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Multiple Criteria Decision Making Approach for Evaluating Management Options: A Case of New Zealand Dairy Farming

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Authors' contributions

This work was carried out in collaboration between all authors. Author RS managed the literature searches, conceptualized and formulated the problem performed the analysis and wrote the first draft of the manuscript. Author AK managed the analyses of the study. Author DC managed the data collection. All authors read and approved the final manuscript.

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ABSTRACT

The continuous evolvement of dairy industry in countries like New Zealand, with increased dairy conversions and intensification, has resulted in remarkable economic development, though at the cost of environmental degradation. The increasing use of nitrogen fertilizers to sustain increasing number of cows has increased the risk of enhanced nitrate leaching and methane and nitrous oxide emissions. In this study, Compromise Programming (CP) and Weighted Goal Programming (WGP) have been applied to a Waikato dairy farm to reconcile economic goals with environmental and resources management goals. The models are based on *Tier 2 methodology*, developed specifically for New Zealand, for determining the energy requirements of cattle. The models are first applied with the current farm management practices to analyse the performance of the farm in meeting the two specific objectives of: (i) Attaining the production target of 1320kg MS ha^{-1} $year^{-1}$, set by the farm management for maximizing profit and (ii) Keeping the nitrogen leaching limit to

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26kg N ha^{-1} year^{-1}, as calculated by the agricultural management model *OVERSEER nutrient budget*. Model results show that with the existing management practices, it is not possible to meet the MS production and nitrogen leaching targets simultaneously. The production target of 1320kg MS ha^{-1} year^{-1} results in nitrogen leaching loss of 29kg N ha^{-1} year^{-1} whereas the nitrogen leaching target limits the production to 1195kg MS ha^{-1} year^{-1}. The results further shows that by keeping the number of cows calving in autumn within 150–200, and by putting an optimum area under the maize crop, it is possible to meet the twin objectives of minimizing the nitrogen leaching and maximizing the profit margins, though the production target has to be lowered significantly.

Keywords: Dairy farming; multiple criteria decision making; Nitrogen leaching; tier 2 methodology; waikato.

1. INTRODUCTION

Dairy farming systems throughout the world are facing numerous environmental, technical and economic challenges. This is especially true for countries like New Zealand (NZ) whose export economy depends on dairying. The dairy industry in the country is continuously evolving with increased dairy conversions and intensification. In the last ten years (2001-02 to 2010-11), the total effective dairy farming area has increased by 16.6% whilst the number of cows has gone up by 22.6%, with a corresponding 27.4% increase in the total processed milk [1]. This remarkable economic development, however, has been achieved at an environmental cost as increasing use of nitrogen fertilizers has given rise to nitrate leaching [2]. The increased number of cows and increasing use of nitrogen fertilizers have also raised the risk of increased methane and nitrous oxide emissions, thus compromising New Zealand's commitment under the Kyoto protocol [3].

The NZ dairy industry, therefore, has to make trade-off among the potentially conflicting economic and environmental goals, and tackle them simultaneously. In this context, multiple criteria decision making (MCDM) models are most appropriate and may play a useful role in decision making. MCDM models have been widely used for strategic planning purposes in agricultural systems [4,5], dairy farming systems [6,7], regional farm level modelling [8], livestock feed blend optimization [9] and in environmental sciences [10]. MCDM models have also been applied to dairy farming systems in conjunction with bio-economic or simulation models [11-13). Though several simulation models have been developed for pasture-based dairy farming systems in NZ [14-17], the application of optimization techniques has mostly remained limited to Linear Programming (LP) models [18-21] with the exception of the Integrated Dairy Enterprise Analysis (IDEA) framework which is based on nonlinear programming [22]. However, simulation models are usually complex and require detailed information that may not be readily available whereas LP models can only deal with a single objective.

In this study, two MCDM techniques, Compromise Programming (CP) and Weighted Goal Programming (WGP) have been applied to a Waikato dairy farm to reconcile economic goals (maximizing milksolids (MS; fat+protein) production per ha; maximizing profit margin over purchased feed cost (MoFC); maximizing metabolizable energy (ME) for milk production) with environmental (minimizing nitrogen leaching per ha) and resources management (minimizing water use) goals. The developed models are based on NZ-specific *Tier 2 methodology* for determining the energy requirements of cattle, and estimation of the methane and nitrous oxide emissions from the agricultural sector [23] and may be categorized as a '*support modelling*' tool for making '*tactical/strategic*' decisions at the farm level [24]. The models are first applied with the current farm management practices, and subsequently the management options of: (i) Deciding the number of cows calving in two seasons, i.e., spring and autumn; (ii) Selecting the most appropriate forage/crop production and feed purchase strategy to meet the cattle needs, and (iii) Combining (i) And (ii) Together, are evaluated.

The paper is structured as follows: in Section 2 we present the methodology including the details of the case study farm. In Section 3, the results of the optimization are presented. This is followed by a discussion (Section 4) and conclusions (Section 5).

2. METHODOLOGY

2.1 Case Study Farm

A 345 ha pasture-based dairy farm located in the prime dairying area of the Waikato region is selected for the case study. The Waikato region has fertile volcanic ash derived soils, and it contributes about 30% to the NZ milk production. In the selected farm, perennial pastures and annual crops are grown over 296ha. The perennial pastures include mixed pasture (85% perennial ryegrass+15% white clover), tall fescue, chicory and ryegrass, whereas annual crops include maize and turnip. Maize is grown during October - March and fed during April–September, while turnip is grown during October - December and fed during January–February. The farm database, maintained at a monthly time step, shows that mixed pasture accounts for a minimum of 190 ha whereas annual crops are limited to a maximum of 50ha. The area under maize is further limited to 21ha. The home-grown feed is supplemented by purchased feeds like meal concentrate, palm kernel extracts (PKE), molasses and kibbled maize to meet the animal nutritional requirements. The farm has a maximum annual budget of NZ $ 500000 for purchasing feed.

The animal herd at the farm includes milking and dry cows of Friesian-Jersey breed. The cows milk over 305 days and dry-off for two months. Two categories of calves, less than one year old and in between one and two year old, are maintained at the farm, and their number is kept at about 50% of the cows. Bulls (limited to one bull for eighty cows) are typically brought to the farm for a three-month period during November–January. In the Waikato region, cows are generally calved in early spring (late July-August) to match the high feed demand near the beginning of lactation with the period of greatest pasture growth, however, a few farms are now adopting a new management practice of calving a small number of cows in the autumn (March–April) [14]. The case study farm adopts this new management practice and has cows calving in both seasons, with autumn calving maintained at around 150.

The farm has a bore well to meet the water requirements. The upper limit on the groundwater use from this well is 250 m^3 during a day and 40000 m^3 during a year (1 June-31 May). Surface water, however, is available to supplement the groundwater supply. Though water supply is free now, it is expected to be levied soon as several district/regional councils in the neighborhood have already started the practice.

The farm management has set a production target of 1320kg MS ha^{-1} $year^{-1}$ while demonstrating the industrial responsibility of keeping the nitrogen leaching losses within the desirable limit of 26 kg N ha^{-1} $year^{-1}$. The desirable limit on the nitrogen leaching is estimated by the *OVERSEER nutrient budget* model [25,26], which is the standard tool adopted by NZ agricultural industry for estimating the nutrient losses.

2.2 Technical Coefficients

The monthly data related to number and category of animals maintained, milk and MS production, pasture and crop production, water use, and fertilizer application were taken from the farm database for the 2010-11 season. The available information, however, was further supplemented using the existing literature, especially for the average pasture production in the study region, crop yield, feed requirement of animals, and ME content of various feeds [27-29]. The milk price for 2010-11 ($7360 t^{-1} MS) was taken from DairyNZ [30]. All monetary values, throughout the paper, are stated in New Zealand dollars.

The energy requirements and dry matter intake (DMI) of cattle, and subsequently the methane (CH_4) and nitrous oxide (N_2O) emissions were calculated using the *Tier 2 methodology* developed specifically for New Zealand [23]. This Inventory model [31] uses the Australian Feeding Standards algorithms for freely grazing ruminants [32] and calculates ME requirement for animal weight maintenance, milk production, conception/gestation, live weight gain and grazing. The amount of CH_4 released includes methane from dairy cattle and from manure management (both pasture and storage), whereas N_2O emission includes N_2O from direct sources (fertiliser, animal waste, nitrogen fixing crops, and urine and faeces deposited during grazing) and indirect sources (nitrogen volatilisation from soils and nitrogen leached from soils). The methane and nitrous oxide emission are converted into the carbon dioxide equivalents (CO_2-e) by using the conversion factors of 25 for CH_4, and 298 for N_2O [33]. The CO_2 emission is neglected here due to non-availability of relevant information. The N-leaching estimation depends on the amount of nitrogen fertiliser applied to soils, nitrogen excreted by animals and nitrogen from atmospheric deposition (assumed here as 2kg N ha^{-1} $year^{-1}$ [34]. A value of 0.07 is used to represent the fraction of nitrogen input to soils that is lost through leaching and runoff [35].

2.3 Mathematical Model

The mathematical model is developed based on the basic information described above. The model involves five animal categories, and ten home-grown pasture/crop and purchased feeds. A monthly time step is used with June representing the beginning of the annual farming cycle. The decision variables include tactical choices of the areas under different pastures/crops, quantities of purchased feeds, and number of cows calving in spring and autumn. A total of five objectives are considered: Maximization of milksolids production (Max_MSP), minimization of nitrogen leaching (Min_N_leach), maximization of metabolizable energy for milk production (Max_MEP), maximization of margin over purchased feed cost (Max_MoFC), and minimization of annual water use (Min_AWU). The constraints represent ME and DM requirements of animals and their availability through home-grown and purchased feeds, area available for cultivation, maximum and minimum limits on land allocation to individual pasture or crops, budget available for purchasing feed and daily limits on the water use. Appendix A presents the model description.

2.4 MCDM Techniques

There are numerous techniques that are available for handling MCDM problems, with varying suitability in different decision situations. Multi-Objective Programming (MOP) and Compromise Programming (CP) are suitable when only the direction of improvement of the decision attributes relevant to the decision situation at hand is known, whereas Weighted Goal programming (WGP) is recommended when the target values for the relevant decision attributes are known a priori. Further, when the number of objectives considered is more than two, CP is preferred over MOP [36]. Both CP and WGP are considered to be robust methods of analysing decision-making problems in complex environments such as agricultural systems [37].

2.4.1 Compromise Programming (CP)

Compromise programming seeks to obtain a solution representing the best compromise amongst the different objectives rather than optimizing only one of them. It seeks a solution as close as possible to the ideal point (vector) comprising of the ideal values for all the relevant objectives. A distance function, minimizing the distance between the solutions and the ideal point, is introduced into the analysis. Two metrics are usually considered: L_1 representing the longest distance geometrically, and L_∞, the largest deviation from among the individual deviations [38].

The first metric, L_1 is minimized by solving the following LP problem [39]:

$$Minimize \qquad L_1 = \sum_{g=1}^{n} W_g \left(\frac{Z_g^* - Z_g(x)}{Z_g^* - Z_{*g}} \right) \qquad (1)$$

$$\text{Subject to:} \quad x \in F$$
$$x \geq 0$$

Where ***F*** is the feasible set, ***x*** is the vector of decision variables, Z_g^* and Z_{*g} are the ideal and anti-ideal values for objective *g,* $Z_g(x)$ is the *g*th objective function, and W_g(>0) is the weight attached to objective *g*.

The second metric, L_∞ is minimized by solving the following LP problem [39]:

$$Minimize \qquad L_\infty = d_\infty \qquad (2)$$

Subject to:

$$W_g \left(\frac{Z_g^* - Z_g(x)}{Z_g^* - Z_{*g}} \right) \leq d_\infty \qquad for \quad all \quad g \qquad (3)$$

$$x \in F$$
$$x, d_\infty \geq 0$$

Where d_∞ is the largest deviation. In this study, W_g is taken as one for both metrics.

2.4.2 Weighted Goal Programming (WGP)

WGP considers all the goals simultaneously by using a composite objective function. The objectives are converted into goals and incorporated into the model in the form of approximate equalities. Positive (p_g) and negative (n_g) deviational variables, indicating over-achievement or under-achievement, are introduced in the objectives, with the right hand side values representing the targets set by planner that may or may not be satisfied. The composite objective function minimizes the deviations between achievement of the goals and their targets [4]. In WGP, goal satisfaction may be traded-off using relative weights on deviations from the targets in the objective function. Mathematically, the WGP problem is expressed as follows:

$$Minimize \quad \sum_{g=1}^{n} W_g \left(\frac{n_g + p_g}{G_g} 100 \right) \tag{4}$$

Subject to:

$$Z_g(x) + n_g - p_g = G_g \qquad for \ all \ g,$$
$$x \in F$$
$$x, n_g, p_g \geq 0$$

Where G_g is the objective target for the goal g. If all the goals have the same importance, then W_g is taken as one, which is the case here. The objective function includes n_g or p_g depending on whether the G_g is to be underachieved or overachieved. A normalization constant, G_g/100, is used here to overcome the incommensurability [40].

2.5 Pay-off Matrix

The application of CP involves definition of ideal (Z_g^*) and anti-ideal (Z_{*g}) values, and WGP definition of target (G_g) values, for each objective. These values were obtained by solving the conventional LP problems for each objective [38]. A pay-off matrix was prepared by maximizing or minimizing the five objectives defined by (A1) – (A5) (Appendix A). However, to reflect the existing farm management practice of maintaining 150 milking cows during the winter season, an additional constraint was included in the model to keep the number of cows calving in March-April fixed at 150.

2.6 Modelling Scenarios and Management Options

The CP and WGP models are first applied to the case study with the existing farm management practices. Based on the results, the WGP model is then applied to evaluate the performance of the farm with the two specific objectives of: (i) Meeting the production target of 1320kg MS ha^{-1} year^{-1} and (ii) keeping the nitrogen leaching losses within the desirable limit of 26kg N ha^{-1} year^{-1}. In these two model runs, goals reflecting maximization of MSP and minimization of N_leach, (A1) and (A2) (Appendix A), are treated as rigid constraints and assigned fixed objective targets (G_g) of 1320 and 26 respectively.

The WGP model is further applied to evaluate the management options of: (i) Deciding the number of cows calving in two seasons, i.e., spring and autumn; (ii) Selecting the most appropriate forage/crop production and feed purchase strategy to meet the cattle needs, and (iii) combining (i) and (ii) together. This is because with the growing focus on N-leaching and GHG emissions, there has been increased interest in alternative forages and feeding strategies to supplement the traditional perennial ryegrass-white clover feed-base in pasture-based dairy farms [41,42]. These alternative feeding strategies may also alter the herd structure, especially the number of cows calving in the two seasons, to match the nutrient availability [18,43]. To analyze the management option (i), the number of cows calving in the autumn is varied around 150, i.e., 100, 200, 250 and 300, and the WGP model is run for each case. For the management option (ii), The WGP model is run without constraints on individual pastures/crops, i.e., by eliminating constraints (A9) – (A12) (Appendix A). The effectiveness of the different management options is compared in terms of attributes like MSP, N-leaching, MEP, MoFC, feed cost and the resultant GHG emissions in terms of CO_2-e.

2.7 Validation of Model Results

Though it is difficult to validate the results of an optimization model, an attempt is made here to validate the N-leaching values obtained from the WGP model runs by setting up the *OVERSEER nutrient budget* model for select cases. The *OVERSEER* model has been chosen because it is extensively validated for leaching load estimation from NZ farming systems [35] and thus could be used as a validation tool. The key outputs of the optimization model, *i.e.,* number of animals of different categories, quantity of milk produced, area under different forages/crops and quantity of supplements purchased are used as input while setting up the *OVERSEER* model, along with the farm specific data on climate, soil characteristics, nitrogen fertiliser use and effluent application. The N-leaching loads determined from the *OVERSEER* model runs are used to validate the optimization results.

3. RESULTS

3.1 Pay-off Matrix

Table 1 presents the pay-off matrix obtained by optimizing each objective separately using LP. Each row of Table 1 shows the optimal objective function value (underlined) along with the corresponding values of the other objectives. For example, the first row of Table 1 shows that the optimal milksolids production (MSP) is 1428kg MS ha^{-1} year^{-1}, which corresponds to nitrogen leaching (N_leach) of 31kg N ha^{-1} year^{-1}, metabolizable energy for milk production (MEP) of 23790597 MJ, margin over feed cost (MoFC) of 2.149 M$ and annual water use (AWU) of 50515 m^3.

The pay-off matrix clearly reflects the wide range that each objective can attain. It shows that objectives Max_MSP, Max_MEP and Max_MoFC are complementary to each other. It further shows that objectives Max_MSP and Min_N_leach or Min_AWU are at opposite extremes, which implies the need for compromise between these. Such results can be explained by the fact that maximizing MSP entails larger number of milking cows which in turn results in higher N-leaching or necessitates higher amount of water consumption. A careful examination of the payoff matrix leads to an important conclusion that the production target of 1320kg MS ha^{-1} year^{-1} set by the farm management cannot be attained while keeping the nitrogen leaching losses within the desirable limit of 26 kg N ha^{-1} year^{-1}.

The best value of each objective in Table 1 was further used to define the ideal values (Z_g^*) in CP and to set the target values (G_g) in WGP, whereas the worst value of each objective defined the anti-ideal values (Z_{*g}) in CP.

3.2 Compromise and Weighted Goal Programming

Table 2 presents the most efficient compromise set obtained by the CP model for the two metrics L_1 and L_∞, and goal values attained by the WGP model with the existing farm management practices. As evident, the compromise solution obtained by CP corresponding to metric L_1, and WGP solution are exactly the same, showing about 99% achievement of the ideal values for milk solids production, ME for milk production and margin over feed cost. The ideal values for N-leaching and annual water use are, however, overachieved by about 19%. It further emphasizes the conflict between the objectives of milk solids production and N-leaching.

Table 3 presents the herd structure, land allocated to different pastures/crops and cost of purchased feed obtained by CP and WGP models. The major difference between the solutions obtained by CP model corresponding to metric L_1 and WGP model, and CP model corresponding to metric L_∞ lies in the number of cows calving in spring (and the resultant reduction in the number of calves due to model assumption). This explains the reduced milk solids production and N-leaching obtained in the L_∞ solution, as number of cows drives the milk solids production whereas total animals at the farm govern the N-leaching losses. In all three solutions, the entire 296 ha area was cultivated and the entire budget available for purchasing feed was invested. All three models assigned maximum possible area to the annual crops, maize and turnip, indicating a possibility of increasing the cultivable area under these crops from the present limit of 50ha. Among the pastures, models preferred mixed pasture and chicory (WGP and L_1 metric of CP). GHG emissions (sum of CH_4 and N_2O emissions converted into CO_2-e) is estimated at 3466 tonnes CO_2-e for the solution corresponding to metric L_1 of CP model and WGP model, and 2943 tonnes CO2-e for solution corresponding to metric L_∞ of CP model. In terms of per litre of milk, the estimated GHG emissions are about 0.8 kg CO_2-e l^{-1} of milk. This value is similar to those reported for dairy farms in New Zealand, UK and other European countries [44,45].

Table 4 presents the WGP model results for farm specific objectives of meeting the production target of 1320kg MS ha^{-1} year^{-1} (MSP_1320) and keeping the nitrogen leaching losses within the desirable limit of 26kg N ha^{-1} year^{-1} (N_leaching_26). Results reiterate that the production target of 1320kg MS ha^{-1} year^{-1} set by the farm management cannot be attained while keeping the nitrogen leaching losses within the desirable limit of 26kg N ha^{-1} year^{-1}. This is because MSP of 1320kg MS ha^{-1} year^{-1} results in N-leaching loss of 29kg N ha^{-1} year^{-1} whereas N-leaching loss of 26kg N ha^{-1} year^{-1} limits MSP to 1195kg MS ha^{-1} year^{-1} (Table 4). Thus, within the existing constraints, farm management has to compromise on either of the two targets. The production target of 1320kg MS ha^{-1} year^{-1} requires 666 cows (516 calving in spring) resulting in MoFC of 2 M$ compared to 604 cows (454 calving in spring) with MoFC of 1.949 M$ for the N-leaching target of 26kg N ha^{-1} year^{-1}. GHG emissions are estimated at 3222 tonnes CO_2-e for MSP_1320, and 2932 tonnes CO2-e for N_leaching_26. Results further show that the annual water requirement exceeds the 40000 m^3 of groundwater available at the farm in all cases (Tables 2 and 4), thus necessitating reliance on surface water. Since the water supply in the near future may be on payment basis, farm management may have to keep a check on this additional expenditure.

Table 1. The pay-off matrix

Objective	Objective Optimised				
	Max_MSP (kg MS ha^{-1} year^{-1})	Min_N_leach (kg N ha^{-1} year^{-1})	Max_MEP (MJ)	Max_MoFC (M $)	Min_AWU (m^3)
Max_MSP	1428	31	23790597	2.149	50515
Min_N_leach	1200	26	20003291	1.874	42322
Max_MEP	1428	31	23790597	2.149	50515
Max_MoFC	1428	31	23790597	2.149	50515
Min_AWU	1200	26	20003291	1.779	42322

Table 2. Most efficient compromise set (CP model) and attained values of goals (WGP model) for the case study farm

Objective function	Compromise Programming (CP)		Weighted Goal Programming (WGP)
	Metrics		
	L_1	L_∞	
Max_MSP (kg MS ha^{-1} year^{-1})	1426	1200	1426
Min_N_leach (kg N ha^{-1} year^{-1})	31	26	31
Max_MEP (MJ)	23785547	20016594	23785547
Max_MoFC (M$)	2.144	1.726	2.144
Min_AWU (m^3)	50246	42322	50246

Table 3. Herd structure, land allocation and feed cost obtained from compromise and goal programming models

Attributes	Compromise Programming (CP)		Weighted Goal Programming (WGP)
	Metrics		
	L_1	L_∞	
Herd structure			
Cows calving in spring (July-August)	570	460	570
Cows calving in autumn (March-April)	150	150	150
Bulls	9	8	9
Calves	360	305	360
Land allocation (ha)			
Mixed pasture	190	246	190
Chicory	56	0	56
Maize	21	21	21
Turnip	29	29	29
Feed cost (NZ $)	500000	500000	500000
GHG emission (tonnes CO_2-e)	3466	2943	3466

Table 4. Weighted goal programming results in meeting farm specific milk solids production and Nitrogen-leaching targets

Attributes	MSP_1320*	N_leaching_26†
Max_MSP (kg MS ha^{-1} $year^{-1}$)	1320	1195
Min_N_leach (kg N ha^{-1} $year^{-1}$)	29	26
Max_MEP (MJ)	22022243	19935479
Max_MoFC (M$)	2.000	1.949
Min_AWU (m^3)	46539	42151
Herd structure		
Cows calving in spring (July-August)	516	454
Cows calving in autumn (March-April)	150	150
Bulls	8	8
Calves	333	302
Land allocation (ha)		
Mixed pasture	234	234
Chicory	12	12
Maize	19	21
Turnip	31	29
Feed cost (NZ $)	448230	267471
GHG emission (tonnes CO_2-e)	3222	2932

** Fixed production target of 1320kg MS ha^{-1} $year^{-1}$*
† Fixed nitrogen leaching target of 26kg N ha^{-1} $year^{-1}$

3.2.1 Validation of model results

TheWGP model runs corresponding to the farm specific objectives of meeting the production target of 1320kg MS ha^{-1} $year^{-1}$ (MSP_1320) and keeping the nitrogen leaching losses within the desirable limit of 26kg N ha^{-1} $year^{-1}$ (N_leaching_26) were randomly selected for validating the N-leaching losses estimated by the optimization model. The key outputs of these runs were extracted at monthly time step (Table 4 presents the consolidated results), and used to set up the *OVERSEERnutrient budget* models. Additional data on climate, soil characteristics, nitrogen fertiliser use and effluent application were taken from the farm database. The *OVERSEER* model resulted in a nitrogen leaching loss of 28.5kg N ha^{-1} $year^{-1}$ with MSP_1320 inputs, and 27 kg N ha^{-1} $year^{-1}$ with N_leaching_26 inputs. The corresponding N-leaching losses estimated by the optimization model are 29 kg N ha^{-1} $year^{-1}$ and 26kg N ha^{-1} $year^{-1}$ (Table 4), and hence, the optimization model results may be treated as quantitatively validated. The minor difference in the results by two approaches may be attributed to the fact that *OVERSEER* is acomprehensive model that takes into account the farm climate and soil characteristics whereas *Tier 2 methodology* used in the optimization model is based on empirical relationships.

3.3 Analysis of the Management Options

3.3.1 Number of cows calving in two seasons

Fig. 1 presents the effect of varying the number of cows calving in autumn on MSP, N-leaching, MoFC, GHG emissions, and annual water use. As evident, the total number of cows maintained at the farm and N-leaching loss remain almost the same in all cases; however, reducing the number of calving in the autumn from 150 to 100, or increasing it to 250 or 300, decreases the milk solids production and the margin over feed cost slightly. It is seen that increasing the number of autumn calving to 200 produces almost the same results as with the existing 150 calving, though there is a minor increase in MoFC. The results show that the existing farm management practice of 150 calving in autumn is near optimal. Therefore, the farm should maintain around 720 cows, with 150 or 200 cows calving in autumn.

3.3.2 Forage/crop production and feed purchase strategy

Since both 150 and 200 cows calving in autumn produce similar results, management option (ii) and (iii), i.e., selecting the most appropriate forage/crop production and feed purchase strategy, and combination of autumn calving and selecting the most appropriate forage/crop production and feed purchase strategy are taken together. The management option (ii) is considered with 150 calving in autumn and option (iii) with 200 calving; WGP models corresponding to these options are then run without constraints on individual pastures/crops. Table 5 presents the results. The exclusion of constraints on individual forage or crop leads to abundant supply of metabolizable energy for milk production, and increases the number of cows that could be maintained at the farm to 788. This leads to a considerably higher MSP of 1561kg MS ha^{-1} $year^{-1}$ and 1559kg MS ha^{-1} $year^{-1}$ for options (ii) and (iii), with corresponding margin over feed cost of 2.541 M$ and 2.539 M$. This may be because land allocation to forage/crops changes completely, with chicory replacing the mixed pasture and maize being assigned a higher area of 94 ha in both options. The preference for chicory is because of its high ME content, and for maize because of its high DM yield. The superior economic achievements under these two management options, however, has a negative aspect as N-leaching shoots to 34kg N ha^{-1} $year^{-1}$ in both cases, with GHG emissions of 3772 tonnes CO2-e and 3771 tonnes CO2-e for options (ii) and (iii).

To tackle this unwarranted situation, WGP model runs were repeated with N-leaching fixed at 26kg N ha^{-1} $year^{-1}$ (similar to the N_leaching_26 case), and the results are presented in Table 6. It is seen that though the number of cows, MSP and GHG emissions are similar to N_leaching_26 model run (Table 4), exclusion of constraints on individual forage or crop area leads to sharp reduction in purchased feed cost and results in higher margin over feed cost. The MoFC for management options (ii) and (iii) are 2.107 M$ and 2.162 M$, with both surpassing even the MoFC of 2.0 M$ obtained in MSP_1320 case (the other farm objective of meeting the production target of 1320kg MS ha^{-1} $year^{-1}$; Table 4). Therefore, both options (ii) and (iii), when considered in conjunction with the fixed N-leaching loss of 26kg N ha^{-1} $year^{-1}$, meet the twin targets set by the farm management, one directly (N-leaching) and other indirectly (MSP, in terms of MoFC). Fig. 2 presents the land allocation to pasture or crops for management options (ii) and (iii) with N-leaching fixed at 26kg N ha^{-1} $year^{-1}$ along with those for N_leaching_26 case. It is seen that with no constraints on the individual forage/crop area, the model allocates higher area to maize: 60ha in option (ii) and 104 ha in option (iii) compared to the constrained 21 ha in N_leaching_26 case. This appears to be the major reason behind the sharp reduction in purchased feed cost in options (ii) and (iii). PKE is the only feed purchased in all three cases (data not shown here), though its quantity varies from 148 tonnes in option (iii) to 777 tonnes in N_leaching_26 case.

4. DISCUSSION

This study focused on formulation of MCDM models, incorporating NZ specific *Tier 2 methodology*, to tackle potentially conflicting multiple goals facing the dairy industry, and to analyze the management options that may lead to improved farm performance.

Table 5. Effect of the forage/crop production strategy on the selected attributes

Attributes	Option (ii)*	Option (iii)†
Total number of cows	788	788
MSP (kg MS ha^{-1} $year^{-1}$)	1561	1559
N-leaching (kg N ha^{-1} $year^{-1}$)	34	34
MEP (MJ)	26046324	26009279
MoFC (M$)	2.541	2.539
Feed cost (NZ $)	354142	353556
GHG emission (tonnes CO_2-e)	3772	3771
Land allocation (ha)		
Chicory	202	202
Maize	94	94

** 150 calving in autumn with no constraints on individual forage/crops*
† 200 calving in autumn with no constraints on individual forage/crops

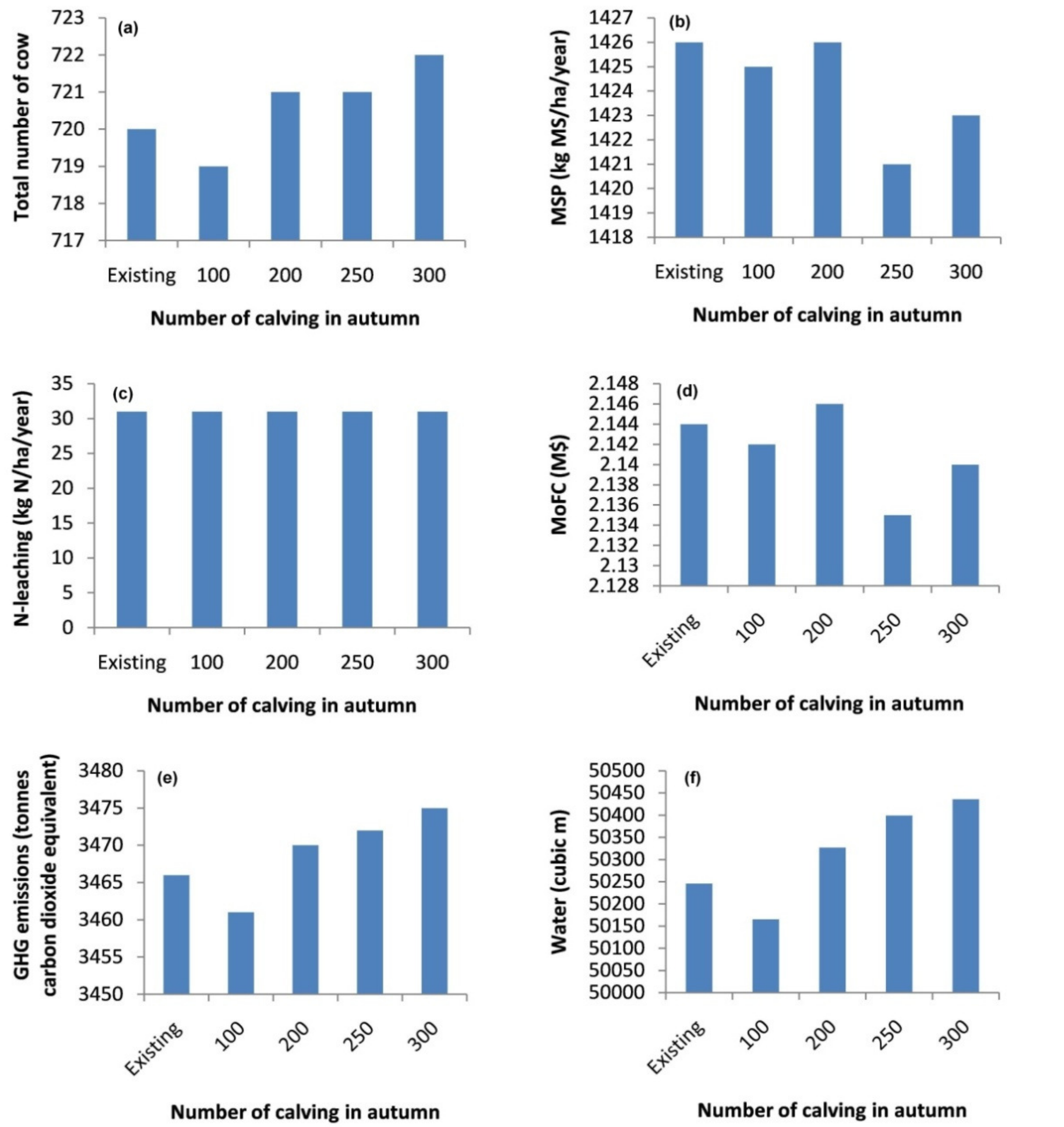

Fig. 1. Effect of number of calving in autumn on (a) Total number of cow, (b) Milk solids production, (c) N-leaching, (d) Margin over feed cost, (e) GHG emissions and (f) Annual water use

Table 6. Results of options (ii) and (iii) runs with N-leaching fixed at 26kg N ha^{-1} year^{-1}

Attributes	**Option (ii)***	**Option (iii)**†
Total number of cows	604	604
MSP (kg MS ha^{-1} year^{-1})	1195	1193
N-leaching (kg N ha^{-1} year^{-1})	26	26
MEP (MJ)	19935479	19891454
MoFC (M$)	2.107	2.162
Feed cost (NZ $)	109751	51044
GHG emission (tonnes CO_2-e)	2928	2919

* 150 calving in autumn with no constraints on individual forage/crops + N_leaching target fixed at 26 kg N ha^{-1} year^{-1}; † 200 calving in autumn with no constraints on individual forage/crops + N_leaching target fixed at 26kg N ha^{-1} year^{-1}

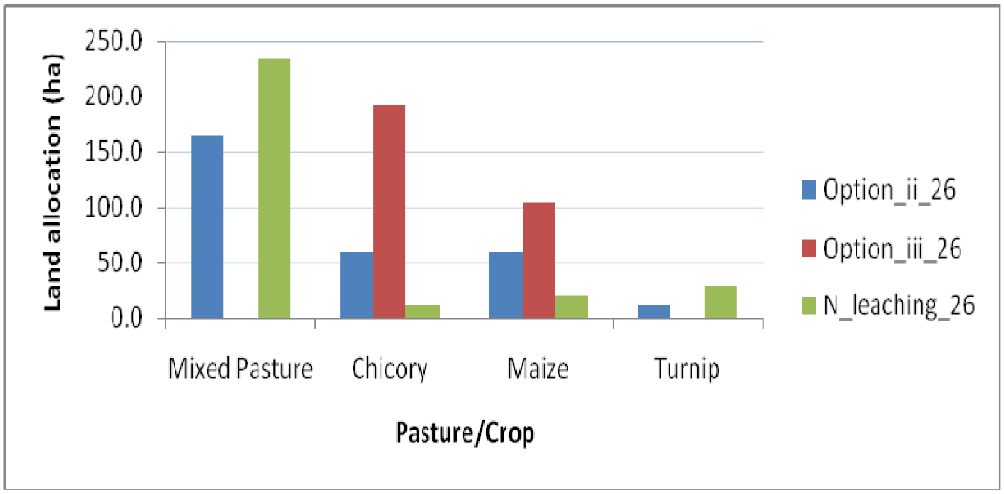

Fig. 2. Land allocated to pasture or crops for weighted goal programming model runs corresponding to management option (ii) with nitrogen leaching fixed at 26 kg N ha^{-1} year^{-1} (Option_ii_26), management option (iii) with nitrogen leaching fixed at 26 kg N ha^{-1} year^{-1} (Option_iii_26) and existing farm management practice with nitrogen leaching fixed at 26 kg N ha^{-1} year^{-1} (N_leaching_26)

We chose two MCDM techniques: Compromise programming (CP), which defines the 'best' based on distance function, and weighted goal programming (WGP), which is based on the Simonian philosophy of 'Satisfying' [37]. Though CP is considered to be the best option amongst MCDM techniques [36,38], in our case, the compromise solution obtained by CP corresponding to metric L_1, and WGP solution were exactly the same. Similar results were also reported by Val-Arreola et al. [6]. WGP model was particularly useful in analysing two specific targets set for the case study farm, i.e., production target of 1320kg MS ha^{-1} year^{-1} and N-leaching target of 26kg N ha^{-1} year^{-1}. The comparison of results obtained by WGP in N_leaching_26 case (Table 4) and LP in Min_N_leach case (Table 2) clearly established the advantage of WGP because in spite of slightly lower level of milksolids production, it brought considerable improvement in the margin over feed cost. Fleskens and de Graaff [8] also found WGP to be flexible and efficient in performing scenario analysis. WGP also has an added advantage as it offers the decision maker with the option of assigning different weights to goals reflecting the preferences of the stakeholder. In this study, however, all goals were assigned equal weight.

Model validation is usually recommended to address the question whether the model produces realistic and reliable results. Since the optimization methodology used here is based on empirical relationships included in *Tier 2 methodology*, we felt it necessary to validate the model outputs. We, therefore, used the *OVERSEER nutrient budget* model, as described in Section 2, to validate the N-leaching load component for two selected cases, thus bringing confidence in the estimations of ME requirement and GHG emissions (N-leaching estimation being an off-shoot of the N_2O emission estimation, Section 2). There may still be uncertainties in the optimization outputs due to uncertainty in model inputs, however, evaluation of these could be possible only if algorithms that support multi-objective optimization under uncertainty are used [46].

We analyzed two management options dealing with the herd structure, in terms of number of cows calving in spring or autumn, and forage/crop production strategies. This is because in a recent review, Le Gal et al. [24] highlighted the complexity of dairy farm production systems as majority of reviewed literature focused on balancing the feed inputs (farm produced and purchased) with herd demand. The selection of these management options was also motivated by the fact that NZ dairy farmers are slowly adopting the new management practice of calving a small number of cows in the autumn (March – April) and taking interest in alternative forages and feeding strategies [14,41,42]. Our analysis for the case study farm showed that the number of cows calving in autumn should be within 150 – 200 for optimal adjustment between animals and feeds leading to maximum system output (Fig. 1).

According to the solutions provided by the WGP model, chicory and maize were preferred under the most appropriate forage/crop production strategy (Table 5). These results are in agreement with earlier research promoting chicory as a prominent component of an alternative forage production strategy because of its high yield quality forage, micro nutrients content and deep tap root system that supports growth through dry conditions [28,42,47]; and maize because of its high DM yield and nitrogen use efficiency [43,48]. In our case, allocation of larger area to maize (Fig. 2) lowered the purchased feed cost and affected the margin over feed cost (Tables 4 and 6). The provision of higher land allocation to maize, however, needs further investigation as there are conflicting research findings regarding the effect of feeding maize on N-leaching and CH_4 emissions. Maize has been reported to reduce urinary nitrogen and N-leaching loss [41,48,49,50,51], and reduce CH_4 emission [50]. Conversely, maize has been reported to enhance N-leaching [13] and CH_4 emission [41].

Although our results establish the utility of MCDM models in dairy farming system, we need to include cost of other inputs like fertilizer and labour for true representation of the profit margins. Similarly, models could be strengthened by incorporating crop growth functions, reflecting the effect of fertilizer and effluent application on pasture/crop growth. We also need to develop a user interface for ease of application of the model and its acceptance by the end-users.

5. CONCLUSION

The MCDM models proved to be effective in analyzing the environmental and economic performance of a Waikato dairy farm that was selected for this study. The models supported the evaluation of the existing farm management practices and analyzed the efficacy of the management options. Optimal calving in autumn and planting large area under maize appeared to be the key to attaining twin objectives of maximum milk solids production and minimum N-leaching. Desirable modifications of the models include development of a user interface, inclusion of crop growth functions and consideration of cost of inputs other than feed. We conclude that the application of MCDM techniques has a strong potential to support the decision-making processes in pasture-based dairy farms.

COMPETING INTERESTS

Authors have declared that there are no competing interest exits.

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APPENDIX-A

The model involves five animal categories, represented by set *i* (*i* = 1 for cows calving in spring, i.e., July-August; *i* = 2 for cows calving in autumn, i.e., March-April; *i* = 3 for calves less than one-year old; *i* = 4 for calves, one to two year old; *i* = 5 for bulls). A monthly time step, represented by set *j*, is used (*j* = 1 for June; *j* = 2 for July; *j* = 3 for August; *j* = 4 for September; *j* = 5 for October; *j* = 6 for November; *j* = 7 for December; *j* = 8 for January; *j* = 9 for February; *j* = 10 for March; *j* = 11 for April; *j* = 12 for May). Set *k* represents the home-grown pasture/crop and purchased feed (*k* = 1 for mixed pasture; *k* = 2 for tall fescue; *k* = 3 for chicory; *k* = 4 for annual ryegrass; *k* = 5 for maize; *k* = 6 for turnip; *k* = 7 for meal concentrate; *k* = 8 for palm kernel extract (PKE); *k* = 9 for molasses; *k* = 10 for maize kibbled; with *k* = 1 to 6 representing home-grown pasture/crop and *k* = 7 to 10, purchased feed).

A.1 Objectives

The following five objectives are considered.

A.1.1 Maximization of Milksolids Production (Max MSP)

$$Max \sum_{i=1}^{2}\sum_{j=1}^{12} X_{i\,j}\, MSY_{i\,j} \qquad \text{(A1)}$$

Where $X_{i\,j}$ is the number of cow *i* in month *j*, and $MSY_{i\,j}$ is the MS yield of cow *i* in month *j*, kg MS cow^{-1}.

A.1.2 Minimization of nitrogen leaching (Min N leach)

$$Min \sum_{j=1}^{12} N_{Des}\left(\sum_{k=1}^{6} A_{jk}\right) \qquad \text{(A2)}$$

Where N_{Des} is the desirable quantity of nitrogen that could leach, kg N ha^{-1} $year^{-1}$, and A_{jk} is the area under pasture or crop, ha.

A.1.3 Maximization of Metabolizable Energy for Milk PRODUCTION (Max MEP)

$$Max \sum_{i=1}^{2}\sum_{j=1}^{12} X_{i\,j}\, MEP_{i\,j} \qquad \text{(A3)}$$

Where $MEP_{i\,j}$ is ME required by cow *i* in month *j* for "Milk Production", MJ.

A.1.4 Maximization of Margin over Purchased Feed Cost (Max MoFC)

$$Max \sum_{j=1}^{12}\left[\sum_{i=1}^{2}(X_{i\,j}\, MSY_{i\,j}\, P_{MS}) - \sum_{k=7}^{10}(Y_{j\,k}\, C_{j\,k})\right] \qquad \text{(A4)}$$

Where P_{MS} is the price of milksolids, NZ \$ kg^{-1} MS, Y_{jk} is the quantity of feed *k* in month *j*, kg, and C_{jk} is the unit price of purchased feed *k* in month *j*, NZ \$ kg^{-1}.

A.1.5 Minimization of Annual Water Use (Min AWU)

$$Min \sum_{j=1}^{12}\left(\sum_{i=1}^{5} X_{i\,j}\, W_{drink_i} + \sum_{i=1}^{2} X_{i\,j}\, W_{mp_i} + \sum_{i=1}^{2} X_{i\,j}\, W_{FDM\_manage_i}\right)(N_{day_j}) \qquad \text{(A5)}$$

Where W_{drink_i} is the water required by animal *i* for drinking, L day^{-1}, W_{mp_i} is the water required for milking procedure of animal *i*, L animal^{-1} day^{-1}, $W_{FDM\_manage_i}$ is the water required for faecal dry management (FDM) of animal *i*, L animal^{-1} day^{-1}, and N_{day_j} is the number of days in month *j*.

A.2 Constraints

The above objectives are subject to the following constraints.

A.2.1 ME requirement constraint

$$\sum_{i=1}^{2}\sum_{j=1}^{12} X_{ij}\, MEP_{ij} + \sum_{i=1}^{5}\sum_{j=1}^{12} X_{ij}\, MEO_{ij} \le \sum_{j=1}^{12}\sum_{k=1}^{10} Y_{jk}\, ME_{jk} \qquad \text{(A6)}$$

Where MEO_{ij} is the ME required by animal *i* in month *j* for “Other than milk production”, MJ, and ME_{jk} is the ME content of feed *k* in month *j,* MJkg^{-1} DM

(Dry Matter).

The constraint states that the ME required by animals for milk production, maintenance, gestation, pregnancy, weight change and grazing must be met by the Diet.

A.2.2 DM intake constraint

$$\sum_{i=1}^{5}\sum_{j=1}^{12} X_{ij}\, DMI_{ij} \le \sum_{j=1}^{12}\sum_{k=1}^{10} Y_{jk} \qquad \text{(A7)}$$

Where DMI_{ij} is the dry matter intake of animal *i* in month *j,* kg DM.
The constraint ensures that DM intake requirement is met by the feeds selected by the model.

A.2.3 Area constraints

$$\sum_{k=1}^{6} \frac{Y_{jk}}{DMY_{jk}} \le A_{cultivable} \qquad for\ all\ j \qquad \text{(A8)}$$

Where DMY_{jk} is the dry matter yield of the home-grown feed *k* in month *j,* kg DM ha^{-1}, and $A_{cultivable}$ is the farm area available for cultivation, ha.

$$\sum_{k=1} A_{jk} \ge 190 \qquad for\ all\ j \qquad \text{(A9)}$$

$$\sum_{k=1}^{4} A_{jk} \le 246 \qquad for\ all\ j \qquad \text{(A10)}$$

$$\sum_{k=5}^{6} A_{jk} \le 50 \qquad for\ j=5\ to\ 10 \qquad \text{(A11)}$$

$$\sum_{k=5} A_{jk} \le 21 \qquad for\ j=5\ to\ 10 \qquad \text{(A12)}$$

Constraint (A8) states that the area available for home-grown feed is limited by the cultivable farm area, whereas (A9) ensures a minimum area of 190 ha under mixed pasture. Constraint (A10) limits the maximum area under perennial crops to 246 ha and ensures that the annual crops are indeed grown, whereas (A11) limits the maximum area under annual crops, and (A12) under maize.

A.2.4 Budget constraint

$$\sum_{j=1}^{12}\sum_{k=7}^{10} Y_{jk}\, C_{jk} \leq U_{cap} \tag{A13}$$

Where U_{cap} is the maximum fund available for purchasing feed in a year, NZ $.

The constraint ensures that the limit on the maximum fund available for purchasing feed holds good.

A.2.5 Daily water use constraint

$$\left(\sum_{i=1}^{5} X_{ij}\, W_{drink_i} + \sum_{i=1}^{2} X_{ij}\, W_{mp_i} + \sum_{i=1}^{2} X_{ij}\, W_{FDM\_manage_i}\right) \leq W_{limit\_daily} \qquad for\ all\ \ j \tag{A14}$$

Where W_{limit_daily} is the maximum limit on the daily water use, L.

The constraint states that the daily water limit restricts the daily water use.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history.php?iid=706&id=5&aid=6402