Reintegrating Land and Livestock

Agroecological Solutions to Beef System Challenges

Marcia DeLonge

October 2017

Union of Concerned Scientists

Marcia DeLonge is a Senior Scientist in the UCS Food and Environment Program.

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ACKNOWLEDGMENTS

This report was made possible through the support of the TomKat Foundation, the Grantham Foundation for the Protection of the Environment, and UCS members.

The analysis was completed with the assistance of Rebecca Wasserman-Olin and George Boody, MS (Land Stewardship Project), and Alexandra Parisien (graduate student, University of Virginia; Stanback Intern, Duke University). For their thoughtful reviews, the author would like to thank Jonathan Gelbard, PhD (Conservation Value Solutions); Peter Byck, filmmaker & Professor of Practice (Arizona State University); Kari Hamerschlag, Deputy Director, Food and Technology Program (Friends of the Earth); and an anonymous external reviewer. At UCS, the author especially thanks Kranti Mulik, Karen Perry Stillerman, Sarah Reinhardt, Mike Lavender, Andrea Basche, Sharon Smith, Doug Boucher, and Rachel Cleetus.

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NATIONAL HEADQUARTERS
Two Brattle Square
Cambridge, MA 02138-3780
t 617.547.5552
f 617.864.9405

WASHINGTON, DC, OFFICE
1825 K St. NW, Ste. 800
Washington, DC 20006-1232
t 202.223.6133
f 202.223.6162

WEST COAST OFFICE
500 12th St., Suite 340
Oakland, CA 94607-4087
t 510.843.1872
f 510.451.3785

MIDWEST OFFICE
One N. LaSalle St., Ste. 1904
Chicago, IL 60602-4064
t 312.578.1750
f 312.578.1751

[ANALYSIS]

Overview

Current eating habits and farming practices are depleting natural resources, polluting air and water, and contributing to climate change. Beef, which in the United States is produced mostly in industrialized systems, creates outsized consequences—in part from intensive monocropping of animal feed and massive cattle-feeding operations. Many experts have recommended producing and eating less beef to deliver health and environmental benefits. However, farmers can contribute to the reduction of beef's environmental impact by adopting best practices and diversifying farms: varying the crops they plant, and integrating livestock. This report evaluates those practices, which could maintain or improve farmers' profits while reducing their fertilizer and fuel use and cutting water pollution. The report also contains policy recommendations for the US Department of Agriculture and Congress.

Introduction

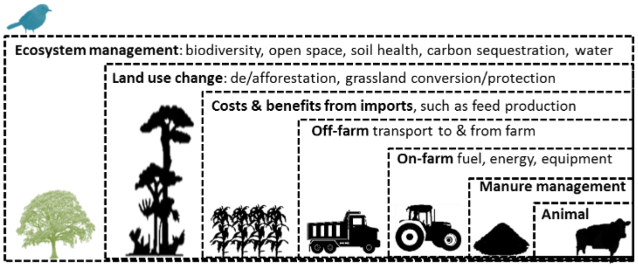
Beef production systems have been linked to a range of problems, including degradation of croplands and grasslands, air and water pollution, and climate change. Because of these and other issues, there has been a growing consensus among many scientists and health experts that reducing beef production and consumption can deliver both environmental and health benefits (Boxes 1 and 2; Figure 1). An additional or alternative solution calls for farmers and ranchers to engage in improved land and animal management. For the many US farmers connected to industrial beef systems primarily through feed-crop production, options to contribute to improved systems may include adopting more ecological cropping practices and reintegrating livestock into operations. In this report, we explore how introducing ecological cropping and grazing practices into areas now dominated by monoculture croplands could improve outcomes for farmers and the environment.

Overall, our analysis suggests that farmers could profitably transition land that is part of intensive monocropping systems to more diversified crop and livestock systems. Such a switch would offer beef raised within alternative systems that can generate environmental and economic benefits. However, mitigating challenges associated with various beef production systems will require the creation of circumstances and policies that consider multiple factors and encourage more regenerative, economically viable practices for farmers.

CONVENTIONAL BEEF PRODUCTION SYSTEMS

Understanding some key features of conventional beef production systems is a prerequisite for understanding opportunities and trade-offs among alternatives. The cattle life cycle involves different phases, but this study focuses on the finishing phase in the United States (Table A1). Grain, particularly corn, represents a large portion of feed in this phase, as it helps cattle reach market weight faster than grass and is relatively cheap (Siegel et al. 2016).[1] Moreover, a majority of the US beef market (97 percent; Cheung et al.

FIGURE 1. **Various Components of Beef Production Systems**



Beef production systems include several components and can cause climate emissions and pollution in various ways, including from animals, manure management, on- and off-farm activities and inputs (such as feed), land-use change (such as deforestation), and broader ecosystem management. Conversely, well-managed grazing lands and diversified farms can support soil carbon sequestration and wildlife, and reduce erosion and runoff.

2017) uses grain finishing, which typically takes five to 10 months and represents much of total weight gain.[2] As a result, 9 to 20 percent of US corn production is consumed by beef cattle.[3] Substantial quantities of corn also go to other livestock (especially poultry and hogs, as well as dairy cows), but the portion consumed by beef cattle is of interest, considering that it is relatively large and that, as ruminants,[4] they do not require grain.

The consumption of large amounts of corn by livestock, including beef cattle, is intertwined with several agricultural trends that have raised concerns, including the separation of crop and animal systems (Gliessman 2014),[5] loss of diversity on farms (Dimitri, Effland, and Conklin 2005), rise in corn acreage (Nickerson et al. 2011), and transition of areas of the Corn Belt and Great Plains from grasslands to croplands (Wimberly et al. 2017; Lark, Salmon, and Gibbs 2015; Wright and Wimberly 2013). These changes, which have been dominated by a trend toward low-diversity corn cropping (planted as a monoculture or in biologically simple rotations), have occurred even as total US cropland area has declined (Nickerson et al. 2011). While these land-use changes result from multiple drivers—most notably demand for corn ethanol—the demand for animal feed stands out (von Reusner 2017).

Another important feature of the finishing phase of beef production is that it often occurs in concentrated animal feeding operations (CAFOs).[6] A majority (more than 95 percent) of CAFOs are relatively small (with fewer than 1,000 cattle) and produce only 10 to 20 percent of feedlot cattle. The largest CAFOs, however (holding more than 32,000 cattle), produce about 40 percent of feedlot cattle.[7] These large facilities tend to concentrate environmental problems—such as air, water, and soil contamination—and often disproportionally affect impoverished communities and communities of color (Harun and Ogneva-Himmelberger 2013; Lenhardt and Ogneva-Himmelberger 2013).[8]

Despite the problems linked to grain-based CAFOs, some scientists have calculated that these CAFOs produce beef with fewer climate-disrupting emissions than grass-based alternatives (Capper 2012). This result is based on analyses showing that grain feeding leads to lower daily digestive methane emissions, faster finishing times, and smaller farmland requirements. Critiques of these analyses note that they have commonly ignored soil carbon dynamics and the diversity of grass-finishing systems (Rowntree et al. 2016; Teague et al. 2016; Wang et al. 2015), and that they have not fully considered other critical variables such as water pollution, biodiversity, and social factors (Janzen 2011). Clearly, this complexity shows that addressing the challenges of beef production systems must involve balanced consideration of the potential trade-offs of alternative systems, including the impact on the climate and farmers.

IMPROVING BEEF PRODUCTION SYSTEMS WITH REGENERATIVE AGRICULTURE

Research has identified several practices that farmers can adopt to improve aspects of beef production systems, including management of crop- and grazing lands, animals, and diversified agroecosystems. In particular, researchers have proposed reintegrating animals into regions dominated by biologically simple farms to address challenges (Liebman and Schulte 2015; Hellwinckel and Phillips 2012; Janzen 2011). Integrated systems can involve practices such as including forages in crop rotations, grazing crop residues or cover crops, planting crops that can be either harvested or grazed, or simply having crop fields and livestock operations more closely situated to foster exchange of fertilizer and feed (Sulc and Franzluebbers 2014). Potential effects of improving and integrating grazing and cropping systems include:

- **Protection and expansion of beneficial grasslands.** Well-managed grasslands deliver numerous ecosystem services—reducing runoff, erosion, and risk of drought and flood—while supporting wildlife habitat, recreation, biodiversity, and livelihoods (Peters et al. 2016; Briske et al. 2015; Yahdjian, Sala, and Havstad 2015; Werling et al. 2014; Sayre et al. 2013; Franzluebbers et al. 2012; Thornton et al. 2009). Adopting an adaptive approach to optimizing stocking rates and patterns (timing, intensity, and duration of grazing and rest periods) can restore degraded grassland soils, build soil health, and improve sustainability (Teague et al. 2016; Franzluebbers et al. 2012). For these reasons, farming practices that prevent conversion of critical grasslands to croplands should be prioritized (Wimberly et al. 2017). Furthermore, restoring grass in areas dominated by croplands could be beneficial in many cases, especially in regions less suited for crops (such as areas where there is limited water; Allen et al. 2005).
- **Sequestration of soil carbon.** Recent studies indicate the importance of not only reducing climate-disrupting emissions, but also removing carbon from the atmosphere, in part through soil sequestration (Paustian et al. 2016). Soil carbon sequestration rates vary, depending on many factors, such as region, climate, and the rate and duration of sequestration (Paustian et al. 2016; West and Six 2007).

However, there is evidence that soil carbon can be enhanced in several ways. For example, one study estimated that widespread conversion of US cropland to pasture could sequester carbon at 0.61 t CO_2e/ac/y for a total of about 10 Tg CO_2e/y,[9] enough to reduce US agricultural production emissions by 36 percent (Hellwinckel and Phillips 2012).[10] Comparable rates have been observed from integrating crop and livestock systems (4.45 t CO_2e/ac/y; Franzluebbers 2007), increasing or decreasing grazing intensity (~0.5 t CO_2e/ac/y; McSherry and Ritchie 2013; Conant, Paustian, and Elliott 2001), adopting conservation practices (~0.2 t CO_2e/ac/y in response to cover crops, crop rotations, conservation tillage; Poeplau and Don 2015; Powlson et al. 2014), and using agroforestry (18 to 338 t CO_2e/ac/y in trees and soils; Albrecht and Kandji 2003).[11] In some cases, soil carbon sequestration in crop and graz-ing systems could mitigate other emissions from livestock production (Rowntree et al. 2016; Teague et al. 2016). Despite the potential, soil carbon is typically excluded from life cycle assessments and similar analyses due to uncertainties (de Vries, van Middelaar, and de Boer 2015).

- **Reduction of reliance on inputs.** Diverse agroecosystems with healthy soils can provide additional benefits to farmers and the environment by reducing the need for costly and energy-intensive inputs. For example, practices such as improved grazing management, cover cropping, and legume-based rotations can reduce requirements for synthetic nitrogen addition and, in some cases, reduce soil N_2O emissions (Davis et al. 2012; Wolf et al. 2010; Tonitto, David, and Drinkwater 2006). In addition, having crops and animals co-located can improve the efficient disposal and use of manure (potentially further reducing synthetic fertilizer needs and transportation costs; Franzluebbers et al. 2014; Sulc and Tracy 2007; Peterson and Gerrish 1995). Also beneficial, crop diversity, which can be facilitated by integrated systems, can break pest cycles and lower the prevalence of pests that cause disease in plants and animals, thereby reducing the need for pesticides (Karp et al. 2015; Keesing and Ostfeld 2015; Gliessman 2014). Finally, animal health problems and therefore the need for therapeutic antibiotic use are reduced in well-managed grazing-based systems, with benefits for both animal and human health (Mathews and Johnson 2013).
- **Reduction of water footprints.** Water footprints can be very high in beef management systems (Box 1), but best management practices can reduce them (to around 1.6 to 3.3 gallons/ounce;[12] Mekonnen and Hoekstra 2012; Allen et al. 2005). Water footprints include three types of water: blue (surface and groundwater), green (rainwater), and gray (an indicator of water pollution). Demands on water resources (blue and green water) can be reduced by growing and breeding crops (including animal feeds) that require less water and improve soil health, which in turn can reduce risks of drought and floods (DeLonge and Basche n.d.; Basche and DeLonge n.d., 2017; Janzen 2011; Hudson 1994). Water pollution can also be reduced through ecologically based practices. For example, strategic incorporation of perennials on farms (Helmers et al. 2012) and reduced reliance on chemical inputs (Hunt, Hill, and Liebman 2017; Seitzinger and Phillips 2017) can reduce nutrient and chemical runoff from farms.
- **Mitigation of animal emissions**. Emissions from both enteric fermentation and manure depend on the variety and maturity of feeds, and can be reduced by factors such as improved diets, genetics, grazing management, and herd health (Hristov et al. 2013).[13] Diet is the primary determinant of animal emissions. Grass finishing leads to higher methane emissions and less weight gain per day, thereby requiring more time; in other words, grain has a higher “feed efficiency” (Capper 2012). However, emerging research suggests that higher-quality pasture can reduce these differences (Chiavegato et al. 2015; Chadwick et al. 2011) and that soil carbon in well-managed grasslands can mitigate some of these emissions (Teague et al. 2016; Wang et al. 2015). In integrated systems, improvements in both grass and grain diet components could reduce net emissions.

While there are several ways for farmers to improve aspects of beef production systems, trade-offs—including those related to productivity, climate, and land use—must be closely evaluated. Furthermore, a key constraint for farm-based solutions is that they must be practical and profitable for farmers. Therefore, developing options for farmers must involve a joint evaluation of the economic and environmental opportunities and trade-offs. In the following section, we investigate how reintegrating cattle and ecological practices into landscapes currently dominated by intensive corn and soy acres could affect farmers and the environment.

BOX 1.

Why Focus on Beef?
There Is a Lot of Room for Improvement

Beef production systems in the United States are intertwined with an industrial-scale farming system that brings challenging consequences and significant room for improvement (Springmann et al. 2016; Porter, Mitchell, and Moore 2015; Veenstra and Burras 2015; Ripple et al. 2014; Greger and Koneswaran 2010; Montgomery 2007). Outlined here are some of the most significant environmental concerns (see Box 2 for concerns linked to consumption):

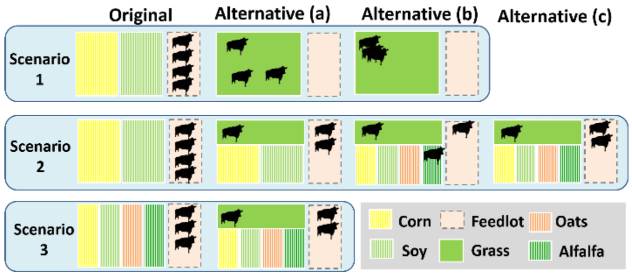
- ***Water depletion and pollution:*** Animal products can have large water footprints that contribute to drought risk, pollute surface and groundwater, create dead zones, damage fisheries, and deplete water reservoirs (Basche and Edelson 2017; Sobota et al. 2015; Barton and Clark 2014). In US industrial systems, beef's footprint has been estimated to be on average 29 gal/oz,[14] depending on cattle diet and management (Mekonnen and Hoekstra 2012). This value is partly attributable to corn feed; corn receives more irrigation water than any other crop (17.9 million acre-feet per year) and 87 percent of irrigated corn is grown in areas with high or extremely high water stress (Barton and Clark 2014; NASS 2014).[15] Grazing systems can have even higher water footprints when green water (rainwater) is included, because more feed is needed per animal due to lower feed efficiency and longer finishing times. However, such systems can conserve and boost water resources (e.g., blue and green water use; Mekonnen and Hoekstra 2012), especially when best management practices are used to improve soil water properties (e.g., water holding capacity and infiltration rates; DeLonge and Basche n.d.; Basche and DeLonge n.d., 2017; Basche 2017).

- ***Climate-disrupting emissions*:** Beef cattle have a large climate footprint, including emissions from digestion (enteric fermentation), manure management, and soils (from fertilizers and manure deposited by cattle).[16] In the United States, beef cattle have been estimated to contribute about 2 to 3 percent of total emissions (Gurian-Sherman 2011), which is high, considering that the agriculture sector contributes 7.9 percent of emissions (EPA 2017).[17] Studies in various systems have reported that the climate footprint of one pound of beef is around 0.03 to 0.07 t CO_2e (de Vries, van Middelaar, and de Boer 2015).[ii] Grain-based systems have been found to have 4 to 48 percent (average 28 percent) lower footprints than grass-based systems, due largely to higher enteric fermentation and longer finishing times in the latter. However, such comparisons have typically excluded soil carbon dynamics and are sensitive to several management factors (de Vries, van Middelaar, and de Boer 2015).[18]

- ***Soil health***: Agriculture often leads to erosion[19] and soil carbon losses, creating climate-disrupting emissions while reducing soil health and farm resilience (Sanderman, Hengl, and Fiske 2017; Amundson et al. 2015). Losses associated with beef production can result from practices such as conversion of grasslands to croplands (typically 0.7 to more than 3 t CO_2e/ac/y; Paustian et al. 2016) and poor grazing-land management (including overgrazing, up to 2.2 t CO_2e/ac/y; McSherry and Ritchie 2013). While there are no estimates of soil carbon losses due specifically to beef production, significant acreage could be affected. For example, 21 to 46 million acres of US corn were likely used for beef cattle in 2016.[20] Also, there are about 777 million acres of US grazing land (Nickerson et al. 2011), and previous studies have estimated that more than 100 million are poorly managed or degraded.[21] Finally, recent conversion of grasslands to croplands may be associated with losses of soil carbon (6 million acres or more; Gage, Olimb, and Nelson 2016; Lark, Salmon, and Gibbs 2015).[22]

- ***Overuse of antibiotics:*** Antibiotics are administered to livestock to treat and prevent illness or to promote growth. Seventy percent of antibiotics sold in the United States and that are considered important for humans are used for livestock and poultry production—though many of the animals are not sick—and this use can lead to antibiotic resistance in humans (Stashwick et al. 2016). While therapeutic uses of antibiotics are critical to treat sick animals, nontherapeutic uses are common and problematic. The estimated annual health care cost for antibiotic-resistant infections totals around $20 billion (CDC 2013), and despite recent Food and Drug Administration guidance directing producers to avoid antibiotic use for growth promotion, overuse has not substantially improved (Stashwick et al. 2016).[23] Conventional beef production systems rely on nontherapeutic use of antibiotics typically to maximize growth and prevent the contraction and spread of illness in concentrated facilities (Mathews and Johnson 2013; Gustafson and Bowen 1997).

FIGURE 2. **Original and Alternative Model Scenarios**



In Scenarios 1 and 2, the original system is a conventional corn-soy rotation with no animals on-farm. In Scenario 3, the original system is a four-crop rotation with oats and alfalfa, and no animals on-farm. All alternative scenarios include at least a partial conversion to pasture with continuous (Scenario 1a) or intensively managed (all others) grazing. Cattle are not drawn to scale but illustrate whether animals supported by the model farm production are located off-field (feedlot) or on-field (grazing). Also, all scenarios that include an assumption of reduced feed efficiency relative to the Scenario 1 case are represented with one fewer animal, as an indicator of potentially reduced productivity.

Analysis: Assessing the Benefits of Integrating Grass, Grazing, and Agroecology into Cropping Systems

To explore the effects of transitioning conventional farming practices to integrated, conservation-based alternatives, we developed and analyzed several scenarios for economic and environmental modeling (Figure 2). We based our analysis on a simple, farmer-tested economic tool, which we expanded to consider environmental and policy implications. The economic tool was designed for farmers to evaluate financial returns from different cropping systems, including options for integrating continuous living cover and grazing (Land Stewardship Project Cropping Systems Calculator [CSC]; Wasserman-Olin 2016).[24] The CSC model does not predict specific income, but rather a range of returns. Originally optimized for a 10-county region in Minnesota's Chippewa River Watershed, the model is most applicable to neighboring regions in the US Corn Belt. However, we designed our scenarios to be relevant to areas in the Great Plains and eastern United States that have sufficient access to water to be used for commodity crops. Critically, this analysis does not directly pertain to the more arid western grasslands, where grazing is already in place and many grasslands remain but are degraded (Box 1). For those areas, regenerative grassland management practices are the highest priority.

In our analysis, we modeled various cases of crop-based farms transitioning fully or partially to grasses, grazing, and complex crop rotations (Figure 2). For all scenarios, the integration of grazing in farms was modeled as a custom grazing operation during the finishing phase of cattle production. In addition, the "improved" grazing option we used from the CSC was "managed intensive," which is characterized by higher forage productivity, as opposed to both "continuous" and standard "rotational" grazing (Teague and Barnes 2017). The model scenarios included:

- **Full transition of conventional crops to grass (Scenario 1).** To explore the potential effect of a significant management change, we considered the case of 100 percent conversion of a corn-soy system to perennial pasture with either continuous (Scenario 1a) or improved (Scenario 1b) grazing.
- **Partial transition of conventional crops to grass (Scenario 2).** To evaluate a more moderate shift in practices, we considered the effect of partial conversion (33 percent) of a corn-soy system to perennial pasture with improved grazing. In Scenario 2a, we assumed that the rest of the farm (67 percent) remained in the corn-soy rotation. In Scenarios 2b and 2c, these corn-soy acres were converted to a four-crop rotation (corn-soy-oats/alfalfa-alfalfa) where alfalfa was either grazed (Scenario 2b) or harvested (Scenario 2c). In addition, to test the sensitivity of our results to yields and prices, we made simple modifications to Scenario 2c. We first considered the case where yields of corn and soy increased in the four-crop rotation due to boosted soil health.[25] We then also considered the additional circumstance of increased prices of corn and soy.[26]
- **Partial transition of diversified crops to grass (Scenario 3).** To assess the impact of adding grasses and grazing to a farm already using conservation practices, we considered the effects of converting 33 percent of land in a four-crop rotation (corn-soy-oats/alfalfa-alfalfa) to perennial pasture with improved grazing.

In addition to using the CSC to explore on-farm economic outcomes of these conversion scenarios, we estimated the value of select environmental outcomes, including climate and water variables. For climate emissions, we considered potential soil carbon gains as well as prevented emissions from reduced synthetic fertilizer and fuel use, but not changes to cattle emissions from manure or enteric fermentation (Table A2). We did not include changes to cattle emissions because the model was not capable of estimating altered total cattle numbers at a larger scale due to changes in supply and demand. However, the shift in proportion of animal feeds represented in the scenarios are likely to be linked with changing animal performance, productivity, and related changes to emissions and land requirements (de Vries, van Middelaar, and de Boer 2015). We therefore conducted some simple calculations to explore the number of cattle likely supported by each land base, using common assumptions regarding feed efficiencies, and we discuss the potential implications (Box 3).

For calculations involving climate emissions, we approximated the public value associated with net changes to greenhouse gas emissions using published estimates for the social costs of carbon and nitrous oxide (\$41/t CO_2 and \$14,860/t N_2O in 2015 dollars; IWGSCGG 2016a, b[27]). For the purposes of this analysis, we used these values to approximate the value of reduced climate emissions from the farm scale, assuming that cattle numbers and emissions overall stayed the same or decreased (Box 3). We also estimated payments for which farmers may be eligible through US Department of Agriculture (USDA) conservation programs, to get a sense for the existing public incentives that farmers could benefit from for adopting such practices and to compare these amounts to the estimated public value of farm-based benefits (soil carbon, reduced synthetic fertilizer and fuel). While conservation payments are highly uncertain, we assumed \$18/ac for land converted to perennial pasture and \$15/ac for adopting complex, “resource conserving” crop rotations.[28] Finally, we also estimated the impact of our scenarios on farm-level water footprints (green and gray water;[29] Table A2; Mekonnen and Hoekstra 2012).

To offer perspective on the ecological outcomes that may be possible through broader adoption of conservation practices, we conducted a simple scale-up analysis. We first identified land areas in Minnesota, the Corn Belt, and the Great Plains where the model scenarios could be applied, based on current corn and soy acreage and recent estimates of grassland conversion to croplands. The areas selected for the scale-up scenarios were between 0.2 and 5.7 million hectares, equal to 1 to 36 percent of total current Minnesota corn and soy acres (see table). The upper end of this range, 5.7 million acres, also equals the area of grassland (including native/planted, pasture, hay) estimated to have been recently converted to croplands in the western Corn Belt (acreage converted between 2008 and 2012, 1.6 million acres of which had been uncultivated for at least 20 years; see table; Lark, Salmon, and Gibbs 2015).[30] We extrapolated farm-scale results from profitable conversion scenarios and select variables only (fertilizer and fuel-cost savings, climate emissions reductions from soils, and gray water). As noted above, though the model does not estimate changes to total beef production based on shifts in supply and demand, we did conduct simple estimates of the implications of scaling up our scenarios on ecological aspects of beef production (Box 3).

We did not extrapolate total net returns, as noted earlier, because a fully dynamic economic model was outside the scope of this study and would be needed to predict how supply and demand would realistically adjust under policy and price environments. Thus, we have not considered the economic and political feasibility of a significant scale-up. However, a recent analysis based on results from Iowa showed that conservation crop rotations could be scaled up significantly before supply and demand effects would limit their profitability (Mulik 2017). Also, only some costs specific to the alternative grazing systems (such as fencing) were accounted for, while others were not (for example, changes to water access points or additional training and assistance that could be required). Further, the model included only a simplified estimate of changes to labor costs and likely underestimated these,

TABLE. **Acres Used for Scale-Up Scenarios**

Mill. Ac.	US Land Use Statistics of Interest	% MN C-S
5.7	Grass (native/planted, pasture, hay) to crops, 2008–2012, US[a]	35.6
3.0	Corn for animal feed, MN[b]	18.9
1.3	Grass to corn or soy, 2006–2011, W Corn Belt[c]	8.1
0.2	Grass to corn or soy, 2006–2011, MN[c]	1.2

Areas used for scale-up scenarios were based on statistics of grassland conversion and corn and soy acreage (shown as a percentage of total 2016 Minnesota corn and soy acreage [MN C-S], 16 mill. ac.).

particularly during the early stages of transition. However, we have likely also underestimated the value of improved synergies that would be facilitated by more integrated systems—such as reduced costs of transportation, fertilizer, or feed—because of proximity or economic efficiencies.[31]

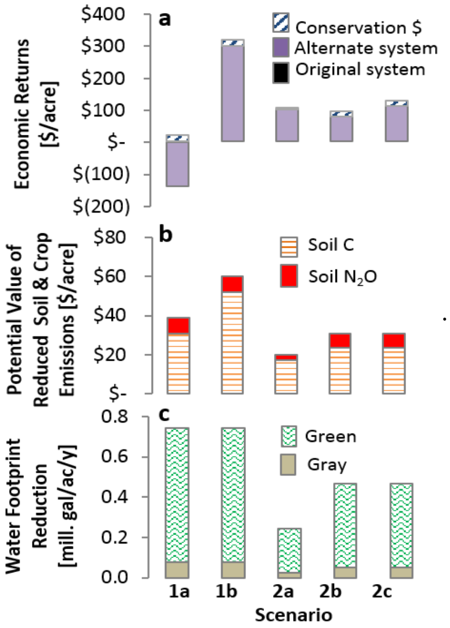
RESULTS: POTENTIAL FOR PROFITS AND ENVIRONMENTAL VALUE

Despite trends toward increasingly separated animal and crop production due to economies of scale and cheap feed crops, our model shows scenarios where it is viable for farmers with cropping systems to integrate grass and grazing into their farms. In most scenarios, economic returns to farmers were greater in the new versus the original management scenarios (Figure 3a; Table A3). Scenario 1a, with continuous grazing, was the exception, pointing to the sensitivity of these results to grazing management practices and skills.

While outcomes estimated here would vary by region and depend on soils, climate, and other factors, our results indicated that net returns to farmers for the new system were the largest ($298/ac) in the scenario where 100 percent of land was converted to perennial pasture with intensively managed grazing (Scenario 1b). Transitioning only partially to perennial pasture was less profitable but still increased returns (Scenario 2a; $98/ac). In this case of partial transition, converting the remaining corn-soy area to a complex crop rotation was a relatively less profitable option but still increased returns whether alfalfa was grazed ($76/ac) or harvested for sale ($11/ac). However, profits from scenarios with complex crop rotations increased when we assumed boosted yields of corn and soy due to conservation practices ($135/ac; Table A3; Figure A2). These profitable farm returns could still be possible under economic circumstances with stronger commodity prices, conditions in which the original scenarios (more focused on commodity crops) would be more favorable and farmers would have less incentive to make changes (Scenario 2c; Table A3; Figure A2).[32]

Our model demonstrated that certain scenarios converting simple monocrops to more diverse systems yielded environmental benefits, as well. If soil carbon sequestration and reduced fertilizer and fuel use achieved on-farm represented net climate emissions reductions, then the benefits of adopting the alternative practices could be even greater (Figure 3b). Further, in this case, the estimated social value from alternative scenarios exceeded the monetary value of estimated conservation payments. The value of the reduced on-farm emissions was the largest in Scenario 1, where the full acreage was converted to perennial grasses. However, even in the case where the original system was a conservation crop rotation (Scenario 3), a partial conversion to pasture increased the return on investment (Table A3). Further, when we explored the impact of assuming a less conservative soil carbon sequestration rate, the benefits of alternative scenarios may be more significant (Figure A3). Finally, farm water footprints were reduced in all scenarios, with large savings in green water footprints (reducing water needs and improving drought

FIGURE 3. **Outcomes of Model Scenarios**



Model results from transitions from corn-soy to alternative systems with conservation grazing and cropping practices. (a) Farmer profits, including returns from original system and additional returns from alternative system. Farmers may also be eligible for payments for conservation practices, so average payments from USDA conservation programs are shown for comparison. (b) Potential value of changes to climate emissions from crop and soil management, including soil carbon sequestration and reduced fertilizer and energy use (based on estimates for the social costs of CO_2 and N_2O and assuming no net change in cattle emissions). (c) Water footprint reductions, relative to the original system and based on planted crops/grasses, including reduced green and gray water (indicating drought resilience and reduced pollution, respectively; Table A3).

resilience) and additional savings in gray water (indicating reduced water pollution; Figure 3c).

Based on our model results, if a farmer converted one-third of a 1,000-acre conventional corn-soy farm to a well-managed, grass-based grazing system (Scenario 2a),[33] each year they could potentially save $28,000 in fertilizer costs and $1,500 in fuel costs; reduce climate emissions from fertilizer, fuel, and soils by more than 400 t CO_2e;[34] reduce the farm water footprint by 280 million gallons;[35] and generate $98,000 in profit. Other conversion scenarios—such as transitioning additional corn-soy acreage to grasslands (Scenario 1), adopting complex crop rotations (Scenarios 2b and 2c), or otherwise improving aspects of the cropping systems—could add to these farm-scale economic and environmental benefits (for a discussion of impact on productivity and cattle emissions, see Box 3).

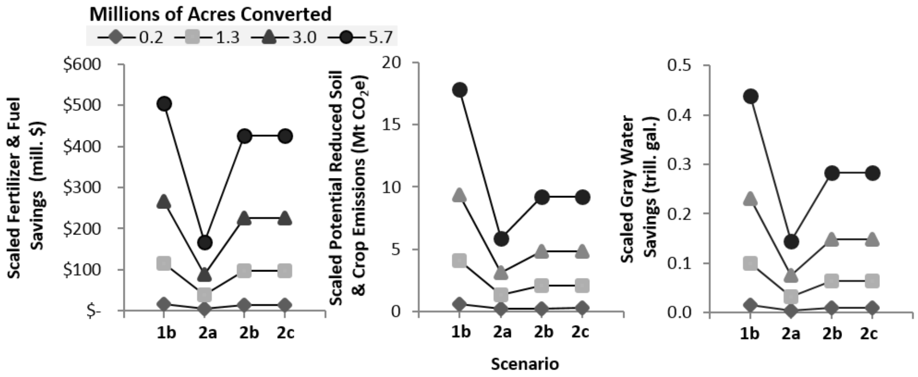
Finally, if more farmers adopted these ecological practices, more benefits could be accrued. While we did not estimate the scaling potential of total net returns, as stated earlier, we calculated that scaling the conservation scenarios to 5.7 million acres could bring cumulative fertilizer and fuel savings of approximately $506 million; reductions in emissions associated with fertilizer, fuel, and soils of around 8 Mt CO_2e; and reductions in gray water footprint of about 0.5 trillion gallons (Figure 4).

UNCERTAINTIES AND IMPLICATIONS

Overall, our analysis suggests that integrating cattle and grazing into conventional farms can provide economic and environmental benefits, but these benefits are sensitive to management, economic circumstances, local factors, and other variables. For example, profitable grazing systems depend on management and environmental conditions that can produce quality forage at low cost. The CSC assumes that good management practices are in place and that improved grazing produces significantly more feed than continuous grazing. If producers are not able to achieve comparable yields, returns will not be as high as our scenarios predicted. However, if producers achieve higher yields, returns could be even greater.

By several standards, our results are relatively conservative. For example, the high costs of planting alfalfa often deter farmers from planting the seed. They may therefore grow alfalfa only in cases where they plan to reap benefits for multiple seasons, opting otherwise for a cheaper crop such as clover for a four-year rotation. Thus, alternative complex cropping systems may be preferable to the ones we modeled,

FIGURE 4. **Impact of Scaling Up Select Conservation Scenarios**



Results from scaling up Scenarios 1b and 2a–c (Figure 2), including reduced fertilizer and fuel expenses (left); on-farm changes to soil carbon sequestration, soil N_2O emissions, and energy emissions (center); and gray water savings (right). Scenarios were scaled to 0.2 to 5.7 mill. ac.—representing 1 to 36 percent of current corn and soy acres in Minnesota—but could be distributed among various regions (see table).

but such systems require additional research to be optimized for different regions. Additionally, our analysis generally does not capture the "economies of scope" of diverse farms—such as reduced feed costs, pesticide costs, and manure-based fertilizer availability—possible under best management practices (Gameiro, Rocco, and Caixeta Filho 2016).

Current knowledge gaps about the environmental benefits of alternative practices created some uncertainties in our analysis. For example, the potential carbon sink resulting from different practices remains an area of active research (Paustian et al. 2016; Teague et al. 2016; West and Six 2007), but it is known to vary considerably, depending on factors such as climate, region, soil type, land-use history, and grazing management. We assumed relatively conservative sequestration rates, but in cases where higher rates are attainable, benefits could be greater, and vice versa (Figure A3). In contrast, conventional monocrop systems often experience soil carbon losses through erosion (4.7 t soil/ac, about 58 percent of which is carbon; NRCS 2015), a factor for which we did not account. Another area of active research is the magnitude of N_2O emissions from fertilizer application. We used the same emissions factor to estimate N losses from both the corn-soy and alternative systems. Thus, we may have underestimated potential savings from the ecological practices (Shcherbak, Millar, and Robertson 2014). Likewise, water footprints for different crops are sensitive to local landscapes, soils, climates, and practices. Since we based our model on average published values for water footprints, it is likely that farmers who are applying the best management practices could further improve water savings. Lastly, uncertainties surround other variables, such as enteric fermentation and manure emissions, that we were not able to include our model (described earlier). Additional research could be targeted toward improving understanding of these variables and identifying best management practices for alternative production systems.

Extrapolating our model results to explore the impact of scaling up scenarios also included numerous uncertainties, as wider adoption rates of such practices could affect total cattle inventories and therefore influence livestock-sector emissions, particularly those related to enteric fermentation and manure management. Our ecologically based scenarios were still productive and even more profitable for farmers, but implementing such systems may require more land and emit more total climate emissions if beef production rates were to remain constant. Therefore, maintaining or decreasing climate emissions overall while transitioning to such systems would require reduced beef production and/or optimized integrated systems with substantial soil carbon sequestration (Box 3).

Finally, our analysis focused on a limited set of cropping system scenarios, and additional research is needed to evaluate the likely profitability and benefits of other integrated and diverse systems. To date, only a handful of studies on integrated crop-livestock systems have been conducted, but several have found that integrating grazing animals into cropping systems can be profitable due to a variety of factors such as lower fertilizer and irrigation needs and improved waste management (Poffenbarger et al. 2017; Gameiro, Rocco, and Caixeta Filho 2016; Hilimire 2011).[36]

Conclusions and Recommendations

Beef production systems, including intensive monocropping of animal feed, have been linked to significant environmental and human health challenges, and Congress and the USDA can mitigate these challenges through policy changes. We propose that shifting farming practices and reducing conventional beef production together can benefit farmers while potentially reducing climate-disrupting emissions; increasing resilience to droughts and floods; reducing water pollution; and restoring diversity of native plants, fish, and wildlife. Our analysis shows that farms including cattle can contribute to this broader push through ecological, integrated crop-livestock production systems that are expanded alongside reduced conventional beef production. However, to achieve desirable and balanced outcomes, integrated systems must be optimized through strategic diversification of systems from local to regional levels, and by incorporating crop rotations, cover crops, and more techniques. Such a transformation could benefit farmers and the public, and we propose several policy recommendations that can help to support farmers and researchers in building better beef production systems and that can facilitate a food system that relies on less total beef.

- **Bolster programs to encourage farming practices that boost soil health.** The Natural Resources Conservation Service (NRCS) offers programs and financial incentives to support farmers' adoption of practices that conserve resources, build farm resiliency, and sequester soil carbon. These practices include conversion to perennial pasture, grassland conservation, improved grazing management, complex crop rotations, cover cropping, improved manure management, conservation tillage, and agroforestry.

Congress and the USDA should protect and enhance NRCS programs to incentivize a transformation that could benefit farmers and taxpayers:

- The Conservation Stewardship Program (CSP) offers financial and technical assistance to farmers to promote conservation and improvement of soil, water, and air. Payments for regenerative and climate-friendly practices—including integration of animals into well-managed diversified farms—should be increased. Also, managed grazing systems (such as management-intensive rotational grazing or adaptive multi-paddock grazing) should be added as a practice qualifying for a supplemental payment within CSP.
- The Conservation Reserve Program (CRP) offers an important avenue to protect land and deliver numerous services (Johnson et al. 2016). However, contracts limit the availability of land for agricultural use and last just 10 to 15 years, and benefits can be lost when contracts end (Hellerstein 2017; Morefield et al. 2016; Vandever and Allen 2015). The CRP could be improved by expanding CRP Grasslands, a program that allows grazing on protected acres, and by offering additional technical assistance to help producers implement sustainable grazing management plans.
- The Environmental Quality Incentives Program (EQIP) provides financial and technical assistance to producers and landowners to plan and install structural, vegetative, and land management practices. The program could promote adoption of regenerative agricultural practices by shifting more resources to farms that implement diverse crop and livestock farming systems and moving resources away from CAFO expansion. Such a shift could be facilitated by emphasizing grazing management for pasture quality within EQIP funding for prescribed grazing, and by reimbursing land management practices at 75 percent while reimbursing infrastructure at a maximum of 50 percent. In addition, the Conservation Innovation Grants within the EQIP program should be increased, and new funds should prioritize innovations related to cropping and grazing in diverse, integrated systems.

- **Improve education, technical assistance, and regulations to support farmers and ranchers in adopting**

BOX 2.

What about Health? Less Beef Is Better, and Source Matters

Today, the US Dietary Guidelines for Americans recommends that Americans consume 26 oz.-equivalents per week (3.7 oz-eq/day) of meat, poultry, and eggs,[37] and most Americans are close to meeting these recommended amounts—or they exceed them.[38] Based on data about current diets and decades of scientific literature, the 2015 Dietary Guidelines Advisory Committee (DGAC) recently recommended that Americans shift to diets lower in red and processed meat and higher in fruits and vegetables.[39] This recommendation was based largely on scientific evidence that such dietary patterns can reduce health risks, particularly for cardiovascular disease but also for obesity, type 2 diabetes, and some types of cancer (DGAC 2015). The committee made science-based recommendations that the Dietary Guidelines consider sustainability and noted that beef was the food with the greatest environmental impact. However, this recommendation was not integrated into the final US Dietary Guidelines. Nevertheless, recommendations from the expert advisory committee suggest that eating less beef can contribute to positive health for many Americans, while also delivering environmental benefits.[40]

But what about “better” beef? Studies have shown that grass-finished cattle may have improved fatty acid composition and antioxidant content (Daley et al. 2010). Similarly, other research has indicated that organic meat, which could be produced with organic grass or grains, may reduce risks of cardiovascular disease (Srednicka-Tober et al. 2016). Such research demonstrates that meat produced in alternative systems may offer greater nutritional benefits than conventional beef. However, as described in this report, research has found that many alternative beef production systems produce less beef per acre and more emissions per pound of beef, posing potential challenges and trade-offs (Box 3). Therefore, consumers seeking “better” beef may want to purchase products from farms using the best management practices and to eat less beef if they aim to reduce the carbon or land footprints of their diets. Currently, such beef can be hard to find and more expensive (Cheung et al. 2017), a condition that is unlikely to change if the USDA or other stakeholders do not take measures to increase marketing and education.

innovative practices. Despite the economic and environmental viability of improved, integrated cropping and grazing systems, scaling these up will require much stronger support for farmers who must overcome barriers (DeLonge and Basche 2017). For example, additional technical service providers will be needed to assist farmers seeking to begin or improve grazing practices. Congress should direct the NRCS to significantly expand its pool of technical service providers in the field of mixed crop-livestock and adaptive management systems so that farmers can get the support they need. Ensuring greater access to the nation's broader network of grazing system management trainers would be a great step forward. On public lands utilized for grazing, Congress should direct the Bureau of Land Management to review federal regulations regarding grazing programs to ensure that they reflect the latest science on sustainability (with respect to soil carbon, water, and climate emissions) and that producers can implement the most ecologically sound practices.

- **Revamp crop insurance to remove obstacles that hamper farmers' ability to reduce risks.** Current farm policy overwhelmingly incentivizes large-scale, monocrop grain systems and presents obstacles for farmers interested in alternatives (Wright 2015). Congress and the USDA should shift the federal crop insurance program toward incentivizing more regenerative practices and away from disproportionately incentivizing industrial animal and monocrop production systems.
    - The Federal Crop Insurance Corporation is the USDA's largest farmer safety net, providing producers with insurance policies that protect them against losses to their yields and revenue. However, the program does not consider the role of soils and discourages resilient farming strategies, such as cover cropping (Woodard and Verteramo-Chiu 2017; Ristino and Steier 2016). We recommended that future policies include soil data in insurance formulations and develop risk management programs specific to sustainable products.
    - The Whole-Farm Revenue Protection Pilot Program (WFRP), established in the 2014 farm bill, is a new type of crop insurance designed for diverse farms that are growing a range of commodities, including farms selling to local or regional markets and producing specialty, value-added crop and animal products. As the program is relatively new, the current priority is to increase awareness and educational and staff training materials in support of WFRP.
- **Increase public investment in agroecological research.** Currently, a lack of public research funding for agroecology is slowing the adoption and continued improvement of regenerative farming practices (Miles, DeLonge, and Carlisle 2017; DeLonge, Miles, and Carlisle 2016). Congress and the USDA should increase funding for key research programs and prioritize projects investigating more regenerative and integrated cropping and grazing systems, including adaptive grazing management and diverse feed production systems. Key programs include the Agriculture and Food Research Initiative (the USDA's largest competitive grants program), the Sustainable Agriculture Research and Education program (the only funding program dedicated to sustainable farming practices), and the Organic Agriculture Research and Extension Initiative (a critical program supporting agroecological research for organic farming). Also, because long-term research is particularly needed for these areas of study, programs such as those affiliated with the USDA's Long-Term Agroecosystem Research Network should be directed to support more research into regenerative integrated cropping and grazing systems.
- **Improve and develop programs that help regenerative producers thrive**. Small and midsize farming systems transitioning to regenerative practices are often more disadvantaged than conventional systems, but Congress and the USDA could create a more level playing field by adjusting policies to:
    - Allow producers who receive relevant certifications (such as third-party organic, grass-fed and humane certifications) to opt out of the beef check-off program so that they can use their resources to promote products that the check-off program does not market.[41]
    - Improve and develop aggregation programs, such as the Local Food Promotion and Value-Added Producer Grant programs, to make small and mid-scale improved beef production more viable.
    - Support programs and strategies that develop or use certifications, labeling, or consumer education to help distinguish beef produced in more regenerative systems. Such programs should verify not only what the cattle consume, but also that they were raised on credible, well-managed ranches and farms.

  - Increase the accessibility and affordability of beef from improved systems. Currently, beef products from specialized systems typically cost 25 to 40 percent more than conventionally produced meat (Cheung et al. 2017). Thus, the latter is the only economically viable option for many people.
- **Begin to transform existing policies and regulations that disproportionately incentivize industrial-scale production of feed crops in monoculture and cattle in CAFOs.** The USDA could take several steps to reduce the negative impact of large-scale monocultures and CAFOs, such as reducing nontherapeutic uses of antibiotics and pushing back against consolidation. However, these changes must be paired with strengthened conservation compliance on grasslands and rangelands to avoid any shifts that unintentionally further degrade those systems.
- **Align the US Dietary Guidelines for Americans with science-based Dietary Guidelines Advisory Committee recommendations to encourage a shift toward more nutrient-dense protein sources and more rigorous sustainability standards**. The current Dietary Guidelines recommend that the general population shift dietary patterns to include a greater variety of nutrient-dense protein options—including seafood, legumes, and lean and low-sodium meats—and that teen boys and adult men reduce overall intake of protein foods such as meat, poultry, and eggs. The guidelines should be strengthened to match those of the 2015 Dietary Guidelines Advisory Committee (DGAC 2015), which more broadly recommended shifting to diets lower in red and processed meat and higher in fruits and vegetables, based in part on their finding that these products (and especially beef) had the greatest environmental impact. The guidelines should also recognize the different nutritional profiles and environmental effects between and among protein sources, including differences between grass- and grain-based meat. Due to the human, animal, and environmental health benefits associated with well-managed beef systems that do not rely heavily on antibiotics, growth hormones, chemical fertilizers, and pesticides, products from these systems should be prioritized over those sourced from highly concentrated, feedlot systems associated with environmental degradation and growing antibiotic resistance.

BOX 3.

Balancing Trade-Offs by Producing Less and Better Beef

In the alternative systems considered in this analysis, we estimated higher profits for farmers and more environmental benefits on a per area basis. However, we also estimated lower beef production per acre, based on our model assumptions. Under these circumstances, farms were more ecologically and economically sustainable, but less beef production was supported per acre. This outcome could put the overall benefits of alternative systems at risk if demand were to remain constant. For example, while there are cases where using more land could be beneficial (for example, if that land is protecting or improving grasslands), doing so could also be detrimental (e.g., diverse grasslands could be converted to nondiverse croplands, or diverse forests to poorly managed grasslands). Furthermore, since incorporating more grass into cattle diets would increase animal emissions, use of the currently available alternatives to maintain a constant level of production would contribute additional emissions.

For these reasons, optimal outcomes may result from pairing best land management practices with policies that simultaneously reduce overall conventional beef consumption. With this idea in mind, we explored how much US beef consumption may need to decline to keep land use constant and to secure reduced net climate emissions in some of our scenarios.[42] Our calculations indicated that the required decrease in beef production as a result of scaling scenarios to 5.7 mill. ac. might amount to 347 to 924 mill. lbs. per year. This reduction, when spread across the US population, would equate to a reduction of just a fraction of one serving of beef per week (0.3 to 0.9 oz/wk less beef; Figure A4),[43] a relatively small amount that could potentially contribute to improved diets for many Americans (Box 2).

An important thing to consider is that the productivity of any agroecosystem could be increased or reduced in response to management and environmental factors, and that yields and total production are likely to change over both spatial and temporal scales. Furthermore, additional products and services (tangible and intangible) are delivered by such systems but not captured in this analysis. Therefore, our results offer just a snapshot of the potential outcomes of adopting alternative practices.

Ultimately, healthier soils are expected to support more resilient and productive farms. Thus, a key first step to improve sustainability is to implement and develop practices that build soil health. Additional policies and programs should then be put into place to prevent the expansion of any systems that are not ecologically sustainable.

[ENDNOTES]

[1] Cheap prices are driven by factors such as high yields, government incentives, and economies of scale.

[2] Finishing time depends on factors such as entry weight and diet (Table A1).

[3] In 2016, 86.7 million acres of corn (138 million metric tons [Mt]) were harvested in the United States (NASS 2017). Of all corn, 35.8 percent went to feed (ERS 2017). Beef cattle consumed 24.7 percent of feed (poultry and hogs consumed 33.1 percent and 30.5 percent, respectively; the remainder went to dairy and other livestock) (ERS 2017). While these proportions were calculated using additional feeds (sorghum, barley, oats, wheat), corn represents a majority (more than 90 percent). Thus, if 24.7 percent of corn for feed went to beef cattle, this represents 8.8 percent of all corn. Alternatively, one could assume that all 17 million steers (or all 31 million cattle) slaughtered were finished on a ration with 1,037 kilograms of corn (Lupo et al. 2013), which would indicate that 17 to 32 Mt of corn (or 13 to 23 percent of corn) were used for cattle finishing in 2016. These estimates are in the range of previously reported estimates in various years: 10 percent (Barton and Clark 2014), 15 percent (Williams 2016), and 20 percent (Gurian-Sherman 2011). In addition, about 35 percent of all corn goes to ethanol and by-products, including distillers grains, which are also oftentimes used to feed cattle (Barton and Clark 2014).

[4] Ruminants (such as cattle, sheep, and goats) have stomachs that can digest some foods, such as grasses, that nonruminants (such as poultry and hogs) cannot.

[5] Farmers in sixteenth-century Europe discovered that growing livestock and crops together could boost yields, prompting an agricultural revolution, but integration declined after World War II, due to new machinery designed to operate in uniform systems and the use of chemical pesticides and fertilizers (Gliessman 2014). In 2014, 48 states grew grain, but only four integrated livestock into at least 4 percent of operations (Figure A1).

[6] For definition and details on CAFOs see EPA (2012).

[7] The remaining 20 to 30 percent of production occurs in CAFOs with between 1,000 and 32,000 cattle.

[8] Harun and Ogneva-Himmelberger (2013) investigated chicken, hog, and cattle CAFOs and only found significant environmental justice issues with respect to minority populations for chicken CAFOs. Cattle farms had significantly higher white populations near CAFOs as compared to other areas, but also had a higher percentage of white population below the poverty line.

[9] CO_2e is CO_2 equivalents, the unit for Global Warming Potential (GWP). GWPs quantify gases' ability to trap heat in the atmosphere (GWPs of CO_2, CH_4, and N_2O are 1, 25, and 298 CO_2e, respectively, 100-year time horizon; IPCC 2014)

[10] The study considered only sequestration in rain-fed grazing land east of the 100th parallel, where there is greater certainty. The researchers assumed nearly 25 mill. ac. of cropland could be converted.

[11] Agroforestry with livestock is called silvopasture and can create wildlife habitat, shade, and shelter; improve water cycling; and provide windbreaks, riparian buffers, and lumber (Schoeneberger et al. 2012).

[12] Assuming consumption rates of 12.11 oz/person (Bentley 2017), the average daily water footprint associated with beef would be 2.8 to 5.7 gal/person. By comparison, a 10-minute shower consumes about 25 to 50 gal., and household water use of a US family of four is estimated to be 400 gal/day (EPAWS 2008).

[13] For example, manure emissions can be lowered by adding tannins in pasture (Chadwick et al. 2011).

[14] At this rate (including blue, green, and gray water) and assuming consumption rates of 12.11 oz/person (Bentley 2017), the average daily footprint associated with beef is ~50 gal/person. Note that the global average water footprint for beef is higher, at 115 gal/oz (Mekonnen and Hoekstra 2012).

[15] The Great Plains region produces 25 percent of US corn and relies on the High Plains aquifer (including the Ogallala) for irrigated water (Barton and Clark 2014).

[16] Emissions from enteric fermentation and manure depend on feed variety and maturity, and other management factors (Gerber, Henderson, and Makkar 2013; Hristov et al. 2013). Soil N_2O may be higher for heavily fertilized crops (Shcherbak, Millar, and Robertson 2014) or in areas with more runoff (e.g., the Corn Belt; Turner et al. 2015).

[17] US agriculture emissions include enteric fermentation, manure management, rice cultivation, soil management, and burning. Beef emissions include enteric fermentation, manure emissions, and soil N_2O loss from corn and pasture, but exclude other feeds and soil carbon. Globally, livestock (mostly beef and dairy cattle) are estimated to contribute 8 to 18 percent of total emissions (Herrero et al. 2015; Gerber, Henderson, and Makkar 2013).

[18] Assuming 0.03 t CO_2e/lb beef and 12.11 oz. beef /person/week (Bentley 2017), this is 4.72 t CO_2e/y for a family of four, slightly less than annual emissions from a passenger vehicle (EPA n.d.).

[19] Sheet and rill erosion on nonfederal rural lands in 2012 was 2.99±0.05 t soil/ac/y in cultivated US croplands and 0.69±0.03 t soil/ac/y in US pasture; wind erosion was 2.20±0.06 t soil/ac/y and 0.18±0.03 t soil/ac/y on cultivated croplands and pasture, respectively (NRCS 2015).

[20] Based on finding that 9 to 20 percent of corn goes to beef cattle and 94 mill. ac. of corn were planted in 2016.

[21] Not all grazing land is used for beef production. However, most acres designated as pasture or range west of the Mississippi (~300 mill. ac.) are devoted to beef cattle (Conner et al. 2001). The percent of land degraded by beef cattle grazing is unknown, but Schuman, Janzen, and Herrick (2002) estimated 297 mill. ac. of US grasslands were poorly managed, and Herrick et al. (2010) found that 21 percent of western US rangelands were at least moderately degraded. Follett, Kimble, and Lal (2001) estimated even more degradation, concluding that only 60 percent of western US rangeland was in good condition for forage production. Assuming 300 mill. ac. are used for beef cattle and 21 percent are degraded, 63 mill. ac. could benefit from improved management.

[22] US soil carbon losses related to beef could be ~152 Mt CO_2e/y (by comparison, US Agricultural Soil Management emissions were 318.4 Mt CO_2e in 2014). This assumes 63 mill. ac. of grazing land are degraded by beef cattle; 21 mill. ac. of corn are used to feed beef cattle (5.7 mill. of which were recently converted from grasslands); and that carbon losses are 2.2, 1.5, and 0.3 t CO_2e/ac/y for grazing lands, recently converted croplands, and long-term cultivated croplands, respectively.

[23] Food and Drug Administration guidance can be found at *https://ahdc.vet.cornell.edu/programs/NYSCHAP/nysvfrp/vfd.cfm#antimicrobials.*

[24] The model was originally designed for farmers participating in the Chippewa 10% Project. For details, see Wasserman-Olin 2016. Unless stated otherwise, we used default values. The model does not include supply and demand factors. The CSC includes options for year-round or custom grazing and offers various grazing operations (cow/calf, stocker, feeder-to-finish) and management styles (continuous, rotational [6 days/paddock], managed intensive [1 d/paddock], mob [0.5 d/paddock]). The model accounts for grazing differences by assuming different productivity levels (e.g., 5.6 and 1.35 t dry matter/ac for managed intensive versus continuous grazing, respectively). The CRC is also based on the Grass-Fed Beef Decision Calculator (WCWI n.d.)

[25] Yields were changed based on a study in Iowa that found that a four-crop rotation with corn and soy led to higher yields by 5 percent and 27 percent, respectively, compared with a simple corn-soy rotation (Davis et al. 2012). Fertilizer, fuel, and other chemical inputs were assumed to be decreased in these systems, according to data from the same experiment (Table A2). These cost savings were not accounted for in the economic calculations, so calculated profits may be conservative.

[26] It is often more profitable to plant corn-soy versus complex rotations when commodity prices are high.

[27] These values are only an approximation for the broader social costs of net global increases to total atmospheric greenhouse gas concentrations (Metcalf and Stock 2017). They are only used here as a rough indicator of the possible benefits of our modeled scenarios, assuming that the scenarios represent a net reduction in climate emissions.

[28] Although the amount farmers can earn from conservation programs ranges widely, the average payment from the Natural Resources Conservation Service's (NRCS) Conservation Stewardship Program is $18/ac for farms that adopt several practices; an additional $15/ac is available for implementing a resource-conserving crop rotation (NRCS n.d.).

[29] We assumed rain-fed (not irrigated) systems and therefore did not investigate blue water footprints.

[30] For perspective, the entire state of Minnesota is about 51 mill. ac.

[31] Diversification in farms can reduce transaction costs for obtaining resources and managing wastes, improving economic viability. This is referred to as "economy of scope" (Gameiro, Rocco, and Caixeta Filho 2016).

[32] Supply and demand factors were not considered for this analysis, so these results reflect only a simple scenario of increased prices and farm-scale cropping system conversions.

[33] Including profits from grazing based on a custom grazing operation with intensively managed grazing during the finishing phase, as simulated with the CSC. Farm-level calculations are separate from the larger-scale estimates for total possible beef production, which are based only on feed production and not directly tied to the farm production system. This simplification is due to the complexities of beef systems and because much of beef production happens off-farm in the original scenario. On-farm CSC calculations offer insight into beef production through grazing systems, but not into overall beef production.

[34] A passenger vehicle emits 4.73 t CO_2e/y (EPA n.d.), so this equates to removing 85 cars from the road.

[35] An Olympic-sized pool holds 660,430 gal., so these savings are equivalent to 424 swimming pools.

[36] For example, transitioning a cotton monoculture to a cotton-forage-livestock system increased profits from $77/ac to $147/ac, and winter grazing of a cover crop in a cotton-peanut rotation increased revenue by $126/ac (Franzluebbers 2007; Allen et al. 2005).

[37] Based on a 2,000-calorie-level Healthy US-Style Eating Pattern.

[38] Teen boys and adult men exceed recommended intakes. Average consumption per person of meat, poultry, fish, and shellfish is 5.74 oz-eq/d; beef is 1.73 oz-eq/d (12.11 oz-eq/wk; Bentley 2017).

[39] Beef, pork, lamb, veal, goat, and nonbird game are considered red meat.

[40] Consumers seeking meat-based protein alternatives for environmental reasons should be aware that many of today's other animal products also rely heavily on industrial cropping systems and contribute to similar environmental problems (von Reusner 2017) but at much smaller amounts per serving (Eshel et al. 2014; Hedenus, Wirsenius, and Johansson 2014). Further, equity issues regarding health and safety in concentrated feedlots and meat-processing facilities exist across meat categories (Gunderson 2012). Animal welfare issues are also present across animal agricultural systems (Robbins et al. 2016; Grandin 2014).

[41] Mandatory check-off programs tax producers of specific commodities and use those funds for research, development, and promotion that do not benefit all producers equally.

[42] We assumed that a reduction in production of high-efficiency feeds on the farm would be associated with a reduction in cattle production. We assumed crop yields as described in the scenarios and standard moisture levels. We estimated potential beef production with available feeds using efficiency rates of 7.8 kg. beef per kg. dry matter for common feeds (corn, oats, and soy) and 27 kg. beef per kg. dry matter for forage feeds (grass and alfalfa) (Wilkinson 2011; because these ratios assumed bone-in carcass fresh weight, we calculated boneless edible meat as 70 percent of the beef totals; Nijdam, Rood, and Westhoek 2012). We did not consider how the proportions of feeds in our scenarios affected feed ration composition, as our goal was to obtain only a basic sense of the degree to which a switch to farming more forages on a farm producing animal feed could affect production.

[43] A serving is 3 oz. (USDA 2012). This reduction is a fraction of current consumption (12.11 oz/wk).

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[APPENDIX]

TABLE A1. **Cattle Life Phases**

Phase	Duration, End Weight[a,b]	Feed	Details
Cow-Calf	180–240 d, 400–700 lbs.	Grazed forage	Mothers stay on-farm for next breeding cycle, bringing additional costs. Most operations are small (average cowherd of 40 head). While the majority (91%) of operations maintains <100 cows, these represent only 49% of the beef cow inventory.[c]
Backgrounding/ Stocking	120–200 d, 800 lbs.	Stocking: grazed forage. Backgrounding: cheap feeds.	Phase can be co-located with cow-calf, but most farmers manage only one. Backgrounding diets often include ~40% grain, 60% forage (including corn, alfalfa hay, wheat, barley, oats, distillers grains).[d]
Feedlot Finishing	120–240 d, 1,350 lbs.	Large proportions of grain and protein concentrates (up to 70–90%).	Usually occurs in feedlots (confined animal feeding operations [CAFOs]). While the majority (>95%) are small (<1,000 head), these operations produce only 10–20% of feedlot cattle, whereas the largest (>32,000 head; <5% of feedlots) produce about 40%.
Grass Finishing	180–480 d,[e,f] 1,150 lbs.	Grazed forage. High-quality forage can reduce duration and animal emissions.[e,f]	Grass-finished system representing less than 3% of the US beef market.
Beef from Dairy			18% of US beef are from the dairy industry (6% from old dairy cows; 14% from fed, mostly male dairy calves).[h] The footprints of these animals are different, as they are products of distinct systems.

Beef production systems tend to be more complex than other animal operations, and cattle are managed differently as they move through phases. Phase durations and end weights depend on various factors, such as entry weights and diets.

Notes: In the Upper Midwest, about 50 percent of production involves sending calves directly to feedlots for longer finishing periods (303 days, 10 months), whereas the other 50 percent entails 300 d on pasture followed by 150 d (5 mos.) in feedlots (Pelletier, Pirog, and Rasmussen 2010). Finishing can be shorter in some environments (e.g., California; Stackhouse-Lawson et al. 2012; 121–212 d). While rates of weight gain are 5–7 lbs. dry matter/lb on grain-based feeds, they are lower on forage (usually 7–25 lbs. dry matter/lb, depending on forage quality; Coffey 2011).

DATA SOURCES: (A) CHEUNG ET AL. 2017; (B) LUPO ET AL. 2013; (C) ERS 2016; (D) LARDY 2013; (E) CAPPER 2012; (F) PELLETIER, PIROG, AND RASMUSSEN 2010; (G) MATHEWS AND JOHNSON 2013; (H) LOWE AND GEREFFI 2009.

TABLE A2. **Values of Key Variables Used to Calculate Effects of Scenarios Including Corn-Soy Rotations and Four-Crop Rotations**

Category	Value(s)	
Soil Carbon Fluxes	**Low Carbon Case**	**High Carbon Case**
Cropland to Pasture [a,b]	0.20 t C/ac/y	0.40 t C/ac/y
Managed Grazing (vs. Continuous) [a,b]	0.14 t C/ac/y	0.40 t C/ac/y
Complex Crop Rotation (Four-Crop Rotation) [b,c]	0.06 t C/ac/y	0.20 t C/ac/y
Soil Nitrogen Fluxes	**Value**	
N_2O-N Lost After Application [d,1]	1.0%	
Input Use	**Fertilizer use**	**Energy Use**
Corn in Corn-Soy Rotation	143 lbs/ac/y [e,2]	5.83 BTU/ac/y [h,5]
Corn in Four-Crop Rotation	0 [f,g,3]	2.63 BTU/ac/y [h,5]
Other Crops	Var.[f,g,4]	Var. [h,4]
Water Footprint	**Gray Water**	**Green Water**
Corn [i,6]	187 m^3/ton	1,082 m^3/ton
Soy [i,6]	33 m^3/ton	2,079 m^3/ton
Oats [i,7]	128 m^3/ton	1,479 m^3/ton
Alfalfa/Grass [i,8]	20 m^3/ton	207 m^3/ton

Notes: 1. Recent studies suggest this may be too low in heavily fertilized corn-soy and too high for more sustainable systems (Turner et al. 2015; Shcherbak, Millar, and Robertson 2014). 2. Minnesota state average. 3. Based on use of a legume as fourth crop and corn as first. 4. Based on corn rates and scaled to other crops using Cropping Systems Calculator costs (Wasserman-Olin 2016). 5. Energy units converted to CO_2 using diesel fuel emissions factor (161.30 lbs. CO_2/mill BTU; EIA 2016). 6. Rain-fed (Table 8 in Mekonnen and Hoekstra 2011); 10 percent lower for 4-CR. 7. Table 3 in Mekonnen and Hoekstra 2011. 8. Table 2 in Mekonnen and Hoekstra 2011 (fodder crops).

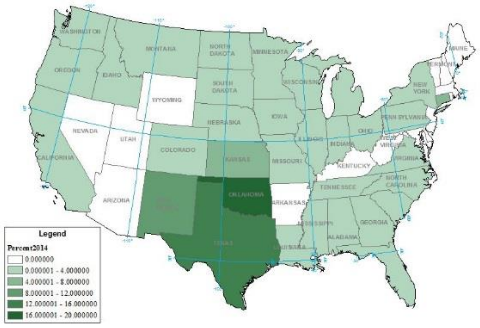
DATA SOURCES: (A) CONANT, PAUSTIAN, AND ELLIOTT 2001; (B) CHAMBERS, LAL, AND PAUSTIAN 2016; (C) MCDANIEL, TIEMANN, AND GRANDY 2014; (D) BOUWMAN, BOUMANS, AND BATJES 2002; (E) NASS 2014; (F) CLARK 2007; (G) DAVIS ET AL. 2012; (H) JOHANNS, CHASE, AND LIEBMAN 2012; (I) MEKONNEN AND HOEKSTRA 2011.

TABLE A3. **Results of Model Analysis**

Scenario	Original Cropping System	Alternate System Return	Fertilizer Savings	Fuel Savings	USDA Conserv. Payment	Soil C Value	Soil N_2O Value	Total Return Alternate System
1a	$4.80	$(137.01)	$84.27	$4.55	$18.00	$30.72	$8.20	$(98.09)
1b	$4.80	$297.58	$84.27	$4.55	$18.00	$52.02	$8.20	$357.79
2a	$4.80	$98.08	$27.81	$1.50	$5.94	$17.17	$2.71	$117.95
2b	$4.80	$76.01	$73.37	$1.56	$15.99	$23.69	$7.14	$106.83
2c	$4.80	$109.85	$73.37	$1.56	$15.99	$23.69	$7.14	$140.67
2c+Y	$152.26	$42.33	$73.37	$1.56	$15.99	$23.69	$7.14	$165.75
2c+Y$	$4.80	$134.93	$73.37	$1.56	$15.99	$23.69	$7.14	$73.16
3	$20.74	$97.77	$5.36	$1.47	$0.99	$13.95	$0.52	$112.25

Notes: Changes shown in value per acre, calculated at the farm scale using the Cropping System Calculator. Changes in climate emissions from altered fuel use were negligible (not shown). Total return includes potential social value from changes to soil carbon sequestration and N_2O emissions (calculated using estimates for social costs of carbon and nitrous oxide; IWGSCGG 2016a, b).

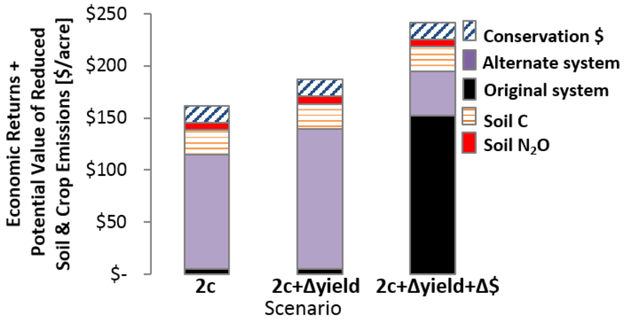
FIGURE A1. **Cropping Systems That Integrate Cattle**



Despite the prevalence of integrated crop-livestock systems in the developing world, US agriculture is dominated by farms that are more specialized. In 2014, while all 48 states in the contiguous United States grew some varieties of grain, most (44) integrated livestock into less than 4 percent of operations, and only Texas and Oklahoma integrated livestock into more than 10 percent of the operations.

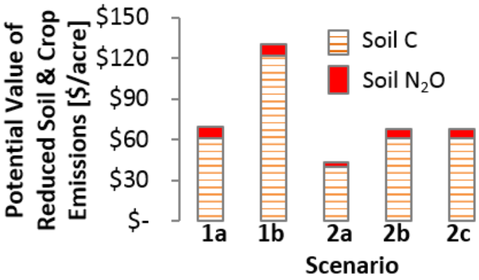
DATA SOURCE: FSA 2015.

FIGURE A2. **Sensitivity to Increased Yields and Prices of Corn and Soy**



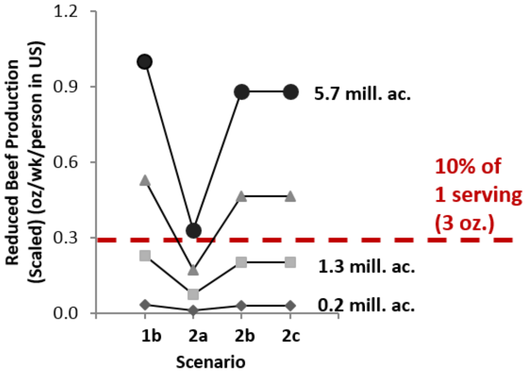
Results are shown for Scenario 2c, conversion of a corn-soy system to perennial grasses with grazing (33 percent) and a four-crop rotation (67 percent). The left bar show results from Figure 3 (a and b; Scenario 2c). The middle bar (Scenario 2c+Δyield) shows results when corn and soy yields were assumed to increase in the new four-crop rotation (due to improved soil health). The bar on the right (Scenario 2c+Δyield+Δ$) shows the same case, but with the additional assumption that corn and soy prices are higher (for both original and new systems).

FIGURE A3. **Sensitivity of Model Results to Carbon Sequestration**



Note: Results assume higher soil carbon sequestration rates are possible for all new practices (Table A2).

FIGURE A4. **Potential Effect of Scaling Up Select Alternative Scenarios**



Effect of scaling up scenarios 1b and 2a–c (Figure 2) on beef production, expressed as the amount of reduced production per US citizen (based on a US population of 323 million; Box 3). We consider the outcome of scaling up scenarios to 0.2 to 5.7 mill. ac. (as in Figure 4).

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