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Optimizing diet and pasture management to improve sustainability of U.S. beef production

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ABSTRACT

System sustainability balances environmental impact, economic viability and social acceptability. Assessment methods to investigate impacts of enterprise management and consumer decisions on sustainability of beef cattle operations are critically needed. Tools of this nature are especially important given the predictions of climate variability and the dependence of beef production systems on forage availability. A model optimizing nutritional and pasture management was created to examine the environmental impact of beef production. The model integrated modules calculating cradle-to-farm gate environmental impact, diet cost, pasture growth and willingness to pay (WTP). Least-cost diet and pasture management options served as a baseline to which environmental-impact reducing scenarios were compared. Economic viability was ensured by a constraint limiting change in diet cost to less than consumer WTP. Increased WTP was associated with improved social acceptability. Model outputs were evaluated by comparing to published data. Sensitivity analysis of the WTP constraint was conducted. A series of scenarios then examined how forecasted changes in precipitation patterns might alter forage supply and opportunities to reduce environmental impact in three regions in the United States. On a national scale, single-objective optimization indicated individual reductions in greenhouse gases (GHG), land use and water use of 3.6%, 5.4% and 4.3% were possible by changing diets. Multi-objective optimization demonstrated that GHG, land and water use could be simultaneously reduced by 2.3%. To achieve this change, cow–calf diets relied on grass hay, continuously- or rotationally-grazed irrigated and fertilized pasture as well as rotationally-grazed pasture. Stocker diets used rotationally-grazed, irrigated and fertilized pasture and feedlot diets used grass hay as a forage source. The model was sensitive to consumer WTP. When alternative precipitation patterns were simulated, opportunities to decrease the environmental impact of beef production in the Pacific Northwest and Texas were reduced by precipitation changes; whereas opportunities in the Midwest improved. Economic viability, rather than biological limitations, reduced the potential to improve environmental impact under future precipitation scenarios. Decreased spring rainfall resulted in lower pasture yields and required greater use of stored forages. Related increases in diet cost reduced opportunities to appropriate funds toward investment in environmental-impact reducing pasture management strategies. The model developed in this study is a robust tool that can be used to assess the impacts of enterprise management and consumer decisions on beef production sustainability.

1. Introduction

Trends in global population, meat demand, and resource availability support the need for improved sustainability of livestock production (Delgado, 2003; Falkenmark et al., 2009; Lambin and Meyfroidt, 2011; U.S. Census Bureau, 2013; United Nations, 2011). Whole-farm models have been used as tools to identify management effects on environmental impact with and without concurrent assessment of economic viability (Beauchemin et al., 2011; Capper and Hayes, 2012; Clarke et al., 2013; Foley et al., 2011; Nguyen et al., 2013; O'Brien et al., 2013; Rotz et al., 2013; Stackhouse-Lawson et al., 2012; Veysset et al., 2010; White and Capper, 2013). These whole-farm assessments have been extensively reviewed (Crosson et al., 2011; Del Prado et al., 2013; Schils et al., 2007). Although the incorporation of economic

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viability is occurring more frequently, true sustainability balances environmental impact, economic viability and social acceptability (WCED, 1987) and this third component has not yet been included in assessments.

A comprehensive examination of the biological relationships governing agricultural sustainability suggested that improving forage quality and nutrient use efficiency will substantially improve the environmental impact of livestock production (FAO, 2013). Assessment of the economic and social implications of these strategies has not been conducted to-date. This omission may be in part because of the variability inherent in social and biological systems. Consumers' interest in, and willingness to pay (WTP) for, products varies substantially with population demographics and product attributes (e.g. Dickinson and Bailey, 2005; Lusk et al., 2003; Tonsor et al., 2009; Umberger et al., 2009). Although previous studies showed consumers were willing to pay more for meat produced with reduced resource use and greenhouse gas (GHG) emissions (Blecher et al., 2007; Hurley et al., 2006; White and Brady, 2013), it is unknown whether this WTP would be sufficient to offset potential increases in operating costs associated with improving forage quality and nutrient use efficiency. Future climate projections indicate additional uncertainty exists in the form of increasing climate variability (Millennium Ecosystem Assessment, 2005). Increased climate variability is expected over the next century (IPCC, 2007), and since forage quality is partially dependent on temperature, humidity and rainfall (Porter and Semenov, 2005); the opportunities to improve forage quality in the face of altered weather conditions may limit the effectiveness of management changes to enhance sustainability. Whole-farm models have been used to assess the implications of climate change on livestock production and profitability (Bell et al., 2012a; Cullen and Eckard, 2011; Del Prado et al., 2013); however, social acceptability assessments are also missing from this body of literature.

The objective of this study was to create a model to optimize nutritional management of beef cattle to minimize land use, water use and GHG from U.S. beef production in an economically viable and socially acceptable manner. A secondary objective was to use the model to examine the impact of altered precipitation patterns on opportunities to improve beef sustainability. It was hypothesized that projected changes in rainfall would decrease forage availability and reduce opportunities to change management to improve beef sustainability.

2. Materials and methods

A model was constructed by integrating whole-system environmental impact and economic production cost modules (White and Capper, 2013), a pasture module (Romera et al., 2009) and a module estimating social acceptability using a meta-regression estimating consumer WTP (White and Brady, 2013). The model is depicted in Fig. 1 and was run by a stepwise procedure simulating a 1-year timeframe. Inputs (cattle populations, weights, nutrient requirements, dry matter intake and feed parameters) were generated, least-cost optimization was conducted as a baseline, single and multi-objective environmental scenarios were optimized and compared to the least-cost scenario. Optimizations used non-linear programming to adjust cattle diets to achieve the target objective subject to biological, practical and consumer-driven constraints. Each optimization outputted land use, water use, GHG emissions and diet cost per kg of hot-carcass-weight (HCW) beef in addition to the feedstuffs identified as optimal diets. The model was run using the General Algebraic Modeling System (GAMS; Generic Algebraic Modeling System Development Corporation, 2012). Outputs were compared to previous peer-reviewed, published estimates of land use, water use and GHG emissions to assess model accuracy. Model sensitivity to WTP estimates was determined by varying the inputted WTP value.

2.1. Model inputs

2.1.1. Cattle group specifications and nutrient requirements

A total of 16 populations were simulated in the model: 4 calf populations (steers, heifers, replacement heifers and bulls), 2 replacement heifer populations (8–15 m and 16–24 m), 2 mature cow populations (24–48 m and 48 m and older), 4 bull populations (8–12 m, 13–24 m, 25–48 m and 48 m and older) 2 growing stocker cattle populations (8–12 m steers and heifers) and 6 growing cattle populations (8–16 m calf-fed steers and heifers; 12–16 m yearling-fed steers and heifers; 6–16 m dairy-origin steers and heifers). Five key parameters were calculated for each group: start weight, finish weight, average weight, average daily gain and population. Populations were calculated following the equations in Table 1 and the rate constants given in Table 2.

Energy and protein requirements to meet maintenance, growth, gestation and/or lactation needs were calculated using the NRC (2000) equations. Energy, protein and predicted dry matter intake were determined on a monthly basis for each group considering changes in body weight and production stage. Cattle groups remained in the model between 4 and 12 months. Nutrient requirements and maximum dry matter intake were averaged over the months an animal group remained in the model and were used by the optimizer as constraints to ensure adequate nutrients for production.

2.1.2. Crop and pasture production parameters

Each run of the optimizer adjusted feedstuffs used in cattle diets to achieve an objective. Individual feedstuff nutrient composition, yield, irrigation and GHG emissions were inputs to the model. For non-pasture feeds, nutrient composition was sourced from the AMTS CattlePro Feed Library (AMTS, 2006). National average yield (USDA/ERS, 2012) and irrigation data (USDA/NASS, 2007) were used for land and water requirements and GHG emissions per ha were sourced from Nelson et al. (2009) and West and Marland (2001). Currently available national average pasture data from the U.S. were insufficient to describe the variety of pasture management options available and were inadequate as inputs into multi-objective optimization (White et al., 2013).

To describe the variety of pasture management systems available, pasture yield and nutrient contents were therefore simulated by the McCall pasture model (McCall and Bishop-Hurley, 2003) as updated by Romera et al. (2009). The McCall model was parameterized and validated for U.S. pasture production as described in Appendix A. Continuous grazing, fertilization, irrigation or irrigation and fertilization were considered. The validation procedure indicated that the parameterization procedure was sufficient to adjust model outputs to simulate U.S. pasture yields under these management strategies. The validation RMSPE was 8% for continuously-grazed pasture, 15% for irrigated pasture, 13% for fertilized pasture and 11% for irrigated and fertilized pasture.

To generate the pasture inputs used in the optimization, the spatial variability in pasture yields needed to be accounted for. Over 7200 total plant growth curves representing pastures in the ten U.S. states with the largest yearly calf crops (USDA/ERS, 2012) were sourced (USDA/NRCS, 2012). Average daily weather data for each state was sourced from NCDC (2012). After uploading the appropriate weather data, the Solver function of Microsoft Excel 2010 was used parameterize the McCall model to simulate each of the available growth curves under eight different management treatments: continuously grazed (C), irrigated continuously grazed (C-I), fertilized continuously grazed (C-F), irrigated and fertilized continuously grazed (C-IF), rotationally grazed (R), irrigated