± 2.17	41.0 ± 2.91
3	Dry cows	13.60 ± 0.94	1.27 ± 0.04	12.92 ± 0.41	53.4 ± 2.98	55.9 ± 2.91	35.6 ± 1.78	26.5 ± 3.14
3	Heifers	9.40 ± 1.36	1.29 ± 0.07	13.93 ± 0.39	51.1 ± 3.69	55.8 ± 3.01	35.5 ± 1.99	26.9 ± 2.98
3	Lactating cows	22.57 ± 1.53	1.67 ± 0.02	16.28 ± 0.91	29.7 ± 2.11	35.9 ± 2.64	22.7 ± 1.85	40.5 ± 3.11
4	Dry cows	11.60 ± 0.61	1.26 ± 0.05	13.34 ± 0.36	56.3 ± 3.47	58.3 ± 3.11	36.8 ± 3.48	24.4 ± 2.59
4	Heifers	8.75 ± 0.81	1.26 ± 0.04	14.17 ± 0.41	54.0 ± 2.98	49.0 ± 2.91	37.6 ± 1.72	23.6 ± 1.97
4	Lactating cows	23.75 ± 0.69	1.66 ± 0.02	16.56 ± 0.98	31.7 ± 4.51	37.6 ± 3.98	23.35 ± 2.17	38.9 ± 1.68

[1]Cluster 1 = dairy farms characterized by having a high stocking rate (4.09 cows per hectare; the average of all of the farms was 3.65 cows per hectare) and a medium level of land addressed to double cropping (i.e., 31.3% of the land; the average of all of the farms considered was 30.2% of the land). In cluster 2, dairy farms were grouped with low incidence of double cropping strategies (i.e., 22.1% of the land). Cluster 3 = dairy farms having a low stocking rate (3.2 cows per hectare) but with high usage of double cropping usage (i.e., 38.6% of the land). Cluster 4 = a small group of perennial grass-based dairy farms with a high stocking rate (3.91 cows per hectare) and high usage on double cropping strategies (33% of the land).

[2]fNDF = NDF from forage.

area for corn grain shows a reduction in cluster 2 and 3, with an overall reduction equal to −4.13 ± 6.5% ($P < 0.05$). Clusters 2, 3, and 4 show an increase in the cultivated area with an overall increase equal to 12.05 ± 13.4% ($P < 0.05$). Corn silage first seeding shows an overall increase of 12.05 ± 13.4%, with a strong increase in cluster 4 of 39.41 ± 0.55%. Small-grain silage cultivated land area among the clusters showed an average overall decrease of −4.53 ± 8.7% ($P < 0.05$), whereas a strong reduction in cluster 1 and an increase in cluster 4 were found. Corn silage second seeding showed a slight reduction on average of all of the clusters considered (−0.9 ± 9.45%; $P < 0.05$); the same pattern was found for small-grain silage, ryegrass hay, and perennial ryegrass ($P < 0.05$). Mixed-crop silage shows an increase in all of the clusters (+15.1 ± 10.9%; $P < 0.05$), with a peak in cluster 1 (24.30 ± 11.03%). After optimization of the total feed cost, a reduction was found in all of the clusters with an average of −€1.39 ± 1.09 per 100 kg of milk ($P < 0.05$). Feed self-sufficiency from an energy standpoint (expressed as % of the total herd requirement) showed an improvement in all of the clusters, with an average of 8.47 ± 6.32% ($P < 0.05$). Thus, the protein feed self-sufficiency showed an improvement in all of the clusters, with an average of 3.57 ± 3.11% ($P < 0.05$). The model increased the whole-farm IOFC in all clusters ($P = 0.057$) by €0.38 per cow per day due to the feed cost reduction ($P < 0.05$) from €20.4/100 kg of milk (52.5% of milk income) to €19/100 kg of milk (48.9% of milk income).

The difference in forage allocation by diets and cluster of the baseline situation and optimized scenario can be found in Table 6 and Figure 2, whereas modifications in dietary ingredients are shown in Figure 3. Lactating cow diets were suggested to decrease alfalfa by 4.22%, 12.2%, and 1.6% in clusters 2, 3, and 4, respectively, and to increase it by 1.6% in cluster 1. Ryegrass hay inclusion in lactating cows' diets showed a reduction in all of the clusters. A similar trend was found in perennial grass hay, which was substituted with mixed-crop silage. Soybean grain in second seeding showed an increase for cluster 3 (1.5%) and a reduction in clusters 2 and 4 (−1.25% and −2.3%, respectively).

Among dry cow diets, inclusion of corn silage in first seeding showed a reduction in cluster 1 (−0.7%), whereas it showed an increase in clusters 2, 3, and 4 (3.77, 1.18, 5.78%, respectively). Similarly, corn silage in second seeding was suggested to increase its utilization among diets. Perennial grass hay utilization among dry cows diet showed a reduction in clusters 1 and 4 (−6.7 and 8.5%, respectively) and a slight increase for cluster 2 and 3. Mixed-crop silages increased in all of the clusters, whereas the total amount of feeds pur-

Table 4. Descriptive statistics (arithmetic mean ± SD) of yield and costs of farm-grown feeds among studied farms (n = 29) and clusters of farms

	Cluster[1]									
	1 (n = 7)		2 (n = 11)		3 (n = 9)		4 (n = 2)		**Mean (n = 29)**	
	Yield	Cost	Yield	Cost	Yield	Cost	Yield	Cost	Yield	Cost
Farm-grown feed	t of DM/ha	€ t of DM	t of DM/ha	€ t of DM	t of DM/ha	€ t of DM	t of DM/ha	€ t of DM	t of DM/ha	€ t of DM
Alfalfa hay	9.46 ± 1.55	184.3 ± 45	9.9 ± 0.6	149.9 ± 22.6	9.57 ± 0.87	161.24 ± 38.6	9.8 ± 0.65	173.5 ± 31.9	9.7 ± 1.1	163.2 ± 37.3
Mixed-crop silage[2]	9.23 ± 0.8	119.9 ± 33.2	9.1 ± 0.6	109.3 ± 12.1	9.62 ± 0.33	108.5 ± 30	9.52 ± 0.17	149.6 ± 39.6	9.3 ± 0.6	114.1 ± 28.2
Corn grain[3]	10.9 ± 1.1	220.1 ± 23.9	10.5 ± 0.6	218.5 ± 15.1	10.11 ± 0.6	225.45 ± 32.1	10.35 ± 0.55	240.9 ± 17.4	10.5 ± 0.8	222.6 ± 24.5
Corn silage first seeding	20.2 ± 2.15	115.9 ± 20.7	19.9 ± 1.35	109.1 ± 7.3	20.2 ± 1.51	106.64 ± 14.2	20.13 ± 0.99	117.9 ± 15.9	20.1 ± 1.6	110.6 ± 14.5
Corn silage second seeding	17.8 ± 2.03	135.7 ± 24.4	16.4 ± 1.38	134.8 ± 12.7	17.3 ± 1.21	129.5 ± 13.8	17.7 ± 0.8	126.6 ± 14.9	17.1 ± 1.6	132.8 ± 17
High-moisture ear corn first seeding	11.8 ± 1.2	192.7 ± 25.5	12.1 ± 0.95	163.6 ± 18.5	11.7 ± 0.47	169.6 ± 24.8	11.65 ± 0.5	188.3 ± 36.1	11.8 ± 0.9	174.4 ± 26
High-moisture ear corn second seeding	9.9 ± 0.9	244.9 ± 37.4	9.49 ± 0.6	224.9 ± 24.65	9.41 ± 0.17	224.4 ± 30.6	9.88 ± 0.44	243.9 ± 52.4	9.6 ± 0.7	234.0 ± 33.7
Perennial grass hay	8.65 ± 1.1	148.2 ± 43.2	9.1 ± 0.8	128.9 ± 26.5	8.62 ± 0.51	112.7 ± 40.9	10.01 ± 0.9	164.4 ± 37.3	8.9 ± 0.9	129.6 ± 39.5
Ryegrass hay	5.93 ± 0.45	157.3 ± 30.2	5.92 ± 0.2	144.1 ± 21.2	5.98 ± 0.23	151.7 ± 26.8	5.57 ± 0.1	197.4 ± 48.6	5.9 ± 0.3	153.3 ± 30.8
Soybean grain first seeding	2.91 ± 0.5	513.7 ± 148.1	3.3 ± 0.25	384.9 ± 71.1	3.32 ± 0.28	384 ± 110.4	3.61 ± 0.21	414.4 ± 113.6	3.2 ± 0.4	417.8 ± 121.9
Soybean grain second seeding	2.53 ± 0.38	543.3 ± 104.4	2.85 ± 0.19	461.4 ± 56.93	2.87 ± 0.25	434.9 ± 84.6	2.97 ± 0.6	466.1 ± 84.5	2.8 ± 0.3	473.3 ± 91
Sorghum silage first seeding	12.2 ± 0.9	127.1 ± 19.7	12.7 ± 0.7	112.1 ± 14.6	12.8 ± 0.47	110.8 ± 28.1	12.24 ± 0.7	138.9 ± 28.3	12.6 ± 0.7	122.7 ± 25.1
Sorghum silage second seeding	10.96 ± 0.94	134.1 ± 15	11.8 ± 1.05	121.4 ± 15.8	11.8 ± 0.6	116.4 ± 22.1	11.20 ± 1.1	136.4 ± 0.21	11.7 ± 0.9	127.5 ± 20.9
Small-grain silage	9.6 ± 1	108.1 ± 13.8	9.22 ± 1.2	108.4 ± 15.8	9.4 ± 1.4	105.5 ± 28.6	10.37 ± 1.3	112.2 ± 18.9	9.5 ± 1.2	105.9 ± 20.4

[1]Cluster 1 = dairy farms characterized by having a high stocking rate (4.09 cows per hectare; the average of all of the farms was 3.65 cows per hectare) and a medium level of land addressed to double cropping (i.e., 31.3% of the land; the average of all of the farms considered was 30.2% of the land). In cluster 2, dairy farms were grouped with low incidence of double cropping strategies (i.e., 22.1% of the land). Cluster 3 = dairy farms having a low stocking rate (3.2 cows per hectare) but with high usage of double cropping usage (i.e., 38.6% of the land). Cluster 4 = a small group of perennial grass-based dairy farms with a high stocking rate (3.91 cows per hectare) and high usage on double cropping strategies (33% of the land).

[2]Mixed-crop silage = small grains and vetch/pea harvested as wilted silage.

[3]This crop can be a cash crop, can be sold or used as feed.

Table 5. Differences (arithmetic mean ± SD) in cropping plan, feed cost, and income over feed cost (IOFC) between baseline and optimized scenario by farm clusters, in which simple data average was used

Variable	Unit	Cluster[1] 1 (n = 7)	Cluster[1] 2 (n = 11)	Cluster[1] 3 (n = 9)	Cluster[1] 4 (n = 2)	Mean (n = 29)	MSE	*P*-value
Corn grain as cash crop	% total land[2]	−1.10 ± 2.82	−1.35 ± 4.28	−0.16 ± 0.47	0 ± 0	−0.83 ± 3.1	3.41	0.719
Corn grain	% total land	0.29 ± 4.94	−5.52 ± 6.13	−6.12 ± 6.65	−3 ± 3	−4.13 ± 6.5	7.67	<0.05
Corn silage first seeding	% total land	−2.96 ± 8.43	12.78 ± 8.46	16.76 ± 7.05	39.41 ± 0.55	12.05 ± 13.4	8.046	<0.05
Corn silage second seeding	% total land	3.94 ± 9.05	1.87 ± 5.53	−9.33 ± 6.4	4.59 ± 11.74	−0.9 ± 9.45	7.818	<0.05
High-moisture ear corn first seeding	% total land	1.41 ± 8.37	5.01 ± 8.24	4.98 ± 4.82	−7.3 ± 7.77	3.3 ± 8.2	7.648	0.169
High-moisture ear corn second seeding	% total land	−2.99 ± 7.32	−1.5 ± 4.74	2.24 ± 4.62	0 ± 0	−0.6 ± 5.8	5.651	0.309
Alfalfa hay	% total land	−2.79 ± 10.78	−10.18 ± 8.49	−14.96 ± 5.52	−6.52 ± 6.52	−9.63 ± 9.6	8.628	0.086
Small-grain silage	% total land	−12.34 ± 8.63	−3.2 ± 5.91	−3.41 ± 4.14	10.41 ± 7.98	−4.53 ± 8.7	6.951	<0.05
Ryegrass hay	% total land	−8.24 ± 9.3	−0.35 ± 1.09	−19.95 ± 10.24	−24.83 ± 0.17	−10.2 ± 11.9	7.891	<0.05
Perennial grass hay	% total land	0 ± 0	−2.48 ± 6.71	−0.53 ± 1.09	−20.81 ± 0.19	−3.5 ± 8.2	4.503	<0.05
Soybean grain first seeding	% total land	−2.03 ± 9.91	−0.03 ± 2.78	4.11 ± 5.76	5.01 ± 5.01	−2.1 ± 4.9	6.796	0.251
Soybean grain second seeding	% total land	0.76 ± 1.85	0.17 ± 3.19	4.69 ± 10.22	−12.50 ± 12.50	0.85 ± 8.2	7.379	0.051
Sorghum silage first seeding	% total land	−0.03 ± 0.17	−0.93 ± 2.93	0 ± 0	0 ± 0	−0.4 ± 1.9	1.907	0.674
Sorghum silage second seeding	% total land	1.77 ± 6.98	0.82 ± 3.27	0.36 ± 2.80	4.51 ± 4.51	1.2 ± 4.65	4.763	0.69
Mixed-crop silage[3]	% total land	24.30 ± 11.03	4.90 ± 4.9	21.32 ± 2.90	11.02 ± 4.05	15.1 ± 10.9	7.216	<0.05
Land first seeding	% land[4]	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0.458	0.674
Land second seeding	% land	86.4 ± 198.3	56.2 ± 88.8	6.3 ± 24.3	2.5 ± 21.7	31.3 ± 116.9	55.714	0.881
Land first + second seeding	% land	5.7 ± 12.3	6.2 ± 9.2	−2.9 ± 8	0.7 ± 5.9	1.2 ± 10.5	10.56	0.456
Feed cost from homegrown feeds	€ per 100 kg of milk	0.51 ± 0.67	0.72 ± 0.57	−0.05 ± 0.61	0.67 ± 0.47	0.41 ± 0.68	0.799	0.242
Feed cost from purchased feeds	€ per 100 kg of milk	−1.84 ± 1.49	−1.63 ± 0.76	−1.68 ± 0.95	−2.59 ± 2.49	−1.81 ± 1.46	1.358	0.055
Total feed cost	€ 100 kg of milk	−1.33 ± 0.94	−0.91 ± 0.29	−1.73 ± 0.70	−2.06 ± 1.94	−1.39 ± 1.09	1.042	<0.05
NE_L self-sufficiency	% herd used level	6.5 ± 4.9	9.3 ± 4.7	6.4 ± 4.1	13.1 ± 9	8.47 ± 6.32	5.465	<0.05
CP self-sufficiency	% herd used level	5.6 ± 2.7	2.9 ± 2.9	3 ± 2.1	5.2 ± 2.7	3.57 ± 3.11	2.655	<0.05
IOFC[5]	€ per cow per d	0.36 ± 0.26	0.26 ± 0.09	0.47 ± 0.17	0.61 ± 0.42	0.38 ± 0.29	23.923	0.057

[1]Cluster 1 = dairy farms characterized by having a high stocking rate (4.09 cows per hectare; the average of all of the farms was 3.65 cows per hectare) and a medium level of land addressed to double cropping (i.e., 31.3% of the land; the average of all of the farms considered was 30.2% of the land). In cluster 2, dairy farms were grouped with low incidence of double cropping strategies (i.e., 22.1% of the land). Cluster 3 = dairy farms having a low stocking rate (3.2 cows per hectare) but with high usage of double cropping usage (i.e., 38.6% of the land). Cluster 4 = a small group of perennial grass-based dairy farms with a high stocking rate (3.91 cows per hectare) and high usage on double cropping strategies (33% of the land).

[2]% total land = the sum of the land used for a single crop and the land used for 2 crops within the same year.

[3]Mixed-crop silage = small grains and vetch/pea harvested as wilted silage.

[4]% land = the physical land availability of the farm.

[5]Whole-farm IOFC = milk income over feed cost of the herd plus extra income from cash crops.

Table 6. Differences (arithmetic mean ± SD) in diets feed allocation between baseline and optimized scenario by farm clusters in which simple average data were used

Variable[1]	Cluster[2] 1 (n = 7)	2 (n = 11)	3 (n = 9)	4 (n = 2)	Mean (n = 29)	MSE	P-value
Lactating cow diet							
Corn grain	−1.7 ± 2.75	−0.33 ± 4.1	−3.38 ± 4.02	−3.24 ± 3.24	−2.02 ± 4.05	4.11	0.628
Corn silage first seeding	5.02 ± 15.23	14.24 ± 12.41	17.29 ± 11.40	27.64 ± 11.83	13.91 ± 15	14.3	0.102
Corn silage second seeding	1.28 ± 7.81	3.37 ± 11.1	−3.16 ± 10.76	9.53 ± 1.75	−0.24 ± 10.6	11.5	0.659
High-moisture ear corn first seeding	2.05 ± 7.8	3.04 ± 8.5	3.73 ± 9.86	0.17 ± 0.17	3.36 ± 9.04	9.16	0.931
High-moisture ear corn second seeding	−0.53 ± 1.29	0 ± 0	−0.1 ± 5.83	0 ± 0	−0.06 ± 3.43	3.49	0.991
Alfalfa hay	1.57 ± 7.24	−4.22 ± 6.6	−12.20 ± 3.83	−1.6 ± 1.6	−5.71 ± 6.83	5.9	<0.05
Small-grain silage	−3.98 ± 4.02	−2.76 ± 6.15	−1.2 ± 2.92	−0.04 ± 3.02	−3.12 ± 3.91	3.98	0.276
Ryegrass hay	−0.58 ± 1.41	0.25 ± 2.81	−0.042 ± 1.18	−4.28 ± 4.28	−0.5 ± 1.41	1.84	0.06
Perennial grass hay	−1.64 ± 4.01	0.22 ± 3.5	0 ± 0	−11.65 ± 1.46	−1.04 ± 2.91	3	<0.05
Soybean grain first seeding	0.43 ± 0.9	−0.43 ± 1.5	0.68 ± 1.94	0.98 ± 0.98	0.06 ± 1.55	1.62	0.449
Soybean grain second seeding	0.32 ± 0.78	−1.25 ± 2.8	1.56 ± 1.7	−2.33 ± 2.33	−0.08 ± 2.45	2.26	<0.05
Mixed-crop silage	5.90 ± 5.88	4.63 ± 5.2	9.48 ± 6.23	2.12 ± 2.12	6.48 ± 6.05	5.9	0.313
Total feeds purchased on the market	−8.14 ± 4.97	−10.56 ± 9.9	−11.76 ± 7.15	−17.37 ± 5.08	−11.04 ± 6.8	7.23	0.422
Dry cow diet							
Corn grain	−0.67 ± 1.65	0 ± 0.86	0 ± 0	0 ± 0	−0.18 ± 1.1	1.03	0.531
Corn silage first seeding	−0.7 ± 1.88	3.77 ± 5.46	1.18 ± 2.91	5.78 ± 5.78	1.97 ± 4.6	4.43	0.09
Corn silage second seeding	2.06 ± 3.99	2.45 ± 4.47	0.72 ± 2.25	10.43 ± 1.13	2.30 ± 4.2	3.82	<0.05
High-moisture ear corn first seeding	0.62 ± 3.05	−1.76 ± 6.37	0.14 ± 1.53	0 ± 0	0.04 ± 4	4.51	0.323
High-moisture ear corn second seeding	0 ± 0	0 ± 0	0.57 ± 1.07	0 ± 0	0.20 ± 0.7	0.63	0.253
Small-grain silage	−1.59 ± 3.89	−3.51 ± 7.86	0 ± 0	0 ± 0	−2.05 ± 5.9	5.66	0.467
Ryegrass hay	−0.14 ± 0.34	−1.36 ± 4.50	−14.27 ± 13.35	0 ± 0	−4.90 ± 10.3	8.83	<0.05
Perennial grass hay	−6.74 ± 11.89	1.07 ± 2.76	0.64 ± 1.8	−8.51 ± 3.35	−1.17 ± 7.3	6.51	<0.05
Sorghum silage first seeding	−2.89 ± 14.77	−1.02 ± 3.4	0 ± 0	0 ± 0	−2.11 ± 6.6	7.91	0.9
Sorghum silage second seeding	6.85 ± 16.03	9.5 ± 12.7	0 ± 14.63	18.1 ± 18.1	7.62 ± 16.3	15.9	0.66
Mixed-crop silage	3.68 ± 10.19	11.54 ± 14.3	25.76 ± 16.91	0 ± 0	13.03 ± 15.4	15.2	<0.05
Total feeds purchased on the market	−0.48 ± 12.98	20.69 ± 16.2	−14.74 ± 11.56	−25.81 ± 21.65	−14.75 ± 16.8	15.9	0.08
Heifer diet							
Corn grain	−0.15 ± 0.37	−1.34 ± 3.12	0 ± 0	0 ± 0	−0.62 ± 2.22	2.12	0.388
Corn silage first seeding	−0.72 ± 1.71	9.89 ± 6.1	5.61 ± 6.57	15.6 ± 0.06	7.23 ± 7.3	5.45	<0.05
Corn silage second seeding	0.65 ± 2.57	6.63 ± 9.75	0.94 ± 1.92	10.03 ± 5.64	3.81 ± 7.37	6.89	0.07
High-moisture ear corn first seeding	0.26 ± 0.65	0.27 ± 0.6	−0.14 ± 0.59	0 ± 0	0.21 ± 0.54	0.64	0.659
Small-grain silage	−5.79 ± 8.08	−5.85 ± 12.1	−2.52 ± 4.19	12.9 ± 12.9	−3.69 ± 11.23	10.28	0.152
Ryegrass hay	−4.38 ± 7	−7.4 ± 8.23	−14.46 ± 8.77	0 ± 0	−9.44 ± 9.17	8.71	0.131
Perennial grass hay	−6.58 ± 11.01	−2.06 ± 9.8	0.06 ± 0.16	−17.7 ± 15.1	0.02 ± 0.1	9.84	0.159
Sorghum silage first seeding	−3.41 ± 9.73	−1.03 ± 3.43	0 ± 0	0 ± 0	−1.69 ± 5.43	5.55	0.649
Sorghum silage second seeding	3.2 ± 7.83	1.14 ± 3.34	0.55 ± 3.16	4.12 ± 4.12	1.98 ± 5.2	5.13	0.647
Mixed-crop silage	18.36 ± 8.6	16.8 ± 13.15	19.72 ± 12.63	11.9 ± 11.9	16.38 ± 11.43	12.51	0.549
Total feeds purchased on the market	−1.44 ± 4.14	−17.05 ± 11.54	−8.6 ± 9.41	−36.8 ± 25.9	−13.12 ± 14.8	12.53	0.092

[1]Expressed as DM % of total diet.

[2]Cluster 1 = dairy farms characterized by having a high stocking rate (4.09 cows per hectare; the average of all of the farms was 3.65 cows per hectare) and a medium level of land addressed to double cropping (i.e., 31.3% of the land; the average of all of the farms considered was 30.2% of the land). In cluster 2, dairy farms were grouped with low incidence of double cropping strategies (i.e., 22.1% of the land). Cluster 3 = dairy farms having a low stocking rate (3.2 cows per hectare) but with high usage of double cropping usage (i.e., 38.6% of the land). Cluster 4 = a small group of perennial grass-based dairy farms with a high stocking rate (3.91 cows per hectare) and high usage on double cropping strategies (33% of the land).

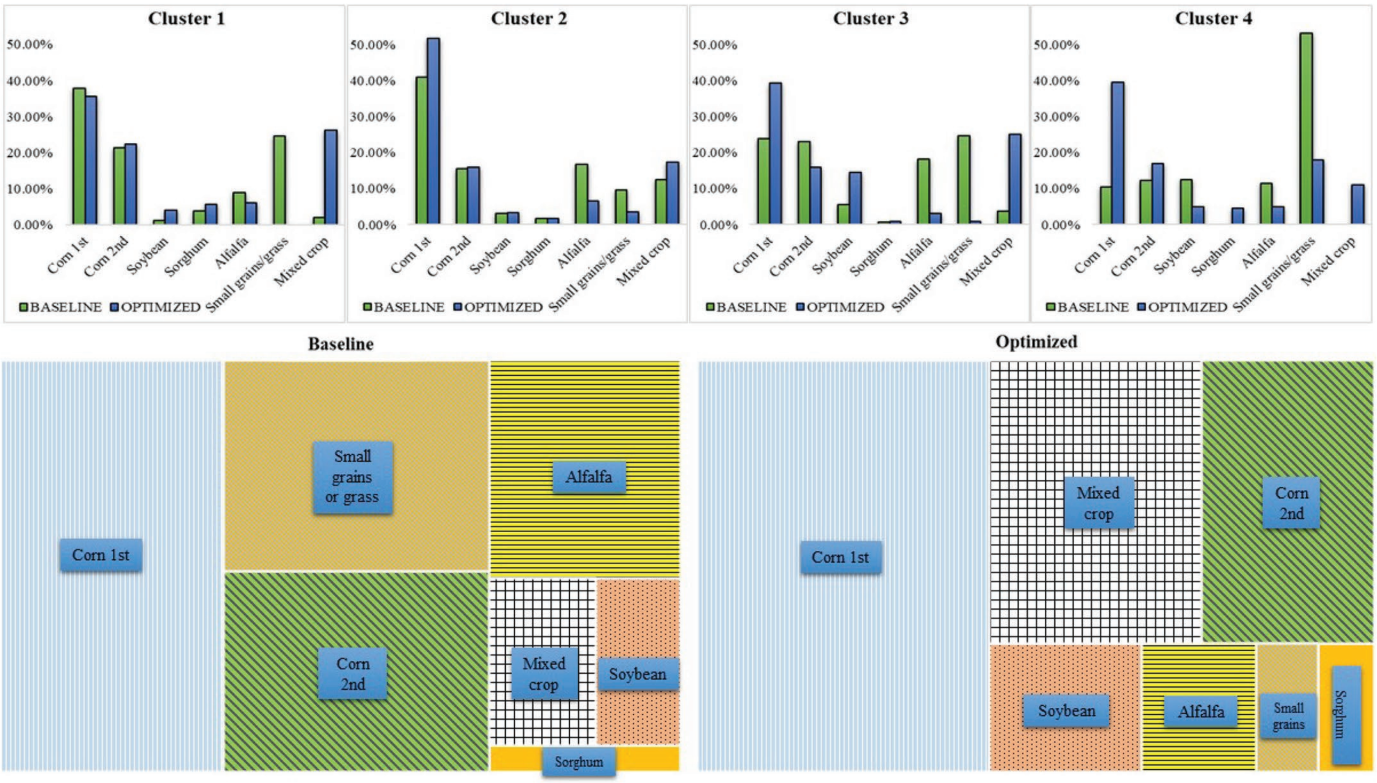

Figure 2. Average crop plan distribution by farm clusters (top graphs) and all farms (n = 29) in the baseline and optimized scenarios. Corn 1st is the aggregated area for corn silage first seeding, high-moisture ear corn first seeding, and corn grain. Corn 2nd is the aggregated area for corn silage second seeding and high-moisture ear corn second seeding. Mixed crop is mixed-crop silage small grains and vetch/pea harvested as wilted silage. Small grains or grass is the aggregated area for perennial grass hay, ryegrass hay, and small-grain silage. Sorghum is the aggregated area for sorghum silage first seeding and sorghum silage second seeding. Soybean is the aggregated area for soybean grain first seeding and soybean grain second seeding. Alfalfa is alfalfa hay. Cluster 1 = dairy farms characterized by having a high stocking rate (4.09 cows per hectare; the average of all of the farms was 3.65 cows per hectare) and a medium level of land addressed to double cropping (i.e., 31.3% of the land; the average of all of the farms considered was 30.2% of the land). In cluster 2, dairy farms were grouped with low incidence of double cropping strategies (i.e., 22.1% of the land). Cluster 3 = dairy farms having a low stocking rate (3.2 cows per hectare) but with high usage of double cropping usage (i.e., 38.6% of the land). Cluster 4 = a small group of perennial grass-based dairy farms with a high stocking rate (3.91 cows per hectare) and high usage on double cropping strategies (33% of the land).

chased on the market was reduced in all of the clusters, except in cluster 2.

Among heifer diets, inclusion of corn silage first seeding increased among clusters 2, 3, and 4 (9.89, 5.61, and 15.6%, respectively), but it was reduced in cluster 1. Thus, corn silage second seeding increased in all of the clusters that were considered. Even in heifers diet, the total amount of feeds purchased on the market were reduced in all of the clusters (−1.4, −17.1, −8.6, and −36.8% in clusters 1, 2, 3, and 4, respectively). If we consider the differences among clusters (Figure 4), corn silage inclusion rate increased in all clusters and in all diet categories. In particular, cluster 4 had the largest increase in corn silage dietary inclusion from baseline situation to optimized scenario at the expense of both grass and alfalfa hay. High-moisture ear corn followed the same increasing trend, except for cluster 4. Alfalfa hay showed a consistent decrease of inclusion rate in all of the clusters as well as ryegrass hay. Mixed-crop silage was preferred in the optimized scenarios to the small-grain silage and grass hays. In general, a higher amount of soybean meal was purchased from the market in all of the clusters between baseline situation and optimized scenarios.

DISCUSSION

Linear programming is a widely used tool to solve cropping plan decisions (Dury et al., 2012). Although farmers have multiple objectives, assuming a gross margin maximization while testing cropping plan and diets can be a feasible way to operate as it has been done in similar models testing different normative approaches (Manos et al., 2013; Cortigliani and Dono, 2014). However, gross margin could not be used in our model due to lack of complete data at the farm level (i.e., farms' complete balance sheets were not available). For this reason, a least-cost diet formulation approach was chosen, resulting in feed cost minimization while maintaining milk yield and components as the fixed factor (milk income fixed for baseline and optimized scenarios). The IOFC was found to be a good indicator of farm profitability (Wolf, 2010), when complete balance sheet data were not available (Ely et al., 2003; Bailey et al., 2005; Cabrera et al., 2010). Even though the model does not maximize IOFC but minimizes feed costs since milk yield and components are considered fixed factors, the integrations of specific equations forecasting changes in milk yield and quality or feed efficiency from dietary nutritional changes would be an interesting future development of the present model. The model framework provides opportunities to improve dairy farm feeding strategies, reorganizing crop plan as well as feed allocation. Importantly, suggested results could be combined with the intuitive rationale of the farmer, nutritionist, or consultant to take more appropriate decisions. Usually, farmers and consultants use diet planning combined with amounts of silage and hay storage availability to define the cropping plan (Schils et al., 2007). The study model concomitantly optimized feeding strategies, diets, and crop plans based on specific nutrient requirements among the nutritional groups of the herd, considering other farm-related factors such as land and market opportunities, intrinsic farm constraints, and real forage cost of production. Concerning market opportunities, a limitation of current approach could be related to the use of first seeding corn crop for grain production as the only available for cash crop. The rationality of this approach was based on some important reasons: (1) dairy farmers prefer to produce crops for dairy feeds and only consider cash crops in limited circumstances; (2) even though farms could sell other crops for cash,

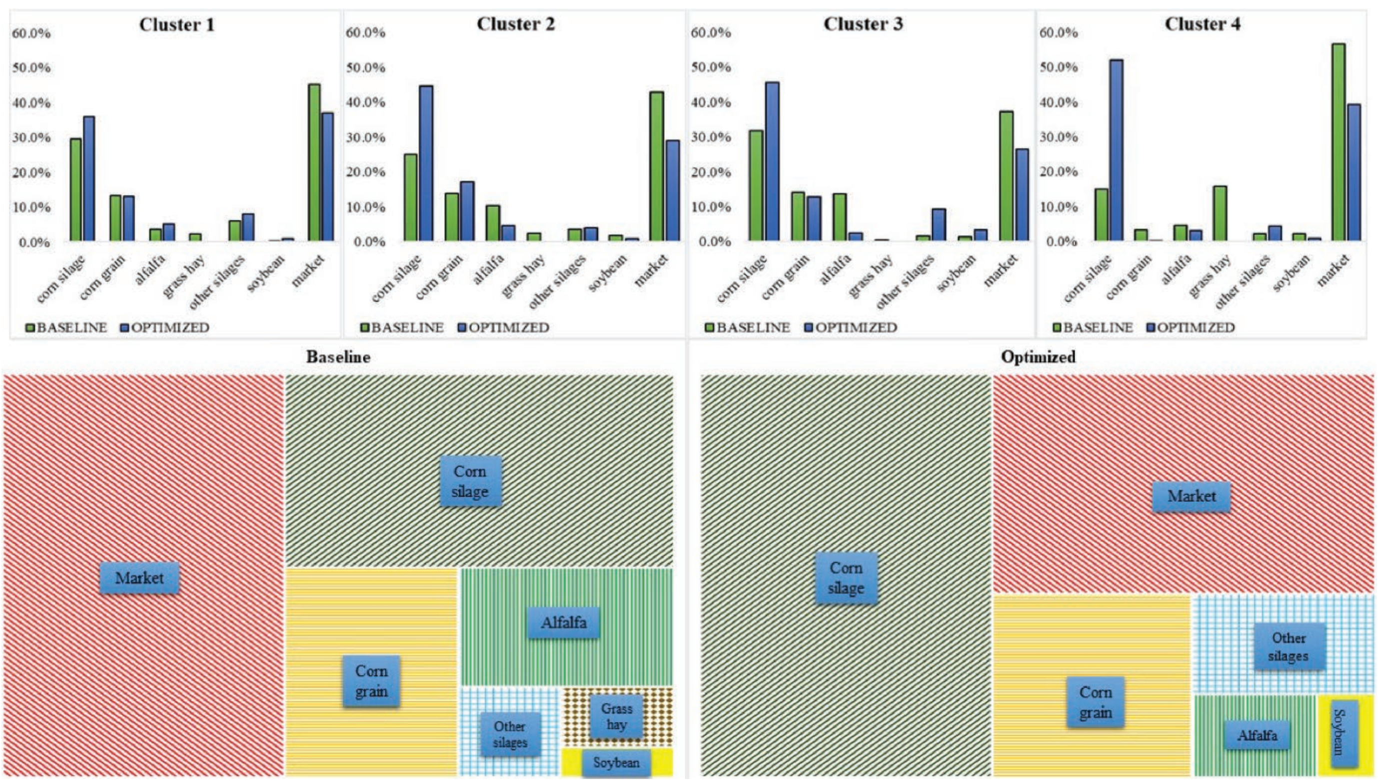

Figure 3. Average distribution of the diet components by farm clusters (top graphs) and all farms (n = 29) in the baseline and optimized scenarios. Corn silage is the aggregated area for corn silage first seeding and corn silage in second seeding; corn grain is the aggregated area for high-moisture ear corn first seeding and high-moisture ear corn in second seeding. "Other silages" is the aggregated area for small-grain silage, sorghum first and second seeding silage, mixed-crop silage (small grains + vetch/pea harvested as wilted silage). Grass hay is the aggregated area of ryegrass hay and perennial grass hay. Soybean is the aggregated area for soybean grain first seeding and soybean grain second seeding. Alfalfa is alfalfa hay. Market is the aggregated area for all of the diet components purchased on the market. Cluster 1 = dairy farms characterized by having a high stocking rate (4.09 cows per hectare; the average of all of the farms was 3.65 cows per hectare) and a medium level of land addressed to double cropping (i.e., 31.3% of the land; the average of all of the farms considered was 30.2% of the land). In cluster 2, dairy farms were grouped with low incidence of double cropping strategies (i.e., 22.1% of the land). Cluster 3 = dairy farms having a low stocking rate (3.2 cows per hectare) but with high usage of double cropping usage (i.e., 38.6% of the land). Cluster 4 = a small group of perennial grass-based dairy farms with a high stocking rate (3.91 cows per hectare) and high usage on double cropping strategies (33% of the land).

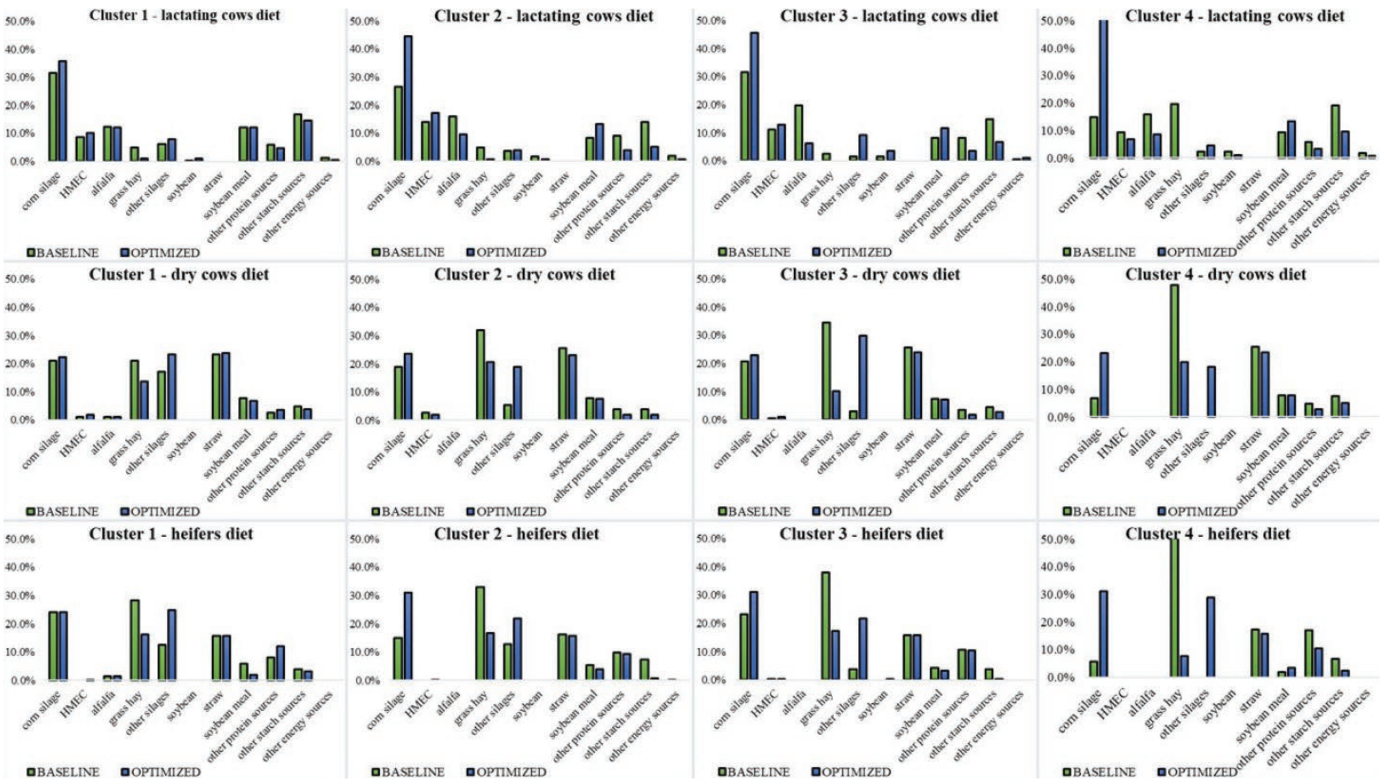

Figure 4. Ingredients of the diets used in farm clusters in the baseline and optimized scenarios. Corn silage is the aggregated amount for corn silage first seeding, and corn silage in second seeding and purchased corn silage; HMEC is the aggregated amount for produced both high-moisture ear corn first seeding and high-moisture ear corn second seeding; alfalfa is the aggregated amount of alfalfa hay both produced and purchased; grass hay is the aggregated amount of grass hay both produced and purchased; and "other silages" is the aggregated amount of small-grain silage, mixed-crop silage, and sorghum silage. Soybean is the aggregated amount for soybean grain produced on farm and directly used after a roasting thermal treatment. "Other protein sources" is the aggregated amount for sunflower meal and whole cottonseed; "other starch sources" is the aggregated amount for corn grain both produced and purchased and purchased high-moisture corn. Straw is the dry stalky wheat plant residue, and "other energy sources" is molasses and rumen-protected fat. Cluster 1 = dairy farms characterized by having a high stocking rate (4.09 cows per hectare; the average of all of the farms was 3.65 cows per hectare) and a medium level of land addressed to double cropping (i.e., 31.3% of the land; the average of all of the farms considered was 30.2% of the land). In cluster 2, dairy farms were grouped with low incidence of double cropping strategies (i.e., 22.1% of the land). Cluster 3 = dairy farms having a low stocking rate (3.2 cows per hectare) but with high usage of double cropping usage (i.e., 38.6% of the land). Cluster 4 = a small group of perennial grass-based dairy farms with a high stocking rate (3.91 cows per hectare) and high usage on double cropping strategies (33% of the land).

the most common farm practice in Northern Italy is to sell only or mostly first seeding corn crop; and (3) avoid overcomplexity of the optimization model and its interpretation.

Feedstuff market prices (adjusted for transport and storage) could be considered appropriate for purchased feedstuffs, but they would represent an oversimplified measurement for the cost of home-produced feedstuffs (O'Kiely et al., 1997). High variability in home-produced feedstuffs production costs exists among farms (Bellingeri et al., 2019). Therefore, we decided to use home-produced feedstuff cost as input data calculated according to the method by Bellingeri et al. (2019).

Concerning intrinsic farm constraints, silage and hay storage availability were considered because overfilling of bunkers or failures in silo management due to extra production could cause severe losses (Ruppel et al., 1995; Wilkinson, 2015; Borreani et al., 2018). The model considered storage availability as a farm constraint, representing a limitation on the farm decision-making process. Another intrinsic farm constraint considered in the model was the amount of land available (Val-Arreola et al., 2006).

The model presented here used as input data the same nutritional and production levels as the real farm situation, with a fixed milk yield (for lactating cows) and daily gain (for heifers), which reflected the average farm performances. The reason for this choice was the fact that complex interactions among multiple biological and management factors affect dairy herd dynamics, efficiency, and productivity, which makes it difficult to predict the milk yield level outcome based solely on a nutritional standpoint (Morton et al., 2016). In Table 3, nutritional characteristics of diets are shown. Among dry cow and heifer diets, there are no large differences in terms of nutritional characterizations among clusters. Among lactating cow diets, similar energy levels are reported, except for cluster 4, in which the lowest energy level (1.66 ± 0.02 Mcal of NE_L/kg) is reported. The reason of it was the high level of inclusion of grasses and alfalfa hays that increased NDF and fNDF and decreased NFC.

An optimal feed allocation through a linear programming was chosen to leave the decision-making process to mathematical computation, using diet nutritional requirements and feed quality as key drivers. In contrast to this, Rotz et al. (1999) proposed a dairy herd model for whole-farm simulation, in which the feed allocation to all animals of farm-grown and purchased forage/concentrates followed a scheme that represented the producer's approach (decision rules to prioritize feed use). Results obtained by running the model on the data of baseline farms showed that the feed allocation through LPO gives reasonable and similar results as the farmers' approach. This further shows that the model represented well the farms' conditions.

Market prices, on average, were relatively higher with respect to production costs. It is important to note that this is not always the case. Several farms produced forage at higher costs than market prices in 2017. This shows an evident crop enterprise inefficiency and different strategies could be suggested for the same. As an example, an extreme scenario could be to rent out all of the cultivated land and become more dependent on the market for feed supplies. A simulation of such a hypothetical situation was carried out and it showed an economic advantage; however, several complications from a management point of view could result from it. For example, higher exposure to market uncertainties is a risk many farmers would not be willing to take. In summary, such an effect is difficult to estimate in an ex ante analysis and could result in an economic evaluation mistake.

The optimized model's suggestions confirmed the high value of corn silage as the main forage in the lactating cow diet. These suggestions led to a simplification of the cropping plan to a higher level of specialization of the farms sustained by a higher IOFC, DM, and NE_L self-sufficiency. Substantial economic differences were highlighted between clusters 2 and 4 [i.e., greater IOFC (€/lactating cow per d) of 0.24 for cluster 2 and 0.96 for cluster 4]. In particular, cluster 4 was characterized by having a numerically higher milk price than other clusters (€41.5/kg of milk vs. €38.7, €39.0, or €38.1/kg of milk for clusters 1, 2, or 3; respectively) primarily because of the value of the products produced from the milk. Furthermore, cluster 4 is characterized by having a grass-based cropping system. The optimization process suggested a change from perennial grasses to corn silage crop plan to minimize feed costs and maximize energy and DM produced on farm. The suggested change in this crop plan and its consequent modifications in diets could be considered feasible from an agro-technical point of view because farms have enough water for corn irrigation and their soil quality and farm equipment allows corn production. This proposed crop and diet plan supports farms in cluster 4 to be more independent from the market for NFC sources. Otherwise, these changes also resulted in decreased RUP self-sufficiency and therefore reliance on purchased soybean meal in the diets. Looking at the 2017 market conditions (i.e., low cost of soybean meal and costs of forage production), the aforementioned proposed cropping plan would be possible from an economic perspective because optimized IOFC in cluster 4 had an improvement of €0.61 per cow per day. Surely, these diet changes can have an effect on milk yield and quality. The potential changes due to diet modifications were not included into the model due to the great number of variables that could affect milk yield and its composition (Morton et al., 2016). This could represent a future model improvement. Considering the average number of lactating cows from our pool of farms, this would translate into an improvement of €27,400/yr for cluster 2 and €109,600/yr for cluster 4. Similar results have been obtained by Gaudino et al. (2014) where gross-income maximization suggested a specialization, decreased cash crop area, and increased farm feed self-sufficiency. However, such specialization induced a strong reduction of alfalfa, perennial grass, and other hay crops, resulting in a reduction of permanent vegetation within the undisturbed fields (i.e., alfalfa and perennial grass), which led to a reduced landscape biodiversity (Bretagnolle et al., 2011) with a worsening situation among soil health and structure, lower water infiltration, altered soil nutrient cycling, downgraded carbon sequestration by the soil, and exacerbated problems with weed, insect, and disease control (Franzluebbers et al., 2011). To deal with those results, the model can be constrained, introducing limitations (upper or lower) on the crop land dedicated to a specific crop, to maintain, for instance, biodiversity, while minimizing feed costs.

The higher proportion of crop plan dedicated to corn silage was possible with the reduction of corn grain, perennial grasses, ryegrass, and alfalfa. The model suggested to decrease the amount of land addressed to alfalfa (on average from 14.9% to 5.3%) due to its high cost of production (€163.2/t of DM on average) and relatively low production of DM per hectare as compared with corn silage (9.7 vs. 20.1 t of DM/ha). Further, the low soybean meal price in the evaluated market scenario favored LPO in maximizing both energy and DM productions per hectare instead of protein. These results do not consider the agronomic benefits of this crop, and in general, the value of a more diversified cropping system and rotations as proven by Davis et al. (2012). The model suggested to decrease the acreage addressed to small-grain silages in all farms considered (from 5.8% to 1.3%) and ryegrass (from 10.2 to 0%) to mixed-crop silage (blend of small grains with legumes species to enhance the protein content). One possible explanation for the higher CP is primarily due to the RDP content and the relatively similar yield of mixed-crop silage versus small-grain silage. Ryegrass reduction in the optimized scenario was mainly due to the lower yield and low quality of the harvested product, due to a late harvest forced by unstable weather conditions that occur frequently during the "ideal" ryegrass harvest period. For these reasons, mixed crop has been favored by the model in contrast to small grain and ryegrass. Mixed-crop silage has a higher CP, mainly RDP fraction, than ryegrass and small grains, allowing a positive effect on the farm CP self-sufficiency (+3.6%), despite the lower alfalfa acreage. Consequently, a higher level of RUP was obtained by purchased feeds, in particular soybean meal. This result aligns with the findings of Borreani et al. (2013). Among perennial grass hay, a strong reduction was noticed in cluster 4 (−21%), which evidences the lack of convenience of perennial grass, especially if there is a lack of available land to grow crops such as in the farms of cluster 4. In particular, the increase of the rate of inclusion of corn silage in cluster 1 is not great as in the other clusters due to specific dairy farm characteristics. Farms belonging to cluster 1 were characterized by having the highest stocking rate (cows/ha) and therefore the maximization of the DM produced by corn silage was already an implemented strategy confirmed by the fact that just corn silage in second seeding showed an increase in the cultivated area, not corn silage in first seeding. This means that farms in cluster 1 have land availability as the major constraint on crop plan decision-making strategy that leads to double cropping intensification under the present market conditions to maximize IOFC. The current strategy has been shown to be economically feasible (IOFC + €0.36 per cow per d) at the current market conditions (low soybean meal price). On the other hand, optimization increased both first and second seeding corn silage cultivated area in cluster 2, at the expense of alfalfa hay. This effect confirms that farms in cluster 2 have a limitation on land availability but not as great as in cluster 1 because the model did not suggest a double cropping intensification in this cluster. Moreover, the model results confirm a higher cost of production of corn silage second seeding compared with corn silage first seeding. This result, once again, confirms the importance of maximizing yield and quality in all farming situations and the potential effect on the cropping plan decision-making to apply at the farm level. For example, farms with low stocking rates usually do not rely on heavy usage of double cropping strategies (i.e., ryegrass hay and corn silage second seeding in the same year) because they do not need extra forage to feed their cows. As example, in cluster 3, characterized by having a low stocking density (3.2 cows/ha), the optimization scenario shows an inefficiency on the alfalfa production system because the model proposed a strong reduction in its cultivated acreage, which would partially be substituted by other sources (mixed-crop silage, soybean meal, corn silage). On the other hand, farms with high stocking rates have 2 choices: (1) rely heavily on double cropping strategies to maximize energy and protein self-sufficiency, or (2) avoid increasing the double cropped area and purchase from the market the amount of feeds they need to counteract their lack of self-produced forage. The right decision-making strategy to apply in this situation is strongly related to the farm management (i.e., can the farm workforce handle a heavy double cropping strategy?) and the cost of production and performance (t of DM per hectare and quality) obtained. For this reason, farm-level decision-making is crucial when it comes to crop plan design. The higher cost of production is mainly due to the higher irrigation costs and a lower DM yield per hectare compared with corn in first seeding (17.1 vs 20.12 t of DM/ha). The present model can be used in "what if" scenario analyses to evaluate, for example: (1) investments in new crop equipment, silage storage, and hay sheds; (2) herd expansion plan and its effect on cropping plan, forage, and storage requirements; and (3) comparing different crops and forage plans considering simultaneously both the crop and dairy farm characteristics.

CONCLUSIONS

The present study demonstrates that a formulation of the crop and feeding plans using a linear programming approach can improve overall farm IOFC by reducing whole-herd feed costs for diets formulated in different animal groups. The model developed in this study contributes to the research literature by providing an integrated approach to the feeding strategy, crop planning, and least-cost diet formulation integrating crops and herd data. The general outcome from these farms' simulations suggests that the optimization process increased, on average, the IOFC by 7.8%. The linear programming model was found to be suitable for building a decision support system. This decision support model could be more likely to be adopted and applied for decision-making at the farm level by commercial dairy enterprises under the oversight of trained dairy farmers or consultants. Future improvements of the current approach could be related to incorporate into the model N and P efficiency, multiyear crop rotation strategies, and effect of dietary changes on milk yield and quality.

ACKNOWLEDGMENTS

Funding for this research was provided through Meccatronica per l'Agricoltura di Precisione (MAP) project from Emilia Romagna under Grant 886 13/06/2016 and by the Fondazione Romeo ed Enrica Invernizzi (Milan, Italy). All authors declare no potential conflicts of interest.

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