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Nationwide shift to grass-fed beef requires larger cattle population

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Abstract

In the US, there is growing interest in producing more beef from cattle raised in exclusively pasture-based systems, rather than grain-finishing feedlot systems, due to the perception that it is more environmentally sustainable. Yet existing understanding of the environmental impacts of exclusively pasture-based systems is limited by a lack of clarity about cattle herd dynamics. We model a nationwide transition from grain- to grass-finishing systems using demographics of present-day beef cattle. In order to produce the same quantity of beef as the present-day system, we find that a nationwide shift to exclusively grass-fed beef would require increasing the national cattle herd from 77 to 100 million cattle, an increase of 30%. We also find that the current pastureland grass resource can support only 27% of the current beef supply (27 million cattle), an amount 30% smaller than prior estimates. If grass-fed systems include cropland-raised forage, a definition that conforms to typical grass-fed certifications, these supplemental feeds can support an additional 34 million cattle to produce up to 61% of the current beef supply. Given the potential of forage feed croplands to compete with human food crop production, more work is required to determine optimal agricultural land uses. Future US demand in an entirely grass-and forage-raised beef scenario can only be met domestically if beef consumption is reduced, due to higher prices or other factors. If beef consumption is not reduced and is instead satisfied by greater imports of grass-fed beef, a switch to purely grass-fed systems would likely result in higher environmental costs, including higher overall methane emissions. Thus, only reductions in beef consumption can guarantee reductions in the environmental impact of US food systems.

1. Introduction

Beef cattle represent an important component of the US economy, totaling over $67bn in sales from more than 32 million cattle slaughtered in 2016 [1], with over three million cattle's worth of meat exported each year [2]. However, beef cattle have recently received focus as an inefficient means of procuring protein, resulting in greater feed and water costs and higher greenhouse gas emissions per unit of protein than other forms of meat or plant-based protein [3–6].

While cattle are evolved to eat a diet primarily of grass and other forages not edible to humans, cattle are fattened in the final stages of their lives, or 'finished', on a diet of primarily grain in feedlots. The feedlot system has been the focus of concerns and investigations regarding food safety [7], environmental externalities [8], and animal welfare [9]. Feedlot systems rely on a high throughput of intensively grown crops, require frequent antibiotic and growth hormone usage, are located in regions where cattle are prone to heat exhaustion [9], and do not permit cattle to perform activities that conform with their natural instincts (i.e. grazing on open pasture). Furthermore, high volumes of manure and intensive manure management create odors which may result in human health consequences for agricultural workers and nearby residents [10] and undesirable aesthetic conditions. However, due to grain feed's higher nutrient density relative to grass, it requires significantly less land and generates less methane per unit of meat produced [3, 6]. Large shifts in cattle herd management following macro-level consumer trends must therefore be quantified in light of environmental tradeoffs.

Because beef is the most land-demanding agricultural product in the US and the world, some have explored restricting cattle feed to pasturelands that are non-competitive with human food production [11]. Currently, 'grass-finished' beef accounts for less than 1% of the current US supply [12]. Imports of grass-finished beef to the US from Australia far outweigh the domestic US grass-finished beef supply [13]. Rapid growth in the grass-fed beef market of 20%–35% per year is leading suppliers to consider shifting domestic production to grass-finished beef [12]. Prior studies have considered market and infrastructure barriers to scaling grass-fed beef production [14]. However, biological and physical limits may inhibit the expansion of US grass-finished beef, including additional land for increased pasture and forage feed requirements.

To model future shifts to exclusively grass-fed beef, the size, lifespan, and weight gain of the present US beef cattle herd must be well understood. Multiple resources and studies have published global and national estimates of beef cattle populations [15–17], but national mean growth rates and residence times have not previously been reported. Grass-finished cattle have lower average daily weight gain (ADG) and finished weights than their grain-finished counterparts, because cattle eating grass have less efficient feed conversion ratios (FCR). This information has been widely reflected in localized studies about grass-finishing operations [18], but no study to date has calculated the consequences for scaling grass-finished operations up to the national level. A recent study found that current pastureland can support 35% of our present day beef output [19]. However, their model assumed a single aggregated FCR across all stages of rearing and finishing and did not model changes in ADG or finishing weight. These recent findings must be updated to adequately reflect differing feed requirements primarily in the finishing stage of production.

Here, we provide a top-down method for understanding the demographic changes and resource constraints for a nationwide shift towards entirely grass-fed. Specifically we ask: (1) *How many more exclusively grass-fed cattle would be required to produce the same amount of finished beef that is currently consumed?* (2) *How much exclusively grass-fed beef can the existing pasture resource support?* To answer these questions we use a simple demographic model of US beef cattle. We then use this model to predict population changes necessary for pasture-finishing systems to keep pace with modern beef production rates and improve estimates of the amount of entirely pasture-raised beef that our present-day pastureland resources can support. We end with a discussion of sustainability metrics that warrant further study, as well as shifts in demand that would be required to keep exclusively grass-fed cattle production within biophysical limits.

2. Methods

2.1. Populations and residence time for feedlot cattle

Cattle on feedlots at any given time represent a fraction of the total US cattle population. Cattle are placed on feedlots only after reaching maturity so that their skeletal development and immune systems can support the high rate of fattening they are subjected to on feedlots. Additionally, the low fecundity rate of cows relative to other farmed animals, of roughly one calf per year, means that many additional cows and bulls are needed to produce calves that replace the slaughtered population. The large population of breeding cattle and their calves are herein referred to as the *cow-calf* beef herd. Within this population, we include stocker cattle, which are more mature than calves but have not yet been placed on feedlots. Beef cattle that have matured and been placed onto feedlots are referred to as feedlot cattle. Dairy cattle are almost an entirely different herd in the United States, and we distinguish them separately from the beef cattle that are the subject of our analysis.

We used the 2012 national annual cattle population reported by the EPA in their Annual Emissions Inventory [20], which were derived from point-in-time cattle censuses conducted by USDA. All beef cattle that were not in feedlots were classified as cow-calf herd cattle, and include calves, dry and lactating cows, bulls, heifer replacements for dairy cows, and stocker cattle. Mean slaughter weight of cattle from feedlots were calculated using 2012 survey feedlot placement numbers, 2013 survey slaughter rates, and 2013 mean dressed weight at slaughter from the USDA NASS [21]. The mean weight of steers and heifers slaughtered in federally inspected commercial slaughterhouses was reported in dressed weight (carcass weight minus blood and internal organs). The dressed weight of commercially slaughtered finished heifers and steers was norMalized by the slaughtered number of each of these subpopulations then divided by 0.604, the ratio of live weight to dressed weight for all slaughtered cattle in aggregate, in order to obtain a live weight for feedlot cattle at slaughter.

$$w_{\text{slaughter}} = \frac{w_{\text{dressed}}}{0.604}. \quad (1)$$

This number may be biased slightly low because 9% of cattle slaughtered in these facilities are culled stocker heifers and steers. Nonetheless, the resulting weight, $w_{\text{slaughter}}$ = 1386 lbs, is our best estimate for the national average live weight of grain-finished cattle from feedlots.

To obtain the mean residence time of cattle on feedlots, the 2012 national yearly mean feedlot population was divided by the 2012 yearly rate of cattle feedlot placements, which we assume is approximately in steady-state and approximately equivalent to 2013 yearly slaughter rates. We then multiply the yearly mean residence time by 366 days to obtain residence time.

$$\tau_{\text{feedlot}} = \frac{n_{\text{feedlot}}}{r_{\text{placement}}} \times 366 \text{ days} \quad (2)$$

where τ_{feedlot} is mean residence time in days, n_{feedlot} is the number of cattle on feedlots averaged over the full year in 2012, and $r_{\text{placement}}$ is the 2012 yearly rate of placements of cattle on feedlots in units of head per year.

To independently corroborate feedlot residence times, the daily weight gain implied by our mean residence time was calculated and compared to literature estimates. The resulting live slaughter weight of feedlot cattle was subtracted from their mean placement weight derived from 2012 USDA surveys to obtain daily feedlot weight gain representing the national average. Feedlot weight gain was then divided by mean feedlot residence time to obtain mean weight gain per day on feedlots, which was compared with literature values of 2.7 to 3.3 lbs day^{-1} [20].

$$\text{ADG}_{\text{feedlot}} = \frac{w_{\text{slaughter}} - w_{\text{placement}}}{\tau_{\text{feedlot}}} \quad (3)$$

where $\text{ADG}_{\text{feedlot}}$ is the average daily weight gain on feedlots, and w_{placed} is the national average placement weight.

2.2. Hypothetical pasture-finished beef populations.

Cattle finished on pasture reach a smaller maximum weight of approximately 1115 lbs [22]. In order to produce the same annual quantity of beef, the rate of cattle shipped to slaughter, hence the rate of cattle graduating to finishing from their cow-calf herds in a new equilibrium grass-fed system, must increase in proportion to the new lower slaughter weight.

$$r_{\text{placed (grassfed)}} = r_{\text{slaughter (grassfed)}} = \frac{w_{\text{slaughter (feedlot)}}}{w_{\text{slaughter (grassfed)}}}. \quad (4)$$

Cattle finishing on pasture also fatten at a slower rate, meaning that cattle must remain finishing on grass for a longer duration than their feedlot counterparts are finished on grain.

$$\tau_{\text{finishing (grassfed)}} = \frac{w_{\text{slaughter (grassfed)}} - w_{\text{placement}}}{ADG_{\text{grassfed}}} \quad (5)$$

where $\text{ADG}_{\text{grassfed}} = 1.4$ lbs day^{-1} is the average daily weight gain of cattle finishing on grass, $w_{\text{slaughter(grassfed)}} = 1115$ lbs is the mean slaughter weight of grass-finished cattle, and $w_{\text{placed}} = 720$ lbs is the mean placement weight which we assume does not change from the present-day system. The longer residence time means that more cattle must reside within finishing operations, assuming steady-state:

$$n_{\text{finishing(grassfed)}} = \frac{\tau_{\text{finishing (grassfed)}} \cdot r_{\text{placed (grassfed)}}}{366 \text{ days}} \quad (6)$$

where $n_{\text{finishing(grassfed)}}$ is the number of cattle finishing on grass, averaged over the year, required to sustain present-day beef production rates. Lastly, we assume that the number of cow-calf herd cattle must increase proportionally to the new rate of placement on grass-finishing operations.

$$n_{\text{calf-cow(grassfed)}} = \frac{r_{\text{placement(grassfed)}}}{r_{\text{placement (feedlot)}}}. \quad (7)$$

The totals do not reflect resource constraints; they merely reflect the increase in population needed to maintain the same yearly beef output in total carcass weight.

2.3. Comparison to previous studies

The estimated proportion of cattle that could be raised in the United States on pastureland grass resources relative to the present-day population has been previously calculated as 35% [19]. The conversion was calculated as the proportion of the present-day total cattle feed on a dry matter (DM) basis consisting of grass from pastureland. However, because less than 1% of cattle are finished on grass, this conversion rate did not appropriately account for the increased energy density, feed efficiency, and maximum fattening rate for finishing cattle on concentrates relative to grass-finished cattle.

We calculate the proportion of the present-day beef output that an exclusively grass-fed system can support as the following:

$$P = \frac{F_{\text{pasture}}}{\text{FR} * (n_{\text{calf-cow (grassfed)}} + n_{\text{finishing (grassfed)}})} \cdot \frac{2205 \text{ lbs MMT}^{-1}}{366 \text{ days}} \quad (8)$$

where F_{pasture} is the national total pastureland-produced grass: 99 million metric tons (MMT) DM per year based on 2012 estimates [5] and used by Eshel *et al* [19]. The sum of $n_{\text{cow-calf(grassfed)}}$ and $n_{\text{finishing(grassfed)}}$ is the total cattle population required to sustain present-day beef output, while FR is the average daily feed requirement for grass-fed cattle, aggregated for the entire herd, in lbs DM head^{-1} day^{-1}. To calculate FR, we used National Research Council (NRC) nutrition requirements [23]. Fact sheets from the Oklahoma State Extension provide summary tables of NRC-derived feed requirements in lbs DM day^{-1} for typical US cow-calf subpopulations (including weaning calves, lactating and gestating cows, bulls, heifer replacements, and stocker cattle, but not finishing cattle) and rations [24]. We referenced these lookup tables using mean US cattle weights from EPA for each subpopulation to find their respective FR, then calculated the aggregate US cow-calf herd mean FR weighted by EPA subpopulation totals, excluding cattle finishing on grass. For grass-finishing cattle, we assumed similar feed requirements as larger stocker cattle, who are presently fed pasture and roughages, and we assumed a mean weight of 918 lbs, the linear mean of their starting placement weight $w_{placement} = 720$ lbs and ending slaughter weight $w_{slaughter(grassfed)} = 1115$ lbs. The resulting aggregated grass-fed cattle FR was 21.8 lbs head^{-1} day^{-1}. The denominator of equation 9 represents the total feed needs for the entire future grass-fed herd.

3. Results and discussion

3.1. Present-day distributions and productivity of beef cattle

A simple box model of national cattle populations is presented in figure 1. The national beef cow-calf herd cattle population is almost five times larger than the population of cattle on feedlots. This imbalance of cattle populations in different stages of rearing before slaughter explains why in the US most cattle can be seen grazing on pastures, but almost all beef in the US comes from confined feedlot operations [12]. This apparent paradox is explained by the facts that (1) many more breeding cattle are needed to replace the feedlot population annually and (2) beef cattle spend only 41% of their 18 month-long lives on feedlots. We calculated a mean residence time of 223 days, or approximately 7.5 months, of cattle on feedlots. Mean placement weight was 720 lbs and mean slaughter weight was 1386 lbs. Over 223 days, this corresponds to 2.98 lbs per day on feedlots, which agrees with the literature reported values of 2.7 to 3.3 lbs per day.

Assuming an approximate steady state, 22 million cattle are slaughtered at 1386 lbs to produce more than 12 billion lbs of beef from feedlot cattle. Additional slaughter from culled dairy cows, beef cows and bulls, replacement steers and heifers, and veal calves, totaling 10 million cattle annually, are not included in this analysis, as their meat either goes towards lower-quality beef products such as ground beef mixtures and pet food or is sold as specialty veal.

3.2. How many more cattle fed exclusively on grass would be required to produce as much beef as is currently consumed?

Replacing the 13 million cattle presently finished in feedlots is not as trivial as raising an equivalent number of cattle on pasture. Cattle on pasture fatten at slower rates than those on feedlots. What follows is an analysis of the necessary increases in residence times and population that are needed in order to produce the same quantity of high-quality beef, approximately 12 billion lbs, currently produced by the feedlot system.

Cattle finishing on pasture fatten at a rate of approximately 1.4 lbs per day and reach a smaller maximum weight of approximately 1115 lbs [22]. Therefore, to gain the necessary slaughter weight, finishing cattle need to spend 281 days, more than 9 months, grazing on pasture (table 1), as well as eating hay and forage supplements outside of their respective regions' growing seasons. To produce the same amount of high-quality beef as the current feedlot system, grass-finishing cattle would need to be slaughtered at a rate of 27 million cattle per year instead of 22 million, with just as many required for placement onto finishing systems (table 2). Due to the slower fattening rate and longer residence time, this would require 21 million cattle instead of 13 million cattle residing in finishing systems on an annually averaged basis, an increase in 67% (figure 2, table 2).

Increases in cattle population, placements, and slaughter rates are demonstrated in figure 2. The increased slaughtering and placement numbers would also require a 24% increase in the size of the national beef cow-calf herd, proportional to the increased annual grass-finishing placement rate, in order to provide additional cattle to stock the grass-finishing stage. Increases in both the cow-calf herd and the grass-finishing population together would result in a total increase to the US cattle population of an additional 23 million cattle, or 30% more than the current US beef cattle population as a whole (table 2).

Supporting a larger grass-fed cattle population would involve environmental tradeoffs. Emissions of methane, a greenhouse gas with a large warming effect relative to carbon dioxide per molecule, come from beef cattle in the forms enteric fermentation and manure emissions. We calculated a 43% increase in methane from enteric fermentation (table 2), assuming that cattle finishing on grass had the same daily methane emissions as present-day stocker cattle, who have nearly identical ADG and are fed primarily on roughage. Modeling the nuanced differences to present-day stocker cattle's diet would be largely hypothetical and subject to large geographic variation. Additionally, manure methane emissions are proportionally small for present-day beef cattle, about 4% relative to enteric fermentation. Future manure methane would thus likely increase proportionally to the cattle population but would be smaller than the increase in enteric fermentation. Taken together, an exclusively grass-fed beef cattle herd would raise the United States' total methane emissions by approximately 8%. Changes in other environmental impacts such as nitrous oxide emissions and water pollution are more challenging to predict, and are discussed further in section 3.4.

The precision of our present-day beef cattle demographic model (figure 1) is made possible by inputs from nationally-representative USDA censuses (equations 1–3). Equivalent sampling does not exist for exclusively grass-fed systems. Because of a high level of heterogeneity in ADG and slaughter weights among individual grass-finished operations, reflecting different climatic conditions, terrain, soil, physical cattle activity, and nuanced management decisions

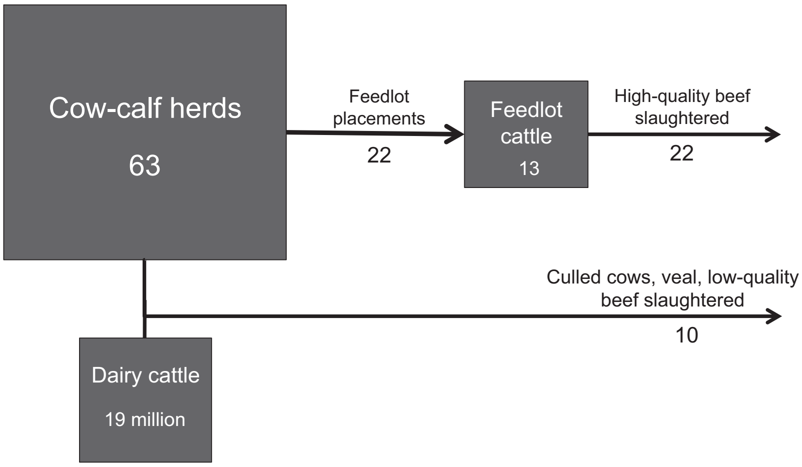

Figure 1. Fluxes and populations of cattle in millions for the current US grain-finishing beef system in 2012.

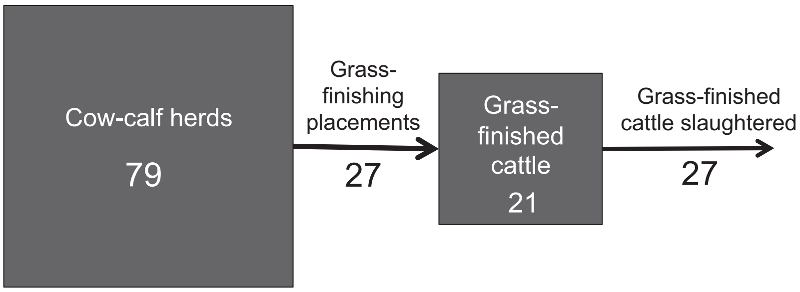

Figure 2. Fluxes and populations of cattle in millions for hypothetical future grass-finishing system. Estimate assumes that the annual slaughtered amount of high-quality beef is held constant from 2012 at approximately 14 billion lbs, that grass-finished cattle are slaughtered at 1115 lbs, and that cattle are fattened on grass at a rate of 1.4 lbs per day. The mean productivity of cow-calf herds remains constant, with total population changing in proportion to the increased placement and slaughter rate.

Table 1. Finishing and slaughter rate parameters for present-day conventional feedlot-finished cattle and future hypothetical grass-finishing cattle. ∗Source: USDA NASS. ∗∗Source: Pelletier *et al* 2010 [22].

	Residence time (τ)	Average daily gain (ADG)	Slaughter rate (r)	Slaughter weight ($w_{slaughter}$)
	days	lb head^{-1} day^{-1}	head year^{-1}	lbs
Conventional	223	3.0	21 864 000∗	1386
Grass-fed	281	1.4∗∗	27 185 000	1115∗∗

such as cultivated forages and rotational grazing regimens, our estimates for exclusively grass-fed beef cattle production in the US are meant to reflect an approximate and hypothetical scenario. Different estimates can be made by assuming different values for ADG and finished weights (table 1) in equations (4–7). We performed a simple sensitivity analysis and found that increasing $ADG_{grassfed}$ and $w_{slaighter(grassfed)}$ each by 10% led to a decrease in the total grass-fed population of 1.9% and 3.7% respectively. This suggests that future developments in nutritional science, animal genetics, pasture management, and forage quality may enable producers to achieve higher efficiency in pasture-based systems than the estimates in this analysis [25].

3.3. How much exclusively grass-fed beef can the existing pasture resource support?

We estimate that present-day pastureland grass resources can sustain only 27% ($P = 0.27$) of our current beef output. The amount of grass feed needed to sustain present-day beef production in an exclusively grass-fed system is 387 MMT DM year^{-1}, a 37% increase in dry weight relative to present-day national total cattle feed of 283 MMT DM year^{-1} [5], which includes grain. Using the present-day total feed weight of 283 MMT DM year^{-1} reproduces the result of 35% ($P = 0.35$) from Eshel *et al* [19]. Therefore, it is apparent that Eshel *et al* assume a constant feed conversion ratio for beef across all feeds, i.e. that grass and grain are interchangeable for beef cattle growth.

Table 2. Beef cattle population and enteric fermentation methane emissions (in millions of metric tons) of present-day conventional beef systems and future hypothetical exclusively grass-fed beef systems. ∗Source: US EPA.

	Cow-calf	Population finishing	Total	Enteric fermentation methane MMT CH_4
Conventional∗	63 493 000	13 328 000	76 821 000	4.76
Grass-fed	78 946 000	20 876 000	99 822 000	6.79

To the contrary, these two feed stocks have disparate feed efficiencies, produce different metabolic byproducts such as methane and manure, and allow cattle to fatten at different maximum rates [23]. We updated their results by calculating the increase in size of the beef cattle herd and increased feed needs for a larger exclusively grass-fed herd (equation 9), rather than simply dividing the dry weight of grass presently fed to cattle by the dry weight of all feeds presently feed to cattle.

This estimate excludes grain, hay, silage, and other roughage grown on croplands as a potential feed source for exclusively pasture-raised cattle to match the definition of 'sustainable beef' used by Eshel *et al* and others [11, 19]. However, hay and silage from these lands provide a critical source of supplemental feed to pasture-raised cattle during dormant cold or dry seasons and pasture-based certifications schemes by third parties allow for supplemental forage feed during dormant seasons [26]. Adding the 126 MMT DM year^{-1} of roughage feed that are presently grown on croplands to $F_{pasture}$ brings the amount of grass-fed beef that pastures in the US could support to 61% ($P = 0.61$) of our current beef supply.

Additionally, croplands currently utilized for grains fed to farmed animals could be substituted for alfalfa, a high-yielding forage crop. On more than 5 million highly-productive cropland hectares on which 38 MMT DM grain beef cattle is presently grown each year, we calculate that farmers could instead grow 34 MMT DM of alfalfa at present yields on high-productivity cropland (assuming 29% dry matter). Including these 'replaced' forages, the US land base could support up to 71% of the current US beef production exclusively grasses and forages. These forages, however, would necessarily be in competition with human food crops, a scenario that advocates for an exclusively grass-fed cattle future would likely hope to avoid.

Research is still needed to assess yield gaps between present and potential future productivity of US pasturelands and roughage croplands. Statistical and processed-based modeling can assess underperforming areas [27], which could be optimized through better fertilizing, soil conditioning, and rotational management. Currently, less than 2% of all agricultural lands in the US undergo a rotation between cropland and pasture [28], though this type of management is known to increase forage productivity [29]. The required 30% increase in the overall cattle population must be accompanied by large increases in the productivity of existing pastures, on the order of 40%–370%, to avoid clearing additional native vegetation or competition with the human food supply.

3.4. Implications for sustainability and future research directions

In a future shift to grass-fed beef, although more cattle would have to be raised for the same quantity of beef, fewer cattle could be raised overall in the US. A reduction in the US cattle population would reduce the aggregate environmental impact of the US beef sector, yet, the average methane footprint per unit of beef produced would increase by 43% (table 2) because of slower growth rates and higher methane conversion rates. Tradeoffs in other environmental impacts demand further quantitative research. For example nitrous oxide emissions associated with grain feed crops would be reduced, but could be outweighed by increased nitrogen oxidation from manure and leguminous forages. Soil carbon sequestration contributes a potential CO_2 sink, however evidence suggests that this sink is unstable and reversible over decadal timeframes [30]. Additionally, moving cattle from feedlots and onto pasture could create additional manure pollution burdens for watersheds that are near or past safe nutrient loads [31]. Harmful effects of air pollution on humans would likely decrease as pollution sources would be more spatially diffuse. Soil erosion and native vegetation suppression from overgrazing are likely to pose additional challenges. Further modeling of both aggregate and marginal environmental impacts is therefore needed. Social outcomes are as unclear as the balance in tradeoffs of environmental impacts, as human society must pay for externalities of production. Vulnerable communities often bear disproportionate burdens of these externalities [32, 33].

Animal welfare, an additional concern motivating the shift towards exclusively pasture-based production, may be better provided for in a shift to exclusively pasture-based management, but with important caveats. There are presently no legal protections for the welfare of cattle on farms at either the federal and state levels in the United States [34]. Improvements in the physical environment, allowing cattle to better express natural behaviors, may be offset by poorer oversight of larger cattle herds. Grass-finished cattle may be subject to disease, injury, and harsh weather such as heat, storms, and freezing temperatures, which presently affect cow-calf herds. The private sector may fill the gap left by legal protection and enforcement, but welfare certification organizations could also face new challenges in the face of large-scale management shifts and would continue to lack legal oversight.

Shifts to a pasture based system need not abandon supplemental feeding. Not all roughage croplands may be put to productive use for human food (or efficient bioenergy sources). Although this likely does not apply to most of the 126 MMT DM year^{-1} of roughages grown in the US, the proportion of these roughages grown on marginal croplands present logical sources of dormant season silage for supplemental feeding on pasture during periods of lower biomass production (a dry and/or winter season). Thus, the definition of 'sustainable beef' used by Eshel *et al* and others [11, 19] as a pasture-only system should be reconsidered.

While the environmental costs of exclusively grass-fed beef under constant US beef consumption are likely quite high, environmental and social sustainability could be enhanced if domestic consumption of beef decreases. Reductions in total beef production could represent a hardship for US farmers, but grass-fed beef currently sells at a higher price. The increased value associated with perceptions of environmental stewardship and changing consumer preferences regarding taste could potentially compensate the cattle sector for a portion of the shortfall from lower productivity and limits to grass resource availability. Presently, prices for grass-fed beef are 47% greater by weight [35] than conventional beef [36] across all cuts. If demand is not perfectly inelastic (the price does not remain constant despite a change in supply), a reduction in the amount of beef produced in the US is likely increase the price of beef domestically. Additionally, imports of grass fed beef could be reduced, shifting demand for this premium product back to US farmers, thus making exclusively grass-fed cattle management more profitable. This outcome could benefit declining rural economies in the US. More nuanced economic modeling is needed to understand the shifts in demand associated with supply-side changes in management and the market prices that would result from changes in demand. However, this analysis suggests that consumer demand for beef could fall while still maintaining farmer livelihoods. Both higher prices and an overall reduction in demand for beef are necessary steps towards a more environmentally and economically sustainable US agricultural system.

4. Conclusions

Understanding the consequences of moving towards entirely grass-fed cattle requires disaggregating the present day herd between cow-calf herds, wherein high-quality beef cattle are bred and raised on grass and roughages before shipping to feedlots, and feedlot cattle who are rapidly fattened on high-grain diets before slaughter. The nearly five-to-one ratio of cow-calf beef cattle to feedlot cattle accounts for the paradox that cattle grazing on pasture are visibly abundant across the country, but the majority of our beef comes from feedlot-fed cattle.

Future management shifts towards grass-finished beef cattle production would require a large increase in the US cattle population, both in finishing cattle and cow-calf herd populations, to accommodate slower fattening rates and lower slaughter weights. The required 30% increase in the overall cattle population must be accompanied by massive increases in the productivity of existing pastures to avoid native ecosystem encroachment or competition with the human food supply. Changes in cattle population and management would also create an even higher land and methane environmental footprint for beef. Other impacts such as fresh water eutrophication, soil erosion and native vegetation suppression from overgrazing, and nitrous oxide emissions are likely to create additional environmental burdens, but must be more precisely quantified. Given the environmental tradeoffs associated with raising more cattle in exclusively grass-fed systems, only reductions in beef consumption can guarantee reductions in the environmental impact of US food systems. If a reduction in the US beef supply increases prices, then lower consumer demand could be feasibly be met using limited present-day grass resources, while still allowing farmers to profit.

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References

[1] National Cattlemen's Beef Association 2015 Beef Industry Statistics (www.beefusa.org/beefindustrystatistics.aspx)
[2] USMEF 2016 Annual Report 2016 (www.usmef.org/news-statistics/usmef-annual-report/)
[3] Nijdam D, Rood T and Westhoek H 2012 The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes *Food Policy* 37 760–70
[4] Ripple W J, Smith P, Haberl H, Montzka S A, McAlpine C and Boucher D H 2013 Ruminants, climate change and climate policy *Nat. Clim. Change* 4 2–5
[5] Eshel G, Shepon A, Makov T and Milo R 2014 Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States *Proc. Natl Acad. Sci.* 1402183111
[6] Poore J and Nemecek T 2018 Reducing food's environmental impacts through producers and consumers *Science* **992** 987–92
[7] McEachran A D, Blackwell B R, Hanson J D, Wooten K J, Mayer G D, Cox S B and Smith P N 2015 Antibiotics, bacteria, and antibiotic resistance genes: aerial transport from cattle feed yards via particulate matter *Environ. Health Perspect.* **123** 337–43
[8] Shi Y, Parker D B, Cole N A, Auvermann B W and Mehlhorn J E 2001 Surface amendments to minimize ammonia emissions from beef cattle feedlots *Trans. ASAE* 44
[9] Grandin T 2016 Evaluation of the welfare of cattle housed in outdoor feedlot pens *Vet. Anim. Sci.* **1–2** 23–8

[10] McGinn S M, Janzen H H and Coates T 2003 Atmospheric ammonia, volatile fatty acids, and other odorants near beef feedlots *J. Environ. Qual.* **32** 1173

[11] Röös E, Patel M, Spangberg J, Carlsson G and Rydhmer L 2016 Limiting livestock production to pasture and by-products in a search for sustainable diets *Food Policy* **58** 1–13

[12] Stone Barns Center for Food and Agriculture 2017 Back to grass: the market potential for US grassfed beef (www.stonebarnscenter.org/blog/future-grassfed-beef-green/)

[13] USDA ERS 2018 Livestock and meat international trade data (www.ers.usda.gov/data-products/livestock-and-meat-international-trade-data/) (Accessed: 25 January 2018)

[14] Gwin L 2009 Scaling-up sustainable livestock production: innovation and challenges for grass-fed beef in the US *J. Sustain. Agric.* **33** 189–209

[15] Gerber P J, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A and Tempio G 2013 *Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities* (Food and Agriculture Organization of the United Nations)

[16] Herrero M, Havlík P, Valin H, Notenbaert A, Rufino M C, Thornton P K, Blümmel M, Weiss F, Grace D and Obersteiner M 2013 Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems *Proc. Natl Acad. Sci. USA* **110**

[17] Hristov A N, Harper M, Meinen R, Day R, Lopes J, Ott T, Venkatesh A and Randles C A 2017 Discrepancies and uncertainties in bottom-up gridded inventories of livestock methane emissions for the contiguous United States *Environ. Sci. Technol.* **51** 13668–77

[18] Pethick D W, Harper G S and Oddy V H 2004 Growth, development and nutritional manipulation of marbling in cattle: a review *Aust. J. Exp. Agric.* **44** 705–15

[19] Eshel G, Shepon A, Shaket T, Cotler B D, Gilutz S, Giddings D, Raymo M E and Milo R 2017 A model for 'sustainable' US beef production *Nat. Ecol. Evol.*

[20] EPA 2017 *Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2015* (Washington: US Environmental Protection Agency, Climate Change Division)

[21] NASS 2017 United States Agricultural Statistical Service (https://quickstats.nass.usda.gov/) (Accessed: September 2017)

[22] Pelletier N, Pirog R and Rasmussen R 2010 Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States *Agric. Syst.* **103** 380–9

[23] National Research Council 2000 *Nutrient Requirements of Beef Cattle: Seventh Revised Edition: Update 2000* (Washington, DC: National Academies Press) (https://doi.org/1017226/9791)

[24] Lalman D and Richards C 2014 *Nutrient Requirements of Beef Cattle, E-974* (Stillwater, OK: Oklahoma State Univerity and Oklahoma Cooperative Extension Service)

[25] Halich G, Martz F, Lehmkuhler J, Rentfrow G, Smith R and Meyer L 2015 Producer's guide to beef finishing *Agric. Nat. Resour. Publ.* **108** 1–52

[26] American Grassfed Association 2018 Our Standards (www.americangrassfed.org/about-us/our-standards/) (Accessed: 9 February 2018)

[27] Mueller N D, Gerber J S, Johnston M, Ray D K, Ramankutty N and Foley J A 2012 Closing yield gaps through nutrient and water management *Nature* **490** 254–7

[28] USDA 2012 Agricultural Census. United States Department of Agriculture (www.agcensus.usda.gov/)

[29] Garrett R D *et al* 2017 Social and ecological analysis of commercial integrated crop livestock systems: current knowledge and remaining uncertainty *Agric. Syst.* **155** 136–46

[30] Garnett T *et al* Grazed and confused?: Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question-and what it all means for greenhouse gas emissions *Food Clim. Res. Netw.* (https://www.fcrn.org.uk/sites/default/files/project-files/fcrn_gnc_report.pdf)

[31] Mekonnen M and Hoekstra A Y 2010 The green, blue and grey water footprint of farm animals and animal products *Unesco* **1** 80

[32] Clark L P, Millet D B and Marshall J D 2014 National patterns in environmental injustice and inequality: outdoor NO_2 air pollution in the United States *PLoS ONE* **9** e94431

[33] Torres M and Boyce J K 1998 Income, inequality, and pollution: a reassessment of the environmental Kuznets curve *Ecol. Econ.* **25** 147–60

[34] Sunstein C R 1999 Standing for animals (with notes on animal rights) *Ucla L. Rev.* **47** 1333

[35] USDA AMS 2018 National grass fed beef report (monthly) *Weekly and Monthly Beef Reports* (www.ams.usda.gov/market-news/weekly-and-monthly-beef-reports) (Accessed: 21 January 2018)

[36] USDA ERS 2018 Interactive Chart: Average dressed weights and beef prices reach record highs (Accessed: 21 January 2018)