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COMMENTARY

Grazed perennial grasslands can match current beef production while contributing to climate mitigation and adaptation

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Abstract
The U.S. grain-finished beef system is highly productive but has many negative consequences for human health and well-being because it pollutes surface and groundwaters, exacerbates flooding, reduces biodiversity, and contributes to climate change. Moving the entire U.S. grain-fed beef production system to a grass-finished system is possible without displacing food production and under conservative soil carbon (C) change estimates would result in a reduced but similar C footprint, while improving soil health, water quality, and biodiversity. More optimistic estimates for soil C accumulation indicate the system would result in significant atmospheric C drawdown. Agroecological transformation like this is limited only by our imagination and policies that incentivize agriculture for the public good rather than profits for a few.

1 | THE GRAIN-FED BEEF FINISHING SYSTEM IS DEVASTATING TO ECOSYSTEM HEALTH

The U.S. agricultural landscape urgently needs transformation (Prokopy et al., 2020). Along with other annual grain crops, maize (*Zea mays* L.) production is devastating soil, water, atmospheric, and biotic resources (Franzluebbers et al., 2020). Of the ∼137 million ha of agricultural land in the United States, ∼41 million ha grows maize, which is either (a) fed to livestock in confinement facilities or feedlots (39%), (b) converted to ethanol for gas tanks (27%), (c) used to make food additives (9%), (d) purchased mostly by affluent countries (16%)(Shahbandeh, 2021), or (e) stored as surplus (9%) (Iowa Corn Growers Association, 2021). About 4.85 million ha of the maize grown is used to fatten beef cattle in feedlots located mostly in the Great Plains region (USDA, 2020). With slaughter rates of ∼21.9 million head yr^{-1}, the amount of grain-finished beef produced in the United States is ∼5.4 billion kg yr^{-1} (Hayek & Garrett, 2018).

The environmental problems associated with beef feedlots resemble the problems with maize production, namely, nutrient losses to water and air that help drive climate change and aquatic eutrophication (Miller et al., 2004; Olson et al., 2005; Vaillant et al., 2009). Concentrating animals in small areas where exogenous nutrients and energy are supplied from wide geographical areas (i.e., typically maize fields), while the nutrients and energy in the livestock's excreta are not returned to the same geographies (i.e., concentrated in and around feedlots and spread on inherently leaky crops), results in inevitable nutrient losses (Jones et al., 2019; Glibert, 2020; Waller et al., 2021).

2 | WELL-MANAGED GRAZED PERENNIAL GRASSLANDS ENHANCE ECOSYSTEM HEALTH

Grass-finishing beef allows cattle to distribute their excreta in more diffuse and uniform ways across the landscape than manure from feedlot facilities spread in pulses in spring and fall (Dahal et al., 2020; Jackson, 2020), and nutrient cycles are less leaky because little to no fertilizer is needed to maintain productive grasslands if stocking rates are managed for optimum, rather than, maximum yields. Eliminating or minimizing synthetic nitrogen (N) additions is key to improving water quality and reducing the carbon (C) footprint of grazed pastures. While it is common for grass farmers to add N, many studies have shown that establishing and maintaining legumes, usually clovers, in cool-season pastures can replace the N harvested from the agroecosystem (Ledgard, 2001; Zemenchik et al., 2001). If managed well with rotational grazing on productive grasslands, grazed cows will have sufficient feed for ample weight gain (Dillon et al., 2020; Rowntree et al., 2020).

Dense, fibrous root systems of well-managed perennial grasses keep soils in place, help build soil aggregates, and foster diverse and dynamic soil microbial communities (Oates et al., 2012; Jarchow et al., 2020; Teague & Kreuter, 2020)—a recipe for potential accumulation of atmospheric C in soil organic matter pools, which has been observed by many (Machmuller et al., 2015; Stanley et al., 2018; Becker et al., 2022; Mosier et al., 2021). Moreover, well-managed grazing affords producers the opportunity to manage land in ways that promote birds, pollinators, fish, and microbes (Lyons et al., 2000a; Lyons et al., 2000b; Weigel et al., 2000; Rook & Tallowin, 2003; Rook et al., 2004; Lyons et al., 2017).

Core Ideas

- The United States has enough land to support current beef production with grazed perennial grasslands.
- Grain-fed beef system has a carbon footprint equivalent to about 16 coal-fired power plants.
- Moving all U.S. beef production to grazed grasslands might help drawdown atmospheric C.
- Soil C accumulation is key to making grass-finished beef an atmospheric C sink.
- Policies incentivizing transformation of beef production from grain to grassland are needed.

3 | IS THERE SUFFICIENT LAND TO PRODUCE 5.4 BILLION KG OF GRASS-FINISHED BEEF EACH YEAR?

As a coarse thought experiment, I used literature estimates to conduct a "back-of-the-envelope" exploration of whether there is enough land to support current beef production levels on grassland alone and what the C footprint ramifications of such a change would be. This is not an exhaustive literature review, nor is it a replacement for a proper life cycle analysis. Rather, the exploration is meant to stoke the imagination of the reader to consider the possibilities of a transformed beef production system that would include a transformed agricultural landscape in the tallgrass prairie region.

The ~4.85 million ha of lands growing maize to feed confined finishing cattle typically are highly productive soils producing average grain yields of 11.53 Mg ha^{-1} yr^{-1} (Schnitkey et al., 2021). When returned to perennial grassland and well-managed rotational grazing, these lands will produce 8–12 Mg of dry matter ha^{-1} yr^{-1}, with the lower value an estimate for continuous grazing and the upper value an estimate for management-intensive rotational grazing (Oates et al., 2011). Finishing a steer (i.e., growing it from ~360 to ~545 kg) requires gains of ~0.95 kg d^{-1} over a 190-d growing season. The steer must consume ~3.2% of its weight each day, which translates to ~2.76 Mg of dry matter ha^{-1} yr^{-1}. At typical forage production levels, 2.9 to 4.4 animals could be brought to finished weight on a hectare of former maize ground per year. So, the 4.85 million ha of current maize land could support 14 to 22 million finishing cattle per year.

In addition to land currently producing maize for feedlot cattle, we must consider returning to grazed grassland some of the other >12 million ha of maize grown for ethanol or the millions of hectares growing soybean [*Glycine max* (L.) Merr.] for cattle fed in confinement, which both desperately need to be transformed into perennial grassland to benefit farmers, communities, and society (Prokopy et al., 2020). While the maize land currently feeding feedlot cattle and gas tanks would be enough to support the additional cattle needed to produce 5.4 billion kg of beef annually, we also must consider the ~9 million ha of Conservation Reserve Program (CRP) land for grass-finishing of beef cattle, which is known to benefit from some degree of aboveground disturbance to maintain them as habitat and reduce weed pressure (Chapman et al., 2004).

This massive transition from annual grain crops to perennial grassland will require significant governmental help with transition costs for infrastructure like fencing and water supply as well as technical support, but these costs are trivial compared with the societal costs for cleaning up waters, stabilizing climate, and restoring biodiversity. Moreover, maize production in the United States has been profitable (without government payments) only ~7 of the last 26 yr (USDA Economic Research Service, 2018), 5 of these being the biofuel boom years of 2008 through 2012, resulting in billions of dollars in government payments to farmers (Imhoff & Badaracco, 2019). Instead, these subsidies could be redirected to improve the environment by providing technical support to farmers making this transition.

4 | WHAT ABOUT THE C FOOTPRINT OF INCREASING CATTLE NUMBERS?

Using the cattle numbers described above and estimates of greenhouse gas fluxes from the literature, I scaled-up the C balance of the current grain-finished beef production system producing 5.4 billion kg of beef each year (Scenario A), a grass-finished beef production system producing the same amount of beef (Scenario B), and the same amount of land used in Scenario B restored to bison-grazed, wetland-pocked tallgrass prairie (Scenario C). The USEPA's Greenhouse Gas Calculator (USEPA, 2021) allows one to translate CO_2 equivalents (CO_{2eq}) to units typical of various emitters and indicates that annual anthropogenic greenhouse gas emissions of 9 Pg $CO_{2eq.}$ are equivalent to ∼2,269 coal-fired power plants worth of C. Terrestrial and aquatic ecosystems take up ∼5 Pg CO_{2eq}. yr^{-1}, resulting in a global imbalance of ∼4 Pg $CO_{2eq.}$ yr^{-1} or ∼1,008 coal-fired power plants worth of C that needs to be scrubbed from the atmosphere each year. The current maize-based feedlot production system (Scenario A) emits ∼63.3 Mt CO_{2eq} yr^{-1}, which is roughly equivalent to the annual C emissions from 15.8 coal-fired power plants (Table 1). For context, the United States currently maintains 241 coal-fired power plants, while China's rapid growth of coal-based energy now supports ∼1,365 plants (Evans & Pearce, 2021). Clearly dominating the greenhouse gas emissions from Scenario A are the nitrous oxide (N_2O) losses from soils producing maize and the enteric methane (CH_4) from cattle consuming maize and other feeds in feedlots. In addition, significant CO_2 emissions are derived from soil organic matter loss and erosion associated with continuous cropping (Spawn et al., 2019), as well as significant N_2O emission from manure-packed feedlots (Waldrip et al., 2016).

Producing 5.4 billion kg of grass-finished beef on land currently growing maize but converted to perennial grassland (Scenario B) translates to ∼74.9 Mt CO_{2eq} yr^{-1}, similar to emissions from ∼18.7 coal-fired power plants each year when using an estimate of zero net change in soil C (Sanford, 2014). This indicates a greater overall C footprint for grazed grasslands than Scenario A but includes improved water quality, reduced flooding, and enhanced biodiversity (Franzluebbers et al., 2012; Spratt et al., 2021). However, as discussed below, when using more optimistic, but conservative estimates of soil C change (e.g., Becker et al., 2022), the grass-finishing system has a C footprint of ∼15.2 coal-fired power plants, which is similar but a bit less than the current grain-fed feedlot system (Table 2).

Scenario C indicates what the role of the original tallgrass prairie might have been in the global C cycle—contributing ∼38.7 Mt CO_{2eq} yr^{-1} or ~9.7 coal-fired power plants worth of CH_4 emitted by bison and wetlands. This comparison provides important context highlighting that biogenic greenhouse gases always cycle between the atmosphere, soils, and organisms and that anthropogenic forcing comes primarily from the liberation of fossil C to the atmosphere (Tian et al., 2016). As with most ecosystem restoration, this analysis presses us to consider the endpoint or outcomes we want and need from our landscapes.

5 | SOIL C BALANCE IS THE WILDCARD

The most uncertain parameter in my C footprint calculations is soil C balance, hence the intense scientific focus on soil C sequestration and socioeconomic focus on standing up C markets. The soil C estimates for Scenarios A and B come from Sanford (2014), a 20-yr randomized and replicated experiment in southern Wisconsin showing losses of soil C from all annual grain systems at an average rate of ∼250 kg C ha^{-1} yr^{-1} (Scenario A) while rotationally grazed pastures gained slightly in surface 30 cm but lost C from 30 to 100 cm so that on net they were unchanged over 20 years.

However, other reviews reported modest soil C gains in annual crops using no-till (Blanco-Canqui, 2021) and cover crops (Jian et al., 2020), so I explored a range of ecosystem C balance outcomes when varying the soil C parameter (Table 2). Similarly, recent studies of managed grazing have reported significant (320 kg C ha^{-1} yr^{-1}; Becker et al., 2022) to moderate (840 kg C ha^{-1} yr^{-1}; Franzluebbers, 2010) to very high (~3,590 kg C ha^{-1} yr^{-1}; Stanley et al., 2018) accumulations of soil C under well-managed grazed pastures. The value of soil C increase making Scenario B net zero was ∼1,630 kg C ha^{-1} yr^{-1}, while the Stanley et al. (2018) soil C change resulted in a system C balance equivalent to taking ∼23 coal-fired power plants offline! Annual grain-feedlot systems did not become atmospheric C sinks until the maize soils were accumulating ∼3,300 kg C ha^{-1} yr^{-1} (Table 2), an exceedingly high and unlikely value.

6 | WE CAN TRANSFORM AGRICULTURE WITH POLICIES DESIGNED TO PROMOTE THE PUBLIC GOOD

Agriculture in the United States can be transformed to reduce its C footprint while improving water quality, reducing flooding, and supporting biodiversity. Grasslands grazed by livestock can do this if managed well, which is to say (a) pastures are grazed but leaving significant residual biomass so that plants are not constantly drawing on belowground reserves to regrow, (b) pastures are allowed significant periods of rest from defoliation to vigorously regrow, and (c) livestock are restricted to relatively small paddocks for short durations

TABLE 1 Estimated greenhouse gas emissions for main sources under three scenarios. Scenario A: maize (4.86 million ha) to feed cows (13.3 million head) to finish 5.4 billion kg beef in feedlots; Scenario B: grassland (12.67 million ha) grazed by cows (20.87 million) to finish 5.4 billion kg beef on pasture; and Scenario C: tallgrass prairie (12.67 million ha) grazed by bison (13.27 million) with 4% wetland cover (Knapp et al., 1999)

		Scenario A: Grain-finished feedlot beef			Scenario B: Grass-finished pasture beef			Scenario C: Bison grazing tallgrass prairie		
Source	Units for rate estimates	Rate estimate	CO_{2eq}	Coal power plants	Rate estimate	CO_{2eq}	Coal power plants	Rate estimate	CO_{2eq}	Coal power plants
			Mt	no.		Mt	no.		Mt	no.
Enteric CH_4	kg CH_4 cow^{-1} yr^{-1}	59.4[a]	19.8	4.9	76.7[b]	40.0	10.0	72.0[c]	23.9	6.0
Soil N_2O	kg N_2O-N ha^{-1} yr^{-1}	10[d]	28.9	7.2	4[e]	30.2	7.5	2[d]	15.1	3.8
Soil balance C	kg C ha^{-1} yr^{-1}	250[f]	4.5	1.1	0[f]	0	0	(100)[g]	(4.6)	(1.2)
Soil erosion C	kg C ha^{-1} yr^{-1}	90[h]	1.6	0.4	1[h]	0	0	(5)[g]	(0.2)	(0.1)
Industrial N fixation	kg CO_{2eq} kg^{-1} applied N	3.8[i]	3.3	0.8	0	0	0	0	0	0
Heavy equipment use	kg C ha^{-1} yr^{-1}	41[j]	0.7	0.2	0	0	0	0	0	0
Feedlot N_2O	g N_2O kg^{-1} carcass	2.5[k]	4.0	1.0	0	0	0	0	0	0
Wetland CH_4	kg CH_4 ha^{-1} yr^{-1}	365[l]	0.4	0.1	365[l]	4.6	1.2	365[l]	4.6	1.2
Total			63.3	15.8		74.9	18.7		38.7	9.7

[a]USEPA, AP-42, https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors. [b]Pinares-Patiño et al., 2003. [c]Kelliher & Clark, 2010. [d]Oates et al., 2015. [e]Wecking et al., 2020. [f]Sanford, 2014. [g]Guess assuming slight annual gain, but near steady state. [h]Unpublished RUSLE2 simulation for Wisconsin Integrated Cropping Systems Trial. [i]Brentrup et al., 2018. [j]West & Marland, 2002. [k]Rotz et al., 2015. [l]Whalen, 2005.

TABLE 2 Soil carbon balance (negative values indicate soil as C sink) and equivalent number of coal-fired power plants for the production system under alternative soil C changes in two scenarios that each annually produce 5.4 billion kg of beef

Scenario	Soil C change	C balance	Coal power plants	Soil C change source
	kg ha^{-1} yr^{-1}	CO_{2eq} Mt	no.	
A: Grain-finished feedlot beef	250	63.4	15.9	Sanford, 2014
	(200)	55.4	13.8	Blanco-Canqui, 2021
	(560)	49.0	12.2	Jian et al., 2020
	(3,300)	0.2	0	–
B: Grass-finished pasture beef	0	75.8	19.0	Sanford, 2014
	(320)	60.9	15.2	Becker et al., 2022
	(840)	36.8	9.2	Franzluebbers, 2010
	(1,630)	0	0	–
	(3,590)	(91.5)	(22.9)	Stanley et al., 2018

before they are rotated to new paddocks. These principles help producers achieve efficient use of available forage and sufficient resting of pastures from defoliation to maintain productivity, all of which minimizes nutrients from concentrating in certain locations and reduces opportunities for losses of soil, nutrients, and C to the atmosphere and aquatic ecosystems (Jackson et al., 2019; Jackson, 2020). This type of managed grazing also affords land managers opportunities for manipulating grassland structure in ways that can be beneficial to wildlife (Lyons et al., 2000a; Lyons et al., 2000b; Rook & Tallowin, 2003).

In addition to the climate *mitigation* capacity of grazed perennial grasslands, these agroecosystems represent our best option for climate *adaptation*. The grassland biome is the plant kingdom's response to low and erratic rainfall coupled with periodic aboveground disturbance, so managing grasslands well to provide for our needs and wants in a sustainable fashion is paramount to a resilient agriculture as climates become more uncertain. This requires policies that incentivize production systems for the public good rather than profit of a few (Streit Krug & Tesdell, 2020; Reynolds et al., 2021). Policies must encourage grass-fed markets with ample processing and supply chain development and must incentivize soil building, nutrient retention, and biodiversity gain and penalize soil, nutrient, and biodiversity loss.

Many people may choose not to consume beef for health and/or ethical reasons—and we should reduce our meat consumption to help constrain greenhouse gas emissions—but we *can* meet our current demand for beef in the United States with cattle finished on perennial grasslands restored to lands where the tallgrass prairie plant community once dominated, and where Mollisols are still found. Doing so will improve our ecosystem health. It does not require displacing food production. It does not require more land to be converted to agriculture. And it will improve our quality of life overall. We must envision an agriculture that provides for our needs now while building the capacity of future generations to do the same. Well-managed grazing on perennial grasslands provides us this opportunity.

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AUTHOR CONTRIBUTIONS

Randall D. Jackson: Conceptualization; Data curation; Formal analysis; Funding acquisition.

CONFLICT OF INTEREST

No known conflicts of interest.

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