THE DEVELOPMENT OF A MODELING PLATFORM TO EXAMINE MANAGEMENT ALTERNATIVES TO IMPROVE THE SUSTAINABILITY OF BEEF PRODUCTION

By

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THE DEVELOPMENT OF A MODELING PLATFORM TO EXAMINE MANAGEMENT ALTERNATIVES TO IMPROVE THE SUSTAINABILITY OF BEEF PRODUCTION

ABSTRACT

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The objective of this research was to develop a modeling platform to test the effects of management practices on sustainability of beef production systems. A simulation model was constructed to examine the role of improved efficiency on environmental impact (land use, water use and greenhouse gas emissions; EI) of beef production systems while increasing economic viability and consumer willingness to pay (WTP). An optimizer was developed to adjust cattle diets to minimize whole-system EI while constraining production costs within the bounds of consumer WTP. Cradle-to-farmgate EI and production costs were calculated following the simulation model. Consumer WTP for environmental attributes of beef was determined by meta-regression of published estimates of consumer WTP. The validated model was then used to assess how nutritional, reproductive and genetic management could help improve sustainability. Nutritional management alone reduced EI by 2%. Twinning or decreasing the calving window decreased EI by 17% or 11%. Selected bulls by expected progeny difference reduced EI by 18%-19%. Finally, Bayesian analysis was used to quantitatively summarize consumer WTP for environmental attributes of meat. The model predicted U.S. consumers WTP ranged from 6.7%
to 32.6%. The confidence range was used to predict probability of consumer purchase across the schedule of WTP. When probability of purchase was ignored, this range in WTP equated to a maximum 65.5 L/kg beef reduction in water use when beef cattle diets were adjusted. When probability of purchase was factored in, a 10% increase in WTP optimized theoretical opportunity to decrease EI, netting a 41.4 L/kg beef reduction in water use. A novel model was successfully developed and used to assess the role of specific management practices and their use in improving beef production sustainability. Optimizing nutritional management, including reliance on precision pasture management, while concurrently improving genetic and reproductive efficiency, substantially improved sustainability. Additionally, when relying on WTP as a method of incentivizing adoption of environmental-impact reducing management practices, focus should be put on obtaining market share rather than sacrificing cost in an attempt to reach the biological ideal opportunity to minimize environmental impact.
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DEDICATION

“Half the world is composed of people who have something to say and can’t, and the other half who have nothing to say and keep on saying it.” – Robert Frost

This dissertation is dedicated to my friends and family, both at home and at university, who provided me with their invaluable support as I attempted to learn to be a person who has something to say and is able to say it.
CHAPTER 1

INTRODUCTION
The global population is expected to reach 9.3 to 9.4 billion by the year 2050 (U.S. Census Bureau, 2008). Along this same timescale, improved affluence in developing nations is expected to increase global demand for meat and milk (Cranfield et al., 1998; Delgado, 2003). Globally, land and water availability are already limited (Gomiero et al., 2011; Hertel, 2011), as a result, concern exists about the opportunity to rely on food production, as it currently functions, to meet this demand increase. Agricultural food production also contributes to atmospheric concentrations of greenhouse gases like methane (CH\(_4\)), nitrous oxide (N\(_2\)O) and carbon dioxide (CO\(_2\); U.S. EPA, 2010). The current challenge requires food production to improve land and water use efficiency and decrease GHG emissions while developing adaptive capacity in the face of climate variability (Nardone et al., 2010). A commonly proposed solution to these challenges is to improve “sustainability” of food production systems (Gomiero et al., 2011). Sustainability is defined as a balance between social acceptability, environmental responsibility and economic viability (National Research Council, 2011, 2013; WCED, 1987). By improving sustainability, ideally, the environmental impact of a system can be reduced so that societal demands for food can be met within the bounds of resource availability and climate conditions.

Beef production in the United States (U.S.) is a socioeconomically valuable system (USDA/ERS, 2013a). The U.S. is not only the largest net consumer of beef globally, but it also houses the largest fed cattle industry in the world (USDA/ERS, 2013a). The beef production system is comprised of three sectors: the cow-calf, stocker and feedlot. Cow-calf operations breed cows and bulls and sell weaned calves. Stocker operations purchase weaned calves, feed them and sell yearlings. Feedlots purchase weaned calves from cow-calf operations, cull dairy calves or yearlings from stocker operations and market finished animals for harvest. Studies cataloging the environmental impact of each sector find that the cow-calf sector is responsible for the greatest
portion of environmental impact, largely because cows are retained in the system year round while the stocker and feedlot populations are transient and their maintenance population is held mainly in the cow-calf sector (Beauchemin et al., 2010).

Many approaches have been taken to identify methods that improve environmental impact of U.S. beef production systems. On farm management practices to reduce CH₄ or N₂O from cattle have been thoroughly investigated (Beauchemin et al., 2008; Boadi et al., 2004; Buddle et al., 2011; Dalal et al., 2003; Eckard et al., 2010; Kebreab et al., 2006; Luo et al., 2010; Saggar et al., 2004b; Webb et al., 2010). These studies identified pasture, manure, nutritional or reproductive management practices that can be employed on-farm to reduce emissions of one or more GHG. Whole-farm models have also been used to assess opportunity to improve beef production sustainability (Crosson et al., 2011b) and these models are efficient because they frequently assess multiple environmental impact metrics (Beauchemin, 2013; Beauchemin et al., 2011; Nguyen et al., 2013; Pelletier et al., 2010; Ridoutt et al., 2011). In addition to comparing management practices (Beauchemin et al., 2011; Nguyen et al., 2013), whole-farm models are often used to assess different production systems (Capper, 2011a, 2012; Foley et al., 2011; Stackhouse-Lawson et al., 2012). In many cases, whole-farm modeling studies have linked improved efficiency with improved environmental impact per kg product (Capper and Bauman, 2013).

Sustainability balances economic, environmental and social concerns, therefore, assessments of sustainability should encompass metrics for each of these areas of focus. Some whole-farm studies have integrated assessment of economic viability with environmental impact (Capper and Hayes, 2012; Stackhouse et al., 2012). However, studies have not yet incorporated metrics of
social acceptability. Before the sustainability of beef production can be improved, a methodology integrating these metrics must be developed and used to assess the relative impacts of management on the sustainability of production systems.

Beyond the horizon of identifying management to improve sustainability, research must identify efficient methods of incentivizing adoption of these management strategies. Top-down regulatory policies based on incentivizing or penalizing management are frequently cost-prohibitive at the farm level (McCarl and Schneider, 2001; Varela-Ortega et al., 1998). Incentivizing adoption of environmentally-oriented management practices through harnessing consumers’ willingness to pay (WTP) for products with reduced environmental impact has not been explored. Although consumer WTP for a good with perceived environmental benefits has been assessed (Corsi and Novelli, 2002; Gil et al., 2000; Napolitano et al., 2009; Tonsor and Shupp, 2009; Umberger et al., 2009a), few studies have focused on pure environmental labels. Additionally, the variability in methodologies associated with estimating WTP makes it difficult to compare across the literature to procure a robust estimate of WTP (Lusk et al., 2004; Lusk et al., 2005).

The overall objective of this research was to examine opportunities for enhancing the sustainability of whole system beef production systems by optimizing management practices.
LITERATURE CITED


alternative land use on environmental impacts of beef cattle production systems. Animal
1: 1-10.

NRC. 2013. Sustainability for the Nation: Resource Connection and Governance Linkages. The
National Academies Press.
of three beef productions strategies in the Upper Midwestern United States. Agr. Syst.
103: 380-389.
for beef cattle production in southern Australia. Sustainability 3: 2443-2455.
methane, ammonia, and nitrous oxide from animal excreta deposition and farm effluent
footprint and ammonia emissions of California beef production systems. J. Anim. Sci. 90:
4641-4655.
decrease the carbon footprint, ammonia emissions, and costs of California beef
Tonsor, G. T., and R. Shupp. 2009. Valuations of 'sustainably produced' labels on beef, tomato,
Bureau, Washington, D.C.


CHAPTER 2

REVIEW OF THE LITERATURE
THE FOOD PRODUCTION CHALLENGE

Between 1950 and 2012, the global human population increased from 2.55 billion to 7.02 billion people and the population is predicted to reach 9.3 to 9.4 billion by 2050 (U.S. Census Bureau, 2013; United Nations, 2011). This growth is predicted to alter world population demographics in unprecedented ways. In 2050, the average age is predicted to increase (Cohen, 2003). Historically, older populations have been correlated with economic depression due to reductions in the labor force but the current ageing of the world population is not predicted to impede economic growth in developing countries (Bloom et al., 2010). In fact, the predicted trends in economic growth are so positive that they suggest a dietary shift will take place, moving the diets of people in developing nations from primarily grain protein sources to primarily livestock protein sources (Cranfield et al., 1998). Consumption of meat and milk in developing nations is expected to increase with improved affluence. Delgado (2003) estimated global demand increases of 107 and 177 million metric tons of meat and milk between the period from 2000 to 2020.

Increased global demand for meat and milk challenges livestock production industries to increase supply which will require land and water availability. By 2050, it is predicted that food demand will outpace water availability in most regions of the world resulting in water shortages for human consumption and for food production (Falkenmark et al., 2009). Several regions of the world are already experiencing water scarcity (Vorosmarty et al., 2000).

Increased demand for livestock products and decreased availability of water for food production is likely to exacerbate land scarcity. Competition for arable land is already occurring as only
about 30% of the ice-free land area of the globe is suitable for agriculture (Lambin and Meyfroidt, 2011). It is frequently questioned whether the population will grow to a point that humans will run out of land for food production. In a response to this fear of “the perfect storm”, Hertel (2011) noted that the question should not be whether we will run out of land for agriculture but rather, what the cost of agricultural land will be. Scarcity will increase land costs which in turn will equate to an increase in the cost of food produced on that land.

In their essay on feeding the growing world population, Conway and Toenniessen (1999) suggested that the rising demand for food will not be met unless crop biotechnology is used. Genetic modifications to crops have been developed to allow herbicide resistance, improved growth, or growth stimulation during the normal senescent season. Socially-driven condemnation of crop biotechnology exemplifies another challenge to food system expansion. A food supply that is socially unacceptable will be just as unsuccessful in feeding the world as a system that is unaffordable.

The Merriam-Webster dictionary defines sustainability as “capable of being kept up or prolonged”. Alternative definitions of sustainability include: a system balancing social acceptability, economic viability and environmental impact (National Research Council, 2011); ensuring the well-being of future generations through responsible resource use (Kuhlman and Farrington, 2010; National Research Council, 2013); or a system able to maintain its organization and vigor in the face of external stress (Costanza et al., 2009). Although sustainability has many definitions, several of these definitions have common themes. The conceptual or theoretical definition of sustainability should be based on what society requires of
a food system, namely to provide an economical, socially-acceptable supply source that is produced with minimal impact on the external environment.

Defining sustainability is vital for two reasons. Without a unified, concrete definition of the qualities of a sustainable system advice to producers about how to improve sustainability will be conflicting. Some recommendations advocate that more concentrated animal production facilities are not sustainable (Tilman et al., 2002); however, other literature asserts that these facilities are more efficient and therefore more sustainable (Capper, 2011a). Furthermore, until we can define sustainability quantitatively, our understanding of the concept will not be scientific (Stine, 1992). Defining sustainability mathematically will allow for measurable benchmarks and quantifiable improvements. A two part solution is required. A theoretical definition of sustainability must be converged upon and a quantitative definition, informed by the theoretical definition, must be developed.

Although the concept of sustainability has existed for several centuries, it was first given a name by forestry professionals in the early 1700’s when it referred to limiting harvest to what a forest could yield in new growth (Wiersum, 1995; Wilderer, 2007). Sustainability did not become an important policy concept until fears of excessive resource use drove the publication of a report by the United Nations World Commission on Environment and Development (WCED, 1987). The Brundtland Report, as it is more commonly known, states that “sustainable development must be conceived and executed by processes that integrate environmental, social and economic considerations” (WCED, 1987). Since this publication, the exact definition of sustainability as it applies to a variety of related disciplines has been debated extensively (e.g. Bonevac, 2010; Chichilnisky, 2011; Costanza et al., 2009; Kuhlman and Farrington, 2010) such that the term has
almost ceased to have any practical meaning (Marshall and Toffel, 2005).

A useful definition of sustainability will answer the question “how will we work within the biological and ecological constraints of production systems to generate an economical, socially-acceptable source of food?” This question indicates that sustainable production systems are those that work within biological and ecological constraints to generate an economical and socially-acceptable source of food for the populations of today and tomorrow. This definition is in line with those proposed previously by Chichilnisky (2011); Costanza et al. (2009); Kuhlman and Farrington (2010); and WCED (1987). The definition borrows the concepts of social, economic and environmental considerations from the Brundtland Report and others (National Research Council, 2011, 2013). Furthermore, it focuses on the importance of the longevity of a production system following other proposed definitions (Costanza et al., 2009). The conceptual definition is broad enough to encompass all sizes and systems of production but specific enough to allow for quantifiable metrics.

Quantifying Sustainability

The quantification of sustainability is not a novel concept. In ecological literature, several different methods of measuring sustainability have been developed. Ecological measurement methodologies frequently rely on physical assessment of the system in question and scoring based on a series of indicators related to environmental quality, human responsiveness to environmental damages (OECD, 1994) or human wellbeing (INUC/IDRC, 1995). Alternatively, in economic literature, Neumayer (2003) noted that most economists would define sustainability as “development that does not decrease the capacity to provide non-declining per-capita utility for infinity”. Although this has been the traditional definition, more recently, economic
performance of a business is often considered in conjunction with its social and environmental performance (Steg et al., 2003).

Ecological assessment of sustainable systems relies on measuring a series of indicator variables specific to a system while economic assessment relies on trends derived from aggregated datasets. The OECD developed an international comparison of environmental indicators based on measurements of environmental quality, environmental state indicators and human response indicators to environmental damages (OECD, 1994). Two downsides of this approach are the cost of measuring 40 indicators and the subjectivity associated with indicators like “human response to environmental damages”. Economic approaches can remedy those issues – deriving trends from data is usually inexpensive (provided the data is available) and is strictly mathematical, leaving no room for subjective interpretation. A disadvantage of economic analysis of sustainability is the specificity of location and scale in assessment. Sustainability analysis of a firm can be conducted just as sustainability analysis of an industry can be conducted; however, applying conclusions from analysis of a firm to a whole industry is inappropriate, as is the converse.

Importantly, the Brundtland report notes that the issues related to developing sustainable solutions are too complex, and the solutions to the issues are too diverse, for a concrete plan to be developed outlining a progression forward. One way to cope with complexity and diversity in systems is the development of tools that are sufficiently robust and flexible to explain the system’s dynamics. Although this is less feasible on a global scale (developing a model of global sustainability) it becomes more realistic when the system in question is clearly specified. In this case, the system of interest is the U.S. beef industry. To develop a tool capable of quantifying the
sustainability of the U.S. beef industry, ideas from previous quantifications should be integrated. Ecological frameworks of sustainability have illustrated the need for selection and quantitative definitions of various sustainability indicators. Economic frameworks have illustrated the need for cost-effective mathematical analysis of aggregated datasets. Together, these trends indicate that a systems model should be developed to quantify various metrics of sustainability of the U.S. beef production system. Before such a model can be developed, it is necessary to understand what mathematical models are, how they can be used to generate quantitative data and test research hypotheses.

**BIO-MATHEMATICAL MODELING**

Dym (2004) defined a mathematical model as a representation of the behavior of real devices and objects in a mathematical manner, noting that mathematical modeling is a cognitive activity. Mathematical models have been classified in multiple ways and can be used at various levels of specificity. Thornley and France (1984) identified a three-part classification scheme for mathematical models. Models can be dynamic or static; deterministic or stochastic; and mechanistic or empirical.

A static model does not incorporate time. Dynamic models simulate a system’s dynamics over a determined time period usually by utilizing differential equations. As a result, dynamic models can trace the impact of previous management decisions on future performance (Baldwin, 1995). Static models require parameterization with values representing a specific set of conditions that exist at one point in time (Baldwin, 1995) and therefore are limited in their utility because their output is only valid for the system described by the parameters inputted. However, static models are easier to use because they are less complex than dynamic models.
Deterministic models have exact solutions; they have no quantification of the variability around an answer. In comparison, stochastic models specifically quantify the variability of a value around a mean. In animal modeling, deterministic models refer specifically to the average animal in a population while stochastic models simulate whole-population attributes (Mendelssohn, 1978). Deterministic models are advantageous when describing a population average; however, the lack of variability in outputs may inadequately describe the system. Lucas (1964) identified that the primary goal of biology was to explain variability in a system. Stochastic models achieve this goal by quantifying system variability. Stochastic models are more complex to develop because the system variability must be tracked along with the overall population mean.

The distinction between mechanistic and empirical modeling was first described by Riggs (1963). Empirical models rely on equations that have been fit to experimental data, frequently serving to relate two variables through indirect observation of system input/output dynamics. When intermediate variables (variables that drive dynamics between the input and output points) are not incorporated into quantification, a model can fail to accurately predict system behavior under alternative initial conditions. Mechanistic models attempt to avoid this pitfall by describing the direct mechanism of interaction within a system through the inclusion of intermediate variables. Mechanistic models are not derived from experimental data but rather, they are based on theory or hypothesis about the nature of the system (Riggs, 1963).

Models have both a type and a level of specificity. Thornley and France (1984) proposed the classification of model specificity level based on the system described. The animal-level is the base level of aggregation and when expanded upward models can describe a herd of animals. At more focused levels of specificity, models can describe organs, cell types, etc. Baldwin (1995)
offered several useful generalizations about the link between aggregation level and model type. Empirical models frequently focus at the animal level and use empirical analysis based on regression equations to link management decisions to animal performance. Mechanistic models describe equations at a more specific aggregation level (organ, tissue or cellular levels).

Modeling is a cognitive activity that can be carried out within the human mind due to our unique ability to formulate concepts and hypotheses; however, the human mind has a limited ability to tract quantitative trends over spatial or temporal scales. Therefore, computer tools are frequently used to overcome the limitations of the human mind (Baldwin, 1995; Forrester, 1971). Whether developing a model by hand or with the help of a computer-based model development tool, it is necessary to follow a step-wise procedure. Several different modeling processes have been outlined but one particularly oriented at mathematical modeling in animal science was presented by Dent and Anderson (1971) and advocated in Baldwin (1995). The steps of this process are as follows:

Identify the modeling objective

As with any experiment, the objective statement drives the focus of the research and should be concise and clear (Baldwin, 1995). The function of the objective statement is to define the type of model, the process that must be accommodated within the block diagram, and the evaluation criteria of the model (Baldwin, 1995).

Construct a block diagram identifying essential elements of the system and their interactions

Block diagrams are used to pictorially represent complex interactions within a system. Although commonly done informally, there is a formal symbolism (Baldwin, 1995). State variables, the
base of the diagram, are depicted by boxes. Arrows and circles are used to represent the flow of material from these boxes and user specified inputs to the model, respectively. A valve or a single dot represents a control point. Solid lines connected to valves represent known influences that should be incorporated as the complexity of the model increases.

**Formulate mathematical statements describing the relationships between elements**

Block diagrams are developed to help organize equations according to goals outlined by the objective (Baldwin, 1995). Several different equation types can be used. Mass action equations calculate the flow of material from one state to another and depend on a rate constant or flux parameter. Possibly the best known mass action equation is the Michaelis-Menten equation which specifies the velocity of substrate movement according to a maximum velocity, a rate constant and substrate concentrate. Saturation kinetics are modeled as a zero-order process where substrate movement is equivalent to the maximum velocity of movement of that substrate. These equation forms are most applicable to metabolic modeling. Mining the literature for previously published equations is another method of deriving mathematic relationships between variables.

**Collect numerical data required to parameterize the mathematical statements**

Parameterization of model relationships is vital. The parameterization process adjusts parameters within mathematical statements to best fit either experimental or mined data. Data for parameterization can be mined from previously published literature, sourced from aggregated databases or experimentally derived. Alternatively, parameterization can be used to adjust an equation output to fit a general curve with an appropriate shape. Parameterization can be conducted by manual manipulation of equation parameters or through an optimization. Linear or non-linear optimization procedures can be used to adjust parameters to best fit experimental data.
Solve, evaluate and verify the model with relation to the objective outlined.

After parameterization, the model should be solved. Before the output is suitable for publication, it should be evaluated and verified according to the criteria outlined in the objective function (Baldwin, 1995). Validation should not be conducted with the same data that was used for parameterization because this can lead to false confidence about the predictive power of the model (Ford, 2009). Validation is extremely important; however, confusion exists about the meaning of validation in the context of simulation models. Validation is not a method to test scientific theory or certify outputs as scientific truth (Rykiel, 1996). The purpose of validation is to affirm that the model is acceptable for its intended use. Specifically, validation ensures that the model meets performance requirements specified in the objective statement (Rykiel, 1996). Although no one verification method is widely accepted as ideal (Banks et al., 1988), several techniques are widely acknowledged as suitable for evaluating a model (Sargent, 1985). Conceptual assessment has been proposed as a means of model validation (Ford, 2009); however, it is more appropriately understood as an integral part of the iterative process that is model development (Brown and Kulasiri, 1996). The purpose of conceptual validation is to ensure the model appears to represent the behavior of the system and is important precursor to subsequent, more vigorous, validation procedures. Face validation is accomplished by presenting model outputs, structure and/or equations for the scrutiny of a field expert. After an expert has verified the model structure and output, numerical validation can take place. Although classified as a type of validation, this procedure is extremely subjective and is not a sufficient ratification of model performance when employed alone. True validation procedures must be objective. There are several objective validation methods. The robustness of a model can be tested through sensitivity analysis, extreme-condition tests, degenerate tests and event validity. Model
agreement with measured data can be tested through concordance coefficients, correlation coefficients, root mean squared error of prediction or other numerical assessment methods. Sensitivity analysis can be conducted in at least a dozen different ways (Hamby, 1994). The simplest method is to repeatedly vary one parameter at a time while holding all others fixed (Gardner et al., 1980). This is a limited approach because it only addresses sensitivity relative to the point estimates chosen rather than sensitivity of the entire feasible parameter distribution. This limitation can be overcome by utilizing a sensitivity index and calculating the percent change in output when each input is varied from its minimum to its maximum value (Hoffman and Gardner, 1983). Differential analysis is another comment method during which a sensitivity coefficient (the ratio of the change in output to the change in input) is developed for each input and compared across inputs to identify the most sensitive. Differential analysis is commonly used in dynamic models but the specific requirements of equation structure for differential analysis make this method cumbersome for empirical or static models. Factorial analysis, another method of sensitivity assessment, is conducted by choosing a given number of samples for each parameter and running the model for all combinations of the samples. Factorial sampling is limited because the number of trials required for thorough examination of a large model requires an excessive number of model runs. Each of these methods can be used to identify which input variables are the most sensitive in the system.

Extreme-condition testing can be used to identify the ability of the model to retain behavioral simulation patterns in the presence of an extreme condition (Ford, 2009). If knowledge about behavior during extreme conditions is incorporated, model behavior under normal operating conditions is generally improved (Forrester and Senge, 1979). Extreme condition testing focuses on state variables rather than inputs and identifies output implications when each state variable
holds a hypothetical maximum or minimum value for some period of time. This test allows for
the discovery of flaws in the model structure stemming from incorrectly specified relationships
and illuminates when important variables have been excluded from model formulation (Ford,
2009).
Degenerative tests address the changes in model behavior when portions of the model are
removed and substituted for input variables (Sargent, 1991). Degenerative tests help to identify
whether the model correctly simulates the breakdown of a system. Degenerative testing is a
variant of extreme-condition testing.
Event validity is the comparison of model outputs to real data (Sargent, 1991). This assessment
can be based on visual or numerical assessment of the agreement between modeled outputs and
real data. Numerical assessments include concordance correlation, correlation coefficients or root
mean squared error of prediction. The concordance correlation coefficient was defined by Lin
(1989) and measures the deviation of each data point from the line y=x when modeled data is
graphed against measured system data. Correlation coefficients such as Pearson’s product-
moment correlation coefficient (r) and its square the coefficient of determination ($R^2$) explain the
variability in a data set explained by a model. These correlation coefficients are particularly
sensitive to extreme values and under-sensitive to additive and proportional differences between
model predictions making them less robust indicators of the performance of a model (Legates
and McCabe, 1999). Root mean squared error of prediction is calculated as the square root of the
squared sum of deviations between modeled outputs and experimental data. Root mean squared
error of prediction is a convenient and practical term because it uses the same units as the model
output variable. Similarly, it is not as sensitive to outliers as traditional correlation coefficients.
The root mean squared error of prediction is one of the most common quantitative measures of model validity used in animal science.

Each of these methods can be used to validate or assess a model. After validation/assessment is conducted, the model structure must be amended until the validation and assessment indicate that the model is suitable to meet the original research objective (Baldwin, 1995). Several mathematical models of environmental impact, economic viability or social acceptability have been published previously. Before compiling these quantifications into one comprehensive model, different existing models should be assessed and the physical occurrences they explain should be understood. As such, it is important to understand the structure of the beef production system in the U.S. as well as metrics of environmental impact, economic viability and social acceptability from this system.

**BEEF PRODUCTION**

Between 2009 and 2013, the U.S. was responsible for approximately 1/5 of global beef production and was the largest beef producing country in the world (USDA/ERS, 2013a). Domestic beef consumption in the U.S. is also larger than consumption in any other country (USDA/ERS, 2013a), and exceeds domestic pork (USDA/ERS, 2013c) or poultry consumption (USDA/ERS, 2013b). The animal agriculture industry in the U.S. employs over 1 million people between animal food manufacturing, animal production and animal processing (Bureau of Labor Statistics, 2014). This production system is of substantial economic and social importance.

**System Structure and Key Entities**

Cow-Calf
The U.S. houses the world’s largest fed cattle industry and primarily produces beef through a system usually described by three sectors. The objective of the commercial cow-calf operation is to breed cows and bulls to yield calves that will enter the beef market. In the U.S. the vast majority of producers keep on-farm bulls. Calves are maintained on farm until they are approximately 7 months old, at which point they are weaned and sold (USDA/APHIS, 2009a). Most producers wean calves based on their age or weight and the average weaning weight is 299 kg (USDA/APHIS, 2009a). Approximately 63% of calves in the U.S. are marketed as conventional beef; 28% are marketed as Natural; 14% are marketed through a breed-influenced program (i.e. Certified Angus Beef) and 1% are organic. Conventional production does not restrict use of growth enhancing technologies such as beta-agonists, ionophores or implants while natural production typically does. Organic production systems must be certified by the USDA, and breed-influenced programs are outlined by breed associations.

Most cow-calf operations in the U.S. are small, maintaining a herd average of 40 cows. It should be noted, however, that the majority of cows in the U.S. are owned by large (>300 hd) operations. Typically, the sale of calves is a secondary source of income (USDA/APHIS, 2009a). Operations are pastoral with 94% of operations grazing cattle on their own land (USDA/APHIS, 2009a). Ponds and streams are the most common water sources (USDA/APHIS, 2009a). Many operations (42%) do not dispose of animal manure; 37% drag pastures and 20% spread manure as fertilizer.

Most cow-calf operations produce commercial cattle, meaning that the calves are marketed for eventual consumption (USDA/APHIS, 2009b). Cattle on cow-calf operations in the U.S. are primarily of British origin (Angus/Hereford) and most commercial operations do not raise
purebred calves (USDA/APHIS, 2009b). A separate production sector, seedstock producers, typically breed purebred animals and market superior genetics in the form of bulls or replacement heifers to commercial cow-calf producers. Surveys indicate that most operations have calves born between February and April and 88% of operations calve during 4 or fewer months (USDA/APHIS, 2009b). Many reproductive technologies are available to cow-calf producers; however, they have not been adopted extensively as only 35% of cow-calf operations utilize any type of reproductive technology (USDA/APHIS, 2009b). This may be because natural service breeding yields reasonable calving percentages (92%) and birth rates (97%; USDA/APHIS, 2009b)

Only 3% of cows are bred through artificial insemination meaning that most operations maintain a bull population. Mature bulls are expected to breed approximately 24 cows during a breeding season while yearling bulls are expected to breed 16 (USDA/APHIS, 2009b). Much like reproductive technologies, genetic tools such as expected progeny differences or sire testing have not been well adopted in the U.S. cow-calf industry (USDA/APHIS, 2009b).

The majority of commercial bull calves are castrated and sold into the beef market (USDA/APHIS, 2009a). Commercial heifer calves can either be used as replacements for the breeding population or sold into the beef market. Most females kept for replacement are raised on farm while most bulls are purchased from off the operation. The remaining calves are typically sold to stocker or feedlot producers. Only 3.5% of cow-calf operations rely on forward pricing (USDA/APHIS, 2009a). As a result, cow-calf operations tend to be very susceptible to price changes and their primary incentive is to produce heavy calves in an economical manner.

Stocker
The objective of the stocker operation is to put weight on calves in a cost-effective manner, commonly by feeding high forage diets. This is an optional, interim step between the cow-calf operation and the feedlot. Approximately 16% of calves do not go through a stockering phase prior to entering the feedlot. Like the cow-calf operation, most stocker operations are a supplementary source of income (Johnson et al., 2008b). Stocker producers typically maintain cattle on pasture with a very short hay feeding season (Johnson et al., 2008b). Cattle are procured post-weaning and are sold to feedlots at an average weight of 320 kg.

Stocker cattle are rarely marketed using contracts and are typically sold in uniform lots in a seasonal manner (Johnson et al., 2008b). Approximately 25% of stocker producers retain ownership of the cattle through the finishing phase (Johnson et al., 2008b). The primary incentive for the stocker producer is to put a substantial amount of weight on the calves in an economical manner.

The reliance on pasture to facilitate economic growth of cattle indicates that, much like the cow-calf, stocker producers rely heavily on the quality of the pasture available to them. Most stocker producers have knowledge of stocking rates and use these to maintain appropriate forage removal rates while cattle are grazing (Johnson et al., 2008b). Although only a quarter of producers test their pastures for quality, nearly half of the producers conduct occasional soil tests to monitor soil health and fertility (Johnson et al., 2008b).

**Feedlot**

The objective of feedlot operations is to procure cattle and feed them until they reach adequate slaughter weight. Feedlots primarily feed calves from the other beef production sectors (cow-
calf/stocker); however 8.5% of cattle in feedlots are from dairy breeding (USDA/APHIS, 2011). As such, dairies could be considered a 4th beef production sector. Most cattle in feedlots are steers or heifers (USDA/APHIS, 2011); 2% of animals placed in feedlots were cows or bulls (USDA/APHIS, 2011). Only 1.1% of cattle in feedlots were born on the lot or at another operation operated solely by the feedlot indicating minimal vertical integration in the beef industry (USDA/APHIS, 2011). Feedlot cattle typically enter the lot between 230 kg and 320 kg and are slaughtered between 545 and 635 kg. Most cattle are slaughtered at 15 – 16 months of age. Depending on whether cattle were acquired as yearlings or as calves, average daily gain in the feedlot can range from 1.2 kg/d – 1.5 kg/d.

Feedlots typically use high concentrate rations to maximize the energy concentration of diets (USDA/APHIS, 2011). The majority of feedlot operations base diets on published or modeled nutritional guidelines to ensure adequate nutrients for maintenance and growth (Vasconcelos and Galyean, 2007). The primary feed grain used is corn; however sorghum and wheat are popular secondary grains (Vasconcelos and Galyean, 2007). Grain co-products are an important part of feedlot diets; 69% of feedlots use distillers grains and 27% use corn gluten feed (Vasconcelos and Galyean, 2007) as a primary co-product. The roughage content of feedlot diets helps to maintain rumen health. Most feedlot diets include 8% to 9% roughage in the diet (Vasconcelos and Galyean, 2007). Corn silage and alfalfa hay are the most popular forms of roughage (Vasconcelos and Galyean, 2007). Most feedlots gradually increase the concentrate portion of the ration as the animals become accustomed to the feed (Vasconcelos and Galyean, 2007). Given the precision required in feedlot diet formulation, 95% of feedlots employ or rely on a nutritionist (USDA/APHIS, 2011). Feedlots typically use ground water from wells as their water source although 11% do rely on the municipal water supply (USDA/APHIS, 2011).
Feedlot diets must possess a net energy for gain content ranging from 5.5 Mcal/d to 7 Mcal/d (National Research Council, 2000). Most high grain diets can accomplish this; however, to further promote gain there are several management options available to feedlot operators that help to improve growth.

ENVIRONMENTAL IMPACTS FROM BEEF PRODUCTION

Each of the U.S. beef industry sectors has an associated environmental impact. Environmental impacts include resource use, waste production and greenhouse gas (GHG) emissions. Beef cattle consume feed and water daily. Byproducts of feed consumption include enteric CH$_4$ emissions from breakdown of feeds in the rumen; nutrient excretion and waste production (N, P and manure); and CH$_4$ and N$_2$O emissions from stored manure. Although feed is an input to the beef production system, feed produced for consumption by cattle is attributed to the environmental impacts associated with beef production. Traditional tillage cropping in the U.S. requires land availability, fertilizer, herbicide, seed and irrigation water as inputs. Outputs from the cropping system include CO$_2$ emissions from internal combustion engines in farming equipment; N$_2$O emissions from fertilizer application; and N$_2$O emissions from crop or pasture land. Each source of environmental impact within beef production is the product of complex biological and ecological systems and should be addressed in detail.

Resource Use

Feed Consumption

The average bovine consumes between 2% and 3% of its body weight in dry feed on a daily basis. Feed intake can be measured several ways. The most common method is to calculate the
difference between feed offered and feed refused. Although this method of measuring intake is
the most widely used in beef studies, it is really only conducive to measurements on animals
housed in confinement facilities. Measuring feed intake on pasture is far more difficult (Macoon
et al., 2003; Reeves et al., 1996) because establishing the amount of pasture offered and the
amount refused is less effective due to spatial and temporal variability in yield. Feed intake can
also be predicted using a variety of regression equations that estimate intake based on
requirements of the animal and physical/chemical composition of the feed. Fox et al. (1992)
predicted DMI for beef cows based on body weight, energy concentration of feed, ambient
temperature, mud conditions and milk production. National Research Council (2000) used
similar predictive equations to estimate feed intake for growing calves and yearlings.

Several factors influence feed intake. Distention of the reticulorumen can physically limit feed
intake on high fiber diets (Allen, 1996; Ellis, 1978) as ruminants appear to eat to a constant
rumen fill (Ulyatt et al., 1967). Forage dry matter content and water addition to the rumen also
impact voluntary forage intake (Campling et al., 1961). Van Soest (1965) determined that
voluntary forage intake was better correlated to NDF intake than to other forage measures.
Although NDF is highly correlated with intake, additional factors must be considered. In a
literature survey, Oba and Allen (1999) demonstrated the NDF digestibility, rather than content,
was important in determining intake. This agreed with the literature survey conducted by Conrad
et al. (1964) which found that body weight, forage digestibility and manure production
accounted for 99.7% of the variability in feed intake. Stage of production is also important in
determining dry matter intake as pregnancy decreases rumen capacity (Forbes, 1969).

Feed intake is regulated by feedback to the central nervous system. Forbes and Barrio (1992)
documented the role of tension receptors in the rumen wall on feedback to the hypothalamus to decrease feed intake. Forbes and Barrio (1992) also identified epithelial receptors in the rumen which are sensitive to chemical components of the digesta; mechano- and chemoreceptors in the abomasum and duodenum sensitive to fill and acid concentration; and chemoreceptors and osmoreceptors in the liver which respond to glucose concentration and osmotic stimuli. The hypothalamus was originally thought to be the primary brain center governing intake regulation (Stellar, 1954); however, more recently it has been hypothesized that the control is regulated by the forebrain for neuroendocrine response and the brainstem for behavioral response (Grill and Kaplan, 2002). Important signaling molecules in this response network include: leptin, insulin and glucose (Grill and Kaplan, 2002). Progesterone concentration also affects feed intake (Provenza, 2006). When attempting to explain the variability in feed intake, models should reflect physical limitations such as body size, fiber content and digestibility as well as potential precursors of biological feedback mechanisms.

The National Research Council (2000) models feed intake for different physiological stages. The primary driver in the NRC equations is the metabolic body weight of the animal. Energy content of the diet, body fat, dietary additives, temperature, mud effects, milk yield (when lactating) are additional parameters accounted for by the models (National Research Council, 2000). When cattle are grazing, the NRC model adjusts intake based on the stocking rate, initial pasture mass, grazing area, and days on pasture. Stocking rate is the primary driver in the equation. These equations account for 63% to 69% of the variability in measured intake in the validation dataset. The predictions do not account for the effect of fiber content or fiber digestibility on dry matter intake. Illius and Gordon (1991) developed a mechanistic model of dry matter intake that was primarily driven by the fractional digestion, passage or breakdown rates of various cell wall or
cell soluble components of forage. This model explained 61% of the variability in the validation dataset and incorporated forage chemical composition in addition to animal size parameters. The first model incorporating physiological feedback was published by Gregorini et al. (2013) to predict pasture intake by grazing dairy cattle. This model RMSPE was 36.2%, of which 78.9% was random error. Although the model error was rather high, much of the unexplained variability occurred through random variance in the measured data. It is unknown how this model would perform when predicting dry matter intake of grazing beef cows.

When using feed consumption as a component of environmental impact, the most common method of quantifying efficiency of feed use in animal agriculture is the feed conversion ratio (feed intake per kg live weight gain). Efficiency of feed use within beef production systems has been scrutinized because simplistic comparisons indicate that other animal meat products (pork and chicken) are more efficient from a feed use standpoint (Godfray et al., 2010). What proponents of this argument fail to understand is that most ruminant animals consume primarily forages, feed by-products and other human-inedible food. Large areas of land incapable of supporting human food crop production are used for grazing beef cattle (CAST, 2013; Oltjen and Beckett, 1996). Galloway et al. (2007) illustrated this misconception in a quantification of the global conversion ratio of total feed to meat with and without an adjustment for crop residue and non-arable forage. The ruminant feed conversion was 20:1 compared to a non-ruminant 3.8:1 before removal of crop residue and non-arable forage. After adjustment, ruminant conversion ratio was reduced to 3:1 while the non-ruminant conversion ratio was 3.4:1 (Galloway et al., 2007). Wilkinson (2011) compared beef production to other animal products based on total concentrate conversion efficiency and human-edible concentrate efficiency. On a total concentrate conversion efficiency basis, beef production required the most input to produce the
same weight of output. When only human-edible concentrate was considered, efficiency of beef production (1.3 to 2.8 kg concentrate/kg product) was comparable to other animal products such as pork (1.4 kg/kg), poultry meat and eggs (1.7 kg/kg), and lamb (2.0 – 4.1 kg/kg).

**Water Consumption**

Depending on temperature, beef cattle generally consume between 1 and 4 gallons of water for each kg of feed intake (Mader and Davis, 2004; Winchester and Morris, 1956). Although water intake can be measured through more advanced technologies, the majority of studies measuring water intake have employed a methodology similar to feed intake. Water allocated to animals each day is measured, water remaining at the end of the day is measured and some accounting for evaporation/wastage is used to determine the amount of water consumed by animals with access to the waterer.

Water consumption is influenced by production stage; feed intake; feed dry matter content; mineral concentrations; ambient temperature; and body surface area. Investigations by Little and Shaw (1978) and Murphy et al. (1983) indicate that water consumption is positively correlated with milk production indicating water intake increases during lactating. The impact of lactation on water intake is closely correlated with the impact of DMI on water intake (Black et al., 1964; Murphy et al., 1983; Wright and Jones, 1974). Feed water is an additional, frequently forgotten, source of water intake and therefore, feed dry matter content is implicitly related to water intake. As feed DM content increases, water intake increases (Castle and Thomas, 1975). In an assessment of 240 cross-bred beef steers, sulfate concentration in drinking water had a quadratic relationship with water consumption (Lonegragan et al., 2001). Sodium concentration also increases water intake (Riggs et al., 1953).
Water intake is not frequently modeled. Winchester and Morris (1956) developed a model predicting daily intake of water as dependent on ambient temperature, dry matter intake and breed. Although this model agreed well with the validation dataset, it did not include variables to account for the dry matter content of the feed, the ion content of the diet or the physiological state of the animal. Beckett and Oltjen (1993) developed individualized equations for animals differing in productive stage and included model parameters for weight and ambient temperature. These models explained 94% to 99% of the variability in daily water intake. The high $R^2$ values may have been due to the use of a homogeneous diet across the validation datasets because variability in feed dry matter content, and feed intake would be expected to cause additional unexplained variation in water intake. Meyer et al. (2006) developed an equation to predict daily water consumption of bulls based on dry matter intake, dry matter content of the feed, the percent of roughage in the diet, ambient temperature and body weight. The model had originally contained additional parameters for daily sodium and potassium intake; however, these parameters were not significant and were removed in the model development process.

When assessing water use as an environmental impact metric, water-use efficiency is used as a metric to compare water use between production systems. Previous studies have focused on the water-use efficiency of different animal production systems. Water use efficiency takes into account drinking water and water used for irrigation. Beckett and Oltjen (1993) characterize water use from beef production into specific sources. Water used for direct animal consumption is substantially lower than water used for feed irrigation (Beckett and Oltjen, 1993). Many subsequent studies agree with this finding (Capper, 2011a; Ridoutt et al., 2011). Additionally, Beckett and Oltjen (1993) identified that water use in the cow-calf sector was substantially greater than water used in the feedlot because of the irrigation water required for pasture and hay
production. This is in agreement with Beauchemin et al. (2010) who demonstrated that cow-calf carbon emissions account for 80% of whole-system emissions. Estimates of whole-system water use are detailed in the “Whole System Water Use Efficiency” section.

Irrigation Water Use

Many feeds used in beef production require irrigation. Within the plant, light photons stimulate the release of electrons from chlorophyll molecules in the photosystem II complex in the thylakoid membrane of the plant chloroplast. These electrons are replaced by the splitting of water molecules. This process is an important step in plant energy metabolism and thus water is vital to plant survival and growth.

Globally, only 10% to 30% of irrigation water is utilized by plants for growth (Wallace, 2000). Irrigation water use is typically measured directly and reported at varying geographic scales by USDA/ERS (2012b) and USDA/NASS (2007). Factors affecting water use efficiency from irrigation include plant water use, soil density, runoff, soil management practices and plant type and yield. Within the plant, water use can be stimulated by increasing efficiency of transpiration or by fixing more carbon per unit of water (Wallace, 2000). Improving transpiration can be achieved by increasing water availability to the plant through improving storage, decreasing runoff and decreasing soil evaporation (Gregory et al., 1997). Storage of irrigation water is improved by improved infrastructure (storage tanks, transport, etc.). Runoff can be decreased by improving soil infiltration and above-ground storage. Terracing (Wallace, 2000) and tillage (Stroonsnijder and Hoogmoed, 1984) improve infiltration of water into the soil. Use of cover crops (Kiepe and Rao, 1994) or mulches (Lal, 1989) increase above-ground storage capacity. Soil evaporation can be decreased by application of cover crops or mulches (Barros and Hanks,
1993). Although these studies primarily focus on crop production, many of the same principles are applicable to water use efficiency in pasture management.

Water use efficiency of irrigation can be measured or modeled. Crop yield per unit water (Viets, 1962) is the most common way of measuring water use efficiency. Several attempts have been conducted to improve the applicability of this unit to real-world water concerns. Bos (1980) proposed that efficiency should be defined as the difference in irrigated and dry yield divided by the difference in irrigated and dry evapotranspiration. This term was then redefined again as the difference between dry and irrigated yield over the irrigation applied (Bos, 1985). These terms are more useful than the original term of water use efficiency because they target production response due to applying water. This trend has continued through agronomical research. More recently, Wang et al. (1996) proposed that general water use efficiency should be related to the fraction of evapotranspiration that was transpired water taken up from irrigation and stored within the plant. Although this definition is more applicable to biological efficiency of irrigation water use, the inputs for calculation make it more feasible for use in case studies rather than average, national assessments. Crop yield per unit irrigation or the difference between irrigated yield and dry yield per unit irrigation are the most common metrics of irrigation water use efficiency for national studies.

Models estimating irrigation water use efficiency predict evapotranspiration of crops. The most commonly used equation to predict evapotranspiration is the Penman-Monteith equation which relates evapotranspiration to temperature, wind speed, relative humidity and solar radiation (Beven, 1979; Monteith, 1965, 1981). The equation covers many of the biological and physical factors that cause variability in evapotranspiration and is relied upon by many of the Global
Information System Integrated hydrological models. The Priestley-Taylor equation is another method of predicting evapotranspiration which is less accurate that the Penman-Monteith equation but requires fewer input parameters as it relies only on irradiance to predict evapotranspiration (Stannard, 1993).

**Whole System Water Use Efficiency**

Water use is broadly classified into three categories: blue water includes surface and ground water; green water refers to rainwater; and grey water refers to the volume of freshwater requires diluting pollutants to adequate water quality standards (Mekonnen and Hoekstra, 2011). Whole-system water use within beef production has been estimated frequently and usually only includes blue water use although studies have assessed blue, green and grey water footprints of farm animal products (Mekonnen and Hoekstra, 2010; Mekonnen and Hoekstra, 2012, 2011). Estimates of water use include 108 L/kg (HCW equivalent) for European cattle production in Australia (Ridoutt et al., 2012); 209 L/kg for Australian production systems (Foran et al., 2005); 350 L/kg (HCW equivalent) for yearling-fed beef produced in Australia (Ridoutt et al., 2012); 499.3 L/kg for beef produced in modern U.S. systems not utilizing growth enhancing technologies (Capper and Hayes, 2012); 529 L/kg in 2002 in New South Wales (Peters et al., 2010b); 582.5 L/kg for natural beef production systems (Capper, 2012); 1,149 L/kg in 2004 in New South Wales (Peters et al., 2010b); 1,763 L/kg for modern U.S. systems (Capper, 2011a); 1,957.2 L/kg for grass-fed beef production systems (Capper, 2012); 3,682 L/kg for U.S. production systems in 1993 (Beckett and Oltjen, 1993). Water use from beef production has considerable variability. Beckett and Oltjen (1993) and Peters et al., (2010b) both account for processing water use while the studies by Capper (2011; 2012) do not. Furthermore, the water
footprints calculated by Ridoutt et al. (2012) incorporate flows of surface and ground water into the system, precipitation and evapotranspiration, drainage and runoff (both blue and green water use). Ridoutt’s values are likely lower because flows like drainage and evaporation allow for more specific accounting of water and subsequently reduce the water footprint attributable to production.

**Land Use**

Beef cattle require land for pasture, crop production and confined housing. Land use is increased when beef cattle consume feeds with low yield or housing area is expanded. As a result, conserving land used for beef production is difficult because welfare issues become problematic when space allocated to animals is limited. Land use conservation occurs primarily by increasing the yield of feedstuffs used in diets. Yield improvements can be made through alternative pasture or crop management. Land use can be measured by physically calculating the land area responsible for housing and feeding cattle. Alternatively, land use can be modeled according to average area allocations per animal and average crop and pasture yield data.

When land use is used as a metric of environmental impact, beef production is frequently compared to other animal products on a land-use efficiency basis. Elferink and Nonhebel (2007) compared the land-use efficiency of beef, pork and chicken. Numbers were generated using conversion efficiency values for dressing percentage, feed conversion ratio, feed processing conversion and yield. Researchers found that production systems in developed countries used 23 m²/kg beef, about 8 m²/kg pork and about 6 m²/kg chicken. This study was limited because it treated all land as equal with respect to land use. Oltjen and Beckett (1996) noted that most assessments of land use in beef production incorrectly assume that all land used for beef
production could also be used for human food production. Additional estimates of land use from beef production range include 61.1 m²/kg for modern U.S. systems (Capper, 2011a); 16.5 m² for intensive European systems (Nguyen et al., 2010); 98.7 m²/kg for grass-finishing systems (Capper, 2012); and 29.1 for a modern U.S. system not utilizing growth enhancing technologies (Capper and Hayes, 2012). Estimates of land use vary considerably. This variability is largely due to differences in the types of land accounted and the yield of crops produced on that land. For example, the study by Nguyen et al. (2010) accounts credits from avoiding palm oil production while the studies by Capper (2011; 2012) and Capper and Hayes (2012) do not include an adjustment for avoiding palm oil production.

An additional environmental concern related to land use is that of land use change. Several methodologies have been proposed to estimate land use change in beef production systems but there is no consensus about whether these impacts should be considered and if so, how they should be accounted (Flysjö et al., 2012). Nguyen et al. (2010) calculated the impact as a pulse effect which was evenly depreciated over a period of 20 years. Although no ISO standard methodology has been published to account for environmental impact attributable to land use change, the method described by Nguyen et al. (2010) is also suggested by IPCC (2006). Using this methodology, Cederberg et al. (2011) found that environmental impact of beef produced on newly deforested land was orders of magnitude greater than conventional production systems. Given the impacts of land use change on environmental metrics of beef production, assessment of environmental impact should include land use change if deforestation is a likely result of management. In the U.S. land use change is not a substantial component of production because most of land use occurs on established range and pastureland.
Greenhouse Gas Emissions

Greenhouse gas molecules are uniquely dangerous to the climate because they contribute to radiative forcing i.e. the trapping of heat within Earth’s atmosphere. These molecules have the ability to absorb and emit various wavelengths of light. In the atmosphere, the ozone layer reflects much of the sun’s UV radiation because ozone absorbs UV radiation and reflects it away from Earth. As GHG molecules accumulate in the troposphere, the same phenomenon occurs. Visible light from the sun passes through the atmosphere and is absorbed by Earth. Earth then emits infrared radiation out toward space. If troposphere concentrations of GHG are high, the majority of infrared radiation is captured and trapped within earth’s atmosphere. Infrared radiation is essentially heat energy traveling along a path, therefore, when radiation is trapped, heat is also trapped. If there is enough heat trapped, the temperature of the planet may slowly rise.

There is much speculation about the consequences of climate change, whether catalyzed by increasing atmospheric GHG content or not. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change reviewed the physical science basis on changes in the climate (IPCC, 2007). This report identified that over the last 100 years (1905 to 2005) global average surface temperature has increased by 0.74°C. In addition to increasing temperatures, heat waves and other extreme temperature events have increased during the latter half of the 20th century. Changes in temperature have influenced normal cycling of water on the planet – water vapor in the troposphere has increased, extreme rainfall events have increased and there is evidence for increased tropical storm activity.

Climate models are used to predict how these changes in climate will continue into the future.
Three levels of complexity exist in global climate models: Simple Climate Models, Earth System Models of Intermediate Complexity and Atmosphere-Ocean General Circulation Models (IPCC, 2007). Projections in the IPCC report rely on the combination of data from multiple models to more comprehensively develop a range of possible outcomes. The most conservative model scenario predicts a warming trend of 0.1°C per decade until about 2025; less conservative scenarios predict warming trends that are much more severe (2.0°C per decade). Sea level is expected to rise about 1.3 mm per year in most scenarios modeled. Extreme rainfall, extreme drought and incidences of tropical storm activity are expected to become more frequent (IPCC, 2007). The assessment report found that anthropogenic forcing due to GHG emissions, along with aerosols and land use change have likely stimulated a net warming effect on the climate since 1750 and will likely continue to do so for at least the next century (IPCC, 2007).

Three primary GHG are emitted from animal production systems; CO₂, CH₄, and N₂O. Gases are compared on a CO₂-equivalent basis. The most recent inventory of emissions and sinks gives the 100-year global warming potential of CH₄ to be 21 and the 100-year global warming potential for N₂O to be 310 (EPA, 2012). Practically, these values mean that a molecule of CH₄ (N₂O) is responsible for 21 times (310 times) more radiative forcing than what is attributed to a molecule of CO₂. Some estimates indicate that agriculture is responsible for 18% of global GHG emissions (FAO, 2006). Alternative studies, calculating the impact of agriculture in the U.S., have found that agriculture’s contribution is closer to 5% (EPA, 2006a) or 7.2% (EPA, 2012). Notable differences between these studies that influence their outcomes include the area of interest (global vs. U.S.) and the types of emissions accounted to agriculture. In global assessment, land use change and deforestation are accounted to agriculture and have a substantial influence on the final outcome. Deforestation and land use change do not occur in the U.S. on the scale that they
do in other countries thus these influences are much lower in when only U.S. agriculture is accounted for. Additionally, expressing emissions as a percentage can be misleading because they numbers will depend on emissions in other sources like transport.

Between 1990 and 2011, agricultural soil management was responsible for 56% of emissions from agriculture, enteric fermentation accounted for 24% and manure management was responsible for 9% (EPA, 2012). In 2011, beef cattle were responsible for 72% of CH$_4$ emissions from enteric fermentation and 15% of emissions from manure management (EPA, 2012). It is difficult to parse, from national figures, what proportion of agricultural soil management emissions should be accounted to beef production. More in depth accounting must be undertaken to better account emissions from cropping and pasture lands to beef production.

**Enteric Fermentation**

Cattle emit between 2% and 12% of their gross energy intake as CH$_4$ (Johnson and Johnson, 1995) from the fermentation of organic matter in the rumen. As H$^+$ is released from carbohydrates during the fermentation process, H$_2$ and CO$_2$ are formed. These two molecules are the primary substrate for methanogenesis in the rumen (Kebreab et al., 2006).

Factors affecting CH$_4$ emissions include feed intake; dietary digestibility; carbohydrate type; feed processing method; dietary lipid concentration; feed additives; and microbial populations (Beauchemin et al., 2008; Boadi et al., 2004; Eckard et al., 2010; Johnson and Johnson, 1995; Kebreab et al., 2006). Increasing dietary concentrate content increases propionate production and subsequently results in lower CH$_4$ emissions (Johnson and Johnson, 1995). Processing forages or grains to reduce particle size increases digestibility and rate of passage resulting in decreased CH$_4$ emissions (Blaxter, 1989). DeRamus et al. (2003) found that management intensive grazing
reduced CH₄ emissions per unit beef produced compared with continuous grazing. Grazing grass-alfalfa pastures also reduced energy loss through CH₄ production in grazing beef cows (McCaughey et al., 1999). Grass-legume mixed pastures and intensively-managed pastures are expected to result in greater forage digestibility than continuously-grazed, grass pastures which may help reduce CH₄ emissions. McGinn et al. (2004) assessed the impact of feed ingredients and additives on CH₄ loss and found beneficial effects from sunflower oil, ionophores and some yeast products. Dietary tannin content has been shown to reduce CH₄ emissions (de Oliveira et al., 2007; Makkar, 2003) potentially because tannins decrease growth of methanogenic bacteria (Scalbert, 1991); however, results are conflicting between studies (Beauchemin et al., 2007).

Several technologies exist to measure CH₄ emissions from cattle. Respiration chamber calorimetry is the golden standard for measuring CH₄ emissions due to the accuracy of the procedure. Unfortunately, the cost per unit and artificial environment make respiration chambers prohibitive for many research objectives (Kebreab et al., 2006). A less expensive, portable adaptation of the respiration chamber is the polythene tunnel system (Lockyer and Jarvis, 1995). The polythene tunnel system requires temperature control within the tunnel and therefore this system incurs a significant space limitation. As a result, it is most commonly used for measuring emissions from sheep. Methane from cattle on pasture can be measured through the use of a tracer gas. This technique requires the placement of a permeation tube containing a tracer gas into the rumen of a cow. The most common gas used as a tracer is SF₆ as outlined in Johnson et al. (1994). Samples of the emissions from the animal’s nose and mouth are retained by a collection canister pressurized as a vacuum. Disadvantages of this technique include close monitoring of the wind speed and direction required to obtain a background ratio of SF₆ and CH₄. Micrometeorological mass balance can also be employed to measure CH₄ emissions. This
method requires a mobile, high-precision CH₄ analyzer (Harper et al., 1999). This method is also limited by the influence of wind and requires the attendance of a supervisor with in-depth understanding of air movement (Kebreab et al., 2006).

Alternatively, CH₄ emissions from animals can be modeled using mechanistic or empirical approaches. IPCC (2006) models CH₄ emissions as a direct proportion of gross energy intake. This approach implicitly accounts for most of the factors impacting CH₄ emissions but fails to account for the digestibility of feed or addition of feed additives. Blaxter and Clapperton (1965) developed a model to predict emissions based on digestibility of the diet and dry matter intake. This model accounted for feed digestibility and had an error value of about 8% of the mean predicted CH₄ emissions. Moe and Tyrrell (1979) developed a model based on non-fiber carbohydrate, hemicellulose and cellulose concentrations. This model had very small error bounds around the coefficient estimates; however, that may be due to comparison against a particularly homogeneous population of emission estimates. The values predicted by Moe and Tyrrell were developed for dairy cattle and do not perform well on beef cattle datasets (Ellis et al., 2007). Mills et al. (2003) developed a nonlinear model of CH₄ emissions that is based on theoretical maximum and minimum CH₄ emissions as well as starch intake and ADF concentration of the diet. This model demonstrates reasonable predictive ability when compared to a dataset of CH₄ emissions from beef cattle (Ellis et al., 2007). Ellis et al. (2007) fit a linear model based on energy, ADF and lignin intakes to a dataset of beef cattle emissions which performed better than previous equations. However, this equation has been criticized because it does not include a parameter for dietary lipid content. An updated model assessment (Ellis et al., 2009) indicated that other equations including parameters for lipid or forage content performed better. Mechanistic models of CH₄ emissions from cattle include Baldwin et al. (1987), Benchaar
et al. (2001), Mills et al. (2001) and Kebreab et al. (2004). Kebreab et al. (2008) demonstrated that mechanistic models could result in more precise estimates of enteric CH$_4$ emissions than empirical models; however, most whole-farm models continue to rely on simple empirical equations (Ellis et al., 2010).

Westberg et al. (2001) reported average emissions for various classifications of beef cattle. Beef cows emitted 188 g/d to 231 g/d; replacement heifers 135 g/d – 223 g/d; breeding bulls 228 g/d; stocker cattle 175 g/d; and feedlot cattle 193 g/d. In a life cycle assessment, enteric CH$_4$ emissions accounted for 63% of total emissions from beef production (Beauchemin et al., 2010). Across the U.S., enteric fermentation produces 23% of anthropogenic CH$_4$ emission and is the largest single source of CH$_4$ emissions (United States Environmental Protection Agency, 2013). From 1990 to 2011, beef cattle were the largest source of enteric CH$_4$ emissions, producing 96.2 – 104.0 Tg CO$_2$e/y.

Manure Methane

Emissions of CH$_4$ from cattle manure are emitted when methanogenic bacteria interact with various substrates. Manure CH$_4$ emissions are influenced by O$_2$ concentrations, density, total solids, NH$_3$ concentration, pH, and S-content of the manure (Kebreab et al., 2006). Air temperature, rainfall and storage method also impact manure emissions. Yamulki (2006) demonstrated that incorporating straw into manure stockpiles decreased CH$_4$ emissions. Composting manure has been shown to decrease emissions in some studies (Pattey et al., 2005) and increase them in others (Hao et al., 2004). This discrepancy likely has to do with the manner in which manure was composted. Anaerobic condition with low redox potential, neutral pH, high substrate availability and high organic matter content facilitate CH$_4$ emissions (Conrad, 1989).
Composting methods that incorporate oxygen; high ammonia levels; or high sulfur content all help inhibit methanogenesis (Hao and Larney, 2011; Massé et al., 2003).

Manure CH$_4$ emissions can be measured by methodologies similar to enteric CH$_4$ measurement; both chamber-based and free-air approaches have been used. A downside of measuring manure CH$_4$ emissions in chambers is that manure must be removed from its normal storage environment. Micrometeorological techniques can remedy this disadvantage because they are able to measure the CH$_4$ content of large areas in a more real-world context without disturbing the normal manure management. A downside of this technique is that it requires careful observation of wind speed and direction (Kebreab et al., 2006).

Manure CH$_4$ emissions are typically predicted through the use of empirical models. The most widely used model to predict manure CH$_4$ emissions is IPCC (2006) which indicates that CH$_4$ emission is proportional to the volatile solids content of the manure, and is dependent on the manure management strategy. Sommer et al. (2004) developed a dynamic model of manure CH$_4$ emissions that depends on volatile solid excretion in addition to atmospheric variables like oxygen, temperature and soil water potential. The model has greater variability than empirical estimates of manure emissions.

Manure CH$_4$ emissions make up 9% of anthropogenic CH$_4$. Beef cattle are not a significant contributor to manure CH$_4$ emissions in the U.S. as dairy cattle and swine production systems produce substantially more CH$_4$ annually than beef production systems. IPCC (2006) predicts that the average cow will produce 55 g of manure CH$_4$ per day.

**Manure Nitrous Oxide**
Nitrous oxide emissions from cattle are produced primarily as a by-product of nitrification and denitrification. Emissions by nitrification require the presence of CO$_2$, H$_2$O, O$_2$, and either NH$_4^+$ or NO$_2^-$ within the manure to facilitate microbial growth (Galbally, 1989); whereas, denitrification requires anaerobic conditions, organic carbon, and high concentrations of NO$_3^-$, NO$_2^-$ or NO (Firestone and Davidson, 1989).

Manure N$_2$O emissions are dependent on the concentration of substrate, temperature, pH and particle size. Storage or soil oxygen content are also primary factors affecting N$_2$O emissions (de Klein et al., 2001; Luo et al., 2010). Storage method, rainfall and particle size all affect oxygen availability. Wet soil has lower oxygen availability than dry soil; likewise, small particle sizes also decrease oxygen availability. Chadwick (2005) found that compaction and covering of beef cattle manure significantly reduced N$_2$O emissions without increasing CH$_4$ emissions. When applying manure to soil, as many beef production systems do, surface application results in lower emissions than a 5 cm incorporation depth (Velthof et al., 2003); however, surface application has greater opportunity for runoff. Composted manure generally results in lower N$_2$O emissions during soil application than slurry manure (Paul et al., 1993). Manure N$_2$O emissions are also impacted by dietary protein content (Külling et al., 2001). As excess protein is fed to cattle, urinary and fecal N excretion increases and subsequent N$_2$O emissions increase.

Most manure from beef production is attributable to the cow-calf and stocker sectors. These sectors rely primarily on grazing and therefore, emissions from grazing systems should also be considered. Under unmanaged conditions, soil emits N$_2$O and NH$_3$ though nitrification and denitrification. Luo et al. (2010) identified different classes of management that can be used to manipulate soil properties; plant composition; animal interactions; and feed-N intake to decrease
N$_2$O losses from manure in grazing systems. Nitrification inhibitors; soil management; precision N management; and pasture renovation can all be used to restrict soil O$_2$ and N$_2$ availability to mitigate emissions (Luo et al., 2010). Similarly, adjusting plant type and composition; stocking rate; and type of animals stocked can improve N use efficiency in plants and animals, leaving less available for N$_2$O production (Luo et al., 2010).

Manure N$_2$O can be measured by methods similar to manure CH$_4$. Portable chambers can be built around cattle windrows (Hellebrand and Kalk, 2001) or feedlot manure storage (Hao et al., 2004). Portable chambers are inexpensive, mobile and easy to use. Micrometeorological methods can also be utilized to measure N$_2$O from manure. Micrometeorological methods have the disadvantage of requiring specialized tracking of wind patterns. Although other methods exist, these are the most commonly used.

The most common model for modeling N$_2$O emissions from beef cattle manure is the IPCC (2006). This methodology assumes emissions are directly related to the quantity of N excreted daily and the type of manure management system used. This method is overly simplistic if exact N emission rates are not known as it assumes a constant percentage of N intake is excreted daily. As a result, the IPCC methodology fails to incorporate changes in N-use efficiency stemming from dietary manipulation, genetic improvement or other cattle management options. Complex models of N dynamics are available (Sommer et al., 2004; Webb and Misselbrook, 2004); however, their intricacy frequently reduces their usefulness in most whole-farm models and life cycle assessments.

In the U.S., soil management practices are the greatest single contributor to agricultural N$_2$O emissions, accounting for 69% of the total (EPA, 2013). Manure management is a fairly small
contributor, accounting for only 6.7% (EPA, 2013). Beef cattle contribute greater manure N\textsubscript{2}O emissions than dairy cattle, swine, poultry, sheep or goat production (EPA, 2013). Although quantitatively, less N\textsubscript{2}O is emitted than CH\textsubscript{4}, the global warming potential of N\textsubscript{2}O is 310 times that of CO\textsubscript{2} while CH\textsubscript{4} is only 21 time greater (IPCC, 2007).

**Nitrogen and Phosphorus Excretion from Manure Management, Cropping and Pastures**

Indirect emissions of N and P include leaching and volatilization. Manure handling greatly impacts leaching of N and P. Frequent manure removal has been shown to decrease N loss from stored feedlot manure (Rotz, 2004). Additionally, bottom loaded storage facilities conserve more N than top loaded storages largely because of decreased air infiltration (Muck and Steenhuis, 1982). IPCC (2006) emission factors predict that daily spread of manure will result in minimal N\textsubscript{2}O emissions. Gilbertson et al. (1971) found that 42% to 55% of manure N was lost during storage. Manure N losses during storage occur primarily through runoff and gaseous emissions (Eghball and Power, 1994) while losses of P occur primarily through runoff. Both N and P losses are affected by dietary content (Ebeling et al., 2002; Rotz, 2004). Loss of N and P are also affected by rainfall (Kleinman and Sharpley, 2003; Sharpley, 1997); soil and surface water dynamics (Blanco-Canqui et al., 2002; Carpenter et al., 1998; Gburek and Sharpley, 1998); temperature (Phipps and Crumpton, 1994); soil and surface permeability (Blanco-Canqui et al., 2002); and surface texture/resistance (Blanco-Canqui et al., 2006). During rainfall events, N runoff can be hard to control, however, riparian filter barriers around animal confinement operations have been shown as an effective method of reducing N runoff into surface water (Butler et al., 2008; Mankin et al., 2007).

IPCC (2006) estimate that 30% of N in dry lot manure storage systems will be lost to
volatilization, compared to 45% in solid storage systems and 30% in deep bedding systems. Volatilization losses occur in the form of N-NH$_3$ and N-NO$_x$. The error bounds on these estimates are substantial: 20% to 50% for dry lot storage, 10% to 65% for solid storage and 20% to 40% for deep bedding. IPCC (2006) estimates 40% of N in dry lot storage systems is leached, 50% in solid storage systems and 40% in deep bedding. The IPCC emission factors are in contrast to the findings of Rotz (2004) and Webb et al. (2012) who determined that deep-bedded systems had greater N emissions than other systems. Direct N$_2$O emissions represent the largest N loss; leaching is the second greatest loss, followed by volatilization. Leaching is a concern as it can promote eutrophication of surface water (Stevenson and Cole, 1999), increase NO$_3$ concentrations in municipal water sources (Almasri and Kaluarachchi, 2004) and cause potential concerns related to infant methemoglobinemia (Walton, 1951).

Leaching and volatilization of N and P is of particular importance when these substrates are applied to crop or pasture land. On a global level, the vast majority of nitrogen is in the form of atmospheric N$_2$ (Galloway et al., 2003). This nitrogen can only be utilized by a small number of N-fixing bacteria which convert the N$_2$ into NH$_4$. These bacteria live in the soil and in root nodules of legumes. Nitrogen gas is unique because it forms an extremely strong covalent triple bond which can only be broken by energy-intensive processes, such as lighting strikes. With so few ways to convert atmospheric N to usable N, N is often a limiting nutrient in plant growth.

In the soil, microbial populations of N-fixing bacteria convert atmospheric N primarily to NH$_4^+$, which is not readily taken up by plant roots (Hart et al., 1994; Lemaire and Gastal, 1997). Nitrifying bacteria convert soil NH$_4$ to NO$_3$ (Hart et al., 1994); there is an inefficiency associated with this conversion as bacteria give off some N$_2$O gas in the process. Nitrification rate increases
with temperature and decreases with soil moisture, as reaction rate increases, so does the proportion of N₂O to NO₃ in the end product (Hart et al., 1994). There are several other fates of NH₄ in the soil; NH₄ can be immobilized in the form of soil organic matter where it will eventually mineralize back to NH₄. Mineralization increases with temperature and moisture. NH₄ can also be lost through volatilization as NH₃ during high temperature or high pH.

Nitrogen applied to soil is of vital importance to plant growth. Plants take up NO₃ from soil at a rate dependent on the concentration in the soil; the volume of the roots; rooting density; and the efficiency of NO₃ absorption by roots (Lawlor, 2002). Within the plant, NO₃ is converted to NH₃ which is linked to carbon skeletons from the tricarboxylic acid cycle and used to form amino acids. Phosphorus is vital to plants as it is a primary component of adenosine triphosphate. Addition of N and P to agricultural soil increases yield at a decreasing rate (Colwell, 1963; Lawlor, 2002). To optimize this relationship, it is vital to quantify the available N and P in soil, and add additional nutrients only if required (Dobermann, 2009). Precision fertilizer management is projected to decrease nutrient losses and improve plant use efficiency (Khosla et al., 2002). Initial field trials show promise (Kaivosoja et al., 2013); however, fields must be managed down to the 1m level to accurately control for spatial and temporal heterogeneity (Raun et al., 2002). In addition to application rate, fertilizer application method also significantly affects plant yield. When synthetic fertilizer was used, point-injecting N resulted in greater N uptake and greater cereal grain yields compared with surface broadcast or surface pooling (Blackshaw et al., 2002). Application method also affects weed growth and competition between weeds and cereal grains (Blackshaw et al., 2004).

IPCC predicts that the average beef cow in the North America will excrete 0.31 kg N per day.
Estimates from developed livestock systems show that 30% of N excreted in housed animal facilities is lost; 19% from ammonia; 7% as NO, N2O or N2 and 4% as leaching and runoff (Oenema et al., 2007). Worldwide N-use efficiency for cereal grain production is approximately 33% (Raun and Johnson, 1999). When this is considered with the IPCC animal N-use efficiency value of 7%, the losses of N from agricultural systems are substantial. Given the global warming potential of N2O in addition to the water quality and health concerns related to NO3 and P leaching, improvement of N- and P- use efficiency in agriculture is an important focal point.

**Direct and Indirect Carbon Dioxide Emissions from Cropping**

Emissions of CO2 are associated with production of fertilizer, herbicide and seed manufacture. Sources of CO2 in fertilizer production include burning fossil fuels to extract minerals; manufacturing fertilizer (Bhat et al., 1994); and post-production packaging, transport and field application (Mudahar and Hignett, 1987). These emissions are typically accounted based on CO2 emissions associated with combustion of different fossil fuels and the amount of each used in production (West and Marland, 2001). Similarly, because pesticides are produced almost entirely from crude petroleum and natural gas products, quantification of emission from pesticide manufacture is done by accounting for fuel use and expected carbon emissions from combustion (West and Marland, 2001). Carbon emissions from seed production should be calculated based on energy requirements for seed cleaning, packaging and transportation (Heichel, 1980). West and Marland (2001) summarized carbon emissions from production and combustion of fossil fuels based on data from United States Office of Technology Assessment (1990); Waste Recovery (1986); Energy Information Administration (1999); and Wright et al. (1992) and used these values to estimate emissions attributed to tillage equipment.
West and Marland (2001) and Nelson et al. (2009) accounted for the GHG emissions associated with the entirety of crop production. Emissions included those associated with inputs into the cropping system, emissions of N\textsubscript{2}O from fertilizer application and emissions of CO\textsubscript{2} from tillage and irrigation. Tillage inputs were accounted based on energy consumed in manufacture transportation and repair of machines (Bowers, 1992) and were based on national average tillage practices. Estimates for energy use in irrigation were derived from the energy expenses of U.S. farms and average energy price estimates. Carbon emissions from irrigation were based on the resulting calculated energy use. West and Marland (2001) used this methodology to generate estimates for carbon emissions associated with corn, soybeans and wheat. Nelson et al. (2009) expanded the quantification to include barley, cotton, hay, oat, rice and sorghum. Emissions tended to be higher in no till systems that in conventional tillage systems. Emissions for barley, soy and wheat production tended to be lower while corn and hay production were carbon-intensive. Emissions in this study were expressed on a land-area basis. When emissions are converted to a kg product basis, the high yield of corn grains reduces its carbon requirement.

Emissions of CO\textsubscript{2} from manufacture of inputs into the cropping sector are minimal in comparison with other beef-related emission sources such as enteric CH\textsubscript{4} (Beauchemin et al., 2010). These emissions are also frequently outside the control of animal or cropping system managers and therefore difficult to mitigate. Reduced use of fertilizers or herbicides is an option but frequently reduces efficiency given the subsequent decreases in yield (Nikièma et al., 2011). No-till systems can have lower CO\textsubscript{2} per hectare (Regina and Alakukku, 2010) but have variable effects on N\textsubscript{2}O emissions (Abdalla et al., 2013). Increased N\textsubscript{2}O may be attributable to increased fertilizer use in no till systems or due to emissions from decaying biomass. No till systems must be implemented for long durations (>10 years) before N\textsubscript{2}O reductions are observed (Kessel et al.,
Additional consideration of conservation tillage, particularly with respect to emissions per kg yield, is required before full assessment of this management practice is reliable.

MODELS OF BEEF ENVIRONMENTAL IMPACT

Life Cycle Assessments

Environmental impact of animal agriculture systems has traditionally been quantified by partial life cycle assessment (e.g., Beauchemin et al., 2010; Ogino et al., 2004; Pelletier et al., 2010). Life cycle assessment is a “cradle-to-grave” approach for assessing the environmental impact of industrial systems (EPA, 2006b). A life cycle assessment calculates environmental impact metrics from the acquisition of raw materials through manufacturing, use/reuse and maintenance and recycling/waste management. Life cycle assessment requires declaration of a system boundary and functional unit. A system boundary details the sources included in assessment and those excluded from assessment while a functional unit is the production metric on which emissions are reported (kg hot carcass weight beef).

Life cycle assessments of beef production typically are referred to as partial life cycle assessments because their system boundaries extend from manufacture of inputs to the cropping system, through to the feedlot farm gate. Historically, this has been the case because little data is available for environmental impact from slaughter facilities, transportation, cold storage and retail beef outlets. The International Standards Organization has published a standard methodology for Life Cycle Assessment as follows:

Goal definition and scoping

This phase requires definition and description of the system. Inputs and outputs from the system
need to be explicitly defined. Outputs generally include both environmental impact metrics and quantities of product/co-product produced. This step also requires defining a functional unit. The functional unit is the amount or quality of product to be produced. This serves as the denominator for comparison between studies (e.g. kg CO\textsubscript{2}-equivalents / kg hot carcass weight beef).

**Inventory Analysis**

Inventory analysis requires identification and quantification of energy, water and material usage within the system boundaries. This phase also includes assessment of environmental releases associated with processes within the system boundaries. Environmental releases can include GHG emissions, solid waste disposal, waste water discharges, among others.

**Impact Assessment**

Human and ecological effects of resource use and environmental releases are evaluated during impact assessment. Human impacts include health impacts, economic implications or other greater-societal consequences of environmental releases. Ecological effects include alteration of environmental health due to pollution or excessive resource use, inhibition of ecosystem services, biodiversity loss and other ecological implications.

**Interpretation**

Interpretation evaluates results from the inventory analysis and impact assessment against the original project goal. In life cycle assessments comparing two production systems that yield the same product, this might be identifying which production practice is more ideal. Interpretation should include a discussion of uncertainty within and assumptions used to generate study results.
**Allocation in Life Cycle Assessments**

A frequent problem with lifecycle assessment is related to by-product use. When by-products are used as inputs to life cycle assessment, impacts must be allocated between the by-product production system and the production system under investigation. For example, dried distillers grains, a by-product of corn ethanol production, are frequently used as a feed input to beef production. If dried distillers grains are used as an input in a life cycle assessment of beef production, impacts from the production of dried distillers grains must be allocated between the beef production system (the system under investigation) and ethanol production (the by-product production system). In the 2006 ISO standards, specific guidelines explain how to allocate emissions from by-products. These guidelines outline procedures for allocating resource use and waste product production in systems with multiple product outputs. The recommendation of the ISO is first to avoid allocation altogether. This can be done by expanding the processes outlined in the system to include enough detail in the production process to separate out emissions related to production of one co-product from production of the other. If allocation cannot be avoided, the ideal methodology is to allocate impact based on the underlying physical (or biological) relationship between co-products. If such a physical relationship is unknown or cannot otherwise be established, then allocating the emissions based on economic returns received for the co-products is advised.

These allocation methods are based on the same foundational concept. System expansion and physical allocation both rely on an understanding and quantification of “real world” processes. Similarly, economic allocation assumes that the co-product with the greater economic returns drives the production processes and therefore is responsible for a greater portion of resource use and waste production.
Some sources identify physical accounting as a different procedure from biological accounting. Physical accounting is based on physical processes used in production and biological accounting is based on underlying biological relationships involved in production. The ISO does not differentiate between these methods and includes biological accounting as a type of physical accounting. Biological allocation allows greater calculation flexibly and a more logical breakdown of environmental impact between systems.

Economic allocation is the least desirable method. In an economic allocation, yearly revenues from product and by-product production within the external system are tallied. The proportion of economic returns attributable to co-product production would then be used to determine impact associated with co-product production. Although economic allocation can be useful in situations where no data is available about the production practices, it is a gross over simplification of how emissions are created and can severely over- or under estimate the emissions that should be allocated to co-products. Additionally, economic production is time-point dependent because price estimates are required in this allocation method. As a result, impacts based on economic allocation are only valid for the time point from which price data was sourced.

Life Cycle Assessments in Beef Production

Several life cycle assessments have been conducted to describe GHG emissions of beef production systems in various countries. Some of these assessments have additionally described other metrics of environmental impact. Crosson et al. (2011a) reviewed different models used to quantify GHG from cattle production.

One of the first quantifications of GHG from beef production was conducted by Phetteplace et al. (2001). This comparison was based on data from cow-calf facilities in Alabama, Texas, Utah,
Virginia and Wisconsin and feedlot facilities in Iowa and Texas. Cattle were grouped by age, production stage and gender; diets were balanced based on the equations from National Research Council (1989) and National Research Council (1996). System boundaries spanned from the cropping system through manure management. When converted to hot carcass weight using a dressing percentage of 63%, the C-footprint of the whole beef production system was 24.6 kg CO$_2$ / kg HCW beef.

Ogino et al. (2004) and Ogino et al. (2007) calculated emissions for the cow-calf system and the finishing system in Japan. The comparison was based on experimentally derived empirical data from the systems. System boundaries spanned from the cropping system through manure management. Total emissions were calculated at 21.5 kg CO$_2$ / kg HCW beef. Notably, Ogino et al. (2004) calculated that reducing the time animals were in the system improved environmental impact indicating that efficiency improves environmental impact.

Edwards-Jones et al. (2009) used IPCC tier II methodology to calculate the C-footprint of beef and lamb produced in the UK. Two farms were compared, an upland farm with fertile land and a hilly farm with less fertile land. System boundaries spanned from production of inputs into the cropping system through manure management. Emissions were accounted between lamb and beef systems based on economic allocation. The fertile land farming system was predicted to produce 24.6 kg CO$_2$ / kg HCW beef while the less fertile system was predicted to produce 75.5 kg CO$_2$ / kg HCW beef. Again, this study reinforces the link between efficiency and improved environmental impact.

Peters et al. (2010a) used IPCC methodology to calculate the environmental impact associated with 1 sheep and 2 beef farms in Australia over 2 different years based on survey data from each
farm. Only the finishing systems were considered. System boundaries spanned from production of inputs into the cropping system through beef leaving the processing facility. When dressing percentage was adjusted to 63%, beef from cattle finished on grass produced 10.1 kg CO₂ / kg HCW beef and beef from cattle finished on grain produced 8.3 kg CO₂ / kg HCW beef. This study also revealed considerable year-to-year variability in C-footprint indicating that natural year-to-year fluctuations in management efficiency could greatly impact C-footprint.

Capper (2011a) compared emissions from the U.S. beef industry in 1977 to those from 2007 using national average production data. System boundaries stemmed from the production of inputs into the cropping system through manure management. This assessment accounted for land use and water use in addition to C-footprint. In 1977 the C-footprint of beef was 21.4 kg CO₂ / kg HCW beef and in 2007, the C-footprint was 17.9 kg CO₂ / kg HCW beef. Land use in 1977 was 91.1 m²/kg and decreased to 61.1 m²/kg by 2007. Water use in 2007 was 176 L/kg HCW beef, down from the 200 L/kg HCW beef calculated for the 1977 production system. As efficiency improved over time, GHG emissions, land use and water use decreased.

Ridoutt et al. (2011) also compared multiple metrics of environmental impact from beef production systems. System boundaries extended from inputs into the cropping system through manure management. Both GHG and water use were accounted in this study. Six different management systems were modeled in accordance with regional average production for systems in Australia. Carbon emissions ranged from 16.0 kg CO₂ / kg HCW beef to 20.2 kg CO₂ / kg HCW beef when adjusted to a 63% dressing weight. Water use ranged from 5.2 L/kg HCW beef to 350 L/kg HCW beef. Although C-footprints were relatively similar between these systems, the water footprints varied considerably.
Stackhouse-Lawson et al. (2012) considered only air emissions in their study, but in addition to considering GHG, they also incorporated NH₃. The Integrated Farm System Model (Rotz et al., 2013) was used to quantify emissions from beef production systems representative of management in California. The mean C-footprint calculated for cattle production in California was 22.6 kg CO₂ / kg HCW beef and ammonia emissions were 98 g NH₃ / kg HCW beef.

Life cycle assessment techniques have also been used to assess specific production locations (Lupo et al., 2013); different allocation methods (Beauchemin, 2013; Roer et al., 2013); specific feedstuffs (Bonesmo et al., 2013); or manure management techniques (Wu et al., 2013). Life cycle assessments have been increasingly incorporated into whole-farm models to more explicitly model farm activities and their environmental and economic implications.

**Whole Farm Models**

Given the numerous sources of environmental impact from farming systems, whole-system analysis is vital to understand the full implications of management practices applied to one sector on the environmental impact of the whole system (Crosson et al., 2011a; Schils et al., 2007). Using whole-farm models can help to understand the differences between production systems and help identify management to improve environmental impact. There are several whole farm models available for assessing the impact of management practices of GHG emissions from animal agriculture.

**Integrated Farm System Model (IFSM)**

The Integrated Farm System Model (IFSM; Rotz et al., 2013) is the most recent product of the USDA/ARS modeling team. The IFSM evolved from the Dairy Forage System Model
(Rotz et al., 1989); incorporating the CERES-maize model (Hodges et al., 1987); models for manure management (Borton et al., 1995); tillage and planting (Harrigan et al., 1996); and new feeds (Rotz et al., 2001). Eventually the model was expanded to simulate beef production systems (Rotz et al., 2005) and additional pasture management strategies (Corson et al., 2007).

The systems simulated within IFSM include: crop and soil; grazing; machinery; tillage and planting; crop harvest; crop storage; herd and feeding; manure handling and economic analysis (Rotz et al., 2013). Exchange of crop biomass and nutrients between these systems govern the nutrient dynamics within the model.

Model inputs include weather data, farm parameters and machinery available. The farm parameters for the model include soil characteristics; equipment and structures available; animal populations; harvest, tillage and manure management strategies; and pricing for farm inputs and outputs (Rotz et al., 2013). The machinery dataset includes information about machine sizes, initial costs, operating parameters and repair costs and rates (Rotz et al., 2013). Weather data can be sourced from the program based on average data from most states. Users may also upload their own weather data; however, creating a new weather file can be problematic and requires precision formation of a text file. Required weather data include solar radiation; mean, maximum and minimum temperature; precipitation and average wind speed (Rotz et al., 2013).

Outputs from the model include farm performance, costs and returns; crop yields; feed purchases and sales; manure production and handling; other farm costs; and net profitability of the farm (Rotz et al., 2013). The model also calculates N, P and K budgets in addition to NH₄, CO₂, N₂O, CH₄, volatile organic compound emissions, water use and energy use (Rotz et al., 2013).
Compared with other whole-farm models, IFSM has several advantages. The list of environmental outputs is more comprehensive than some other models. The sources of emissions and resource use accounted for within the model represent a full cradle-to-farmgate impact assessment. The model additionally integrates assessment of economics with environmental impact, helping to identify the relationship between management practices, profitability and environmental efficiency (Soder and Rotz, 2001; Stackhouse et al., 2012).

The IFSM is most applicable to time-series estimation. The accounting period is one year, meaning that within-year variability is not well described by the model (Rotz et al., 2013). Additionally, although IFSM is designed to operate over long periods of time, there is little year-to-year exchange meaning that rather than assessing system performance over several consecutive years, the simulation better represents single-year system performance under different weather conditions (Rotz et al., 2013). An additional constraint within IFMS is the assumption that the farm has no interaction with surrounding markets (Rotz et al., 2013).

Holos

Holos is a GHG calculator developed by Agriculture and Agri-Food Canada. Much like IFSM, Holos is a multi-year simulation model that calculates on a yearly time step. Holos is based largely on the calculations from the IPCC (2006) methodology for GHG estimation. Soil N dynamics from land-applied manure, crop residue and fertilizer are modeled following Rochette et al. (2008). Cropping system parameters and related CO₂ emissions as well as N and P fertilizer emissions were also sourced from country specific data (Beauchemin et al., 2010).

The system modeled by Holos is fairly extensive. The model is broken down into four
subsystems: the cropping/pasture system; cow-calf production; feedlot cattle; and manure management. The GHG accounted for include CO$_2$, N$_2$O and CH$_4$. Inputs include soil information, weather, cropland type and cropping practices, cattle parameters, and manure management strategy. The model runs for a series of years and maintains cattle pools throughout the years as dependent on culling or replacement rate, although it does not include an economic module (Beauchemin et al., 2010, 2011).

Holos outputs emissions from the production system based on their classification. Specific outputs include soil-derived N$_2$O; enteric CH$_4$; manure CH$_4$; manure N$_2$O; CO$_2$ from on-farm energy use; CO$_2$ from input manufacturing; and CO$_2$ from management changes in soil carbon stocks (Beauchemin, 2013). This breakdown of inputs helps users identify where on-farm emissions are most concentrated. Additionally, the model allows for simulation of mitigation scenarios to help identify how specific management options will change whole-farm environmental impact (Beauchemin et al., 2011; Mc Geough et al., 2012).

Holos is a user-friendly model that can help researchers and animal professionals identify sources and intensity of emissions on-farm. One specific benefit of the model is the incorporation of soil C gains or losses. This is a C pool not included in many whole-farm models and represents one means of calculating CO$_2$ consequences of land use change.

A primary weakness of Holos is the lack of economic information. Without information about the costs and returns of the farm across different management scenarios, it is difficult to assess whether the management suggestions made by the model represent sustainable business decisions.

FarmSim
FarmSim was developed by INRA and is based on the continual updates of the model proposed by Saletes et al. (2004). The model integrates PaSim, a pasture simulation model adapted from the Hurley Pasture model (Thornley, 1998) and relies on IPCC (2006) emission factors to predict GHG emissions. The PaSim model was extended (Riedo et al., 1998; Riedo et al., 2000; Vuichard et al., 2007a; Vuichard et al., 2007b) to simulate C, N and H₂O flows in pasture across grazing schemes and variable water stress conditions. A cropping model was incorporated based on the CERES – EGC model (Jones and Kiniry, 1986) modified to suit French management conditions (Gabrielle et al., 1998a, b). The sophistication of N dynamics in the model was improved by the addition of the NCSOIL model (Molina et al., 1983) to simulate endogenous soil organic matter pools.

The FarmSim model combines empirical and mechanistic modeling to simulate pastoral livestock production. The model is structured into seven modules: feed and straw storage; cattle housing; animals; pasture; meadows; arable crops and manure storage (Fiorelli et al., 2008). Inputs to the model include energy resources; feed and bedding available; fertilizer required; and seed use (Fiorelli et al., 2008). Outputs from the model include gaseous C and N loss from input manufacturing; animal management; crop production and manure management (Fiorelli et al., 2008). N loss through irrigation, runoff and leaching are modeled and C and N fixation are also accounted for (Fiorelli et al., 2008).

The FarmSim model places explicit focus on modeling pasture C and N flows. In contrast to other models, this framework does not calculate on an annual basis. Feeding strategies and pasture management are the primary focus of the model. Integration of a specific animal module within FarmSim improved model ability to predict cattle responses to pasture and climate change.
Like Holos, the FarmSim model allows for input of specific mitigation scenarios (Fiorelli et al., 2008) to help identify management options that reduce environmental impact. However, FarmSim does not include an economics module which makes it less useful to assessing sustainability of management decisions.

**Overseer®**

Overseer® is the model developed by Ministry for Primary Industries, Fertilizer Association of New Zealand and AgResearch NZ. The model is based on databases of P, K and S fertilizer trails conducted in New Zealand in the 1990’s and was originally available as an economic model of fertilizer dynamics called Outlook (De Klein et al., 1997). Wheeler et al. (2003) expanded the model to simulate N, P, K, S, Ca, Mg, Na, H⁺, Energy and GHG emissions from a farming system. The model was adapted for regional resource management suggestions and expanded to include GHG estimation for a wide array of on-far management practices (Wheeler et al., 2008). Overseer® has been favorably externally reviewed as a tool to estimate N dynamics from farming systems in New Zealand (Edmeades et al., 2013). Formal lifecycle assessment standards have also been adopted by the model (Wheeler et al., 2013).

Overseer® defines farm subunits as management blocks. The blocks are assigned a type: pastoral; fodder; cut and carry; fruit; arable crop; trees; riparian; wetland and house. Blocks are added to the model by the user until the geography of the farm is adequately characterized. Inputs to the model require specifying location and descriptions of each block (Wheeler et al., 2003). Outputs from the current model include N, P, K, S, Ca, Ma, Na, and H⁺ balances as well as energy use and GHG emissions attributable to products and co-products (Wheeler et al., 2013).
Overseer® is unique in the spectrum of outputs available. Additionally, overseer was developed with end-users, and surveys have been conducted on the usefulness of the tool as a decision support system (Wheeler et al., 2003). Although developing decision support systems is vital to improving agricultural sustainability, frequently the end-user of a decision support system has different needs than a researcher. The user interface of Overseer® has been noted as “behind” other, similar tools (Edmeades et al., 2013). Overseer®, like FarmSim, operates at a shorter time step than model such as IFSM or Holos. This allows for simulation of within-year dynamics.

Although many additional whole-farm models exist, those reviewed here were the most applicable to determining the sustainability of beef production systems. Notably, the DairyNZ Whole Farm Model (Beukes et al., 2008), DairyMod (Johnson et al., 2008a) and the Moorepark Dairy Model (Shalloo et al., 2004) have been excluded from this review as they assess dairy, rather than beef production systems. An additional concern with whole-farm models is the specification of the pasture component. Pasture management will greatly impact the opportunities to improve livestock sustainability (FAO, 2013) and as such, models drawing inferences about livestock sustainability should carefully consider how pasture is simulated.

**Pasture Simulation Models**

**The Agricultural Production Systems Simulator (APSIM) and AusFarm**

The agricultural production systems simulator (APSIM) is a modeling framework that evolved from the Agricultural Production Systems Research Unit in Australia (Keating et al., 2003). The original model simulated crop and pasture production and management (McCown et al., 1996). The model has been expanded to cover many different cropping systems and management strategies (Asseng et al., 1998; Farre et al., 2002; Wang et al., 2002). This model was integrated
with the AusFarm model which integrates a suite of models including GrazPlan (Donnelly et al., 1997; Freer et al., 1997; Moore et al., 1997).

Inputs to the GrazPlan model include weather data; pasture parameters; animal population descriptions; soil information and pasture and animal management rules. The GrazPlan model then transfers information to the pasture simulation in APSIM which uses the soil and plant production parameters to develop nutrient budgets and GHG estimates. These models can be integrated with the MIDAS whole-farm economic model to yield estimates of returns and expenses associated with different management choices (Moore et al., 2011). Outputs from APSIM and AusFarm include N and P balance; H2O use; runoff; crop and animal production parameters; herbage nutritional values; and some GHG estimates.

Benefits of these models include remarkable specificity and the resulting capability to simulate very explicit systems (Robertson and Friend, 2013). The APSIM modeling effort is international and represents a substantial accomplishment in the detailed integration of biophysical cropping and soil models. Further integration with livestock production systems is required for this model to be useful as a whole-farm simulator of livestock products. The links with AusFarm move toward this goal; however, minimal investigations have been conducted that utilize these tools in concert. The AusFarm, GrassGro and GrazPlan models represent some of the most complete, applicable forage models available to researchers investigating beef grazing systems. The complexity of these models does make running and appropriately specifying them difficult. Because these models are so detailed and so integrated, using them as components of a different model is difficult because the model must have similar complexity.

Sustainable Grazing Systems Pasture Model
The sustainable grazing systems (SGS) pasture model (Andrew and Lodge, 2003; Johnson et al., 2003) was developed from the sustainable grazing system national experiment in Australia (Mason and Andrew, 1998). This model has gone on to be a component of many whole-farm models such as DairyMod and EcoMod (Johnson et al., 2008a). The equations from the model are based on Johnson and Thornley (2000) and Thornley and France (2006).

The SGS model includes a pasture growth module, water dynamics, soil characterization, animal simulation and a farm management scheme that allows for different pasture management simulations. The model is mechanistic and runs over a period of years with a daily timestep. The inputs to the model include climate data; soil types; pasture species; fertilizer or irrigation; animal type and grazing management (Johnson, 2013). Climate data are usually sourced from SILO, an online database of weather data records for various locations around Australia. Outputs from the model include annual summaries and daily data for soil N and P, water balance and pasture and animal production.

Benefits of the SGS model include extremely specific, technical descriptions of pasture, soil and hydrological dynamics. If the model is to be used for investigation outside Australian systems, difficulty arises from obtaining accurate, appropriate weather data. Additionally, the inclusion of an animal grazing component in the model precludes its use with many other nutritional systems such as a nutritional optimizer.

The McCall-Bishop Hurley Pasture Model

The McCall pasture model (McCall and Bishop-Hurley, 2003) is a simple, semi-mechanistic model describing pasture growth and quality. This model tracks pasture growth only and does
not have a simulation for N or P dynamics in the soil or in plants (McCall and Bishop-Hurley, 2003; Romera et al., 2009). The parameters of the model can be adjusted to simulate efficiency improvements that might come from N fertilizer addition or increased irrigation. Inputs to the model include weather data and initial pasture parameters. Outputs from the model are pasture yield and quality parameters (Romera et al., 2009). The model considers most physiological influences on plant growth and has performed well in validation exercises (McCall and Bishop-Hurley, 2003; Romera et al., 2009). The model is included in a number of whole-farm models (Beukes et al., 2008; Bright et al., 2000; Marshall et al., 1991; Romera et al., 2004).

The main benefit to the McCall model is its usefulness when integrating into larger modeling frameworks. The model is simple and can be re-written into new frameworks without issue. The inputs are not extensive and the model can be readily parameterized to simulate different growth curves. A major disadvantage of the model is the lack of a sophisticated soil biophysical module. Without the simulation of N and P dynamics, inferences drawn from the model about N and P dynamics are less precise than from models which explicitly describe these nutrient flows.

**MANAGEMENT TO REDUCE ENVIRONMENTAL IMPACT**

**Dilution of Maintenance**

Efficiency is implicitly related to sustainability in agricultural systems (Capper and Bauman, 2013). The mechanism linking environmental impact and efficiency has been described as the “dilution of maintenance” concept (Capper et al., 2009; Capper et al., 2008). When dilution of maintenance occurs, on a percentage basis, the proportion of energy used for production (as compared to maintenance) is greater and animals are more efficient. When the production system is viewed as a biological entity, sustaining the cow-calf herd is a constant, fixed cost equivalent
to maintenance energy in the individual animal. Improving the efficiency of the system through increasing productive output from either the whole system or the cow-calf herd will help to reduce overall environmental impact (Capper and Bauman, 2013). Dilution of maintenance at the production system level differs from the biological level because the investment required to sustain the cow-calf herd can, itself, be reduced through improved efficiency of the cows.

In a case study of beef production in Western Canada, Beauchemin et al. (2010) identified that the cow-calf sector contributed 80% of the emissions from the entire beef production system. Most of those emissions were from enteric CH\(_4\) and manure N\(_2\)O as manure CH\(_4\), soil N\(_2\)O and CO\(_2\) were minimal contributors. These findings hold across similar whole-farm studies (Casey and Holden, 2006b; Pelletier et al., 2010).

There are several reasons why cow-calf production is the greatest contributor to environmental impact. Cows are in the system constantly (until culling) while the feedlot or stocker animals only remain in the system for a matter of months. Cows and bulls tend to be larger than the average growing yearling animal and subsequently will consume more feed daily. Finally, the diets fed to cows and bulls are primarily forage. The percentage of energy lost to CH\(_4\) production is greater on forage diets than on grain diets.

When viewing the production system through the lens of dilution of maintenance, decreasing the environmental impact of the cow-calf herd would be analogous to decreasing maintenance energy required by an individual animal. Because the cow-calf herd is the area of greatest impact, it is a logical area of focus for management to improve sustainability. Although the feedlot has been targeted as an area for GHG reduction (Subak, 1999), focus on nutrient use efficiency and forage management to improve cow-calf GHG emissions may be a more efficient
avenue to affect improvements (FAO, 2013). Studies comparing cow-calf and feedlot abatement options have found greater opportunity to reduce GHG emissions within the cow-calf sector (Beauchemin et al., 2011; Nguyen et al., 2013). Several management goals can be used to help increase outputs from the beef production system or decrease inputs.

Increasing Output

Increasing Calves per Cow

One common suggestion for increasing output from beef production system is to produce 1 calf per cow per year. Calving rate in the U.S. is less than this ideal (USDA/APHIS, 2009a). In the U.S. most cow-calf producers do not operate under a strictly defined breeding season (USDA/APHIS, 2009a). Breeding seasons can help to focus management efforts on one time of year and can therefore allow for better attention to be paid to each animal. One means of shortening the breeding season is through shortening the breeding window and culling cows that do not conceive. In addition, conception rate can be improved by proper nutritional supplementation (Richards et al., 1986; Stalker et al., 2006). Estrus synchronization can also be used to concentrate the breeding window (Miksch et al., 1978). In the U.S. today, only 8% of operations utilize estrus synchronization protocols. Conception rates from estrus synchronization when coupled with artificial insemination (Larson et al., 2006) tend to be much lower than natural service conception rates (USDA/APHIS, 2009b) and so these technologies frequently appear cost-prohibitive. Benefits of estrus synchronization include increased calf uniformity, opportunity to increase average calf age at weaning and decreased labor associated with the calving period.
Estrus synchronization is typically linked with artificial insemination. Artificial insemination is one method of increasing the number of cows serviced by a bull and propagating high quality genetics. With or without estrus synchronization, artificial insemination is correlated with lower pregnancy rates than natural service (Larson et al., 2006; Pursley et al., 1997); however, genetic gains from artificial insemination in the dairy industry have demonstrated substantial improvements in animal performance and operation profitability (DeJarnette et al., 2004). Such improvements might be possible in the beef industry if AI or on-farm sires were selected based on genetic merit.

Nguyen et al. (2013) identified increasing calves per cow through reducing age at first calving to be the most promising single management practice when several management scenarios were compared. Beauchemin et al. (2011) and Capper (2013a) identified increasing calves per cow as a promising method to reduce GHG emissions; Capper (2013a) additionally linked this to improved economic viability. As yet, no known assessment has integrated social acceptability to explain how improved calves per cow could affect all metrics of sustainability.

**Increasing Finishing Weight**

Increasing the finishing weight of cattle is another primary method by which output from beef production systems can be increased. Finishing weight can be improved through genetic selection, proper nutrition and use of growth-promoting technologies. Expected progeny differences are a metric commonly available on most sires to indicate how that sire’s offspring are predicted to perform relative to the herd average. Expected progeny differences can help to identify sires that have offspring with improved carcass quality (Gwartney et al., 1996; Marshall, 1994; Vieselmeier et al., 1996), maternal (Berger, 1994; Northcutt and Wilson, 1993) or growth
characteristics. Use of expected progeny differences or other genetic evaluation metrics when purchasing bulls or semen presents a substantial opportunity to improve productivity of beef production systems (Garrick, 2011; Golden et al., 2009). However, one criticism of current genetic evaluation schemes is the lack of accuracy (Golden et al., 2009). The impact of genetic selection on beef production’s environmental impact has not been explicitly investigated.

Growth-promoting technologies such as implants and beta-adrenergic agonists have been adopted at variable levels across the beef industry. Anabolic implants shift composition of gain by increasing protein deposition and decreasing fat accumulation. As a result, implanted animals reach the same body composition at a heavier weight (Hutcheson et al., 1997; Perry et al., 1991). Although infrequently used in the cow-calf sector (USDA/APHIS, 2009a), about half of stocker operators utilize implants (Johnson et al., 2008b) and the majority of feedlot cattle are implanted (USDA/APHIS, 2011). Aggressive implant regimens have been shown to increase average daily gain and reduce yield grade of feedlot steers without affecting feed efficiency or quality grade (Schoonmaker et al., 2001). In stocker cattle, implant regimens improve gain when cattle were not over-stocked (Aiken et al., 2006). Increasing daily gain of growing cattle decreases the amount of time required to produce beef because cattle reach heavier weights at younger ages. Capper (2013b) demonstrated that steroidal implant use substantially improved environmental impact of beef production systems without compromising economic viability.

In the feedlot, Beta-agonists are frequently used to improve the productivity of cattle in the last part of the finishing period (USDA/APHIS, 2011). Beta-adrenergic agonists increase muscle deposition; decrease muscle degradation; increase fat utilization; and decrease fat accretion in
cattle resulting in an extra 10 to 15 kg of lean-muscle growth when administered in the last 20 to 30 days of finishing (Mersmann, 1998). When added to diets for 28 d prior to slaughter, use of beta-agonists in heifer feedlot diets increased finishing weight and hot carcass weight without affecting yield or quality grade (Walker et al., 2006). Average daily gain and feed efficiency were also improved (Walker et al., 2006). Both Capper (2013b) and Capper and Hayes (2012) demonstrated that use of beta-agonists in the U.S. beef industry has substantial environmental and economic benefits through improved efficiency.

Use of technologies in food production has been linked with reduced consumer willingness to pay (WTP; Li et al., 2004; Thilmany et al., 2003; Tonsor and Schroeder, 2003). Improved consumer education is therefore vital to help consumers understand the benefits of technology use in food production. Until consumers understand these benefits, the use of growth promoting technologies may not prove sustainable as they reduce social acceptability of the product.

Decreasing Inputs

Adjusting Feedstuffs

Decreasing the inputs required by the production system represents another means by which efficiency can be improved. Cattle must consume feed in order to live and reproduce. Thus, nutritional management provides an excellent area of focus for improving productivity. On many cow-calf and stocker operations, cattle are on pasture for most of the year. Forage testing can help producers understand the exact nutritional value of their pasture or supplementary forage so they can better match the nutritional requirements of their cattle. In the U.S., only 31% of stocker producers test their forage and rely on published nutrient requirements to balance diets for cattle.
This value is not known for cow-calf producers but it is expected to be low.

While cattle are on pasture or fed primarily stored forage, they may be deficient in one or more nutrients, depending on the time of year. In the U.S. 75% of producers feed a protein supplement and 51% of producers feed an energy supplement (USDA/APHIS, 2010). Protein supplementation has been shown to increase cow body condition score, calf weaning weight and steer finishing weight (Larson et al., 2009). Energy and protein supplements have been shown to decrease weight loss during lactation or over winter (Forcherio et al., 1995; Sanson et al., 1990).

Most cow-calf and stocker producers provide a commercial trace mineral salt while cattle are grazing (Johnson et al., 2008b). Supplementing trace minerals improved cow weight maintenance, increased conception rates and better calf average daily gains (Stanton et al., 2000). Planning a supplementation strategy without balancing diets or knowledge of the forage nutrient content can be an economically adverse decision that can lead to unnecessarily high feed costs. Using forage evaluation to identify the quality of pasture available for cows will help decrease inputs to the cow-calf system by helping producers identify when supplements are required, what types are required and how much is needed.

The environmental impacts of differing pasture management strategies were evaluated by Nguyen et al. (2013). Reducing N fertilizer use moderately improved greenhouse emissions and land use from beef production systems (Nguyen et al., 2013), although it is important to note that this study assumed N fertilizer use could be decreased without impacting forage yield. Improved grass use through grazing management or adding linseed meal to cow diets decreased GHG emissions and land use but utilizing alfalfa hay rather than a concentrate protein supplement or replacing soybean meal with rapeseed both resulted in moderate increases in environmental
impact (Nguyen et al., 2013). Beauchemin et al. (2011) also assessed nutritional management strategies and reported that adding oilseeds or DDG to cow diets as energy supplements were the most promising methods examined in the study for decreasing GHG emissions. Improved forage quality over winter by reducing forage maturity at harvest was also a promising method of decreasing GHG emissions from beef production because digestibility was improved. However, neither of these studies assessed water use or economic and social implications of feeding management practices.

**Reducing Production Time**

Reducing the amount of time required to produce a set quantity of beef through improved rate of gain can be another method of reducing the environmental impact of production systems. Growth promoters such as implants and beta-agonists will improve the average daily gain of cattle (Aiken et al., 2006; Walker et al., 2006) and help decrease environmental impact (Capper, 2013b; Stackhouse et al., 2012). Genetic selection can also be used to improve average daily gain (Arnold et al., 1991; Rodríguez-Almeida et al., 1997).

In an assessment of conventional, natural and grass-based finishing systems, increased days to finishing in natural and grass-based finishing systems resulted in substantial increases in environmental impact (Capper, 2012). Pelletier et al. (2010) also found the extending the days from birth to slaughter increased environmental impact when comparing calf-finishing, yearling-finishing and grass-finishing. Many additional studies concur with this finding (Foley et al., 2011; Ruviaro et al., In Press; Stackhouse-Lawson et al., 2012; Stackhouse et al., 2012).

Environmental impact can be improved in a variety of ways, many of which are not detailed here. Any management practice that improves productivity will likely decrease environmental
impact per unit product (Capper and Bauman, 2013). Although improved efficiency is correlated with improved environmental impact (Capper and Bauman, 2013) and economic viability (Capper and Hayes, 2012; Foley et al., 2011), specific methods of quantifying economic viability of production systems and their applicability as metrics of sustainability should be reviewed.

QUANTIFYING ECONOMIC VIABILITY

Although several studies quantify metrics of environmental impact and compare between production systems, few studies have incorporated other metrics of sustainability. Economic viability should be incorporated into these LCA assessments to determine the economic implications of management changes for producers. An example of this incorporation can be found in Foley et al. (2011) or Capper and Hayes (2012). To incorporate economic viability into such an assessment, a background and understanding of quantification in economic science is required.

The quantification of economic science is an idea that has existed since the early 1700’s. Daniel Bernoulli (1738), possibly the first to apply mathematics to economics, began the movement by using probability and a game with infinite expected value to support the hypothesis that consumers valued utility rather than price of a good (Bernoulli, 1954). The second major push to apply mathematics into economic analysis occurred during the 1920’s and 1930’s when the average page count devoted to mathematics in economic journals increased from about 5% to over 25% (Mirowski, 1991). The subsequent infiltration of mathematics into economics has been categorized as a natural movement, evolving as a matter of course over time (Debreu, 1986). Although the original philosophizing about applications of mathematics to economics was conducted by many of the great minds of the 1700’s and 1800’s, few theories developed pre-
world war II are still applicable today (Mirowski, 1991). In today’s economic theory, the basis of nearly all economic publications is mathematical. This is of benefit because it eases the difficulty of finding quantifiable, economic metrics of sustainability.

Economics is the science of making decisions in the presence of scarce resources (Baye, 2010). Specifically, managerial economics is the study of how to direct scarce resources in the way that most efficiently achieves a managerial goal (Baye, 2010), in this case the production of beef. Therefore, economic metrics of sustainability should focus on quantifying the efficiency of resource use to produce beef. One chief metric of economic resource use efficiency in an operation is profitability. Profitability of an operation attests to careful input utilization so as to optimize net returns from outputted products. Profitability is not exclusively a metric of income over costs, as it is mathematically defined. From a Darwinian perspective those operations that continue to subsist are those that successfully make a profit (Hodgson, 2002; Witt, 1999). The ability to garner profit in society comes from social acceptance of outputted product as much as it comes from efficient resource use. In economic sciences, social acceptance of a product is therefore quantified by demand or WTP for that product.

Demand Functions

The demand curve is the line describing total quantity of a good that all consumers are willing and able to purchase at any given price while holding prices of related goods, income, advertising and other variables constant (Baye, 2010). Demand curves typically predict demand for a product based on price and various demand shifters i.e. variables that adjust demand for a good. In beef production, a multitude of demand models have been outlined over the past few
decades (Chavas, 1983; Dahlgran, 1987; Eales and Unnevehr, 1993; Kinnucan et al., 1997; Piggott et al., 2007; Schroeder et al., 2000; Tonsor et al., 2010; Tonsor and Olynk, 2011).

One of the first attempts at modeling market demand for beef in the U.S. was conducted by Chavas (1983). Chavas used data for U.S. meat consumption to the general model:

\[ \frac{\partial Q_{it}}{Q_{it-1}} = \beta I_0 + \sum_{j=1}^{N} \beta_{ij} \frac{\partial P_{jt}}{P_{jt-1}} + \delta_I \frac{\partial I_{t-1}}{I_{t-1}} + e_{it} \]

In this function, \( t \) denotes time, \( Q_i \) is the consumption of the \( i \)th commodity and \( I \) is the consumer income. The study used a seemingly unrelated regression to estimate parameters for the function using data of U.S. beef consumption from 1950 to 1970 and again using data from 1970 to 1979. The focus of this study was on beef, poultry and pork meat and unfortunately only cumulative \( R^2 \) values are presented for the combination of all three meat types. The \( R^2 \) value for the best model of 1950 to 1970 was 0.89 indicating that 89% of the variability in meat consumption was described by the relationship defined with meat price and income. The most notable contributions of this study to future forecasting of beef demand included identifying and describing structural change in beef demand during the latter half of the 1970’s. Chavas concluded that price and income elasticities of beef decreased from 1975 to 1979 and that during that time, the pork price elasticity of beef increased meaning that a 1% change in pork price had a greater impact on beef demand in 1979 than it did in 1975. These dynamics reflect changes in consumer preferences unexplained by price dynamics indicating more variables are required for accurate understanding.

The quantification by Chavas was expanded by Dahlgran (1987) to further investigate structural changes in the demand for beef and the time-scale of the model was expanded to investigate
demand from 1950 to 1985. Dahlgran fit demand data to the Rotterdam demand model (Barten, 1964; Theil, 1965) which expresses demand equations as a function of income expenditure and consumer utility (Theil, 1965). Again, Dahlgran was focused on beef, pork and poultry meat and therefore the $R^2$ value presented (0.82) represents the value for the cumulative model. The conclusions from the demand model in Dahlgran’s work indicated that the structural change in meat demand during the late 1970’s, as observed by Chavas, stabilized again in the early 1980’s. Dahlgran also noted that the structural changes observed in beef demand may actually be caused by fluctuations in beef supply while demand remained constant.

This assertion was further investigated by Eales and Unnevehr (1993) who used an Almost Ideal Demand System Model (Deaton and Muellbauer, 1980) and an Inverse Almost Ideal Demand System (Eales and Unnevehr, 1994) model to specifically investigate whether structural changes in beef demand in the 1970’s were due to supply chain fluctuations rather than demand shifts. Eales and Unnevehr concur with Dahlgran’s inference that the decline in beef demand in the late 1970’s was due to changes in supply rather than an absolute, permanent decline in demand.

Until the mid-1990’s, studies of beef demand were primarily focused on investigating structural change in meat demand. Eventually, however, studies began to broaden their focus to identify what types of variables other than price and income could be used to quantify meat demand. An excellent example of this is the study by Kinnucan et al. (1997) who used the Rotterdam model (Barten, 1964; Theil, 1965) to determine the effects of health information and generic advertising on meat consumption patterns. In this study, data from 1976 to 1993 were used to identify how advertising for different meats and dissemination of general health information influenced meat demand. Kinnucan and collaborators concluded that dissemination of health information
contributed to a decrease in beef demand and an increase in the demand for poultry. Interestingly, in this time period, beef advertising did not influence the demand for beef but was negatively correlated with poultry demand. The health information elasticity for beef was -0.5830 while the advertising elasticities for beef, pork or fish were all very small, -0.0003, 0.0003 and 0.0005.

The trend of expanding the parameters influencing meat demand has continued in more recent studies (Tonsor et al., 2010; Tonsor and Olynk, 2011). Meat demand models have expanded to incorporate household dynamics and media information (Tonsor et al., 2010) and animal well-being and welfare media (Tonsor and Olynk, 2011). Both of these studies expanded the Rotterdam model (Barten, 1964; Theil, 1965) to incorporate additional demand shifters. Tonsor et al. (2010) found that household dynamics and health oriented media information significantly impacted meat demand, specifically noting that contemporary fads (e.g. Atkins diet) had measurable, important effects on meat demand. When advertising indexes for zinc, iron and protein or low-carbohydrate diets increased by 1%, demand was expected to increase by 0.020% or 0.008%, respectively. When advertising for fat or cholesterol increased by 1%, beef demand was expected to decrease by 0.023%. Families consuming food away from home or families in which females worked were also correlated with decreasing beef demand (elasticities of -1.589 and -0.555). Tonsor and Olynk (2011) showed that animal welfare-related media has a significant effect on meat demand. The short-run welfare elasticity of beef was 0.005 and the long-run elasticity was 0.006. Although statistically significant, the numerical influence of welfare media was quite small; as beef animal welfare index improved by 1%, demand was expected to change by less than a hundredth of a percent.
Although the complexity of beef demand models has increased over the last few decades, several qualities of those models have remained the same. Across all demand studies addressed above, beef is modeled as a luxury good. The positive sign of the income elasticity of demand shows that as income increases, the demand for beef increases (Baye, 2010). Additionally, across all demand studies addressed above, beef and pork are substitutes. The positive sign of the pork price elasticity of demand shows that as the price of pork increases, the demand for beef increases (Baye, 2010).

To date, although consumer WTP for environmental meat attributes has been tested, the author knows of no studies that have assessed effects of environmental labeling on meat demand. Before demand analysis will be useful to assess meat sustainability, an investigation on the impact of environmental advertising on meat demand should be conducted.

Supply Functions

To understand market dynamics, both supply and demand must be simulated. The market supply function is a curve indicating total quantity of a good that all producers in a competitive market would produce at each possible price (Baye, 2010). Along the supply curve, input prices, technology and other variables affecting supply are held constant.

Supply for beef was first modeled by Reutlinger (1966) who calculated the output of slaughtered steers as a product of the one-year lagged beef-corn price ratio and the number of beef cows and heifers from the previous year. Cull cow slaughter was modeled as a function of the expected beef-corn price ratio and the inventory of beef cows. Heifer slaughter was also modeled as a function of available heifers for slaughter, placement of heifers in the cow herd and the demand
for heifer-inventory change. This model is a mechanistic model of the beef industry. These equations were compared to slaughter data from 1947 through 1962. This model explained between 74% and 95% of the variability in the slaughter of different populations of beef animals. The equations did a better job explaining the yearly population of steers ($R^2=0.95$) than cows ($R^2=0.74$) or heifers ($R^2=0.85$). This may be because the equations relied on a beef-corn price ratio as the major determinant of supply and the price ratio was not well related to decisions to cull cows or retain heifers.

The downfall of simplistic empirical methods of estimation is that the decision-making structure of the U.S. beef industry is ignored. Historical analysis of cattle populations and beef prices shows oscillatory behavior approximating a sinusoidal wave with a period of 10 years (Rosen et al., 1993). In most oscillatory systems, the fluctuations in this system are due to disparities in the forecasting interval of decision makers and the required production interval for the product generation (Ford, 2009). Every year, the number of calves that get sent into feeder operations are the product of breeding/culling decisions made the previous year and retaining decisions made 2 to 3 years previous (Aadland, 2003). When prices are high, producers retain more heifers and cull fewer cows (Rosen et al., 1993). As the U.S. cow herd grows, more calves are sent to be fed out, supply of beef increases and, assuming demand is held steady, beef price is driven down (Rosen et al., 1993). To properly model the supply of beef, these intrinsic lags in the system need to specifically be accounted for.

Several models exist that successfully predict cattle cycles using system dynamics approaches. A dynamic model was first applied to beef supply by Rosen (1987) who quantified the population of breeding cattle, calves, replacements and finishing animals as well as the exchange between
these groups over time. Although the model simulated cycling in beef supply, disadvantages included incorrect specification of the replacement development delay and a simplistic producer decision function. These errors were corrected and the model was updated by Rosen et al. (1993). The replacement delay was adjusted to two years. Additionally, producer decision algorithms allowed for forecasting beef prices 2 years in advance. The model generated in this study explained 97% of the variability in beef cattle populations. This prediction scheme is the basis of most modern supply functions. Aadland (2003) additionally modeled three types of producers and tracked animals’ age for culling decisions.

Zhao et al. (2006) expanded Aadland’s model to include import and exports. The resulting international model was used to track economic implications of disease transmission. The model by Zhao additionally predicts yield and quality of carcasses based on feeding strategy. The model was used to test policy scenarios that could be implemented in the event of a foot and mouth disease outbreak in the U.S. beef supply. The model demonstrated that depopulating herds as a result of disease outbreak would result in decreased consumer surplus and inflated producer surplus. The authors concluded that the model was a useful policy tool to help understand tradeoffs between different policy alternatives. Such a tool could be linked with a model of genetic improvement would be useful in assessing the long-term impacts of culling decisions on beef sustainability.

Market Equilibrium and Surplus Metrics

The advantage to modeling long-run supply in beef production is to quantitatively predict producer decisions to keep or cull cattle. When attempting to assess market equilibrium, short-run beef supply is used. Short-run beef supply is equivalent to per capita consumption
Price is a tool used by retailers to encourage consumers to purchase product, moving the system towards market clearing (Schroeder et al., 2000). Price is increased to curb beef purchasing during times of shortage and price is decreased during times of surplus to facilitate purchasing.

Consumer and producer surplus are additional tools that can be useful in assessing market equilibrium. Consumer surplus is a measure of the value that consumers receive for a good that they do not pay for (Baye, 2010). Consumer surplus is represented by the area below the demand curve and above the market price of the good. This value is traditionally used as a welfare metric because it helps managers understand the total amount that consumers would be willing to pay for a particular set of goods. Producer surplus indicates the benefit to producers from selling at a market price that is greater than the minimum that they would be willing to sell a good for. Sacrificing producer surplus to increase consumer surplus is indicative of a pricing strategy that is beneficial to the consumer more than the producer.

Changes in consumer and producer surplus are often used to compare differing market equilibrium simulations. This has frequently been done in environmental policy literature (Costanza et al., 1997; Milliman and Prince, 1989). Comparing consumer and producer surplus has been used to assess the introduction of new goods (Falck-Zepeda et al., 2000), and expanding consumer surplus is generally associated with socially beneficial policies. For the purpose of investigating the economic viability of low-environmental-impact beef, a demand system representative of an impure environmental product (Kotchen, 2005) could be used to assess how labeling environmental attributes of beef could impact consumer and producer surplus. An
impure environmental product is one that has environmental attributes in addition to private attributes such as improved health, safety or quality.

**LINEAR PROGRAMMING**

On-farm management decisions can be optimized through the use of linear programming models. Linear programming models adjust choice variables within the bounds of various constraints to find a mathematically optimal level of a response variable dictated by an objective function. Linear programming models have been employed in agriculture to balance diets (National Research Council, 2000, 2001); manage land (Attavanich and McCarl, 2012); manage soil nutrients (Stokes and Tozer, 2002a); make decisions about breeding cattle (Stokes and Tozer, 2002b; Tozer and Stokes, 2001a); or reduce environmental impact (Moraes et al., 2013; Tozer and Stokes, 2001b).

There are several components of a linear programming problem. First, there is the objective which has an associated direction, target and an equation (Hazel and Norton, 1986). The direction of the optimization function dictates whether the optimizer attempts to maximize the target value or minimize the target value. The objective target value is the product of the associated equation. The objective function is written as:

$$\max(Z) = f(X)$$

Where max indicates the direction of the optimization, Z is the target value, f(X) is the single-value function calculating Z, and X is a vector of real variables. This optimization equation is subject to constraints. Constraints limit the range within which X is viable (Hazel and Norton, 1986). Constraints are typically written as:
\[ G^i \leq 0, \text{all } i \]

\[ X_j \geq 0, \text{all } j \]

Where \( G^i \) is the \( i \)th constraint function and \( X_j \) is the same vector or real variables with \( j \)th element \( X_j \).

The parameterization of constraint functions determines the feasible set of values that \( Z \) can hold.

Graphically, an optimization can be represented as shown in Figure 1. The x-axis represents the quantity of any given Input 1 used while the y-axis represents the quantity of Input 2. The solid line and the large dashed line represent hypothetical constraints on the system. The small dotted line represents a production isoquant. The feasible set is defined by the shape ABCD. The production frontier is outlined by the surface ABC.

In animal science, diet optimizers are the most common form of linear optimizer (Glen, 1987). The vast majority of diet balancing software programs include some form of optimizer generally configured to minimize diet cost while meeting the requirements of the animal (Glen, 1980). The mathematics that governs these types of optimizers generally follows the following specific form of the above outlined general equation.

\[
\text{min}(\text{Cost}) = \sum_f \text{Cost}_f \times \text{Amt}_f
\]

\[
\text{Req}_n \geq \sum_f \text{Amt}_n \times \text{Amt}_f
\]

Where the objective is to minimize diet cost (given as the product of feed cost and amount of
feed) subject to the constraint the requirements of all nutrients \( n \) be less than or equal to the amount of a nutrient provided by the diet (given as the product of the amount of nutrient in a feed and the amount of feed in the diet).

In agricultural economics, the basic linear optimizer is termed “the farm model” wherein the goal is to optimize profitability subject to land constraints (Hazel and Norton, 1986). Mathematically, this model is written as:

\[
\text{Max}(Z) = \sum_{j=1}^{n} C_j \times X_j
\]

\[
\sum_{j=1}^{n} a_{ij} \times X_j \leq b_i, \text{ all } i = 1 \text{ to } n
\]

\[
X_j \geq 0, \text{ all } j = 1 \text{ to } n
\]

Mathematical optimizations have been used in animal science to optimize diets minimizing environmental impact metrics. Moraes et al. (2012) conducted a least-cost linear optimization of diets fed to lactating dairy cattle under various environmental policy scenarios. The objective function of the study was to minimize diet cost and the constraints specified that dry matter intake be less than the predicted intake; that all nutrients (NDF, ADG, RDP, RUP) be greater than the animals requirement; and that specific feedstuffs (cottonseed, wheat middlings, DDG, DGM, linseed meal, SBM, molasses, tallow, whey, canola meal) were below a fixed maximum proportion. This optimization was run once to identify the \( \text{CH}_4 \) output from the least cost scenario and run again after an additional constraint on the \( \text{CH}_4 \) emissions was included. The authors concluded that \( \text{CH}_4 \) emissions could not be reduced without increasing diet costs between 5% and 49% (depending on the \( \text{CH}_4 \) restriction). This study was limited because the
dynamics did not allow for a feedback for consumption of higher quality, more digestible feeds to improve milk yield. It was additionally restricted because although N, K, P and Na excretion were quantified, no attempt was made to identify if CH4 emissions could concurrently be minimized with any of these other environmental outputs.

Previous studies have also used mathematical optimizations to assess the impacts of dietary changes on multiple environmental variables. Tozer and Stokes (2001b) used a multi-objective optimization to alter diet composition to simultaneously minimize diet cost, N excretion and P excretion. This assessment first ran three individual optimizations, the objective function of each being to minimize one of the objective metrics (diet cost, N excretion and P excretion). Constraints for all optimizations were similar to those in Moraes et al. (2012). After the individual, single-objective optimizations were run, different multi-objective scenarios were calculated. The objective function of the multi-objective optimization was structured to maximize the minimum percentage deviation of each objective metric from a defined minimum value (usually the value of the parameter outputted in a least-cost baseline simulation). This study found that a 29% increase in cost decreased N emissions by 2.3%, and a 15% increase in cost decreased P emissions by 33%. The simultaneous minimization of N and P excretion was not possible either because feedstuffs were not available that allowed for simultaneous minimization, or because animals’ requirements dictated that simultaneous minimization was not feasible. As with the study by Moraes et al. (2012), this study did not incorporate feedback between diet composition and animal performance, nor did it calculate emissions on a per product basis.

There are several gaps within optimization work in animal nutrition. Few studies have
incorporated equations representing feedback between diet and animal productivity. As a result, the biology of the animal has not been taken into account in an appropriate level of detail. Additionally, few studies have incorporated multiple metrics of environmental impact while addressing production costs. Finally, no known studies have incorporated metrics of social acceptability into diet based optimizations. As a result, when attempting to utilize nutritional management of cattle to improve the sustainability of beef production, these gaps should be filled.

**QUANTIFYING SOCIAL ACCEPTABILITY**

When discussing methods to quantify social acceptability of management practices, it becomes imperative to identify whether quantifying social acceptability is appropriate. Through the history of social research two primary schools of thought have persisted. Some researchers assert that quantifying human behavior is inappropriate and only allows a surface-level understanding of phenomena (Denzin and Lincoln, 2011). The opposing argument stresses that quantifying behavior is necessary for definitive, unbiased interpretation (Denzin and Lincoln, 2011). To better understand these thought processes, a deeper discussion of the underlying assumptions of each school of thought is beneficial.

Quantitative research refers to the systematic empirical investigation of social phenomena via statistical, mathematical or computational techniques (Denzin and Lincoln, 2011). These methods are associated with a positivist or post-positivist paradigm and serve to investigate objectives aimed at developing mathematical models, theories and or hypotheses pertaining to phenomena. Quantitative methods center on measurement and quantification and thus data is
presented in numerical form and is processed as statistics, percentages, etc. (Denzin and Lincoln, 2011). Under this paradigm, the presentation of data in numerical form, one eliminates subjective bias from the result and subsequent interpretation. Researchers prescribing to these paradigms believe the knowledge is held in verified (or non-falsified) hypotheses representing established (or highly probable) facts and laws (Denzin and Lincoln, 2011). Knowledge is accepted if the method by which that knowledge was acquired passes sufficient conventional benchmarks of rigor (replication, peer review, etc; Denzin and Lincoln, 2011).

Beef consumer research has ample examples of quantitative research. Survey methods have been employed to explore consumer attitudes toward meat quality (Platter et al., 2003; Voges et al., 2007), traceability (Verbeke and Viaene, 1999), safety (McCluskey et al., 2005), health (Lusk and Parker, 2009) or animal welfare (Harper and Makatouni, 2002). These surveys regularly find different niches of consumers with preferences for particular attributes. Consumers can be roughly broken down to those that consume beef regularly and purchase based on price and quality; those that consume beef and have health/safety concerns; those that consume beef and have welfare/environmental concerns; and those who do not consume beef. While quantitative research methods help to categorize consumers by a type and assess the proportion of consumers in each type, they fail to develop a robust understand of why consumer a consumer falls into a particular classification and how they could be motivated to consume more beef.

Qualitative research refers to the broad spectrum assessment of phenomena through literary interpretation (Denzin and Lincoln, 2011). This method highlights questions such as why and how a decision is made and are centered on targeted, small-scale samples providing empirical support for research hypotheses (Berg and Lune, 2004). Data is presented in literary form as
participant quotes, true to the integrity of the form in which they were collected (Spiggle, 1994). Qualitative researchers assume all data are inherently biased and by collecting data specific to a unique population, a more valid or truthful representation can be obtained. These researchers believe knowledge is held in individual and collective reconstructions of phenomena that sometimes generate consensus (Denzin and Lincoln, 2011; Spiggle, 1994). Rather than relying on conventional quality standards, researchers find trustworthiness of data to be the standard for quality (Glesne, 2011). Qualitative beef consumer research has been infrequently conducted. Verbeke et al. (2010) used focus group discussions to assess how marketing schemes were received by European consumers, finding that consumers accepted marketing but were skeptical of it because they were concerned that they would receive poor quality cuts.

Although these research methods appear contradictory, a new paradigm, “mixed methods” research, has evolved to synthesize the elements from quantitative and qualitative studies (Creswell and Clark, 2007). The research question should contain the development of a mathematical model or theory, and subsequent support as to why or how that model or theory is upheld (Johnson and Onwuegbuzie, 2004). Because mixed methods research is a new idea, there are still several issues that should be resolved before it is advocated as a functional research methodology (Teddlie and Tashakkori, 2003). Perhaps most importantly, the deeply ingrained epistemological differences between qualitative and quantitative research make integrating the research methodologies difficult (Teddlie and Tashakkori, 2003). In response to this concern with mixed methods research, Leech and Onwuegbuzie (2009) developed a typology for mixed methods research which categorizes methods along a continuum from single method (strictly quantitative or strictly qualitative) to fully mixed designs. The resulting ideal mixed method study has the benefit of testing hypotheses (does X affect Y) with a deeper level of understanding.
(why does X affect Y). In beef consumer research, Makatouni (2002) used a mixed-methods approach to understand what motivated consumers to purchase organic food. The study found that consumers valued the individual self-relevance of certain types of organic food; consumers perceived that purchasing organics was a way of achieving individual and social values usually centering on health, environment, or animal welfare. This study was not only able to categorize consumers but to also explain the motivation for why they were categorized in a particular way. By using a mixed approach, data from studies like this can be integrated under both qualitative and quantitative epistemologies for improved acceptance from a wide range of research fields and improved representation of the underlying phenomenon governing a relationship.

**Qualitative Social Research Methods**

Two primary qualitative field methods are ethnography and participatory design (Spinuzzi, 2000). Each methodology has its own theoretical background, data collection specifics and analysis methods. Ethnography was developed within the field of anthropology and focuses on utilizing non-invasive observation to understand a phenomena (Spinuzzi, 2000). Ethnographic methods employ a variety of data collection strategies including field notes, video tapes, audiotapes and questionnaires. The collection of these data focuses on un-obtrusive observation of phenomena (Agar, 1996). In ethnographic research, analysis requires sifting through data and allowing patterns to emerge; results focus on description more than explanation. A weakness of ethnographic research is the time required to develop a robust understanding of baseline behavior, additionally hypothesis testing is nearly impossible as introducing a novel treatment into the system would violate the observer-only tradition of ethnographic research methods (Denzin and Lincoln, 2011).
Ethnographic study of consumer purchasing behavior is unique in that it attempts to understand the cultural or social aspects of purchasing rather than the cognitive, affective aspects (Arnould, 1998). In this manner, ethnography may be able to explain more of the variability in purchasing behavior (Goulding, 2005). In beef research, ethnographic methods have been used to identify that food learning in a household occurs both from parents to children and from children back to parents (Ayadi and Bree, 2010). These methods have also been employed to understand the factors affecting producers adoption of technology (Wright, 2007) or decision to finish cattle on-farm (Lozier et al., 2006). All three studies highlight the role of personal communication and experience in learning and decision making. When attempting to improve sustainability of beef cattle production, these approaches should be carefully considered both when introducing product to consumers and when advocating management options to producers.

Participatory design is a research methodology focused on working with research subjects to explore goal-directed actions (Spinuzzi, 2000). Participatory design focuses on collecting data by co-constructing materials with participants. Typically, participatory design is used to develop prototypes, simulations and games. Data are analyzed by both researchers and subjects to produce, examine and modify new prototypes. Participatory design encourages incremental changes and focuses on developing solutions to issues presented by participants. Benefits of participatory design lie in community comfort and service. Participatory design research seeks to identify the needs of a community and work with that community to identify and implement a solution (Spinuzzi, 2000). A limitation of this methodology is that it is difficult to affect any sort of radical change and the gradualist nature of the research design can lead to some stakeholders being over served while others are ignored (Spinuzzi, 2005). Participatory methods have been
employed in beef cattle research, typically when assessing technology adoption (Parminter, 1997; Parminter et al., 1996) or understanding farm system dynamics (Gouttenoire et al., 2010). When attempting to advocate on-farm management to improve beef sustainability, a participatory approach may be useful.

Several types of data are used in qualitative research; each is most appropriate to particular experimental methods. Two of the most commonly used methods to acquire data are focus groups and in depth interviews. Focus groups are a research technique to collect data from group interaction on a topic determined by the researcher (Morgan, 1996). Data collected from focus groups is based on the interaction of the group rather than individual opinions. For this reason, focus group data can be more applicable to studies focused on group interaction, interpersonal dynamics, public opinion or other broad focuses. Focus groups can be problematic when strong personalities or poor group dynamics bias the response data. In beef consumer research, focus groups have been used to understand how consumers perceive beef safety, quality, welfare and other attributes (De Barcellos et al., 2010; McCarthy and Henson, 2005; Verbeke and Viaene, 2000). These find that consumer perceptions of beef attributes are deeply rooted in previous personal experience and current advertising or social trends; therefore, these factors should be taken into consideration when attempting to educate consumers about beef product sustainability.

In-depth interviews are a technique to collect data from individual participant responses to an interview protocol. Interview protocols can be structured, partially structured or free form based on the needs of the research (Glesne, 2011). Interview questions can range in depth and can either be closed- or open-ended. Data obtained through interviews is more applicable to studies focused on individual opinion, individual interaction with a stimulus or other specific focuses
In-depth interviews can be beneficial because strong personalities do not color responses as severely as in focus group data. In consumer research, in-depth interviews have been used to determine target consumer profiles (Wolf and Thulin, 2000) and the effects of publicity on consumer valuations of labeling schemes (Verbeke et al., 2002). Interviews were valuable when identifying a target consumer profile for local food products because self-identification of attributes resulted in more accurate profile description than hypothesized attributes generated by researchers. Likewise, these studies concur that advertising and social pressures influence consumer perceptions of food labels.

Quantitative Social Research Methods

Survey research is the most common method of measuring social phenomena. Development of questions in survey research is imperative to the success of the research. Surveys should be validated extensively to identify whether respondents interpret questions correctly (Evans, 1991). Leading questions often unintentionally bias survey responses (Davies, 1999). Populations surveyed should be compared to the demographics of the responding sample to ensure the sample adequately represents the population. Non-response bias and response bias are difficult to manage in survey research; ensuring the sample demographic matches the population demographic is a good way to manage these forms of bias. A common method of assessing consumer perceptions of beef attributes is through measuring their willingness to pay (WTP).

**CONSUMER WILLINGNESS TO PAY**

Several methods of quantifying behavior are available. The subclass of behavioral quantification most related to sustainability is quantification of consumer WTP. Consumer WTP is a metric of the price premium that a consumer would pay for a good with a particular quality. Increased
WTP is correlated with increased consumer satisfaction (Homburg et al., 2005). Estimates of consumer WTP can be used to forecast market response to price changes and for modeling demand functions.

Several methods exist to quantify consumer WTP (Breidert et al., 2006). These measurement methods can either be monadic or competitive (Marbeau, 1987) meaning that price information can either be based on the good by itself or by comparing the good to other, similar goods. Studies can either measure WTP on an individual level or on an aggregate level (Breidert et al., 2006). Finally, studies can either measure WTP in experimentally controlled settings or in uncontrolled settings (Nagle and Holden, 2002). Breidert et al. (2006) organized these distinctions into a flowchart where WTP can be either measured by revealed preference or stated preference. Revealed preference methods can either use market data or experiments. Experimental methods include lab tests, field tests and auctions. Stated preference studies can either use direct surveys or indirect surveys. Direct surveys include expert judgments or consumer surveys while indirect surveys include conjoint analysis and discrete choice analysis.

Market data can be derived from purchase data reported by a customer panel or from sales records of stores. Using market data for WTP estimates is advantageous because it is based on real purchases rather than hypothetical, stated purchase preferences. This is perhaps the most authentic research setting for WTP research. Not only do consumers purchase food in an environment where they would normally purchase, they must spend their own money and distinguish between several different competitive goods. Disadvantages to this method are related to the application of WTP results to products that do not yet exist. Price variations in market data are usually small and are therefore insufficient to cover the desired span of WTP
estimates. Both Schulz et al. (2012) and Martinez (2008) used scanner data to assess real premiums paid for various beef labels. Martinez (2008) found that company-specific labels related to natural, grass-fed or organic attributes had the highest premiums. Schulz et al. (2012) identified high-quality, organic and novel products garnered the largest premiums. These data demonstrate that consumers value meat products with personal health and perceived environmental attributes and that novelty improves WTP.

Lab experiments seek to simulate real purchasing environments by giving participants money and requiring them to spend that money on a specific set of goods. Laboratory experiments have several advantages. Whereas market data provides an authentic setting, laboratory data yield an experimentally convenient dataset. In a lab experiment, treatments (the desired product and span of WTP) are selected by the researchers indicating that the resulting data will be applicable to the research objective. Furthermore, results are obtained quickly because experiments need only be designed and coordinated. Lab experiments are disadvantageous because of their context – consumers are aware that they are in an experimental setting and therefore may adjust their behavior accordingly - the context of lab experiments therefore results in low external validity (Nessim and Dodge, 1995). Furthermore, lab experiments do not allow consumers to take possession of the purchased goods after the experiment and do not allow require participants to use their own money (Nagle and Holden, 2002). These traits of the experimental design further remove the context from that actual market and therefore generate results with even lower external validity.

Field experiments follow the general setup of a lab experiments but they take place in-store. A difference between field experiments and lab experiments is that in some field experiments,
participants are not aware that they are participating in an experiment and thus behave more naturally. Field experiments have the advantage of controlling product labeling and pricing to generate applicable data. Although field experiments have results that are more externally valid compared to laboratory experiments, they are less convenient because they require more time, closer monitoring and cost more to put together (Urban and Hauser, 1993). Field experiments have a more applicable experimental context but sample size of field experiments is rarely sufficient to represent true national market dynamics. As a result, field experiments may be a poor method of determining WTP for environmental meat attributes.

Auctions can be classified as either laboratory or field experiments. Several different types of auctions can be used however, the Vickrey second-price auction is frequently used in experimental auctions because it is designed to elicit the consumers’ true valuation of a production (Vickrey, 1961). In a Vickrey auction, all bids are closed and the bidder with the second-highest bid receives the good. Another type of auction form used is the Becker, DeGroot and Marshak (BDM) auction (Becker et al., 1964). In this auction form, each bid is submitted simultaneously – the sale price is randomly drawn from a distribution of the prices submitted. All participants bidding higher than the randomly selected sale price receive the good (Becker et al., 1964). Experimental comparisons between Vickrey auctions and BDM auctions show that Vickrey auctions are superior when attempting to elicit WTP of private goods because the dispersion of bids is narrowed to a true-valuation more rapidly (Noussair et al., 2004). Most advantages or disadvantages of an auction depend on whether the auction is conducted in a laboratory or field setting. Auctions are beneficial because they require consumers to spend money to purchase goods and in the context the external validity of auctions is higher than
traditional laboratory experiments. Estimates of WTP for environmental beef attributes should ensure that non-hypothetical valuation, like an auction method, is used.

Consumer surveys estimate consumer WTP for a good by directly asking a consumer what they would consider paying for a good. Direct surveying asks the individual to give maximum price they could afford to pay for a good and subsequently asks the minimum price they would pay without suspecting quality issues with the product (Marbeau, 1987). Alternative takes on the approach use a price sensitivity measure by including questions about a reasonable cheap price and a reasonable expensive price for the product (Van Westendorp, 1976). Surveys typically use a conjoint analysis or a choice experiment approach. Conjoint analysis relies on the additive compensatory decision rule (Lilien et al., 1992) which assumes that the utility of a product is the sum of the part-worths of the levels of all of its attributes. Discrete choice analysis allows respondents to choose between alternative product profiles (Ben-Akiva and Lerman, 1985; McFadden, 1980), goods are broken down into attribute levels and part-worths are estimated based on those levels. Rather than asking consumers to value each attribute combination presented in the survey, discrete choice analysis requires consumers to select one attribute combination that they would rather purchase.

Several disadvantages exist with consumer surveys. Surveys place an abnormal focus on price which distracts from other attributes of a good. Surveys give consumers no incentive to reveal their true WTP and even if the true WTP is given there is no guarantee of it transferring to real purchasing behavior. The task of responding to these surveys is cognitively challenging for participants (Brown et al., 1996) and perceived valuation of a product is not usually consistent over time or between participants. Advantages to a survey include the ability to structure the
questions to produce applicable data. Furthermore, surveys are time and cost efficient. Many studies have used survey approaches to test WTP for beef attributes (e.g. Alfnes et al., 2006; Tonsor and Schroeder, 2003; Umberger et al., 2009a). Variability between valuations in survey studies and auction studies make developing average WTP values across studies difficult.

Willingness to Pay Studies in Beef

Several of these methodologies have been employed in studies measuring the WTP of beef products. These studies are particularly important because they give estimates of the consumer WTP for specialty attributes of beef. When attempting to measure social acceptability of management practices, WTP estimates can help to identify whether costs incurred by producers when changing management will be offset by consumer WTP.

A survey of the AGRICOLA database was conducted by Fingerhut et al. (2001). The objective of this study was to evaluate consumer acceptance of pathogen-reducing technologies available to beef packers. The study surveyed participants in Manhattan and Topeka, KS using a discrete choice approach, with results analyzed using a logistic regression model. The results of the study indicated consumers were willing to pay a $0.34 premium per lb for ground beef that was steam-pasteurized rather than irradiated. Similarly, consumers would pay $0.31/lb premium for ground beef that was hot-water pasteurized rather than irradiated. This result indicates a WTP for beef with personal health benefits.

Thilmany et al. (2003) measured the consumer WTP for natural beef products in Colorado. Researchers mailed a survey to beef consumers in Colorado using contingent valuation methods to identify stated WTP for natural beef products. In this case, natural beef products were from
“animals raised using sound grazing practices with no antibiotics or hormones and never
confined to small or crowded pens”. Results showed that most consumers would pay a of 24% premium for natural ground beef. These findings show that consumers have a measurable WTP for beef with personal or environmental health benefits. This is one of few studies focusing on WTP for a public good.

Lusk et al. (2003) conducted a 4-country study on WTP for beef from cattle not administered growth hormones nor fed genetically modified corn. The research employed a discrete choice survey of consumers in France, Germany, the United Kingdom and the U.S. to identify what consumers would be willing to pay for two rib eye steaks with four different quality attributes and one price attribute. Data were analyzed using a multinomial logit model to identify the part worths of each of the four attributes (marbling, tenderness, growth hormones and genetically modified corn). In the U.S., consumers were willing to pay an $8.12/lb premium for beef from animals not treated with growth hormones and a $3.31/lb premium for beef from animals not fed genetically modified corn. These premiums were, on average, lower than those elicited in European countries. In this study, consumers were further shown to have a strong WTP for beef with personal health benefits. Furthermore, although the overall trend in WTP is consistent between countries but cross-culture differences in the absolute value of beef WTP were demonstrated.

Consumer WTP for marbling and tenderness of beef was studied by Platter et al. (2005). An experimental auction was used to identify what consumers were willing to pay for beef with ideal marbling and tenderness. A sealed-bid Vickrey auction was used to elicit consumer WTP. Data were analyzed by stepwise logistic regression. When comparing across USDA quality grades using Select as a base, consumer were willing to pay a $0.51/lb premium for low Choice
beef, a $0.89/lb premium for high Choice beef and a $2.47/lb premium for Prime beef. This study was novel in its use of an experimental auction to measure WTP for quality attributes of beef. The results of the study indicate that consumers have a relatively high WTP for tenderness and marbling in beef. This WTP is reflected in retail markets by the price spreads between Select, Choice and Prime beef.

Blecher et al. (2007) used a conjoint analysis survey to distinguish consumer WTP for beef produced under different production techniques with different environmental impacts or purchasing rules. Two separate studies were used, one of the general population and one from an environmental society. Specifically, the researchers tested three labels: natural, conventional and natural with vaccinations. Some beef was labeled with no environmental benefit, some was labeled with an explanation that the beef was produced using practices to preserve wildlife habitat in riparian zones and some was labeled with an explanation that that the beef was produced using practices to preserve vegetation. Results for WTP were presented in an aggregated form. The general population was willing to pay a 13.8% premium for beef produced with environmentally beneficial attributes. The environmental group was willing to pay a 29.6% premium for beef produced with environmentally-beneficial attributes. This study, like the research from Thilmany et al. (2003) indicated that consumers are willing to pay a premium for public goods. Additionally, this study illustrated opportunity for niche marketing to specific societal entities such as environmental awareness groups.

The WTP for food safety, country of origin labeling and food traceability were studied by Loureiro and Umberger (2006) using a discrete choice survey. The study focused on WTP for
different beef safety attributes to identify which were most highly valued by consumers. Results indicated that consumers were willing to pay a $2.57 premium for beef labeled with its country of origin or a $1.90 premium for beef traceability. These WTP values were higher than the WTP for tender beef ($0.95) but much lower than the WTP for USDA food safety inspected beef ($8.07). These results indicate that consumers prefer safety inspected beef to traceable beef, and prefer beef with personal health attributes to beef with quality attributes.

The study of consumer WTP for beef safety was further explored by Tonsor et al. (2009). A discrete choice experiment was used in a survey of approximately 1000 consumers in the U.S., Japan, Mexico and Canada. Food safety attributes studied included country of origin labeling, assured tender, 40% enhanced safety or 80% enhanced safety. Results were presented for three different consumer groups in each country. These groups were “frequent consumers, low income”, “frequent consumers, high income”, “infrequent consumers, low income”. In general, infrequent consumers with low income were willing to pay more for tender beef and safe beef than frequent consumers. Consumers in the U.S. were willing to pay lower premiums than consumers in other countries. Japanese consumers were willing to pay the greatest premiums for beef. Consumers were willing to pay more for improved safety than for tender beef. Much like the results presented by Lusk et al. (2003), this study shows similar trends in WTP across countries but demonstrated differences in the magnitude of that WTP. These results concur with previous studies that WTP for personal health attributes is greater than for quality attributes.

Although most studies of consumer WTP for beef products explore the valuation of a product based on its attributes, some studies explore the impact of consumer knowledge on WTP. Beriain et al. (2009) identified consumer WTP for U.S. and Spanish beef under different information
scenarios. The study was conducted in-person and used a contingent valuation method to identify purchase intention and WTP. Three different information scenarios were used: taste only; knowledge of production conditions and fat level; and knowledge of production conditions, fat level and origin. Consumers were willing to pay $15.05/lb for U.S. grain fed beef when only taste was used as information. When consumers were aware of the production conditions and the fat level in the beef, that WTP decreased to $8.31/lb, but when origin of beef was added as information, WTP increased to $10.00/lb. These results indicate that attributes that influence flavor (marbling, tenderness, color) increase consumer WTP but health information associated with those attributes (higher fat content) reduces WTP. This data supports the idea that consumers are willing to pay more for beef with personal health benefits than they are for high quality beef.

Another study centered on the relationship between information and WTP identified WTP for grass-finished beef in the U.S. (Umberger et al., 2009a). An experimental action was used to determine what a consumer would pay for grass-fed beef with various levels of information. First, consumers were only allowed to taste products and then bid for them based on taste test – consumers purchasing grass-finished beef were only willing to pay 96% of the price of grain-finished beef. In the second phase, consumers were allowed to taste test and visually assess the products prior to bidding – consumers purchasing grass-finished beef were only willing to pay 92% of the price of grain-finished beef. Consumers were then allowed to visually assess products and read about the production practices for each – there was no statistically significant difference in bids for grain-fed and grass-fed beef. In the fourth phase, consumers were allowed to visually assess products and read about the fat content information related to each – consumers
purchasing grass-finished beef were willing to pay 13% more than the price of grain-finished beef. Finally, consumers were allowed to visually evaluate products, read production and fat content information and taste test the products – there was no statistically significant difference in the average bid for grain-fed and grass-fed beef. These data indicate that, although production information had a positive impact on consumers’ WTP for grass-fed beef, the health information about grass-fed beef was a far more important factor. Additionally, the quality differences between grass-fed and grain-fed beef have negative implications on consumer’s WTP for grass-fed beef.

A different application of WTP studies is the testing of new brands. Froehlich et al. (2009) noted that there was a lack of fresh, brand-name beef products in the Canadian market. To test the success of various different types of brands, experimental auctions were used to identify consumer WTP for one of four proposed products. Consumers were willing to pay a $1.20/lb premium for Prairie Prime beef, a grain-fed beef product of Canadian origin with assured tenderness, flavor and juiciness. A $1.32/lb premium WTP was identified for Tender Grill beef, a grain-fed beef product with assured tenderness. Nature’s Diamond was proposed as a beef product with no hormones or antibiotics from cattle fed a vegetarian diet without by-products or chemicals on pasture most of their life with management oriented toward welfare, low stress, and low environmental impact. A WTP of $1.31/lb was identified for Nature’s Diamond. The final product tested was Original Angus beef, a premiere Angus product focused on flavor, tenderness and Angus origin. The WTP for this product was $1.31/lb. These results indicated that Canadian consumers were more interested in brands representing personal health or environmental health than they were in brands representing local economic health.
The impact of impure (organic, pasture based) and pure (low-environmental impact) environmental labels for meat were investigated by Tonsor and Shupp (2009). The researchers conducted an online survey of U.S. consumers and used a contingent valuation approach to determine WTP for beef from family owned, smaller than average, pasture based, organic or environmentally friendly production systems. The results of this study showed that environmentally friendly products (WTP = 19.4%) resulted in higher marginal WTP than organic (18.4%) or pasture-based (16.3%) products. Environmental impact (19.4%), organic or pasture production resulted in much higher price premiums than family owned (1.86%) or smaller than average (-10.3%). This study identified that on average, WTP for sustainably produced beef was -5.9% when all variables were taken into account. This negative WTP does not agree well with most other studies of environmental attributes which typically identify small, positive WTP (Corsi and Novelli, 2002; Krystallis and Chryssohoidis, 2005; Napolitano et al., 2009; Thilmany et al., 2003).

Recent studies of WTP have focused on impure environmental labeling, particularly for local food (Adalja et al., 2013; Chang et al., 2013). Chang et al. (2013) identified that consumers would pay $0.48/lb for locally produced ground beef. Importantly, in the marketing of this beef, cut difference, grass-feeding or organic practices did not significantly impact WTP determination. An important advance in the understanding of consumer perceptions of environmental labeling came through the study by Adalja et al. (2013) who identified that most consumers view the attribute “local” as a substitute for production method attributes (i.e. “organic”, “grass-fed”, etc.). This indicated that niche products are viewed as interchangeable. As such, introducing a new niche “low-environmental impact” product may be an inefficient method of affecting a whole-system improvement in beef sustainability.
Several studies have measured consumer WTP for various environmental attributes of beef. Before relying on WTP for environmental beef attributes as a means of incentivizing consumer WTP it is important to gain a better understanding of the nature of consumer WTP. Specifically, if consumers are only willing to pay for impure environmental attributes of beef (organic, grass fed, etc.) this may be an inefficient strategy due to the increased environmental impact of these production systems (Capper, 2012) compared with conventional production. Consumers WTP for environmental attributes can be distilled by quantitatively summarizing currently available data about WTP for beef labels such as: organic, grass-fed, natural, environmental or sustainable. Meta-analysis is a traditional method of synthesizing the findings of several studies into one overall relationship.

META-ANALYSIS

Meta-analysis was first proposed by Glass (1976) who defined it as “statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating the findings”. Meta-analysis is a subset of systematic review (Lean et al., 2009) which is a research methodology aimed at answering a specific research question by collecting data from existing publications that meet a selection criteria (Sargeant et al., 2006). Application of meta-analysis to economics was proposed by Stanley and Jarrell (1989) and conducted by Walsh et al. (1989). Meta-analysis can be used to synthesize studies on beef WTP. Multiple analysis methods can be used but the most appropriate for WTP studies is meta-regression analysis (Nelson and Kennedy, 2009).

Meta-analysis is a useful tool when answering many types of objectives. For some time, the technique was used only to identify the absolute effect of a treatment (Nelson and Kennedy, 2009). As analysis methods have become more sophisticated, meta-analyses have been designed
to identify what is responsible for the heterogeneity in responses (Nelson and Kennedy, 2009). Finally, equations derived from meta-regression analysis can be used to predict values of an output variables based on a particular set of inputs (Nelson and Kennedy, 2009).

Within the meta-analysis, a literature search is utilized to identify as many relevant studies as possible. It is not feasible to identify every relevant study available but identifying a wide array of studies is important to avoid bias (Lean et al., 2009), therefore, the literature search framework should be clearly defined prior to investigation. After literature has been collected, studies are chosen for inclusion in the meta-analysis. When outlining the framework of the literature search, the inclusion criteria for studies should also be defined. Inclusion criteria are specifically outlined to filter out data that will not be applicable to the objective. In economic studies, this inclusion criteria should ensure that all studies are measuring the same economic concepts (Nelson and Kennedy, 2009).

After a literature set has been identified for inclusion in the study, literature is summarized quantitatively. This frequently includes defining independent variables using binary dummies (Nelson and Kennedy, 2009). Previous meta-analysis of studies on WTP have used independent variables characterizing study design, location, valuation method, model specification and data analysis (Lusk et al., 2005). Dependent variables in meta-analysis of WTP studies include either the numerical WTP premium presented in the study or that premium as a percentage of a base price. Meta-regression models can either be fixed-effect or random-effect models. Fixed-effect meta-regression is used typically for studies attempting to identify the absolute effect of a treatment on a response variable because fixed-effect meta-analysis assumes that the sole source of variation is within-studies (there is no between-study variation). Random-effect meta-analysis is usually used for studies focused on understanding the between-study variation because it
assumes that a distribution of effects exists. This distribution results in heterogeneity across studies.

To determine whether a dataset is appropriate for meta-regression, the publication bias within the dataset can be examined through the use of a funnel plot (Light and Pillemer, 1984). An ideal funnel plot demonstrates symmetry and indicates that there is minimal publication bias. Another test for publication bias identifies over-emphasis of small study effects (Egger et al., 1997). Together, these tests can be used to ensure a sample is appropriate size and distribution for meta-analysis.

**Frequentist Fitting Procedures**

Most meta-regression fitting procedures adjust equation parameters to minimize a target summary statistic in much the same way that ordinary least-squares regression minimizes the sum of the squared deviations between the predicted line and the data observations. Meta-regression can be conducted using the metareg command of Stata version 10 (Borhan et al., 2011). This software fits data to the standard random-effects meta-regression model.

\[ Y_i = \sum_j (\beta_j x_{i,j}) + u_i + \varepsilon_i \]  

Where \( Y_i \) is the true effect response in the \( i \)th study, \( \beta x_{i,j} \) is a linear predictor of \( Y_i \) related to attribute \( j \), \( u_i \) is the between study error and follows a normal distribution with mean = 0 and variance \( \tau^2 \) and \( \varepsilon_i \) is the within study error and follows a normal distribution with mean = 0 and variance equivalent to the variance of study \( i \) (\( \sigma_i^2 \)). Restricted estimated maximum likelihood estimation (REML) is often used to minimize \( \tau^2 \) by iterating the values of \( \beta_j \) based on maximizing the residual log likelihood (see Harbord and Higgins, 2008; Harville, 1977).
Although several methods are available to estimate $\tau^2$, REML is the most common because it is an iterative estimation method noted for accurate and robust coefficient estimation (Thompson and Sharp, 1999).

The REML algorithm uses the $\tau^2$ estimated by the non-iterative Method of Moments method (DuMouchel and Harris, 1983) as a starting value. The Method of Moments algorithm estimates $\tau^2$ based on the relationship between the observed and expected values of $Q_{res}$, the residual weighted sum of squares (DuMouchel and Harris, 1983). The $\tau^2$ value is then iteratively updated based on maximization of the residual log likelihood of $\tau^2$ as outlined by Harbord and Higgins (2008). During each iteration of $\tau^2$ estimation, the model coefficients, $\beta$, are subsequently estimated by weighted least squares using weights $1/(\sigma_i^2 + \tau^2)$ following Thompson and Sharp (1999). In this weighting scheme, $\sigma_i^2$ is the square of the within-study variance. This allows the individual study variability to be accounted for as is recommended within meta-analyses of economic data (Nelson and Kennedy, 2009).

Several metrics of regression quality are used in Frequentist fitting procedures. The adjusted proportion of between-study variance explained by the covariates, $R^2$, represents the proportional difference in the modeled $\tau^2$ and the between-study variance when no covariates were fit.

Significance values, $p$, for each coefficient can be calculated by comparing the means and their variability to a student’s $t$ distribution (Harbord and Higgins, 2008; Higgins and Thompson, 2004). An overall model significance value can also be calculated through a multi-parameter Wald test which comparison of the test statistic to an $F$ distribution. Finally, the proportion of residual between-study variation, $I^2_{res}$, is a measure of the ratio of the residual weighted sum of
squares less the degrees of freedom to the residual weighted sum of squares following Higgins and Thompson (2004).

Bayesian Fitting Procedures

An alternative means of fitting models is Bayesian fitting. Bayesian inference is based on Bayes' theorem which states that the probability of event X given event Y is proportional to the ratio of the product of the product of Y given X and the probability of X. Bayesian fitting procedures typically use a linear regression model with unequal variance as outlined by Gelman et al. (2004):

\[ y = X \beta + \epsilon \]

where \( y \) is a matrix of dependent variable observations, \( X \) is a matrix of independent variables with \( \beta \) representing the regression coefficients. The error term \( \epsilon \) is normally distributed with mean zero and non-constant variance. Heteroskedasticity occurs when a sample is derived from subsamples of different populations which have unique variances. This is a common occurrence in meta-analyses because the samples used in each valuation are often sourced from widely different populations and valuations utilize different methodologies. In most Bayesian models, the exact form of heteroskedasticity is assumed as an unknown where the error variances originate from the normal distribution and the prior is estimated from previous data.

Specification of priors is a very important part of Bayesian model fitting.

While REML methods reduce the deviation of the modeled data from the observed data, Bayesian fitting methods adjust the probability of the observed data, as predicted by the model to make the observed data the most likely (Wasserman, 2000). The prior distribution is used to
represent how likely different values of a parameter are prior to accounting for the observed data (Wasserman, 2000). The algorithm then observes the data and computes the posterior distribution based on Bayes theorem (Wasserman, 2000). Improper specification of the prior can initiate the model in entirely the wrong portion of the distribution and as such, non-informative priors are commonly used (Jeffreys, 1961; Wasserman, 2000). When information is available to properly specify an informative prior, these commonly result in improved model poster probabilities (Ahtiainen and Vanhatalo, 2012).

Model fitting typically relies on Gibbs sampling of Markov Chain Monte Carlo simulations because this method allows for fitting models of virtually unlimited complexity (Carlin and Chib, 1995). Traditional fit statistics like the R² can be used with Bayesian analysis but they are discouraged as a means of selecting models (Carlin and Chib, 1995). Model comparison and selection is more appropriately performed by calculating Bayes Factors (Kass and Raftery, 1995). During fitting, the log marginal likelihood of different proposed models can be calculated and compared to identify models that are different from each other. Bayes Factors can also be calculated and compared (Kass and Raftery, 1995) to determine which models were substantially different from each other. Model error terms and log marginal likelihood can be used to evaluate the Bayesian models. Bayes factors can even be used to average models based on their posterior probabilities (Hoeting et al., 1999).

**Meta-Analyses of Consumer Willingness to Pay**

**Frequentist Approaches**

Several studies have used meta-analyses to summarize studies estimating consumer WTP. Lusk et al. (2005) used 57 WTP valuations to estimate WTP for genetically modified food. The model
presented was estimated using Frequentist estimation of a linear model with WTP as the dependent variable and several binary indicators as independent variables. The resulting model explained 89% of the variability in WTP estimates. This analysis identified that the consumer characteristics studied, the method of eliciting the WTP valuation and the food characteristics significantly impacted WTP. Although a large proportion of the variability in WTP was explained, the study did not appear to take individual study variability into account as is suggested by (Nelson and Kennedy, 2009).

Cicia and Colantuoni (2010) assessed WTP for meat traceability. The researchers acquired 88 valuation of WTP and used multiple regression to estimate WTP as dependent on independent variables for meat type, consumer characteristics, and meat labeling. The model had problems with heteroskedasticity between variables selected. Re-specification of the model did not improve the issues. The model only explained 29% of the variability in WTP. This low $R^2$ indicates that the researchers did not select variables that correlated well with the sources of variability in the dataset. The lack of fit in comparison to Lusk’s study may be because of the larger sample size in this study or because WTP estimates of traceability vary more than estimates of WTP for genetically modified food. Again, the study did not appear to take individual study variability into account.

Lagerkvist and Hess (2011) used 106 valuation to estimate WTP for farm animal welfare. The researchers used independent variables similar to Cicia and Colantuoni (2010) and Lusk et al. (2005) in addition to more specific variables about respondents (age, income, etc.). Lagerkvist and Hess (2011) used a weighted least squares fitting procedure following Stanley (2001). The authors compared models using robust standard error estimates to those with no accounting for
standard error. The models explained between 91% and 94% of the variability in WTP. Although this model fitting procedure resulted in models with greater correlation to the data, there was substantial co-linearity between the variables included in the models. Using Frequentist methods to fit meta-regression models frequently results in issues with multi co-linearity between variables. A Bayesian approach is one way that this pitfall can be avoided.

Bayesian Approaches

Bayesian model fitting approaches have also been used to identify models to predict consumer WTP. The author knows of no Bayesian approach that has been used in valuations of consumer WTP for beef attributes. Ahtiainen and Vanhatalo (2012) estimated WTP for water quality preservation and eutrophication prevention from 29 valuations of WTP. The researchers estimated eight models differing in error term, functional form and prior distributions. The models were then compared using log likelihoods and averaged based on their posterior probabilities. The models with informative priors performed significantly better than the models with uninformed priors. This indicates that informed priors improve the posterior probability of models estimating consumer WTP. Additionally, the researchers found that consumers were willing to pay a premium to preserve water quality and prevent eutrophication.

McCarron et al. (2013) compared Bayesian model estimation methods with non-parametric bootstrapping methods. The resulting models developed by these two approaches were similar; however, the Bayesian model allowed for incorporating additional data in for form of informed priors. This subsequently changed the results and conclusions that would be drawn from the model. This study assessed cost-effectiveness and incremental net monetary benefit of medical technology. Few studies have compared Bayesian approaches to other estimation approaches.
when modeling WTP data. This type of comparison is vital to understanding whether Bayesian methods can be used to improve the predictive capability of WTP models.

SYNTHESIS AND SUMMARY

Current trends in population dynamics, meat demand and resource availability indicate that improved sustainability of meat production systems is paramount. To affect improvements in beef production sustainability, researchers must have an understanding of the environmental, economic and social implications of management practices and be able to make logical, scientific suggestions to producers regarding these implications. Within the current body of literature, there are readily available methods to quantify environmental impact, economic viability and social acceptability of products. Whole-farm assessment approaches can be used to understand the whole-system implications of management practices on environmental impact. Assessments of firm profitability or income over variable costs, beef supply and demand dynamics are all tools to understand the economic viability of beef production systems. Consumer WTP is a good indicator of consumer satisfaction and can be used as a measure of social acceptability.

Previous studies have integrated environmental and economic assessments, typically through the use of whole farm models. Whole farm models can be optimized to identify management practices that will reduce environmental impact of beef production systems. To the author’s knowledge, an optimization model simultaneously minimizing GHG, land use and water use from beef production systems has not been developed. Additionally, the current body of literature has not described the social implications of management practices. These gaps within the literature should be investigated before management practices that improve sustainability can be reliably identified.
LITERATURE CITED


IPCC. 2006. IPCC Guidelines for national greenhouse gas inventories. Institute for Global 
Environmental Strategies for the IPCC, Kanagawa, Japan.

Change, Geneva, Switzerland.


Johnson, I. 2013. DairyMod and the SGS Pasture Model: A mathematical description of the 
biophysical model structure. IMJ Consultants, New South Whales, Australia.

DairyMod and EcoMod: biophysical pasture-simulation models for Australia and New 

Johnson, I., G. Lodge, and R. White. 2003. The sustainable grazing systems pasture model: 
Sci. 43: 711-728.

plant and crop physiology. The Blackburn Press, Caldwell, NJ.

methane emissions from ruminant livestock using a SF₆ tracer technique. Environ. Sci. 

2492.

Johnson, R. J., D. Doye, D. L. Lalman, D. S. Peel, and K. C. Raper. 2008b. The adoption of best management practices in stocker cattle production. Masters, Oklahoma State University, Stillwater, OK.


Mekonnen, M., and A. Hoekstra. 2010. The green, blue and grey water footprint of farm animals and animal products.


Provenza, F. D. 2006. Postingestive feedback as an elementary determinant of food preference and intake in ruminants. J. Range Manage. 48: 2-17.


Watershed Management Research Unit, USDA Agricultural Research Service, University Park, PA.


USDA/APHIS. 2011. Feedlot 2011 Part I: Management practices on U.S. feedlots with a capacity of 1,000 or more head. USDA/APHIS, Fort Collins, CO.

USDA/ERS. 2013a. Beef and Veal Summary Selected Countries. URL:


USDA/ERS. 2013b. Broiler Meat Summary Selected Countries. URL:


USDA/ERS. 2013c. Pork Summary Selected Countries. URL:


2003. OVERSEER® nutrient budgets—moving towards on-farm resource accounting. In:  
740.  
Witt, U. 1999. Bioeconomics as economics from a Darwinian perspective. Journal of  
Bioeconomics 1: 19-34.  
17: 417-421.  
Wright, M. D. 2007. Technology diffusion and the beef industry: A communication  
investigation. ProQuest.


Figure 1. Visual depiction of a linear optimization with two constraints. The x-axis represents the quantity of any given Input 1 used while the y-axis represents the quantity of Input 2. The solid line and the large dashed line represent hypothetical constraints on the system. The small dotted line represents a production isoquant. The shape outlined by ABCD is the feasible set. The line sections ABC represent the production frontier.
Figure 2. A visual representation of the dilution of maintenance effect. The control scenario, representative of an average steer, uses 51% of daily energy consumed for maintenance. The efficient scenario, representing a 15% improvement in finishing weight, only uses 40% of daily energy consumption for maintenance. In the Economic Capital portion, the improved biological efficiency of the animal translates to an improvement in the proportion of diet cost going to maintaining the animal.
CHAPTER 3

BEEF EFFICIENCY AND SUSTAINABILITY

INTRODUCTION

Throughout human societal evolution, the term sustainability has had myriad definitions. Although first defined by forestry professionals in the early 1700’s (Wiersum, 1995; Wilderer, 2007), sustainability did not become an important policy concept until the 1980’s, when concern about excessive resource use drove publication of a report by the United Nations World Commission on Environment and Development (WCED, 1987). The Brundtland Report, as it is more commonly known, indicates that sustainable development must integrate social, economic and environmental concerns and that on a global scale, an absolute plan to improve sustainability is difficult to develop because of the complexity of the systems involved (WCED, 1987).

Although the exact definition of sustainability has been debated extensively since the Brundtland report (e.g. Bonevac, 2010; Chichilnisky, 2011; Kuhlman and Farrington, 2010), most scholars agree that the three sustainability pillars presented in the report (environmental impact, economic viability and social acceptability) are qualities of sustainable systems. Environmental impact, economic viability and social acceptability of a system can be quantified. Therefore, investigation of these three qualities allows for quantitative and scientific assessment of food production sustainability.

The objective of this work was to quantify metrics of environmental impact, social acceptability and economic viability for beef production systems varying in efficiency. It was hypothesized that improving productivity through increasing finishing weight (FW) or average daily gain (ADG) would concurrently reduce environmental impact, improve profitability and enhance beef’s social acceptability.
MATERIALS AND METHODS

A deterministic model of the environmental impact of beef production in the U.S. described by Capper (2012) was adapted and used to quantify resource use and greenhouse gas emissions (GHGe) from beef production. These metrics of environmental impact were calculated for each production scenario (control, increased FW and increased ADG). Dietary inputs to the above model, animal populations sold and animal sale weights were used to calculate enterprise budgets for cow-calf, stocker and feedlot subsystems. Economic viability was quantified by income over variable costs (feed and animal acquisition costs; IOVC). There is no widely accepted definition of social acceptability as it pertains to beef sustainability. Selecting a metric of social acceptability began with exploring how altered acceptability directly affected beef production. When assessing the ability of beef production systems to sustain into the future, social acceptability could affect production in two primary ways. First, improved social acceptability could increase interest in purchasing a product, while decreased acceptability could decrease purchasing interest. In the more extreme scenario, decreased social acceptability could lead to legislation impeding the freedom of operation of beef producers. Quantitatively predicting consumer voting patterns and likelihood of legislation proposal was outside the scope of this paper. Therefore, the best available method of quantitatively describing social acceptability was to use consumer willingness to pay (WTP) estimates as an indicator of consumer interest in purchasing beef produced through different management practices. Due to uncertainty in predicting producer and consumer behavior, a series of socioeconomic scenarios were modeled for each production scenario to identify a range of changes in IOVC due to differences in producer response to improved efficiency and packer, distributor, retailer and consumer WTP based on marketing information. Changes in WTP were used as a predictor of a
product’s social acceptability; if a product more acceptable, WTP for the product will increase. Likewise, as a product becomes less acceptable, the price of the product must decrease to incentivize purchase.

The control scenario represented the average FW, ADG and days from birth to slaughter representative of animals within the modern U.S. beef industry based on data from USDA/ERS (2012b), USDA/APHIS (2009a) and USDA/APHIS (2009b). The other two scenarios represented a 15% increase in either FW or ADG. Practical methods to improve FW or ADG might include selecting for animals of superior genetic merit or utilizing growth-enhancing technologies such as beta-agonists, implants or ionophores. In the FW treatment, the length of time animals existed in a subpopulation remained identical to the control scenario and ADG was adjusted to ensure that animals could finish at a weight 15% greater than the control. In the ADG treatment, FW of each subpopulation was kept identical to FW in the control but ADG from birth to slaughter was increased by 15% over the control. Increasing ADG reduced the amount of time animals were kept in a subpopulation. These treatments represent two methods by which animals with improved biological efficiency could be finished in today’s industry. Animals with superior growth rates would either be marketed for slaughter at a particular weight (ADG treatment) or be allowed to grow until their age dictated that slaughter should occur (FW treatment). Animals produced in more efficient systems will be of greater value to packers, distributors and retailers because these animals are more likely finish at an appropriate weight early in life meaning that they are more likely to grade well. The specific ADG, FW and days in a subpopulation for each treatment are shown in Table 1. All metrics of environmental, economic or social sustainability are expressed per 1.0 x 10⁹ kg of hot carcass weight (HCW) beef produced in 365 d.
Production System Characteristics

The production system was parameterized to represent average management practices in the United States (USDA/APHIS, 2009a, b). Three sub-systems were represented within the model: the cow-calf, stocker/backgrounder and feedlot. Populations of animals required to produce $1.0 \times 10^9$ kg HCW beef were calculated according to finishing weights, average mortality rates and known relationships between populations. The cow-calf system comprised cows, calves, replacement heifers, adolescent bulls, yearling bulls and mature bulls. The stocker system contained weaned steers and heifers that were fed until they reached the target exit weight. The feedlot system contained calf-fed (calves that were weaned directly into the feedlot) and yearling-fed (calves that were previously in the stocker system) steers and heifers. These animals were retained in the model until they reached the target FW. Following annual slaughter summaries (USDA/ERS, 2012b), the slaughter populations used in this study were comprised of 12% cull dairy cattle, 5% cull beef cows, 2% cull beef bulls and 81% feedlot cattle of which 12.9% were of dairy origin.

Feedlot and stocker cattle had a mortality rate of 5%. Dressing percentage for feedlot cattle was 63% and average FW are as described in Table 1. From Capper (2011a), the feedlot population was assumed to contain 11.5% Holstein steers from dairies; 1.4% Holstein heifers; 16.5% calf-fed beef steers and heifers; and 70.6% yearling-fed steers and heifers. Feeder cattle from the cow-calf and stocker systems were assumed to be crossbred Angus and Hereford. For conventionally raised beef animals, the proportion of female animals made up 46.5% of the populations after weaning to account for the removal of replacement females from the feeder population. Emissions and resource use from dairy-origin animals in the feedlot were accounted
biologically based on the requirements of a dairy cow during gestation following Capper (2011a).

Female cattle had a conception rate of 89%, of which 96.5% were predicted to birth a live calf (USDA/APHIS, 2009a). Calf mortality rate was 9% (USDA/APHIS, 2009b). Bulls were maintained in the population at a rate of 23.7 cows per mature bull and 16.3 cows per adolescent bull (USDA/APHIS, 2009b). Total herd size was assumed to remain constant, giving a bull replacement rate equivalent to the proportion of bulls that died or were culled annually and heifer replacement equivalent to cow slaughter. Cows weighed 567 kg (Capper, 2011a), had an annual gestation length of 285 d, a lactation length of 207 d (USDA/APHIS, 2009a), milk yield of 1,625 kg/lactation (Miller et al., 1999), milk fat content of 4.03% and milk protein content of 3.38% (National Research Council, 2000). Over the production year, cows were assumed to gain weight during mid-to-late gestation and lose weight during early lactation such that on average, weight was maintained as a constant on a year-to-year basis.

The Environmental Model of Beef Production

The model used to calculate environmental impact was based on that described by Capper (2012). This model quantifies water use, land use, feed consumption, N and P excretion, and CO₂, CH₄ and N₂O emissions. The system boundaries extended from manufacture of cropping system inputs (fertilizers, herbicides and pesticides) to finished cattle arriving at the slaughterhouse door.

Feedstuffs required for the production of 1 x 10⁹ kg of HCW beef were based on diets balanced for metabolizable energy and protein. A ration was formulated for animals within each
population using nutrient requirements predicted by Agricultural Modeling and Training System’s (AMTS) CattlePro diet balancing software (AMTS, 2006) based on breed, age, weight, gender and production level. Rations were formulated using nutritive values for feedstuffs from the AMTS CattlePro feed library (AMTS, 2006) to ensure sufficient energy and protein for each animal’s production requirements. Total amounts of each feedstuff were calculated based on ration composition, days spent in the sub-system and the number of animals in a population. Feed quantities were used to calculate related cropping inputs. Feed wastage during feeding, storage, transportation and harvest were not accounted for, because reliable values for transportation and harvest waste were not readily available.

Land use for beef production was calculated based on the pasture required in the diet for cow-calf and stocker production. Land use associated with cropping was calculated from total crop requirements and the U.S. average yield for that crop (USDA/ERS, 2012b). Water use included the total drinking requirement of animal populations and the requirement for crop irrigation. Drinking water required for each animal population was calculated from a regression equation linking drinking water intake to ambient temperature, animal size and various feed qualities (Meyer et al., 2006). The water use associated with cropping was calculated from total land use and irrigation requirements per ha (USDA/NASS, 2007).

The GHGe included in the study were CO$_2$, N$_2$O and CH$_4$ emitted within the system boundaries and expressed on a CO$_2$-equivalent basis (IPCC, 2007). Sources of CO$_2$ emissions included industrial manufacture of cropping system inputs and emissions associated with tillage and fertilizer application. Emissions from cropping input manufacture were calculated based on quantities of fertilizer, herbicide or pesticide required and the related emission factors published
by Bhat et al. (1994) and Mudahar and Hignett (1987). Emissions from tillage and other crop management inputs were calculated based on the tillage practices required for production and the emissions associated with each process (West and Marland, 2001). Sources of N$_2$O included fertilizer application, direct emissions from manure, and downstream emissions from leached or volatilized N. Emissions of N$_2$O were calculated from N excretion predicted by AMTS CattlePro (AMTS, 2006) and emission factors given by the IPCC (2006), while fertilizer N$_2$O emissions were quantified based on fertilizer requirements for each crop (USDA/ERS, 2012b) and IPCC (2006) emission factors. Emissions of CH$_4$ comprised enteric and manure CH$_4$ production. Enteric CH$_4$ emissions were calculated based on the equation for beef cattle reported by Ellis et al. (2007). Manure CH$_4$ emissions were calculated from volatile solids outputted from AMTS CattlePro (AMTS, 2006) and emission factors given by the IPCC (2006).

The Economic and Social Model of Beef Production

The economic and social components of the model were linked to the environmental impact component through diet and animal characteristics. The economic portion calculated IOVC for the cow-calf, stocker and feedlot. Revenue in the cow-calf operation stemmed from sales of cull cows, cull bulls and feeder calves; whereas stocker and feedlot revenue were generated by selling yearlings and finished animals, respectively. For each sector, animal FW and populations were used to calculate the total weight of four classes of animal sold: culls, calves, yearlings and finishers. Socioeconomic scenarios were used to adjust the value of different cattle classes. These values were used in calculating animal acquisition cost and sales revenues.

For each scenario, enterprise budgets were calculated for each beef production sector based on revenue, feed and animal acquisition costs. In all sectors, feed costs were calculated from the
amount of each feed required and the 5-year-average price received for sales of that feedstuff (USDA/ERS, 2012b). In the cow-calf operation, only feed costs were included in the budget whereas in the stocker and feedlot operations, both feed costs and cattle purchase costs were tracked. Cattle purchase costs were calculated from the number of calves entering each sector, their average weight and the beef price, as dependent on the modeled socioeconomic scenario.

Substantial uncertainty exists when predicting packer, distributor, retailer, consumer and producer behavioral responses to improvements in efficiency of this magnitude. To account for this uncertainty, thirteen socioeconomic scenarios were used to calculate IOVC. Each socioeconomic scenario consisted of one assumption about beef supply dynamics and one assumption about WTP. Supply of beef was expected to react to improved efficiency in one of two ways, either supply would remain constant as efficiency improved or supply would increase (shift outward) to capitalize on improvements in efficiency. When supply was held constant, revenue was based on the weight of each animal class sold and the 5-year-average price received for sale of animals within the class (USDA/ERS, 2012b). When supply shifted outward, flexibility of demand was used to identify the percentage reduction in beef price expected when production increased by 15%. Flexibility of demand is the inverse of own-price elasticity of demand. In this study, own-price elasticity of beef was estimated as the mean of values presented by the USDA/ERS Commodity and Food Elasticities application (USDA/ERS, 2012a). The application identified ten studies presenting an own-price elasticity of beef and the mean elasticity was calculated to be -0.683. Inverse supply and demand functions were log-linear. The inverse of this elasticity (1.464) indicates that for a 15% increase in beef supply, price was expected to decrease by 21.96%.

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The second element of each socioeconomic scenario was a WTP assumption. Predicted WTP was assumed to change in one of three ways depending on how beef was marketed. As efficiency improved, beef could be marketed as: (1) being more efficiently produced (MEP scenario); (2) more efficiently produced with consumer awareness of growth enhancing technology use (MEP+GET scenario); or (3) no change in marketing could occur (noWTP scenario). Estimates of packer/distributor/retailer WTP for more efficiently produced beef were sourced from Igo et al. (2013) based on data for WTP for weight and size of cattle. This premium was used in both the MEP scenario and the MEP+GET scenario. In the MEP scenario, no change in consumer information was assumed and therefore consumer WTP was static and WTP was based entirely on packer/distributor/retailer WTP for more efficiently produced beef. In the MEP+GET scenario, consumer WTP for beef without growth-enhancing technologies as predicted by Thilmany et al. (2003), Tonsor and Schroeder (2003), Lusk and Schroeder (2004) and Umberger et al. (2009b) was included as a penalty and was added to the premium for more efficient production. In the noWTP scenario, no change in WTP occurred.

RESULTS AND DISCUSSION

Whole System Environmental Impact

Animal Populations, Feedstuffs and Land Use

A summary of the population of animals required by each treatment is given in Table 2. In the ADG treatment, days from birth to slaughter decreased but finishing weight did not change; therefore the number of animals required in any population was not different from the control scenario. By contrast, as yield per animal increased, the population required to produce a target amount of beef decreased, thus in the improved FW treatment, the total animal population was
reduced by 11.5% (Table 2). The FW treatment yielded a larger improvement than the ADG treatment for most metrics. This difference between treatments is largely due to changes in herd population - improving the ratio of feeder cattle to the supporting population has a greater impact on all metrics of sustainability than reducing the days from birth to slaughter. The populations simulated in this study were very similar to the populations reported in Capper (2011a) and Capper (2012).

Total feed required to produce $1.0 \times 10^9$ kg beef was $5.04 \times 10^{10}$ kg in the control system. This value is comparable to the value of $5.93 \times 10^{10}$ presented in Capper (2011a). Feed required in the ADG treatment was $4.72 \times 10^{10}$ kg. The system-wide feed efficiency (47.2 kg feed DM/kg HCW beef) in this treatment was 6.39% greater than the efficiency of the control system (50.4 kg feed DM/kg HCW beef). In the improved FW treatment, $4.43 \times 10^{10}$ kg was required. The resulting feed efficiency of this system was 44.3 kg feed/kg HCW beef. This figure is somewhat misleading because it included feed consumption by the supporting population rather than consumption by growing animals alone (a metric reported with much greater frequency). For reference, the mean feed efficiency of growing animals in the control system was 5.8 kg feed DM/kg live weight gain. This efficiency agrees well with the industry standard 6.0 kg feed DM/kg live weight gain (Retallick and Faulkner, 2012).

In the control system $5.95 \times 10^6$ hectares of land were required to produce $1.0 \times 10^9$ kg HCW beef. This figure is greater than the $4.3 \times 10^6$ ha reported in Nguyen et al. (2010) and lower than the figure presented in Capper (2011a) of $6.1 \times 10^6$ ha. Land use predicted in this study may be greater than use calculated by Nguyen et al. (2010) due to differences in US and EU production systems. In the EU system 30% of fed beef animals are derived from dairy calves (compared
with 12.9% in the US) which may help to reduce land-use efficiency because land used to feed and house cows producing dairy-beef calves can be partially accounted to the dairy sector. The difference in land-use efficiencies estimated in this study and by Capper (2011a) are substantially smaller and likely are due to differences in year-to-year crop yields rather than production system differences. Increasing ADG by 15% decreased land use by 3.17% compared to the control system. Increasing FW by 15% decreased land use by 9.2%. One concern with feeding the growing global population is the future lack of arable land for food production (Lambin and Meyfroidt, 2011). Hertel (2011) noted that concern should focus on the cost, rather than the quantity of land in that scarcity will increase land costs, which in turn will increase the cost of food produced on that land. If beef production costs increase, consumers will be asked to bear the cost. Models of beef demand (Chavas, 1983; Dahlgran, 1987; Schroeder et al., 2000; Tonsor et al., 2010) indicate that the beef price is one of the most significant determinants of beef demand. To avoid increasing future beef prices beyond a socially-acceptable threshold, the quantity of land required to produce beef should be reduced through improved productivity.

An additional concern regarding land use is the ongoing debate as to how to use land most efficiently on a feed-efficiency basis. Elferink and Nonhebel (2007) calculated that chicken, pork and beef production required 14.5 m²/kg, 17 m²/kg, and 43 m²/kg, respectively. Arguments against beef production based on land-use efficiency frequently incorrectly assume that all land used for ruminant feed production is of sufficient quality to produce human-food crops, as is often the case with monogastric feed production (Oltjen and Beckett, 1996). The cow-calf sector uses the majority of land within the U.S. beef production system, and it is common practice for cow-calf herds to graze mountain rangeland or forests. This land is not tillable for cereal grain
production (Lubowski et al., 2006; Oltjen and Beckett, 1996). In this study, 86% of total land use was attributed to the cow-calf sector; of that land 63% was low-quality pasture. These figures show that over 50% of land used in beef production is from grazing low-quality pasture, when this percent of non-tillable land was removed from assessment land use per kg beef was reduced to 26 m²/kg. This figure is much more competitive to the metrics for pork and chicken. This result, along with similar metrics from other studies such as the comparison of meat production systems on the basis of human-edible input to output ratios in Wilkinson (2011), reinforce the necessity of selecting appropriate metrics when comparing across production systems.

Water Use

In the control system, water use was 2,409 L water/kg HCW beef. This value was greater than the 1,763 L/kg presented in Capper (2011a) and lower than the number calculated by Beckett and Oltjen (1993) of 3,682 L/kg. Differences in cattle diets and irrigation water required by crops could easily give rise to these differences, in conjunction with Beckett and Oltjen’s (1993) inclusion of processing water. Improving efficiency reduced water use by 12.3% in the ADG scenario (2,112 L/ kg HCW beef) and by 15.5% in the FW scenario (2,036 L/kg HCW beef).

Irrigation accounted for the majority of water use. Irrigation of feedstuffs typically produced off-farm (cereal grain and soy products) accounted for 88% of total water use. Producers importing feed to finish their animals from off-farm only directly control about 12% of the total water used in beef production, and consequently must depend primarily on crop production advances to reduce total water use. Such advances include increasing yield per unit of evapotranspiration; reducing losses and pollution; targeted allocation to more productive areas (Seckler, 1996); or altering irrigation application method (Howell, 2001). Until there is an economic incentive to
purchase crops produced with less water, it is doubtful that cattle producers would elect to purchase crops based on their water usage.

**Nutrient Excretion**

The control system excreted $5.31 \times 10^{10}$ kg of manure, $2.17 \times 10^8$ kg of N and $3.21 \times 10^7$ kg of P. When ADG or FW were increased, manure production was reduced by 4.3% or 8.5%, respectively. Similar dynamics were observed with N and P levels. When ADG was increased, N excretion decreased by 4.09% and P decreased by 13.8% compared to the control system. In the increased FW treatment, N excretion decreased by 10.09% and P decreased by 17.2%. The differences in improvement in N- and P-use efficiency may be due to adjustment of the feedstuffs used according to differences in ADG. Alternatively, the greater improvement in P-use efficiency may be due to differences in biological N and P cycling. Reduced N and P excretion from cattle has both biological and environmental benefits. Improved N- and P-use efficiency stems from proportionally greater utilization of consumed N and P. Reduced N and P excretion also reduces potential for acidification and eutrophication of surface waters. It is difficult to simultaneously minimize N and P excretion through dietary manipulation (Tozer and Stokes, 2001b) but results from the current study reveal that improved productivity decreased both N and P excretion per unit of beef.

**Greenhouse Gas Emissions**

Within the current study, the control system yielded 20.15 kg CO$_2$-equivalents/kg HCW beef. The GHGe from beef production reported by several previous studies (corrected for 63% dressing percentage) are shown in Table 3. Despite inherent difficulties in comparing across
studies (Bertrand and Barnett, 2011; Capper, 2011b), GHGe reported in our study are similar to the values presented by Capper (2011a), Capper and Hayes (2012) and those outlined in Pelletier et al. (2010). Results of the current study concurred with previous studies showing that improved efficiency reduced GHGe (Capper, 2011a; Capper and Hayes, 2012; Ogino et al., 2004; Pelletier et al., 2010). Increasing ADG by 15% reduced GHGe to 18.5 kg CO₂-equivalents/kg HCW beef. Increasing FW by 15% decreased GHGe to 17.8 kg CO₂-equivalents/kg HCW beef. Capper and Hayes (2012) modeled the removal of growth-enhancing technologies from US beef production, and showed that a 10% increase in GHGe per unit of beef would occur if technologies were removed. This change in GHGe is similar to the 12% and 14% reductions associated with improved efficiency related to the ADG and FW treatments in this study. The GHGe of this study differs from other studies in Table 3 due to differing biological parameters, cropping system data, industrial processes accounted, system boundaries (Edwards-Jones et al., 2009) or GHGe sources or sinks accounted for (Stackhouse-Lawson et al., 2012).

Uncertainty associated with the predictive equations for calculating CH₄ and N₂O from animal systems is of greater importance than study-to-study variability. Parameters in the equations predicting enteric CH₄ and manure N₂O were varied according to the confidence intervals presented in Ellis et al. (2007) and IPCC (2007) and the resulting change in GHGe is shown in Table 4. The range of parameter adjustment was similar between the two equations (200% for N₂O and between 122% and 146% for CH₄). Prediction of enteric methane proved vital to GHGe estimation because adjusting CH₄ equation parameters within the reported error bounds caused GHGe to increase by 47% (high bound) or decrease by 53% (low bound). Adjusting manure N₂O parameters only caused GHGe to increase by 8% or decrease by 5%. Although these results indicate that absolute value of GHGe assessments are not infallible, the study conclusions are
unaffected because the change in the difference between the improved efficiency scenarios and the control scenario varied by less than 1% when the adjusted and unadjusted CH₄ parameters were used.

Whole-System Economic and Social Impacts

Baseline Enterprise Budgets

As interest in reducing the environmental impact of production systems increases, there is growing concern from producers about whether reducing environmental impact can be achieved in an economically viable manner. Cattle with increased average daily gain require higher dietary energy concentrations to provide sufficient energy for growth. Likewise, cattle that finish at a heavier weight and have an increased ADG consume more feed on a daily basis (due to their larger size) and also require higher energy concentrations for growth. Increased feed consumption and increased energy requirements frequently result in increased feed costs. To investigate the economic viability of improving efficiency, the baseline scenario was compared to the FW and ADG scenarios before applying any socioeconomic adjustments.

In the control treatment, IOVC in the cow-calf sector was $0.87/d, $0.60/d in the stocker system and $1.27/d in the feedlot. When ADG was increased, cow-calf sector IOVC increased to $0.88 while stocker and feedlot IOVC increased to $0.83/d and $1.51/d, respectively. Under the FW treatment, IOVC in the cow-calf, stocker and feedlot increased to $1.09/d, $0.82/d and $1.53/d, respectively. The breakdown of feed costs, animal acquisition costs and revenue for each sector under each treatment is included in Table 5. In most cases, improving efficiency resulted in reduced costs and improved profitability per unit of beef. In the stocker system, the ADG scenario resulted in lower feed costs than the FW scenario. This was not congruent with the
expected relationship between feed costs and improved efficiency. In this case, the feedstuffs required to meet the nutrient requirements of the animals in the FW scenario were more expensive (due to greater energy density), and this expense was not recouped by the reduced number of animals required. This dynamic illustrates that increases in variable costs can be a very real concern when improving efficiency to reduce environmental impact. It should be noted, however, that revenue increases from sale of heavier cattle resulted in a net improvement in IOVC. Economic efficiency can be modeled using IOVC because feed costs are the highest variable cost on beef operations. It is therefore predictable that despite increased feed costs, IOVC increased in the scenarios representing improved biological efficiency.

In all treatments, the feedlot sector returned the greatest profit margins. The stocker sector had the lowest profit margins and the cow-calf had moderate margins. It is important to note that budgets in this study were based on point-estimates of national-average feed and cattle prices (USDA/ERS, 2012b) and the resulting comparisons of predicted profitability between sectors are limited in their outside applicability. Temporal price fluctuations were not accounted for by this model and the relative increase in the price of corn and soy products in 2012 and 2013 was not represented by the input data. The purpose of this study was not to compare between sectors but rather, to assess how improved efficiency impacted profitability. In all sectors, improved efficiency improved profitability. This study accounted feed costs for all feed consumed by animals. At first glance, feed costs in the cow-calf sector appear inflated because this sector is not usually thought to have exorbitant feed costs. Cost breakdown indicates that 34% of total feed costs are due to pasture and an additional 55% of feed costs are from purchasing stored forages. Pasture and stored forages are not frequently accounted for in partial budgets because they are grown on-farm. This assessment assumed that all forage was purchased at market price.
(USDA/ERS, 2012b) and pasture was leased at $12.00/animal unit month. Inclusion of these forage costs may lead to the seemingly high cow-calf feed cost observed throughout the study.

**Implications of Shifting Supply on IOVC**

When an outward shift in the supply curve was modeled, aggregated industry IOVC decreased regardless of packer, distributor, retailer and consumer behavior. Specific IOVC outputted in each socioeconomic scenario are recorded in Table 6. Across all cases, a 21.75% reduction in beef prices related to the modeled outward shift in supply was not recoverable via improved WTP. This result indicates that economic viability of improving efficiency was jeopardized by situations where supply drastically increased. The outward shift in supply would facilitate a 21.75% growth of the industry and allow consumers to benefit from the lower retail price of beef.

Since 1977 substantial improvements in beef production efficiency have occurred (Capper, 2011a); however, deflated beef retail prices over a similar timeline have decreased (USDA/ERS, 2013d). Historical data appears to suggest that improving productivity does not confer increased retail price. This may be due to the fact that an improvement in productivity does not always convey an improvement in total beef production. On January 1st of 1977 41x10^6 cows were inventoried in the US compared to 33x10^6 on January 1st of 2007 (USDA/ERS, 2012b). Capper (2011a) found that in 2007 compared with 1977 cattle finished 28% heavier in only 80% of the time. Based on national production data (USDA/ERS, 2012b) these improvements in efficiency are related to only a 5% increase in annual beef production during this time period (11.5x10^9 kg in 1977 compared with 12.1x10^9 kg in 2007). Although it is important to note the possibility of an outward shift in supply occurring due to the efficiency improvements modeled in this study, it
appears unlikely that this scenario would occur given that productivity improvements have not necessarily conveyed supply increases in the past.

**Implications of Willingness to Pay on IOVC and Social Acceptability**

Willingness to pay impacted IOVC substantially. In all cases, MEP scenarios resulted in increased IOVC when compared to the noWTP scenario. In the MEP+GET scenario the decreased consumer WTP for growth-enhancing technologies beef outweighed increased packer/retailer WTP for more efficient production and resulted in a net decrease in IOVC compared to the noWTP scenario. Shifting beef supply outward affected the magnitude of the changes in IOVC based on WTP changes but did not change the general trends. The aggregated and sector specific IOVC for each socioeconomic scenario are presented in Table 6.

Percentage changes in IOVC related to different socioeconomic scenarios were determined by comparing the IOVC of the scenario of interest to the baseline scenario where there was no efficiency change, no demand shift and no WTP change. The ADG socioeconomic scenario with the lowest IOVC included a demand shift and WTP based on improved production efficiency and consumer knowledge of growth enhancing technology use (Gain/Shift/MEP+GET). This scenario returned cow-calf, stocker and feedlot IOVC of $0.44/d, -$0.23/d and $0.47/d which were 51%, -38% and 37% of the control scenario IOVC. This socioeconomic scenario also returned the lowest IOVC for the FW treatment. Cow-calf, stocker and feedlot IOVC were $0.59/d, -$0.25/d and 0.84/d, respectively. These IOVC were 67%, -41% and 37% of the control scenario IOVC. The socioeconomic scenario returning the highest IOVC required no demand shift, and marketing was based on improved production efficiency only. In the ADG treatment, cow-calf, stocker and feedlot IOVC in this scenario were $1.02/d, $0.94/d and $1.70/d,
respectively. These IOVC values represented 117%, 157% and 134% of the control IOVC. In the FW treatment, cow-calf, stocker and feedlot IOVC were $1.25/d, $0.93/d, and $1.73/d, 143%, 155% and 136% of the control scenario IOVC.

Comparing the noWTP and MEP+GET scenarios across the ADG and FW treatments yielded particularly interesting results. In the noWTP scenario, ADG and FW improved IOVC compared to control efficiency treatment (industry average efficiency, no demand shift and no change in WTP). In the MEP+GET scenario, the ADG treatment resulted in IOVC below the control efficiency treatment while the FW scenario resulted in IOVC above the control efficiency treatment. This indicates that the opportunity to use efficiency to improve economic viability is dependent on the magnitude and structure of the efficiency improvement. In this case, reducing the number of cattle required to produce a set quantity of beef was more economically viable than reducing the time required to produce beef.

Beef’s social acceptability differed by socioeconomic scenario. Social acceptability in the MEP scenario was increased because WTP for more-efficiently produced beef was estimated at a 9% premium (Igo et al., 2013). Averaged estimates of consumer WTP for beef without growth-enhancing technologies (Lusk et al., 2003; Thilmany et al., 2003; Tonsor and Schroeder, 2003; Umberger et al., 2009b) revealed a 21% decrease in WTP when growth-enhancing technologies were used. When these WTP estimates were applied to the MEP+GET scenario, the increased packer/distributor/retailer WTP (10% increase) for efficient production practices was outweighed by consumer WTP for beef without growth-enhancing technologies resulting in a 12% net decrease in WTP and thus a net decrease in social acceptability. When efficiency improvements were made through management that was not socially acceptable, both the social acceptability
and the economic viability of the system were compromised to achieve improvements in environmental impact. It should be noted that this decrease in social acceptability and WTP stemmed from consumer interest in beef produced without growth-enhancing technologies rather than retailer/packer disapproval of growth-enhancing technologies. Although WTP in this study focused on consumer response to growth-enhancing technologies use, recent beef demand literature (Tonsor et al., 2010; Tonsor and Olynk, 2011) indicates that beef price is a more influential determinant of beef demand.

**Linking Efficiency, Environmental Impact, Economic Viability and Social Acceptability**

Results of this study indicate that improved efficiency results in improved environmental impact. The method by which environmental impact is influenced by efficiency has been described as the “dilution of maintenance” concept (Capper et al., 2009; Capper et al., 2008), which, in this study, is extended to economic and social systems through the conversion of energetic capital (animal gain) to economic capital. The dilution of maintenance concept shows that on a percentage basis, the proportion of energy used for production is greater in animals that are more efficient. Energy partitioned into product rather than maintenance creates an asset. Growth in beef animals is an asset that receives continual deposits as more feed energy is consumed by the animal. The economic input required to procure the feed energy necessary for growth to occur is a quality (or liability) associated with the asset. As more of the feed energy is partitioned into growth assets, the liability associated with the growth is lower than when less feed energy is partitioned. The energetic capital of feed energy partitioned to weight gain is converted to revenue (monetary capital) during the sale of an animal. When the asset to liability ratio is reduced, the conversion efficiency of the energetic capital to economic capital is improved. Similarly, packers,
distributors and retailers value the improvement in energetic efficiency associated with more efficient animals and are willing to pay more for animals from this system. This increased WTP illustrates the conversion of an improvement in social capital to economic capital.

To the authors’ knowledge, this study is the first to simultaneously, quantitatively assess environmental impact, economic viability and social acceptability of an animal production system. As the global population continues to expand (U.S. Census Bureau, 2013) and demand for meat and milk increases (Delgado, 2003), such analysis can be used to adapt animal agriculture to meet the needs of the growing global population within the constraints of biological, ecological and economic systems. The goal of feeding the growing global population is frequently defined as the provision of a sustainable food supply (Hobbs, 2007; Tilman, 1999), yet debate over the true definition of sustainability has caused the word to be effectively meaningless (Marshall and Toffel, 2005). In the current study we suggest that sustainable systems should begin with the end goal; namely, sustainable practices should focus on preserving resources, minimizing environmental impact, ensuring an affordable and safe food supply and doing so by methods that are economically feasible for producers. As such, we propose that the quantification of environmental impact, social acceptability and economic viability undertaken in this study can be used as an assessment of the relative sustainability of different beef production systems.

CONCLUSIONS

Improving efficiency through improved ADG or FW demonstrated opportunities to improve environmental impact, economic viability and social acceptability. These results were highly dependent on packer, distributor, retailer, consumer and producer responses to improved system
productivity. When efficiency improvements resulted in an outward shift in the demand curve, beef price decreases negatively impacted economic viability. For improved efficiency to positively impact economic viability and social acceptability, drastic supply shifts should be avoided (where possible) and efficiency improvements should be achieved using socially-acceptable management practices. Alternatively, marketing should focus on helping consumers understand the need for technology in producing affordable beef with a reduced environmental impact.
LITERATURE CITED

Cornell Research Foundation, Ithaca, NY.


determining U.S. consumer preferences and willingness to pay for natural and regionally

in the United States, 2007-08. USDA/APHIS-VS, Fort Collins, CO.

practices in the Unites States, 2007-08. USDA/APHIS-VS, Fort Collins, Co.

USDA/ERS. 2012a. Commodity and Food Elasticities. URL: http://www.ers.usda.gov/data-
products/commodity-and-food-elasticities/demand-elasticities-from-literature.aspx

May 2013.

USDA/ERS. 2013. Retail prices for beef, pork, poultry cuts, eggs and dairy products.

USDA/ERS.

USDA/NASS. 2007. Census of Agriculture: Farm and Ranch Irrigation Survey. USDA/NASS,
Washington, DC.


West, T. O., and G. Marland. 2001. A synthesis of carbon sequestration, carbon emissions, and


Table 1. Animal populations required to produce $1.0 \times 10^9$ kg hot carcass beef under control settings, increasing average daily gain (ADG) by 15% or increasing finishing weight by 15%

<table>
<thead>
<tr>
<th>Animal Group</th>
<th>Control Scenario</th>
<th>Increased FW Scenario</th>
<th>Increased ADG Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SW $^2$ FW $^3$ ADG $^4$ Days $^5$</td>
<td>SW FW ADG Days</td>
<td>SW FW ADG Days</td>
</tr>
<tr>
<td>Finishing Steers</td>
<td>347 552 1.47 140</td>
<td>399 635 1.69 140</td>
<td>347 552 1.69 122</td>
</tr>
<tr>
<td>Finishing Heifers</td>
<td>308 473 1.18 140</td>
<td>355 544 1.35 140</td>
<td>308 473 1.35 122</td>
</tr>
<tr>
<td>Calf-fed Steers</td>
<td>221 552 1.27 260</td>
<td>254 635 1.47 260</td>
<td>221 552 1.47 226</td>
</tr>
<tr>
<td>Calf-fed Heifers</td>
<td>204 473 1.04 260</td>
<td>234 544 1.19 260</td>
<td>204 473 1.19 226</td>
</tr>
<tr>
<td>Dairy Steers</td>
<td>81 516 1.45 300</td>
<td>93 593 1.67 300</td>
<td>81 516 1.67 261</td>
</tr>
<tr>
<td>Dairy Heifers</td>
<td>75 473 1.33 300</td>
<td>86 544 1.53 300</td>
<td>75 473 1.53 261</td>
</tr>
<tr>
<td>Stocker Steers</td>
<td>221 347 0.80 158</td>
<td>254 399 0.92 158</td>
<td>221 347 0.92 137</td>
</tr>
<tr>
<td>Stocker Heifers</td>
<td>204 308 0.66 158</td>
<td>234 355 0.76 158</td>
<td>204 308 0.76 137</td>
</tr>
<tr>
<td>Steer Calves</td>
<td>42 221 0.86 207</td>
<td>42 254 1.03 207</td>
<td>42 221 0.86 207</td>
</tr>
<tr>
<td>Heifer Calves</td>
<td>42 204 0.78 207</td>
<td>42 234 0.93 207</td>
<td>42 204 0.78 207</td>
</tr>
<tr>
<td>Replacement Heifer Calves</td>
<td>42 212 0.82 207</td>
<td>42 244 0.98 207</td>
<td>42 212 0.82 207</td>
</tr>
<tr>
<td>Growing Replacement Heifers</td>
<td>212 375 0.75 218</td>
<td>244 375 0.60 218</td>
<td>212 375 0.75 218</td>
</tr>
<tr>
<td>Bred Replacement Heifers</td>
<td>375 454 0.28 280</td>
<td>375 454 0.28 280</td>
<td>375 454 0.28 280</td>
</tr>
<tr>
<td>Replacement Bull Calves</td>
<td>42 221 0.49 365</td>
<td>42 221 0.49 365</td>
<td>42 221 0.49 365</td>
</tr>
<tr>
<td>Young Bulls</td>
<td>221 500 0.76 365</td>
<td>221 500 0.76 365</td>
<td>221 500 0.76 365</td>
</tr>
<tr>
<td>Mature Bulls</td>
<td>500 640 0.38 365</td>
<td>500 640 0.38 365</td>
<td>500 640 0.38 365</td>
</tr>
<tr>
<td>Dry Cows</td>
<td>567 567 0.00 365</td>
<td>567 567 0.00 365</td>
<td>567 567 0.00 365</td>
</tr>
<tr>
<td>Lactating Cows</td>
<td>567 567 0.00 365</td>
<td>567 567 0.00 365</td>
<td>567 567 0.00 365</td>
</tr>
</tbody>
</table>

$^1$Animal populations used in the model are listed. These populations include all animals from the cow-calf, stocker and feedlot sectors.

$^2$Starting weights (SW) are reported in kg and represent the weight of an animal as it enters the population in the model

$^3$Finishing weights (FW) are reported in kg and represent the weight of an animal as it leaves the population in the model

$^4$Average daily gain (ADG) is reported in kg/d and represents the daily weight change estimated for each population
Days animals remain in the model (days) is reported in d and represents time animals are retained in each population.
Table 2. Populations of animals required to produce 1.0 x 10⁹ kg of beef under each production scenario

<table>
<thead>
<tr>
<th>Animal Type</th>
<th>Control (x 10³)</th>
<th>ADG⁴ (x 10³)</th>
<th>FW⁵ (x 10³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supporting</td>
<td>6,365</td>
<td>6,365</td>
<td>5,699</td>
</tr>
<tr>
<td>Stocker</td>
<td>1,666</td>
<td>1,666</td>
<td>1,492</td>
</tr>
<tr>
<td>Feedlot</td>
<td>2,188</td>
<td>2,188</td>
<td>1,959</td>
</tr>
<tr>
<td>Cull</td>
<td>498</td>
<td>498</td>
<td>446</td>
</tr>
<tr>
<td>Slaughtered</td>
<td>2,675</td>
<td>2,675</td>
<td>2,395</td>
</tr>
<tr>
<td>Total Animals</td>
<td>13,392</td>
<td>13,392</td>
<td>11,991</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emission Type (CO₂e)</th>
<th>Control (x 10⁶)</th>
<th>ADG</th>
<th>FW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enteric CH₄ (x 10⁶)</td>
<td>17,431</td>
<td>15,203</td>
<td>14,649</td>
</tr>
<tr>
<td>Manure CH₄ (x 10⁶)</td>
<td>3,079</td>
<td>2,771</td>
<td>2,752</td>
</tr>
<tr>
<td>Direct N₂O (x 10⁶)</td>
<td>1,693</td>
<td>1,665</td>
<td>1,537</td>
</tr>
<tr>
<td>Volatized N₂O (x 10⁶)</td>
<td>101</td>
<td>84</td>
<td>86</td>
</tr>
<tr>
<td>Leached N₂O (x 10⁶)</td>
<td>84</td>
<td>70</td>
<td>72</td>
</tr>
<tr>
<td>Crop and Transport CO₂ (x 10⁶)</td>
<td>543</td>
<td>450</td>
<td>456</td>
</tr>
<tr>
<td>Total CO₂ Emissions (x 10⁶)</td>
<td>22,932</td>
<td>20,245</td>
<td>19,553</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Land Type (ha)</th>
<th>Control (x 10³)</th>
<th>ADG</th>
<th>FW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop Land</td>
<td>2,678</td>
<td>2,370</td>
<td>2,301</td>
</tr>
<tr>
<td>Pasture Land</td>
<td>3,268</td>
<td>3,388</td>
<td>3,098</td>
</tr>
<tr>
<td>Total Land Use</td>
<td>5,946</td>
<td>5,758</td>
<td>5,399</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water Type (L)</th>
<th>Control (x 10⁹)</th>
<th>ADG</th>
<th>FW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Drinking H₂O (x 10⁹)</td>
<td>71</td>
<td>66</td>
<td>64</td>
</tr>
<tr>
<td>Irrigation H₂O (x 10⁹)</td>
<td>2,338</td>
<td>2,047</td>
<td>1,972</td>
</tr>
<tr>
<td>Total H₂O Use (x 10⁹)</td>
<td>2,409</td>
<td>2,113</td>
<td>2,036</td>
</tr>
</tbody>
</table>

¹Animal numbers not adjusted for length of time spent within each subsystem

²Includes cows, calves, replacement heifers and bulls

³Includes all animals within the system excluding culled cattle.

⁴ADG represents the scenario where daily gain was increased by 15%

⁵FW represents the scenario where finishing weight was increased by 15%
Table 3. Comparison of GHGe metrics calculated in various studies worldwide

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Country</th>
<th>GHGe (kg CO$_2$-equivalents / kg HCW beef)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Australia</td>
<td>13.1</td>
<td>Peters et al. (2010a)</td>
</tr>
<tr>
<td>Model</td>
<td>Australia</td>
<td>13.4</td>
<td>Peters et al. (2010a)</td>
</tr>
<tr>
<td>Model</td>
<td>Australia</td>
<td>16.0</td>
<td>Ridoutt et al. (2011)</td>
</tr>
<tr>
<td>Model</td>
<td>Australia</td>
<td>20.2</td>
<td>Ridoutt et al. (2011)</td>
</tr>
<tr>
<td>Model</td>
<td>UK</td>
<td>25.1</td>
<td>Williams et al. (2006)</td>
</tr>
<tr>
<td>Model</td>
<td>USA</td>
<td>20.1</td>
<td>This study</td>
</tr>
<tr>
<td>Model</td>
<td>USA</td>
<td>18.5</td>
<td>This study</td>
</tr>
<tr>
<td>Model</td>
<td>USA</td>
<td>17.8</td>
<td>This study</td>
</tr>
<tr>
<td>Model</td>
<td>USA</td>
<td>22.6</td>
<td>Stackhouse-Lawson et al. (2012)</td>
</tr>
<tr>
<td>Model</td>
<td>USA</td>
<td>17.9</td>
<td>Capper (2011a)</td>
</tr>
<tr>
<td>Model</td>
<td>USA</td>
<td>15.9</td>
<td>Capper (2012)</td>
</tr>
<tr>
<td>Model</td>
<td>USA</td>
<td>16.0</td>
<td>Capper and Hayes (2012)</td>
</tr>
<tr>
<td>Model</td>
<td>USA</td>
<td>16.2</td>
<td>Pelletier et al. (2010)</td>
</tr>
<tr>
<td>National Survey Data</td>
<td>Canada</td>
<td>16.5</td>
<td>Verge et al. (2008)</td>
</tr>
<tr>
<td>National Survey Data</td>
<td>Ireland</td>
<td>17.9</td>
<td>Casey and Holden (2006b)</td>
</tr>
<tr>
<td>Real Farm Data</td>
<td>Ireland</td>
<td>20.1</td>
<td>Casey and Holden (2006a)</td>
</tr>
<tr>
<td>Real farm data</td>
<td>UK</td>
<td>24.6</td>
<td>Edwards-Jones et al. (2009)</td>
</tr>
</tbody>
</table>

1Carbon footprint is reported in kg CO$_2$-equivalents adjusted for a dressing percentage of 63%.
Table 4. Sensitivity analysis of the impacts of the CH$_4$ and N$_2$O predictive equations on greenhouse gas emissions

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>ADG$^2$</th>
<th>FW$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Bound$^1$</strong></td>
<td>33.80</td>
<td>29.78</td>
<td>28.71</td>
</tr>
<tr>
<td><strong>Original Value</strong></td>
<td>22.93</td>
<td>20.25</td>
<td>19.55</td>
</tr>
<tr>
<td><strong>Low Bound</strong></td>
<td>12.07</td>
<td>10.71</td>
<td>10.39</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>ADG</th>
<th>FW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Bound</strong></td>
<td>24.70</td>
<td>21.98</td>
<td>21.16</td>
</tr>
<tr>
<td><strong>Original Value</strong></td>
<td>22.93</td>
<td>20.25</td>
<td>19.55</td>
</tr>
<tr>
<td><strong>Low Bound</strong></td>
<td>22.04</td>
<td>19.37</td>
<td>18.74</td>
</tr>
</tbody>
</table>

$^1$Parameters in each equation were adjusted between the high side of the presented confidence interval (high bound) and the lower side of the confidence interval (low bound).

$^2$ADG refers to the treatment with 15% improved daily gain

$^3$FW refers to the treatment with 15% increased finishing weight
Table 5. Partial budgets for the cow-calf, stocker and feedlot sectors with control settings, improved daily gain and improved yield

<table>
<thead>
<tr>
<th>Metrics(^1)</th>
<th>Cow-Calf</th>
<th>Stocker</th>
<th>Feedlot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>ADG(^2)</td>
<td>FW(^3)</td>
</tr>
<tr>
<td>Feed Costs</td>
<td>$0.53(^2)</td>
<td>$0.52</td>
<td>$0.52</td>
</tr>
<tr>
<td>Acquisition Cost</td>
<td>$0.00</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Revenue</td>
<td>$1.41</td>
<td>$1.41</td>
<td>$1.61</td>
</tr>
<tr>
<td>IOVC</td>
<td>$0.87</td>
<td>$0.88</td>
<td>$1.09</td>
</tr>
</tbody>
</table>

\(^1\)Feed costs include costs for all feed consumed by animals in each sector, acquisition costs refer to the cost incurred within each sector to purchase cattle (only accounted for stocker and feedlot), revenue represents money received from sale of growing or culled cattle, IOVC represents revenue over feed and acquisition costs.

\(^2\)All values are displayed in $ animal\(^{-1}\) day\(^{-1}\)

\(^3\)ADG refers to the treatment with 15% improved daily gain

\(^4\)FW refers to the treatment with 15% increased finishing weight
Table 6. Individual sector and aggregated industry income over feed costs for different socioeconomic scenarios

<table>
<thead>
<tr>
<th>Scenario¹</th>
<th>Cow-Calf</th>
<th>Stocker</th>
<th>Feedlot</th>
<th>Aggregate²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control² (Base/NoShift/NoWTP)</td>
<td>0.87</td>
<td>0.60</td>
<td>1.27</td>
<td>2.75</td>
</tr>
<tr>
<td>Gain³/Shift⁵/MEP+GET⁶</td>
<td>0.44</td>
<td>-0.23</td>
<td>0.47</td>
<td>0.69</td>
</tr>
<tr>
<td>Yield/Shift/ MEP+GET</td>
<td>0.59</td>
<td>-0.25</td>
<td>0.50</td>
<td>0.84</td>
</tr>
<tr>
<td>Gain/Shift/NoWTP</td>
<td>0.57</td>
<td>-0.23</td>
<td>0.60</td>
<td>0.95</td>
</tr>
<tr>
<td>Yield/Shift/NoWTP</td>
<td>0.74</td>
<td>-0.24</td>
<td>0.62</td>
<td>1.12</td>
</tr>
<tr>
<td>Gain/Shift/MEP</td>
<td>0.68</td>
<td>-0.22</td>
<td>0.70</td>
<td>1.17</td>
</tr>
<tr>
<td>Yield/Shift/MEP</td>
<td>0.86</td>
<td>-0.24</td>
<td>0.73</td>
<td>1.35</td>
</tr>
<tr>
<td>Gain/NoShift/ MEP+GET</td>
<td>0.71</td>
<td>0.70</td>
<td>1.27</td>
<td>2.69</td>
</tr>
<tr>
<td>Yield/NoShift/ MEP+GET</td>
<td>0.90</td>
<td>0.69</td>
<td>1.30</td>
<td>2.88</td>
</tr>
<tr>
<td>Gain/NoShift/NoWTP</td>
<td>0.88</td>
<td>0.83</td>
<td>1.51</td>
<td>3.23</td>
</tr>
<tr>
<td>Yield/NoShift/NoWTP</td>
<td>1.09</td>
<td>0.82</td>
<td>1.53</td>
<td>3.44</td>
</tr>
<tr>
<td>Gain/NoShift/MEP</td>
<td>1.02</td>
<td>0.94</td>
<td>1.70</td>
<td>3.67</td>
</tr>
<tr>
<td>Yield/NoShift/MEP</td>
<td>1.25</td>
<td>0.93</td>
<td>1.73</td>
<td>3.91</td>
</tr>
</tbody>
</table>

¹Socioeconomic scenarios were classified by three factors, the efficiency scenario, whether a demand shift occurred and change in willingness to pay

²Income over feed costs was listed separately for the cow-calf, stocker and feedlot sectors and collectively as “Aggregate” income over feed costs.

³The control scenario was used as the baseline for comparison

⁴Efficiency scenario is listed first and includes the control scenario (Control), the 15% improved gain scenario (ADG) and the 15% improved yield scenario (FW)

⁵Demand scenario is listed second, “Shift” indicates supply was shifted to decrease retail prices while “NoShift” indicates that no shift in supply was modeled

⁶Willingness to pay scenario was listed third, “NoWTP” indicates no change in willingness to pay, “MEP” indicates willingness to pay was modeled based on cattle produced more efficiently
and “MEP+GET” indicates willingness to pay included efficiently produced cattle that were produced with growth-enhancing technologies.
CHAPTER 4

OPTIMIZING BEEF SUSTAINABILITY

This chapter was submitted to Agricultural Systems as: Optimizing diet and pasture management to improve sustainability of U.S. beef production
INTRODUCTION

Trends in global population, meat demand, and resource availability support the need for improved sustainability in United States (U.S.) beef 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 to identify management effects on environmental impact (Beauchemin et al., 2010, 2011; Capper, 2011a, 2012; Stackhouse-Lawson et al., 2012) and many of these models also integrate economic assessment (Capper and Hayes, 2012; Rotz et al., 2013; Veysset et al., 2010; White and Capper, 2013). True sustainability balances environmental impact, economic viability and social acceptability (WCED, 1987).

A comprehensive examination of the biological relationships governing agricultural sustainability has 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, partially because of the variability inherent in social and biological systems. Consumers’ interest in, and willingness to pay (WTP) for, products varies substantially with demographics and product attributes (eg. Dickinson and Bailey, 2005; Lusk et al., 2003; Tonsor et al., 2009; Umberger et al., 2009a). Although previous studies showed consumers were willing to pay more for meat produced with reduced resource use and greenhouse gas emissions (GHG; 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. Additional uncertainty exists in the form of climate variability. Increased weather variability is expected over the next century (IPCC, 2007). Since forage quality is partially dependent on temperature, humidity and rainfall; the opportunities to
improve forage quality in the face of climate variability may limit the effectiveness of management changes that enhance sustainability.

The objective of this study was to create an optimization model to identify feeding practices that reduced land use, water use and GHG from U.S. beef production in an economically viable and socially acceptable manner and to use that model to examine the impact of altered precipitation patterns. It was hypothesized that projected changes in rainfall would decrease forage availability and reduce opportunities to change management to improve beef sustainability.

MATERIALS AND METHODS

A model was constructed by integrating a whole-system environmental impact and production cost module (White and Capper, 2013), a pasture module (Romera et al., 2009) and an estimate of social acceptability using a meta-regression estimating consumer WTP (White and Brady, 2013). Inputs to the environmental model included cattle productivity measures and nutrient requirements; crop yield and resource use; pasture location, weather and management strategy as well as crop, pasture, fertilizer and irrigation costs. Outputs were land use, water use, GHG emissions and diet cost; all were expressed per kg of hot carcass weight (HCW) beef. The model was run using the General Algebraic Modeling System (GAMS; GAMS Development Corporation, 2012). Non-linear programming was used to adjust diets to achieve various environmental-impact-reducing objectives subject to biological, practical and consumer-driven constraints. 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 WTP on a sliding-scale.
Model Inputs

Cattle Group Specifications and Nutrient Requirements

Cattle groups modeled were categorized according to age and gender into populations representing animals in the cow-calf, stocker and feedlot systems as well as calf-fed cattle from the dairy system (Table 1). The population required to yield 1,000,000 kg HCW beef was calculated based on annual slaughter summaries (USDA/ERS, 2012b), conception, birth and mortality rates and bull to cow ratios (USDA/APHIS, 2009a, b). Calculation of cattle populations followed Capper (2011a) and White and Capper (2013). Specific parameters required to calculate animal populations are included in Table 2.

Nutrient requirements were predicted by Agricultural Modeling and Training System’s (AMTS) CattlePro diet balancing software (AMTS, 2006) and balanced diets were constructed for each group. Energy, protein and predicted dry matter intake were determined on a monthly basis for each group considering changes in body weight and production stage. Monthly requirements were averaged for each cattle group and used by the optimizer as constraints to ensure adequate nutrients for production. Weights used for determining nutrient requirements are listed in Table 1. Additional population-specific parameters required for determining nutrient requirements are listed in Table 2. The chemical composition of grains, byproducts, hays and silages were sourced from the AMTS CattlePro feed bank (AMTS, 2006).

Crop and Pasture Production Parameters

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., 2013a). To describe the variety of pasture management systems available, pasture nutrient contents were simulated by the McCall pasture model (McCall and Bishop-Hurley, 2003) as updated by Romera et al. (2009).

The McCall model was selected for use after comparing its predictive accuracy to other available pasture models (Donnelly et al., 1997; Mohtar et al., 1997). To simulate U.S. pasture, the pasture module was fit to a dataset from the Oak Ridge National Laboratory (2012). The solver function in Microsoft Excel was used to adjust several model parameters to minimize the root mean squared error of prediction (RMSPE) of the modeled data compared to one year of data for each management option. The model parameters adjusted were efficiency of photosynthesis, efficiency of vegetative relative to reproductive growth and time parameters governing initiation of reproductive growth, time of inflorescence emergence, decline of the reproductive period and end of the reproductive period. Unmanaged pasture growth was parameterized using data from eight locations around the U.S. Data from irrigated, fertilized or irrigated and fertilized pasture was obtained from a research site in Colorado, U.S. (Oak Ridge National Laboratory, 2012). The outputs from parameterization were validated against the remaining three years of data for each management strategy at each location. The validation RMSPE was 8% for unmanaged pasture, 11% for irrigated pasture, 15% for fertilized pasture and 13% for irrigated and fertilized pasture which indicated the module had sufficient predictive capability to simulate U.S. pastures.

To generate data for average U.S. pastures, the module was fit to growth curves from USDA/NRCS (2012) for ten U.S. states with the largest yearly calf crops (USDA/ERS, 2012b). States parameterized, number of growth curves for each state and average RMSPE after parameterization are given in Table 3. The resultant growth curves were used to simulate
continuously grazed (C), irrigated continuously grazed (C-I), fertilized continuously grazed (C-F), irrigated and fertilized continuously grazed (C-IF), rotationally grazed (R), irrigated rotationally grazed (R-I), fertilized rotationally grazed (R-F) and irrigated and fertilized rotationally grazed (R-IF) pastures. Parameterization resulted in over 7,200 simulations which were aggregated to give estimates of yield and quality data for each pasture management strategy. These strategies were used as different feedstuff options in the optimization (Table 4).

Determining Climate Effects on Pasture Growth

In the scenarios investigating climate effects on pasture growth, pasture parameters were selected to simulate a mixed warm-season cool-season grass pasture in three locations across the U.S.: the Pacific Northwest, the Midwest and Texas. In each location, pastures were simulated using current precipitation data (Baseline) and adjusted precipitation data following the projections given by U.S. Global Change Research Program (2009; Projected). Monthly yield and quality information for eight pasture management options were outputted for each location and precipitation scenario combination.

Economic module

The economic module calculated production costs and consumer WTP. Feed costs were based on the 5-year-average price of each feed (USDA/ERS, 2012b); pasture management costs were calculated based on equipment and labor associated with rotational grazing (Gillespie et al., 2008); fertilizer cost with updated prices (Khakbazan et al., 2009; USDA/NASS, 2007) and updated irrigation rates and costs (USDA/ERS, 2012b).
**Willingness to Pay**

Consumer WTP was the measure of social acceptability. White and Brady (2013) conducted a meta-regression and calculated U.S. consumers’ non-hypothetical WTP for beef produced with a reduced environmental impact by quantitatively summarizing sixteen previously-published studies. The regression followed a Hedonic approach where it is assumed that consumers value beef products as a bundle of their constituent attributes. This approach allowed estimates for “healthy”, “safe”, “grass-fed”, “organic”, “hormone-free” or “high-quality” beef to be used to predict what consumers might pay for a product that had a perceived reduced environmental impact. Products contributing to the estimate of WTP for reduced environmental impact included anything with a perceived benefit to natural resources (water quality or use, land use, etc.) or GHG or ammonia emissions. The meta-regression predicted a 4% premium WTP for beef products with a reduced environmental impact. This value was conservative compared with the 13.8% and 19.4% WTP for beef products with environmental attribute labeling identified by Blecher et al. (2007) and Tonsor and Shupp (2009). Consumer beef purchases are based on retail price of meat and therefore must be converted to a HCW equivalent basis. Retail yield ranges between 50% and 70% of HCW (Schweihofer, 2012). In this assessment, a ratio of 75:25 bone-in to boneless beef was assumed resulting in a retail yield of 65% of HCW. Given the national average retail price in 2012 ($11.05/kg retail beef; USDA/ERS, 2013), the 65% conversion of HCW beef to retail beef and the 50% conveyance rate of consumer WTP to farm level (USDA/ERS, 2013); a 4% premium WTP equated to a $0.144 allowable increase in cost per kg HCW beef. Consumer WTP is highly variable based on demographics and location (Krystallis and Chryssohoidis, 2005; Lusk et al., 2003). To encompass this variability, a sensitivity analysis was performed by varying WTP on a sliding scale from a 1% premium to the premium required
for unconstrained minimization of environmental impact. Subsequent changes in optimal management were assessed.

Model Outputs

Modeled outputs included environmental impact metrics: land use, water use and GHG emissions per kg beef hot carcass weight (HCW). Land use for the production of grain, silage and hay was calculated based on total feed intake and crop yield (USDA/ERS, 2012b). When pasture was used as a feed, land use was determined based on projected yields from the pasture module based. Water use included irrigation for crop production (USDA/NASS, 2007) or pasture growth (McCall and Bishop-Hurley, 2003); drinking water was also accounted for (Meyer et al., 2006). Greenhouse gas emissions included CO$_2$, N$_2$O and CH$_4$. Included in the carbon footprint were crop and pasture CO$_2$ emission estimates (Bhat et al., 1994; Mudahar and Hignett, 1987; Nelson et al., 2009; West and Marland, 2001); direct, leached and volatilized manure and fertilizer N$_2$O emissions (IPCC, 2006); enteric CH$_4$ emissions (Ellis et al., 2007) and manure CH$_4$ (IPCC, 2006).

Optimization Framework and Equations

The system described by the Model Input and Output sections was optimized using two different forms of an objective function. The baseline scenario was least-cost management. To yield baseline outputs, the model was first run using the following objective function:

\[
\text{Minimize}(LC_c) = \sum_a (d_a * n_a * \sum_f (DMI_{f,a} * c_f))
\]
where $d_a$ is days an animal population ($a$) is alive, $n_a$ is number of animals in population ($a$), $DMI_{f,a}$ is an animal population’s ($a$) daily intake of each feedstuff ($f$) and $c_f$ is the unit price of each feed ($f$). In all other scenarios, the following objective function form was used:

$$\text{Minimize}(\text{Obj}) = W_m * (PV_m - BV_m) / BV_m$$

where $Obj$ is the objective value, $W_m$ is the weight of metric ($m$), $PV_m$ is the present value of metric ($m$) and $BV_m$ is the base value of metric ($m$). Metric, $m$, could hold any of four values (land use, water use, GHG and diet cost) meaning that during any given optimization $Obj$ is determined by four separate equations each following the above form (Tozer and Stokes (2001b)). The choice variable in the model was $DMI_{f,a}$. Nutrient requirements of each animal group were used to ensure adequate nutrition without exceeding maximum predicted dry matter intake:

$$\sum_f DMI_{f,a} \cdot ME_f \geq ME_{req_a}$$
$$\sum_f DMI_{f,a} \cdot MP_f \geq MP_{req_a}$$
$$\sum_f DMI_{f,a} \leq DMI_{x,a}$$

where $DMI_{f,a}$ is intake of feed ($f$) for each animal ($a$); $ME_f$ is the metabolizable energy content of feed ($f$); $ME_{req_a}$ is each animal’s ($a$) metabolizable energy requirement; $MP_f$ is the metabolizable protein content of each feed ($f$); $MP_{req_a}$ is the metabolizable protein requirement for an animal ($a$), $DMI_{x,a}$ is maximum predicted dry matter intake for an animal ($a$). In addition to biological constraints, practical constraints were put in place to ensure reasonable limits on specific feeds in the diet of particular animal groups. This constraint is represented by the equations:
where $DMI_{f,a}$ is intake of feed $f$, for animal $a$, $Up_{f,a}$ is the upper limit of feedstuff $f$ in the diet of animal $a$ and $Low_{f,a}$ is the lower limit of feedstuff $f$ in the diet of animal $a$ (Table 5). This constraint was used to restrict the amount of grain and byproducts in a cow-calf or stocker diet, the proportion of forage and pasture in feedlot diets and the maximum proportion of byproducts such as molasses or distillers dried grains in all diets.

Increases in diet cost associated with reducing environmental impact were restricted to less than WTP. This constraint is represented as:

$$BV_{cost} + BV_{cost} \times WTP \geq PV_{cost}$$

Where $PV_{cost}$ is the diet cost simulated, $WTP$ is the willingness to pay for low-environmental impact beef and $BV_{Cost}$ is the cost outputted from the baseline scenario.

Evaluating Model Performance

Model performance was evaluated by comparing results of the least-cost scenario to previously published measurements of GHG and resource use from beef production. Sensitivity analysis was employed to evaluate model robustness. The WTP estimate was varied between a 0% increase in WTP and the maximum required WTP to achieve the results seen in the unconstrained scenarios. As WTP was varied, diets and changes in GHG and resource use were
recorded and used to evaluate sensitivity of the model results to WTP. Model robustness was improved by demonstrating results across a range of WTP.

**Determining Climate-Related Effects on Sustainability**

A scenario to explore the impact of projected climate-variability-induced precipitation changes on pasture growth was simulated. Subsequent opportunities to reduce resource use were identified by the optimization model. Pasture yield and quality information outputted from the pasture module were inputted into the optimizer to assess how opportunities to reduce land use, water use and/or GHG emissions changed when the projected precipitation patterns (U.S. Global Change Research Program, 2009) impacted forage growth. The Pacific Northwest, Midwest and Texas were selected because they were projected to have distinct, unique changes in their precipitation patterns. The Midwest experienced only slight seasonal changes. Texas experienced a substantial reduction in rainfall year-round. The Pacific Northwest had increased rainfall in the winter, spring and fall and decreased rainfall during the summer. These distinct rainfall pattern changes were expected to have unique influences on forage yield or quality and subsequent opportunities to improve sustainability.

**RESULTS AND DISCUSSION**

**Least-Cost Diet Optimization Outputs**

In the least-cost baseline scenario, cow-calf and stocker animals grazed pasture managed under two management strategies, C-IF and R-IF. Feedlot diets consisted primarily of corn grain, dried distillers grains and grass hay which were similar to those fed across the US. Over 90% of feedlots use distillers grains in their diets (USDA/APHIS, 2011). Vasconcelos et al. (2007)
surveyed feedlot nutritionists and found the inclusion rate of distiller’s grains in feedlot diets ranged from 5% to 50% with the reminder of the diet being corn grain and alfalfa hay. The time period from birth to slaughter for calves in the system averaged 490 d.

Diet costs averaged $0.90/hd/d in the cow-calf sector which compared favorably to the yearly average cow feed costs ($0.82/hd/d to $1.02/hd/d) observed in Hughes (2013). Stocker diet cost was predicted to be $0.88/hd/d by the model. Average stocker breakeven cost of gain has been estimated at $1.21/kg (Zimmerman, 2013) which is similar to the model prediction of $0.94/kg. The model estimate may be slightly lower because only feed costs were accounted for and Zimmerman (2013) included labor, overhead and other costs. Feedlot cost of gain was predicted at $0.97/hd/d which compares favorably with Gadberry and Beck (2013) who estimated cost of gain in the feedlot $1.50/kg. Given the differences in costs accounted, these values were relatively similar indicating that the costs used in this study were reasonably representative of industry feed costs.

The baseline environmental impact metrics are listed in Table 6. Land use was predicted at 60.0 m²/kg HCW beef which was within the range predicted by previous studies: 43 m²/kg HCW beef estimated by (Elferink and Nonhebel, 2007) and 61 m²/kg HCW beef from Capper (2011). Land use in the modeled grain-based finishing system was lower than the land use reported for forage-based finishing systems (Cederberg et al., 2009). The model predicted water use at 1,281 L/kg HCW beef which was in the range of previous studies estimating water use. This value was greater than some previous estimates of beef water use (Capper, 2011a, 2012; Ridoutt et al., 2011) likely because of irrigated pasture use. A different water foot printing methodology estimated substantially more water use attributable to beef (Hoekstra and Chapagain, 2007)
because different water sources were considered.

The carbon footprint of beef production was 20.3 kg/kg HCW beef which was similar to previous studies of US systems (Capper, 2011a; Pelletier et al., 2010; Stackhouse-Lawson et al., 2012; White and Capper, 2013). Outputted carbon footprint values were similar to values from other regions including: Ireland (20.1 kg/kg HCW beef; Casey and Holden, 2006a), Canada (16.5 kg/kg HCW beef; Verge et al., 2008), the UK (24.6 kg/kg HCW beef; Edwards-Jones et al., 2009) and Australia (20.2 kg/kg HCW beef; Ridoutt et al., 2011). Given the variability in efficiency between these systems, carbon footprints differing by 20 – 25% were expected.

Minimizing Individual Metrics of Environmental Impact

Land Use

Diets were adjusted to minimize land use, water use or GHG emissions given the constraint that diet cost could not increase greater than consumer WTP. Two scenarios were simulated to minimize land use, one constrained by the $0.144 predicted increase in consumer WTP and one without the constraint (Table 7). When land use was constrained, a $0.144 increase in diet cost reduced land use by 5.4% through adjusting cow-calf and stocker diets to consume more R-IF pasture with supplemental alfalfa hay. Feedlot diets were predominantly corn grain and dried distillers grains with alfalfa as a forage source. Alfalfa was used as a forage source because yields were higher than grass hay and therefore land use was decreased. Although this scenario also decreased GHG emissions by 1.3% as a result of reduced enteric CH₄ emissions related to increased pasture digestibility, the environmental benefits were at the expense of a 3.2% increase in water use. The benefits of improved forage yield and land use efficiency under management
intensive grazing practices have been well documented (Gammon, 1978; Oates et al., 2011; Parker et al., 1992). Pasture yields typically increase with irrigation (Waldron et al., 2002) or fertilization (Monaghan et al., 2005). Additionally, Pelletier et al. (2010) demonstrated that improved forage utilization was positively correlated with reduced GHG emissions per kg of beef. The improvement in intensively-managed pasture yields facilitated the decreases in land use and GHG emissions observed.

When the WTP constraint was not included, an 11.1% increase in diet cost resulted in a 7.8% reduction in land use and a 2.3% reduction in GHG emissions at the expense of a 57.7% increase in water use. The diet in this scenario differed from the constrained scenario because the quantity of alfalfa hay used in cow-calf and stocker diets was maximized. Alfalfa had a higher yield than any other forage source and was the optimal feed to select when minimizing land. The increase in diet cost was due to the alfalfa hay price (USDA/ERS, 2012b). Alfalfa pastures resulted in lower CH₄ emissions than grass pastures as a percent of energy intake (McCaughey et al., 1999) and therefore, the increased alfalfa consumption and the modeled reduction in CH₄ emissions concurred with previous studies in which GHG emissions were measured. Conversely, alfalfa hay required more irrigation than other forage sources and water use increased accordingly.

**Water Use**

When diets were constrained by consumer WTP, a $0.144 /kg increase in diet cost reduced water use by 4.2% and resulted in a concurrent 1.2% decrease in GHG emissions and a 3.8% decrease in land use. To achieve these results, cow-calf diets were balanced with C-F, R-F and R-IF pastures, stocker diets relied entirely on R-IF and feedlot diets used grass hay as a forage source. The R-IF pasture had the highest water-use efficiency of an irrigation treatment in part because
of the higher stocking density and increased fertilizer use (Armstrong et al., 2000). Similarly, reliance on C-F and R-F pasture in the cow-calf allowed for decreased overall water use. The reduction in land use was uncharacteristic because typical model outputs found land use and water use to be highly competitive. Armstrong et al. (2000) also noted a correlation between improved water use efficiency and reduced land use. In the presence of a budget constraint, increasing land use intensity on irrigated land could help improve water use efficiency in an economical manner (Armstrong, 2004). The C-F, R-F and R-FI pastures were expected to exhibit higher CO₂ emissions per ha because increased use of N fertilizer was correlated with increased N₂O emissions from pasture (Mosier et al., 1996) particularly under wet conditions (Luo et al., 2008; Saggar et al., 2004a; Saggar et al., 2007). However in this scenario, decreased land required, in combination with moderate decreases in enteric CH₄, may have counterbalanced the predicted increase in N₂O emissions.

When the WTP constraint was not included in simulation, a 53.2% increase in diet cost reduced water use by 22.6% and CO₂ emissions by 4.8% while increasing land use 70.5%. The scenario minimizing water relied on C and R diets in the cow-calf sector, R in the stocker enterprise and grass hay as forage for the feedlot. Minimizing water resulted in the use of feeds that did not require irrigation thus increasing land use substantially because of lower pasture yield. The use of C and R pastures resulted in lower GHG emissions than the R-IF or C-IF pastures because N fertilizer was reduced and it took fewer hours of machinery operation to fertilize and irrigate. Although low-intensity pasture systems (low water and chemical use) are commonly perceived as beneficial to the environment (Bignal and McCracken, 1996), in this scenario the costs were prohibitive to improved sustainability. Furthermore, given the constrictions on agricultural land
availability (Lambin and Meyfroidt, 2011), scenarios which required substantial increases in land use were not practically feasible.

**Greenhouse Gas Emissions**

Targeting GHG emissions resulted in a 3.6% reduction while minimally altering land use and increasing water use by 21.2%. Cow-calf diets were C-I, C-IF and R-IF pasture with supplemental grass hay. Stocker diets were composed of R-IF and grass hay. Grass hay also became the feedlot forage source. Decreased enteric CH$_4$ emissions from cattle consuming intensively-managed pasture were also reported by DeRamus et al. (2003). Substantial concern has been raised about N$_2$O emissions from intensively-grazed pasture (Luo et al., 2010) but in this study, switching to intensively-managed pasture reduced N$_2$O emissions because less land was required. The use of irrigated pasture in the cow-calf sector reduced N fertilizer use but resulted in lowered GHG emissions from pasture production by using irrigation to maintain comparable forage quality and yield.

Without the WTP constraint, a 48.7% increase in diet cost reduced CO$_2$ emissions by 7.2% at the expense of a 2.6% increase in water use and a 64.0% increase in land use. Diets used grass hay, C and R for the cow-calf enterprise, grass hay and R to the stocker cattle and grass hay as forage in the feedlot. Minimizing GHG emissions required converting diets to rely on feedstuffs with minimal N fertilizer use and CO$_2$ emissions from the fertilization and irrigation processes. Although extensive grazing reduced GHG emissions, substantial increases in diet cost and in land required (Howden et al., 1994) make this management strategy impractical. In this case, unlike when minimizing water, water use increased due to increased grass hay in the diets.
Simultaneous Minimization of Land, Water and Greenhouse Gases

The inter-dependence of environmental metrics illustrated in single objective optimizations support examination of simultaneous minimization of land use, water use and GHG emissions as an important option. When land use, water use and GHG emissions were all minimized, the increase of $0.144 /kg HCW beef (WTP) resulted in a 3.6% decrease in GHG, water use and land use. To achieve this change, cow-calf diets relied on grass hay, C-IF, R-IF and R pasture, stockers used R-IF and R pasture and feedlot diets used grass hay as a forage source. The R-IF and C-IF feeds helped to minimize land use and subsequently reduce GHG emissions due to reduced land required and reduced enteric CH₄ emissions. Rotational grazing of pasture reduced total water required and reduced GHG emissions from N fertilizer use. Rather than advocating a single management protocol as ideal, these results suggest that heterogeneous management of forage resources will help to improve sustainability. Heterogeneous management of pasture improves biodiversity (Rook et al., 2004), grass species diversity and productivity (Ovalle et al., 2006) and grazing system durability (Schwinning and Parsons, 1999). Although these results speak to a balance of objectives in management decisions, they also support implementation of precision management in grazing systems. Precision irrigation and fertilization allows for improved water and nutrient balance of grazed systems and understanding pasture heterogeneity at the field level will aid in implementing precision management on grasslands (Schellberg et al., 2008).

Given current economic conditions, the management options identified in this model can help to simultaneously reduce land use, water use and GHG emissions by 3.6%. A historical comparison of the US beef industry indicated 16.3%, 12.1%, 33% reductions in GHG emissions, water use and land use over a 30 year period (Capper, 2011a). The reductions modeled in our study
represent an instant change in management given the feedstuffs available today. Assuming that the trend demonstrated in Capper (2011) endures and new efficiency-improving technologies continue to become available over the next several years, these results demonstrate ample opportunities to improve future beef sustainability. Models like this one can be used to assess optimal adoption of technologies to ensure economic viability, social acceptability and improved environmental impact.

In Capper (2011), the 30 yr. changes in environmental impact were associated with decreasing finishing time while concurrently increasing finishing weight. In this assessment, finishing time and weight were constrained and only dietary composition was allowed to vary. Composition of feedlot diets did not differ substantially by scenario. By comparison, the diets of forage-based animal populations changed considerably. Although the feedlot has been targeted as an area to improve environmental impact (Subak, 1999), this analysis indicates that, following recent reviews (FAO, 2013), forage management in the cow-calf and stocker systems is a more promising area of focus. In fact, promoting responsible utilization and management of pasture resources has been identified as a key component to improving cattle production environmental impact (Beauchemin et al., 2011; FAO, 2013; Nguyen et al., 2013).

Pasture Management, Cow-Calf Efficiency and Whole-System Sustainability
The model indicated that increasing pasture yield and quality by management intensification reduced GHG emissions and resource use per unit product. Other studies examining pasture management intensification (Asgedom and Kebreab, 2011; Bell et al., 2012; Foley et al., 2011) have also identified this relationship. Pasture yield and forage quality are highly dependent on climate. As a result the predictions of increasing climate variability are expected to impact
forage production (Maracchi et al., 2005). The cow-calf sector grazes the majority of the year and is responsible for the majority of environmental impact of beef production (Beauchemin et al., 2010; Pelletier et al., 2010). In the U.S., most cow-calf operations supplement cows with roughages for 90 to 180 d (USDA/APHIS, 2010). The exact amount of supplement given per day and the frequency of supplementation is not known. The US Global Change Research Program (2009) has predicted changes in precipitation patterns due to climate variability. Identification of opportunities for beef producers, particularly cow-calf and stocker managers, to change pasture management strategies in the face of variable precipitation is critical to the sustainability of grazing lands used in beef production. To examine how alterations in precipitation might change the management strategies investigated previously, the pasture module was used to link predicted precipitation changes to subsequent changes in forage production and management (Table 8). The optimization model was used to assess the impact on improving beef sustainability in three locations (Table 9).

The Pacific Northwest

When modeling the current precipitation patterns in the Pacific Northwest, a cost increase of $0.144/kg HCW beef reduced land use, water use and GHG emissions by 3.6% - 4.0% each. In the current scenario, grass hay was used for winter feeding while C-IF and R-F were used as spring and summer forage. The R-IF was used briefly in the fall. When adjusted precipitation patterns were modeled, opportunity to reduce land use, water use and GHG emissions was decreased by 3.3% to 3.6% each. In the projected precipitation scenario, grass hay was fed for longer into the spring and earlier in the fall. As a result, less R-F could be afforded during the summer months, no R-IF was fed and more C-IF was used. Compared with C-IF, grass hay
required more land, water and GHG. Thus because more supplemental forage was required, less environmentally efficient feeds could be afforded within the bound of consumer WTP.

The Midwest

When pasture simulation used values representative of the Midwestern U.S., land use, water use and GHG emissions were reduced by 5.8% to 6.0% with a cost increase of $0.144 /kg HCW beef. Diets in the current precipitation scenario used grass hay through winter, R-IF and C-IF throughout spring and fall and R-F through the summer. Opportunities to reduce land, water and GHG emissions ranged from 5.9% to 6.1% when projected precipitation patterns were modeled. In the Midwest, precipitation changes acted favorably on pastures to increase yield resulting in less grass hay required through fall and winter and more use of R-IF pasture. Yield increases due to adjusted precipitation were unique in the Midwest and allowed for improved opportunities to optimize operation sustainability.

Texas

In Texas, a cost increase of $0.144 /kg HCW beef reduced land use water use and GHG emissions by 1.8% to 2.2% each under current precipitation patterns. Diets to achieve these results relied on winter feeding of grass hay, use of R-IF, C-IF and C-F in the spring, late summer and fall with R-F in midsummer. When climate-variability influenced precipitation was modeled, opportunities to reduce land, water and GHG emissions decreased by 1.2% to 1.6% each. Under the altered precipitation patterns, diets used less R-IF, C-F and R-F and relied more on C-IF. Expense increases due to decreased pasture availability resulted in more C-IF to be fed.

Trends in Climate Impacts across Regions
The Midwest had the greatest opportunities to improve sustainability of beef production of any region and was the only region that was positively impacted by climate variability. This is a result of improved pasture yield, decreased use of stored forages and C-IF and increased use of R-IF, yielding a net decrease in environmental impact. Texas had the fewest opportunities to improve sustainability of beef production. The Midwest and the Pacific Northwest may have had greater opportunities to improve sustainability because of higher annual pasture yields in these regions. Of the locations modeled, none had a severe winter and all could feasibly graze cattle for most of the year potentially reducing needed supplement costs. In all cases, extending the length of the grazing season improved economic viability and allowed for increased investment in grazing strategies that could reduce environmental impact. This is supported by previous studies evaluating economic viability of maintaining cows on pasture over winter (Adams et al., 1994; Anderson et al., 2005). Moderate to intensive grazing management improves the economic viability of grass-based cattle operations (Hanson et al., 1998; Parker et al., 1992; Swain et al., 2007). In these scenarios, any time the grazing season could be extended or more R-IF could be afforded in the diet, the environmental impact tended to decrease. When climate negatively impacted pasture growth, more stored forage was required and environmental impact tended to increase. Future analyses should focus on improving the pasture simulation component of the model to accurately simulate pasture heterogeneity to help identify ideal management practices across a varied landscape including modeling the long-term response of pastures to variation in climate and grazing management system. Additionally, these analysis should identify how pasture management could be adjusted to improve environmental impact in locations where extending the grazing season is impractical.
CONCLUSIONS

The model was capable of identifying diet and pasture management to simultaneously reduce land use, water use and GHG in an economically viable and socially acceptable manner. Evaluation of the least-cost scenario outputted by the model agreed well with previously-published estimates of beef environmental impact. Opportunities to improve environmental impact were constrained by a conservative WTP estimate. In markets with greater WTP, as demonstrated by the unconstrained scenarios, an increased variety of management practices became economically viable and more substantial reductions in environmental impact were possible. However, predicted variation in rainfall amount and timing may markedly affect the management options available for reduced resource use. The model developed in this study represents a robust and sensitive tool that can be used to identify specific management practices that may help improve sustainability of beef in the US.
LITERATURE CITED


USDA/APHIS. 2011. Feedlot 2011 Part I: Management practices on U.S. feedlots with a capacity of 1,000 or more head. USDA/APHIS, Fort Collins, CO.


Table 1. Start weight, end weight and time spent in the model for each cattle group

<table>
<thead>
<tr>
<th>Animal Group</th>
<th>Start Weight (kg)</th>
<th>End Weight (kg)</th>
<th>Time (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactating Cow</td>
<td>535</td>
<td>535</td>
<td>183</td>
</tr>
<tr>
<td>Gestating Cow</td>
<td>535</td>
<td>535</td>
<td>182</td>
</tr>
<tr>
<td>Lactating, Gestating Cow</td>
<td>535</td>
<td>535</td>
<td>60</td>
</tr>
<tr>
<td>Heifer Calf</td>
<td>34</td>
<td>225</td>
<td>207</td>
</tr>
<tr>
<td>Steer Calf</td>
<td>34</td>
<td>254</td>
<td>207</td>
</tr>
<tr>
<td>Bull Calf</td>
<td>36</td>
<td>318</td>
<td>207</td>
</tr>
<tr>
<td>Yearling Bull</td>
<td>318</td>
<td>503</td>
<td>160</td>
</tr>
<tr>
<td>Adolescent Bull</td>
<td>503</td>
<td>675</td>
<td>365</td>
</tr>
<tr>
<td>Mature Bull</td>
<td>675</td>
<td>797</td>
<td>365</td>
</tr>
<tr>
<td>Growing Replacement Heifer</td>
<td>225</td>
<td>425</td>
<td>217</td>
</tr>
<tr>
<td>Bred Replacement Heifer</td>
<td>375</td>
<td>535</td>
<td>285</td>
</tr>
<tr>
<td>Lactating Replacement Heifer</td>
<td>535</td>
<td>500</td>
<td>183</td>
</tr>
<tr>
<td>Replacement heifer, 2nd Gestation</td>
<td>500</td>
<td>535</td>
<td>182</td>
</tr>
<tr>
<td>Stocker Steer</td>
<td>254</td>
<td>405</td>
<td>157</td>
</tr>
<tr>
<td>Stocker Heifer</td>
<td>225</td>
<td>365</td>
<td>157</td>
</tr>
<tr>
<td>Calf-Fed Steer</td>
<td>254</td>
<td>615</td>
<td>280</td>
</tr>
<tr>
<td>Calf-Fed Heifer</td>
<td>225</td>
<td>566</td>
<td>280</td>
</tr>
<tr>
<td>Finisher Steer</td>
<td>405</td>
<td>615</td>
<td>130</td>
</tr>
<tr>
<td>Finisher Heifer</td>
<td>365</td>
<td>566</td>
<td>130</td>
</tr>
<tr>
<td>Dairy Steer</td>
<td>92</td>
<td>615</td>
<td>414</td>
</tr>
<tr>
<td>Dairy Heifer</td>
<td>92</td>
<td>566</td>
<td>389</td>
</tr>
</tbody>
</table>

1 A diet was balanced for each of these animal groups within the model.

2 Start weight refers to the assumed weight of the animal at the beginning of their time in the model.

3 End weight refers to the assumed weight of the animal at the end of their time in the model. This is slaughter weight for culled cows and bulls, calf-fed beef and dairy cattle and yearling-fed beef cattle.
### Table 2. Parameters required for determining cattle populations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cows per Yearling Bull¹</td>
<td>16.3</td>
</tr>
<tr>
<td>Cows per Mature Bull¹</td>
<td>23.7</td>
</tr>
<tr>
<td>Cows Calving Yearly¹</td>
<td>89%</td>
</tr>
<tr>
<td>Proportion of Breeding Population Made up by Heifers¹</td>
<td>9.3%</td>
</tr>
<tr>
<td>Calves Born Alive¹</td>
<td>96.5%</td>
</tr>
<tr>
<td>Calf Death Loss¹</td>
<td>9%</td>
</tr>
<tr>
<td>Stocker Death Loss²</td>
<td>5%</td>
</tr>
<tr>
<td>Finisher Death Loss²</td>
<td>5%</td>
</tr>
<tr>
<td>Proportion of Slaughter Population Made Up by Bulls³</td>
<td>1.7%</td>
</tr>
<tr>
<td>Proportion of Slaughter Population Made Up by Beef Cows³</td>
<td>10.6%</td>
</tr>
<tr>
<td>Proportion of Slaughter Population Made Up by Dairy Cows³</td>
<td>8.6%</td>
</tr>
<tr>
<td>Proportion of Slaughter Population Made Up by Heifers³</td>
<td>29.7%</td>
</tr>
<tr>
<td>Proportion of Slaughter Population Made Up by Steers³</td>
<td>49.4%</td>
</tr>
<tr>
<td>Proportion of Calf-Fed Beef Calves⁴</td>
<td>16.5%</td>
</tr>
<tr>
<td>Proportion of Calf-Fed Dairy Calves⁴</td>
<td>8.5%</td>
</tr>
<tr>
<td>Gestation Length²</td>
<td>285 d</td>
</tr>
<tr>
<td>Lactation Length⁶</td>
<td>207 d</td>
</tr>
<tr>
<td>Annual Milk Yield⁷</td>
<td>1,625 kg</td>
</tr>
<tr>
<td>Milk Fat Content⁸</td>
<td>4.03%</td>
</tr>
<tr>
<td>Milk Protein Content⁸</td>
<td>3.38%</td>
</tr>
</tbody>
</table>

¹ USDA/APHIS (2009b)
² Values were assumed
³ USDA/ERS (2012b)
⁴ Capper (2011a)
⁵ USDA/APHIS (2011)
⁶ USDA/APHIS (2009a)
⁷ Miller et al. (1999)
⁸ National Research Council (2000)
Table 3. Locations and root mean squared error of prediction (RMSPE) for parameterized growth curves used in pasture simulation

<table>
<thead>
<tr>
<th>State</th>
<th>Number of Curves</th>
<th>RMSPE&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas</td>
<td>486</td>
<td>9.7%</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>7</td>
<td>7.0%</td>
</tr>
<tr>
<td>Mississippi</td>
<td>1</td>
<td>7.8%</td>
</tr>
<tr>
<td>Nebraska</td>
<td>84</td>
<td>9.1%</td>
</tr>
<tr>
<td>South Dakota</td>
<td>87</td>
<td>9.4%</td>
</tr>
<tr>
<td>Montana</td>
<td>4</td>
<td>8.7%</td>
</tr>
<tr>
<td>Kansas</td>
<td>212</td>
<td>7.5%</td>
</tr>
<tr>
<td>Kentucky</td>
<td>1</td>
<td>9.0%</td>
</tr>
<tr>
<td>Arkansas</td>
<td>8</td>
<td>8.6%</td>
</tr>
<tr>
<td>Iowa</td>
<td>1</td>
<td>9.0%</td>
</tr>
</tbody>
</table>

<sup>1</sup>Number of curves indicates the number of growth curves that were parameterized for each state.

<sup>2</sup>Average root mean squared error of prediction (RMSPE) for the monthly yields predicted for all growth curve.
Table 4. Feedstuff and pasture chemical composition\(^1\), costs\(^2\) and environmental attributes\(^3\)

<table>
<thead>
<tr>
<th>Feed(^4)</th>
<th>CP (%)</th>
<th>ME (Mcal/kg)</th>
<th>Cost ($/kg)</th>
<th>Irrigation (L/kg)</th>
<th>CO(_2)-Equivalents(^5) (kg/ha)</th>
<th>Yield (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa (AH)</td>
<td>17.0</td>
<td>2.24</td>
<td>0.178</td>
<td>257.1</td>
<td>224.57</td>
<td>7,556</td>
</tr>
<tr>
<td>Grass (GH)</td>
<td>10.0</td>
<td>1.65</td>
<td>0.129</td>
<td>119</td>
<td>103.95</td>
<td>4,334</td>
</tr>
<tr>
<td>Corn Grain (CG)</td>
<td>8.5</td>
<td>3.39</td>
<td>0.206</td>
<td>77.3</td>
<td>228.98</td>
<td>9,521</td>
</tr>
<tr>
<td>Soybean Meal (SBM)</td>
<td>49.0</td>
<td>3.04</td>
<td>0.552</td>
<td>74.5</td>
<td>117.77</td>
<td>2,841</td>
</tr>
<tr>
<td>Molasses (MOL)</td>
<td>46.4</td>
<td>2.83</td>
<td>0.518</td>
<td>175.4</td>
<td>193.3</td>
<td>3,701</td>
</tr>
<tr>
<td>Distillers Grains (DDG)</td>
<td>29.5</td>
<td>3.18</td>
<td>0.350</td>
<td>86.7</td>
<td>452.33</td>
<td>3,564</td>
</tr>
<tr>
<td>Control Pasture (C)</td>
<td>14.5</td>
<td>2.57</td>
<td>0.131</td>
<td>0</td>
<td>11.8</td>
<td>3,261</td>
</tr>
<tr>
<td>Irrigated Pasture (I)</td>
<td>14.5</td>
<td>2.57</td>
<td>0.111</td>
<td>37.7</td>
<td>23.5</td>
<td>4,155</td>
</tr>
<tr>
<td>Fertilized Pasture (F)</td>
<td>14.5</td>
<td>2.57</td>
<td>0.115</td>
<td>0</td>
<td>161</td>
<td>4,255</td>
</tr>
<tr>
<td>Irrig+Fert Pasture (I-F)</td>
<td>14.5</td>
<td>2.56</td>
<td>0.083</td>
<td>25.7</td>
<td>184.5</td>
<td>6,111</td>
</tr>
<tr>
<td>Rotated Pasture (R)</td>
<td>14.1</td>
<td>2.68</td>
<td>0.146</td>
<td>0</td>
<td>11.8</td>
<td>3,313</td>
</tr>
<tr>
<td>Rotated Irrig Pasture (R-I)</td>
<td>14.1</td>
<td>2.68</td>
<td>0.123</td>
<td>37.3</td>
<td>23.5</td>
<td>4,209</td>
</tr>
<tr>
<td>Rotated Fert Pasture (R-F)</td>
<td>14.1</td>
<td>2.68</td>
<td>0.127</td>
<td>0</td>
<td>161</td>
<td>4,309</td>
</tr>
<tr>
<td>Rot. Fert + Irrig Pasture (R-FI)</td>
<td>14.1</td>
<td>2.68</td>
<td>0.091</td>
<td>25.7</td>
<td>184.5</td>
<td>6,168</td>
</tr>
</tbody>
</table>

\(^1\)Chemical composition of non-pasture feeds was from the Agricultural Modeling and Training Systems CattlePro (AMTS, 2006) Feed Library. Pasture chemical composition was modeled.

\(^2\)Costs were modeled for pasture feeds and from USDA/ERS (2012b) for non-pasture feeds.

\(^3\)Environmental attributes including irrigation required, CO\(_2\) production and yield were modeled within the pasture module or from USDA/ERS (2012b) or USDA/NASS (2007).

\(^4\)Feeds available during diet formulation.

\(^5\)Carbon emissions included CO\(_2\) from manufacture of cropping system inputs and tillage as well as N\(_2\)O from fertilizer application.
Table 5. Population-specific limits on forage, pasture and other specific feeds

<table>
<thead>
<tr>
<th>Constraint(^1)</th>
<th>Cows</th>
<th>Bulls</th>
<th>Replacements</th>
<th>Stocker</th>
<th>Feedlot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forage Upper</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>15%</td>
</tr>
<tr>
<td>Forage Lower</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>5%</td>
</tr>
<tr>
<td>Pasture Upper</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Pasture Lower</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
<td>85%</td>
<td>0%</td>
</tr>
<tr>
<td>Molasses Upper</td>
<td>0.136 g/d</td>
<td>0.136 g/d</td>
<td>0.136 g/d</td>
<td>0.136 g/d</td>
<td>0 g/d</td>
</tr>
<tr>
<td>CG Upper</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>95%</td>
</tr>
<tr>
<td>SBM Upper</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>40%</td>
</tr>
<tr>
<td>DDG Upper</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>40%</td>
</tr>
</tbody>
</table>

\(^1\)Constraints included upper and lower limits for forage percentage in the diet (forage upper and forage lower), upper and lower limits for pasture percentage in the diet (pasture upper and pasture lower), upper limit for quantity of molasses fed (molasses upper) and upper limit for the concentrate feeds corn grain (CG), soybean meal (SBM) and dried distillers grains (DDG).
Table 6. Baseline Scenario Outputs of Environmental Impact

<table>
<thead>
<tr>
<th>Output(^1) (kg HCW(^{-1}))</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Footprint (kg CO(_2)e)</td>
<td>20.3</td>
</tr>
<tr>
<td>Enteric Methane (kg CO(_2)e)</td>
<td>15.6</td>
</tr>
<tr>
<td>Manure Methane (kg CO(_2)e)</td>
<td>0.5</td>
</tr>
<tr>
<td>Direct Nitrous Oxide (kg CO(_2)e)(^2)</td>
<td>2.7</td>
</tr>
<tr>
<td>Indirect Nitrous Oxide (kg CO(_2)e)</td>
<td>0.1</td>
</tr>
<tr>
<td>Carbon Dioxide (kg CO(_2)e)</td>
<td>1.4</td>
</tr>
<tr>
<td>Water Use (L)</td>
<td>1,280</td>
</tr>
<tr>
<td>Irrigation Water Use (L)</td>
<td>1,157</td>
</tr>
<tr>
<td>Daily Drinking Water Use (L)</td>
<td>123</td>
</tr>
<tr>
<td>Land Use (m(^2))</td>
<td>60.0</td>
</tr>
<tr>
<td>Cropland (m(^2))(^3)</td>
<td>4.1</td>
</tr>
<tr>
<td>Pastureland (m(^2))</td>
<td>55.9</td>
</tr>
</tbody>
</table>

\(^1\)All outputs are given per kg of hot carcass weight (HCW) beef.

\(^2\)Direct N\(_2\)O emissions included only those predicted to emit directly from manure storage while indirect N\(_2\)O emissions included downstream leached and volatilized N\(_2\)O.

\(^3\)Cropland included land used for growing concentrate feeds, byproduct feeds and hays.
Table 7. Changes in environmental impact and diet cost from baseline scenario. Values are reported as percent changes from the least cost baseline.

<table>
<thead>
<tr>
<th></th>
<th>Scenario Unconstrained(^1) by WTP</th>
<th>Scenarios Constrained(^2) by WTP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimizing Land</td>
<td>Minimizing Water</td>
</tr>
<tr>
<td>Diet Cost</td>
<td>+11.3%</td>
<td>+53.2%</td>
</tr>
<tr>
<td>GHG</td>
<td>-2.3%</td>
<td>-4.7%</td>
</tr>
<tr>
<td>Water Use</td>
<td>+57.7%</td>
<td>-22.6%</td>
</tr>
<tr>
<td>Land Use</td>
<td>-7.8%</td>
<td>+70.5%</td>
</tr>
</tbody>
</table>

\(^1\)Unconstrained scenarios were simulated without constraining diet cost increases to less than consumer willingness to pay (WTP).

\(^2\)Constrained scenarios were simulated with the constraint that diet cost be less than consumer willingness to pay.
Table 8. Projected changes in seasonal precipitation in the Pacific Northwest, the Midwest and Texas

<table>
<thead>
<tr>
<th>Season</th>
<th>Pacific Northwest</th>
<th>Midwest</th>
<th>Texas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>+5%(^1)</td>
<td>+5%</td>
<td>-15%</td>
</tr>
<tr>
<td>Spring</td>
<td>-2%</td>
<td>+0%</td>
<td>-20%</td>
</tr>
<tr>
<td>Summer</td>
<td>-20%</td>
<td>-10%</td>
<td>-15%</td>
</tr>
<tr>
<td>Fall</td>
<td>+5%</td>
<td>-5%</td>
<td>-7%</td>
</tr>
</tbody>
</table>

\(^1\)Data represent projected percent change in rainfall over the season U.S. Global Change Research Program (2009).
Table 9. Outputted changes in land use, water use and greenhouse gas emissions related to precipitation changes in the Pacific Northwest, the Midwest and Texas

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Location</th>
<th>Rainfall</th>
<th>GHG</th>
<th>Water</th>
<th>Land</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimizing Land Use</td>
<td>PNW</td>
<td>Average</td>
<td>-3%</td>
<td>+6%</td>
<td>-28%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>-3%</td>
<td>+6%</td>
<td>-26%</td>
</tr>
<tr>
<td></td>
<td>Midwest</td>
<td>Average</td>
<td>-5%</td>
<td>+6%</td>
<td>-33%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>-5%</td>
<td>+6%</td>
<td>-34%</td>
</tr>
<tr>
<td></td>
<td>Texas</td>
<td>Average</td>
<td>-2%</td>
<td>+8%</td>
<td>-26%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>-2%</td>
<td>+9%</td>
<td>-24%</td>
</tr>
<tr>
<td>Minimizing Water Use</td>
<td>PNW</td>
<td>Average</td>
<td>-1%</td>
<td>-5%</td>
<td>+4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>-1%</td>
<td>-5%</td>
<td>+5%</td>
</tr>
<tr>
<td></td>
<td>Midwest</td>
<td>Average</td>
<td>-2%</td>
<td>-7%</td>
<td>+4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>-2%</td>
<td>-7%</td>
<td>+4%</td>
</tr>
<tr>
<td></td>
<td>Texas</td>
<td>Average</td>
<td>-1%</td>
<td>-3%</td>
<td>+9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>-1%</td>
<td>-2%</td>
<td>+10%</td>
</tr>
<tr>
<td>Minimizing Greenhouse Gas Emissions</td>
<td>PNW</td>
<td>Average</td>
<td>-6%</td>
<td>+2%</td>
<td>+0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>-6%</td>
<td>+3%</td>
<td>+1%</td>
</tr>
<tr>
<td></td>
<td>Midwest</td>
<td>Average</td>
<td>-8%</td>
<td>+1%</td>
<td>+0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>-8%</td>
<td>+1%</td>
<td>+0%</td>
</tr>
<tr>
<td></td>
<td>Texas</td>
<td>Average</td>
<td>-4%</td>
<td>+4%</td>
<td>+0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>-4%</td>
<td>+5%</td>
<td>+0%</td>
</tr>
<tr>
<td>Minimizing Land Use, Water Use,</td>
<td>PNW</td>
<td>Average</td>
<td>-3.6%</td>
<td>-3.6%</td>
<td>-3.6%</td>
</tr>
<tr>
<td>Greenhouse Gas Emissions</td>
<td></td>
<td>Predicted</td>
<td>-3.3%</td>
<td>-3.3%</td>
<td>-3.3%</td>
</tr>
<tr>
<td></td>
<td>Midwest</td>
<td>Average</td>
<td>-5.8%</td>
<td>-5.8%</td>
<td>6.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
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<td>-5.9%</td>
<td>6.1%</td>
</tr>
<tr>
<td></td>
<td>Texas</td>
<td>Average</td>
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<td>-1.8%</td>
<td>-2.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>-1.2%</td>
<td>-1.2%</td>
<td>-1.6%</td>
</tr>
</tbody>
</table>

1 Outputs are reported as percentage differences from the least-cost baseline scenario.

2 Regions modeled included the Pacific Northwest (PNW), Midwest and Texas.

3 Average rainfall was sourced from NCDC (2012) and predicted rainfall used the projected changes in rainfall reported by U.S. Global Change Research Program (2009).
CHAPTER 5

NUTRITION, REPRODUCTION, GENETICS AND SUSTAINABILITY
INTRODUCTION

Whole-farm models have integrated different levels of biological organization to compare management strategies that reduce environmental impact (Beauchemin et al., 2011; Crosson et al., 2011a; Nguyen et al., 2013). These models indicate that improved cattle production efficiency is frequently tied to reduced environmental impact (Bell et al., 2011; Capper, 2011a; Capper and Bauman, 2013). Until recently, the link solidifying environmentally-oriented management practices with economic viability (Capper and Hayes, 2012; Oishi et al., 2012) and social acceptability (Stackhouse-Lawson et al., 2013; White and Capper, 2013) was less well investigated. To date, studies exploring all three components of sustainability have focused on comparing production systems rather than comparing specific management practices. Biological and farm-system efficiency can be optimized through targeting nutritional, genetic and reproductive management. Selecting sires by expected progeny difference (EPD) is one genetic management strategy that can be employed to improve productivity (Allan and Smith, 2008). Artificial insemination (AI) has not been widely adopted in the beef industry but is one means of impregnating a large number of cows with semen from a single high-genetic merit bull (Nicholas, 1996). Other reproductive strategies that might improve efficiency include maintaining a 60 d calving window or moving toward cattle with a high rate of twinning (Guerra-Martinez et al., 1990; Sinclair et al., 1995). As producers adopt these various technologies, nutritional programs must be adapted accordingly. Assessment of management effects on sustainability must therefore concurrently account for genetic, reproductive and nutritional changes on productivity and their subsequent impact on environment, economics and consumer acceptance.
The objective of this study was to use a model optimizing pasture management and cattle nutrition to identify the impact of nutritional changes and reproductive or genetic technologies on opportunities to minimize whole-system land use, water use and greenhouse gas (GHG) emissions from beef production in an economically viable, socially acceptable manner.

**MATERIALS AND METHODS**

An environmental and economic nutritional optimizer was used to optimize monthly diets for six production scenarios. Scenarios included a scenario representing average US production practices with adjusted nutritional management alone (NUT); twinning cattle (TWN); sire selection by expected progeny differences using either on-farm bulls (EPD-B) or artificial insemination (EPD-AI); or decreasing the calving window (CW) from 80 d to 60 d. To simulate a concurrent improvement in genetic and reproductive management, a final scenario was modeled that explored improved genetic selection through EPDs along with a decreased calving window (EPD-CW). Farm system data for the scenarios are described in Table 1. Optimized nutritional management was incorporated into each scenario because diets were optimized to reduce environmental impact. This methodology therefore allowed for simultaneous assessment of how nutritional, genetic and reproductive management could impact opportunities to improve sustainability. Inputs to the model included weather data (NCDC, 2012) and cattle performance data (USDA/APHIS, 2009a, b; USDA/ERS, 2012b) adjusted according to the scenario modeled. Outputs from the model included diet costs as well as land use, water use and GHG per kg of hot carcass weight (HCW) beef produced. The model ran in the Generic Algebraic Modeling System (GAMS Development Corporation, 2012) and used non-linear programming to identify optimal diets.
Model Structure and Calculation Method

An in-depth description of the model is provided in the Appendix of this chapter. The model integrated environmental impact (Capper, 2011a, 2012; White and Capper, 2013), farm economics (White and Capper, 2013), pasture management (McCall and Bishop-Hurley, 2003; Romera et al., 2009) and consumer willingness to pay (Igo et al., 2013; White and Brady, 2013). The model was used to assess how management could be optimized to reduce beef’s environmental impact while maintaining production within the bounds of biological, economic and practical constraints. Cattle populations, animal nutrient requirements and performance parameters were simulated for each treatment. Expected progeny differences, twinning and calving interval changes were simulated as adjustments to national average data. Predicted cattle performance (weight, daily gain, etc.), nutrient requirements and expected populations required were used as inputs to the optimization framework. For each treatment, scenarios were modeled to minimize land use, water use and/or GHG emissions. Each scenario was compared to the baseline which was defined as the least-cost optimization of the NUT treatment. All scenarios were constrained so that dry matter intake was less than the predicted maximum for each cattle group, and nutrients provided by the diet were greater than requirements predicted by National Research Council (2000).

Environmental scenarios were additionally constrained to limit increases in diet cost to less than the consumer WTP for efficient production practices (Igo et al., 2013) or environmental products (White and Brady, 2013). Consumer WTP is an indicator of consumer satisfaction (Homburg et al., 2005) and was the selected metric of social acceptability. Packer and wholesaler WTP for improved genetic merit or improved uniformity (Igo et al., 2013) was used to describe premiums received for beef sold from the EPD-AI, EPD-B, CW and EPD-CW scenarios. The 4% increase
in WTP outlined by White and Brady (2013) was used to describe premiums received for beef sold in scenarios where environmental impact was reduced. Packer, wholesaler and consumer WTP was summed, assuming 50% of packer and wholesaler WTP and 25% of consumer WTP was returned to the farm level.

A breakdown of packer/wholesaler and consumer contributions to the modeled increases in WTP is included in Table 2. Percentage premium WTP was converted to a $/kg HCW basis using a 63% dressing weight and an assumed 65% conversion of HCW beef to retail beef. Aggregated WTP varied by treatment with the NUT and TWN treatments receiving a premium of $0.072/kg HCW beef, reflecting only increased consumer WTP for environmental products. The EPD-AI, EPD-B and EPD-CW scenarios received premiums of $0.282/kg HCW beef which included a premium for genetically superior cattle and a premium for reduced environmental impact. The CW scenario received $0.248/kg HCW beef as a result of more uniform cattle and reduced environmental impact.

In addition to accounting for feed costs (USDA/ERS, 2012b) and pasture management costs (Gillespie et al., 2008; Khakbazan et al., 2009; USDA/NASS, 2007) as outlined in the supplement; breeding and specialty feeding costs were also included depending on the scenario. Average retail cost of semen, prostaglandin and gonadotropin injections and progesterone implants (ABS Global, 2013; Genex Cooperative, 2013; Select Sires Beef, 2013; Valley Vet Supply, 2013) were factored into the EPD-AI scenario.

National average yields (USDA/ERS, 2012b) and feed nutrient contents (National Research Council, 2000) were used as input parameters for the hay, concentrate and by-product feeds used to balance cattle diets. Pasture management inputs were simulated using the pasture module as outlined in the supplement. Mixed warm- and cool-season grass pasture was modeled under eight
management strategies: continuously-grazed (C); continuously-grazed irrigated (C-I); continuously-grazed fertilized (C-F); continuously-grazed, irrigated and fertilized (C-IF); rotated (R); rotated irrigated (R-I); rotated fertilized (R-F) and rotated irrigated and fertilized (R-IF). Monthly yield and quality data for each strategy were used as inputs to the nutritional optimizer. Yield, quality and environmental parameters for each available feed are included in Table 3. For each treatment, opportunities to reduce land use, water use and/or GHG emissions were calculated relative to a baseline. The least-cost optimization of the NUT scenario was used as the baseline for all comparisons. Opportunities to reduce environmental impact were compared between treatments to identify how reproductive and genetic technologies, coupled with optimized nutrition, could change the opportunity to improve sustainability of beef production.

Scenarios Simulated

Six scenarios were simulated to identify opportunities to improve U.S. beef sustainability by ensuring adequate nutrition to cattle within production systems adopting different genetic and reproductive technologies. The NUT scenario was simulated using average production data for cattle in the United States as outlined in Table 1. The TWN scenario simulated twinning in cows with an allowance for supplemental feed required during gestation and lactation. Twinning was used as a treatment, not to suggest it as a management practice, but rather to explore effects of the biologically-allowable maximum increase in calves per cow per year. That said, twinning may be a reasonable management strategy in some unique systems where twinning is more profitable than single-calf systems (De Rose and Wilton, 1991). Proportional differences in conception rate, assistance rate, live birth rate, calf loss, birth weight, weaning weight and post-weaning average daily gain in a twinning
and conventional system (Echternkamp et al., 1990; Gregory et al., 1996; Gregory et al., 1990) were used to adjust national average values to represent a hypothetical twinning system. Additional nutritional requirements for gestation and lactation (Guerra-Martinez et al., 1990) were incorporated into energy and protein requirement estimates to ensure sufficient supplemental nutrition supplied to cows carrying twins. Population parameters for this and all other scenarios are included in Table 1. Specific values for the TWN scenario are listed in Table 3.

The CW scenario simulated a reduction in the calving window from 80 d to 60 d. Given that most cow-calf producers wean calves based on age or weight, it was assumed that the date of weaning would remain the same when calving window decreased. On farm, decreasing the calving window would require a series of transition years during which mature cows calving outside the desired window would be culled. For the purposes of this comparison, it was assumed that culling rates between the NUT and CW scenarios did not change as the treatments compared a farm with an 80 day window and a farm with a 60 d window, not necessarily the transition period to change from 80 to 60 d. Calves in the CW scenario were older on average and weighed more than calves in the NUT scenario. The CW scenario was assumed to require an additional 2 hours of labor per day for the 60 d breeding window. The national average wage for agricultural laborers (Bureau of Labor Statistics, 2012) was used to identify the increase in labor costs associated with this scenario.

The EPD profiles used in the EPD-AI, EPD-B and EPD-CW scenarios are included in Table 3 are were designed to represent reasonable profiles of top sires in many popular breeds (American Angus Association, 2013; American Hereford Association, 2013; American Simmental Association, 2013). The selection scheme balanced interest in maternal, performance and carcass
traits. Accuracies were estimated based on known accuracies for high performance proven bulls. Expected progeny differences for heifer pregnancy adjusted the conception rate of heifers. Maternal calving ease was incorporated into the birth rate of cows while direct calving ease was added into the birth rate of heifers. Birth, weaning, yearling and carcass weight adjustments were added onto the average weights for animals. Post-weaning average daily gain was used to calculate the change in finishing weight due to improved genetic merit. No change in feed efficiency was assumed except what normally would be calculated by the NRC energy and protein requirements. Because of the challenges with low conception rate in AI breedings, estrus synchronization was assumed with the EPD-AI scenario and conception rate reflected a rate achievable with estrus synchronization (Larson et al., 2006). Costs for progesterone ($10.00/CIDR), prostaglandin ($2.68/dose) and gonadotropin releasing hormone ($1.30/dose) injections were identified using current retail prices (Valley Vet Supply, 2013). The EPD-AI scenario was modeled to simulate an AI program with a clean-up bull. Bull populations were adjusted to assume AI semen purchased from 1 bull per 300 cows with a conception rate of 58%. The remaining cows were served by average bulls at the standard rates of 1:23 for mature bulls and 1:17 for adolescent bulls (USDA/APHIS, 2009b) and no change in progeny performance was expected from these offspring. Semen costs were assumed at $25.00/straw based on prices listed from several sire services (ABS Global, 2013; Genex Cooperative, 2013; Select Sires Beef, 2013) making the total AI cost approximately $40/cow. A labor cost of $10/cow was included to account for an AI technician. In the EPD-B scenario, expected performance improvement in progeny was modeled identical to the EPD-AI scenario. However, conception rate was assumed to be equal to the industry average for natural service breedings (USDA/APHIS, 2009b) and no change in bull population parameters was simulated.
RESULTS

Baseline Outputs

In the baseline, least-cost NUT scenario, diet costs for the cows ranged from $0.33/hd/d during late spring to $1.38/hd/d during winter. Stocker diet cost averaged $0.25/hd/d and feedlot diet cost averaged $1.19/hd/d. Cow-calf and stocker diets relied on C-IF pasture throughout most of the year with supplemental grass hay through winter when pasture was in short supply. Feedlot diets used corn grain and dried distillers grains as a base with grass hay as a forage source. The diet costs and their respective cost of gain for growing populations agreed well with current estimates of cow diet cost and stocker or feedlot cost of gain (Gadberry and Beck, 2013; Hughes, 2013; Zimmerman, 2013). Environmental metrics from the CON least-cost scenario are listed in Table 4.

Treatment Effects on Environmental Impact

For each treatment, opportunities to minimize land use, water use and GHG emissions simultaneously and individually are listed in Table 5. Simultaneous minimization of these three environmental metrics was important because previous multi-objective optimizations indicated that environmental metrics are highly competitive and reducing only one often results in an increase in others (White et al., 2013a, b). Changes in the NUT treatment reflect opportunities to improve sustainability based on nutritional management alone. This scenario was the least effective alternative; however, a 2.1% opportunity to reduce land use, water use and GHG emissions was still achievable. The TWN and EPD-CW scenarios resulted in the greatest opportunities to simultaneously improve land use, water use and GHG emissions.
Improved genetic merit or reproductive technology use is ineffective without adequate nutritional management. Dietary management in the cow-calf and stocker sectors varied by scenario largely as a function of predicted WTP. This result reflects the greater freedom of operation associated with systems that attain higher profit margins. Feedlot diets did not change substantially from the baseline scenario. Average cow-calf diets in the environmental-impact reducing scenarios are included in Table 6. In general, scenarios with higher WTP (EPD-AI, EPD-B, EPD-CI) relied on less C, C-IF and R-IF pasture and increased use of R-F pasture. In this example, utilizing a moderately-intensive grazing strategy was the best option to improve land use, water use and GHG emissions given a relaxed budget constraint. Scenarios with lower WTP (NUT, TWN) relied on more C, C-IF and R-IF pasture because these management strategies were less expensive per unit of feed produced and provided a good compromise when reducing environmental impact.

**DISCUSSION**

**Baseline Scenario Evaluation**

The estimated environmental impacts in the baseline scenario were within the ranges established by previously published estimates for land use (Capper, 2012, 2011b; Cederberg et al., 2009; White and Capper, 2013), water use (Beckett and Oltjen, 1993; Capper, 2011a; Capper and Hayes, 2012; Ridoutt et al., 2011; Robbins, 1998; White and Capper, 2013) and GHG emissions (Capper, 2011a, 2012; Capper and Hayes, 2012; Casey and Holden, 2006b; Edwards-Jones et al., 2009; Pelletier et al., 2010; Ridoutt et al., 2011; Stackhouse et al., 2012; Verge et al., 2008). Differences between the values simulated in this study and those predicted in other studies are due to differences in sources accounted, production system modeled, animal productivity and
assumptions about the pasture and cropping systems. For example, Edwards-Jones et al. (2009) calculated higher GHG emissions than the values in this study; however, they also accounted for emission sources not included in this study (processing, packaging, retailing, consumption and waste disposal emissions).

Nutritional Management Used Across Treatments

Nutritional management used to optimize land use, water use and GHG emissions in each treatment scenario are listed in this section. With the exception of the NUT scenario, reductions in environmental impact due to each scenario are presented in the following sections. The NUT scenario diets relied on grass hay and C pasture through winter, R-IF pasture in spring, C pasture through summer and C-IF and R-IF pasture in fall. This scenario isolated the impact of nutritional management on improving environmental impact, identifying a 2% opportunity to improve environmental impact with nutritional management alone. Beauchemin et al. (2011) found 1% to 8% reductions in whole-farm GHG emissions when employing nutritionally-based mitigation strategies. The estimate of a 2% reduction fits well within this established range. Stewart et al. (2009) found that reduced forage management intensity through decreased fertilizer, fallow or use of low quality forage resulted in increased GHG emissions while improving pasture quality by using a grass-legume mixed pasture decreased GHG emissions. Similarly, Foley et al. (2011) calculated a 15% reduction in emissions per kg beef when moving from extensive pasture management to moderately intensive. These results are supported in this study as feeding strategies tended to center around improved pasture productivity and forage quality.

Nutritional management differed as WTP was adjusted in each scenario. The EPD-AI and EPD-
B scenarios increased use of C pasture and decreased grass hay and R-IF pasture. Use of C-IF pasture was swapped for R-F pasture. The CW scenario used more R-IF pasture than the NUT scenario. Grass hay content increased and C pasture made up most of the pasture. The C-IF pasture was eliminated in favor of R and R-F pastures. When TWN was implemented, diets relied on increased C pasture and grass hay. The C-IF and R-IF pasture use was decreased and some R-I pasture was added. Studies on management intensive grazing in ruminant production systems have frequently identified moderate-to-intensive grazing management as a system with greater returns per cow (Dartt et al., 1999; Hanson et al., 1998; Parker et al., 1992). Our study found C-IF and R-IF pastures to be less expensive per unit forage produced than C or R pastures. Treatments with more stringent budget constraints due to lower WTP (NUT, TWN) relied on more C-IF and R-IF pasture because of the economic pressure while treatments with more liberal budget constraints (EPD-AI, EPD-B) were able to selectively utilize feeds that would help to simultaneously reduce land use, water use and GHG emissions. Specifically, simultaneously minimizing land use and water use is very difficult (White et al., 2013b) due to the correlation between irrigation and yield. In the pastures used in this model, fertilizing provides a method of improving land-use efficiency without increasing water use.

Effects of Reproductive and Nutritional Management
The CW and TWN scenarios examined the effects of focused improvements in reproductive and nutritional management on sustainability. The CW scenario improved beef yield by 5.3 kg HCW/cow. Although more beef was produced, feed costs also increased because calves were older, on average, and consumed more feed than the calves in the NUT scenario. Cattle in the TWN scenario had lower weaning weights and took an extra month to reach finishing weight.
Heifers had lower reproductive rates and more cows were culled annually resulting in greater heifer retention requirements. Cost of dystocia increased to $1648/y. Although an expensive management option, twinning increased beef output by 94.4 kg HCW/mature cow.

The CW treatment resulted in a reduction in environmental impact compared with NUT. Reducing CW would improve quality of life for beef producers. Although there was improved environmental impact from decreasing calving window, it was not on the same scale as the improvements seen with improving genetic merit or adopting twinning. By comparison, increasing calves per cow in the TWN scenario substantially improved environmental impact.

Improved reproductive performance has been shown to reduce GHG (Beauchemin et al., 2011; Garnsworthy, 2004). When nutritional management and improved reproductive performance were employed together, more substantial GHG reductions were possible (Nguyen et al., 2013). The 13% reduction seen in this study extends these conclusions to show that improved reproductive efficiency, when coupled with optimized feeding management has ample opportunity to improve beef sustainability.

Historically, twinning has been viewed as having a negative impact on beef operations due to the increased labor required, and the increased stress and health risks to cows and calves. As a result, low adoption rates of twinning technology have been predicted (Parminter, 1997; Parminter et al., 1997). Previous conceptions about a specific technology, coupled with natural resistance to change, can present a serious barrier to technology adoption (Parente and Prescott, 1994; Straub, 2009). Although twinning in cattle might be an efficient method of improving sustainability, it is not likely to be adopted by producers.
Effects of Genetic Merit and Nutritional Management

The EPD-AI scenario reflected the practical trade-offs associated with selecting for improved reproductive and performance traits. Annual cost of dystocia decreased from $743 to $168, but technology and labor costs from semen purchase, estrus synchronization and insemination increased from zero to $49/cow. Energy and protein requirements for growing cattle increased 13.2% and 9.0%, respectively, but annual HCW beef output per cow by increased by 29.2 kg. In the EPD-B scenario, the costs from semen purchase and estrus synchronization were eliminated but the benefit of decreased incidence of dystocia and increased beef output per cow was still realized. Because a portion of the bull population was culled yearly, this scenario produced more beef than the EPD-AI scenario, marginally increasing output per mature cow to 39.8 kg.

The EPD-AI and EPD-B scenarios substantially improved environmental impact compared with the NUT scenario. The opportunity to reduce environmental impact metrics in the EPD-AI and EPD-B scenarios was comparable with the historical improvement between 1977 and 2007 (Capper, 2011a), the benefit received from growth enhancing technology use (Capper and Hayes, 2012) or the payout from a 15% increase in efficiency (White and Capper, 2013). Wall et al. (2010) found genetic selection for improved efficiency in dairy systems helped reduce GHG.

Evidence indicates that producers have utilized genetic selection, with varying degrees of sophistication, since the domestication of livestock (Bruford et al., 2003). Our results indicate that as producers continue to become more selective in choosing the genetics of their herds, the sustainability of beef production in the U.S. should improve.

The EPD-AI scenario resulted in slightly lower environmental benefits compared with the selecting on-farm bulls by EPD (EPD-B). The increase in animals required by the EPD-B scenario was outweighed by a small increase in beef produced from culling bulls and the greater
efficacy of conveying genetic merit from one generation to the next. Technologies such as improved selection by use of EPD have been suggested as methods to reduce GHG from livestock production systems (Bell et al., 2011; Garnsworthy, 2004), yet AI protocols typically have low conception and pregnancy rates (Larson et al., 2006; Martínez et al., 2002) which may contribute to low adoption by the US beef industry (USDA/APHIS, 2009a). Because the environmental benefits predicted in the EPD-B and EPD-AI scenarios were similar, using EPDs to purchase bulls for on-farm use represents a reasonable alternative for producers who are hesitant to adopt AI.

Genetic, Reproductive and Nutritional Management

The EPD-CW scenario was designed to assess the impact of a combination of improved genetic selection, reproductive efficiency and nutritional management on sustainability. This scenario benefitted from reduced dystocia incidence, improved fertility rates, increased weaning and finishing weights and improved dressing percentage as a result of improved genetic merit. Concurrently, improved reproductive management resulted in an increase in calves per year and a more uniform calf crop. Tradeoffs in this scenario included increased labor costs from reducing the calving window, increased feed consumption and energy requirements of heavier cattle and increased mature weight of bulls and heifers. Overall, the scenario resulted in a net improvement of 47.0 kg HCW beef/cow.

Individually, improving genetic merit or improving reproductive efficiency was not as effective at reducing environmental impact as when the strategies were used in concert. The findings demonstrate that when cattle nutritional requirements are met, improving genetic merit of beef cattle while maximizing reproductive efficiency presents the most promising, practical method to
improve sustainability of cattle production. The benefits of increasing intensity of genetic
selection have been shown in the US dairy industry. Between 1944 and 2007, milk yield per cow
increased from 2,074 kg/y to 9,193 kg/y (Capper et al., 2009). Although the increase in milk
yield can partially be attributed to changes in nutrition, housing and management, use of artificial
insemination increased from 0% to 70% over the time period indicating that a substantial
increase in genetic selection intensity took place. The relationship between environmental impact
and improved efficiency has been explained by the dilution of maintenance concept (Capper et
al., 2009; Capper et al., 2008). Dilution of maintenance shows that on a percentage basis, the
proportion of energy used for production is greater in animals that are more efficient. White and
Capper (2013) proposed an economic extension of this concept. When the production system is
viewed as a biological entity, development of reproductive females is an energetic and economic
cost analogous to maintenance energy at the animal level. Just as the ratio of maintenance energy
to growth energy is increased with biological efficiency in an animal, the partitioning of energy
from reproductive females to offspring bound for the beef market is improved with higher
reproductive rates and reduced calf losses. Managing for improved genetic merit and nutritional
management helps to promote the dilution of maintenance at the animal level while improving
reproductive efficiency of cattle helps to promote the dilution of maintenance at the farm-system
level. As noted in White and Capper (2013) stakeholders value the improvement in efficiency
both at an animal and farm-system level and have measurable WTP for products from these
efficient systems. The WTP represents the conversion of social capital into economic capital that
can then be re-invested in the system to help adopt technologies that will continue to improve
efficiency and ensure the subsistence of the system into the future.
When reproductive efficiency was improved concurrently with selection intensity, opportunities to improve beef production efficiency and sustainability were remarkable. In 2012, 16.8x10^9 kg of HCW beef were produced in the US (USDA/ERS, 2012b). If only 25% of that beef was produced with improved genetic and reproductive management, a 14% reduction in land, water and GHG on a national scale equates to 10.6x10^6 ha of land, 4.0x10^11 L of water and 1.3x10^10 kg of GHG no longer required by the system. In practical terms, the land area was approximately the size of the state of Ohio (United States Census Bureau, 2012a), the amount of water would supply all the households in Idaho, Montana and North Dakota (United States Census Bureau, 2012a; based on the estimate of 380 L/person/d) for a year, and the GHG emissions reduction would be equivalent to 65% of the city of Los Angeles, CA (United States Census Bureau, 2012b) ceasing use of their personal vehicles for a year. Although these numbers represent a theoretical example on a national scale, efficiency improvements from increased reproductive efficiency and genetic selection intensity will likely confer improvements in sustainability on a regional and farm-level scale. System-specific analysis is required to ensure that these management practices will have similar impacts on-farm.

CONCLUSION

This study provides a unique assessment of opportunity to combine nutritional, reproductive and genetic management of cattle and cattle production systems to minimize land use, water use and GHG in an economically viable and socially acceptable manner. The treatments in this study reflect several currently available, often poorly utilized, technologies that could be employed by beef producers to improve the efficiency and sustainability of their operations. Results indicate that synchronized efforts to improve nutrition, reproductive management and genetic merit will
result in substantial improvements in operation sustainability. Using EPDs to select bulls, decreasing the calving window and optimizing nutritional management resulted in a 19% reduction in land use, water use and GHG emissions from the beef production system.
LITERATURE CITED

ABS Global. 2013. ABS Global Store. URL:


American Hereford Association. 2013. 2013 Spring Sire Summary; Proven Sires. URL:

URL:http://www.simmental.org/site/userimages/Sire_Summary.pdf


Genex Cooperative. 2013. Beef: Sire Catalog. URL: 


Select Sires Beef. 2013. Online Semen Store. URL:


**Table 1.** Population parameters for nutrition only (NUT), twinning (TWN), artificial insemination (EPD-AI), on-farm bull selection with EPD (EPD-B), reduced calving window (CW) and improved selection and decreased calving window (EPD-CW) scenarios

<table>
<thead>
<tr>
<th>Metric</th>
<th>NUT</th>
<th>TWN</th>
<th>EPD-AI</th>
<th>EPD-B</th>
<th>CW</th>
<th>EPD-CW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calves weaned per cow (#)</td>
<td>0.85</td>
<td>1.28</td>
<td>0.86</td>
<td>0.86</td>
<td>0.85</td>
<td>0.86</td>
</tr>
<tr>
<td>Incidence of Dystocia (%)</td>
<td>7</td>
<td>21</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Cow to Bull Ratio (#)</td>
<td>22.2</td>
<td>22.2</td>
<td>322.5</td>
<td>22.2</td>
<td>22.2</td>
<td>22.2</td>
</tr>
<tr>
<td>Calf Birth Weight (kg)</td>
<td>39.7</td>
<td>30.3</td>
<td>39.5</td>
<td>39.3</td>
<td>39.7</td>
<td>39.3</td>
</tr>
<tr>
<td>Weaning Weight^2 (kg)</td>
<td>266</td>
<td>231</td>
<td>282</td>
<td>292</td>
<td>285</td>
<td>292</td>
</tr>
<tr>
<td>Yearling Weight^2 (kg)</td>
<td>402</td>
<td>367</td>
<td>424</td>
<td>435</td>
<td>414</td>
<td>435</td>
</tr>
<tr>
<td>Finishing Weight (kg)</td>
<td>566</td>
<td>561</td>
<td>599</td>
<td>612</td>
<td>574</td>
<td>612</td>
</tr>
<tr>
<td>Dressing Percentage (%)</td>
<td>62.1</td>
<td>61.6</td>
<td>62.9</td>
<td>62.9</td>
<td>62.1</td>
<td>62.9</td>
</tr>
<tr>
<td>Days from Birth to Slaughter (d)</td>
<td>480</td>
<td>510</td>
<td>480</td>
<td>480</td>
<td>480</td>
<td>480</td>
</tr>
</tbody>
</table>

^1Indicates the number of cows serviced by the average bull

^2Weaning weight is the weight of cattle (kg) when they were weaned, yearling weight is the weight of cattle at 12 months of age
Table 2. Breakdown of willingness to pay from packer/wholesaler and consumers by treatment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Packer/Wholesaler (% Premium)</th>
<th>Packer/Wholesaler ($/kg HCW)</th>
<th>Consumer (% Premium)</th>
<th>Consumer ($/kg HCW)</th>
<th>Total ($/kg HCW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUT</td>
<td>0.0</td>
<td>0.00</td>
<td>4.0</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>EPD-AI</td>
<td>10.0</td>
<td>0.21</td>
<td>4.0</td>
<td>0.07</td>
<td>0.28</td>
</tr>
<tr>
<td>EPD-B</td>
<td>10.0</td>
<td>0.21</td>
<td>4.0</td>
<td>0.07</td>
<td>0.28</td>
</tr>
<tr>
<td>CW</td>
<td>8.8</td>
<td>0.18</td>
<td>4.0</td>
<td>0.07</td>
<td>0.25</td>
</tr>
<tr>
<td>TWN</td>
<td>0.0</td>
<td>0.00</td>
<td>4.0</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>EPD-CW</td>
<td>10.0</td>
<td>0.21</td>
<td>4.0</td>
<td>0.07</td>
<td>0.28</td>
</tr>
</tbody>
</table>

1 Treatments included Control (NUT), sire selection using expected progeny differences through artificial insemination (EPD-AI) or on-farm bulls (EPD-B), reducing the calving window (CW), twinning (TWN) or improving genetic selection intensity and reducing the calving window (EPD-CW)

2 Packer/Wholesaler premiums were based on overall industry WTP sourced from Table 3 of Igo et al. (2013)

3 Calculations based on a wholesaler price of $6.402/kg and retail price of $11.044/kg (USDA/ERS, 2013d) and 45% and 25% conveyance of wholesaler and retailer WTP back to the farm level.
Table 3. Twinning treatment population parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cow Conception Rate</td>
<td>79.1%</td>
</tr>
<tr>
<td>Heifer Conception Rate</td>
<td>70.6%</td>
</tr>
<tr>
<td>Dystocia Rate</td>
<td>21.3%</td>
</tr>
<tr>
<td>Live Calves per Cow</td>
<td>1.64</td>
</tr>
<tr>
<td>Live Calves per Heifer</td>
<td>1.58</td>
</tr>
<tr>
<td>Calf Birth Weight</td>
<td>31 kg</td>
</tr>
<tr>
<td>Pre-weaning ADG</td>
<td>0.87 kg/d</td>
</tr>
<tr>
<td>Weaning Weight</td>
<td>210 kg</td>
</tr>
<tr>
<td>Post-weaning ADG</td>
<td>0.92 kg/d</td>
</tr>
</tbody>
</table>

1Values for the proportional difference between twinning and single calving systems (Echternkamp et al., 1990; Gregory et al., 1996; Gregory et al., 1990) were used to adjust national average values (USDA/APHIS, 2009a, b; USDA/ERS, 2012b) to reflect a hypothetical twinning scenario.
### Table 4. Baseline Scenario Summary of Environmental Impact Outputs

<table>
<thead>
<tr>
<th>Output</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Footprint (kg CO$_2$e)</td>
<td>21.6</td>
</tr>
<tr>
<td>Enteric Methane (kg CO$_2$e)</td>
<td>15.2</td>
</tr>
<tr>
<td>Manure Methane (kg CO$_2$e)</td>
<td>0.5</td>
</tr>
<tr>
<td>Direct Nitrous Oxide (kg CO$_2$e)$^2$</td>
<td>1.3</td>
</tr>
<tr>
<td>Indirect Nitrous Oxide (kg CO$_2$e)</td>
<td>0.1</td>
</tr>
<tr>
<td>Carbon Dioxide (kg CO$_2$e)</td>
<td>2.0</td>
</tr>
<tr>
<td>Water Use (L)</td>
<td>793</td>
</tr>
<tr>
<td>Irrigation Water Use (L)</td>
<td>759</td>
</tr>
<tr>
<td>Daily Drinking Water Use (L)</td>
<td>34</td>
</tr>
<tr>
<td>Land Use (m$^2$)</td>
<td>96.6</td>
</tr>
<tr>
<td>Cropland (m$^2$)$^3$</td>
<td>4.8</td>
</tr>
<tr>
<td>Pastureland (m$^2$)</td>
<td>91.8</td>
</tr>
</tbody>
</table>

$^1$All outputs are given on a per kg of hot carcass weight (HCW) beef basis

$^2$Direct N$_2$O emissions included only those predicted to emit directly from manure storage while indirect N$_2$O emissions included downstream leached and volatilized N$_2$O

$^3$Cropland included land used for growing concentrate feeds, byproduct feeds and hays
Table 5. Opportunity to reduce environmental impact under each treatment as percentage differences from baseline

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Change¹ in Environmental Impact</th>
<th>Nutrition Only</th>
<th>Land Use</th>
<th>Water Use</th>
<th>GHG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimizing Land</td>
<td>-30</td>
<td></td>
<td>+12</td>
<td>-4.9</td>
<td></td>
</tr>
<tr>
<td>Minimizing Water</td>
<td>+5.2</td>
<td></td>
<td>-3.9</td>
<td>-0.8</td>
<td></td>
</tr>
<tr>
<td>Minimizing GHG</td>
<td>+22</td>
<td></td>
<td>-2.9</td>
<td>-11</td>
<td></td>
</tr>
<tr>
<td>Minimizing All</td>
<td>-2.1</td>
<td></td>
<td>-2.1</td>
<td>-2.1</td>
<td></td>
</tr>
<tr>
<td>Artificial insemination with EPD selection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimizing Land</td>
<td>-71</td>
<td></td>
<td>+36</td>
<td>-19</td>
<td></td>
</tr>
<tr>
<td>Minimizing Water</td>
<td>+31</td>
<td></td>
<td>-17</td>
<td>-16</td>
<td></td>
</tr>
<tr>
<td>Minimizing GHG</td>
<td>+25</td>
<td></td>
<td>-12</td>
<td>-24</td>
<td></td>
</tr>
<tr>
<td>Minimizing All</td>
<td>-12</td>
<td></td>
<td>-12</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>On-Farm bulls with EPD selection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimizing Land</td>
<td>-78</td>
<td></td>
<td>+48</td>
<td>-21</td>
<td></td>
</tr>
<tr>
<td>Minimizing Water</td>
<td>+31</td>
<td></td>
<td>-21</td>
<td>-24</td>
<td></td>
</tr>
<tr>
<td>Minimizing GHG</td>
<td>+21</td>
<td></td>
<td>-7.9</td>
<td>-26</td>
<td></td>
</tr>
<tr>
<td>Minimizing All</td>
<td>-13</td>
<td></td>
<td>-13</td>
<td>-13</td>
<td></td>
</tr>
<tr>
<td>Decreased Calving Window</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimizing Land</td>
<td>-69</td>
<td></td>
<td>+35</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>Minimizing Water</td>
<td>+38</td>
<td></td>
<td>-13</td>
<td>-8.6</td>
<td></td>
</tr>
<tr>
<td>Minimizing GHG</td>
<td>+39</td>
<td></td>
<td>-6.9</td>
<td>-17</td>
<td></td>
</tr>
<tr>
<td>Minimizing All</td>
<td>-5.6</td>
<td></td>
<td>-5.6</td>
<td>-5.6</td>
<td></td>
</tr>
<tr>
<td>Twinning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimizing Land</td>
<td>-48</td>
<td></td>
<td>+5.5</td>
<td>-13</td>
<td></td>
</tr>
<tr>
<td>Minimizing Water</td>
<td>-13</td>
<td></td>
<td>-13</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>Minimizing GHG</td>
<td>+2.7</td>
<td></td>
<td>-12</td>
<td>-19</td>
<td></td>
</tr>
<tr>
<td>Minimizing All</td>
<td>-13</td>
<td></td>
<td>-13</td>
<td>-13</td>
<td></td>
</tr>
<tr>
<td>Decreased Calving Window with EPD Selection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimizing Land</td>
<td>-78</td>
<td></td>
<td>+48</td>
<td>-22</td>
<td></td>
</tr>
<tr>
<td>Minimizing Water</td>
<td>+29</td>
<td></td>
<td>-22</td>
<td>-25</td>
<td></td>
</tr>
<tr>
<td>Minimizing GHG</td>
<td>+19</td>
<td></td>
<td>-8.0</td>
<td>-27</td>
<td></td>
</tr>
<tr>
<td>Minimizing All</td>
<td>-15</td>
<td></td>
<td>-15</td>
<td>-15</td>
<td></td>
</tr>
</tbody>
</table>

¹Environmental impact metrics were compared to the baseline scenario and are reported as percentage differences.
Table 6. Average diets\(^1\) fed when optimizing land use, water use and GHG in each treatment\(^2\)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Grass hay</th>
<th>C</th>
<th>C-IF</th>
<th>R</th>
<th>R-F</th>
<th>R-IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUT</td>
<td>12.2</td>
<td>22.1</td>
<td>31.0</td>
<td>--</td>
<td>--</td>
<td>34.6</td>
</tr>
<tr>
<td>EPD-AI</td>
<td>11.7</td>
<td>32.0</td>
<td>--</td>
<td>--</td>
<td>25.4</td>
<td>21.2</td>
</tr>
<tr>
<td>EPD-B</td>
<td>13.2</td>
<td>16.7</td>
<td>--</td>
<td>--</td>
<td>33.3</td>
<td>11.8</td>
</tr>
<tr>
<td>CI</td>
<td>13.6</td>
<td>57.2</td>
<td>--</td>
<td>--</td>
<td>4.4</td>
<td>20.0</td>
</tr>
<tr>
<td>TWN</td>
<td>13.2</td>
<td>59.6</td>
<td>3.1</td>
<td>0.9</td>
<td>--</td>
<td>23.2</td>
</tr>
<tr>
<td>EPD-CI</td>
<td>12.6</td>
<td>16.7</td>
<td>--</td>
<td>--</td>
<td>33.3</td>
<td>12.4</td>
</tr>
</tbody>
</table>

\(^1\)Diets included grass hay, continuously grazed pasture (C), continuously grazed irrigated and fertilized pasture (C-IF), rotated pasture (R), rotated, irrigated pasture (R-I) and rotated, irrigated and fertilized pasture (R-IF)

\(^2\)Treatments included Control (NUT), sire selection using expected progeny differences through artificial insemination (EPD-AI) or on-farm bulls (EPD-B), reducing the calving window (CW) or improving genetic selection intensity and reducing the calving window (EPD-CW)
APPENDIX I

Model Description

The model was comprised of five primary sections: a population and production calendar module; a pasture module; an environmental impact module; an economics module; and a willingness to pay module. These modules provided the input data for a nutritional optimizer that was programmed to adjust cattle diets to minimize land use, water use and greenhouse gas emissions. The model ran on a monthly basis for one year. Outputs were expressed on a per kg hot carcass weight beef basis. Because the consumer willingness to pay module is explained in detail in the paper text, it is not elaborated on further in this section.

Population and Production Calendar Module

A total of 16 populations were simulated in the model: 4 calf populations (steers, heifers, replacement heifers and bulls), 2 replacement heifer populations (growing yearling replacements and 1st calf heifers), 2 mature cow populations (young mature cows and old mature cows), 4 bull populations (yearling bulls, adolescent bulls, young bulls and mature bulls) and 4 growing cattle populations (beef steers and heifers, dairy-origin steers and heifers). Five key parameters were calculated for each group: start weight, finish weight, average weight, average daily gain and population. In contrast to previous versions of the model (White and Capper, 2013), this monthly optimizer forward-calculated populations based on the size of the cow herd. In this simulation, a 300 cow herd was assumed. Equations used in this module are presented in Supplement Table 1. Baseline population rate constants are given in Supplement Table 2.

Cattle group populations were calculated and used to determine the amount of beef outputted
from the system as well as the amount of cattle within each group that would be fed. To match a yearly production cycle, calves were assumed to be born in March, weaned in October and finished the following July. Monthly change in weight was calculated and energy and protein requirements to meet maintenance, growth, gestation and/or lactation needs were calculated using the NRC (2000) equations.

Some cattle groups were not in the model for a full year. A binary variable was used to indicate when a cattle group was accounted for in the model. For all months where the indicator variable held a value of 1, nutrient requirements were calculated. For months were the indicator variable held a value of 0, nutrient requirements were set to 0. Diets for pre-weaned calves were not formulated until the 4th month of age.

**Pasture and Feeding Module**

The McCall pasture model (McCall and Bishop-Hurley, 2003), as updated by Romera et al. (2009), was used to simulate eight different pasture management strategies. The model was fit to a dataset of measured net primary production data for eight locations: Bridger, MT; Dickinson, ND; Hays, KS; Jornada, NM; Konza, KS; Osage, OK; and CPER, CO (Oak Ridge National Laboratory, 2012). Weather inputs for each location were sourced from National Ocean and Atmospheric Administration (NOAA) (2011). Model parameters for efficiency of photosynthesis, efficiency of vegetative relative to reproductive growth and time parameters governing initiation of reproductive growth, time of inflorescence emergence, decline of the reproductive period and end of the reproductive period were adjusted by the Microsoft Excel Solver function to minimize the root mean squared error of prediction of the outputted pasture yields for one year of data. The parameterized model was then validated against the remaining
years of data. The average RMSPE of the validated dataset was 3.82% which indicated that the model predicted U.S. pasture growth well. The same procedure was used to parameterize and validate the response of pastures to irrigation and/or fertilization. The RMSPE for simulating irrigated pasture was 11%, RMSPE for fertilized pasture was 15% and RMSPE for irrigated and fertilized pasture was 13%.

After the initial parameterization and validation procedure was concluded and the model was deemed sensitive enough to simulate effects of management practices on U.S. pastures, a set of over 8,000 growth curves (USDA/NRCS, 2012) were parameterized for pasture simulation. These growth curves represented different pasture growth patterns in thirteen U.S. states producing 63% of the U.S. calf crop annually. Average pasture was simulated by calculating an average of the monthly yield and quality outputs from the parameterized McCall model. The average was weighted by the number of calves produced in each state. Feedstuff yield, quality and environmental impact outputs are listed in Table 3. Feedstuff yield and quality data not modeled by the pasture module were sourced from the NRC (2000) feedbank and the USDA/ERS (2012b) records for national average crop yields.

Environmental Impact Module

Calculation of environmental impact metrics closely followed the model outlined by White and Capper (2013). Environmental impact metrics included land use, water use and GHG emissions per kg HCW beef. The system boundary spanned from inputs into the farming system until the feedlot farmgate. Land use was calculated based on the total amount of each feedstuff required and the average yield of that feed, as predicted in the pasture and feed module.

\[
P_{V_{land}} = \sum_{j \in P} \left( DMI_{j,p} * P_d * Days_p \right) / Yield_f
\]
Where $PV_{land}$ is the present value of the land use objective, $DMI_{f,p}$ is the dry matter intake of feed $f$ by animal population $p$ and $yield_f$ is the yield of feed $f$. Both irrigation and daily drinking water were accounted for when calculating land use. Irrigation was based on the average irrigation water used per kg feed produced (Beckett and Oltjen, 1993) using current values for national average irrigation rates (USDA/NASS, 2007). Drinking water was estimated based on diet composition following (Meyer et al., 2006).

$$PV_{h2o} = \sum_{f,p} (DMI_{f,p} * P_p * Days_p * Irrig_f) + \sum_p (Drink_p * P_p * Days_p)$$

The GHG emissions estimates included CO$_2$, N$_2$O and CH$_4$. Crop and pasture CO$_2$ emission estimates (Bhat et al., 1994; Mudahar and Hignett, 1987; Nelson et al., 2009; West and Marland, 2001); direct, leached and volatilized manure and fertilizer N$_2$O emissions (IPCC, 2006); enteric CH$_4$ emissions (Ellis et al., 2007) and manure CH$_4$ (IPCC, 2006) were all included when calculating GHG emissions.

$$PV_{ghg} = CO2 + 25*CH4 + 299*N2O$$

Economics Module

Modeled economics focused on costs of production. Feed, pasture management, reproductive management and labor costs were all accounted within the model. Reproductive management and labor costs attributable to individual treatments are included in the main body of the paper and are therefore excluded from this description. Feed costs were calculated as:

$$FC = \sum_p (Days_p * P_p * \sum_f (DMI_{f,p} * cst_f))$$
Where \( Days_p \) is the amount of time an animal is alive, \( P_p \) is the number of animals in a population, \( DMI_{f,p} \) is an animal population’s daily intake of each feedstuff \((f)\) and \( c_{stf} \) is the unit price of each feed \((f)\). The unit price of each feed was sourced either from the USDA/ERS data for price received for feedstuffs (USDA/ERS, 2012b) or from the pasture module. Within the pasture module, feed costs were calculated as increases to a base rate reflecting a lease costing $12.00 per animal unit month. Equipment and labor costs associated with rotational grazing (Gillespie et al., 2008); fertilizer cost with updated prices (Khakbazan et al., 2009; USDA/NASS, 2007) and updated irrigation rates and costs (USDA/ERS, 2012b) were used to account for the cost of each management practice modeled. Cost of each feed is listed in Supplement Table 3. Costs were assumed to be constant over the year.

**Optimization Framework and Equations**

The system outlined was optimized using two different forms of objective function. The baseline scenario was least-cost management of the NUT treatment. To yield baseline outputs, the model was first run to achieve only one objective: 

\[
\text{Minimize}(\text{Cost}) = FC + PC + LC + RC
\]

Where \( FC \) is total feed costs, \( PC \) is pasture management costs, \( LC \) is labor costs dependent on the management scenario and \( RC \) is the cost of reproductive management.

After the least-cost baseline was simulated, environmental impact reducing scenarios were simulated. Scenarios either had one objective (eg. minimize water use) or multiple objectives (minimize water, land and GHG). The scenarios with one objective minimized:

\[
\text{Minimize}(Out_e) = (PV_e - BV_e) / BV_e
\]
where $PV_e$ is the present value of the environmental metric in question and $BV_e$ is the base value of the environmental metric. The scenarios with multiple objectives minimized an objective function following the form:

Minimize($Obj$):

$$Obj = (PV_{h2o} - BV_{h2o}) / BV_{h2o}$$

$$Obj = (PV_{land} - BV_{land}) / BV_{land}$$

$$Obj = (PV_{ghg} - BV_{ghg}) / BV_{ghg}$$

The various subscripts on the present and base value variables represent water use ($h2o$), land use ($land$) and GHG emissions ($ghg$). The multi-objective function form followed Tozer and Stokes (2001b). In each optimization, the choice variable was $DMI_{f,p}$. Nutrient requirements of each animal group in each month were used to ensure adequate nutrition without exceeding the maximum predicted dry matter intake:

$$\sum_f DMI_{f,p} * ME_f \geq MReq_p$$

$$\sum_f DMI_{f,p} * MP_f \geq MrEq_p$$

$$\sum_f DMI_{f,p} \leq DMIx_p$$

where $DMI_{f,p}$ is intake of feed ($f$) for each animal; $ME_f$ is the metabolizable energy content of feed ($f$); $MReq_a$ is each animal group’s metabolizable energy requirement; $MP_f$ is the metabolizable protein content of each feed ($f$); $MrEq_p$ is the metabolizable protein requirement for an animal, $DMIx_p$ is maximum predicted dry matter intake for an animal group. In addition to biological constraints, practical constraints were put in place to ensure reasonable limits on specific feeds in the diet of particular animal groups. This constraint is represented by the equations:
\[
\sum_{f} DMI_{f,p} \leq Up_{f,p}
\]

\[
\sum_{f} DMI_{f,p} \geq Low_{f,p}
\]

where \( DMI_{f,p} \) is intake of feed \( f \), for animal group, \( Up_{f,p} \) is the upper limit of feedstuff \( f \) in the diet of animal group and \( Low_{f,p} \) is the lower limit of feedstuff \( f \) in the diet of an animal group. This constraint was used to restrict the amount of grain and byproducts in a cow-calf or stocker diet, the proportion of forage and pasture in feedlot diets and the maximum proportion of byproducts such as molasses or distillers dried grains in all diets. Values for the upper and lower constraint values are listed in Supplement Table 4.

Increases in diet cost associated with reducing environmental impact were restricted to less than WTP. This constraint is represented as:

\[
BV_{\text{cost}} + BV_{\text{cost}} + WTP \geq PV_{\text{cost}}
\]

Where \( PV_{\text{cost}} \) is the diet cost simulated, \( WTP \) is the willingness to pay for low-environmental impact beef and \( BV_{\text{Cost}} \) is the cost outputted from the baseline scenario.
### Supplement Table 1. Equations used to define animal populations and weights

<table>
<thead>
<tr>
<th>Population Name</th>
<th>Name</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heifer calves</td>
<td>( P_{fhc1} )</td>
<td>( \left( (P_{mc4} + P_{mc5}) \cdot K_{sc} \cdot K_{lh} + P_{mc3} \cdot K_{ch} \cdot K_{lh} \right) \cdot K_{hc} \cdot (1 - K_{cd}) - P_{fhc1} )</td>
</tr>
<tr>
<td>Steer calves</td>
<td>( P_{sc1} )</td>
<td>( \left( (P_{mc4} + P_{mc5}) \cdot K_{sc} \cdot K_{lh} + P_{mc3} \cdot K_{ch} \cdot K_{lh} \right) \cdot (1 - K_{hc}) \cdot (1 - K_{cd}) )</td>
</tr>
<tr>
<td>RH calves</td>
<td>( P_{hc1} )</td>
<td>( K_{ecall} \cdot I_{cows} )</td>
</tr>
<tr>
<td>Bull calves</td>
<td>( P_{mb1} )</td>
<td>( P_{hc4} \cdot K_{bcall} )</td>
</tr>
<tr>
<td>Growing Steers</td>
<td>( P_{sc2} )</td>
<td>( P_{sc1} \cdot (1 - K_{bcd}) )</td>
</tr>
<tr>
<td>Growing Heifers</td>
<td>( P_{fhc2} )</td>
<td>( P_{fhc1} \cdot (1 - K_{bcd}) )</td>
</tr>
<tr>
<td>Dairy Steers</td>
<td>( P_{ds1} )</td>
<td>( (P_{sc2} + P_{fhc2}) \cdot K_{ds} )</td>
</tr>
<tr>
<td>Dairy Heifers</td>
<td>( P_{dh1} )</td>
<td>( (P_{sc2} + P_{fhc2}) \cdot K_{dh} )</td>
</tr>
<tr>
<td>Yearling Bulls</td>
<td>( P_{mb2} )</td>
<td>( K_{abmb} \cdot \frac{(P_{mc3} + P_{mc4} + P_{mc5})}{K_{abc}} )</td>
</tr>
<tr>
<td>Adolescent Bulls</td>
<td>( P_{mb3} )</td>
<td>( P_{hc2} )</td>
</tr>
<tr>
<td>Young Bulls</td>
<td>( P_{mb4} )</td>
<td>( (1 - K_{abmb}) \cdot \frac{(P_{mc3} + P_{mc4} + P_{mc5})}{K_{mbc}} )</td>
</tr>
<tr>
<td>Mature Bulls</td>
<td>( P_{mb5} )</td>
<td>( P_{mb4} - P_{mb4} \cdot K_{bcall} )</td>
</tr>
<tr>
<td>Yearling RH</td>
<td>( P_{hc2} )</td>
<td>( K_{ecall} \cdot I_{cows} )</td>
</tr>
<tr>
<td>1st calf heifer</td>
<td>( P_{mc3} )</td>
<td>( P_{hc2} )</td>
</tr>
<tr>
<td>Young cow</td>
<td>( P_{mc4} )</td>
<td>( I_{cows} \cdot 0.5 )</td>
</tr>
<tr>
<td>Mature cow</td>
<td>( P_{mc5} )</td>
<td>( P_{mc4} - I_{cows} \cdot K_{ecall} )</td>
</tr>
<tr>
<td>Average Daily Gain</td>
<td>( ADG_p )</td>
<td>( \frac{\left( FW_p - SW_p \right) / Days_p}{\left( FW_p - SW_p \right) / ADG_p} )</td>
</tr>
<tr>
<td>Days</td>
<td>( Days_p )</td>
<td>( (FW_p - SW_p) / ADG_p )</td>
</tr>
<tr>
<td>Finishing Weight</td>
<td>( FW_p )</td>
<td>( SW_p + Days_p \cdot ADG_p )</td>
</tr>
<tr>
<td>Beef outputted</td>
<td>( \text{Beef} )</td>
<td>( I_{cows} \cdot K_{ecall} \cdot FW_{mc5} \cdot K_{ds} + P_{mb4} \cdot K_{bcall} \cdot FW_{mb5} \cdot K_{do} + P_{dh1} \cdot FW_{dh1} \cdot K_{dy} + P_{hs1} \cdot FW_{hs1} \cdot K_{dy} + \frac{\left( FW_{hc2} \cdot K_{dh} + P_{sc2} \cdot FW_{sc2} \cdot K_{dy} + P_{fhc2} \cdot FW_{fhc2} \cdot K_{dy} \right)}{K_{bcall}} )</td>
</tr>
</tbody>
</table>
**Supplement Table 2.** Equation parameters used for defining cattle populations

<table>
<thead>
<tr>
<th>Name</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cow conception rate</td>
<td>$K_{cc}$</td>
<td>0.934</td>
</tr>
<tr>
<td>Cow live birth rate</td>
<td>$K_{lbc}$</td>
<td>0.968</td>
</tr>
<tr>
<td>Heifer conception rate</td>
<td>$K_{ch}$</td>
<td>0.893</td>
</tr>
<tr>
<td>Heifer live birth rate</td>
<td>$K_{lbh}$</td>
<td>0.935</td>
</tr>
<tr>
<td>Proportion of heifer calves born</td>
<td>$K_{hcb}$</td>
<td>0.5</td>
</tr>
<tr>
<td>Calf death loss</td>
<td>$K_{cdl}$</td>
<td>0.03</td>
</tr>
<tr>
<td>Cow culling rate</td>
<td>$K_{ccull}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Bull culling rate</td>
<td>$K_{bcull}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Stocker death loss</td>
<td>$K_{sdl}$</td>
<td>0.05</td>
</tr>
<tr>
<td>Proportion of dairy heifers in feedlot</td>
<td>$K_{dh}$</td>
<td>0.1363</td>
</tr>
<tr>
<td>Proportion of dairy steers in feedlot</td>
<td>$K_{ds}$</td>
<td>0.03</td>
</tr>
<tr>
<td>Proportion of cows bred by adolescent bulls</td>
<td>$K_{abmb}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Cows bred per adolescent bull</td>
<td>$K_{abc}$</td>
<td>16.3</td>
</tr>
<tr>
<td>Cows bred per mature bull</td>
<td>$K_{mbc}$</td>
<td>23.7</td>
</tr>
</tbody>
</table>
Supplement Table 3. Feedstuff nutritive value, environmental impacts and costs

<table>
<thead>
<tr>
<th>Feed</th>
<th>CP (%)</th>
<th>ME (Mcal/kg)</th>
<th>Cost ($/kg)</th>
<th>Irrigation (L/kg)</th>
<th>CO₂-Equivalents (kg/ha)</th>
<th>Yield (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa (AH)</td>
<td>17.0</td>
<td>2.24</td>
<td>0.178</td>
<td>257.1</td>
<td>224.57</td>
<td>7,556</td>
</tr>
<tr>
<td>Grass (GH)</td>
<td>10.0</td>
<td>1.65</td>
<td>0.129</td>
<td>119</td>
<td>103.95</td>
<td>4,334</td>
</tr>
<tr>
<td>Corn Grain (CG)</td>
<td>8.5</td>
<td>3.39</td>
<td>0.206</td>
<td>77.3</td>
<td>228.98</td>
<td>9,521</td>
</tr>
<tr>
<td>Soybean Meal (SBM)</td>
<td>49.0</td>
<td>3.04</td>
<td>0.552</td>
<td>74.5</td>
<td>117.77</td>
<td>2,841</td>
</tr>
<tr>
<td>Molasses (MOL)</td>
<td>46.4</td>
<td>2.83</td>
<td>0.518</td>
<td>175.4</td>
<td>193.3</td>
<td>3,701</td>
</tr>
<tr>
<td>Distillers Grains (DDG)</td>
<td>29.5</td>
<td>3.18</td>
<td>0.350</td>
<td>86.7</td>
<td>452.33</td>
<td>3,564</td>
</tr>
<tr>
<td>Control Pasture (C)</td>
<td>14.5</td>
<td>2.57</td>
<td>0.131</td>
<td>0</td>
<td>11.8</td>
<td>3,261</td>
</tr>
<tr>
<td>Irrigated Pasture (I)</td>
<td>14.5</td>
<td>2.57</td>
<td>0.111</td>
<td>37.7</td>
<td>23.5</td>
<td>4,155</td>
</tr>
<tr>
<td>Fertilized Pasture (F)</td>
<td>14.5</td>
<td>2.57</td>
<td>0.115</td>
<td>0</td>
<td>161</td>
<td>4,255</td>
</tr>
<tr>
<td>Irrig+Fert Pasture (I-F)</td>
<td>14.5</td>
<td>2.56</td>
<td>0.083</td>
<td>25.7</td>
<td>184.5</td>
<td>6,111</td>
</tr>
<tr>
<td>Rotated Pasture (R)</td>
<td>14.1</td>
<td>2.68</td>
<td>0.146</td>
<td>0</td>
<td>11.8</td>
<td>3,313</td>
</tr>
<tr>
<td>Rotated Irrig Pasture (R-I)</td>
<td>14.1</td>
<td>2.68</td>
<td>0.123</td>
<td>37.3</td>
<td>23.5</td>
<td>4,209</td>
</tr>
<tr>
<td>Rotated Fert Pasture (R-F)</td>
<td>14.1</td>
<td>2.68</td>
<td>0.127</td>
<td>0</td>
<td>161</td>
<td>4,309</td>
</tr>
<tr>
<td>Rot. Fert + Irrig Pasture (R-IF)</td>
<td>14.1</td>
<td>2.68</td>
<td>0.091</td>
<td>25.7</td>
<td>184.5</td>
<td>6,168</td>
</tr>
</tbody>
</table>
**Supplement Table 4.** Upper and lower bounds for feedstuff inclusion in animal diets

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Cows</th>
<th>Bulls</th>
<th>Replacements</th>
<th>Stocker</th>
<th>Feedlot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forage Upper</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>15%</td>
</tr>
<tr>
<td>Forage Lower</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>5%</td>
</tr>
<tr>
<td>Pasture Upper</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Pasture Lower</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
<td>85%</td>
<td>0%</td>
</tr>
<tr>
<td>Molasses Upper</td>
<td>0.14 g/d</td>
<td>0.14 g/d</td>
<td>0.14 g/d</td>
<td>0.14 g/d</td>
<td>0 g/d</td>
</tr>
<tr>
<td>CG Upper</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>95%</td>
</tr>
<tr>
<td>SBM Upper</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>40%</td>
</tr>
<tr>
<td>DDG Upper</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>40%</td>
</tr>
<tr>
<td>DDG Lower</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>

1Constraints included upper and lower limits for forage percentage in the diet (forage upper and forage lower), upper and lower limits for pasture percentage in the diet (pasture upper and pasture lower), upper limit for quantity of molasses fed (molasses upper) and upper limit for the concentrate feeds corn grain (CG), soybean meal (SBM) and dried distillers grains (DDG).
CHAPTER 6

DETERMINING CONSUMER WILLINGNESS TO PAY

The chapter was submitted to Food Policy under the title: Will consumers’ willingness to pay incentivize adoption of environmental meat production practices?
INTRODUCTION

Global population is increasing (U.S. Census Bureau, 2013; United Nations, 2011) and concurrent improvements in developing nations’ affluence will result in increased global consumption of livestock products (Cranfield et al., 1998; Delgado, 2003). Livestock production is resource-intensive and agricultural water (Vorosmarty et al., 2000) and land (Lambin and Meyfroidt, 2011) availability is already limited. By 2050, food demand is predicted to outpace water availability in most regions of the world (Falkenmark et al., 2009) and the cost of agricultural land is expected to rise significantly (Hertel, 2011). Improving the sustainability of livestock production is a frequently proposed solution to this global food production challenge.

Top-down regulatory policies have been suggested as a means of improving agriculture’s sustainability (Deckers, 2010; Edjabou and Smed, 2013; Lybbert and Sumner, 2012). Many top-down policies rely on some mandated reduction in environmental impact with incentives for adopting efficient practices and penalties for excessive environmental impact (Golub et al., 2012). This approach often requires a substantial sacrifice of farm income (Varela-Ortega et al., 1998) because the policies fail to account for cost heterogeneity at the farm level. Improving sustainability of food production systems should balance environmental, economic and social focuses (National Research Council, 2011, 2013; WCED, 1987). Therefore a policy that has negative effects on farm revenue will not be sustainable. An alternative approach to decreasing agricultural environmental impact is manipulation of consumer purchasing decisions by policy, taxation or labeling (Deckers, 2010; Gadema and Oglethorpe, 2011; González et al., 2011). Demand for environmental labels on food products is increasing (Gadema and Oglethorpe, 2011). Before food labeling can be relied upon as an alternative policy option, studies should investigate the confidence range around estimates of consumer WTP for environmental meat.
labels and compare to cost increases associated with reducing environmental impact (e.g. White et al., 2013a, b).

Consumers have demonstrated willingness to pay (WTP) for meat products with perceived reductions in environmental impact (Hurley et al., 2006; Tonsor and Shupp, 2009). Much of the literature on environmental labeling has focused on impure environmental labels (organic, grass-fed, all natural, local, etc.) which have some personal health or safety attributes in addition to perceived environmental attributes. This focus makes it difficult to identify whether there is WTP for pure environmental meat attributes (i.e. reduced water use). Studies have assessed WTP for pure environmental labels (Hurley et al., 2006; Nilsson et al., 2006; Tonsor and Shupp, 2009). Variability in study methodology and the resulting impacts on WTP estimates (List and Shogren, 1998) make it difficult to rely on any of these individual values as robust WTP estimate. Past studies have relied on quantitative summary techniques to synthesize literature assessing WTP for a variety of attributes or utilizing several methodologies to better isolate WTP for a single attribute (Cicia and Colantuoni, 2010; Lagerkvist and Hess, 2011; Lusk et al., 2005). In this case, quantitative summary can be used to partition out WTP for health/safety from environmental attributes in impure environmental valuations to estimate WTP for pure environmental attributes while taking methodological variability into account. This WTP can then be compared to estimates of production cost increases related to reducing water use within meat production systems (White et al., 2013a, b). This comparison can help assess efficacy of using a labeling approach to incentivize adoption of environmental impact reducing technologies.

In this study, we had two objectives: (1) to develop a robust estimate of consumer WTP for
environmental meat attributes and (2) to use a hypothetical beef production case study to estimate whether WTP could offset on-farm costs of adopting water-reducing technologies. The Theory section discusses the theoretical framework. The Materials and Methods section discusses data collection and quantitative analysis conducted. The Results and Discussion details outcomes of the models and assesses impacts of WTP on opportunity to reduce beef’s environmental impact. Finally, concluding remarks and future research directions are presented.

**THEORY AND CALCULATIONS**

Standard utility theory for consumer behavior (Deaton and Muellbauer, 1980) assumes that consumers seek to maximize utility through consumption of food subject to a budget constraint. It has been proposed that consumers value the attributes represented by a good rather than the good itself (Rosen, 1974). In a hedonic sense, consumers view individual food items as a bundle of attributes. Willingness to pay for individual food items is then based on the associated attributes of the items. Food attributes typically considered in economic analyses are those that provide private benefits in terms of nutrients and quality, the latter of which includes a range of characteristics including taste, texture, physical appearance, etc. Consumers in the United States (U.S.) have demonstrated increasing demand and willingness to pay (WTP) for food products with pure or impure environmental good characteristics. Examples include dolphin safe tuna (Teisl et al., 2002), rainforest enhancing coffee (Rice and McLean, 1999), locally produced food (Darby et al., 2008, 2006), organic foods (Corsi and Novelli, 2002; Krystallis and Chryssohoidis, 2005), cage-free or free range eggs and poultry (Bennett and Larson, 1996) or grass-fed beef (Umberger et al., 2002). Each of these products is perceived by the consumer to contain attributes associated with some aspect of a sustainable food system. Although the existence of
these markets is somewhat taken for granted now, each began with uncertainty about whether there were enough consumers willing to pay a premium for the proposed environmental good relative to conventional goods.

MATERIAL AND METHODS

A three part methodology was used. First, a literature search was employed to identify studies that assessed consumer WTP for pure or impure (organic, grass-fed, all natural, local, etc.) attributes of meat. Three models were then fit to these data using a Bayesian regression. The models employed different explanatory variables designed to separate WTP for pure environmental attributes from valuations assessing goods with additional health/safety attributes. The models were evaluated and compared using the correlation coefficient, $R^2$, the root mean squared error of prediction, RMSPE, and the posterior model probability. The models were averaged based on their posterior probabilities and used to estimate a confidence range for non-hypothetical consumer WTP for pure environmental meat attributes. Finally, a multi-objective nutritional optimizer was used to explore whether WTP could offset increases in cost associated with adopting water-reducing management practices on-farm. The optimizer identified the range in water use reduction that was achievable within the bounds of consumer WTP.

Data Collection

A literature search of the Agricola and Google Scholar databases was conducted using the keywords “consumer willingness to pay meat [beef/pork]”. Studies were included if they presented a numerical estimate of consumer WTP for a meat attribute. Studies assessing pure or impure environmental attributes were identified as a subset from the literature search. Conference publications, white papers and extension oriented publications relating to consumer
WTP for meat attributes were identified through the AgEconSearch engine again using the keywords “consumer willingness to pay meat [beef/pork]”. Authors who had published several papers on WTP were contacted for copies of their most recent work. Studies were excluded from analysis if they presented WTP estimates from a dataset already included in analysis. Studies failing to present a numerical value of consumer WTP or assessing WTP for a cut of meat rather than a meat attribute were also excluded. Percentage premium WTP estimates were used in analysis to standardize over currencies and years. Therefore, if a base comparison value was not clearly stated within a study, it was excluded to eliminate bias from incorrect assumption of a base value. The selection process returned 61 studies representing 269 treatments conducted on over 34,000 consumers in 18 different countries. A total of 46 studies contained treatments assessing pure or impure environmental goods and 26 studies contained treatments that assessed a purely private meat attribute (quality, health, safety, etc.). As the values would suggest, some studies had both environmental and non-environmental valuations. Studies are summarized in Tables A.1 and A2 organized alphabetically based on the first author’s last name.

Bayesian Model Fitting

Bayesian regression analysis was used to fit three models varying in independent variables. Bayesian model fitting was used for several reasons. A large amount of explanatory variables were employed and Bayesian regression analysis is better equipped to deal with numerous explanatory variables (Gelman et al., 2004; Mitchell and Beauchamp, 1988). Additionally, a small sample size was anticipated and Bayesian model fitting, due to reliance on Markov Chain Monte Carlo simulation, is particularly well equipped to estimate models based on small datasets (Martin et al., 2011). Given the variability in the valuation techniques employed within the
dataset, the models needed to account for study variability and differentiate between hypothetical and non-hypothetical valuation methods. Prior information was available about how study methodology influenced consumer WTP. To improve the predictive capacity of the model, the researchers wanted to include this prior information in the assessment. The use of priors in Bayesian analysis (Lenk and Orme, 2009) allowed for the information to be incorporated. Improperly specified informative priors can bias a model. To ensure this was not the case, an initial model fitting included both informative and non-informative priors. Comparison of the posterior probabilities, $R^2$ and RMSPE indicated informative priors improved probability, explained more variability in WTP and reduced model error.

All regression models followed the general form:

$$y = X\beta + \varepsilon \quad where \quad \varepsilon \sim N(0, \sigma^2)$$

where $y$ is a matrix of dependent variable observations, $X$ is a matrix of independent variables with $\beta$ representing the regression coefficients. The error term $\varepsilon$ is normally distributed with mean zero and non-constant variance. The exact form of heteroskedasticity is not known but the error variances originate from the normal distribution. The coefficient $b$ and error $\sigma^2$ priors are specified as:

$$b \sim N(b_0, B_0^{-1})$$

$$\sigma^2 \sim \text{Gamma}(c_0 / 2, d_0 / 2)$$

Bayesian analysis uses iterative simulation that supplements the data available with information from the prior distribution based on Bayes theorem (Gelman et al., 2004). After data is inputted,
the uncertainty in the model parameters is estimated by summarizing a set of random draws from each parameter vector based on a posterior distribution (Gelman et al., 2004). Because the posterior distribution is unknown, the Metropolis-Hastings algorithm, a Markov chain Monte Carlo method for random sampling of a probability distribution, is commonly used to estimate the distribution (Chib and Greenberg, 1995). The Metropolis algorithm is carried out in a series of steps (Chib and Greenberg, 1995). For each coefficient $\beta$, a desired probability distribution $P(\beta)$ exists. The algorithm is initialized by selecting an arbitrary point $P(\beta_o)$ and a probability density $Q(\beta|\beta_o)$ – these are based on the mean and standard error inputted as priors to the model. During each iteration, the next candidate for $\beta$ is selected from the distribution $Q(\beta|\beta_o)$. The acceptance ratio of the candidate, $P(\beta_c)/P(\beta_o)$, is then calculated. If this ratio is greater than 1, $\beta_c$ is more probable than $\beta_o$ and $\beta_c$ is accepted as the new value of the equation coefficient $\beta$. If less than zero, then $\beta_c$ is rejected and $\beta_o$ is set to the new current value. This Markov process was carried out using the MCMCpack package of R software (Martin et al., 2011). The data from the literature search were supplemented with random samples from the prior distributions and the three models were estimated. For each model, the iteration process was continued for 500,000 iterations. To improve computational efficiency while maintaining estimation rigor, the first 5000 iterations were burned and every subsequent $2^{nd}$ iteration was used for sampling. Because the algorithm accepts or rejects a value of $\beta$ based on the probability of the current and previous values, it is important to ensure enough iterations to allow the algorithm to converge on a highly probable value. Geweke (1993) identified one method of post-hoc analysis to determine adequate convergence by testing equality of the means in the first and last part of a Markov chain. In this analysis we compared the first 10% of the chain and the last 50% (Geweke, 1993) to ensure convergence of each parameter.
Regression Models Fit

Three models were fit to explore how consumers might view pure and impure environmental labels. One model looked at characterizing meat attributes as either purely public or impure public. This model was formed based on the assumption that consumers view environmental goods as either purely public (no direct personal benefit) or impure (some direct personal benefit). It was hypothesized that this structure would be too simplistic and so two additional models were considered. One model coded meat labels based on their constituent attributes (environmental, healthy, safe, local etc.) following the theory that consumers value goods as a bundle of attributes. The final model coded each labeling scheme individually (environment only, grass-fed, organic, etc.). This final model assumed each meat label had a unique bundle of constituent attributes inadequately explained by categorical variables like health or safety. In all models, the environmental term was used to represent pure environmental labeling.

The Dependent Variable

For all models, the dependent variable was the natural logarithm of the percentage premium WTP for the meat product attribute isolated in any particular treatment. Percentage premiums were used following the example of several previous WTP analyses to standardize across study year and currency type. In many cases, studies presented dollar value estimates of WTP premiums and a base price was sourced from the text. Base prices were either the average of the prices used in elicitation, the market price of the base product at the time of the study, or the WTP reported for a generic product, whichever was presented within the study. Table A.1 specifies the base prices used for each treatment along with the source of the base price.
Explanatory Variables

The explanatory variables used in each model are listed in Table 1. In all models, a series of explanatory variables were included to account for the variability in study methodology, consumers assessed and study date. Study methodology is known to have substantial influence on the valuations obtained (List and Gallet, 2001). Studies conducted in-person lead to overstated WTP estimates. In addition, studies assessing hypothetical and non-hypothetical valuation methods find that non-hypothetical valuations are lower (List and Shogren, 1998; Little and Berrens, 2004). To account for these methodological influences on WTP estimation binary dummy variables for in-person and non-hypothetical valuations were included.

Willingness to pay was expected to vary with meat type and cut. As studies on beef and pork were included in the assessment, a binary dummy was included identify studies on pork. Most studies assessed WTP for beef steak or pork chops, studies focusing on alternative products (ground beef) were coded separately to identify how meat cut affected WTP.

The data demonstrated a general trend of increasing percentage premium WTP with publication date. Ideally, data collection date would have been included in the assessment (Nelson and Kennedy, 2009); however, many studies failed to report the collection date and thus publication date was used as a proxy. Binary dummies to indicate half decade of publication were coded and used to explain the influence of publication date on WTP. Finally, WTP was expected to vary with location and gross domestic product per capita (GDP). Studies were categorized regionally. A variable was used to code studies in the U.S. or Canada, Europe, Asia or other locations. To account for the expected personal wealth of individuals in each study, GDP was sourced based on location and publication year (World Bank, 2014).
Prior Distributions

Informative prior distributions for the methodological coefficients were derived from a meta-regression analysis. Studies identified during the literature search process that tested purely private good attributes were set aside into a secondary dataset. This collection of studies is included in Table A.2. Studies were coded using the same methodological variables used in the Bayesian analysis. The Metafor package of R version (Viechtbauer, 2010) was used to conduct a random-effects meta-regression of the natural log of percentage premium willingness to pay against the methodological variables detailed previously. Outputted coefficients and variances were used to define informative prior distributions for the methodological variables. Non-informative priors were used for all subject specific variables because insufficient data was available to develop informative priors. Additionally, this helped avoid biasing the outcome with improperly specified priors. Informative priors are presented in Table 2.

Model Evaluation and Comparison

Models were evaluated using the correlation coefficient, $R^2$ and the root mean squared error of prediction, RMSPE. As each model was estimated, the Bayes factor of the model was calculated. After all models had been estimated, the posterior model probabilities were calculated (Kass and Raftery, 1995). The ranking of model probabilities as well as inferences from the most probable model were used to draw conclusions about consumer preferences. The average model was used to determine a range of WTP estimates for purely public and impure public environmental labeling schemes.
Impact Assessment

One challenge with assessment of top-down regulatory policies is that they fail to account for cost structure at the farm level. To avoid this pitfall, we employ a multi-objective optimization model to assess how WTP could be used to offset on-farm management costs related to reducing water use. The optimizer was used to simulate beef production systems in three locations throughout the U.S. The optimizer integrated environmental impact (Capper, 2011a, 2012; White and Capper, 2013), farm economics (White and Capper, 2013), pasture management (McCall and Bishop-Hurley, 2003; Romera et al., 2009) and consumer willingness to pay. The model simulated a whole beef production system and adjusted cattle diets and pasture management strategies to reduce beef production’s environmental impact while maintaining the production system within the bounds of biological, economic and practical constraints. Although presented in the context of a simulation, the cattle populations, production calendar, environmental impact and calculation of farm economics employed by this optimizer are thoroughly outlined in (White and Capper, 2013). A description of the weights and times for each cattle population is listed in Table B.1. Parameters used to determine the number of animals in each cattle population are given in Table B.2. Yield and quality of feedstuffs available in each region, as predicted by the pasture module (McCall and Bishop-Hurley, 2003; Romera et al., 2009), are included in Table B.3.

The production system was optimized using two different forms of objective function. The baseline scenario, least cost management, was simulated by optimizing:

$$\text{Minimize(\text{Cost})} = \text{FC} + \text{PC} + \text{LC}$$
Where FC (feed), PC (pasture) and LC (labor) costs were accounted based on the feedstuffs selected. After the least-cost baseline was simulated, environmental impact reducing scenarios minimizing water and land use were conducted. Both land and water were targeted because water use can easily be reduced by increasing land use (White et al., 2013a, b); however, this is not practically feasible. These scenarios relied on the objective function:

\[
\text{Minimize}(\text{Obj}) : \\
\text{Obj} = \frac{(PV_{h2o} - BV_{h2o})}{BV_{h2o}} \\
\text{Obj} = \frac{(PV_{land} - BV_{land})}{BV_{land}}
\]

The subscripts on the present (PV) and base value (BV) variables represent water use (h2o) or land use (land) per kilogram hot carcass beef produced. These values are calculated for the production system, based on the diets selected by the optimization process, following the equations enumerated in White and Capper (2013). The multi-objective function form followed Tozer and Stokes (2001b). In each optimization, the choice variable was \( DMI_{f,p} \). Nutrient requirements of each animal group in each month were used to ensure adequate nutrition without exceeding the maximum predicted dry matter intake:

\[
\sum_f DMI_{f,p} \times ME_f \geq ME_{req_p} \\
\sum_f DMI_{f,p} \times MP_f \geq N_{Pr eq_p} \\
\sum_f DMI_{f,p} \leq DMI_{eq_p}
\]

where \( DMI_{f,p} \) is intake of feed \( (f) \); \( ME_f \) is the metabolizable energy content of feed \( (f) \); \( ME_{req_a} \) is the metabolizable energy requirement of the animal (National Research Council, 2000); \( MP_f \) is the metabolizable protein content of each feed \( (f) \); \( M_{Pr eq_p} \) is the metabolizable protein
requirement for an animal (National Research Council, 2000), $DMI_{x_{p}}$ is maximum predicted dry matter intake. These values can be found in Table B.3. Increases in cost associated with reducing water use were restricted to less than WTP:

$$BV_{cost} + BV_{cost} + WTP \geq PV_{cost}$$

Where $PV_{cost}$ is cost simulated, $WTP$ is the willingness to pay for low-environmental impact beef and $BV_{Cost}$ is baseline cost. The WTP was varied within the confidence range outputted from the averaged regression models. Consumer WTP was back-calculated to the farm level assuming a 65% conversion of retail beef to hot carcass weight beef (Schweihofefer, 2012) and a conveyance rate of 25% of consumer WTP returning to the farm-level. The reductions in water use outputted from the optimizer were assumed to be the theoretical environmental impact reduction possible.

Given that only a portion of the population will pay a premium for environmental attributes, the WTP range was used to develop a cumulative normal distribution estimating probability of purchase at any given WTP value. The product of the theoretical environmental impact reduction and the predicted probability of purchase was used as an estimate of the realistic opportunity to reduce environmental impact.

**RESULTS AND DISCUSSION**

The outputted variable coefficients and standard errors are included in Table 3. Model fit parameters are also reported. Analysis of the convergence indicated significant evidence of convergence for all coefficients in all models.
Willingness to Pay Model Comparison and Evaluation

Three models were fit to explore how consumers might view pure and impure environmental labels. The model with the lowest error and highest $R^2$ evaluated WTP assuming consumers view each label as an individual good. This could be the case for several reasons; most likely, each label has its own individual bundle of goods perceived by consumers but these unique bundles were insufficiently explained by healthy, local, welfare, safe and environmental attributes. Alternatively, the combination of attributes together may be of greater value to the consumer than the sum of the individual attribute values. Evaluation of the log marginal likelihood also yielded strong evidence (Kass and Raftery, 1995) for the hypothesis that consumers view each label as an individual good over the explanations provided by other models.

Estimating Consumer Willingness to Pay

The models found that WTP was influenced by study methodology, meat type, location and environmental label.

Environmental Labels and WTP

For the purpose of comparison, North American consumers WTP for pure and impure (local, all natural, grass-fed, organic) environmental labeling, as calculated by the most probably model, is shown in Figure 1. On average consumers would pay a 29.1% premium for impure environmental products (range: 13.9% - 64.3%); pure environmental products only garnered a 14.8% premium (range: 6.7% – 32.6%). As was expected, the impure labels resulted in higher WTP than pure environmental labels.

When the impure environmental labels were assessed individually, some interesting dynamics
were revealed. Consumer WTP for grass-fed, natural and local products were the highest of any impure environmental attribute. Martinez (2008) analyzed retail price data and found that company-specific (natural, grass-fed, organic and/or food safety) labeling schemes resulted in the highest price premiums for beef cuts compared with other labeling schemes. These branding schemes garnered premiums from 48% to 84%. The premiums for grass-fed and natural meat products predicted in this study were on the low end of this range but likely represent a realistic average WTP given that relatively small portions (collectively, 3%) of the population actually pay the listed retail premium for these specialty products (Mathews Jr and Johnson, 2013).

Scanner data analyses consistently show high price premiums for organic products (Martinez, 2008; Schulz et al., 2012). Schulz et al. (2012) found that organic labeling increased beef cost by $6.56 / kg. That represents a 46.7% premium when compared to the intercept (or base) price of $14.06 / kg. Our model predicts premiums of 4.2% to 30.0% for organic products. The upper range of our confidence estimate is not within the range described by scanner data. This underprediction could be because consumers purchasing organic are more concerned with the natural properties of the product (no hormones, no antibiotics or genetically modified organisms) and therefore the true WTP for organic products is reflected by the natural category in our model. Alternatively, there were very few studies assessing WTP for organic products (likely because they are already available on the market) and our sample may have been insufficient to adequately characterize WTP for organic meats.

**Methodological and Meat Type Effects**

Previous literature has found that studies conducted in person or using non-hypothetical valuation methods result in over-estimation of WTP (List and Gallet, 2001; List and Shogren,
1998; Lusk et al., 2005). The model generated in this analysis agrees with these previous studies. When North American consumers’ WTP for a pure environmental beef steak product was tested, in-person valuations lead to an 11.2% decrease in WTP and non-hypothetical valuation decreased the WTP estimate by 17.2%.

Location and beef type influences on WTP for a pure environmental product are depicted in Figure 2. Pork chops and beef steak had similar predicted WTP premiums. Cicia and Colantuoni (2010) found that consumers were willing to pay a 5.94% lower premium for pork products. Cicia and Colantuoni studied WTP for traceable meat products. It is possible that observed difference in WTP for beef and pork observed in that study was due to concerns with bovine spongiform encephalopathy related to beef raised in some countries. When an environmental meat attribute was tested rather than an attribute implicitly related to human health, beef and pork environmental attributes are valued similarly. Interestingly, consumers were predicted to pay much higher premiums for chops and steaks than they would for ground products. This may be because chops and steaks are high quality and therefore consumers are prepared to ensure they purchase the best product possible.

The greater WTP for steaks and chops is of concern when exploring the options to rely on food labeling to help improve meat environmental impact. Without a substantial WTP for all products on the carcass, there may be minimal incentive to adjust production practices. Packers and retailers may prove key players in the use of labeling to improve meat production water use. As consumer preferences have become better understood, packers and retailers have adjusted their WTP for meat animals to better reflect the desires of the consumer (Igo et al., 2013). For
example, consumers consistently show high WTP for tender, high quality steak grades (Schulz et al., 2012). Although an equivalent WTP does not exist for tender ground beef, packers, retailers and even feedlot operators will pay premiums for cattle with superior genetics for tenderness (Igo et al., 2013). As such, the intervention of packer or retailer WTP, in response to better understanding of consumer WTP, may help to more effectively incentivize adoption of water conserving production practices.

**Gross Domestic Product and Regional Effects**

When GDP was held constant, both North American and European consumers had substantially lower WTP than Asian consumers. North American consumers had higher WTP than European consumers. Similar WTP between North American and European consumers was expected because surveys conducted in Europe (Fotopoulos and Krystallis, 2002), North America (Dettmann and Dimitri, 2009) and elsewhere (Aguirre, 2007) find similar characteristics in consumers interested in environmentally-labeled products. The comparative regional dynamics in Cicia and Colantuoni (2010) and Lusk et al. (2005) concur with those outlined here; however, Yu and Gao (2010) found European consumers had lower WTP than North American consumers. Additionally, the high WTP predicted for Asian consumers does not agree well with the WTP estimates generated by Yu and Gao (2010) and Lusk et al. (2005). This may be because none of the studies had a large number of samples from Asian consumers (2 studies in Lusk et al. (2005), 3 studies in Yu and Gao (2010) and 4 in this study). With so few estimates of Asian consumers WTP, the high between-study variability in WTP estimates is to be expected.

When GDP was varied and regional dummies were held constant, GDP had a substantial, positive impact on WTP. For every $1,000 increase in GDP, WTP increased 1.03%. Previous
studies have used GDP as a measure of welfare across countries (Jones and Klenow, 2010). It is frequently hypothesized that as GDP increases, welfare will improve, citizens will become more altruistic and more willing to donate to public goods like environmental protection (Duroy, 2008). The current body of literature finds very diverse relationships (positive linear, negative linear, marginal linear, quadratic, etc.) between GDP and environmental donations (Duroy, 2008; Menges et al., 2005) or environmental good purchases (Vigani and Olper, 2013). This model indicates that as GDP increases, consumers do appear to be willing to partition more of their budget toward impure or pure environmental goods. This differs from most previous studies finding a negative or quadratic effect possibly because impure environmental goods were included and the analysis did not strictly test donations to a purely environmental good.

Implications of WTP on Beef Environmental Impact

Baseline Scenarios by Region

A multi-objective nutritional optimizer was used to explore the extent to which consumer WTP could offset increases in production costs attributed to reducing whole-system water use. Three different regions were simulated to account for some of the cost-heterogeneity that exists at the farm level. Baseline production costs, water use and land use are included in Table 4. Production costs to yield a kg of hot carcass weight (HCW) beef were relatively homogeneous ($\pm$ $0.02) across regions in the least-cost baseline scenario. Land use and water use between the regions exhibited more variability. Substantial regional variability in environmental impact attributable to beef production was also found in previous studies (Pelletier et al., 2010; Peters et al., 2010a; Peters et al., 2010b; Stackhouse-Lawson et al., 2012). In this study, most of the variability was
due to differences in pasture yield as dictated by variable rainfall and solar radiation in each region.

Total Water Use Reductions

The optimizer was used to assess how opportunity to decrease water use changed as WTP increased. Water use predicted by the optimizer for each region is included in Table 4. Water use decreased at a decreasing rate as WTP increased (Figure 3). Regions demonstrated unique inflection points and different opportunities to improve water use. In the Pacific Northwest and the Midwest, substantial reductions in water use were achieved (55.4 L/kg HCW beef or 63.8 L/kg HCW beef). A premium WTP of about 20% was required in the Pacific Northwest while only a 15% premium was required in the Midwest. In the South, water use could only be reduced by 39.1 L/kg HCW beef. This reduction required a 23% premium WTP.

Effects of Probability of Purchase on Reducing Water

The cumulative normal distribution outlined by the WTP 95% confidence interval was used to calculate probability of purchase across the WTP range. The probability began to decrease substantially as WTP increased to about 10%. Probability of purchase reached nearly 0 at WTP 30%. Theoretical opportunities to reduce water use were calculated as the product of the environmental impact reduction and the probability of purchase at each WTP value. The curves for theoretical water use reduction are included in Figure 4. Regions demonstrated different opportunities to reduce water use but the ideal WTP was 10% in all regions. For reference, a 10% premium equates to $1.10/kg given the average retail price of beef in the U.S. (USDA/ERS, 2013d). At the farm-level, this WTP translates to a $0.17 increase in operating costs per kg
HCW beef produced or $52.77 per mature breeding cow per year. The Midwest had the greatest opportunity to reduce water use (41.4 L/kg HCW beef). The Pacific Northwest and the South had lower opportunities (33.6 L/HCW beef or 24.4 L/HCW beef).

In the U.S. in 2013, 7.44x10^9 kg HCW beef were produced. When applied at the national scale, the water reductions calculated in this study would conserve between 1.82x10^{11} L and 3.08x10^{11} L per year. In the U.S., a frequent estimate of daily water use per person is 378 L (100 U.S. gallons). In practical terms, these water use reductions would enough water to supply the annual usage of 1.32x10^6 to 2.24x10^6 people.

CONCLUSIONS AND POLICY IMPLICATIONS

Improving sustainability is a promising solution to the global food production challenge. Attempts to employ top-down regulatory policies to mandate improvements in meat production sustainability may be unsuccessful because these policies frequently fail to account for farm level cost heterogeneity. This study investigated opportunities to rely on food labeling as an alternative means of incentivizing adoption of water-reducing technologies in meat animal production. The approach relied on estimating a confidence range for consumers’ WTP for pure environmental meat attributes and subsequently using that confidence range and a farm system optimizer to identify optimal on-farm nutritional management of beef cattle to reduce water use. The WTP assessment found that WTP was significantly influenced by demographic factors and study methodology. Importantly, WTP for pure environmental products was substantially less that WTP for impure environmental products. The outputted range in consumers’ WTP was then used to test the extent to which WTP could offset on-farm costs of reducing water use in three regions across the U.S. The optimizer detected different opportunities to decrease water use in
each region. Probability of purchase was factored into the analysis to make a realistic statement about the extent to which food labeling would influence management practices. The ideal consumer WTP was 10% and water conservation of 24.4 L – 41.4 L was possible.

This analysis identified several important points. First, there is a WTP for pure environmental meat attributes, distinct from currently available impure environmental products (organic, grass-fed, etc.). This is imperative because consumers have many misconceptions about food labeling (Gadema and Oglethorpe, 2011). Although consumers perceive that impure environmental products reduce the environmental impact of meat production, frequently these systems are less efficient than conventional meat production (Capper, 2012) and as a result, they have higher environmental impacts per kg product (Capper and Bauman, 2013). Additionally, small premiums paid at a retail level, if even conveyed 25% to the farm level, can offset operating cost increases attributable to decreasing water use. Many studies have identified management practices that will reduce environmental impact; however, producers are leery to adopt these practices because farm-level economic analysis is rarely included in the assessment. By demonstrating how WTP premiums could feed back to offset operating costs, this study integrates on-farm economic analysis with environmental impact reduction. As a final contribution, this study demonstrated moderate WTP increases that are palatable to the average consumer will have a greater aggregated impact on reducing water use than niche products with excessively high retail prices. This finding suggests that when using a labeling approach to reduce water use, the objective should not be to pioneer a new niche product but rather, to appeal to the majority of consumers.
LITERATURE CITED


Darby, K., M. T. Batte, S. Ernst, and B. Roe. 2006. Willingness to pay for locally produced
Econ. Assn.: 1-31.

Darby, K., M. T. Batte, S. Ernst, and B. Roe. 2008. Decomposing local: a conjoint analysis of

326.

Deckers, J. 2010. Should the consumption of farmed animal products be restricted, and if so, by

Delgado, C. L. 2003. Rising consumption of meat and milk in developing countries has created a


traceability in the United States, Canada, the United Kingdom and Japan. J. Agr. App.
Econ. 37: 537-548.

Dransfield, E., T. M. Ngapo, N. A. Nielsen, L. Bredahl, P. O. Sjoden, M. Magnusson, M. M.


USDA/APHIS. 2011. Feedlot 2011 Part I: Management practices on U.S. feedlots with a capacity of 1,000 or more head. USDA/APHIS, Fort Collins, CO.


USDA/ERS. 2013. Retail prices for beef, pork, poultry cuts, eggs and dairy products.

USDA/ERS.


Table 1. Variable definitions

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<tr>
<th>Variable</th>
<th>Definition</th>
<th>Models</th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
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<td>GDP</td>
<td>Gross domestic product per capita</td>
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<td>10,472</td>
<td>2,441</td>
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1Gross domestic product was based on publication year and study location and sourced from World Bank (2014)
Table 2. Informative priors used in analysis

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<td>GRASS $^2$</td>
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<td>NOHAG $^2$</td>
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$^1$Priors were calculated by random effects meta-regression

$^2$Priors are weakly informative following Gelman et al. (2004)
Table 3. Model\(^1\) coefficients and goodness-of-fit parameters

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<th>M2</th>
<th>M3</th>
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<td>2.254 (1.236, 3.274)</td>
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<td>2.84x10(^{-5}) (9.57x10(^{-6}), 4.72(^{-5}))</td>
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<td>GDP</td>
<td>2000</td>
<td>0.896 (0.314, 1.478)</td>
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<td>-0.733 (-1.238, -0.220)</td>
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<td>0.245 (-0.142, 0.637)</td>
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<td>EUR</td>
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<td>IMPURE</td>
<td>0.404 (-0.092, 0.900)</td>
<td>-0.086 (-0.734, 0.562)</td>
<td>0.040 (-0.748, 0.830)</td>
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<td>0.389 (-0.137, 0.911)</td>
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<td>HEALTH</td>
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<td>0.540 (-0.156, 1.236)</td>
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<td>ORGANIC</td>
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<td>GRASS</td>
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<td>NOHAG</td>
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\(^1\)M1 assumed consumers valued goods only based on their impure/pure public good classification. M2 assumed goods were valued based on their constituent parts. M3 assumed each good label was valued individually.
### Table 4. Baseline operating costs, water use and land use to produce beef in each region

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<td>Land (m²/kg HCW)</td>
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<td>16.3</td>
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Figure 1: 95% confidence ranges for North American or European consumers’ willingness to pay for pure and impure environmental labeling of beef products. The boxes represent the range between 25% and 75% confidence with the mean indicated by the middle bar. The error bars represent 95% confidence.
Figure 2: A comparison of the 95% confidence ranges for pure environmental products when meat type, GDP and location parameters were varied. The boxes represent the range between 25% and 75% confidence with the mean indicated by the middle bar. The error bars represent 95% confidence.
Figure 3. Water use attributed to a whole-farm beef production system over a schedule of allowable increases in operating costs. Operating cost increases were constrained to less than consumer WTP. Consumer WTP was varied within the confidence range for North American consumers WTP for pure environmental beef products.
Figure 4. Water use attributed to a whole-farm beef production system over a schedule of allowable increases in operating costs when probability of purchase was factored in. Probability of purchase was calculated from a cumulative normal distribution based on the confidence range for North American consumers WTP for pure environmental beef products.
## APPENDIX A.

**Table 1.** Studies used in Bayesian Estimation of Environmental WTP

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<th>Study</th>
<th>Location</th>
<th>Elicitation Method</th>
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<th>Val. Type²</th>
<th>Meat Type</th>
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<th>Base Reference</th>
<th>Product</th>
<th>Base Price</th>
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<td>Norway</td>
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Dickinson and Bailey (2002)
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1. Values were averaged across consumer types.
2. Only values from the no endowment treatment were sourced as the Generic meat was used as a baseline.
3. Mean WTP values for produces compared to U.S. hormone-treated beef were used.
4. Values with base price NA presented WTP estimates as percentage premiums.
5. With Opt-Out value was used.
6. Values were sourced from the multinomial logit model.
Values from different university sources were averaged

Only the no-endowment treatment – five goods values were used because “generic” was used as a base

Reported WTP were averaged using the class probabilities listed on page 575

Base price was calculated as the average price in the schedule listed Table 3 for the second attribute indicated comparison listed in table 5.

Values were sourced from A4 and A5 because these scenarios included information about the product but did not include a taste test
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1. Values were averaged across rows in Table 4
2. Only data from the Exchange scenario was included
3. Only the No Endowment treatment values were sourced as the generic price was used as a base
4. The 3-3-3 chop was used as a base and was compared to improving marbling (2-4-3), improving size (3-3-4) or improving color and marbling (4-2-3). Only values for the appearance bids were used as few studies allowed participants to sample the beef they were purchasing.
5. Select beef was used as a baseline
6. Base price was calculated as the average price in the schedule listed Table 3 for the second attribute indicated comparison listed in table 5.
Base prices were calculated from as the average from the values in table 1 for each country using exchange rates of $1.47 CAN$/USD, $119.83 Yen/USD and 106500 Pesos/USD. WTP values were averaged over income classes.
## APPENDIX B

**Table B.1.** Start weight, end weight and time spent in the model for each cattle group

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<td>Stocker Heifer</td>
<td>225</td>
<td>365</td>
<td>157</td>
</tr>
<tr>
<td>Calf-Fed Steer</td>
<td>254</td>
<td>615</td>
<td>280</td>
</tr>
<tr>
<td>Calf-Fed Heifer</td>
<td>225</td>
<td>566</td>
<td>280</td>
</tr>
<tr>
<td>Finisher Steer</td>
<td>405</td>
<td>615</td>
<td>130</td>
</tr>
<tr>
<td>Finisher Heifer</td>
<td>365</td>
<td>566</td>
<td>130</td>
</tr>
<tr>
<td>Dairy Steer</td>
<td>92</td>
<td>615</td>
<td>414</td>
</tr>
<tr>
<td>Dairy Heifer</td>
<td>92</td>
<td>566</td>
<td>389</td>
</tr>
</tbody>
</table>

1 A diet was balanced for each of these animal groups within the model.

2 Start weight refers to the assumed weight of the animal at the beginning of their time in the model.

3 End weight refers to the assumed weight of the animal at the end of their time in the model. This is slaughter weight for culled cows and bulls, calf-fed beef and dairy cattle and yearling-fed beef cattle.
Table B.2. Parameters required for determining cattle populations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cows per Yearling Bull&lt;sup&gt;1&lt;/sup&gt;</td>
<td>16.3</td>
</tr>
<tr>
<td>Cows per Mature Bull&lt;sup&gt;1&lt;/sup&gt;</td>
<td>23.7</td>
</tr>
<tr>
<td>Cows Calving Yearly&lt;sup&gt;1&lt;/sup&gt;</td>
<td>89%</td>
</tr>
<tr>
<td>Proportion of Breeding Population Made up by Heifers&lt;sup&gt;1&lt;/sup&gt;</td>
<td>9.3%</td>
</tr>
<tr>
<td>Calves Born Alive&lt;sup&gt;1&lt;/sup&gt;</td>
<td>96.5%</td>
</tr>
<tr>
<td>Calf Death Loss&lt;sup&gt;1&lt;/sup&gt;</td>
<td>9%</td>
</tr>
<tr>
<td>Stocker Death Loss&lt;sup&gt;2&lt;/sup&gt;</td>
<td>5%</td>
</tr>
<tr>
<td>Finisher Death Loss&lt;sup&gt;2&lt;/sup&gt;</td>
<td>5%</td>
</tr>
<tr>
<td>Proportion of Slaughter Population Made Up by Bulls&lt;sup&gt;3&lt;/sup&gt;</td>
<td>1.7%</td>
</tr>
<tr>
<td>Proportion of Slaughter Population Made Up by Beef Cows&lt;sup&gt;3&lt;/sup&gt;</td>
<td>10.6%</td>
</tr>
<tr>
<td>Proportion of Slaughter Population Made Up by Dairy Cows&lt;sup&gt;3&lt;/sup&gt;</td>
<td>8.6%</td>
</tr>
<tr>
<td>Proportion of Slaughter Population Made Up by Heifers&lt;sup&gt;3&lt;/sup&gt;</td>
<td>29.7%</td>
</tr>
<tr>
<td>Proportion of Slaughter Population Made Up by Steers&lt;sup&gt;3&lt;/sup&gt;</td>
<td>49.4%</td>
</tr>
<tr>
<td>Proportion of Calf-Fed Beef Calves&lt;sup&gt;4&lt;/sup&gt;</td>
<td>16.5%</td>
</tr>
<tr>
<td>Proportion of Calf-Fed Dairy Calves&lt;sup&gt;4&lt;/sup&gt;</td>
<td>8.5%</td>
</tr>
<tr>
<td>Gestation Length&lt;sup&gt;2&lt;/sup&gt;</td>
<td>285 d</td>
</tr>
<tr>
<td>Lactation Length&lt;sup&gt;6&lt;/sup&gt;</td>
<td>207 d</td>
</tr>
<tr>
<td>Annual Milk Yield&lt;sup&gt;7&lt;/sup&gt;</td>
<td>1,625 kg</td>
</tr>
<tr>
<td>Milk Fat Content&lt;sup&gt;8&lt;/sup&gt;</td>
<td>4.03%</td>
</tr>
<tr>
<td>Milk Protein Content&lt;sup&gt;8&lt;/sup&gt;</td>
<td>3.38%</td>
</tr>
</tbody>
</table>

<sup>1</sup> USDA/APHIS (2009b)

<sup>2</sup> Values were assumed

<sup>3</sup> USDA/ERS (2012b)

<sup>4</sup> Capper (2011a)

<sup>5</sup> USDA/APHIS (2011)

<sup>6</sup> USDA/APHIS (2009a)

<sup>7</sup> Miller et al. (1999)

<sup>8</sup> National Research Council (2000)
Table B.3. Feedstuff and pasture chemical composition\(^1\), costs\(^2\) and environmental attributes\(^3\)

<table>
<thead>
<tr>
<th>Feed(^4)</th>
<th>CP (%)</th>
<th>ME (Mcal/kg)</th>
<th>Cost ($/kg)</th>
<th>Irrigation (L/kg)</th>
<th>CO(_2)- Equivalents(^5) (kg/ha)</th>
<th>Yield (kg/ha)(^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All Regions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfalfa (AH)</td>
<td>17.0</td>
<td>2.24</td>
<td>0.178</td>
<td>257.1</td>
<td>224.57</td>
<td>7,556</td>
</tr>
<tr>
<td>Grass (GH)</td>
<td>10.0</td>
<td>1.65</td>
<td>0.129</td>
<td>119</td>
<td>103.95</td>
<td>4,334</td>
</tr>
<tr>
<td>Corn Grain (CG)</td>
<td>8.5</td>
<td>3.39</td>
<td>0.206</td>
<td>77.3</td>
<td>228.98</td>
<td>9,521</td>
</tr>
<tr>
<td>Soybean Meal (SBM)</td>
<td>49.0</td>
<td>3.04</td>
<td>0.552</td>
<td>74.5</td>
<td>117.77</td>
<td>2,841</td>
</tr>
<tr>
<td>Molasses (MOL)</td>
<td>46.4</td>
<td>2.83</td>
<td>0.518</td>
<td>175.4</td>
<td>193.3</td>
<td>3,701</td>
</tr>
<tr>
<td>Distillers Grains (DDG)</td>
<td>29.5</td>
<td>3.18</td>
<td>0.350</td>
<td>86.7</td>
<td>452.33</td>
<td>3,564</td>
</tr>
<tr>
<td><strong>Pacific Northwest</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control Pasture (C)</td>
<td>16.1</td>
<td>2.76</td>
<td>0.131</td>
<td>0</td>
<td>11.8</td>
<td>3,360</td>
</tr>
<tr>
<td>Irrigated Pasture (I)</td>
<td>16.1</td>
<td>2.76</td>
<td>0.111</td>
<td>37.7</td>
<td>23.5</td>
<td>4,285</td>
</tr>
<tr>
<td>Fertilized Pasture (F)</td>
<td>16.1</td>
<td>2.76</td>
<td>0.115</td>
<td>0</td>
<td>161</td>
<td>4,387</td>
</tr>
<tr>
<td>Irrig+Fert Pasture (I-F)</td>
<td>16.1</td>
<td>2.75</td>
<td>0.083</td>
<td>25.7</td>
<td>184.5</td>
<td>6,305</td>
</tr>
<tr>
<td>Rotated Pasture (R)</td>
<td>15.9</td>
<td>2.69</td>
<td>0.146</td>
<td>0</td>
<td>11.8</td>
<td>3,417</td>
</tr>
<tr>
<td>Rotated Irrig Pasture (R-I)</td>
<td>15.7</td>
<td>2.69</td>
<td>0.123</td>
<td>37.3</td>
<td>23.5</td>
<td>4,342</td>
</tr>
<tr>
<td>Rotated Fert Pasture (R-F)</td>
<td>15.7</td>
<td>2.69</td>
<td>0.127</td>
<td>0</td>
<td>161</td>
<td>4,444</td>
</tr>
<tr>
<td>Rot. Fert + Irrig Pasture (R-IF)</td>
<td>15.7</td>
<td>2.69</td>
<td>0.091</td>
<td>25.7</td>
<td>184.5</td>
<td>6,362</td>
</tr>
<tr>
<td><strong>South</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control Pasture (C)</td>
<td>16.3</td>
<td>2.82</td>
<td>0.131</td>
<td>0</td>
<td>11.8</td>
<td>2,831</td>
</tr>
<tr>
<td>Irrigated Pasture (I)</td>
<td>16.3</td>
<td>2.82</td>
<td>0.111</td>
<td>37.7</td>
<td>23.5</td>
<td>3,610</td>
</tr>
<tr>
<td>Fertilized Pasture (F)</td>
<td>16.3</td>
<td>2.83</td>
<td>0.115</td>
<td>0</td>
<td>161</td>
<td>3,696</td>
</tr>
<tr>
<td>Irrig+Fert Pasture (I-F)</td>
<td>16.6</td>
<td>2.85</td>
<td>0.083</td>
<td>25.7</td>
<td>184.5</td>
<td>5,312</td>
</tr>
<tr>
<td>Rotated Pasture (R)</td>
<td>15.7</td>
<td>2.79</td>
<td>0.146</td>
<td>0</td>
<td>11.8</td>
<td>2,883</td>
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<tr>
<td>Rotated Irrig Pasture (R-I)</td>
<td>15.7</td>
<td>2.80</td>
<td>0.123</td>
<td>37.3</td>
<td>23.5</td>
<td>3,662</td>
</tr>
<tr>
<td>Rotated Fert Pasture (R-F)</td>
<td>15.7</td>
<td>2.80</td>
<td>0.127</td>
<td>0</td>
<td>161</td>
<td>3,749</td>
</tr>
<tr>
<td>Rot. Fert + Irrig Pasture (R-IF)</td>
<td>15.4</td>
<td>2.81</td>
<td>0.091</td>
<td>25.7</td>
<td>184.5</td>
<td>5,365</td>
</tr>
<tr>
<td><strong>Midwest</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control Pasture (C)</td>
<td>16.3</td>
<td>2.79</td>
<td>0.131</td>
<td>0</td>
<td>11.8</td>
<td>3,042</td>
</tr>
<tr>
<td>Irrigated Pasture (I)</td>
<td>16.1</td>
<td>2.78</td>
<td>0.111</td>
<td>37.7</td>
<td>23.5</td>
<td>3,879</td>
</tr>
<tr>
<td>Fertilized Pasture (F)</td>
<td>16.1</td>
<td>2.78</td>
<td>0.115</td>
<td>0</td>
<td>161</td>
<td>3,972</td>
</tr>
<tr>
<td>Irrig+Fert Pasture (I-F)</td>
<td>15.9</td>
<td>2.77</td>
<td>0.083</td>
<td>25.7</td>
<td>184.5</td>
<td>5,709</td>
</tr>
<tr>
<td>Rotated Pasture (R)</td>
<td>15.2</td>
<td>2.71</td>
<td>0.146</td>
<td>0</td>
<td>11.8</td>
<td>3,097</td>
</tr>
<tr>
<td>Rotated Irrig Pasture (R-I)</td>
<td>15.2</td>
<td>2.71</td>
<td>0.123</td>
<td>37.3</td>
<td>23.5</td>
<td>3,935</td>
</tr>
<tr>
<td>Rotated Fert Pasture (R-F)</td>
<td>15.2</td>
<td>2.71</td>
<td>0.127</td>
<td>0</td>
<td>161</td>
<td>4,028</td>
</tr>
<tr>
<td>Rot. Fert + Irrig Pasture (R-IF)</td>
<td>15.3</td>
<td>2.71</td>
<td>0.091</td>
<td>25.7</td>
<td>184.5</td>
<td>5,765</td>
</tr>
</tbody>
</table>
Chemical composition of non-pasture feeds was from the Agricultural Modeling and Training Systems CattlePro (AMTS, 2006) Feed Library. Pasture chemical composition was modeled.

Costs were modeled for pasture feeds and from USDA/ERS (2012b) for non-pasture feeds.

Environmental attributes including irrigation required, CO₂ production and yield were modeled within the pasture module or from USDA/ERS (2012b) or USDA/NASS (2007).

Feeds available during diet formulation.

Carbon emissions included CO₂ from manufacture of cropping system inputs and tillage as well as N₂O from fertilizer application

Yields were modeled in the pasture module or sourced from USDA/ERS (2012)
CHAPTER SEVEN

COMPARING FREQUENTIST AND BAYESIAN ESTIMATION APPROACHES
INTRODUCTION

For centuries, scientists have employed structured investigative methods to utilize measureable phenomena to decipher and inform theories that explain the world around us. Contemporary to the rise of the scientific method was the struggle to define acceptable standards for the truth or reliability of theories. For the past century, young scholars have been educated under the doctrine of Frequentist hypothesis testing where the scientific method relies on statistical analysis and results are used to update our current theories based on a true or false conclusion from a significance test. Since the 1980’s there has been remarkable growth in an alternative method of statistical analysis, Bayesian inference. This growth occurred primarily as a result of improved computational power and the advent of Markov Chain Monte Carlo sampling. With this increase in computational capability, more and more investigators are questioning whether the standards for educating young scientists should expand from Frequentist statistics to include Bayesian inference as an equally useful alternative (Johnson, 1999; Sterne and Smith, 2001).

There are several advantages to Bayesian inference. Bayesian inference allows for informative priors so that previous models, data or understanding can be used in inform and improve a current model. This approach is much more in tune with scientific epistemology than the Frequentist standard of ignoring prior information. Additionally, Bayesian inference treats the data as fixed and the model as random while Frequentist approximation assumed the data are random and the model is fixed. Given the errors in specifying models and humanity’s imperfect ability to properly specify a model, assuming a random model is often more appropriate than a fixed model. Bayesian inference estimates the probability of the hypothesis given the data available while Frequentist approaches estimate the probability of the data given the hypothesis. Again, the Bayesian approach is more congruent with scientific epistemology in which a
hypothesis is first identified and data are subsequently collected to test said hypothesis. The reliance on probability intervals and estimation from prior distributions often result in more precise estimates than confidence intervals. Finally, Markov Chain Monte Carlo algorithms are virtually guaranteed to converge if run long enough while Maximum Likelihood Estimation has no guarantee of convergence. These advantages are only a few of the many identified by Bayesian statisticians.

The epistemological differences inherent in Frequentist and Bayesian approaches can be explored by an example research question. In this study, we retrospectively explore the analysis of two alternative estimates of consumer’s willingness to pay (WTP) for environmental attributes of meat. This question is unique in that it presents the challenge of comparing Frequentist and Bayesian approaches to quantitatively summarize a body of literature. Tradeoffs between these approaches include sample size, confidence level, precision and accuracy of estimation. Additionally, the means of evaluating each method and their relative implications are explored within the context of predicting WTP.

MATERIALS AND METHODS

Review of the Literature

The Agricola and Google Scholar databases were searched to identify studies measuring WTP for impure and pure environmental met attributes. Conference publications, white papers and extension publications were identified using the AgEconSearch engine. Authors publishing frequently on the subject were contacted for copies of their most recent work. Studies were excluded if they were based on a dataset from a study already included in analysis, if they failed to present a numerical estimation of WTP for a meat attribute and if they failed to present a clear
base price. The selection process resulted in 35 studies representing 139 treatments conducted on over 16,000 consumers in 14 countries. Full explanation of the literature review and the studies used can be found in White and Brady (2014).

Variables and Model Specification

In both the REML and the Bayes estimation methods, the dependent variable was consumer willingness to pay for the meat product attribute isolated in any particular treatment. Willingness to pay was presented in one of two ways: as a dollar amount; or as a percentage premium. All values were converted to percentage premiums based on the base price of a good. Base prices were sourced from the text and included either the average of the prices used in elicitation, the market price of the base product at the time of study or the WTP reported for a generic product, whichever was clearly presented in the study. The base prices for each treatment can be found in White and Brady (2014).

Three classes of independent variables were used: methodological, location and attribute. Methodological variables were used to specify whether the study was conducted in person; what meat type was tested; and whether a non-hypothetical valuation method was employed. Location variables specified if the study was conducted in the US or Canada, Europe or Asia. Attribute variables were developed to explain whether WTP for environmental meat products was best explained by Impure/pure public good preferences or if additional information about the environmental benefit of the good had an effect on WTP. A variable was included to specify if a purely public good attribute was tested, good with only environmental attributes and goods aimed at improved animal welfare were classified in the category. An additional variable for pure environmental good attributes was included. Impure environmental good variables were
included to specify grass feeding, organic labeling, and natural production (no hormones, no antibiotics and/or no growth enhancing technologies). Finally, variables for a non-environmental purely public good (improved animal welfare) and a non-environmental impure public good (local/traceable) were included.

Two different groupings of explanatory variables were tested to identify whether WTP was sufficiently explained by pure/impure dynamics or whether adding subject specific variables (grass-feeding, organic, local, welfare, etc.) would further improve understanding of WTP. Both models were estimated using Maximum Likelihood Estimation and using Bayesian Inference. Maximum Likelihood Estimation was carried out using the MetaReg program in Stata version 9.2. Bayesian fitting was done with the MCMCpack package of R version 3.0.2. Informative priors for variables and error terms were used for the Bayesian fitting as described in White and Brady (2014).

Means of Evaluating Each Model
All models were evaluated using the proportion of between-study variance explained by the covariates, $R^2$ and root mean squared error of prediction, RMSPE. Significance of variables in each model were determined by the p-values of a student’s t distribution. The REML models were additionally evaluated using the between study error variance, $\tau^2$, and the proportion of residual between-study variance, $I^2_{res}$. Model error terms were used to evaluate the Bayesian models. The 95% intervals on the model coefficients were used to estimate non-hypothetical WTP for a beef product with pure environmental attributes. The range in estimation was compared and inferences on model precision were discussed.
RESULTS

The variable coefficients, $R^2$ and RMSPE values for all models are included in Table 1. In the Bayesian models, informative priors improved model predictive capability and decreased model error. The addition of subject specific explanatory variables also improved model predictive capacity and decreased error. The meta-regression models had $\tau^2$ values of 16% - 22% and very small I-squared values. The $R^2$ for the pure/impure Frequentist model was 4.6% and the $R^2$ for the subject-specific Frequentist model was 43%. Neither model was not significant; p-values were 0.96 and 0.75. When the most probable Bayesian model was compared to the Frequentist model, the Bayesian model had substantially higher ability to explain the variability in WTP. Additionally, the Bayesian model improved error by 5% - 11% over the Frequentist models.

The range in WTP for different pork and beef attributes as predicted by the most probable Bayesian model and the most accurate Frequentist model are listed in Table 2. The WTP for impure pork products tended to be more variable that WTP for beef products and impure products were more variable that pure products. The error range on impure environmental beef attributes was 6% in the Bayesian model and 1,652% in the Frequentist model. Error ranges in the Bayesian model for impure environmental pork attributes were 15.4%. This error increased to 28,886% in the Frequentist model. In generate, the Bayesian model improved precision of WTP estimates.

DISCUSSION

Sample Size

The results of this comparison illustrate the trade-offs between these two methods of statistical analysis. The Bayesian model fit the data better than the Frequentist model. This result is
supported by other similar investigations (Layton and Levine, 2005; Negrín et al., 2008). Bayesian models seem to fit WTP data better than Frequentist models because they have greater capacity to explain the heterogeneity inherent within consumers (Negrín et al., 2008). Food consumers on a global scale are a remarkably large and remarkably diverse group. Frequentist hypothesis testing relies implicitly on the assumption that the sample size is sufficient to accurately reflect the variability of the population (Lenth, 2001). Scanner data of US consumers’ WTP for beef attributes show considerable variability in WTP (Schulz et al., 2012; Ward et al., 2008). In WTP literature, emphasis has been placed on non-hypothetical rather than hypothetical valuation techniques (List and Gallet, 2001; List and Shogren, 1998; Little and Berrens, 2004). As a result, sample sizes used in WTP studies have decreased substantially. These smaller samples may not accurately represent the variability of the population and may impede the reliability of the conclusions drawn from the sample.

Informative priors in Bayesian analysis can help improve accuracy of model estimation when sample sizes are small (Lenk and Orme, 2009). The need for specified priors is one inconvenience of Bayesian modeling. In models with a large number of variables, specifying priors within the structure of the model can be difficult if not impractical (West, 2003). On the other hand, results in this study and others demonstrate substantial improvements in model predictive capacity when properly specified model priors are employed during estimation (Ahtiainen and Vanhatalo, 2012).

Confidence Level and Model Accuracy

The Frequentist models analyzed here were not significant and therefore yield a poor example of the difference in confidence level between Frequentist and Bayesian approaches. Significance in
a Frequentist model is typically determined by a p-value. The p-value is the probability of obtaining a test statistic at least as extreme as the one actually observed assuming that the null hypothesis is true. In the typical regression, the null hypothesis states that the effect sizes obtained by regression are equal to the true effect size within the population. In our study, there was a 96% chance of obtaining a more severe test statistic in the first model and a 75% chance in the second model. We can infer in both cases that there was insufficient evidence to reject the hypothesis that the effect sizes predicted by the model were equal to those displayed by the population. In this scenario, these results give no information about whether one model fit the data better than the other as both p-values indicated the models were insignificant. In a purely Frequentist study, the best option would be to return to the data or to the model parameterization and attempt to find a different model or additional data.

In Bayesian model fitting, the p-value is not the standard for model confidence. One downside of the p-value is the yes-or-no nature of the statistic. If the model is insignificant, minimal useful conclusions can be drawn about the nature of the system. In Bayesian analysis, the Bayes Factor is the factor of importance. The Bayes Factor (Jeffreys, 1935) is the posterior probability of the null hypothesis when the prior probability on the null is one-half (Kass and Raftery, 1995). Rather than focusing on rejecting or failing to reject a null hypothesis, Jeffreys’ Bayes Factor (Jeffreys, 1935) allows for an evaluation of evidence in favor of a null hypothesis. This method holds the additional advantage of yielding an estimate of the confidence of the model, rather than relying on previously, often arbitrarily, assigned levels. In our studies, the Bayes Factors of the models with informative priors were substantially higher than models without informative priors. Additionally, the Bayesian models allow us to make inferences about whether WTP was better explained by subject specific labeling than by pure/impure environmental attribute classification.
In the models with informative priors, using subject specific variables improved model probability from 7.5% to 82.7%. In a the doctrine of 95% confidence, neither model would be significant; however, use of the Bayes Factors helps us to draw the useful conclusion that adding subject specific priors greatly improved model probability.

Pearson’s $R^2$ correlation was used as a means to objectively evaluate both modeling methods. The $R^2$ represents the degree of variability in the sample explained by the variables in the model. In the most probable Bayesian model, 61% of the sample variability was explained. In the best Frequentist model, only 43% of the sample variability was explained. As with previous studies investigating Bayesian and Frequentist estimation of WTP data, the Bayesian model explained more of the sample variability (Layton and Levine, 2005; Negrín et al., 2008).

**Confidence Range and Model Precision**

An additional means of evaluating a model is the precision of the model or the confidence range associated with the model estimates. In both model fitting techniques, 95% confidence intervals for the environmental variables used in the model. To assess model precision, the models using the values on the minimum and maximum range of the 95% confidence intervals were used to simulate WTP for pure and impure meat attributes in the US, Europe and Asia. The average range in WTP estimates for pure environmental beef or pork predicted by the Bayesian model were 4.7% and 12.1%. The WTP estimates predicted by the Frequentist model were 17.5% and 15.1%. When WTP for impure environmental pork attributes were assessed by the Bayesian model, a 15.4% confidence range was established. In the Frequentist model, the confidence range was 28,886%. Similarly, with impure environmental beef attributes, the Bayesian model estimated a 5.7% confidence range while the meta-regression yielded a 1,650% range. The
Bayesian model not only had better accuracy with respect to the validating dataset but it also had greater precision in estimating WTP.

When evaluating consumer WTP, a confidence range is useful as it allows for predicting the probability that a consumer will purchase the product in question at any given WTP. That said, unreasonably large confidence ranges (i.e. ± 1,650%) do little to improve this understanding. Because prior information about WTP was included in the estimation, the Bayesian model was better able to isolate the influence of individual variables, thus improving both the accuracy of the model and the precision of its estimates.

CONCLUSIONS

Most scholars across scientific disciplines will agree that the purpose of scientific inquiry is to support, contribute to or identify theories that explain the world around us. To achieve this purpose, one must ask the question: what makes a theory defendable, reliable or even, true? This is a question that has been continually re-assessed through time as new methods of observation become available. The advent of the telescope, the microscope and most recently, the computer, have all changed the way that scientists view the world (Stewart, 2011). The present scientific approach relies heavily on ratifying findings with Frequentist statistics. Namely, reliance on thresholds for statistical significance ($p < 0.05$) and avoidance of Type I error (Parascandola, 2010). Bayesian statisticians have cited numerous shortcomings in Frequentist statistical analysis (Bernardo and Rueda, 2002; Lenk and Orme, 2009); many of which are applicable to models explaining consumer WTP. Given the shortcomings of Frequentist statistics when applied to some types of data, it becomes timely to assess alternative methods of conferring validity to experimental findings. The analyses in this study demonstrated that Bayesian statistical analysis
yields more accurate and more precise estimates of WTP than Frequentist analysis.
LITERATURE CITED


Table 1. Model\(^1\) coefficients, R\(^2\), Root Mean Squared Error of Prediction and Posterior Probabilities

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<tr>
<th>Variable</th>
<th>m1</th>
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<th>m3</th>
<th>m4</th>
<th>m5</th>
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<th>m8</th>
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<td>Probability</td>
<td>(6.5 \times 10^{-5}) (6.0 \times 10^{-5}) (6.7 \times 10^{-5}) (5.1 \times 10^{-4})</td>
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P-value/Tau\(^2\) 0.96/0.51 0.75/0.48

\(^1\) Models included: non-informative error and coefficient priors for impure/pure variables only (m1), non-informative error and coefficient priors for subject specific variables (m2), informative error priors for impure/pure variables (m3), informative error priors for subject specific variables (m4), informative coefficient priors for impure/pure variables (m5), informative coefficient priors for subject specific variables (m6), informative error and coefficient priors for impure/pure variables (m7), informative error and coefficient priors for subject specific variables (m8), meta-regression with impure/pure variables (Meta1) and meta-regression with subject specific variables (Meta2).
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CHAPTER 8

SUMMARY AND CONCLUSIONS
The current global food production climate (Delgado, 2003; U.S. Census Bureau, 2013) is characterized by a misbalance of resource availability and consumer demand. To remedy this discrepancy, the food production system must improve sustainability to help ensure a secure global supply. Improving sustainability is not a short term goal; it will require educating stakeholders throughout the production chain about the attributes of a sustainable system. Before this can be done, a scientific understanding of sustainability must be achieved and the effects of management practices on beef sustainability determined. A sustainable food production system must balance environmental impact, economic viability and social acceptability (WCED, 1987).

Although environmental-impact-reducing management practices have been identified, few assessments have integrated estimates of economic viability and social acceptability. The overall objective of this research was therefore to examine opportunities for enhancing the environmental impact, economic viability and social acceptability of whole system beef production by optimizing management practices.

To accomplish this objective a whole farm system model was constructed to examine increased production efficiency (increased rate of finishing or improved finishing weight) as a method by which greenhouse gas emissions, water and land use could be reduced. The model relied on national average pasture data as a primary feedstuff for cow-calf and stocker cattle. Income over variable costs was used to assess economic viability and literature estimates of stakeholder willingness to pay (WTP) served as a social acceptability metric. At a U.S. level, this early version of the model determined that there are opportunities for producers to enhance all three metrics of sustainability by improving efficiency. Improving productivity consistently reduced environmental impact per unit product. Income over variable costs improved in situations where supply did not shift with improved productivity. Social acceptability was increased in
socioeconomic scenarios where growth and productivity attributes were marketed to stakeholders and consumers had a non-negative willingness to pay. This assessment revealed that sustainability was highly dependent on socioeconomic assumptions. Additionally, national average pasture data were insufficient to explain true variability in grazing system options. Additionally, the study left the effect of specific management strategies on beef sustainability unexplored.

To improve specificity of assessment, an optimization model was developed to assess how management practices could be adjusted at the regional level to improve sustainability. A pasture management module was added to examine how fertilization, irrigation and/or rotational grazing could be used to improve sustainability. To ensure changes in management were both economically feasible and socially acceptable, consumer WTP estimates were determined through meta-analysis of previous literature estimating WTP for environmental goods. These inputs were incorporated into the model and at a national level, a simultaneous 2.3% reduction in land use, water use and greenhouse gas emissions was possible without cost increases exceeding consumer WTP. Regional assessment was also conducted. In Texas, optimizing nutritional and pasture management reduced environmental impact by 1.8% - 2.2%. This opportunity was much greater in the Pacific Northwest (3.6%) and in the Midwest (5.8% - 6.0%). These regional differences influence how each location responded to climate-variability-related changes in precipitation patterns. In the Pacific Northwest and Texas, decreased spring rainfall resulted in lower pasture yield and required greater use of stored forages. Purchase of stored forages diminished available capital for adopting environmental-impact-reducing management practices and as a result, opportunities to improve sustainability in the Pacific Northwest and Texas were
reduced by projected precipitation changes. The opposite occurred in the Midwest where increased spring precipitation was projected.

The model was sensitive enough to detect differences across regions as well as differences in management practices. Employing genetic, reproductive and nutritional management together improved environmental impact by 19%. This opportunity was greater than improving genetic merit alone (18%), utilizing reproductive management strategies like twinning cattle (17%) or decreasing calving window (11%) and substantially larger than relying on nutritional management alone (1.9%). The cow-calf sector has the greatest environmental impact within the beef production system. As such, optimizing management practices employed within this sector may be the most promising method to improve the sustainability of beef production.

The foundation of the social acceptability and economic viability metrics used in the model was consumer WTP and was estimated by meta-regression analysis. This procedure could be conducted using Frequentist or Bayesian model fitting procedures. These fitting procedures were compared and the Bayesian model could explain 63% of the variability in WTP while the Frequentist model could only explain 42%. The error bounds around the Frequentist estimate were substantially greater than those in the Bayesian model. This comparison indicated that Bayesian model fitting techniques could produce more accurate and precise estimates of WTP than Frequentist methods.

Non-hypothetical U.S. consumers’ WTP for low-environmental impact beef ranged from 6.7% to 32.6%. This WTP range equated to a possible 65.5 L per kg beef reduction in water use. Ranges in consumer WTP can be used to estimate the probability of a consumer purchasing a good at any given WTP. When probability of purchase was factored in, optimal WTP decreased to 10%
and theoretical opportunity to reduce water use between 24.4 L and 41.4 L per kg beef. This indicates that when exploring WTP as an alternative method to incentivize adoption of environmental-impact reducing management practices, focus should be put on obtaining market share rather than attempting to achieve the biologically optimal reduction in environmental impact. Therefore, improving environmental impact of conventional meat production by increasing productivity is a more effective method of achieving whole-scale environmental impact improvements than relying on niche markets.

Overall, this research has contributed to the body of knowledge about beef production sustainability by providing a useful tool to assess the regional implications of management practices on environmental impact, economic viability and social acceptability. The model demonstrated that improving genetic potential of cattle while maintaining reproductive efficiency and optimal diet composition resulted in the greatest opportunity to improve the sustainability of beef production systems. Although incorporating environmental, economic and social metrics into assessments of beef sustainability was an important step forward, the issue of sustainability is far from solved. This model is primarily a research tool and would not be an appropriate decision support tool at the farm level until further validation efforts are undertaken. As such, the results, although useful in identifying attributes of a sustainable system, may be less helpful to producers seeking to improve the sustainability of their individual operations. Future work should focus on decision support system development to build tools that can be used on-farm.

Another related question lies in the use of WTP as a metric of social acceptability. Consumers are a vital part of the food production chain; however, variability in WTP by cut, attribute, location, etc. makes it difficult to rely on consumers’ interest in environmental products.
Furthermore, consumers rarely directly interact with beef producers when purchasing products and substantial uncertainty exists surrounding what proportion of retail price actually makes it back to farmers. As a result, WTP may be a more reliable metric in niche-type markets where direct marketing is used but, as demonstrated in Chapter Six, niche markets are an unreliable method of improving whole-system environmental impact. Although WTP may be an imperfect metric of social acceptability in a practical setting, it is an indicator of consumer awareness and general stakeholder interest. As publications about consumer WTP for environmental attributes of food products have become more prominent, beef industry stakeholders has also demonstrated a commitment to improving sustainability through groups like the Global Roundtable on Sustainable Beef. As such, it can be concluded that while WTP is a metric of social acceptability, future assessment of beef sustainability should incorporate a wider variety of indicators to create a more comprehensive understanding of the social implications of management practices.

As the global population continues to expand, impinging on resources required for food production, the beef industry will need to focus more stringently on improving sustainability. Concurrently, societal mistrust of agriculture, as propagated largely by inflammatory popular media sources, provides a real challenge. Outreach efforts must be a focus to improve consumer understanding of the food production chain to help foster informed consumerism. A long-term commitment to improved productivity, careful monitoring of farm economics and increased focus on consumer education will all help to ensure the viability of the beef industry in the current changing food climate. By helping to increase understanding of management practices that improve meat production sustainability and exploring one method of quantifying social acceptability, this research puts us one small step closer toward the goal of proving a secure, sustainable global food supply.
LITERATURE CITED


APPENDIX A

CLIMATE AND DAIRY DIET FORMULATION FREQUENCY

This chapter was published as White, R.R. and J.L. Capper. Precision diet formulation to improve performance and profitability across various climates: Modeling the implications of increasing the formulation frequency of dairy cattle diet. Journal of Dairy Science. 97:1563-1577
INTRODUCTION

Precision dairy nutrition has been defined as the use of information technology to optimize economic, social and environmental farm performance (Spilke and Fahr, 2003). Precision feeding optimizes these performance attributes by facilitating the economically and ecologically sound production of a quality milk product that is highly acceptable to the consumer (Spilke and Fahr, 2003). It is gaining interest as a robust management practice capable of increasing efficiency, reducing costs, improving product quality, minimizing environmental impact and improving health and well-being of dairy cattle (Bewley, 2010). Several studies have modeled the effect of precision nutrition on whole-farm nutrient balance (Cerosaletti et al., 2004; Gehman, 2011; Ghebremichael et al., 2007; Wang et al., 2000a). These models indicate that precision nutrition improves dairy productivity by meeting each individual animal’s or pens of animal’s nutrient requirements more accurately (Cerosaletti et al., 2004; Gehman, 2011; Wang et al., 2000b). On farm studies have also shown the benefits of precision nutrition. Real-time monitoring of lactating cow feed intake can improve DMI (Halachmi et al., 1998) and on-farm implementation of feeding suggestions from a precision management model can improve milk yield and income over feed costs (Andre et al., 2007). These results indicate that precision feeding may be one method to concurrently improve nutrient-use efficiency and productivity.

Thus far, few studies have explored the robustness of precision nutrition strategies across variable climates. However, two major model systems in dairy nutrition have the capacity to specifically account for additional energy required under conditions of environmental stress (Fox et al., 2004; Fox and Tylutki, 1998; NRC, 2001). The influence of climate on dairy production is
well documented (Blackshaw and Blackshaw, 1994; Collier et al., 2006; St-Pierre et al., 2003; West, 2003; Wheelock et al., 2010), and there is strong evidence to indicate that climate variability is increasing (IPCC, 2007; McKibben, 2007; Nardone et al., 2010).

Therefore the objective of this study was to use a precision nutrition model to simulate the effect of diet formulation frequency on the predicted milk yield (MY), dry matter intake (DMI) and metabolizable energy (ME) balance of a representative average dairy cow under various climate conditions, and to assess the effect of diet formulation frequency and climate variability on returns over variable costs. It was hypothesized that formulating diets more frequently would result in improved ME balance, increased MY and improved profitability regardless of climate.

MATERIALS AND METHODS

This study utilized data from existing reports and databases to generate modeled outputs and required no Animal Care and Use Committee approval. Weather data sourced from Climatic Data Center (NCDC, 2010) were inputted into Agriculture Modeling and Training Systems (AMTS) Cattle Pro diet balancing software. Weather data representing a hot, humid year, a cold, windy year and a highly variable year were entered on a weekly, monthly and seasonal basis. Modeled MY, ME and DMI were recorded and compared across weather scenarios and formulation frequencies using a fixed effects analysis of variance (ANOVA). Feed cost and milk price data were sourced from USDA/ERS (2012) and used with modeled MY and DMI to calculate income over feed and labor costs. Results were compared to previously-published modeled and measured estimates of climate stress or precision feeding impacts on dairy productivity and profitability. To account for variability in feed cost and milk price data, sensitivity analysis on the income over feed and labor cost calculation was conducted.
Generation of Performance Outputs

Diets were formulated and cattle performance simulated using AMTS CattlePro (AMTS, 2006). CattlePro calculations are based on the Cornell Net Carbohydrate and Protein System (CNCPS; AMTS, 2006). CattlePro was used because it specifically accounts for the influence of environment on nutrient requirements during a wide array of environmental conditions (Fox et al., 2004; Tylutki et al., 2008).

In this study, diets were formulated on a seasonal, monthly and weekly basis for a lactating Holstein cow to test whether reformulating diets more frequently would increase milk production in an average animal. Nutritional requirements were generated for cows weighing 680 kg producing 36.5 kg of milk per d at 153 d in milk, with a milk fat content of 3.8% and a milk protein content of 3.1%. A full list of input variables used to describe the cows and housing system are included in Table 1. The data describing cows were selected to best simulate an average animal on an operation at any given point during the year. Given the variability in production responses to nutritional modification across lactation and productivity level it is important to note that these results are the mean predicted response of an average animal and should not be extrapolated to explain the responses of individual cows during different lactation stages or levels of productivity. This study aimed to simulate a freestall housing system; however, in many but not all freestall systems, wind speed (WS) may not have a significant influence upon animal nutrient requirements due to the presence of sheltered areas. In this study WS was included without accounting for decreases due to sheltered areas or windbreaks. Attenuation of WS was not modeled in this study because insufficient data were available to develop a defendable numerical relationship between WS within a protected freestall system and outside WS. The study may over-estimate negative implications of cold stress on dairy cattle in
freestall systems and the results may be more applicable to a drylot or pasture-based system. That said, substantial proportions of US operations keep cows in an outside drylot (with or without freestalls; 27%) or allow access to pasture (49%) for some length of time during lactation (USDA/APHIS, 2007).

Feedstuff inputs for diet formulation were sourced from the feedbank in CattlePro (AMTS, 2006). Diets were formulated using an identical base composition, (comprising steam-flaked corn grain, corn distiller’s grains, corn silage, soybean meal, grass hay and alfalfa hay) with corn grain content varying to meet energy requirements as predicted by CattlePro. Dry hay rather than haycrop silage was selected as a feed in this study because nutrient content was assumed to be more consistent due to the high variability of dry matter content in haycrop silage. Diet ingredient composition, ME and metabolizable protein (MP) values are shown in Table 2. Table 3 shows chemical composition of feedstuffs used. Environmental inputs required for CattlePro included previous and current values for daily temperature (T), WS and relative humidity (RH) and minimum nighttime temperature (Fox et al., 2004). Current conditions predicted the immediate effects of the climate on nutrient requirements and previous conditions accounted for acclimatization of the animal to the conditions (Fox and Tylutki, 1998). When diets were formulated, current conditions referred to the average expected temperature for the feeding period and previous conditions referred to the average temperature in a set period before the feeding period.

Diets were balanced using weekly, monthly, and seasonal (3-month) periods. When entering weather data, the “current” weather input was used to represent an average year following the assumption that diet formulators use long-term-average weather data when balancing diets. Daily weather data were averaged over the 10 years of available data. The “current” weather data
inputted into CattlePro was the average of this daily average data representing the time period during which the diet would be fed. The “previous” weather data was the average of the daily data for the period immediately prior to the period during which the diet would be fed as it was assumed the diet formulators would have access to this weather data. For the diets using 3-month periods, the seasons were defined as follows: winter from January 1st to March 31st; spring from April 1st to June 30th; summer from July 1st to September 31st; and fall from October 1st to December 31st. Monthly formulation defined seasons by the conventional calendar month. Weekly formulation based periods on 7-day intervals beginning with January 1st.

In each case, required inputs were entered into the model and diets were balanced the ME allowable MY was 36.5 kg/d and so that the ME balance was 0.00 Mcal/d. This would represent the best possible scenario (requirements were predicted perfectly). These points were chosen as reference points, which is what any ration evaluation or formulation program outputs as a target, not because this result is expected to be consistently achieved in the field. Although 0.00 Mcal/d represents precision that is not achievable on most farms, it is the degree of precision allowable within CattlePro. In an industry situation, when rations are reformulated it is assumed that the formulator would adjust the diet to the degree of precision allowed by the diet balancing software. This level of precision was therefore use as a theoretical optimal. After the diet for a time period was balanced, the daily climate data for that period were entered into the program, one day at a time and the predicted ME balance, ME allowable MY and the DMI were recorded. At the end of the period, the diet was rebalanced.

Selection of Climate Data

Weather data for the years between 1999 and 2010 were downloaded from the National Ocean
and Atmospheric Association database for the weather station in Buffalo, NY (NOAA, 2011) Buffalo was chosen because this location had data available, has a characteristically variable climate and was near a high concentration of dairy cattle. The three climate parameters that were collected included T, WS, RH. Examples of extreme and variable weather years were identified and investigated to determine their effects on milk production.

The three years with data best suited to the climate scenarios of interest (a hot, humid year; a cold, windy year; and a highly variable year) were identified using a ranking procedure. Figures for the annual mean, 10-yr overall mean and variance were calculated for T, WS and RH. Differences between the annual and overall means were calculated (Figure 1), temperature and RH were ranked from 1 to 10 with the year with the highest T and RH ranked 1. Wind speed was also ranked from 1 to 10 but the year with the highest value was ranked 10. Rankings for the climate variables were summed for each year and the sum of the rankings was used to determine the hot, humid year and the cold, windy year. The year with the lowest score was selected as the hot, humid year and was expected to have the most extreme combination of high T, high RH and low WS. The year with the highest score was selected as the cold, windy year and was expected to have the most extreme combination of low T and high WS. To select the highly variable year, the year with the highest cumulative variance was identified. Cumulative variance was calculated as the ratio of the climate parameter variance to the climate parameter mean, summed for all climate parameters (T, RH and WS) within a year. The variance used for this determination is shown in Figure 2. The year best representing a hot, humid climate was 2001 because this year had the second highest RH and the second highest average T; the year selected as the cold, windy year was 2008 because it had the best combination of low T and high WS. Climate variability in 2004 was almost twice that in other years (Table 4). Days above/below the thermoneutral zone,
as defined by Johnson (1986) were identified for each year. The hot, cold and variable climates were below thermoneutral \((T < -0.5 ^\circ C)\) for 90 d, 100 d and 102 d and above thermoneutral \((T > 20 ^\circ C)\) for 53 d, 39 d and 49 d, respectively.

Data Analysis

In this modeling analysis treatments were applied to time (week) as the experimental unit: three levels of the formulation frequency treatment (weekly, weekly and seasonally) and each of three levels of the climate variability treatment (hot, cold and variable). This resulted in a 3 X 3 factorial design with fixed effects. Data were analyzed using PROC GLM of the Statistical Analysis Software version 9.2. Individual analyses were conducted for each response variable. A multivariate ANOVA was used to test how each response variable was affected by formulation frequency and climate variability. The general linear model used to analyze the effects is as follows:

\[
Y_{ijk} = a_i + b_j + ab_{ij} + e_{ijk}
\]  

(1)

Where: \(Y_{ijk}\) = the response of any of the above variables to the \(k\)th data point of the \(i\)th level of frequency and the \(j\)th level of variability; \(A_i\) = the effect of the \(i\)th level of frequency; \(B_j\) = the effect of the \(j\)th level of variability; \(Ab_{ij}\) = the interaction effect of the \(i, j\) treatment combination and \(E_{ijk}\) = the error for the \(k\)th data point of the \(i, j\) treatment combination. In this model, \(i\) contained three levels: weekly, monthly and seasonally; \(j\) contained three levels: hot, cold and variable; \(k\) contained 52 values. Data were summed within week. Main effects and interaction terms were generated to visually display the effects of the factors on each response variable. When interactions were significant, the main effects error term could not be used and therefore,
interaction terms were examined to ascertain the nature of the effect. For each factor that was found to be significant, Tukey’s 95% confidence intervals were used to differentiate between the levels of that factor. Using the main effect and interaction plots, in combination with the results of the Tukey comparisons, the optimal level of diet formulation frequency was determined for each level of climate variability. Significant effects were assumed to occur at a $p < 0.05$, trends were defined at $p < 0.10$.

Economic Analysis

To analyze the economics of formulating diets more frequently, costs were assumed to be limited to feed and labor; and milk income (by volume) was the only income source included in the analysis. The cost associated with labor was calculated as per equation 2.

$$C_{L,ij} = \sum_t (n_{ref} \cdot t_{ref} \cdot C_{hl})$$

Where $C_{L,ij} =$ the cost of the labor required to reformulate the diet in the $i, j$ treatment combination; $n_{ref} =$ the number of times the diet was reformulated; $t_{ref} =$ the time to reformulate a diet (assumed to be 1h); and $C_{hl} =$ the cost of hourly labor. Mixing was not included as a labor cost as it was assumed to occur daily regardless of diet reformulation frequency or weather patterns. Feed cost and returns over variable costs were calculated daily. Within each level of climate variability, the returns generated by seasonal and monthly formulation were compared to weekly formulation.

Sensitivity Analysis of Economic Simulation

A sensitivity analysis was performed on the above economic simulation to test the range over which the findings held. The parameters used in this analysis were the cost of labor, the price of
corn and the price of milk. The economic simulation described above was conducted using national averages from the year 2011 as base values (USDA/ERS, 2012). The base labor cost was $40.00/h, the base corn price was $0.32/kg and the base milk price was $0.44/kg. In the sensitivity analysis, the economic simulation was repeated twice, once using a labor cost that was 50% of the base and again using a labor cost that was 200% of the base. This process was followed again for the corn prices, simulating once with a corn price 75% of the base price and once with a corn price at 150% of the base. Finally, the process was repeated for milk prices. In the case of milk prices, the simulation was conducted once with a price 75% of the base and once with a price of 150% of the base. Ranges were selected to represent realistic fluctuations in corn price, labor costs and milk revenues.

RESULTS AND DISCUSSION

Dry Matter Intake

Time-series data for dry matter intake are included in Figure 3. These data appear less variable than the data for milk yield and ME balance shown in Figures 4 and 5 because intake was controlled as part of the formulation frequency treatment. Climate variability (p<0.01) significantly impacted DMI but diet formulation frequency (p = 0.51) and the interaction effect did not confer significant effects (p=0.14; Table 5). Figure 3 shows that DMI followed similar trends across diet formulation frequency levels; however, the weekly treatment allowed cattle to consume more feed during times of weather-variability induced negative energy balance. Additionally, there was no significant DMI difference between hot and cold climates (P>0.05; Table 6). The consistency of DMI in these climates is shown in Figure 3. Although the lack of a difference appears inconsistent with heat stress literature, weather conditions in this study were
less severe than those typically associated with heat stress. The lack of difference between hot and cold climates could indicate that cattle were not significantly heat-stressed in the hot climate; however, it is more likely that the number of days the cow experienced heat stress may have been insufficient to substantially affect average yearly DMI. West (2003) noted that in the southeastern U.S. heat stress conditions exist for between 4 and 6 months of the year (120 d/yr to 182 d/yr). In this study heat stress conditions occurred for 39 d/yr to 53 d/yr, depending on the treatment. The less frequent incidence of heat stress modeled in this study may explain why many performance responses predicted were less severe than those reported from studies measuring responses of cattle performance in heat-stressed conditions.

Unpredictable climates were the focus of this study because climate predictability is expected to decrease over the next several decades (IPCC, 2007) and erratic climates will negatively impact livestock production (McKibben, 2007). In this study, the treatment representing a variable climate resulted in a higher DMI than either hot (p=0.001; Table 6) and or cold climates (p=0.003; Table 6). In the variable climate treatment, cows were simulated to increase daily DMI by 0.28 kg over DMI simulated in the cold climate, and 0.30 kg over DMI simulated in the hot climate. Increased DMI in the variable climate may be due to increased days under the thermoneutral zone. Number of days below the thermoneutral zone was greater in the variable climate treatment (102 d) than in the cold (100 d) or hot (90 d) climate treatments. Cold temperatures cause short-term increases in DMI (Johnson, 1986) and therefore the greater number of days under the thermoneutral zone may have contributed to the increased DMI in the variable scenario. Additionally, Beede and Collier (1986) noted that DMI decreases in lactating dairy cattle were not observed until temperatures exceed 25°C. The variable climate treatment only included two days where mean temperature was over 25°C, therefore DMI reductions from
heat stress would not have been observed in this scenario. This increase in DMI did not confer a statistically significant improvement in milk yield. For a moderate-sized dairy (300 cows), this increase in climate variability would result in a net herd-wide increase in DMI of between 31.4 and 33.4 metric tonnes per year. Previous studies have demonstrated that reformulating diets during periods of negative energy balance can improve DMI. West et al. (1999) showed that reduced DMI due to heat stress could be mitigated by increasing dietary NDF concentrations. On average, reformulating the diet on a weekly basis required adding/removing 0.1 kg of corn grain/hd/d. When the diet was reformulated on a monthly basis, reformulation required adding/removing 0.2 kg of corn grain/hd/d. To achieve this level of precision, the cumulative error in the feeding system must be less than 1% by weight. Maximum DMI change was also recorded. In the reformulation with the largest change in intake, DMI was adjusted by 0.83 kg. In reformulation with the greatest DMI change, feeding system margin of error needed to be less than 4%. Although still requiring extreme accuracy from the feeding system, this margin of error is more achievable. The implications of this required precision level are discussed in the Implications and Feasibility section of this study.

Milk Yield

Time-series data of daily MY are included in Figure 4. Diet formulation frequency had a significant influence on MY (p=0.05) but neither climate variability (p=0.24) nor the frequency by variability interaction (p=0.21) conferred statistically significant differences to MY (Table 5). The hot, cold and variable climate resulted in yearly average MY of 36.2 kg/d, 36.2 kg/d and 36.0 kg/d, respectively (Table 5). It is possible that climate variability did not influence milk yield because weather in the years selected was insufficiently severe to effect substantial climate
stress. When means were compared across all levels of climate variability, seasonal diet formulation generated lower MY (35.9 kg) than weekly (36.5 kg; p=0.02) and monthly formulation (36.2 kg; p=0.03) but monthly and weekly diet formulations were not significantly different (P > 0.05; Table 6). Figure 4 shows that as diet formulation frequency moved from seasonal to weekly the variability in daily MY response decreased. Although the mean daily difference in MY was small (0.59 kg), formulating diets weekly rather than seasonally equated to a 182 kg MY increase per lactation. When monthly formulation was compared to seasonal formulation, a mean increase of 91.5 kg of milk per cow per lactation was predicted. For reference, when this average improvement in MY is expanded over the population of a moderately-sized US dairy farm (300 cows; USDA/APHIS, 2007), formulating diets more frequently could improve MY between 27,500 (monthly formulation) and 54,900 (weekly formulation) kg per year. Variability in response across lactation, farm size and productivity level will cause actual animal response to vary depending on the production characteristics of the population of interest. USDA/APHIS (2007) data indicate that milk production improves with herd size. Relationships between milk yield and herd size were not accounted for in this study; however, the target milk production selected was based on an average cow’s lactation and therefore should be representative of an average-sized herd. Milk production per cow modeled in this study was similar to average production on a 300 hd operation in the Northeast U.S. as reported by Lidback and Laughton (2012).

Few studies exist that assess the effect of diet formulation frequency on MY, therefore alternative data were sought to ensure the feasibility of the changes predicted by the current study. Reductions in MY due to heat-stressed periods in this study are lower than those presented by other studies reporting the impact of heat stress on milk production. Hahn and Osburn (1969)
reported that in geographic locations typically associated with heat stress, the decline in milk production associated with the period from June 1 through September 30 was 1.5 to 2.2 kg/d over the 4 month period. Klinedinst et al. (1993) modeled the impact of heat stress on milk production between May 1 and September 30. Over the 5 month period, MY was predicted to reduce by between 2.0 – 5.9 kg/d depending on heat stress severity. Hahn and Nienaber (1976) reported expected milk production losses of 95 to 268 kg per year, depending on weather severity. By comparison, West (2003) noted that actual MY losses were between 4.6 and 7.1 kg in the Southern USA - much higher than losses predicted in most previous studies. Within the current study, when seasonal formulation MY was compared to inputted MY (36.5 kg/hd/d) calculated losses during the summer period (May 1 to September 30) ranged from 0.11 to 0.37 kg/d and averaged 0.26 kg/d. The discrepancy between the magnitudes of the reduction in MY over the summer period between the current study and other published studies may be attributed to differences in study location. Figure 4 shows the decrease in MY during the summer months compared to the remainder of the year. When using a thermoneutral zone upper bound of 20°C (Johnson, 1986), the hot climate was only above the thermoneutral zone for 53 d. Most studies of heat stress in dairy cattle use herds based in the southeastern United States because of the severity of the heat and humidity (West, 2003), and days above thermoneutral in this region are generally much greater than observed in this study. As such, although heat-stress induced MY decline was predicted on days with severe weather, when summed over a full year, the impacts of this stress are much lower than seen in most studies occurring in locations where the number of heat-stressed days is substantially greater.

The reductions in MY seen during periods of cold stress are less than those observed during heat stress because dairy cattle are more tolerant of cold stress than they are of heat stress (Blaxter,
In a study comparing average to cold temperatures, Broucek et al. (1991) reported that mean milk production decreased by 1.16 kg when T decreased to -10 °C, and by 2.21 kg when T decreased to -17 °C. Changes in MY due to cold stress predicted by our study were also lower than those identified in previous studies. Under seasonal formulation, analysis of the raw data indicated that, on average, when T decreased between -9 °C and -11 °C, MY did not change from the inputted value (36.5 kg/hd/d). Conversely, when T decreased between -16 °C and -17 °C MY decreased by 0.2 to 1.5 kg/hd/d compared to the inputted value (36.5 kg/hd/d). Figure 4 shows that cold stressed periods resulted in specific days with substantial decreases in performance rather than a general time period with decreased performance as is observed with heat stress during the summer. Measured decreased in MY due to cold stress could have been because Broucek et al. (1991) measured responses of heifers to decreased temperature while cows were modeled in this study. The additional energy requirement for growth of heifers may have amplified the impact of cold stress on milk yield.

The effects of precision nutrition management on milk production have been estimated by several researchers. Ceresaletti et al. (2004) reported MY improvements from -0.4 kg/d to +1.8 kg/d when precision nutrition management was implemented. Within the current study, modeled improvements in MY (0.59 kg/d) conferred by balancing diets weekly or monthly rather than seasonally were within the range previously reported. This improvement held across all levels of climate variability and therefore indicate that precision feeding by more frequent diet formulation could present a reasonable mitigation strategy to preserve MY across a wide climatic range.
Metabolizable Energy Balance

Diet formulation frequency (p=0.045) and the effect of climate variability (p<0.01) significantly impacted ME balance. There was a tendency for interaction between formulation frequency and climate variability (P=0.082; Table 5). The effects of weather variability and formulation frequency on ME balance are clearly demonstrated in Figure 5. The highly variable climate had substantially more variability in ME balance than the hot and cold climates. As formulation frequency was increased from seasonal to weekly formulation, the magnitude of the variability in ME balance response decreased. Seasonal diet formulation resulted in an ME balance of 0.16 Mcal/d lower than weekly diet formulation (p=0.038; Table 6). Cold (p<0.01) and hot climates (p=0.03) resulted in ME balances of 0.26 Mcal/d and 0.09 Mcal/d lower than the variable climate, but no significant difference was detected between hot and cold climates (P>0.05; Table 6). No significant difference between hot and cold climates was expected because mechanisms to maintain body temperature within the thermoneutral zone require energy (Beede and Collier, 1986). During times of heat stress, the biology of a dairy cow relies on energy-intensive heat abatement strategies such as panting and sweating (West, 2003). Similarly, during cold stress, shivering thermogenesis also relies on the utilization of energy (Young, 1983). Hot and cold climates resulted in more negative ME balances than the variable climate. This was surprising because the fluctuations in ME balance caused by both extreme hot and extreme cold weather in the variable climate were expected to compound to a more negative ME balance. This result may be related to the use of average weather data to formulate diets for seasonal and monthly treatments. Weather fluctuations in the variable climate may have caused average weather data used to generate diets to skew toward either the extreme cold (during winter) or the extreme hot (during summer). The amount of dietary ME required to compensate for ME losses due to hotter
or colder weather would increase. On days with moderate weather, the diet balanced would have an excess of ME meaning that cows would have been in a positive energy balance more frequently. An alternative explanation of the ME balance dynamics could be related to the days outside the thermoneutral zone. The variable climate resulted in a total of 151 d outside the thermoneutral zone while the hot and cold climates were outside the zone for 143 and 139 d respectively. The more negative ME balance seen in the variable climate was likely due to the difference in total days outside the thermoneutral zone.

The differences in ME balance reported in Table 5 appear to require precision that is not only unobtainable on-farm but outside the reliable range of prediction for most ME balance equations. Margins of error around ME requirement per kg of metabolic body weight have been estimated at between 7% (Strathe et al., 2011) and 11% (Kebreab et al., 2003) while the values in Table 5 vary by less than 1%. The values in Table 5 are yearly-average ME balances. Across an entire year of data, most individual days did not return ME balances that were different from 0.00 Mcal/d, and as such these yearly average data are not representative of the actual daily ME dynamics that drove the results predicted in this study. For comparison, on days when ME balance was negative, actual reductions in daily ME balance ranged from -0.2 Mcal/d to -25.7 Mcal/d. The actual daily change in ME balance is shown in Figure 5. When converted to a percentage difference in energy requirement, these ME balances equate to a range of 0.3% to 45.3% per kg of metabolic body weight. Given the above error estimates, the lower end of the range in ME balance is not reliably different from 0.00 Mcal/d; however, the majority of the range extends well past the 7% to 11% error bound. Although the ME balances reported in this study may appear to rely on unrealistic precision, many of the actual daily differences represent changes that are substantial and should be measurable on-farm.
Economic Analysis

Economic analysis revealed a substantial decrease in returns over feed and labor costs when diets were formulated less frequently (Figure 6). On average, producers were predicted to lose $68.65/hd/yr when diets were formulated seasonally rather than weekly and $39.38/hd/yr when formulating seasonally rather than monthly (Figure 6). Nearly 60% of the losses associated with formulating seasonally rather than weekly could be recouped by formulating monthly. These changes in returns over feed and labor costs are within the range identified by previous studies modeling the economics of precision nutritional management (Ghebremichael et al., 2007). On average, the cold climate had the greatest loss from formulating less frequently, followed by the hot climate. The variable climate had the lowest loss from formulating less frequently. These dynamics are directly caused by the differences in MY and DMI in the different scenarios. Milk price was the most sensitive parameter within the economic analysis. Increasing corn grain to 150% of the average price decreased returns over feed and labor costs by $35.10/hd/yr. Decreasing corn grain price to 75% of the average price increased returns over feed and labor costs by $16.43/hd/yr. By comparison, returns over feed and labor costs decreased $55.75/hd/yr or increased $26.75/hd/yr when milk price varied between 75% and 150% of the base price. Similarly, decreasing labor costs to 50% of the base scenario increased returns over feed and labor costs by $6.66/hd/yr while increasing labor costs to 200% of the base scenario decreased returns over feed and labor costs by $3.32/hd/yr. The range of outputs calculated in this sensitivity analysis are shown in Figure 7. Feed and milk prices had the greatest influence on profitability. Feed cost is generally acknowledged as the single largest variable cost on animal operations and therefore this result is not surprising. Furthermore, milk production was the only
source of revenue tracked in this assessment and therefore, it would be expected that milk price would have a substantial influence on returns over feed and labor costs.

**Implications and Feasibility**

A previous study assessing various precision management scenarios identified changes in returns over feed and labor costs of between $12/hd/yr and $186/hd/yr associated with implementing precision dairy management (Ghebremichael et al., 2007). On a moderate-sized dairy (300 cows), these increases equated to a $3,600 to $55,800 per year improvement in returns. Within the current study, changes in returns over feed and labor costs of between $39.38/hd/yr and $68.65/hd/yr were revealed by formulating diets more frequently. When scaled up to a moderate-sized dairy (300 cows), the calculated predicted increase in returns over feed and labor costs ($14,400 to $25,000 per year) was slightly lower than the range outlined by Ghebremichael et al. (2007). This may be due to differences in the type of precision management tested, Ghebremichael et al. (2007) assessed crop management practices in addition to precision diet formulation and delivery mechanisms while this study focused only on precision diet formulation. Additionally, economic metrics are highly dependent on specific data (location, feedstuffs used, year, etc.) and therefore, differences in returns over feed and labor costs outlined in this study compared to other studies of precision feeding are most likely explained by study-specific differences rather than variability in the effectiveness of management. The increase in returns over feed and labor costs predicted in this study represents a substantial improvement for a moderate-sized (300 cow) dairy.

Before advocating precision diet reformulation as a viable method to mitigate productivity changes conferred by climate stress, the ability to achieve the predicted profit increases on-farm
should be investigated. Mean DMI was 20.6 kg and on average a reformulation changed DMI by
0.2 kg. Minimum change in DMI during a reformulation event was 0.006 kg while maximum
DMI change was 0.86 kg. To feed a ration differing by 0.2 kg per cow requires a scale sensitive
enough to detect a difference of 60 kg in a feed batch totaling 6,180 kg. The cumulative margin
of error required of the feeding system (feed analysis, diet formulation, weighing, mixing,
transportation, feeding and consumption) to use this level of precision feeding must be much less
than 1% by weight. Before frequently reformulating diets can be advocated as an economically-
sound management practice, further investigation should be conducted into the feeding system
margin of error.

Although estimates of imprecision in weighing mixing, transport and feeding are difficult to
identify, estimates of feed analysis, diet formulation and consumption variability are available. In
an analysis of crude protein and fat content of whole cottonseed analyzed by Purina Mills from
1988 through 1996, the mean coefficient of variation around protein content (11.9%) and fat
content (16.9%) were sufficient to significantly alter diet composition (Kertz, 1998). The most
variable feed component is arguably dry matter content. Weiss et al. (2012) reported that the
coefficient of variation of silage dry matter content ranged from 7.8% to 14.7%. Coefficient of
variation of hay dry matter content was 2.8% and concentrate dry matter content coefficient of
variation ranged from 1% to 7.4%. The results in this study depend on accuracy of feed analysis
and as such, precision diet formulation would require frequent feed analysis. As previously
addressed, the variability around estimates of ME requirements range from 7% (Strathe et al.,
2011) to 11% (Kebreab et al., 2003). In an initial validation, the energy requirements predicted
by CNCPS had a bias of only 4% (Fox et al., 1992). Although these error ranges are better than
previous energy prediction systems, improved accuracy in energy prediction would improve
results seen from formulating diets more frequently. Dry matter intake is also known to vary considerably. When CNCPS DMI predictions were compared to observed DMI for lactating Holstein cows, the standard error of intake was 1.7 kg when mean intake was approximately 20 kg/d, an 8% error (Fox et al., 1992). Together, estimates of individual error in feed analysis, energy requirement and dry matter intake prediction range from 4% to 17%. Implementation of more comprehensive precision nutrition management by controlling these sources of variation and improving precision of feed mixing, transportation and delivery systems will improve results seen from formulating diets more frequently. The results of this study indicate that formulating diets more frequently can theoretically control for weather variability to help improve cow performance and profitability. Improved estimates of feedstuff composition, prediction equations for animal requirements and mixing and delivery machinery are necessary for these theoretical results to be realistically achievable.

**CONCLUSIONS**

Formulating diets more frequently across a range of climates allowed the energy requirements of dairy cattle to be met more precisely, thereby increasing milk production efficiency. Economic analysis indicated that formulating diets more frequently generally increased profitability as any increase in feed cost was mitigated by an increase in profitability through improved MY. The margins of error of average feeding systems used in the industry are unknown; however, considering the aggregated opportunity for error during weighing, mixing, transport, storage and feeding, the error is expected to appreciate. In order to fully reap the potential benefits of precision diet formulation, more accurate weighing and delivery machinery in dairy feeding systems should be adopted as the overall margin of error required for the entire feeding system is
less than 1%. Given the limitations on the typical feeding system used in the industry today and the results of this study, monthly diet formulation appears to be the best compromise to increase efficiency within the achievable bounds of today’s dairy farm infrastructure.
LITERATURE CITED


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Lidback, J., and C. Laughton. 2012. 2011 Northeast Dairy Farm Summary. Farm Credit East 


Table 1. Cow and housing inputs used in diet formulation

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Age (m)</td>
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</tr>
<tr>
<td>Days Pregnant (d)</td>
<td>65</td>
</tr>
<tr>
<td>Days Since Calving (d)</td>
<td>188</td>
</tr>
<tr>
<td>Calving Interval (m)</td>
<td>14.00</td>
</tr>
<tr>
<td>Calf Birth Weight (kg)</td>
<td>44</td>
</tr>
<tr>
<td>Age at 1st Calving (m)</td>
<td>26.10</td>
</tr>
<tr>
<td>Milk Production (kg/d)</td>
<td>36.50</td>
</tr>
<tr>
<td>Milk Fat (%)</td>
<td>3.80</td>
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<tr>
<td>Milk True Protein (%)</td>
<td>3.10</td>
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<tr>
<td>Milk Lactose (%)</td>
<td>4.78</td>
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<td>BCS</td>
<td>3.00</td>
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<td>Housing System</td>
<td>Freestall</td>
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<tr>
<td>Hours Standing</td>
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<tr>
<td>Number of Position Changes</td>
<td>9</td>
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<tr>
<td>Flat distance walked (m)</td>
<td>300</td>
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<td>Sloped distance walked (m)</td>
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Table 2. Dietary ingredient composition, energy content and protein content for each treatment scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Corn (kg)</th>
<th>Dried Distillers Grains (kg)</th>
<th>Soybean Meal (kg)</th>
<th>Corn Silage (kg)</th>
<th>Grass Hay (kg)</th>
<th>Alfalfa Hay (kg)</th>
<th>ME (Mcal/d)</th>
<th>MP (g/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekly, Hot</td>
<td>8.47</td>
<td>1.82</td>
<td>1.80</td>
<td>3.80</td>
<td>2.70</td>
<td>1.80</td>
<td>56.5</td>
<td>2452</td>
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<tr>
<td>Weekly, Cold</td>
<td>8.50</td>
<td>1.82</td>
<td>1.80</td>
<td>3.80</td>
<td>2.70</td>
<td>1.80</td>
<td>56.6</td>
<td>2455</td>
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<tr>
<td>Weekly, Variable</td>
<td>8.49</td>
<td>1.82</td>
<td>1.80</td>
<td>3.80</td>
<td>2.70</td>
<td>1.80</td>
<td>56.6</td>
<td>2454</td>
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<tr>
<td>Monthly, Hot</td>
<td>8.41</td>
<td>1.82</td>
<td>1.80</td>
<td>3.80</td>
<td>2.70</td>
<td>1.80</td>
<td>56.3</td>
<td>2446</td>
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<tr>
<td>Monthly, Cold</td>
<td>8.87</td>
<td>1.82</td>
<td>1.80</td>
<td>3.80</td>
<td>2.70</td>
<td>1.80</td>
<td>57.8</td>
<td>2489</td>
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<tr>
<td>Monthly, Variable</td>
<td>8.44</td>
<td>1.82</td>
<td>1.80</td>
<td>3.80</td>
<td>2.70</td>
<td>1.80</td>
<td>56.4</td>
<td>2449</td>
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<td>Seasonally, Hot</td>
<td>8.42</td>
<td>1.82</td>
<td>1.80</td>
<td>3.80</td>
<td>2.70</td>
<td>1.80</td>
<td>56.3</td>
<td>2447</td>
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<tr>
<td>Seasonally, Cold</td>
<td>8.81</td>
<td>1.82</td>
<td>1.80</td>
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<td>2.70</td>
<td>1.80</td>
<td>57.6</td>
<td>2484</td>
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<tr>
<td>Seasonally, Variable</td>
<td>8.42</td>
<td>1.82</td>
<td>1.80</td>
<td>3.80</td>
<td>2.70</td>
<td>1.80</td>
<td>56.3</td>
<td>2447</td>
</tr>
</tbody>
</table>

Treatment scenarios included two identifiers, one indicating the frequency treatment used (weekly, monthly or seasonally) and one indicating the weather treatment (hot, cold or variable).
Table 3. Dry matter content and nutrient composition of feedstuffs used in diet formulation from AMTS Feedbank (AMTS, 2006)

<table>
<thead>
<tr>
<th>Feedstuff</th>
<th>DM (%)</th>
<th>CP (%)</th>
<th>Sugar (%)</th>
<th>Starch (%)</th>
<th>ADF (%)</th>
<th>NDF (%)</th>
<th>EE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>86</td>
<td>9.0</td>
<td>1.56</td>
<td>75.50</td>
<td>3.4</td>
<td>23</td>
<td>3.67</td>
</tr>
<tr>
<td>Dried Distillers Grains</td>
<td>91</td>
<td>29.7</td>
<td>11.61</td>
<td>30.18</td>
<td>10.0</td>
<td>9</td>
<td>9.00</td>
</tr>
<tr>
<td>Soybean Meal</td>
<td>90</td>
<td>51.5</td>
<td>10.88</td>
<td>2.18</td>
<td>6.0</td>
<td>10</td>
<td>2.80</td>
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<tr>
<td>Corn Silage</td>
<td>35</td>
<td>9.2</td>
<td>0.80</td>
<td>30.87</td>
<td>28.0</td>
<td>45</td>
<td>3.19</td>
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<tr>
<td>Grass Hay</td>
<td>89</td>
<td>10.0</td>
<td>5.10</td>
<td>2.55</td>
<td>50.0</td>
<td>67</td>
<td>3.00</td>
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<tr>
<td>Alfalfa Hay</td>
<td>90</td>
<td>20.0</td>
<td>9.66</td>
<td>1.61</td>
<td>32.0</td>
<td>40</td>
<td>3.00</td>
</tr>
</tbody>
</table>
Table 4. Seasonal temperature (T), wind speed (WS) and relative humidity (RH) for each weather scenario from National Ocean and Atmospheric Association Database for Buffalo, NY (NOAA, 2011)

<table>
<thead>
<tr>
<th></th>
<th>Hot¹</th>
<th>Cold²</th>
<th>Variable³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Winter Temperature (°C)</td>
<td>10.00</td>
<td>13.89</td>
<td>12.22</td>
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<tr>
<td>Mean Winter Temperature (°C)</td>
<td>-1.67</td>
<td>-2.20</td>
<td>-3.07</td>
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<td>Minimum Winter Temperature (°C)</td>
<td>-15.00</td>
<td>-19.84</td>
<td>-16.67</td>
</tr>
<tr>
<td>Maximum Summer Temperature (°C)</td>
<td>28.33</td>
<td>22.22</td>
<td>28.89</td>
</tr>
<tr>
<td>Mean Summer Temperature (°C)</td>
<td>20.88</td>
<td>16.06</td>
<td>21.94</td>
</tr>
<tr>
<td>Minimum Summer Temperature (°C)</td>
<td>11.11</td>
<td>6.67</td>
<td>11.67</td>
</tr>
<tr>
<td>Maximum Winter Relative Humidity (%)</td>
<td>96.55</td>
<td>98.04</td>
<td>103.85</td>
</tr>
<tr>
<td>Mean Winter Relative Humidity (%)</td>
<td>74.28</td>
<td>66.54</td>
<td>72.64</td>
</tr>
<tr>
<td>Minimum Winter Relative Humidity (%)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Maximum Summer Relative Humidity (%)</td>
<td>96.36</td>
<td>92.49</td>
<td>96.92</td>
</tr>
<tr>
<td>Mean Summer Relative Humidity (%)</td>
<td>84.03</td>
<td>79.30</td>
<td>83.86</td>
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<tr>
<td>Minimum Summer Relative Humidity (%)</td>
<td>71.79</td>
<td>63.77</td>
<td>61.21</td>
</tr>
<tr>
<td>Maximum Winter Wind Speed (km/h)</td>
<td>33.87</td>
<td>37.1</td>
<td>32.26</td>
</tr>
<tr>
<td>Mean Winter Wind Speed (km/h)</td>
<td>16.13</td>
<td>20.13</td>
<td>15.23</td>
</tr>
<tr>
<td>Minimum Winter Wind Speed (km/h)</td>
<td>5.16</td>
<td>4.52</td>
<td>6.13</td>
</tr>
<tr>
<td>Maximum Summer Wind Speed (km/h)</td>
<td>29.19</td>
<td>26.45</td>
<td>29.03</td>
</tr>
<tr>
<td>Mean Summer Wind Speed (km/h)</td>
<td>13.77</td>
<td>13.78</td>
<td>13.34</td>
</tr>
<tr>
<td>Minimum Summer Wind Speed (km/h)</td>
<td>4.68</td>
<td>6.61</td>
<td>4.84</td>
</tr>
</tbody>
</table>

¹The “Hot” scenario used weather data from 2001, the year with the greatest score for high temperature and relative humidity

²The “Cold” scenario used weather data from 2008, the year with the greatest score for low temperature and high wind

³The “Variable” scenario used weather data from 2004, the year with the greatest variance in weather parameters
Table 5. Mean response of Milk Yield, ME Balance and Dry Matter Intake Under Weekly, Monthly or Seasonal diet formulation in Hot, Variable and Cold Climates

<table>
<thead>
<tr>
<th>Response Variable</th>
<th>Dry Matter Intake (kg/d)</th>
<th>Milk Yield (kg/d)</th>
<th>ME Balance (Mcal/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weekly</td>
<td>Monthly</td>
<td>Seasonal</td>
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<tr>
<td>Hot</td>
<td>20.56¹</td>
<td>20.57</td>
<td>21.03</td>
</tr>
<tr>
<td></td>
<td>20.57</td>
<td>20.61</td>
<td>20.64</td>
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<tr>
<td>Variable</td>
<td>20.58</td>
<td>20.61</td>
<td>20.88</td>
</tr>
<tr>
<td>Cold</td>
<td>20.58</td>
<td>20.61</td>
<td>20.63</td>
</tr>
<tr>
<td>Mean</td>
<td>20.73</td>
<td>20.70</td>
<td>20.63</td>
</tr>
</tbody>
</table>

¹Mean values for each treatment combination are listed first. Standard error of dry matter intake, milk yield and ME balance responses were 0.089, 0.207 and 0.197, respectively.

²The frequency term represents the p-value associated with the formulation frequency (weekly, monthly, seasonally) term in the ANOVA.

³The variability term represents the p-value associated with the weather scenario (hot, cold, variable) term in the ANOVA.

⁴The interaction term represents the p-value associated with the frequency-variability interaction in the ANOVA.
Table 6. Significance Values (p) of Between-Level Differences for Frequency and Variability Impacts on Milk Yield, Dry Matter Intake and Metabolizable Energy Balance

<table>
<thead>
<tr>
<th>Level</th>
<th>Frequency</th>
<th>Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Milk Yield</td>
<td>ME Balance</td>
</tr>
<tr>
<td></td>
<td>Level</td>
<td>Week</td>
</tr>
<tr>
<td>Week</td>
<td>0.56</td>
<td>n/a</td>
</tr>
<tr>
<td>Month</td>
<td>0.56</td>
<td>n/a</td>
</tr>
<tr>
<td>Season</td>
<td>0.02</td>
<td>0.03</td>
</tr>
</tbody>
</table>

1Levels in the Frequency treatment (Weekly, Monthly and Seasonal Diet formulation) are represented by Week, Month and Season, respectively.

2Levels in the Variability treatment (Hot Climate, Cold Climate and Variable Climate) are represented here by Hot, Cold and Var., respectively.
**Figure 1.** Percent deviation of yearly temperature, relative humidity and wind speed from between-year mean values for years between 1999 and 2010 for weather data from Buffalo, NY (NOAA, 2011)
Figure 2. Summed variance of temperature (T), relative humidity (RH) and wind speed (WS) for weather data from Buffalo, NY (NOAA, 2011) for years between 1999 and 2010.
Figure 3a. Dry matter intake with seasonal diet formulation in variable, hot and cold climates

Figure 3b. Dry matter intake with monthly diet formulation in variable, hot and cold climates

Figure 3c. Dry matter intake with weekly diet formulation in variable, hot and cold climates
Figure 4a. Milk yield with seasonal diet formulation in variable, hot and cold climates

Figure 4b. Milk yield with monthly diet formulation in variable, hot and cold climates

Figure 4c. Milk yield with daily diet formulation in variable, hot and cold climates
Figure 5a. Energy balance with seasonal diet formulation in variable, hot and cold climates

Figure 5b. Energy balance with monthly diet formulation in variable, hot and cold climates

Figure 5c. Energy balance with daily diet formulation in variable, hot and cold climates
Figure 6. Expected differences in returns over feed and labor costs for formulating diets monthly or seasonally compared to formulating diets weekly. Monthly refers to diets that were reformulated 30 days and Seasonally refers to diets that were reformulated every 90 days.
Figure 7. Sensitivity analysis of economic output under three levels of feed costs, labor costs and milk price. Feed costs and milk price were varied between 75% and 150% of their base value; labor costs were varied between 50% and 200% of the base. The High bar refers to the scenario where the value was adjusted to 150% or 200% of the base. The Low bar reflects the scenario where the value was adjusted to 50% or 75% of the base. The moderate bar shows the base scenario.