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Potential mitigation of midwest grass-finished beef production emissions with soil carbon sequestration in the United States of America

Jason E. Rowntree*[1], Rebecca Ryals[2], Marcia S. DeLonge[3], W. Richard Teague[4], Marilia B. Chiavegato[5], Peter Byck[6,7], Tong Wang[8] & Sutie Xu[1]

[1] Department of Animal Science, Michigan State University
[2] Department of Natural Resources and Environmental Management, University of Hawaii
[3] Union of Concerned Scientists, Washington, DC
[4] Department of Ecosystem Science and Management, Texas A & M University
[5] Departmental de Zootecnia, Universida de de São Paulo
[6] School of Sustainability, Arizona State University
[7] Walter Cronkite School of Journalism and Mass Communications, Arizona State University
[8] Department of Economics, South Dakota State University

* Corresponding author: *rowntre1@msu.edu* | Tel.: +1-517-974-9539

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Abstract

Beef production can be environmentally detrimental due in large part to associated enteric methane (CH_4) production, which contributes to climate change. However, beef production in well-managed grazing systems can aid in soil carbon sequestration (SCS), which is often ignored when assessing beef production impacts on climate change. To estimate the carbon footprint and climate change mitigation potential of upper Midwest grass-finished beef production systems, we conducted a partial life cycle assessment (LCA) comparing two grazing management strategies: 1) a non-irrigated, lightly-stocked (1.0 AU/ha), high-density (100,000 kg LW/ha) system (MOB) and 2) an irrigated, heavily-stocked (2.5 AU/ha), low-density (30,000 kg LW/ha) system (IRG). In each system, April-born steers were weaned in November, winter-backgrounded for 6 months and grazed until their endpoint the following November, with average slaughter age of 19 months and a 295 kg hot carcass weight. As the basis for the LCA, we used two years of data from Lake City Research Center, Lake City, MI. We included greenhouse gas (GHG) emissions associated with enteric CH_4, soil N_2O and CH_4 fluxes, alfalfa and mineral supplementation, and farm energy use. We also generated results from the LCA using the enteric emissions equations of the Intergovernmental Panel on Climate Change (IPCC). We evaluated a range of potential rates of soil carbon (C) loss or gain of up to 3 Mg C ha^{-1} yr^{-1}. Enteric CH_4 had the largest impact on total emissions, but this varied by grazing system. Enteric CH_4 composed 62 and 66% of emissions for IRG and MOB, respectively, on a land basis. Both MOB and IRG were net GHG sources when SCS was not considered. Our partial LCA indicated that when SCS potential was included, each grazing strategy could be an overall sink. Sensitivity analyses indicated that soil in the MOB and IRG systems would need to sequester 1 and 2 Mg C ha^{-1} yr^{-1} for a net zero GHG footprint, respectively. IPCC model estimates for enteric CH4 were similar to field estimates for the MOB system, but were higher for the IRG system, suggesting that 0.62 Mg C ha^{-1} yr^{-1} greater SCS would be needed to offset the animal emissions in this case.

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Introduction

There is a growing concern about beef production's impact on the environment, including contributions to climate change. However, beef production systems are variable, ranging broadly from intensive confined feedlots to diverse grazing systems. As a result, these systems contribute differently to climate change through mechanisms such as animal impacts, off-farm inputs, and land management. Identifying opportunities to reduce climate impacts requires a systematic approach that considers the larger agroecosystem. This need for a systems approach has become increasingly urgent, particularly in light of the fact that one outcome of the United Nations Conference on Climate Change (COP21) was a call for greater adoption of regenerative agricultural practices. Specifically, this call includes the "4/1000 Initiative: Soils for Food Security and Climate" and the Life Beef Carbon Initiative, which recommends greater adoption of grazing systems that sequester C and reduce net GHG emissions from beef production.

Life cycle assessments (LCAs) are important tools that have been applied to evaluate the costs and benefits of beef production systems with respect to the environment and climate change. While LCAs can be insightful, the outputs are highly sensitive to the methodologies and boundaries used to develop the analysis. Many existing beef LCAs have concluded that grazing systems have a bigger climate footprint than more intensive, confined systems due to reduced meat yield per unit land and increased enteric methane (CH_4) associated with greater ruminal fiber digestion (Eshel, Shepon, Makov, & Milo, 2014; Ripple et al., 2014; Capper, 2012). However, these assessments have generally not accounted for the important influence that land management and soil dynamics can have on the outcome.

Soil is an important pool of C that is sensitive to land management and can cumulatively have a significant impact on climate change. Recently, Teague et al. (2016) indicated agriculturally induced global soil erosion estimates at 1.86 Gt C yr^{-1}, resulting in an annual 0.5 ppm atmospheric CO_2 increase. Because soils can be either a source or sink of C depending on management practices, soil C is a potentially important component of beef LCAs (Teague et al., 2016). Soil C has often been unaccounted for in LCAs (Stackhouse-Lawson, Rotz, Oltjen, & Mitloehner, 2012; Capper & Bauman, 2013), but has been found to have a large impact on net GHG footprints when explicitly included (Liebig, Gross, Kronberg, & Phillips, 2010; Wang, Teague, Park, & Bevers, 2015) or at least considered (Pelletier, Pirog, & Rasmussen, 2010; Lupo, Clay, Benning, & Stone, 2013). The availability of experimental data on soil C and GHG effects of grazing systems has been an obstacle in filling this critical gap in LCAs.

The purpose of this study is to develop a data-driven partial LCA of upper Midwest grass-finishing beef production systems. Our LCA explicitly considers soil C and GHG dynamics and uses data from localized field experiments. We employ a simple sensitivity analysis to evaluate the potential for soil carbon sequestration (SCS) to offset emissions within grass-finished beef production systems.

Materials and Methods

LCA components and boundaries

An LCA was constructed to determine net GHG impacts of two different grazing management practices for beef production in the upper Midwest, USA. Components of

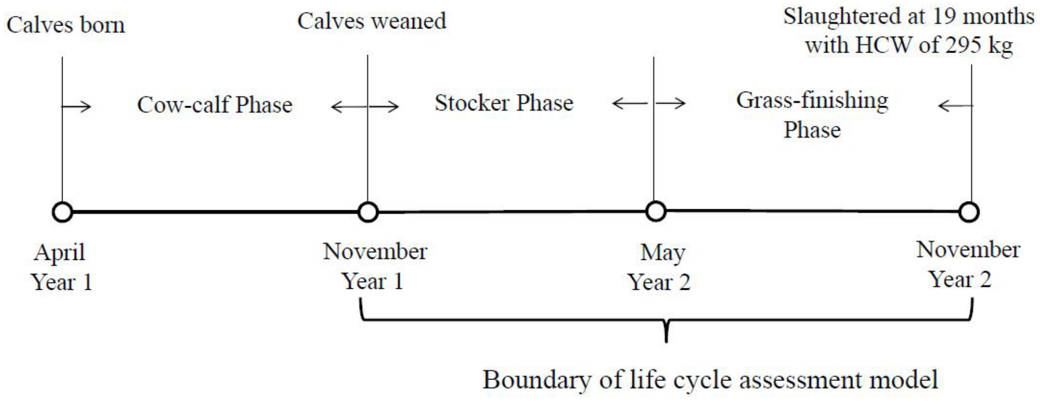

Figure 1 : Grass-Finishing beef production phase

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the LCA include direct and indirect GHG emissions associated with the grassland ecosystem, enteric emissions from cattle, feed production and transportation, and on-farm energy use. The model boundary was restricted to the grass-finishing portion of the beef production cycle, beginning at the time of weaning and ending at slaughter (**Figure 1**).

The model quantified the impacts of grazing management practices on the net greenhouse gas emissions (GHGnet) as:

$$GHG_{net} = GHG_{ecosystem} + GHG_{feed} + GHG_{energy} - GHG_{seq} \quad \text{— Eq. 1}$$

where GHGecosystem represents biological greenhouse gas emissions generated on the pasture. This parameter includes enteric CH_4 emissions from steers (> 1 year old) and the difference in soil nitrous oxide (N_2O) and CH_4 emissions relative to an ungrazed control pasture. Emissions associated with the mining, production, and transportation of supplemental feed and minerals are represented as GHGfeed. Emissions generated from the use of fossil fuels for on-farm technologies (i.e., irrigation) are represented as GHGenergy. The change in soil carbon is shown as GHGseq, where a positive value represents sequestration (i.e., a sink). All model components are expressed as GHG fluxes in CO_2-equivalents using 100-year global warming potentials (Intergovernmental Panel on Climate Change, 2006). Positive values represent a source of GHGs to the atmosphere, whereas negative values represent a GHG sink. Metrics for comparison of GHG impacts due to grazing practices were expressed on a per steer and per area basis.

Study system

Data used for the LCA was derived from two years of on-farm experiments conducted at the Lake City Research Center in Lake City, Michigan. The experiments were composed of grass-finishing beef production systems that compared two different grazing management strategies. The approaches were: 1) MOB: a non-irrigated, high-density grazing system stocked at 1.0 animal units (AU) ha^{-1} (100,000 kg live weight (LW) ha^{-1} d^{-1}) and 2) IRG: an irrigated, low-density grazing system stocked at 2.5 AU ha-1 (30,000 kg LW ha-1 d-1). An AU is considered one 454 kg cow with or without calf. We define stocking rate as the number of AUs assigned to the land base for a given year, while stock density refers to the kg LW/ha of animal weight assigned to a land base for 1 day. While our LCA was driven by data specific to the Upper Midwest, the management characteristics of the IRG system are similar to many grazing dairies and beef systems in New Zealand, parts of Europe, Australia and the United States. The IRG system is characterized by aggressive plant defoliation with short (21-45 day) recoveries to promote a highly vegetative sward. In contrast, MOB is a grazing system characterized by high stock densities with a lower stocking rate. The MOB system allows for longer (> 60 day) plant recovery periods. As a result, forage is typically more mature when compared to IRG and has a higher fiber content when compared to other rotational systems (Chiavegato, Powers, Carmichael, & Rowntree, 2015b). In each grazing strategy, steers were born in April, weaned in November, backgrounded on high quality hay for 6 months, and grazed on pasture until slaughter the following November, with an average age at slaughter of 19 months and a 295 kg hot carcass weight (HCW). Our life cycle model focuses on the period from weaning to slaughter (**Figure 1**).

Ecosystem greenhouse gas emissions

Ecosystem GHG emissions included enteric CH_4 and soil N_2O and CH_4 fluxes measured at the experimental site from 2012-13 (Chiavegato, Rowntree, Carmichael, & Powers, 2015a, Chiavegato et al., 2015b). Emissions were measured in spring (April/May; Period 1) and late summer (August/Sept; Period 2) for 2 years. These time periods were considered to be representative of seasonal fluxes and were scaled by the numbers of days in each season. For the base case scenario, soil emissions during winter months are assumed to be negligible.

Enteric emissions were derived from on-site data from cow-calf pairs with a mean weight of 555 kg (SE= 20 kg) using a standard SF_6 tracer gas technique (Johnson, Huyler, Westberg, Lamb, & Zimmerman, 1994). Sampling was conducted twice daily over 7 days in Periods 1 and 2 in 2012 and 2013. During each sampling period, cattle were also dosed with chromic oxide to determine dry matter intake (DMI). There was no management effect on DMI as cows consumed 2.6 and 2.8% of their body weight daily during the collection periods for MOB and IRG, respectively. There were no differences between years or treatments for enteric CH_4, with emissions ranging from 195 to 249 g CH_4 d^{-1}. We used a metabolic body weight conversion of 0.85 to convert emissions from a mature cow (555 kg) to a growing steer (454 kg). For both systems, we estimated winter CH_4 emissions to be 120 g L^{-1} d^{-1} on high quality hay, based Stewart et al. (2014). We also compared our data to enteric CH_4 calculations using the Tier 1 Methodology of the Intergovernmental Panel on Climate Change (IPCC):

$$DayEmit = [GEI\ XYm\ ] / [55.65\ MJ/kg\ CH_4] \quad \text{— Eq. 2}$$

where:

DayEmit = emission factor (kg CH_4 $head^{-1}$ day^{-1})

GEI = gross energy intake (MJ $head^{-1}$ day^{-1})

Ym = CH_4 conversion rate, which is the fraction of gross

energy in
feed converted to CH_4 (%)

To complete the IPCC equation, site-specific mean GEI forage values (Chiavegato et al., 2015a) and the recommended Ym of 6.5% (Mangino, Peterson, & Jacobs, 2003) were used.

Soil GHG emissions data used for the base case scenario is detailed in Chiavegato et al. (2015b). Briefly, soil N_2O and CH_4 emissions were measured via the static flux chamber method and analyzed by gas chromatography. A 14 day post-graze collection period in both periods in 2012 and 2013 was used.

Greenhouse gas emissions from protein and mineral supplements

The grazed pastures and supplemented feed were primarily alfalfa (Medicago sativa L.). For the supplemental feed GHG assessment, we used the Farm Energy Analysis Tool (FEAT) (Camargo et al., 2013). Assumptions involved in FEAT indicate a three-year lifespan for the alfalfa, with an energy use of 9000 MJ input ha^{-1} y^{-1} and energy production efficiency of 25 MJ output per MJ input (Camargo, Ryan, & Richard, 2013). No differences in supplement consumption were used between the different grazing systems. The on-farm supplemental feed consumption per animal for the production cycle was 2044 kg. Half of the alfalfa was produced on site, while the other half was brought on farm from an average distance of 24 km. In each case, a yield of 7490 kg ha^{-1} y^{-1} was used based on USDA harvest estimates (USDA, 2015). All associated transportation GHG emissions were estimated using diesel heavy-duty truck data from the EPA (2008).

Mineral supplement calculations were based on a daily intake of 77 g head^{-1} across each grazing treatment (Buskirk, 2002). Mineral associated emissions were estimated based on Lupo, Clay, Benning, and Stone (2013). This involves the mining and processing components of NaCl, $CaCO_3$ and $CaHPO_4$ production, along with transport and delivery to the farm.

On-farm energy use

Any associated energy used for alfalfa production and subsequent feeding is accounted for in the feed component. Supplemental irrigation was used in IRG (K-Line Irrigation, St. Joseph, MI) with a goal of providing 2.54 cm water ha^{-1} wk^{-1}. The estimated annual usage of irrigation electricity was 7452 kW yr^{-1}. EPA (2014) emission factors were used to determine emissions associated with electricity use.

Soil carbon sequestration

To account for soil C change in each system, we considered a C-response gradient ranging from -3 Mg C ha^{-1} yr^{-1} to 3 Mg C ha^{-1} yr^{-1}. Grazing lands have the potential to act as C sinks, but reported rates of SCS due to grazing system management vary considerably based on climate, biome, time of observation, and site-specific conditions. A review of 81 ranch sites reported SCS rates ranging from 0.11 to 3.04 Mg C ha^{-1} yr^{-1} (Conant, Paustian, & Elliott, 2001). More recent attention to emerging intensive rotational grazing practices has indicated even greater potential SCS rates. Teague et al. (2011) reported annual sequestration rates of 3 Mg C ha^{-1} yr^{-1} in a 10 year chronosequence study in Texas comparing stocking rate and grazing management influence on beef production and ecosystems services. Machmuller et al. (2015) observed SCS of 8.0 Mg C ha^{-1} yr^{-1} in a 7 year chronosequence of irrigated management-intensive grazing in the southeastern USA. Thus, the relatively wide range of SCS rates used for this LCA provides an opportunity to incorporate soil C dynamics and uncertainties.

Results and Discussion

LCA results of MOB and IRG systems on a kg CO_2-eq ha^{-1} production cycle and animal basis derived from **Eq.1** are indicated in **Figure 2**. The MOB system had lower emissions on a land basis when compared to the IRG system (3.3 vs. 7.1 Mg CO_2-eq ha^{-1}) due to lower stocking rates. The IRG farm energy use was 1064 kg CO_2-eq ha^{-1} due to the electricity used for irrigation, compared to no energy use for the MOB system. For both systems, enteric CH_4 was the largest contributor to overall emissions, ranging from 62 to 66% for the IRG and MOB systems, respectively. This finding is lower than results found by Pelletier, Pirog, & Rasmussen (2010), who estimated enteric CH_4 emissions to make up 79% of total GHG emissions from a grass-finishing system.

Enteric emissions ranged from 142 to 268 g CH_4 d^{-1} (Chiavegato et al., 2015a). These results are similar to those reported by DeRamus, Clement, Giampola, and Dickison (2003), who indicated yearling heifers, first calf heifers and mature cows ranged from emitting 120 to 255 g CH_4 d^{-1}. Similarly, Pavao-Zuckerman, Waller, Ingle, and Fribourg (1999) reported a range of 150 to 240 g CH_4 d^{-1}. However, these data fall slightly lower than estimates by McCaughey, Wittenberg, and Corrigan et al. (1999) and Pinares-Patiño, Baumont, and Martin (2003), who found ranges in emissions from 173 to 273 g CH_4 d^{-1}. The lower stocking rate in MOB also resulted in lower enteric CH_4 emissions compared to IRG (2165 vs. 4430 kg CO_2-eq ha^{-1}) on a land area basis. However, on a per steer basis, IRG enteric emissions were 393 kg CO_2-eq steer^{-1} less than MOB. The grazing effect on enteric CH_4 emissions may be explained by the observed increase in forage crude protein and reduction in fiber content for IRG compared

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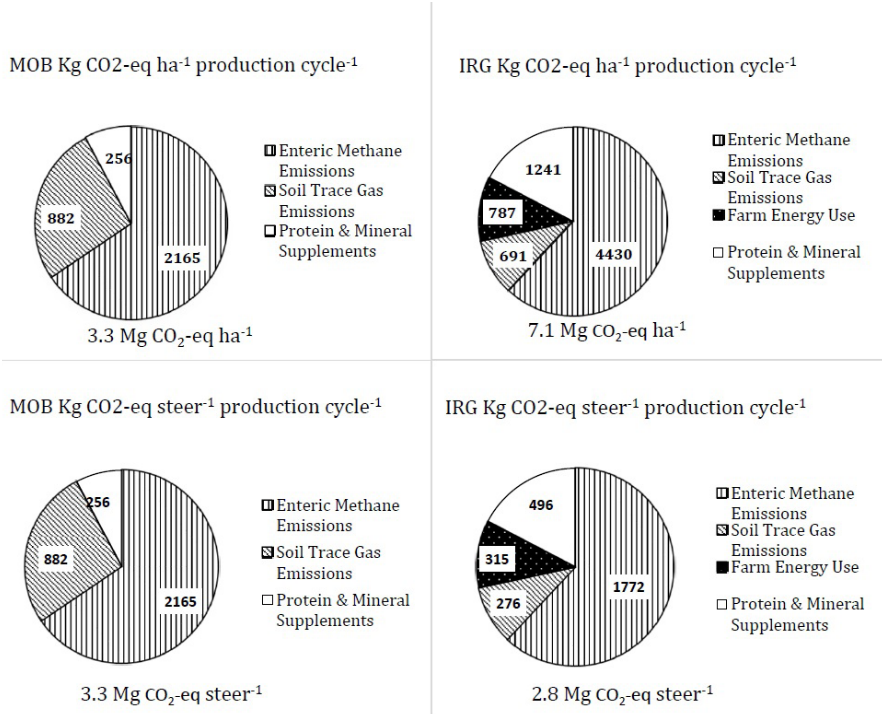

Figure 2 : Life cycle assessment of on-farm data estimated with metabolic body weight

Table 1: Impact of soil C emission gradient on net GHG in two management systems

	Net GHG (Mg C ha^{-1} yr^{-1})			
	On-farm		IPCC	
Soil C Emission (Mg C ha^{-1} yr^{-1})	MOB	IRG	MOB	IRG
-3	-2.11	-1.07	-2.05	-0.45
0	0.89	1.93	0.95	2.55
3	3.89	4.93	3.95	5.55

to MOB (Chiavetago et al., 2015a).

The beef production systems used to calculate this LCA represent improved grazing management as compared to continuous set stocking strategies, which have been shown to reduce plant diversity and productivity due to overgrazing of preferred plants and patches (Murphy, 1998; Gerrish, 2004; Teague, Provenza, Kreuter, Steffens, & Barnes, 2013). The lower enteric CH_4 emissions in the observations reported here might be due to the relatively high plant diversity we observed in the well-managed systems. Both systems included multiple daily to weekly moves to new pasture, allowing for greater forage residual biomass and longer recovery periods, feeding back to the ecosystem by increasing the plant diversity and forage quality (Chiavegato et al., 2015a). Conceptually, this agrees with Bannink et al. (2010), who indicated that forage quality is a primary driver in relative daily enteric emissions.

Enteric CH_4 emissions were also assessed using Tier 1 IPCC daily enteric emission predictive equations (**Eq.1**) (IPCC, 2006), as it is a commonly used methodology when site- or regionally-specific data are lacking. There was very little difference between the MOB GHG footprint calculated using our field observations compared to the IPCC approach (3.3 vs 3.5 Mg CO_2-eq yr^{-1}, respectively) (**Figures 2 & 3**). However, when evaluating the IRG system, the IPCC approach generated a greater enteric CH4 value and concurrently a larger footprint on a land and steer basis by 34%. In a review of measured and simulated enteric emission rates, Stackhouse et al. (2012) indicated the IPCC overestimated emissions by 16.4% on average, with a differential range of -0.01 to 55%.

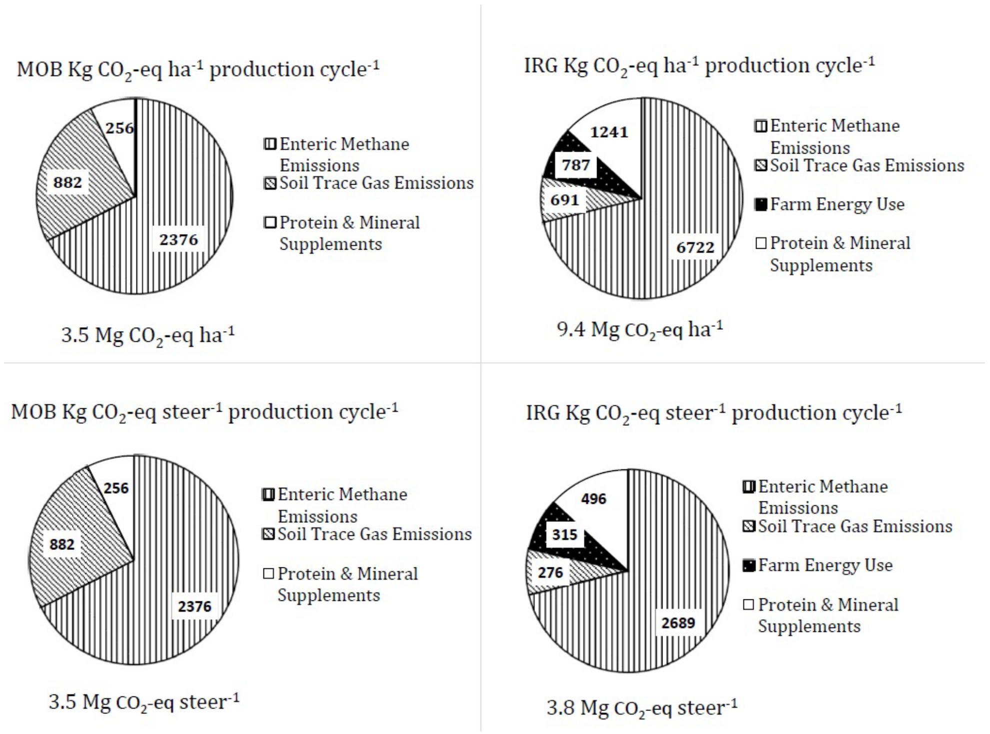

Figure 3 : Life cycle assessment of IPCC data to estimate enteric methane emissions

Table 1 denotes overall C footprint balance (in CO2-eq) based on a plausible gradient of soil C flux, representing soil C loss or gain ranging from ±3 Mg C ha^{-1} yr^{-1}. Assuming a sequestration rate of 3 Mg C ha-1 yr^{-1}, all systems and methods indicate an overall GHG sink ranging from 2.11 to 1.07 (MOB) and 2.0 and 0.45 Mg C ha^{-1} yr^{-1} (IRG), representing on-farm and IPCC calculations, respectively. A soil C flux gradient allows for a greater understanding of soil C influence on the overall environmental footprint. As Stackhouse et al. (2012) indicated, LCA's often consider soil C to be in dynamic equilibrium. However, empirical data suggest otherwise (e.g. Machmuller et al., 2015; Teague et al., 2011). Recent studies such as Ripple et al. (2014) and Eshel et al. (2014) have reported the emissions from ruminants in food production without accounting for the beneficial ecosystem services that well-managed grazing systems can provide. In our study, we used 3 Mg C ha^{-1} yr^{-1} as a potential C sequestration figure, which is relatively high (Conant et al., 2001) but viable based on existing studies (Teague et al., 2011; Delgado et al., 2011; Machmuller et al., 2015; Teague et al., 2016). Importantly, the results presented here suggest that with appropriately managed grazing, a grass-finished beef model can not only contribute to food provisioning but also be ecologically regenerative as well.

Conclusions

The recent call for improved management of grazing systems as part of an international climate change mitigation strategy is critical, particularly in light of many existing beef LCAs that have concluded that beef cattle produced in grazing systems are a particularly large sources of GHG emissions. To identify the best opportunities to reduce GHG emissions from beef production, a systems approach that considers the potential to increase soil C and reduce ecosystem-level GHG emissions is essential. Using a combination of on-farm collected data, literature values, and IPCC Tier 1 methodology, we generated an LCA that indicates highly-managed grass-finished beef systems in the Upper Midwestern United States can mitigate GHG emissions through SCS while contributing to food provisioning at stocking rates as high as 2.5 AU ha^{-1}. From this data, we conclude that well-managed grazing and grass-finishing systems in environmentally appropriate settings can positively contribute to reducing the carbon footprint of beef cattle, while lowering overall atmospheric CO_2 concentrations.

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Conflict of Interests

The authors hereby declare that there are no conflicts of interest.

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