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Increasing energy and protein use efficiency improves opportunities to decrease land use, water use, and greenhouse gas emissions from dairy production

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ABSTRACT

The objectives of this study were to construct a farm-scale diet optimization model to identify opportunities to reduce land use, water use, and greenhouse gas (GHG) emissions within dairy production systems and to assess how improved energy and protein use efficiency affect opportunities to reduce these environmental impacts (EI) of dairy production systems. Non-linear programming was used to adjust monthly diets fed to 10 cattle groups to minimize EI associated with an average United States dairy farm. System boundaries extended from the inputs to the cropping system to the dairy farm gate. The effects of improved feed efficiency were modeled as a 15% decrease in maintenance energy or metabolizable protein requirements. Least-cost optimization was used as a baseline. A total of 28 scenarios were simulated which varied in objective, biological efficiency, and allowable cost increase. Objectives included minimizing land, water, or GHG emissions individually or all together. Biological efficiencies reflected either currently achieved efficiencies, improved energy efficiency, improved protein efficiency or improved energy and protein efficiency. Allowable cost increases were adjusted from 1% to 20% above baseline. Baseline land use (1.20 m^2/kg milk), water use (1.10 m^3/kg) and GHG emissions (0.70 kg CO_2e/kg) agreed with established values for U.S. dairies. Within the allowable cost range, EI metrics could be simultaneously reduced by 4.4 to 25.5%. When both energy and protein efficiency were improved, land use, water use, and GHG emission reductions ranged from 23.4 to 35.5%. Diminishing environmental returns to cost increases were apparent. Cost of achieving a 25% reduction in the environmental impacts considered in this study was decreased 78.9% when energy and protein efficiency improved compared with the national average production efficiency scenario. Improving energy- and protein-use efficiency of dairy cattle represents a promising way to reduce land use, water use, and GHG emissions without sacrificing profitability.

1. Introduction

Global population is expected to reach 9.4 billion by 2050 (U.S. Census Bureau, 2013) and demand for meat and milk is expected to rise substantially (Delgado, 2003). These global dynamics suggest a need to improve the sustainability of food production systems. Optimizing animal nutrition is one method of improving sustainability of ruminant production systems (White et al., 2014, 2015). Within U.S. dairy production, emphasis has been placed on single-target management goals such as minimizing N excretion (Kebreab et al., 2001), controlling ammonia emissions (Hristov et al., 2011) or reducing phosphorus elimination (Ghebremichael et al., 2007; Spears et al., 2003). Within the farm system, these single-target goals often require trade-offs and net increases in other important environmental metrics (Tozer and Stokes, 2001; White et al., 2014).

Whole-farm models have been constructed to better understand the whole-system environmental impact of dairy farm management (Beukes et al., 2008; Capper et al., 2009; Crosson et al., 2011; del Prado et al., 2009; Rotz et al., 2010; Shalloo et al., 2004) and have revealed a strong relationship between efficiency and reduced environmental impact (Capper and Bauman, 2013). Improving feed efficiency is one method of improving productivity. Animal nutrition research has focused on improving energy- and protein-use efficiency; however, the potential environmental benefit of these research avenues has not been well investigated.

The objective of this study was to construct a whole-farm diet optimization model to identify opportunities to reduce land use, water use and greenhouse gas (GHG) emissions within dairy production systems. A subsequent objective was to assess how improved energy- and protein-use efficiency could affect the opportunities to reduce environmental impact of dairy production systems. It was hypothesized that improved energy and protein efficiency would provide substantial opportunity to reduce land, water, and GHG emissions attributable to milk production.

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2. Materials and methods

A multi-objective optimization model (Tozer and Stokes, 2001; White et al., 2014, 2015) was developed to quantify diet cost, land use, water use, and GHG associated with dairy production systems in the U.S (Fig. 1). The model simulated a 1-year timeframe. Inputs to the model included cattle populations, weights, nutrient requirements, dry matter intake, and feed composition. The model used non-linear programming to adjust diets fed to 10 cattle groups to minimize diet cost or land use, water use, and GHG emissions per kg milk produced. The model was run using the Generic Algebraic Modeling System (GAMS; Generic Algebraic Modeling System Development Corporation, 2012). Outputs were compared to previously published estimates of U.S. dairy environmental impact. The environmental and economic benefits of improving nutrient-use efficiency were assessed by optimizing scenarios with improved energy-, protein- or energy- and protein-use efficiency.

2.1. Model inputs

2.1.1. Cattle group specifications and nutrient requirements

Animal populations were based on culling rates, conception rates, proportion of female calves and the number of mature breeding cows in the herd. In a recent survey of U.S. dairies, 82.2% of cows were managed on conventional operations (as defined by USDA/APHIS, 2007) and 90.1% were Holstein (USDA/APHIS, 2007) thus a conventional, Holstein system was modeled. Herd rolling average milk yield per cow was assumed to conform to the national average of 10,219 kg/305 d (USDA/APHIS, 2007). The equations in this model rely on set notation. Set notation applies a common equation type to a series of elements (cattle populations, feeds, etc.) where some aspect of that equation is unique to each element. All sets are comprised of a series of elements and subsets create secondary groupings of elements in a set (lactating cows within cattle populations, forages within feeds). The sets used herein, their elements, and any subsets are listed in Table 1. Equations and key input parameters governing animal populations are included in Table 2. Cows that failed to conceive were assumed to be culled annually. Culling rate was assumed to increase with age, and cows were culled entirely from the herd at 60 m of age. The resultant average culling age was 38 m of age which is representative of the average U.S. culling rate (USDA/APHIS, 2007).

Net energy and metabolizable protein requirements of the cattle groups were calculated based on National Research Council (2001) nutrient requirements of dairy cattle. Diets were also balanced to ensure sufficient macro (Ca, P, Mg, Cl, K, Na, and S) and micro (Co, Cu, I, Fe, Mn, Se, Zn) mineral and vitamin (A, D, E) supplies. Requirements of minerals and vitamins were calculated following the recommendations of the National Research Council (2001) nutrient requirements of dairy cattle model.

Several nutritional constraints were included in the model (Table 3). Diets were balanced for 10 animal groups (a) on a monthly (m) basis. Each diet needed to contain nutrient (n) concentrations greater than or equal to the required amount (Req) of each nutrient (n). The amount of a nutrient provided in the diet was the product of dry matter intake (DMI) and the concentration of the nutrient ($Conc$) in the diet. Total feed consumption needed to be less than the maximum consumption ($MaxDM$) predicted by National Research Council (2001). Practicality constraints were included to limit the maximum amount of a feed ($UpLim$) that could be included in the diet. Additionally, minimum dietary acid detergent fiber (ADF) concentrations were constrained to ensure that realistic balances of forages and concentrates were included.

Environmental calculations are detailed in Table 4. Environmental impacts from animals within the model included enteric and manure CH_4 emissions along with direct, leached and volatilized N_2O emissions. An equation presented in Moe and Tyrrell (1979) was used to predict enteric CH_4 emissions because this equation was more accurate and precise than other CH_4 predictions when evaluated against literature data (Ellis et al., 2010). Tier II methods of the IPCC (2006) were used to calculate manure CH_4 and all N_2O emissions. Manure emission factors (Table 5) were averaged based on the use of manure management systems in the U.S. (USDA/APHIS, 2007). Nitrogen excretion (NE) was calculated based on milk yield and crude protein concentration in the diet with functions specific to stages of production (ASAE, 2005; Thoma et al., 2013b). Greenhouse gas emissions associated with infrastructure ($CO2i$) were based on electricity use for housing, milk cooling and storage following the values from Capper et al. (2008) and the carbon emissions for generation of electricity in the U.S. (0.18 kg CO2-equivalent/kWh; Davis and Diegel, 2010). Drinking water consumption

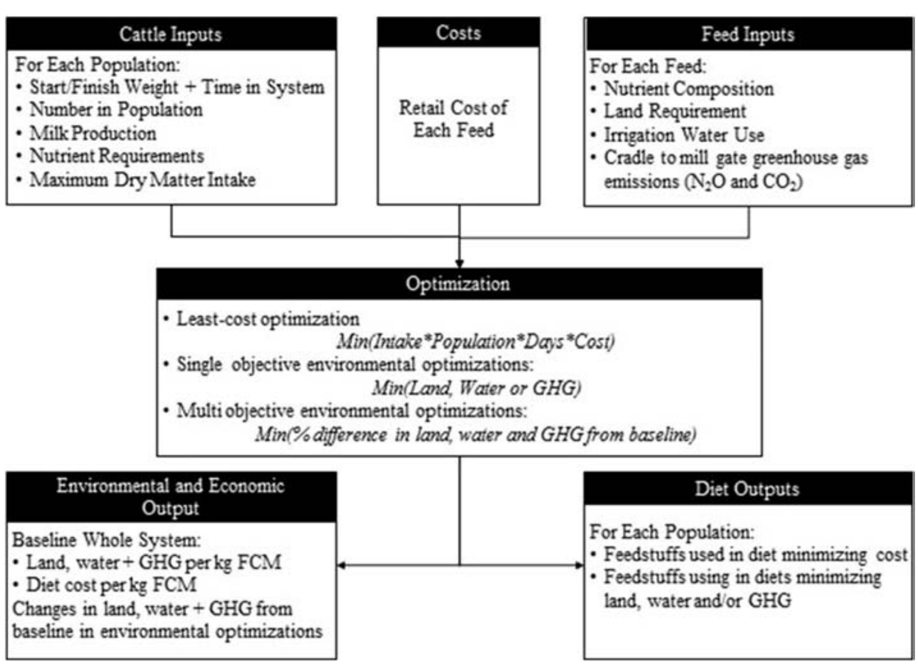

Fig. 1. Representation of dairy farm optimization model.