Optimal management of on-farm resources in small-scale dairy systems of Central Mexico: model development and evaluation

Octavio Alonso Castelán-Ortega[1] & Carlos Galdino Martínez-García[2] & Fergus L. Mould[3] & Peter Dorward[3] & Tahir Rehman[3] & Adolfo Armando Rayas-Amor[4]

[1] Facultad de Medicina Veterinaria y Zootecnia (FMVZ), Universidad Autónoma del Estado de México, Instituto Literario No. 100, Col. Centro, C.P. 50000 Toluca, Estado de México, México

[2] Instituto de Ciencias Agropecuarias y Rurales (ICAR), Universidad Autónoma del Estado de México, Instituto Literario No. 100, Col. Centro, C.P. 50000 Toluca, Estado de México, México

[3] Department of Agriculture, The University of Reading, Earley Gate, PO Box 237, Reading RG6 6AR, Berkshire, UK

[4] Departamento de Ciencias de la Alimentación, Universidad Autónoma Metropolitana Unidad Lerma, Av. Hidalgo poniente No. 46 Colonia la Estación, 52006 Lerma de Villada, Estado de México, México

Abstract

This study evaluates the available on - farm resources of five case studies typified as small scale dairy systems in central Mexico. A comprehensive mixed -integer linear programming model was developed and applied to two case studies. The optimal plan suggested the following : (1) instruction and utilization of maize silage, (2) alfalfa haymaking that added US$140/ha/cut to the total net income, (3) allocation of land to cultivated pastures in a ratio of 27 :41 (cultivated pastures /maize crop) rather than at the current 14:69, and dairy cattle should graze 12 h/day,(4) to avoid grazing of communal pastures because this activity represented an opportunity cost of family labor that reduced the farm net income, and (5) that the highest farm net income was obtained when liquid milk and yogurt sales were included in the optimal plan. In the context of small-scale dairy systems of central Mexico, the optimal plan would need to be implemented gradually to enable farmers to develop required skills and to change management strategies from reliance on forage and purchased concentrate to pasture -based and conserved forage systems.

Introduction

The challenge of maximizing farm profit by means of improving farm-grown forage production and the efficient utilization is a problem facing dairy farming systems all over the world (Chapman et al. 2008), and small-scale dairy systems (SSDS) must improve the efficiency of utilization of all on-farm re- sources and turn them into milk if they want to be competitive in the domestic market. Traditionally, farmers' decisions have relied on experience and commonsense; however, linear programming (LP) helps to assist the management and to assess theim-pacton the profitability of systems (Castelán-Ortega et al. 2003; Chapman et al. 2008). The SSDS contribute 37% of total Mexican milk production (Hemme 2007); however, their profitability is low because milk prices have remained low over the last 20 years. Commercial concentrate supplementation (up to 9 kg/cow) is common among farmers; some farmers formulate their own concentrates that include maize grain mixed with poultry waste or feed industry by-products as an attempt to reduce milk production costs, and native pastures are communally grazed because they are considered a forage resource that farmers can use without any cost.

It is understood that integrating system modeling with field research is an essential step to facilitate decisions to manage efficiently the on-farm available resources for milk production and to reduce the dependency on purchased forages and concentrates.Therefore, the objective of the present study was to develop a mixed-integer LP model that explores alternative changes in the farms’ management strategies and to evaluate the impact of these changes on the farms’ profitability of two case studies.

Materials and methods

Selection of case studies

The study area was located in the central highlands of Mexico (19° 10′ and 99° 35′ W). The environment in the central highlands of Mexico is temperate (Fig. 1), and the forages that can be grown in temperate environments were included in the model.

The participants were identified with a purposive sampling method (Vogt and Burke 2011) in which the farmers were pre-interviewed in order to take into account their willingness to supply technical and economic information. In order to represent SSDS in the central highlands of Mexico, farmers were included if they considered milk production to be their largest single income and had representative land and herd sizes. Although SSDS are specialized in milk production, they manage their farms as mixed farming systems, and different crops and forage resources (maize, oats, triticale, wheat, barley, and different species of cultivated and native grasses) were taken into account in the model.

At the end of the pre-interview, only seven farms were chosen from which five farms were used as data providers (F1, F2, F3, F5, F7) in order to develop a mixed-integer LP model, and the remaining farms were selected as case studies (F4 and F6) in order to evaluate the optimal plan (OPl).

Table 1 presents the land allocated to forage crops, cultivated pastures, and the access to communal pastures. The breeds observed in the herds were Holstein, crossbreeds Holstein × Brown Swiss, and Holstein × indigenous cattle with milk yields between 1800 to 7500 kg/cow/year and lactation lengths up to 305 days.

A formal questionnaire was applied to each farmer at the beginning of the study (July 2006) and updated once a month until the end (June 2007). The main features of forage crop management, labor requirements, and their profitability in the farms are summarized in Tables 2 and 3. The animal genotypes were considered in the model in terms of animal performance. Table 4 shows the average milk yields observed in the farms and reflects the genetic potential of cows.

Model description

The approach in this study was to characterize the farming system, and then the optimizations of the biological components of the mixed farming systems were performed (Castelán-Ortega et al. 2003) by means of a mixed- integer linear programming (ILP) model that maximized the annual farm net income (FNI). The ILP matrix consisted of 166 activities grouped into nine categories and 188 constraints from which 177 were balance constraints ($\leq$ or ≥ 0). The mathematical notation of the ILP model is presented in Eq. 1 (Online Resource 1). The schematic representation of the ILP matrix is shown in the Supplementary Material (Online Resource 2).

Simulation of an optimal plan for case studies

In the following sections, we present firstly the farmers' plan (FEP), which refers to the farms' management commonly practised by farmers in the study area, and then the evaluation of the OPl that involved the simulations of the ILP model for case studies F4 and F6. The outputs were then compared with the set of data obtained from these two farmers (their data were not used for developing the ILP model). Two case studies with similar land size (10 ha) were used in order to evaluate the FNI when alfalfa crop is included or not in the OPl as a forage that could be grown for trading alfalfa hay in local markets. The model was developed in LINGO software v.10, (Users Guide, Copyright© 2006)

Results

Differences between farmers' plan and an optimal plan

Table 5 shows the OPl related to land allocation, farm land, and rent of land. For case studies F4 and F6, land allocated to maize crop was reduced by 2 and 8 ha, respectively; this land can be used for oat, alfalfa, or pasture production. In the OPl, land allocated to cultivated pastures and maize crop had a ratio of 27:41(cultivated pastures/maize crop), rather than 14:69, as farmers usually do.

The OPl of case studies F4 and F6 allocated 3.3 and 1.3 ha to ryegrass-white clover pasture (Table 5), rather than grazing activity of communal pastures, because their nutrient supply was lower than ryegrass-white clover pasture. Additionally, grazing communal pastures represented an opportunity cost of family labor for looking after the cattle while grazing.

Table 6 shows land devoted to crops that can be fed as fresh or conserved forage (silage or hay); oats can be fed as fresh forage in the summer season and harvested in August for hay making. This activity was different to the FEP since farmers bought oats or maize straw for animal feeding dur- ing the dry season. The OPl suggested that the maize crop should be conserved as silage; this was another difference between OPl and FEP because maize silage making was not observed in case studies (Table 2), therefore maize crop for grain production was not included in the OPl unless we force the model to consider this activity. An important change in the OPl was the alfalfa crop, because F6 can allocate 5.7 ha of this crop rather than maize crop; however, this forage must be sold rather than used for animal feeding.

Fertilizer application

Table 7 shows the fertilizers that can be applied to crops and pastures. The OPl reduced amounts of 18-46-0 and urea for the maize crop by 138 and 150 kg/ha, respectively. On the other hand, the OPl suggested applications of 195 kg/ha of urea and 61 kg/ha of triple superphosphate more than FEP for oat crop and 33 kg/ha of KCl, 24 kg/ha of 18-46-0, and 158 kg/ha of 0-46-0 more than FEP for alfalfa crop (Table 2). Farmers may readily adopt the OPl because they know that dry matter (DM) yield of an oat crop may increase, and that represents a benefit in the long term.

Feeding strategies for case studies

The ability of the model to integrate the responses of potential livestock performance based on the environment is shown in Table 8. The potential milk yield of a cow was simulated according to different feeding strategies based on which quality forages are grown on farms and their availability during the different seasons of the year (cultivated pastures plus different crops that could be used as fresh or conserved). Note that metabolizable energy (ME) and metabolizable protein (MP) requirements were satisfied when cultivated pastures were incorporated to the total diet (Fig. 2) versus communal native pastures.

Concentrate supplementation was still required, but the ILP suggested a mixture of maize grain and bread waste (concentrate made on-farm) in all feeding strategies. The addition of this supplement in the diet was up to 22 % in summer, 27 % in autumn, and 23 % during winter and spring; for dry cows, the addition was up to 18 %. This supplementation with concentrates represented a saving up to 30 %/cow.

The use of different forage resources influenced the cost of diet (Table 8); for lactating cows, the lowest cost was attained when ILP included oat hay and maize silage as forage complements to pastures, whereas fresh maize increased the costs by 11.7 and 17.6 % in summer and autumn, respectively. For dry cows, the lowest cost was obtained when oat hay complemented grazing.

Economic performance of the optimal plan

Table 9 shows the FNI derived from the OPl and the FNI obtained from FEP management. If farmers adopt milk- yogurt sales, they can achieve the highest income followed by the milk-cheese sales. The lowest income is obtained with milk sales only. The FNI of F6 increases when alfalfa crop is included in the OPl, adding US$140/ha/cut (Table 9). The FNI of F4 is profitable if the milk-yogurt scenario is adopted; otherwise, the FNI remains unprofit- able (Table 9) due to the milk price in the market area being low.

Discussion

Evaluation of the model

The process of evaluating the OPl was based on the farmers' knowledge and experience of the system. The OPl of F4 and F6 was evaluated by asking the farmers whether the OPl is realistic to them, which, according to Andrieu et al. (2007), is a possible approach to evaluate model simulations of complex systems.

Implications of the optimal plan

The use of simulation models can provide a useful and cost-effective means of introducing farmers to new management strategies and encouraging adoption. Such modeling can be applied to show the improvements management strategies have in terms of the economic benefit. The adoption of new strategies relies on the farmer's experience and education, the positive impact of the new management on the producer's net return, and the applicability of such management to the producer's operations and the possession of the economic means to adopt new management (Gillespie et al. 2007; Martínez-García et al. 2015).

The highest FNI was obtained when the OPl included milk- yogurt sales, but according to case studies F4 and F6, the implementation of these activities would be compromised by the learning process of making yogurt or cheese and the need to invest money for new facilities, fuel, or vehicles in order to market their dairy products. However, F4 and F6 indicated willingness to learn this process and to make the required investments.

For both case studies (F4 and F6), the OPl suggested two low-cost feeding strategies: (1) grazing cultivated pasture + fresh oat+a concentrate supplement and (2) grazing cultivated pasture + maize silage + a concentrate supplement. Pulido and Leaver (2003) proposed continuous grazing of a perennial ryegrass-legume pasture supplemented with concentrate levels of 0 and 6 kg/cow/day, and these strategies supported milk yields of up to 32 kg/cow/day. Bargo et al. (2001) evaluated cows grazing winter oats as a sole forage at vegetative stage supplemented with 6.3 kg DM/day of concentrate, a strategy which supported yields of 20.5 kg/day.

The grazing of communal pastures was an important activity for farmers; however, this activity was not included in the OPl because the family labor cost reduced the total profit by US$1460/year. The adoption of innovations suggested by the OPl was directly discussed with farmers F4 and F6, and they acknowledged potential benefits of implementing this change. However, the OPl should be introduced step by step in order to develop higher skills required for managing efficiently the on-farm resources and to redefine the management from reliance on forage and concentrate buyers (external inputs) to pasture-based and conserved forage systems.

Opportunities for improving the ILP model

The ILP model optimized the operation of the farms based on high-nutritional-density forages grown on-farm at low costs of production. The OPl did not account for the maize stover which is a resource with low nutrient supply that could be used to feed livestock with lower requirements.

Although grazing of communal pastures represented a constraint in terms of family labor cost, these pastures could be valued as soil carbon storage. Despite that, in our model, the mitigation strategies of greenhouse gas (GHG) emissions were not taken into account. There is also scientific literature that supports the replacement of grassland with maize crop that has the potential of reducing GHG emissions from dairy production in the long term (Vellinga and Hoving 2011). However, in a recent study, Hawkins et al. (2015) mentioned that increasing reliance on perennial forages promises to be a strategy for GHG mitigation within the dairy sector, and this finding is supported by Dutreuil et al. (2014) who noted that the incorporation of grazing for lactating cows on convention- al dairy farms in Wisconsin led to a 27.6 % decline in total GHG emissions, with a 29.3 % increase in net farmreturns.

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Compliance with ethical standards

Animal rights The study was carried out in accordance with the guidelines of the Research Ethics Committee of the EU Directive 2010/63/EU for animal experiments.
Conflict of interest The authors declare there are no conflicts of interests.

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