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An optimization model of a New Zealand dairy farm

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ABSTRACT

Optimization models are a key tool for the analysis of emerging policies, prices, and technologies within grazing systems. A detailed, nonlinear optimization model of a New Zealand dairy farming system is described. This framework is notable for its inclusion of pasture residual mass, pasture utilization, and intake regulation as key management decisions. Validation of the model shows that the detailed representation of key biophysical relationships in the model provides an enhanced capacity to provide reasonable predictions outside of calibrated scenarios. Moreover, the flexibility of management plans in the model enhances its stability when faced with significant perturbations. In contrast, the inherent rigidity present in a less-detailed linear programming model is shown to limit its capacity to provide reasonable predictions away from the calibrated baseline. A sample application also demonstrates how the model can be used to identify pragmatic strategies to reduce greenhouse gas emissions.
Key words: dairy system, farm modeling, nonlinear optimization

INTRODUCTION

The potential of grazing systems to increase global milk production is high, given the increasing costs associated with high levels of supplementation and the environmental and welfare concerns associated with intensive dairy production (Dillon et al., 2005). Indeed, the total costs of milk production worldwide have been shown to decline nonlinearly as the proportion of grass contained in cow rations increases, with the greatest benefits observed in pasture-based systems, such as those most popular in New Zealand (Dillon et al., 2008). Nevertheless, pasture-based dairy farms are complex systems in which producers must consider multiple interactions between pasture growth and decay, supplement use, individual animal intake and efficiency, and herd size and structure.

Mathematical programming is an optimization technique that has been broadly applied to analyze the integrated management of the multiple components within complex grazing systems (Cartwright et al., 2007). Primary applications include the assessment of agricultural innovations, evaluation of alternative management practices, experimental design, policy analysis, and research prioritization (Pannell, 1996). Berentsen and Giesen (1995) described a linear programming (**LP**) model of a Netherlands dairy system in which pasture growth was defined in terms of an annual total, and pasture quality was fixed. McCall et al. (1999) presented a comprehensive LP model of a dairy farming system in which the length of grazing rotations was optimized. However, pasture residuals, digestibility, and growth were fixed in each period to maintain tractability. Neal et al. (2007) used a detailed LP model to identify the most profitable mix of 36 alternative forage combinations on a farm in New South Wales, Australia. However, the focus on the evaluation of alternative forages meant that forage residuals, digestibility, and growth were fixed in each period. Doole (2010) extended the model of McCall et al. (1999) to incorporate a link between production and nitrate emissions from multiple farms. However, this work retained fixed pasture residuals, digestibility, and growth to maintain tractability and reduce data requirements.

The objective of this paper is to describe a nonlinear programming (**NLP**) model of a New Zealand dairy farm that incorporates several important processes within pasture-based dairy systems that are not considered in previous frameworks. The framework—the integrated dairy enterprise analysis (**IDEA**) model—is the first optimization model of a grazing system to consider (1) postgrazing residual mass as a decision variable of the producer, (2) pasture growth and digestibility that differ with residual pasture mass and rotation length, (3) pasture utilization that varies by stocking rate, and (4) different levels of intake regulation. Model output is demonstrated to match data from system experiments with reasonable accuracy given these extensions. In

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contrast, the rigidity of a less-detailed LP model containing a high number of fixed relationships is shown to restrict its predictive capacity.

Optimization allows the efficient identification of profitable system configurations, which can be time-consuming if manual trial-and-error is used, particularly in complex farming systems. Moreover, shadow prices that indicate the marginal value of different quantities are computed automatically during solution. For example, the IDEA model computes the shadow price of feed energy, the value of an additional megajoule of metabolizable energy, in all fortnights over an average year. Also, the use of constrained optimization allows the natural addition of constraints to identify how a system can optimally respond to new restrictions to farm management, such as constraints on greenhouse gas (**GHG**) emissions. However, optimization models require a certain structure and size to remain tractable. For example, it is problematic to include integer variables in nonlinear optimization models. Additionally, all meaningful mathematical models of grazing systems require a large number of assumptions to be made, given that these systems are inherently complex and dynamic (Kingwell, 2011). A key example is that most models describe farmers as profit maximizers, but in reality producers consider multiple, interacting objectives, such as risk, leisure, and sustainability.

MATERIALS AND METHODS

Model Description

This section describes a nonlinear optimization model of a New Zealand dairy farming system. The model involves a single management year defined from July 1 to June 30. The year is divided into 26 fortnights (14-d periods) to provide insight into the temporal allocation of feed. The first period follows the last in a cyclical fashion to describe decisions that span the last and first periods. The model was constructed to represent farming systems in the Waikato region of New Zealand, the primary dairy farming region in the country.

The model integrates information from a wide range of sources. Many of the coefficients are drawn from the literature and industry publications, especially DairyNZ (2010, 2011). A more detailed description of the model and the sources of model coefficients are provided in Doole et al. (2012). The IDEA model is solved with the CONOPT3 solver in the General Algebraic Modeling System 23.0 (Brooke et al., 2008).

Overview

The solution algorithm for the NLP model identifies the set of decision variables that maximizes operating profit, which is total revenue minus fixed and variable costs. Decision variables in IDEA represent the key management decisions of farmers. These include crop area, type and amount of supplement to import, lactation length, pregrazing and postgrazing pasture biomass, rotation length, silage conservation, and stocking rate. Decision variables are selected by the solution algorithm to maximize operating profit subject to the key constraints facing producers on a typical farm. Key constraints represent cost and quality of supplements, cow energy demands, cow intake, cow reproductive capacity, farm area, and the quantity and quality of pasture available under different management plans.

Feed supply consists of pasture, supplement, and crops. A fixed farm size is allocated between grazing, silage conservation, and cropping in the land use module (gray box in Figure 1) in each period. The pasture module determines the quantity and quality of grazed pasture based on residual pasture mass and rotation length decisions. A feature of IDEA is that livestock intensity and lactation length also drive pasture utilization. The supplement module (gray box in Figure 1) ensures that supplement supply and demand are balanced while accounting for different degrees of supplement utilization. The degree to which potential intake decreases with supplement intake is computed in the substitution rate module. The cow module describes the production, energy demand, and potential intake of each cow type (Figure 1). These differ for each cow type based on age, calving date, degree of intake regulation, genetic merit, and lactation length. Energy supply and energy demand are balanced within the intake constraints of the herd in the integration module, with an overall goal of maximizing operating profit, which is determined in the profit module (Figure 1).

Land Use Module

In any given fortnight, a proportion of the farm can be grazed directly by the cow herd, cut for silage conservation in spring or summer, or cropped (available crops are maize silage and turnips) at the appropriate times of the year. The model determines the optimum area allocated to each of these activities.

The length of a fortnight is $\delta = 14$ d. Time index $i = [1, 2, \ldots, 26]$ denotes the fortnight in which an area of pasture was previously grazed or harvested for silage. In comparison, time index t, where $t = [1, 2, \ldots, 26]$, denotes the fortnight in which an area of pasture is currently grazed, harvested for silage, or rested for future use. An additional index $u = [1, 2, \ldots, 26]$ is used where a (future) activity occurs in a period greater than t.