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

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ABSTRACT

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

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1. Introduction

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

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

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

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

2. Materials and methods

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

2.1. Model inputs

2.1.1. Cattle group specifications and nutrient requirements

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

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

2.1.2. Crop and pasture production parameters

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

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

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

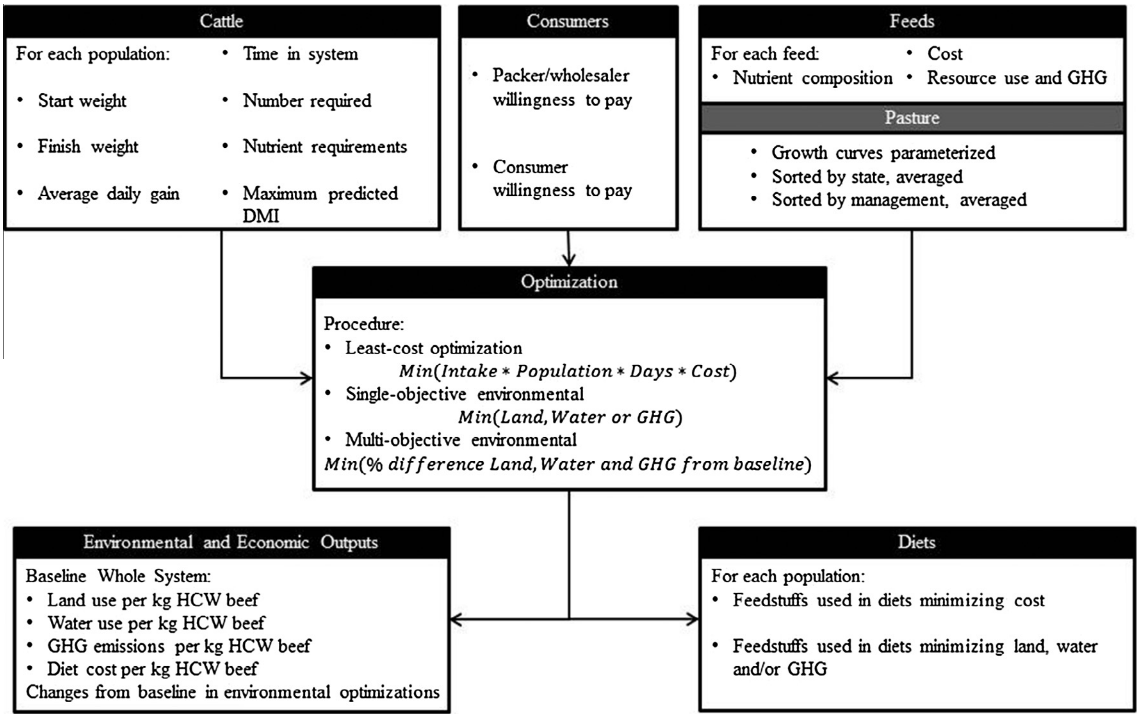

Fig. 1. Depiction of the inputs, outputs and optimization procedure. Model inputs are represented as flows into the Optimization box, outputs are flows out of the Optimization box.

Table 1
Equations for calculating animal populations and key weight parameters.

Eq#	Population name	Name	Equation
1	Heifer calves	P_{fhc1}	$((P_{mc4} + P_{mc5}) * K_{cc} * K_{lbc} + P_{mc3} * K_{ch} * K_{lbh}) * K_{hcb} * (1 - K_{cdl}) - P_{hc1}$
2	Steer calves	P_{sc1}	$((P_{mc4} + P_{mc5}) * K_{cc} * K_{lbc} + P_{mc3} * K_{ch} * K_{lbh}) * (1 - K_{hcb}) * (1 - K_{cdl})$
3	RH calves[a]	P_{hc1}	$K_{ccull} * I_{cows}$
4	Bull calves	P_{mb1}	$P_{bc4} * K_{bcull}$
5	Growing Steers	P_{sc2}	$P_{sc1} * (1 - K_{sdl})$
6	Growing Heifers	P_{fhc2}	$P_{fhc1} * (1 - K_{sdl})$
7	Dairy Steers	P_{ds1}	$(P_{sc2} + P_{fhc2}) * K_{ds}$
8	Dairy Heifers	P_{dh1}	$(P_{sc2} + P_{fhc2}) * K_{dh}$
9	Yearling Bulls	P_{mb2}	$K_{abmb} * (P_{mc3} + P_{mc4} + P_{mc5})/K_{abc}$
10	Adolescent Bulls	P_{mb3}	P_{bc2}
11	Young Bulls	P_{mb4}	$(1 - K_{abmb}) * (P_{mc3} + P_{mc4} + P_{mc5})/K_{mbc}$
12	Mature Bulls	P_{mb5}	$P_{mb4} - P_{mb4} * K_{bcull}$
13	Yearling RH[a]	P_{hc2}	$K_{ccull} * I_{cows}$
14	1st calf heifer	P_{mc3}	P_{hc2}
15	Young cow[b]	P_{mc4}	$I_{cows} * 0.5$
16	Mature cow[a,b]	P_{mc5}	$P_{mc4} - I_{cows} * K_{ccull}$
17	Average Daily Gain	ADG_p	$(FW_p - SW_p)/D_p$
18	Days	D_p	$(FW_p - SW_p)/ADG_p$
19	Finishing Weight	FW_p	$SW_p + D_p * ADG_p$
20	Beef outputted[c]	$Beef$	$I_{cows} * K_{ccull} * FW_{mc5} * 0.5 + P_{mb4} * K_{bcull} * FW_{mb5} * 0.5 + P_{dh1} * FW_{dh1} * 0.62 + P_{ds1} * FW_{ds1} * 0.62 + P_{sc2} * FW_{sc2} * 0.62 + P_{fhc2} * FW_{fhc2} * 0.62$

[a] I_{cows} is a user input to reflect the size of the cow herd in question. A 300 cow herd was used in this study.
[b] Cow populations were further subdivided based on stage of production (lactation, mid gestation, late gestation) for diet balancing.
[c] Dressing percentages of 50% for cull animals and 62% for young animals were used (USDA/ERS, 2012).

Table 2
Rate constants for calculating cattle population and weight parameters.

Name	Parameter	Value
Cow conception rate	K_{cc}	0.934
Cow live birth rate	K_{lbc}	0.968
Heifer conception rate	K_{ch}	0.893
Heifer live birth rate	K_{lbh}	0.935
Proportion of heifer calves born	K_{hcb}	0.500
Calf death loss	K_{cdl}	0.030
Cow culling rate	K_{ccull}	0.200
Bull culling rate	K_{bcull}	0.200
Stocker death loss	K_{sdl}	0.050
Proportion of dairy heifers in feedlot	K_{ds}	0.030
Proportion of dairy steers in feedlot	K_{dh}	0.136
Proportion of cows bred by adolescent bulls	K_{abmb}	0.300
Cows bred per adolescent bull	K_{abc}	16.3
Cows bred per mature bull	K_{mbc}	23.7

rotationally grazed (R-I), fertilized rotationally grazed (R-F) or irrigated and fertilized rotationally grazed (R-IF). Any curve with a RMSPE of greater than 10% was discarded. The yield and nutrient composition of the remaining growth curves were sorted by state, weighted by proportion of calves produced in that state and averaged to estimate national average pasture. This dataset was better suited to the analysis than currently available national average data because it contained data for several important management options to be included and examined. The yield, resource requirements and nutrient composition of pastures and other feeds available are included in Table 3.

2.1.3. Determining precipitation effects on pasture growth

In the scenarios investigating precipitation effects on opportunities to reduce environmental impact and resource use, 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). Baseline weather (temperature, wind speed, precipitation and solar radiation) data were sourced (National Solar Radiation Database, 2011; NCDC, 2012) and the growth curves available for each location were parameterized and aggregated as described previously. Monthly yield and quality information for the eight pasture management options were outputted for each location and precipitation scenario combination.

2.1.4. 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, 2012); 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, 2012).

Consumer WTP was the measure of social acceptability. White and Brady (2013) previously 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 was assumed that consumers value beef products as a bundle of their constituent attributes (Rosen, 1974). This approach allowed estimates for "healthy", "safe", "grass-fed", "organic", "hormone-free" or "high-quality" beef to be used to predict consumer WTP 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 were based on meat retail price and therefore were 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-into 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, 2012), 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

Table 3
Feedstuff and pasture chemical composition[a], costs[b] and environmental attributes.[c]

Feed[d]	CP (%)	ME (Mcal/kg DM)	Cost ($/kg DM)	Irrigation (L/kg DM)	CO_2-equivalents[e] (kg/ha)	Yield (kg DM/ha)[f]
Alfalfa (AH)	17.0	2.24	0.178	257.1	224.57	7556
Grass (GH)	10.0	1.65	0.129	119	103.95	4334
Corn Grain (CG)	8.5	3.39	0.206	77.3	228.98	9521
Soybean Meal (SBM)	49.0	3.04	0.552	74.5	117.77	2841
Molasses (MOL)	46.4	2.83	0.518	175.4	193.3	3701
Distillers Grains (DDG)	29.5	3.18	0.350	86.7	452.33	3564
Control Pasture (C)	14.5	2.57	0.131	0	11.8	3261
Irrigated Pasture (I)	14.5	2.57	0.111	37.7	23.5	4155
Fertilized Pasture (F)	14.5	2.57	0.115	0	161	4255
Irrig+Fert Pasture (I-F)	14.5	2.56	0.083	25.7	184.5	6111
Rotated Pasture (R)	14.1	2.68	0.146	0	11.8	3313
Rotated Irrig Pasture (R-I)	14.1	2.68	0.123	37.3	23.5	4209
Rotated Fert Pasture (R-F)	14.1	2.68	0.127	0	161	4309
Rot. Fert + Irrig Pasture (R-IF)	14.1	2.68	0.091	25.7	184.5	6168

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

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

[c] Environmental attributes including irrigation required, CO_2 production and yield were modeled within the pasture module or from USDA/ERS (2012) or USDA/NASS (2007).

[d] Feeds available during diet formulation.

[e] Carbon emissions included CO_2 from manufacture of cropping system inputs and tillage as well as N_2O from fertilizer application.

[f] Yield referred to yield at harvest and was either modeled in the pasture module or sourced from USDA/ERS (2012).

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, and subsequent changes in optimal management were assessed.

2.2. Model objectives

Modeled outputs included environmental impact metrics: i.e. 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, 2012). When pasture was used as a feed, land use was determined based on projected yields from the pasture module. 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_2O and CH_4. Included in the GHG emissions accounted by the model 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_2O emissions (IPCC, 2006); enteric CH_4 emissions (Ellis et al., 2007) and manure CH_4 (IPCC, 2006). Pasture C-sequestration was not included because the pasture model did not assess carbon flows. Additionally, reviews on this subject acknowledge that estimates are highly variable and further investigation of climate, plant, animal, soil and microbial factors is required to properly understand potential for C-sequestration (Derner and Schuman, 2007; Tanentzap and Coomes, 2012) as current research is often conflicting (McSherry and Ritchie, 2013) and C-sequestration is site specific. The equations governing the environmental outputs within the model are listed in Table 4.

2.3. Optimization framework and equations

The system described by Sections 2.1 and 2.2 was optimized using three different forms of an objective function (Table 5). The baseline scenario was least-cost management and used a single objective function (Eq. (29)). After the baseline environmental values, diet cost and diet composition were recorded for this least-cost baseline scenario, single-objective environmental optimizations were conducted. The objective of these scenarios was to minimize the percentage difference of an environmental impact metric from the baseline value (Eq. (30)). Finally, a multi-objective optimization was conducted balancing the percentage reductions of all environmental metrics (Eq. (31)). This function was modeled following Tozer and Stokes (2001). In all optimizations, the choice variable in the model was $DMI_{f,p}$. The constraints on the system are detailed in Table 5 and used to ensure adequate energy and protein availability as well as realistic dry matter intake and feedstuff usage. The upper and lower diet limits for Eq. (35) are listed in Table 6. Consumer WTP was used as a cost constraint in some scenarios. Model sensitivity to WTP was assessed by conducting two of each environmental optimization, one with the WTP constraint and one without.

2.4. 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. In all data-generating runs, model starting values were not specified; however, during the testing process the model was run with a variety of starting diet values to ensure that results were not sensitive to starting values. Sensitivity to the WTP metric was used to evaluate model robustness. The WTP estimate was varied between a 4.2% 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.

2.4.1. Determining precipitation-related effects on sustainability

A scenario was simulated to explore the impact of projected (U.S. Global Change Research Program, 2009) precipitation changes on pasture growth. 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 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 (Table 7). The

Table 4

Calculation of environmental and economic outputs from the optimization.

Eq#	Metric	Variable	Equation	Notes
21	Land use	PV_{land}	$(\sum_{f,p}(DMI_{f,p} * N_p * D_p)/Yield_f)/Beef$	Yield values from USDA/ERS (2012) or pasture module
22	Water use	PV_{water}	$(\sum_{f,p}(DMI_{f,p} * N_p * D_p * Irrig_f) + \sum_p(Drink_p * N_p * D_p))/Beef$	$Irrig_f$ values from USDA/NASS (2007) or pasture module
23	Drinking water	$Drink_p$	$(-3.85 + 0.507 * Temp + 1.494 * \sum_f(DMI_{f,p}) - 0.141 * k_r + 0.248 * DM_r + 0.014 * BW_p)$	Values for $DMI_{f,p}$, percent roughage (k_r) and roughage DM (DM_r) calculated based on outputted diet composition
24	GHG	PV_{GHG}	$(CO_2 + 25 * CH_4 + 299 * N_2O)/Beef$	Emission intensities from IPCC (2006)
25	Cropping CO_2	CO_2	$\sum_{f,p}(DMI_{f,p} * N_p * D_p * Crop_f)$	Emission factors from cropping were based on West and Marland (2001) and Nelson et al. (2009)
26	CH_4 emissions	CH_4	$\sum_p(2.94 + 0.059 * MEI_p + 1.44 * ADF_p - 4.16 * Lig_p) + \sum_p(VS_p * 0.015 * 0.67)$	Enteric methane emissions (Ellis et al., 2007) and manure methane emissions (IPCC, 2006) are calculated Values assume volatile solids (VS_p) are based on digestibility and cattle are on pasture or in a drylot system
27	N_2O emissions	N_2O	$\sum_p(\sum_f(DMI_{f,p} * CP_f) * 0.96 * 6.25 * EF_3 * 1.571) + \sum_p(\sum_f(DMI_{f,p} * CP_f) * 0.96 * 6.25 * Frac_{gas} * EF_4 * 1.571) + \sum_p(\sum_f(DMI_{f,p} * CP_f) * 0.96 * 6.25 * Frac_{leach} * EF_5 * 1.571)$	Direct, leached and volatilized N_2O emissions were calculated assuming a 96% N excretion rate (IPCC, 2006) and emission factors for pastured or drylot manure management systems (IPCC, 2006)
28	Feed costs	PV_{cost}	$(\sum_p(D_p * N_p * \sum_f(DMI_{f,p} * Cst_f)))/Beef$	Costs of feeds (Cst_f) are from USDA/ERS (2012) or pasture module

Table 5

Objective statements and constraint functions for the optimization.

Eq#	Equation	Notes
29	$Minimize(Cost) = PV_{cost}$	Objective for baseline scenario
30	$Minimize(Out_e) = (PV_e - BV_e)/BV_e$	Environmental metrics (*e*; land use, water use and GHG) are minimized as a percentage difference of their value in the baseline least-cost scenario (BV_e)
31	$Minimize(Obj)$: $Obj = (PV_{h2o} - BV_{h2o})/BV_{h2o}$ $Obj = (PV_{land} - BV_{land})/BV_{land}$ $Obj = (PV_{ghg} - BV_{ghg})/BV_{ghg}$	Multi-objective optimization objective function, structured following Tozer and Stokes (2001), based on the percentage difference in present value (PV_e) and baseline value (BV_e) of environmental metrics
32	$\sum_f (DMI_{f,p} * ME_f) \geqslant rME_p$	Metabolizable energy requirements (rME_p) are inputs to the model calculated based on NRC (2000)
33	$\sum_f (DMI_{f,p} * MP_f) \geqslant rMP_p$	Metabolizable protein requirements (rMP_p) are inputs to the model calculated based on NRC (2000)
34	$\sum_f DMI_{f,p} \leqslant DMIx_p$	Maximum predicted dry matter intake ($DMIx_p$) are inputs to the model calculated based on NRC (2000)
35	$Low_{f,p} \leqslant \frac{DMI_{f,p}}{\sum_f DMI_{f,p}} \leqslant Up_{f,p}$	Intake of particular animal groups was constrained to ensure practical diets. Constraints ($UP_{f,p}$ and $LOW_{f,p}$) listed in Table 6
36	$BV_{cost} + WTP \geqslant PV_{cost}$	Diet cost increases over baseline in environmental scenarios were constrained to less than consumers WTP

Table 6

Population-specific limits on forage, pasture and other specific feeds.

Constraint[a]	Cows	Bulls	Replacements	Stocker	Feedlot
Forage upper	100%	100%	100%	100%	15%
Forage lower	0%	0%	0%	0%	5%
Pasture upper	100%	100%	100%	100%	0%
Pasture lower	90%	90%	90%	85%	0%
Molasses upper	0.14 g/d	0.14 g/d	0.14 g/d	0.14 g/d	0 g/d
CG upper	0%	0%	0%	0%	95%
SBM upper	0%	0%	0%	0%	40%
DDG upper	0%	0%	0%	0%	40%

[a] 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).

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.

3. Results and discussion

3.1. Least-cost diet optimization outputs and comparison to measured estimates

Diets, feed costs and baseline environmental impacts outputted by the model were compared with previous studies estimating these parameters to ensure realistic optima were calculated. Outputted diets were not sensitive to feed starting values. The optimal diets to minimize cost in the least-cost baseline scenario suggested that cow–calf and stocker animals graze C-IF and R-IF pasture. Feedlot diets consisted primarily of corn grain, dried distillers grains and grass hay which were similar to those fed across the U.S. Indeed, over 90% of feedlots use distillers grains in their diets (USDA/APHIS, 2011), and Vasconcelos and Galyean (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.

Diet costs averaged \$0.90/hd/d in the cow–calf sector which compared favorably to the yearly average cow feed costs (\$0.82–\$1.02/hd/d) observed by Hughes (2013). Stocker diet cost was predicted by the model to be \$0.88/hd/d. Average stocker breakeven cost of gain was estimated at \$1.21/kg (Zimmerman, 2013) which is not dissimilar to the model prediction of \$0.94/kg. The model estimate may be slightly lower than Zimmerman's estimate 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 the results of Gadberry and Beck (2013) who estimated cost of gain in the feedlot at \$1.50/kg. Given the differences in costs accounted, the modeled cost and the cost calculated by Gadberry and Beck were relatively similar indicating that the costs used in this study were reasonable and representative of industry feed costs.

The baseline environmental impact metrics are listed in Table 8 and compared to estimates from similar U.S., Canadian and Australian assessments to demonstrate that realistic optima were outputted. Land use was predicted at 60.0 m^2/kg HCW beef which was within the range predicted by previous studies: 43 m^2/kg HCW beef (Elferink and Nonhebel, 2007) and 93 m^2/kg HCW beef (Ridoutt et al., 2013) Land use in the modeled grain-based finishing system was lower than the land use reported for forage-based finishing systems in Brazil (Cederberg et al., 2009). The model predicted water use at 1281 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 in the U.S. or Australia (Table 8; Capper, 2011, 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 (i.e. rainwater) were considered by Hoekstra and

Table 7

Projected changes in seasonal precipitation in the Pacific Northwest, the Midwest and Texas.

Season	Pacific Northwest		Midwest		Texas	
	Current (mm)	Change (%)	Current (mm)	Change (%)	Current (mm)	Change (%)
Winter	95.1	+5[a]	46.0	+5	15.2	−15
Spring	69.3	−2	165.0	+0	96.0	−20
Summer	23.4	−20	175.0	−10	80.3	−15
Fall	41.1	+5%	96.5	−5	83.1	−7

[a] Data represent projected percent change in rainfall over the season U.S. Global Change Research Program (2009).

Table 8
Baseline scenario outputs of environmental impact.

Output[a] (kg HCW^{-1})	This study	Beauchemin et al. (2010)	Capper (2011)	Ridoutt et al. (2013)[d]
Carbon footprint (kg CO_2e)	20.3	21.7	17.9	20.5
Enteric methane (kg CO_2e)	15.6	13.7	13.8[f]	18.0[f]
Manure methane (kg CO_2e)	0.5	1.1		
Direct nitrous oxide (kg CO_2e)[b]	2.7	4.9[e]	2.4[e]	0.8[e]
Indirect nitrous oxide (kg CO_2e)	0.1			
Carbon dioxide (kg CO_2e)	1.4	1.1	1.7	1.6
Water use (L)	1280	–	1,763	224
Irrigation water use (L)	1157	–	–	–
Daily drinking water use (L)	123	–	–	–
Land use (m^2)	60.0	–	61.1	92.5
Cropland (m^2)[c]	4.1	–	–	9.1
Pastureland (m^2)	55.9	–	–	83.4

[a] All outputs are given per kg of hot carcass weight (HCW) beef.

[b] Direct N_2O emissions included only those predicted to emit directly from manure storage while indirect N_2O emissions included downstream leached and volatilized N_2O.

[c] Cropland included land used for growing concentrate feeds, byproduct feeds and hays.

[d] Values were presented in Ridoutt et al. (2013) based on Ridoutt et al. (2011) and (Ridoutt et al., 2012). Northern grass fattened, grain finished cattle were selected as a comparison.

[e] N_2O values were not broken down by direct and indirect.

[f] CH_4 were not broken down by enteric or manure.

Chapagain (2007). This comparison indicates that the model produced plausible values for land use and water use from the production system.

The carbon footprint of beef production was 20.3 kg/kg HCW beef which was similar to previous studies of U.S. systems (17.9 kg/kg HCW beef; Capper, 2011; 16.2 kg/kg HCW beef; Pelletier et al., 2010; 22.6 kg/kg HCW beef; Stackhouse-Lawson et al., 2012; 20.1 kg/kg HCW beef; 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, 2006), 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 between regions. The agreement between the outputted GHG emissions and those presented in other studies demonstrates the model calculated realistic GHG emissions.

3.2. Minimizing individual metrics of environmental impact

3.2.1. Land use

Two scenarios were simulated to minimize land use, one constrained by the $0.144 predicted increase in consumer WTP and one without the constraint (Fig. 2). When cost increases were constrained, 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. 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 CH_4 emissions related to increased pasture digestibility, the environmental benefits were at the expense

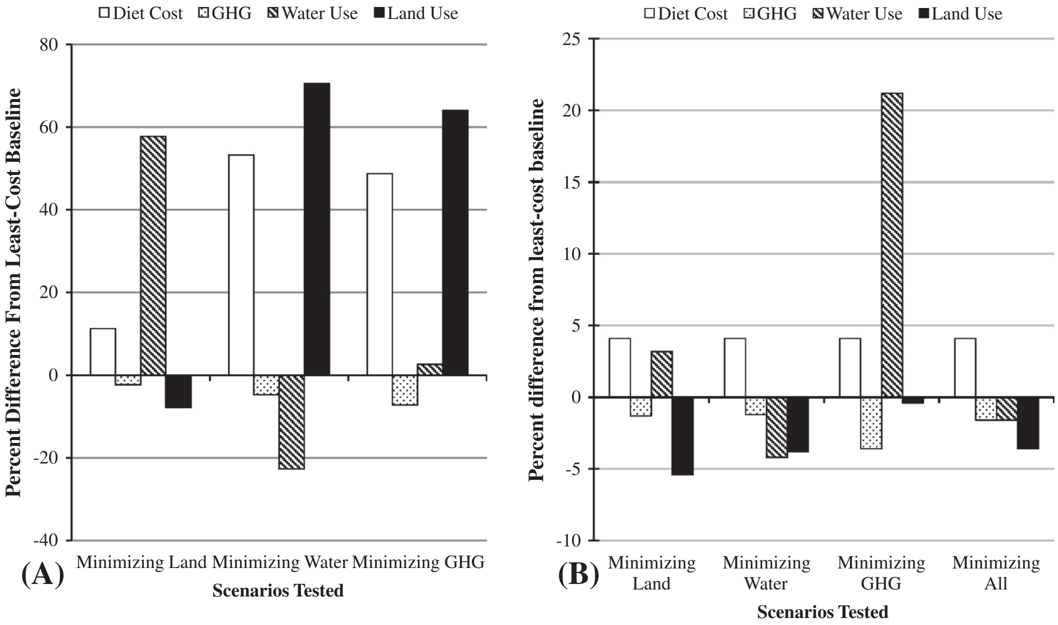

Fig. 2. Land use, water use and greenhouse gas emission changes from the baseline scenario in the simulations with (Panel B) without (Panel A) a WTP constraint. Values below the *x*-axis represent reductions in environmental impact compared with the baseline scenario. Scenarios are listed along the bottom of the graph.

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 use. Yields were higher because of increased irrigation and feeding alfalfa increased water use accordingly. The increase in diet cost was due to the alfalfa hay price (USDA/ERS, 2012). Alfalfa pastures resulted in lower CH_4 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 CH_4 emissions concurred measured GHG emissions (McCaughey et al., 1999).

3.2.2. 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, C-IF 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 all irrigation treatments. This may be because the high stocking density and increased fertilizer use improved water use efficiency (Armstrong et al., 2000). Similarly, addition of C-F pasture for the cow–calf sector allowed for decreased overall water use. The reduction in land use was uncharacteristic because typical model outputs demonstrated that land use and water use were 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, C-IF and R-IF pastures were expected to exhibit higher CO_2 emissions per ha because increased use of N fertilizer was correlated with increased N_2O emissions from pasture (Mosier et al., 1996) particularly under wet conditions (Luo et al., 2008; Saggar et al., 2007). However in this scenario, the decreased land requirement, in combination with moderate decreases in enteric CH_4, may have counterbalanced the predicted increase in N_2O emissions.

When the WTP constraint was not included in the simulation, a 53.2% increase in diet cost reduced water use by 22.6% and CO_2 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 yields. 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. Given the constrictions on agricultural land availability (Lambin and Meyfroidt, 2011), scenarios which required substantial increases in land use were not practically feasible. Additionally, not all land will be suitable for irrigation. The negative own-price elasticity of beef indicates that the substantial cost increases incurred in this scenario would decrease demand for beef (Schroeder et al., 2000).

3.2.3. 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-IF and R-IF pasture with supplemental grass hay. Stocker diets were composed of C-IF and grass hay. Grass hay also became the feedlot forage source. Decreased enteric CH_4 emissions from cattle consuming intensively-managed pasture were reported by DeRamus et al. (2003). Substantial concern has been raised about N_2O emissions from intensively-grazed pasture (Luo et al., 2010) but in this study, switching to intensively-managed pasture reduced N_2O emissions because less land was required. The use of intensively-managed pasture in the cow–calf sector reduced N fertilizer required and resulted in decreased 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 for 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, the substantial increases in diet cost and in land required (Howden et al., 1994) make this management strategy impractical.

As noted in the methodology, C-sequestration was not included as a carbon stock in the model due to uncertainty in determining reliable estimates on a regional or national level. Many studies exploring the effects of grazing on sequestration find that responsible grazing management (not over-grazing) can help to improve carbon sequestered in the soil (McSherry and Ritchie, 2013; Ostle et al., 2009; Schuman et al., 1999). Soil C-sequestration has the potential to be a substantial source or sink of carbon for grass-based livestock production systems (Del Prado et al., 2013). If carbon sequestration was included in this study, the GHG emissions baseline figures may be lower and the impacts of differing pasture management strategies may improve.

3.3. 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, an increase of $0.144/kg HCW beef (WTP) resulted in an average 2.3% 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 enteric CH_4 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 pasture management 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 2.3%. A historical comparison of the U.S. beef industry indicated 16.3%, 12.1%, 33% reductions in GHG emissions, water use and land use over a 30 year period (Capper, 2011). 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) continues and new efficiency-improving technologies become available over the next several years, ample opportunities will exist to improve future beef sustainability. Models, such as the one employed in this study, can be used to assess optimal adoption of technologies to ensure economic viability, social acceptability and improved environmental impact.

In Capper (2011), the 30 year changes in environmental impact were associated with reducing 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, as seen in other recent studies (Beauchemin et al., 2011; FAO, 2013), forage management in the cow–calf and stocker systems is a more promising area of focus. In fact, responsible utilization and management of pasture resources has been identified as a key component to improving the environmental impact of cattle production (Beauchemin et al., 2011; FAO, 2013; Nguyen et al., 2013).

3.4. Pasture management, cow–calf efficiency and whole-system sustainability

This study demonstrated that increasing pasture yield and quality through management intensification reduced GHG emissions and resource use per unit of product. Other studies examining pasture management intensification (Asgedom and Kebreab, 2011; Bell et al., 2012b; Foley et al., 2011) also reported this relationship. Pasture yield and forage quality are dependent on precipitation patterns. As a result, predictions of increasing future climate variability are expected to impact forage production (Maracchi et al., 2005). The cow–calf sector grazes forage for the majority of the year and is responsible for most of beef production's environmental impact (Beauchemin et al., 2010; Pelletier et al., 2010). In the U.S., most cow–calf operations supplement cows with roughages for 90–180 d (USDA/APHIS, 2010), although the exact amount of supplement given per day and the frequency of supplementation is not known.

Substantial decreases in rainfall during the crop growing season are projected in many U.S. regions (U.S. Global Change Research Program, 2009). 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 (Fig. 2). The optimization model was used to assess the impact on improving beef sustainability in three locations (Fig. 3).

3.4.1. 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%. 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 pasture was used briefly in the fall. When adjusted precipitation patterns were modeled, opportunities to reduce land use, water use and GHG emissions were decreased by 3.3–3.6%. 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.

3.4.2. The Midwest

When pasture simulation used values representative of the Midwestern U.S., land use, water use and GHG emissions were reduced by 5.8–6.0% 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.

3.4.3. Texas

In Texas, a cost increase of $0.144/kg HCW beef reduced land use water use and GHG emissions by 1.8–2.2% 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. Under alternative precipitation patterns, opportunities to reduce land, water and GHG emissions decreased by 1.2–1.6%. 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 use of this pasture system.

3.4.4. Trends in precipitation 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 the alternative precipitation patterns. This was 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 was 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

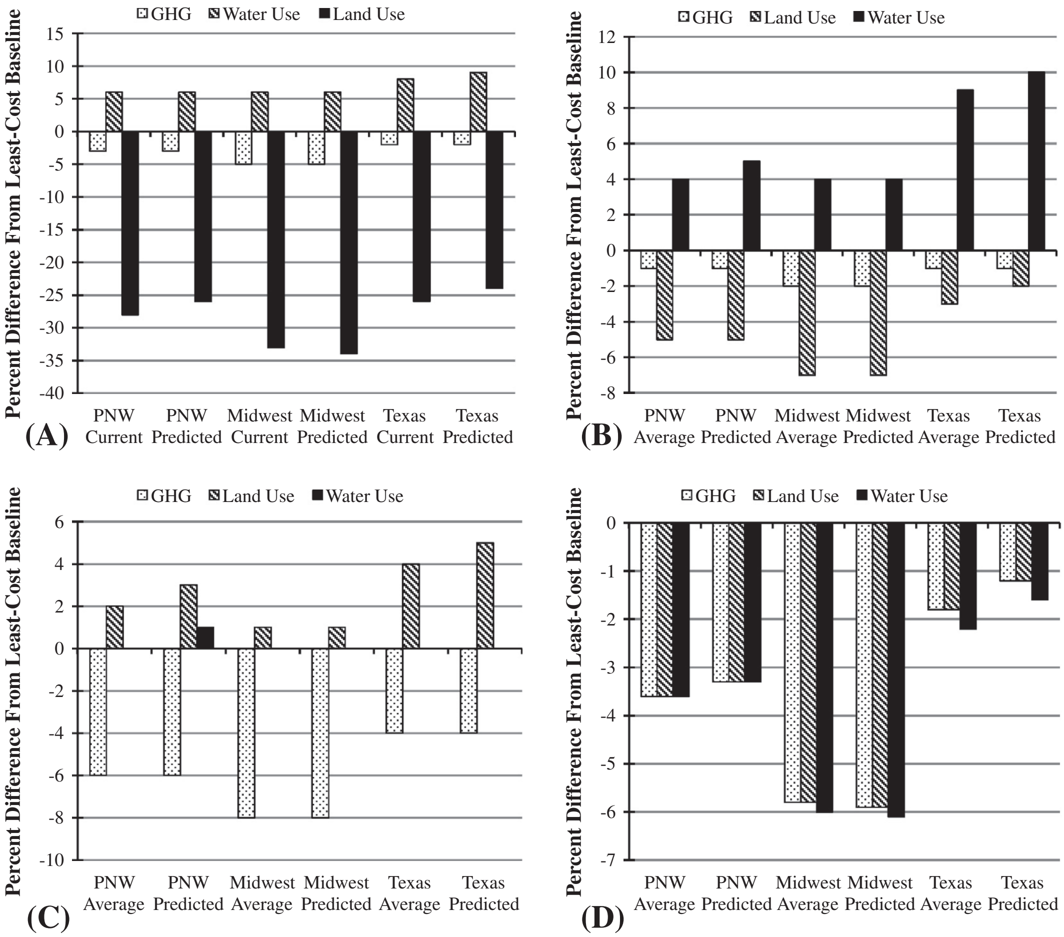

Fig. 3. Regional changes in environmental impact with and without projected precipitation changes. Negative values represent a decrease in environmental impact compared with the least-cost baseline scenario. Scenarios are listed across the bottom of each graph. Average represents current average weather patterns while "Predicted" included the projected precipitation changes projected by the U.S. Global Climate Change Center. Panel A represents scenarios minimizing water; B minimizes land; C minimizes GHG emissions; and D minimizes all.

viability of grass-based cattle operations (Hanson et al., 1998; Parker et al., 1992; Swain et al., 2007). In these scenarios, if the grazing season could be extended or more R-IF could be afforded in the diet, the environmental impact tended to decrease. When precipitation changes negatively impacted pasture growth, more stored forage was required and environmental impact tended to increase. Future analyses should move to a more precise spatial scale and utilize more precise pasture simulation models (Graux et al., 2011; Johnson et al., 2003; Moore et al., 1997; Riedo et al., 1998) to accurately simulate heterogeneity to help identify ideal management practices across a varied landscape. An additional area for future research could be modeling the long-term response of pastures to variation in climate and grazing management system. These analysis should identify how pasture management could be adjusted to improve environmental impact in locations where extending the grazing season is impractical.

4. Conclusion

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's 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 U.S. beef production sustainability. Although U.S. production was the focus of this analysis, the model and the results are applicable to similar pasture-based sectors of production systems worldwide.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agsy.2014.06.004.

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