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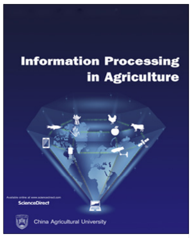

Optimal dairy feed input selection under alternative feeds availability and relative prices

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ABSTRACT

Feed formulation is essential in the dairy production chain from economic, nutritional, and environmental perspectives. Optimizing the feed formulation across those three domains – given uncertainty of input prices, input availability, and regional climatic conditions – is a challenge for those in the industry. The diet formulation method that is widely used by trading firms and feed production facilities employs a static linear programming (LP) approach. This approach does not allow for intertemporal feed formulations and switches between dietary feed commodities under feed availability conditions, which result in foregone economic gains for feed producers.

The current study develops a multi-period LP feed model that uses historical data to capture ration switch opportunities between available feed resources for dairy cows and demonstrates the potential use of the method in different commodity feed availability situations. We apply 14 diet formulations, each covering 150 months, representing a total of 2100 diets. The diet formulation considers a specific milk production level for a "model cow", alternative feed formulations available, and volatility in feed prices. The results demonstrate that there is an opportunity for efficiency gains in the dairy industry with respect to feed formulation. Based on dietary feed inclusion and price spreads, barley can be an important dairy feed grain which completely replaces wheat, corn, and sorghum at price spreads of less than 94%, less than 78%, and less than 67%, respectively. Grain-based feed scenarios represent the lowest nutrient variation while multiple meal feeds had the lowest costs. Furthermore, and on average, multiple meal feed scenarios provided 10% higher dietary crude protein contents compared to grain based feed scenarios (i.e. 163 vs 179 g/kg DM formulated feed). Meanwhile, multiple meal feeding cost was 11% lower than that in the grain based feeding scenarios. Additionally, the use of multiple meals reduces alfalfa dietary inclusion by 7% on dry matter basis. Our analysis shows a strong reduction in feed cost associated with dietary crude protein reduction equivalent to 7.6 USD/tonne per 1% reduction in dietary crude protein level.

The modeling approach allows for the interaction between feed components over time taking into consideration volatile global feed prices, thereby improving feed availability and feed formulation. Overall, the model provides a decision making tool to improve the use of feed resources in the dairy sector.

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1. Introduction

Global demand for meat and milk is expected to increase by 57% and 48%, respectively, between 2005 and 2050 [1]. The projected increase in production of animal products requires an increase in the quantity and quality of feed materials, which could compete with human food –especially cereals, of which one third of their total production is used as animal feeds [2] and of which their production is growing by 1.1% between 2016 and 2017 [3]. The demand for cereals as human food is also expected to grow in the next years [4] and, as such, the livestock feed industry will be more vulnerable to cereal shortages.

The increase in the global and regional demand for particular inputs of animal feeds is subjected to both market availability and price [5]. Therefore, these factors should be considered when assessing feeding scenarios on a per animal basis at a given level of productivity. In dairy production, feed is the most expensive component, typically representing 50 – 70% of total milk production costs [6]. The proportion of feed costs as a share of total production cost is highly dependent on feeding systems, which vary widely worldwide [7]. Feeding costs are driven by the availability of feeds, feed prices, and diet composition. The use of available historical market feed prices in feed formulation could be instrumental in providing estimates on diet composition and historical feed costs in a region with changing feed availability (e.g., availability of corn and absence of wheat or barley).

For trading firms, feed prices are important in the evaluation of a potential trade as they reflect market trends influenced by feed availability in the market and market policies. However, the price spread (difference between feed prices), which is the determinant of a feed change/ switch, has not been well evaluated in the feed production and trading industries. Fundamentally calculated commodity price spreads do not provide in-depth information for decision makers in the feed production sector, as these have to be correlated to formulated diets via linear programming (LP) analysis. LP has been widely used in formulating least cost rations for livestock feed requirements. Previous studies utilizing multi-period LP models have tended to focus on issues such as the variation in feed supply, the quality of feedstuffs, and animal requirements to optimize diets to achieve productivity goals [8,9]. However, the issue of commodity price spread and dietary dynamics over time, and its relationship with dietary feeds and substitution rates, has not been comprehensively evaluated.

The static form of the LP model is often used to formulate diets considering a vector of objective function coefficients, decision variables, model constraints (the right hand side RHS, and the inclusion boundaries). However, in trading and feed production activities decisions need to be made more frequently (daily, weekly, or monthly). Therefore, the traditional LP approach needs to incorporate changing feed prices and time variables to adequately facilitate changes in rations to reduce costs. Doing so could improve the industrial feed production process and reduce production costs [10].

With fluctuating feed commodity prices, multi-period LP modelling could be used to recommend dietary switching from one feed commodity to the other (i.e. switch from corn to wheat, or from soybean meal (SBM) to distiller's dried grains with solubles (DDGS)). Further, this approach can explore dietary switching to local by-products, which are not used in conventional diets as part of the formulated ration. With this approach, it is possible to develop more resilient dairy feeding systems that ensure feed cost reductions when price spreads are large enough to trigger replacement feeds, and to recommend alternative dietary solutions under feed shortage situations (i.e. in changing supply of grains or meals). Alqaisi et al. [6] reported that the inclusion of agro-industrial by-products in animal diets could lead to 14% reduction of feed costs in dairy cattle feeding.

Fundamentally, trade firms and feed producers depend on market feed price to perform trade. These prices are changing on daily, weekly and monthly basis, but it is unreasonable for producers to be changing the feed mix that frequently. The decision to vary feed rations needs to be determined by relative prices that make switching between inputs worthwhile, given that they wish to avoid immediately switching back to the previous mix. In addition to the benefit of reduced input cost in the feed industry, improved information about optimal feed input switching and the potential for reduced information asymmetries present an opportunity for a more efficient social allocation of feed inputs. In this context, we hypothesize that commodity price spread is correlated with the livestock dietary inclusion rate. Therefore, evaluating potential changes in feeding systems, price spread, and feeding system vulnerability requires a periodic (multi-period) tool that mimics the feed trading and feed production process. The objectives of this study are to (1) develop multi-period LP feed models for dairy cows, (2) demonstrate the potential use of the method in different commodity feed availability situations (feeding scenarios), (3) illustrate the impact of feed price spread on the vulnerability of feeding systems (i.e. ration switch between available feed resources) and (4) evaluate the impact of feed resources availability on feed cost.

2. Methods

Feed production and commodity trading are continuous processes based on daily, weekly, and monthly trends. In the current study, we use global monthly commodity prices due to their availability. We hypothesize that trading of a feed commodity in a country or a region is correlated with the feeding systems practised.

The supply chain of feed materials was illustrated by Alqaisi et al. [10]. Within the chain, farmers produce grains and oil crops and sell them either directly to trading companies in the case of feed grains, or to crushing plants in the case of oil rich seeds such as soybean and sunflower seeds. Thereafter the feed meals (derived from the oil rich seeds) are purchased by trading companies. In the second part of the chain, trading companies sell grains and meals to feed producers who, in turn, formulate feed mixes that meet the nutritional requirements of animals. The current analysis is designed to mimic a production process in a feed mill acquiring feed materials from a trading company and selling compound feed to dairy farmers. In addition to the grains and meals used to supply energy and protein to fulfil animal requirements, we include alfalfa hay as a fiber source for dairy cows due to its importance in dairy diets and the availability of its prices. Other interesting feed resources such as grass, grass silage, and corn silage have not been used due to the difficulties in obtaining their monthly prices. The method under investigation is based on monthly analyses (periods) of linear programming models output.

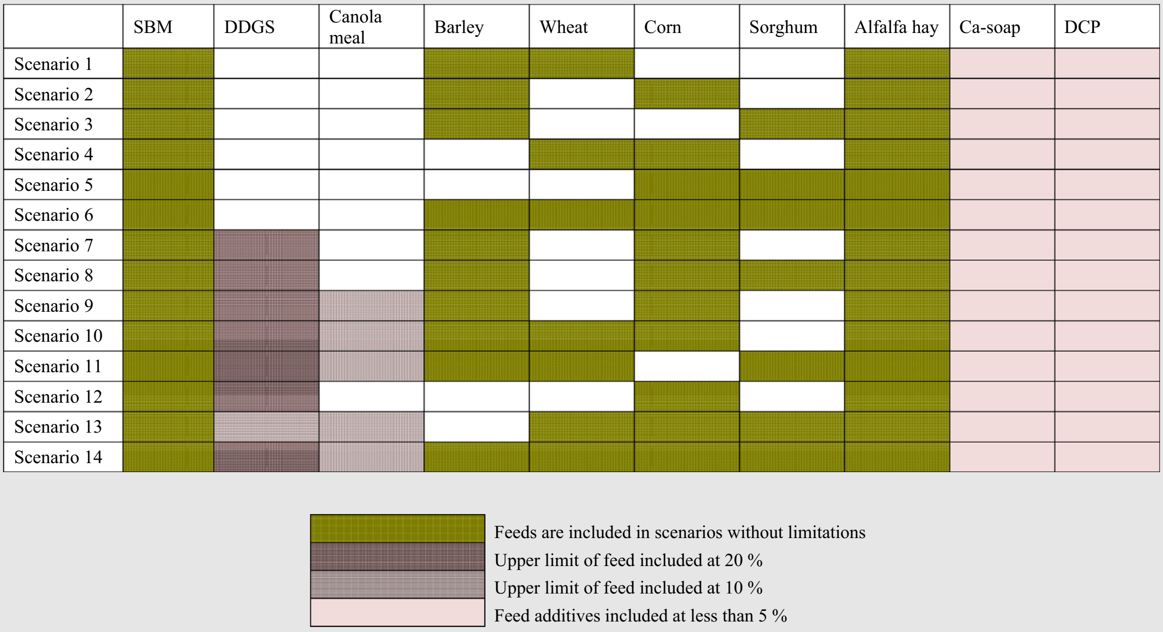
2.1. *Multi-period LP model*

The objective of the multi-period LP models is to produce a feed blend at minimum cost in different periods (defined here as months). The model selects the optimal proportion of feed ingredients to produce a least cost diet given feed nutritional composition, animal nutritional requirements, and feed prices. The problem of determining the commodity of interest in the produced feed blend emerges when the price gap between two protein or energy sources is small. This situation arises regularly because feed prices are volatile. The challenge is exacerbated when designing a commodity trade without knowing the optimal price spread between two commodities, which is a well-known problem for feed commodities trading companies and feed producers. Consequently, this study examines the price commodity spread in comparison with the commodity trading alternative (i.e. corn versus wheat) that could be determined by the LP formulation.

To determine the time (defined by the month) when a diet adjustment is required, and the proportion of an alternative feed commodity to be included to the new diet, a multi-period LP model was developed for dairy cow feeding for 14 case scenarios representing the potential feed commodity availability in a region provided by a trade activity. These feeding scenarios (Table 1) allow for an evaluation of simulated feeding diets and their vulnerability to changes in feed availability options and feed price volatility. The first six scenarios are based on grains and one meal source typically used to formulate diets, while the remaining eight scenarios include additional options for agricultural by-products (meals).

The multi-period LP model developed in this study is a quick and time efficient approach to optimize diets. Unlike static LP models, this multi-period LP model minimizes a sequence of objective functions and provides time series relationships between decision variables and constraints via optimized solutions. The resulting relationships are estimated using the open source R programming software version 3.5 [11]. The model provides, but is not limited to, a sequence of results from multiple periods by retrieving values from a sequence of successfully solved single-period LP models. The results produced by this model allow the decision-

Table 1 – Feeds and feeding limits used in formulation of 14 feeding scenarios.



	SBM	DDGS	Canola meal	Barley	Wheat	Corn	Sorghum	Alfalfa hay	Ca-soap	DCP
Scenario 1	🟩			🟩	🟩			🟩	░	░
Scenario 2	🟩			🟩		🟩		🟩	░	░
Scenario 3	🟩			🟩			🟩	🟩	░	░
Scenario 4	🟩				🟩	🟩		🟩	░	░
Scenario 5	🟩					🟩	🟩	🟩	░	░
Scenario 6	🟩			🟩	🟩	🟩	🟩	🟩	░	░
Scenario 7	🟩	▩		🟩		🟩		🟩	░	░
Scenario 8	🟩	▩		🟩		🟩	🟩	🟩	░	░
Scenario 9	🟩	▩	▨	🟩		🟩		🟩	░	░
Scenario 10	🟩	▩	▨	🟩	🟩	🟩		🟩	░	░
Scenario 11	🟩	▩	▨	🟩	🟩		🟩	🟩	░	░
Scenario 12	🟩	▩				🟩		🟩	░	░
Scenario 13	🟩	▨	▨		🟩	🟩	🟩	🟩	░	░
Scenario 14	🟩	▩	▨	🟩	🟩	🟩	🟩	🟩	░	░

🟩 Feeds are included in scenarios without limitations
▩ Upper limit of feed included at 20 %
▨ Upper limit of feed included at 10 %
░ Feed additives included at less than 5 %

SBM: Soy bean meal, DDGS: Distiller's dried grains with solubles, Ca-soap: by pass fat, DCP: Di Calcium Phosphate.

maker to investigate the relationships between objective function values, values of the decision variables, values of the constraints, dual variables (the reduced costs), and the sensitivity of the objective function. In many respects, the model serves to provide an efficient sensitivity analysis of optimal feed mix under alternative input prices and animal nutritional requirements.

2.2. Model structure

The general structure of the multi-period LP is described as follows:

$$\begin{aligned} &\textit{for} \quad t = 1, \cdots, 150 \\ &\min TC_i = \sum_{i=1}^{n} c_{it} x_{it} \\ &\quad \textit{subject to} \\ &a_{ijt} x_{it} \overset{\geq}{\underset{\leq}{=}} b_{jt} \forall j \in J \\ &x_{it} \geq 0 \end{aligned} \tag{1}$$

where TC_t is the total cost of the feed ration at period t (month), c_{it} is the per-unit cost of feed ingredient i at period t¸ and x_{it} is the quantity of feed ingredient i in the feed ration on period t. J is the set of nutrients that must be considered in the feed ration, with j being one of the nutrients of the set of J, a_{ijt} the quantity of nutrient j in feed ingredient i at period t, and b_{jt} the required amount of each nutrient j in the feed ration in period t. The sign of the relationship for each of the nutrients depends on the particular nutrient and the nutrient balance that must exist in the ration. It is important to note that our model assumes that the nutrient composition of feed ingredients is the same across periods and so are the nutrient requirements for the model cow. Thus, the constraints' coefficients and right hand sides for all t could be described by a single set of a_{ij} and b_j for all periods.

The general structure of the model for one particular month is shown in Table 2. Each table is divided into two parts: the upper part includes multi-period price data of the objective function, namely the monthly feed/commodity prices, while the lower part of the table consists of information relevant to the feed composition and the model right hand side constraints and boundaries. The monthly feed commodity prices are saved in an external text format file and linked to the LP model in the R console with the *apply* function to iterate optimization for each individual monthly set of prices subject to the model parameters. Commodity feed prices were collected from the World Bank [12], Ca-soap (Nurisol) prices were provided by Heinrich Nagel KG, Germany, and the US average alfalfa hay and DDGS prices were obtained from [13,14].

The minimization of the objective function in each period is subject to a set of constraints. These are the standard feed requirement variables which are composed of the weight of total formulated diet in kg or percentage DM, ME in Megajoules (MJ), and the dietary Crude Protein (CP) in gram per kg DM, UCP, Neutral Detergent Fibre (NDF), physically effective NDF (peNDF), fat, non-fiber carbohydrate (NFC), Calcium (Ca), Phosphorus (P). Furthermore, upper boundaries were set to the model for the feed inclusion rate in the case of DDGS and RSM feeding. Ultimately, the optimized feed results are given in percentages. The nutritional requirements for a standard dairy cow and feed composition data were taken from the NRC [15]. In particular, the "model cow" is a standard cow in mid-lactation with 680 kg live weight and daily milk production of 25 kg, milk fat of 3.5%, milk protein of 3%, and gaining 500 g weight per day. The corresponding estimated feed intake is 20.3 kg per cow per day with metabolizable energy (ME) concentration of 10 MJ/kg dry matter (DM) formulated feed and Undegradable Crude Protein (UCP) of 49 g per kg DM formulated feed. Nutrient requirements and feed composition of the "model cow" are listed in Table 2. The reason for choosing this "model cow" was to demonstrate the modelling method and to generate the results. However, the model does not consider the change in cow productivity during the lactation cycle, since this will bring changes in the diet subject to productivity and not to market feed prices. Furthermore, milk production fluctuation due to seasonal differences between regions was not captured due to the added complexity of including it within the same feeding model. Furthermore, the objective of this research is to track dietary changes for a given milk yield under variable feed prices and feed availability. The non-zero, non-negative constraint directions were assumed in equality and non-equality forms.

Although the major objective of this study was to develop a decision making tool with an economic perspective, we have also investigated the amount of enteric methane (CH_4) that would be potentially emitted by the model cow consuming diets at each scenario in each month. The objective of these calculations were i) to demonstrate additional uses of our model, such as in the investigation of environmental and sustainability aspects of dairy farming and ii) to initially explore the relationships between diet costs, feed ingredients switch and the daily CH_4 emissions. The amount of CH_4 was predicted using the equation: CH_4 (MJ/d) = 3.41 + 0.520 × DMI (kg/d) − 0.996 × ADF (kg/d) + 1.15 × NDF (kg/d) [16], Equation 10c), where DMI is the intake of dry matter, ADF is the intake of acid detergent fiber and NDF is the intake of neutral detergent fiber. The daily intakes of ADF and NDF were estimated by multiplying their corresponding monthly LHS computed values by DMI, given that the monthly LP calculated feed ingredients assumed to be representative for the daily DMI. The reason for using this model is that it includes the dietary parameters that were computed in the current LP models, it accounts for the variations in CH_4 emissions caused by NDF and ADF values, and it has low prediction error (RMSPE% = 30.5) and an relatively high R^2 (0.67).

2.3. Statistical analysis

The correlation between feed mix compositions formulated by the LP models was examined through the Pearson's correlation coefficients.

The root mean square error (RMSE) used to calculate the Multi-period LP formulated nutrients deviation from the assigned model constraints is given by the formula:

Table 2 – A multi-period LP Model structure in R with decision variables, RHS constraints, and the objective function.

objfn1			OB1P1	OB2P1	OB3P1	OB4P1	OB5P1	OB6P1	OB7P1	OB8P1	OB9P1	OB10P1		
objfn2			OB1P2	OB2P2	OB3P2	OB4P2	OB5P2	OB6P2	OB7P2	OB8P2	OB9P2	OB10P2		
Objfn3			...	...	...	...	...	...	...	...	...	...		
objfnn			OB1Pn	OB2Pn	OB3Pn	OB4Pn	OB5Pn	OB6Pn	OB7Pn	OB8Pn	OB9Pn	OB10Pn		
		Unit	SBM	DDGS	Canola meal	Barley	Wheat	Corn	Sorghum	Alfalfa hay	Ca-soap	DCP		RHS Constraints
Constraint 1	Weight	kg	1	1	1	1	1	1	1	1	1	1	"="	1
Constraint 2	CP	g/ kg DM	499	297	378	124	142	94	116	192	0	0	">="	147
Constraint 3	UCP	g/ kg DM	175	172	113	35	33	54	71	52	0	0	">="	49
Constraint 4	NFC	%	27	16	19	63	70	76	69	25	0	0	"<="	44
Constraint 5	Fat	%	1.6	10.0	5.4	2.2	2.3	4.2	3.1	2.5	84.5	0.0	"<="	5
Constraint 6	ME	MJ/kg DM	13.8	12.7	11.5	12.2	13.0	13.1	11.5	8.2	26.2	0.0	">="	10
Constraint 7	NDF	%	15	39	30	21	13	10	11	42	0	0	">=", "<="	27-33
Constraint 8	Ca	g/ kg DM	4	1	8	1	1	0	1	15	0	176	">="	6.03
Constraint 9	P	g/ kg DM	7.1	6.6	11.6	3.8	4.3	3.0	2.8	2.4	0.0	205	">="	3.8
Constraint 10	peNDF	%	6.0	15.5	11.9	14.7	8.0	3.8	6.5	39.5	0.0	0.0	">="	22
Upper bound		%	inf	20	15	inf	inf	inf	inf	inf	inf	2		
Lower bound			0	0	0	0	0	0	0	0	0	0		

Objfn: objective function (monthly feed prices). SBM (Soy bean meal), DDGS (Distiller's dried grains with solubles), Ca-soap: by pass fat, DCP: Di Calcium Phosphate. OB: objective function, P1: price decision variable 1, W: weight, ME: Metabolizable energy, P: Phosphorus, CP: crude protein, UCP: undegradable crude protein, NFC: non fiber carbohydrate, NDF: neutral detergent fibre, Ca: Calcium, P: Phosphorus, peNDF: physically effective NDF.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(y_i - x_i)^2} \quad (2)$$

where y_i and x_i are the LHS and RHS constraints of CP, UCP and ME. Accordingly, RMSE % was calculated using to the following formula:

$$RMSE(\%) = \frac{100 \times N}{\sum_{i=1}^{N} y_i}\sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2} \quad (3)$$

2.4. Modeled scenarios

Taking as a basis the model structure described herein, fourteen simulation scenarios were defined. The scenarios represent a potential long term feeding strategy on farm and in a region, given that feeds are provided through trade or production activity. The scenarios therefore assume that some feed items, such as grains or by-products, might be continuously available in some regions at an affordable price, though they might be completely absent or very expensive in other regions. To our knowledge, the capabilities of such a multi-period approach to LP model in long-term trade and animal feed production has not previously been evaluated for its efficacy in this particular industry.

2.5. Scenario definitions

The definition of scenarios and resulting analysis is based on the availability of feeds:

Scenario 1 (S1) assumes wheat, barley and SBM commodities were used in diet formulation. The reasoning for using these feeds is to evaluate the feeding system vulnerability/switch when there are a limited number of feeds available, and to examine if wheat and barley price spreads are correlated with commodity inclusion rates.

Scenario 2 (S2) assumes that wheat is not available and that only corn and barley grains are available in addition to SBM. The simulation elaborates on the corn-barley price spread correlation with their inclusion rates, and the vulnerability/switch of feeding systems for these commodities.

Scenario 3 (S3) assumes that barley and sorghum are available, SBM is included, and there is no access to corn or wheat. The simulation will evaluate price spreads between sorghum and barley and their resulting inclusion rates.

Scenario 4 (S4) assumes that barley is not available, and only wheat and corn grains are accessible. The scenario will elaborate on the corn-wheat price spread and the associated effect on inclusion levels.

Scenario 5 (S5) assumes that only corn and sorghum are available in the market. The scenario will elaborate on the corn-sorghum price spread and the associated dietary inclusion levels.

Scenario 6 (S6) assumes no limitations on grain availability for corn, wheat, sorghum, and barley, and allows for the use of SBM.

Scenario 7 (S7) includes the by-product DDGS as a protein and energy source in addition to SBM, with barley and corn grains available. The objective of the analysis in this scenario is to evaluate the degree to which DDGS inclusion will affect inclusion rates of grains and meals over time.

Scenario 8 (S8) includes the grain commodities of barley, corn, and sorghum in addition to SBM and DDGS.

Scenario 9 (S9) includes grain commodities of barley and corn, and that canola meal is available as a protein source in addition to DDGS and SBM. The scenario explores price spread changes if more than one meal source is used in the diet simulation versus the spreads in grain commodity prices alone.

Scenario 10 (S10) assumes DDGS is not accessible or traded while SBM and canola meal are available as protein feeds. Furthermore, barley, wheat, and corn grains are included to evaluate the price spread between SBM and canola meal versus Scenario 9.

Scenario 11 (S11) omits corn, which is replaced by sorghum and allows for the inclusion of DDGS. The scenario provides information on the DDGS-alfalfa hay price spread impact on DDGS inclusion rates.

Scenario 12 (S12) assumes the availability of dietary SBM, DDGS, and corn. This scenario allows the evaluation of the magnitude of corn use under the availability of DDGS, and the magnitude of DDGS as a partial substitute for alfalfa hay. Furthermore, the scenario is used to evaluate the DDGS-corn price spread and its impact on dietary composition.

Scenario 13 (S13) assesses the use of canola meal under limited DDGS availability (limiting inclusion to a maximum level of 10%) and in the absence of barley. Furthermore, the scenario evaluates the feed inclusion against the price spread.

Scenario 14 (S14) assumes the availability of SBM, DDGS, canola meal, barley, wheat, corn, and sorghum.

In all simulated scenarios, alfalfa hay is included and assumed to be available as a forage source in addition to the bypass fat Ca-soap (a widely used energy feed additive source) and dicalcium phosphate (DCP; a source of Ca and P). This selective inclusion of additional feeds is interesting for feed producers since we hypothesize that alfalfa hay could be partly replaced when high fiber meals and grains are available for feeding or vice versa. The modelled scenarios are justified by the fact that not all feed commodities are available in each region or traded on a regular basis, reflecting the variety of dairy feeding systems available in different regions. These commodities are globally available and extensively used on one hand and; on the other hand, they are often satisfactory to formulate nutritional dairy diets at varying levels of productivity. Price spreads are expressed as the ratio between two feed commodities (i.e., DDGS price and corn price).

3. Results and discussions

The multi-period approach to the LP model was implemented in R with solution time per scenario varied depending on the instance being solved but was within the range of one-half and one second. The solutions of the LP model for each of the scenario-month gives the optimal inclusion rate, in percentage, that minimizes the total formulated feed cost. In total, 2100 diets were formulated representing fourteen scenarios over a period of 150 months each (14 × 150) between

January 2005 and June 2017. A total of 2100 objective functions (least formulated feed cost) and 23,100 constraints (RHS) were obtained from successfully solved LPs. Furthermore, the total of 15,450 decision variables were obtained. Data on upper and lower feed prices, the objective function, and the dual variables (including the RHS duals and sensitivity results) were obtained but not shown due to their large size. Table 3 provides a summary of the minimum, maximum, and average formulated feed inclusion rate (% of DM) in fourteen dairy feeding scenarios.

3.1. *Grain feeding scenarios (Scenarios 1 to 6)*

This section elaborates on the results from scenarios 1 and 6, with analysis of scenarios 2 through 5 provided in the supplementary annex. Across the scenarios, the formulated CP

Table 3 – Minimum, maximum and average feed inclusion rate (% of dry matter) in fourteen dairy feeding scenarios between January 2005 and June 2017.

Scenario					Feed inclusion %						
		SBM	DDGS	Canola meal	Barley	Wheat	Corn	Sorghum	Alfalfa hay	Ca-soap	DCP
Scenario 1	Min	3.0			0.0	0.0			56.5	0.0	0.0
	Max	3.7			39.8	33.7			63.1	0.2	0.0
	Average	3.4			37.1	2.2			57.1	0.1	0.0
Scenario 2	Min	0.0			0.0		0.0		45.3	0.0	0.0
	Max	4.7			50.1		37.8		62.1	0.0	0.0
	Average	1.9			28.4		13.4		56.2	0.0	0.0
Scenario 3	Min	0.0			5.3	0.0	0.0	0.0	45.3	0.0	0.0
	Max	5.9			50.1	0.0	0.0	38.7	56.3	0.0	0.1
	Average	1.2			35.4	0.0	0.0	11.3	52.0	0.0	0.1
Scenario 4	Min	0.0				0.0	0.0		61.8	0.0	0.0
	Max	3.0				34.2	37.8		62.7	0.4	0.4
	Average	0.3				7.9	29.4		62.1	0.2	0.2
Scenario 5	Min	0.0					0.0	0.0	53.3	0.0	0.3
	Max	0.0					37.8	44.3	62.1	2.1	0.4
	Average	0.0					34.6	3.7	61.3	0.2	0.3
Scenario 6	Min	0.0			0.0	0.0	0.0	0.0	45.3	0.0	0.0
	Max	4.7			50.1	28.7	37.6	16.1	62.1	0.0	0.3
	Average	1.0			29.0	1.8	5.7	8.4	53.9	0.0	0.1
Scenario 7	Min	0.0	3.5		0.0		0.0	0.0	29.2	0.0	0.0
	Max	0.0	20.0		54.7		35.6	0.0	61.7	0.0	2.0
	Average	0.0	14.1		36.0		4.9	0.0	44.2	0.0	0.7
Scenario 8	Min	0.0	3.8		0.0		0.0	0.0	32.2	0.0	0.0
	Max	0.0	20.0		45.8		25.6	38.5	61.7	0.0	0.0
	Average	0.0	15.0		31.0		2.3	4.6	46.6	0.0	0.6
Scenario 9	Min	0.0	3.8	0.0	0.0		0.0		29.6	0.0	0.0
	Max	0.0	20.0	4.3	45.8		33.2		61.7	0.0	2.0
	Average	0.0	14.8	0.0	33.0		4.9		46.5	0.0	0.7
Scenario 10	Min	0.0		0.0	0.0	0.0	0.0		39.5	0.0	0.0
	Max	3.7		15.0	43.5	33.7	30.9		67.0	1.8	2.0
	Average	1.5		3.4	32.8	2.2	3.5		56.4	0.1	0.0
Scenario 11	Min	0.0	3.6	0.0	0.0	0.0		0.0	29.6	0.0	0.0
	Max	0.0	20.0	4.3	45.8	37.6		38.5	62.0	0.0	2.0
	Average	0.0	15.0	0.0	29.9	1.8		6.5	46.3	0.0	0.5
Scenario 12	Min	0.0	0.0				22.5		44.4	0.0	0.0
	Max	0.0	20.0				40.2		62.1	2.0	2.0
	Average	0.0	17.1				26.9		55.3	0.0	0.7
Scenario 13	Min	0.0	3.6	0.0		0.0	0.0	0.0	42.6	0.0	0.0
	Max	0.0	10.0	10.0		35.7	32.5	37.7	62.0	0.8	2.0
	Average	0.0	9.6	0.6		8.8	15.4	6.8	58.6	0.0	0.2
Scenario 14	Min	0.0	3.6	0.0	0.0	0.0	0.0	0.0	29.6	0.0	0.0
	Max	0.0	20.0	4.3	45.8	37.6	25.6	38.5	62.0	0.0	2.0
	Average	0.0	15.0	0.0	28.9	1.8	2.3	4.6	46.9	0.0	0.6

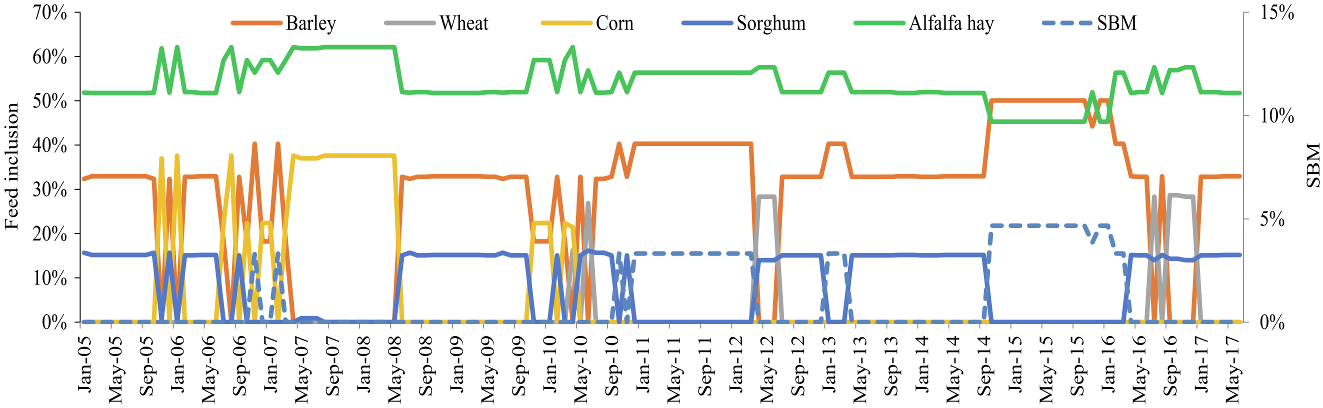


Fig. 1 – Simulated dairy feed diets in scenario 6 between 2005 and 2017.

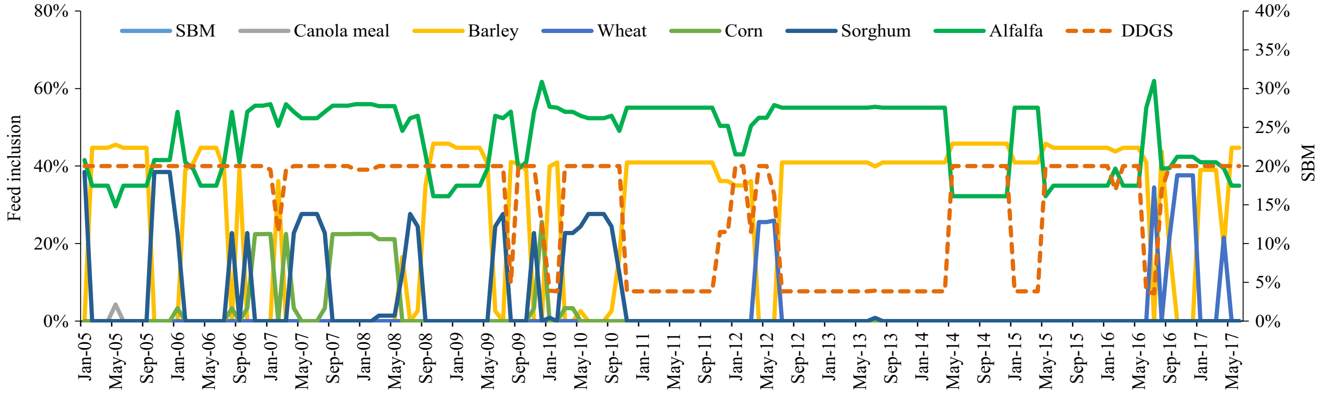


Fig. 2 – Simulated dairy feed diets in scenario 14 between 2005 and 2017.

varied between 154 g/kg DM and 176 g/kg DM with average of 163 g/kg DM (i.e. 10% above the requirements). Meanwhile ME feed concentration was 10 MJ/kg DM of formulated feed across all scenarios and months.

Fig. 1 provides a graphical presentation of the simulated feeding scenarios (scenario 6) while the supplementary file provides a graphical illustration of all simulated feeding scenarios. Each graph shows the dry matter percentage composition of dietary feed that fulfils the constraints on the right hand side (RHS). In Scenario 1, although only one protein source was used, the SBM inclusion rate varied between 3% and 4%. The dietary changes were obvious in switching between barley and wheat at different and limited periods. The average wheat inclusion rate was low at 2%, indicating that in the presence of barley, wheat seems to be a less important dietary component. Also, in Scenario 1 there were few instances when barley was completely replaced by wheat, which corresponded with sharp increases in barley prices and a barley/wheat price spread exceeding 0.94. When barley was substituted completely by wheat, the alfalfa hay inclusion rate increased by 7%, which was confirmed by the negative correlation of −0.99 between wheat and alfalfa inclusion rates. Since NDF in wheat is 36% lower than in barley, additional NDF was provided by alfalfa hay. Dietary combinations of wheat and alfalfa hay is an economic preference when barley is absent or when its prices are higher than the spread threshold. Therefore, in regions with limited alfalfa hay supply, barley would be the preferred feed in dairy rations.

When all grains were used in the simulation (S6), sorghum was included in most of the periods and varied between 0 and 16% with average inclusion rate of 8% of the total DM of formulated feed, which was a lower rate compared to barley (average inclusion of 29%) but slightly higher than corn (6%). In general, the use of barley grains was dominant and wheat could replace barley in conjunction with sorghum in short and scattered periods (i.e. 40% dietary barley was substituted by 28% wheat and 14% sorghum, whilst SBM was omitted) without affecting the inclusion rate of alfalfa hay, or with corn replacing barley but at 10% increased alfalfa hay levels (i.e., at a complete dietary switch from barley to corn).

The use of SBM in S6 was limited to a maximum level of 5% and only in association with barley. Therefore, a dietary combination of corn and alfalfa hay could provide 157 g/kg DM of CP which exceeds the CP requirements of the model lactating dairy cow. This can be compared with the combination of SBM, barley and alfalfa hay which provides a CP level of 174 g/kg DM.

Therefore, and similar to the observations of S3, sorghum showed a negative correlation with alfalfa hay since its use was associated with reduced inclusion of dietary alfalfa hay. The diet further showed a complete switch from a barley and sorghum combination to solely corn in response to a decline in price of the latter. The theoretical switch to a corn based diet slightly reduced the total CP of the formulated diet from 158 g/kg DM to 155 g/kg DM while UCP increased from 49 to 52 g/kg DM. Compared to S3, the availability of dietary sorghum increased the competition between the three major grains and provided several options for a switch between these grains, however with the potential for complementary diets at least cost, total average formulated feed cost over the whole period for the S6 diet was 0.5% lower than that the cost of the S3 diet, but 2.5% lower than the S1 diet. Therefore, using sorghum alongside barley contributes to a considerable reduction in dietary alfalfa hay and in total feed cost, which justify its uses in situations with shortage in alfalfa hay.

Meanwhile, wheat might not be an interesting feed if sorghum and barley grains are available resources in diet formulation.

While this analysis incorporates the cost minimization objective for feed producers and farmers, time series alternative diets are provided and considered price volatility in feed commodities and forage. The analysis shows that if feed grain prices fall in comparison to alfalfa hay prices, the latter might be used to reduce nutrient content variability. S1 clearly shows that when barley prices increased, alfalfa inclusion also increased from 53% to 66% in the total ration, which corresponded with a complete switch from barley to wheat in the diet. Therefore, scenarios 1 and 6 provide illustration to situations in which barley grains are used to substitute alfalfa hay at different levels.

3.2. *Multiple meals feeding scenarios (Scenarios 7 to 14)*

This section elaborates on the results from scenarios 7, 13 and 14, with analysis of scenarios 8 through 12 provided in the supplementary annex. Formulated CP was significantly higher than in grain feeding scenarios and varied between 176 and g/kg DM and 182 g/kg DM with average of 179 g/kg DM (i.e. 18% above the requirements). Similarly, formulated ME feed concentration was higher than in grain feeding scenarios and varied between 10 MJ/kg DM and 10.5 MJ/kg DM with average of 10.25 MJ/kg DM formulated feed.

S7 includes SBM and DDGS as dietary protein sources. In the LP feed formulation model, the upper limit of DDGS inclusion was set at 20% which does not affect dry matter intake or milk production [17]. Results show that DDGS was included in majority of the simulated diets at its maximum upper limit of 20% and with an average inclusion rate of 14%. The use of DDGS in formulation led to the exclusion of SBM from the diets. However, the inclusion of DDGS increased the CP content (176 g/kg DM feed) in the formulated feed to a higher level than that in SBM feed scenarios. Furthermore, the increase in CP concentration was associated with an increase in UCP to 62 g/kg DM feed, and an increase in ME concentration to 10.5 MJ/kg DM feed. Furthermore, the inclusion rates of barley, corn and alfalfa reduced significantly as a result of including DDGS, with an average inclusion rate for alfalfa of 44%, compared with 57% in Scenario 1.

Since DDGS was included in all formulated diets, majority of the dietary changes were caused by a switch between corn and barley that was associated with a changing alfalfa hay inclusion. Similarly, with a stable DDGS inclusion rate, a complete switch from barley to corn was associated with increasing dietary alfalfa hay by 15%, which was reflected in a negative correlation between DDGS, alfalfa hay and barley.

The calculated quantitative barley and DDGS equivalents for their substitutes of corn and alfalfa, was estimated from the amount/percentage of dietary switch between months, by calculating the corn and alfalfa dietary change relative to one unit change in barley (i.e., Δ in monthly barley % $(_{\text{month n-1 – month n}}) = \Delta$ in monthly corn $(_{\text{month (n-1) – month n}})/\Delta$ in monthly alfalfa $(_{\text{month (n-1) – month n}})$).

It was noticed that one unit of barley was equivalent to 70% corn and 30% alfalfa hay. In another dietary switch instance, one unit of DDGS was valued at 10% of barley and 90% of alfalfa hay. Therefore, DDGS feeding has a combined effect of replacing corn and barley, and reducing the dietary alfalfa hay. Compared to grain feeding scenarios, the inclusion of DDGS in dairy diets reduced total average feed cost by 8% (i.e. compared to S1). However, comparing scenarios should also be valuable in providing insight on the cost associated with reduced dietary CP and its impact on diet composition. Considering scenarios 5 & 14, reducing dietary CP from 180 g/kg DM to 154 g/kg DM would cost 7.6 USD per ton of formulated feed for each 1% CP reduction. Therefore, using DDGS will reduce feed cost significantly, but will also increase dietary protein levels.

The DDGS canola meal scenario (S13) was important to evaluate the magnitude of canola meal inclusions under reduced DDGS availability (i.e., when the upper limit of DDGS inclusion is reduced to 10%). Because we find that with an upper DDGS inclusion rate in scenario 9 and 10 (20% maximum from formulated DM) and the presence of barley there is no inclusion of canola meal (with one exception), this scenario provides information on the magnitude of combining these meals in dairy diets in the absence of dietary barley.

The reduction of DDGS dietary inclusion to an upper limit of 10% and the exclusion of dietary barley, increased the instances of including canola meal to 16 times compared to only one time at 20% DDGS upper limit (S11). Further, there was a weak association between canola meal and DDGS inclusion. Contrariwise, a greater association between canola meal and alfalfa hay (correlation = 0.43) was observed, indicating that canola meal was used as a fiber source in addition to CP. Part of the DDGS was not significantly affected by the canola meal dietary presence. However, the degree to which alfalfa hay was replaced by canola meal was dependent on the availability of corn and sorghum. At 10% canola meal inclusion, dietary alfalfa hay inclusion was reduced by 13 percentage points (i.e., from 56% to 43%), this substitution switched the diet from corn to sorghum. The combined inclusion of canola meal and the dietary shift to sorghum caused an increase in CP from 173 g/kg DM to 192 g/kg DM, while ME was limited to 10 MJ/kg DM. Overall, reducing DDGS to feeding limits, will increase the choice to feed canola meal. We further evaluated the canola meal inclusion at limited DDGS availability of 5% (data not shown) in which canola meal was used at maximum 10% in the diet, yielding greater canola meal inclusion instances (52 times).

Fig. 2 provides a graphical presentation of the simulated feeding scenarios (scenario 14). Scenario 14 includes all feed

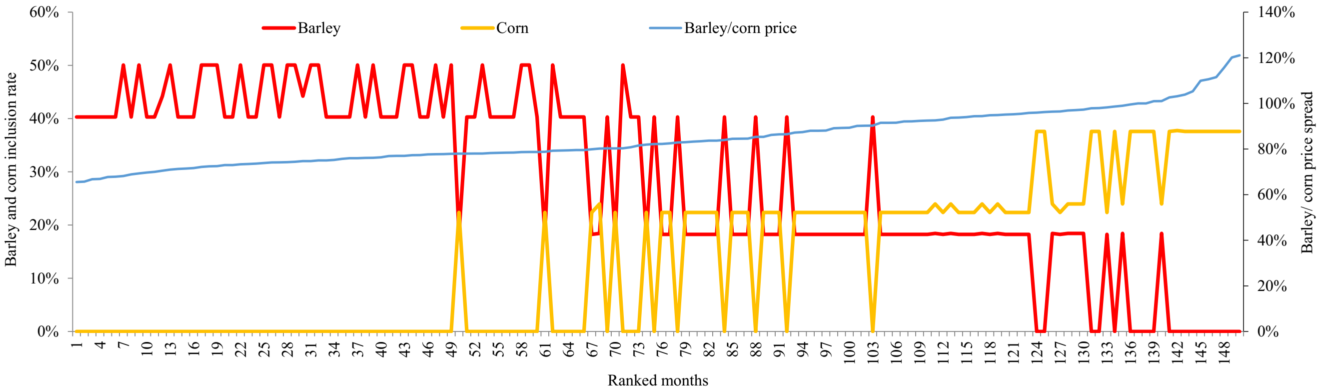


Fig. 3 – Ranking of barley and corn feed inclusion rates in relation to their price spread.

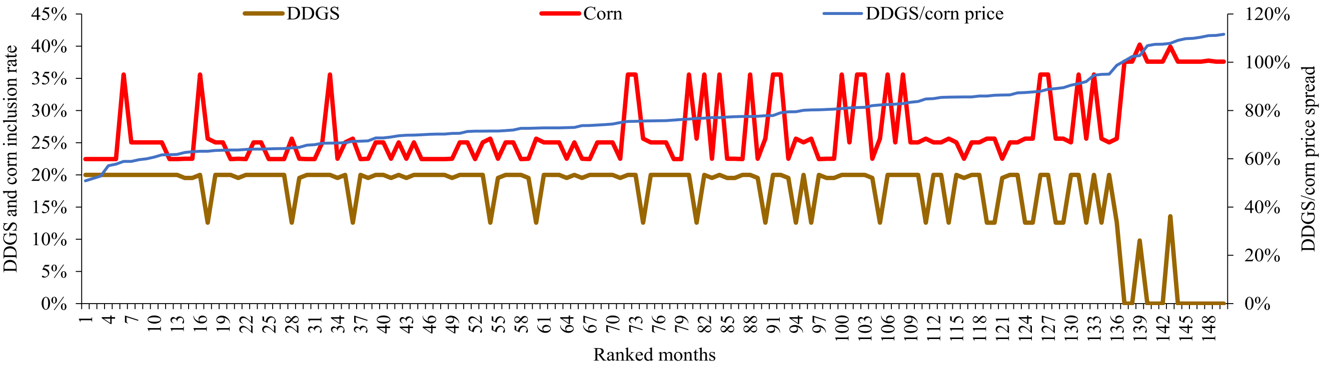


Fig. 4 – Ranking of DDGS and corn feed inclusion rate in relation to their price spread.

meals and grains used in the time series dairy diet simulation. When all feed resources are available, barley was the most used energy feed in the diet, reducing the demand for corn and sorghum and providing very limited demand for wheat grains. Furthermore, availability of DDGS reduced the use of alfalfa hay (with negative correlation of −0.60). Due to the relatively high wheat price, it was only used in few instances to substitute barley and only when barley/wheat price spread exceeded 94%. Including rich fiber barley could reduce the importance of canola meals in substituting forage. Therefore, under the model conditions used in the current study, increasing the number of feeds used in the formulation does not necessarily provide new formulation outputs that lead to a reduced dietary CP levels.

In conclusion, taking into account all feeding scenarios, feed cost was significantly driven by the ME contents of feeds compared to a relatively low effect of CP contents, indicating that ME was often limiting. Since the magnitude of ME availability in the multiple meal feed scenarios was greater than in grain feed scenarios, this may in part explain the reduced feed cost in the feed scenarios 7–14.

3.3. *Dietary CP excess in relation to methane production and feed cost*

The dietary CP excess (i.e., constraint LHS–RHS; RHS stands for right hand side) quantifies the amount of CP that would be fed in excess to our model cow at the fixed DMI of 20.3 kg/day. This quantity in grain and meal feeding scenarios is illustrated in Fig. 5. Recent studies have suggested that linear and goal programming models are particularly suited for examining economic and environmental trade-offs on dairy farming systems (e.g., [18,19]). From an environmental standpoint, the excess CP provides a potential source of environmental impact in dairy systems because excess protein feeding to dairy cows is mostly excreted in urine and feces. Compared to meal feeding scenarios, the magnitude of CP excess in grain feeding scenarios is, on average, 50% (16 g/kg DM) lower than that in the meal feeding scenarios (32 g/kg DM). The considerable variation in CP excess can be partly explained by the use of multiple meals of relatively low price, such as DDGS as protein and energy sources, in which soybean meal and grain feeds are substituted. Moreover, the instances in which DDGS was included in the meal feeding diets is by far greater than the inclusion of SBM in grain feeding diets, thereby substantially increasing the potential of CP excess feeding. It can be suggested that the protective feeding system in grain feeding scenarios based on limited inclusion of expensive SBM can, at least partially, explain the reduced CP excess compared to in multiple meals feeding.

The main objective of this study was to develop an optimization framework that examines and optimizes the economical and practical feeding aspects of dairy cattle farming systems. However, the use of optimization models for the reduction of environmental impacts of dairy systems has been suggested as a great tool, with particular emphasis on the trade-offs between CH_4 emissions and feeding costs

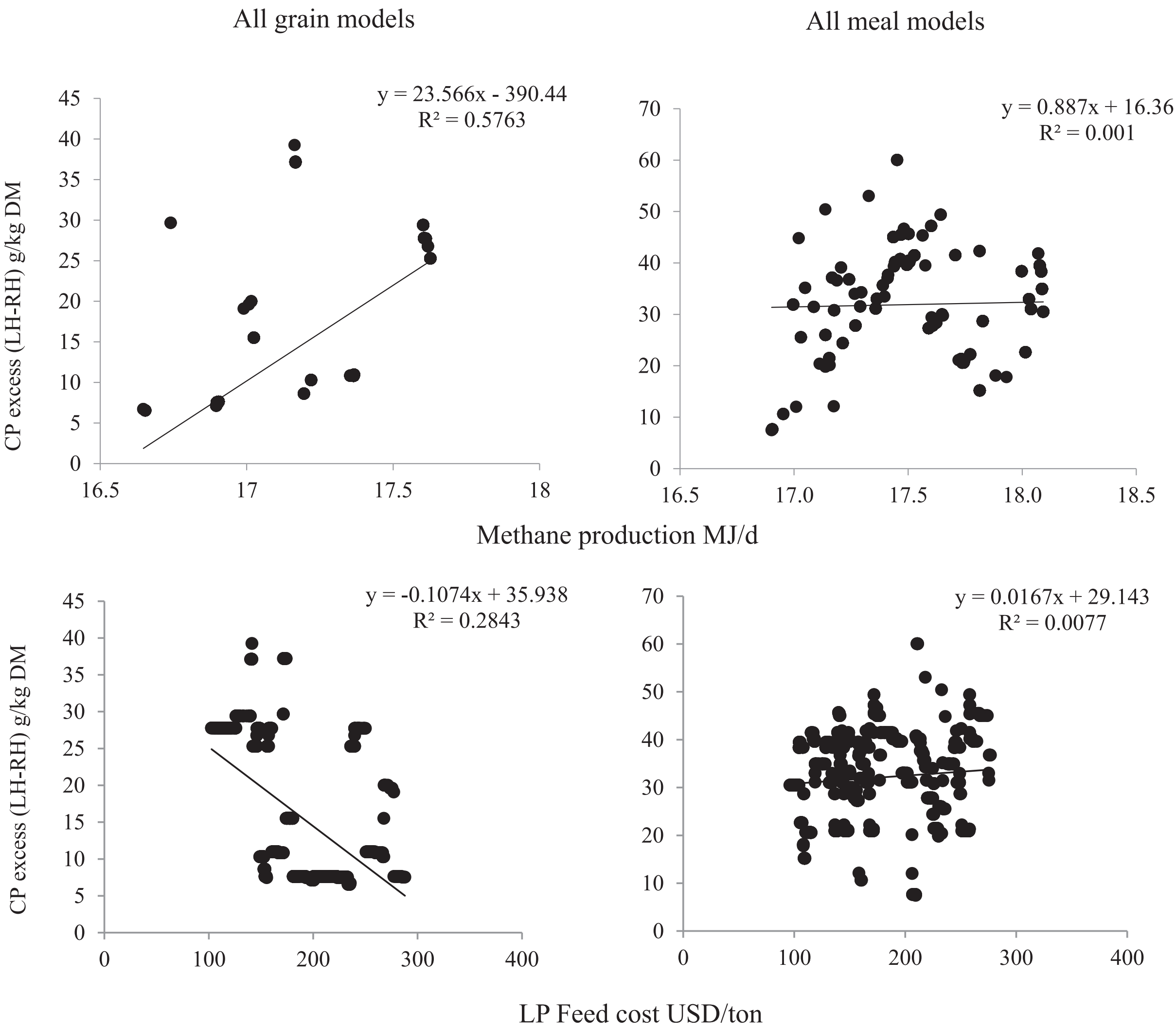


Fig. 5 – CP excess (LH-RH) in relation to calculated methane yield and feed cost in grain and meal feeding scenarios.

[19]. Further, recent studies suggested a relationship between CH_4 emissions and CP feeding for dairy herds [18]. In order to demonstrate the potential of our model to conduct these investigations, we examine the relationships between CH_4 emissions, excess CP and feeding costs. The relationship between excess CP and the predicted CH_4 production (expressed in MJ/d) and estimated feed cost is elaborated in chart 5.

In the grain feeding scenario, an increase in CP excess was associated with increasing CH_4 production; while such a correlation does not present in the meal feeding scenarios. Although these associations may not exhibit a causal relationship, the reason for this could be that, in grain feed scenarios, CH_4 emissions and CP excess were driven by high dietary proportion of barley, alfalfa hay supplemented with SBM, thereby increasing CP excess from the SBM and the CH_4 emission from barley and alfalfa. However, with a dietary switch from barley to wheat, sorghum or corn, SBM was excluded (i.e., substituted by grain and alfalfa CP), thereby reducing CP excess which was also associated with a reduced daily intakes of NDF and ADF, thereby reducing daily CH_4 production. Therefore, even with an increasing alfalfa dietary proportion, a diet composition of grains other than barley would reduce CP excess and CH_4 production, particularly corn-alfalfa based diets which showed the greatest reduction in CP excess (i.e. 25 g/kg DM in barley-alfalfa diets vs 8 g/kg DM in corn-alfalfa diets) and CH_4 yield (i.e. 17.6 vs 16.9 MJ/d) in barley-alfalfa diets, and corn-alfalfa diets, respectively.

Unlike in grain feeding scenarios; CP excess and CH_4 yield had low correlation in meal feeding scenarios since CP is in excess and in all diets as DDGS replaces SBM and at maximum inclusion rate, thereby CP excess is present in all diets. Furthermore, when ranking CH_4 and CP excess, CH_4 declined from 18 MJ/d in barley-DDGS-alfalfa dietary combination (CP excess = 35 g/kg DM), compared with 17.25 MJ/kg DM in corn-DDGS-alfalfa diets (CP excess = 36.7 g/kg DM). Therefore, the relationship between CP access and CH_4 yield is feeding system and price dependent, and could be caused by the type of feed meal that drives the changes on diet structure. The relationships between CP excess in the diet (i.e., delivered minus required) with the diet cost is presented in Fig. 5 separately for all grain models and all meals models. Overall, a

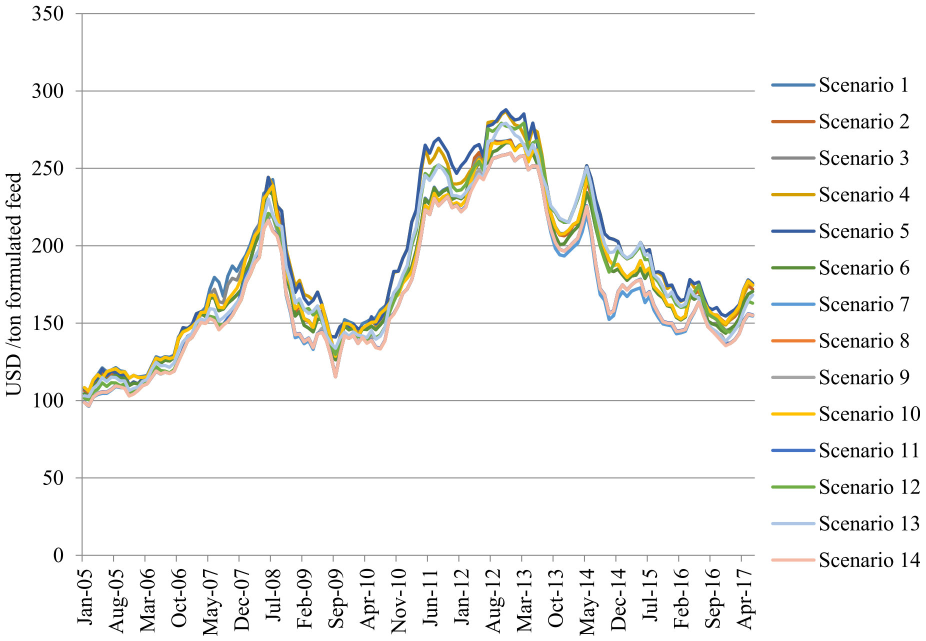


Fig. 6 – Simulated dairy feed costs in 14 feeding scenarios between January 2005 and June 2017.

negative relationship was identified between these two variables for all grain models, suggesting that when using all grains it is costly to feed diets with little to no excess protein in the diet. Contrariwise, when feeding diets with all meals the relationship between CP excess in the diet and diet costs is weak to non-existent.

3.4. *Price spread, dietary switch and feed cost*

Figs. 3 and 4 show the ranked percentage price spread expressed as the ratio between feeds in the evaluated scenarios (i.e. barley/corn and DDGS/corn prices), and the corresponding feed inclusion rate. Ranked as such, this method is important to find the price spread which corresponds to the dietary switch between feeds in the historical diet simulation. Fig. 2 in the supplementary file provides a graphical representation of feed inclusion rates in relation to price spread in several feeding scenarios.

The barley/wheat price spread is illustrated by Scenario 1. When comparing the barley/wheat price spread and their inclusion rate, three spread levels can be identified: (i) a price spread of less than 94% favouring barley inclusion at the maximum level, (ii) a price spread between 94% and 100% where wheat replaces barley in different periods, and (iii) a price spread of greater than 100% favouring wheat over barley inclusion in the diet. Similarly, examining the price spread of barley/corn obtained on Scenario 2, at a price spread of less than 78%, barley was included at the maximum level. At a price spread between 78% and 95%, barley and corn were used in the diet, and at a price spread of greater than 95%, there was a complete switch from barley to corn in the diet. Scenario 3 was used to investigate the barley/sorghum price spread in relation to dietary switch. At a price spread of less than 67% barley was used and sorghum was not included in the diet. At price a spread between 67% and 93% sorghum was frequently included in formulated diets, and at a price spread of greater than 93% sorghum was included in all formulated diets. Therefore, barley would be an important dairy feed grain which completely replaces wheat, corn and sorghum at price spreads of less than 94%, less than 78%, and less than 67% respectively.

The corn/wheat price spread set forth in scenario 4 shows that, at price spread of below 98%, corn was included at its maximum level while wheat was not included. At price spread between 98% and 103%, corn and wheat were included in all diets, and at price spread of greater than 103%, the diet featured a complete substitution between corn and wheat. The corn/sorghum price spread evaluated in scenario 5 reveals that sorghum is included when that spread exceeds 108%.

The DDGS/corn price spread is evaluated in scenario 12. At a price spread of less than 63%, DDGS was included in all formulated diets at its maximum level. At a price spread between 63% and 95%, DDGS inclusion fluctuated between 13% and 20%, and at DDGS price exceeding corn price, corn was included at its maximum rate while DDGS was excluded from the diet.

In scenario 7, at a DDGS/barley price spread below 79%, DDGS was included at its maximum level. When the price spread increased to between 79% and 85%, the use of dietary barley (both in percentage and frequency) was increased, meanwhile at price spreads of greater than 85% barley appeared with greater importance in all formulated diets and DDGS use was greatly reduced.

The price spread of canola meal/SBM is shown in scenario 10. At price spreads of less than 69% canola meal was included at the maximum level while SBM was not used. At price spreads between 67% and 87% canola meal appeared less frequently and was partly replaced by SBM. When the price spread got higher than 87%, canola meal was excluded from the diet and SBM was included at its maximum level.

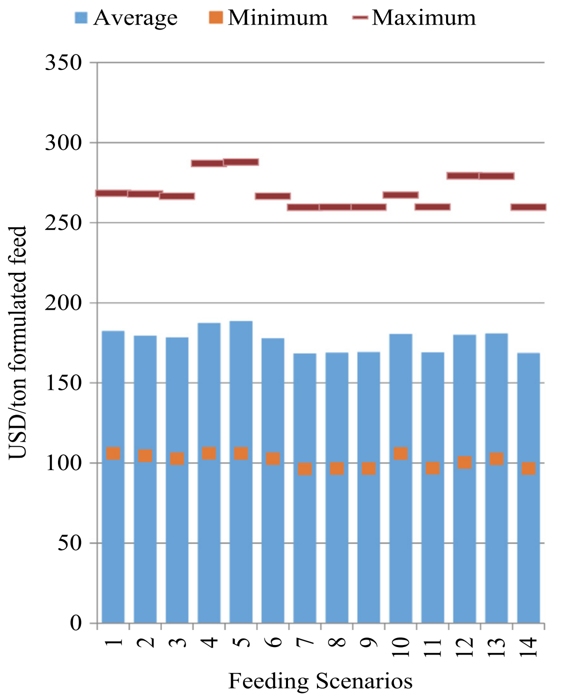


Fig. 7 – Simulated average, maximum and minimum dairy feed cost between Jan. 2005 and June 2017.

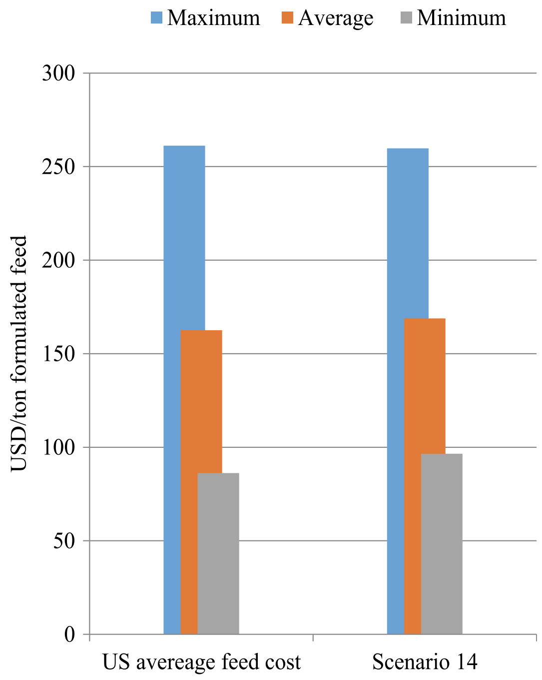


Fig. 8 – Comparing average US dairy feed cost and the average multi-period LP least feed cost in scenario 14 (2005–2017).

Since DDGS was used to partially substitute for alfalfa hay, this relationship is evaluated in scenario 11. At a price spread of less than 64%, alfalfa hay was included at a minimal rate while DDGS was used at higher rate. When DDGS price exceeded alfalfa price, the frequency and amount of DDGS used (ranging between 20% and 4%) were lower, which was compensated by greater alfalfa hay inclusion.

Fig. 6 illustrates the time series formulated feed costs (corrected to as-fed basis) in all studied scenarios. Taking the average cost over the whole simulated period as indicator, the use of DDGS in diet formulation “scenario 14” provided the lowest costs of about 169 USD/ton (see Fig. 7).

Feed costs ranged between 189 and 169 USD in scenarios 5 and 14, respectively. On average, grain-based scenarios yielded feeds of higher costs compared to scenarios using feed by-products. |An exception is scenario 10 where the cost was higher due to the use of the canola meal-SBM combination. Therefore, we find that the magnitude of feed cost reduction with DDGS-based diets is greater than that in canola meal and SBM based diets (see Fig. 8).

Increasing the number of feeds included in the feed formulation has the potential to reduce the total feed cost in dairy rations; however, this depends on the meal that is used. This was evidenced in scenario 10 where feed cost was comparable to grains scenarios. When multiple feeds are used in diet formulations, the LP model minimizes or excludes the use of feeds with relatively high prices and maximizes the use of low price feeds that would provide a feed mix capable of meeting the nutrient requirements of the model cow. However, variations between the average prices of grain-based scenarios may provide a different conclusion. With multiple grains in the diet, feed cost was reduced by 5% (or 10 USD/ton formulated feed, S4 versus S6). Most likely, the use of multiple grains provides a complementary set of relationship between feeds that minimizes the use of expensive SBM.

Scenario 14, the fully flexible feeds alternative, provided the lowest average feed cost during the back-testing period (11% lower than S5, which represents a fairly standard case). However, the reduction in feed cost was associated with increased dietary CP of 18% in S14. The maximum trade-off between a fully flexible feeding option and the more typical constrained option is roughly equivalent to 7.6 USD per ton of feed to reduce 1% of dietary crude protein. Looking back to year 2016, and considering the current analysis of feed cost reduction scenarios, the global industrial dairy feed production could gain up to 2.3 billion USD as a result of an improved monthly feed formulation and from considering multiple dietary meals and grains. It is important to note that this monetary value is referent to our model cow and it provides an estimate assuming that our model inputs and results are largely applicable to the global dairy industry. However, to a large extent, grains and meals used in the current analysis represent a major contribution to global industrial feed production. Further studies are needed to use our proposed LP framework with a different set of cows, potentially herds, feedstuff and geographical feed price variations to capture more precise characterization of the monetary values.

3.5. *Model evaluation*

Table 4 provides a summary of the dairy rations CP, UCP, ME concentrations, and the associated optimization errors (representing deviations from the constraints RHS) in all studied scenarios from the solved time series analyses. The model

Table 4 – Statistics and RMSE of time series formulated crude protein (CP), undegradable crude protein (UCP) and metabolizable energy (ME) in fourteen dairy feeding scenario between January 2005 and June 2017.

	CP						UCP						ME					
Scenarios	Min	Max	Average	SD	Absolute RMSE	RMSE	Min	Max	Average	SD	Absolute RMSE	RMSE	Min	Max	Average	SD	Absolute RMSE	RMSE
1	175	186	176	2	29	16	49	50	49	0	0	1	10	10.0	10.0	0.00	0.00	0.0
2	154	175	165	9	20	12	49	52	49	1	1	2	10	10.5	10.1	0.17	0.19	1.9
3	158	177	163	8	18	11	49	65	49	2	2	5	10	10.5	10.0	0.14	0.15	1.5
4	154	184	160	9	15	10	49	52	51	2	3	5	10	10	10.0	0.0	0.0	0.0
5	154	155	154	0	7	5	52	59	53	2	4	8	10	10	10.0	0.0	0.4	4.1
6	155	175	162	7	30	10	49	53	49	1	1	2	10	10.5	10.1	0.14	0.15	1.5
7	162	188	176	9	30	17	49	77	62	10	17	27	10	11.0	10.46	0.43	0.62	6.0
8	168	193	180	9	34	19	49	83	65	11	20	30	10	10.9	10.3	0.38	0.50	4.8
9	168	189	179	8	33	18	49	77	64	10	18	28	10	11.0	10.4	0.38	0.52	5.0
10	158	187	176	4	29	17	49	58	50	2	2	5	10	10.0	10.0	0.02	0.02	0.2
11	168	196	181	9	35	19	49	83	65	12	20	31	10	11	10.3	0.39	0.51	4.9
12	154	188	182	9	36	20	52	77	73	7	25	34	10	11	10.2	0.3	0.4	3.4
13	167	207	178	8	32	18	50	77	64	5	15	24	10	10	10.0	0.1	0.1	0.8
14	168	196	180	9	35	19	49	65	65	11	20	30	10	11.0	10.3	0.39	0.51	4.9

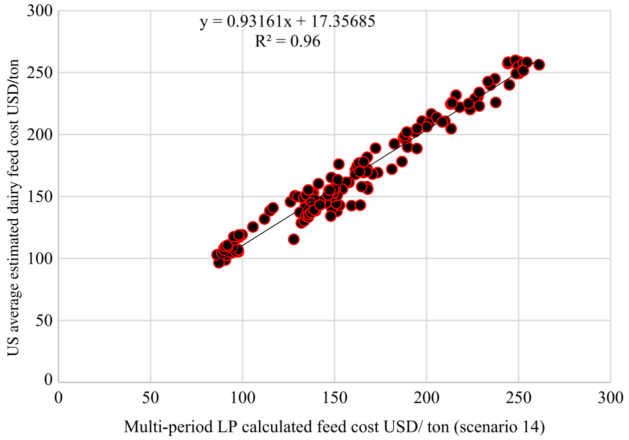


Fig. 9 – Relationship between Multi-period LP calculated feed cost and the US average monthly feed cost in 150 month between Jan. 2005 and June 2017.

evaluation is based on the calculated root mean squared error (RMSE) in absolute and percentage terms. In relation to the multiple formulation data obtained from successfully solved LPs, the magnitude of the error in the proposed models was calculated. The major optimization errors are the result of deviations in crude protein results from the feed formulation requirements constraint. In the grain based scenarios, average RMSE% for CP ranged between 5% and 16% in S5 and S1, respectively, which is significantly lower than that in by-product scenarios.

In a multiple grain diet (i.e. scenarios 5 and 6), a complementary/competing relationship developed between grains which provide an opportunity to satisfy model constrains by omitting the use of expensive protein sources such as SBM, which reduces the CP formulation beyond the RHS values.

Compared to grain feed scenarios, the use of multiple by-products in formulation provided greater RMSE% for CP which varied between 17% and 20%. However, S10 with the canola meal-SBM dietary protein combination has the lowest RMSE %, which was not the case when using non-competing protein sources such as DDGS and canola meal, or DDGS and SBM. Therefore, the magnitude in which the CP formulation error could be minimized depends on the level of competitiveness between meal feeds, which is not only quality dependent, but also price dependent.

Due to the availability of average dairy feed cost data in the US (those published by University of Wisconsin, [14]), and because the average DDGS and alfalfa hay monthly used prices are representative of the US, we compared the least feed costs provided by the multi-period approach to LP model with the US average dairy feed costs per ton (see graphs 7 & 8). Fig. 10 shows the average US dairy feed cost and those calculated in the current study (i.e., in scenario 14). The scenario was chosen due to its fit to the US tonnage feed cost. Furthermore, Fig. 9 shows the relationship between two feed costs in a regression model which captures a relatively large proportion of time series monthly feed costs ($R^2 = 0.96$), with the trend improving over time.

We speculate that scenario 14, which includes all feeds, might capture the largest proportion of dairy feeding systems

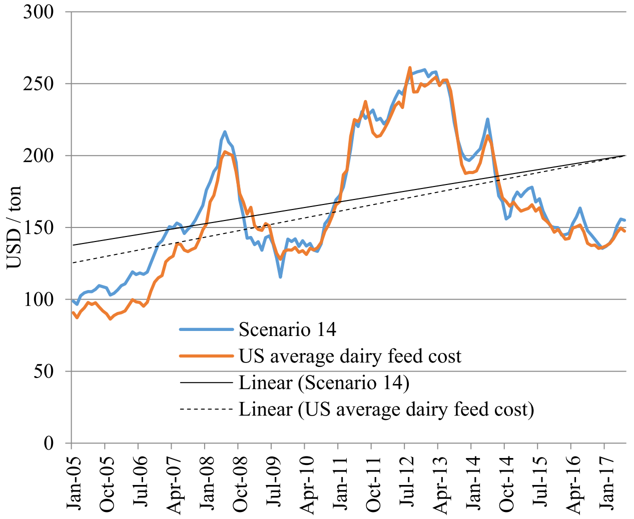


Fig. 10 – Multi-period LP calculated versus US average dairy feed cost between Jan. 2005 and June 2017).

used in the US, although we again stress the dependence of our results on the assumed model cow. This could be a reasonable interpretation because it omits the use of canola meal and minimizes the use of wheat from one hand while maximizing the use of DDGS and alfalfa hay in dairy rations. However, the imperfect cost estimation fit could be in part attributed to the variations between the prices (global feed prices) other than DDGS and alfalfa hay used in the current study, and those local feed grains actually used by producers. Furthermore, the lack of feed composition and feed prices that are of minor contribution, such as by-products not used in the current study, contributes to reductions in fit. Therefore, it might be concluded that the multi-period to LP modelling can be used to estimate dairy feed costs in a region. However, further computation improvements would be possible with improved data (prices, quality, and feeding limits) of feeds that are not included in the current study.

The primary limitation to this model is that the set of linear constraints (minimum nutritional requirements) combined with the relative prices in the objective function consistently yield corner solutions. It is these corner solutions that lead to the discrete changes in feed inputs (e.g. completely substituting barley for corn), in which it might be interesting to further evaluate models that generate smoother transitions between inputs.

4. Conclusion

The objective of the current study was to develop a multi-period LP feed model that captures the least cost ration switch between available feed resources for dairy cows. The results demonstrate the potential use of the method in different commodity feed availability situations in order to improve efficiency in dairy production.

The study shows the potential feed switch between feed grains and meals, on the one hand, and between grains, meals, and forages on the other hand, under volatile market feed prices. Scenario 14, the fully flexible feeds alternative, provided the greatest feed switch variability and the lowest cost (i.e. 11% lower feed cost than grain based feeding scenarios). The use of multiple meals feeding scenarios reduced alfalfa dietary inclusion by 7%, which is potentially important in arid and semi-arid production regions where alfalfa production is limited by water availability.

The model analysis could be of value in providing switching options of dairy rations inputs to feed producers, decision makers, and farmers, thereby providing further choices of dietary solutions to be considered on shorter time intervals. The modelling approach shows the potential to improve efficiency in feed production and dairy diets formulation which, in turn, can improve the overall allocation efficiency of feeds.

Future research needs to address the potential of the method to predict dairy diets under different feed price and feed quality scenarios. Further studies are needed to apply this framework to a larger set of cows, feeds, and possibly herds, and explore the sensitivities and robustness of our results with varying model inputs. Finally, the model has the potential to evaluate the distribution of regional feed input production with consideration for environmental impacts.

Conflict of interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.inpa.2019.03.004.

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