Eliminating Animal Agriculture Would Negate 56 Percent of Anthropogenic Greenhouse Gas Emissions Through 2100

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Abstract

We used public data on greenhouse-gas emissions and land use to evaluate the potential impact of eliminating animal agriculture on atmospheric greenhouse gas levels, and global warming potential. We first updated estimates of carbon dioxide, methane, and nitrous oxide emissions from livestock and livestock feed production. We used these data, along with recent estimates of the atmospheric carbon dioxide that could be converted by photosynthesis into perennial biomass on land currently engaged in animal agriculture, to develop models of net anthropogenic emissions under food-system scenarios ranging from “business as usual” to the complete elimination of animal agriculture. We then used simple simulations to project atmospheric levels of these three gases through the end of the century under each scenario. Using cumulative differences in radiative forcing as a measure of the impact of different diets, we found that a gradual transition over the next 15 years to a plant-only diet would have the same effect through the rest of the century as an annual reduction of 28 Gt of CO_2 emissions. This would effectively negate 56 percent of global emissions at the current rate of 50 Gt CO_2eq per year, with a net negation of 2,200 gigatonnes of CO_2 emissions by the year 2100. The climate benefits would accrue rapidly - most in the first few decades, effectively pausing greenhouse-gas accumulation for 30 years. These results establish the replacement of animal agriculture as by far the most powerful option in our arsenal of climate-defense strategies, especially given the urgency of the climate threat. How to orchestrate such a shift to maximize its beneficial environmental, public health, food security, economic and social consequences and minimize potential harms should therefore be at the center of climate policy discussions.

The catastrophic impact of animal agriculture

Animal agriculture - the use of animals as a food-production technology - has a profoundly negative impact on our climate and environment. The reduction in terrestrial biomass resulting from the destruction of native ecosystems to support grazing livestock and cultivation of feed and forage crops is responsible for a third of all anthropogenic CO_2 emissions to date (Hayek et al., 2021; Strassburg et al., 2020), and is the primary driver of a catastrophic ongoing global collapse of wildlife populations (Newbold et al., 2015; World Wildlife Fund, 2020). Livestock, especially large ruminants, and their supply chains, also dominate anthropogenic emissions of the potent greenhouse gases methane and nitrous oxide (Gerber et al., 2013; MacLeod et al., 2018; Steinfeld et al., 2006).

A global transition to a nutritionally balanced plant-only diet is practical, healthy (Agnoli et al., 2017; American Dietetic Association and Dietitians of Canada, 2003; Craig et al., 2009; Tilman and Clark, 2014; Willett et al., 2019), would have an immediate positive impact on greenhouse gas emissions (MacLeod et al., 2020, 2018; Steinfeld et al., 2006), biodiversity (Maron et al., 2018; Strassburg et al., 2020) and human health (Clark et al., 2019; Satija et al., 2017; Springmann et al., 2016; Tilman and Clark, 2014), and could play an important role in climate-change mitigation (Clark et al., 2020; Gerber et al., 2013).

In this article, we present a simple analytical framework for quantitatively estimating the climate impact of various scenarios for reducing or eliminating the use of animals as food technology. We began with the recent work of (Hayek et al., 2021), who used satellite imagery of biomass and geographically-resolved agricultural data to estimate that the return of land currently used in livestock production to its native state would sequester, over 30 years, approximately 300 Gt of carbon in plant and non-living biomass, relative to continuation of our current diet (Hayek et al., 2021). They refer to this as the “carbon opportunity cost” (COC) of animal agriculture. A similar estimate was obtained by (Strassburg et al., 2020).

To complete the picture with a full accounting of the greenhouse-gas impact of animal agriculture, we used public data on livestock production and associated emissions of CO_2, CH_4 and N_2O to derive updated estimates of the net greenhouse gas impact of animal agriculture. We then combined these results and data from (Hayek et al., 2021) to evaluate how the elimination of livestock-associated emissions and the restoration of livestock-associated land to its native state would impact atmospheric CO_2, CH_4 and N_2O levels and global warming for the remainder of the 21st century.

Our major conclusion is that, if a global switch to a plant-only diet were to occur over the next 15 years, it would result in the effective elimination of 2,200 gigatons of CO_2 emissions this century, approximately half of the reduction projected to be required to prevent global warming from exceeding 2˚C by 2100.

Modeling the elimination of animal agriculture

To estimate current emissions due to animal agriculture, we scaled country-, species- and product-specific estimates of direct emissions from animal agriculture using the Global Livestock Environmental Assessment Model (MacLeod et al., 2018), with country-specific data on primary production of livestock products from the Food and Agriculture Organization (FAO) database FAOSTAT (FAO, 2021).

Based on this analysis, in 2019 (the most recent year for which full data are available), global production of animal-derived foods led to direct emissions of 2.3 Gt CO_2, due primarily to land clearing, 122 Mt CH_4 due to enteric fermentation and manure management, and 7 Mt N_2O due primarily to fertilization of feed crops and manure management (Figure 1 and Figure 1-S1). These numbers are consistent with other recent estimates (Gerber et al., 2013; Steinfeld et al., 2006), and correspond, respectively, to five percent of CO_2, 32 percent of CH_4 and 64 percent of N_2O emissions from all human activities.

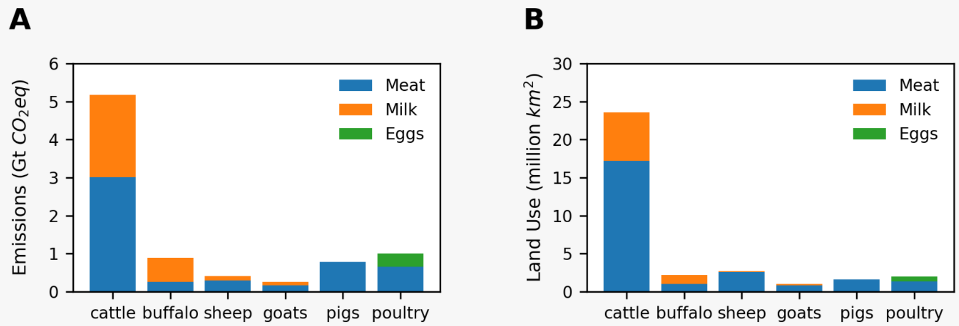


Figure 1. Global emissions and land use footprints of animal agriculture.

Total CO_2 equivalent emissions (A) assembled from species, product and country-specific production data from FAOSTAT for 2018 and species, product, region and greenhouse-gas specific emissions data from GLEAM (MacLeod et al., 2018), using CO_2 equivalents of 34 for CH_4 and 298 for N_2O. Land use (B) assembled from species, product and country-specific production data from FAOSTAT for 2018 and species and product specific land use data from (Poore and Nemecek, 2018).

We evaluated the impact of elimination of all animal agriculture with a simple model that quantifies how the cessation of its associated emissions, the net decay of atmospheric CH_4 and N_2O, and the removal of atmospheric CO_2 by photosynthetic conversion into plant biomass, would impact the atmospheric levels of these GHGs and their combined global warming potential over time.

We considered several dietary perturbations, including the immediate replacement of all animal agriculture with a plant-only diet and elimination of products from subsets of livestock species, but our focus here is what we believe to be a realistic scenario: a gradual, global transition, over a period of 15 years, to a plant-only diet (POD). We compared the effects of this diet to a “business as usual” (BAU) diet in which agricultural emissions are projected to continue at current levels. We assumed in all these hypothetical scenarios that non-agricultural emissions would remain constant, and that, when land is removed from livestock production, the most intense period of conversion of atmospheric CO_2 into terrestrial biomass occurs linearly over the subsequent thirty years.

Figure 2 shows annual emissions and projected atmospheric levels of CO_2, CH_4 and N_2O under the BAU and POD diets through the end of the century (additional scenarios are shown in the supplemental versions of Figure 2). The impact would be greatest in the period between 2030 and 2060, when carbon sequestration on land previously occupied by livestock or feed crops reaches its peak, dramatically slowing the rise of atmospheric CO_2 levels during this interval.

Atmospheric CH_4 and N_2O levels continue to increase in both models during the transition period, but begin to drop significantly with the abatement of animal agriculture-linked emissions. CH4, with a half-life in the atmosphere of around 9 years, approaches a new and significantly lower steady-state level towards the end of the century, while N_2O, with a half-life of around 115 years, does so over a much longer time-scale.

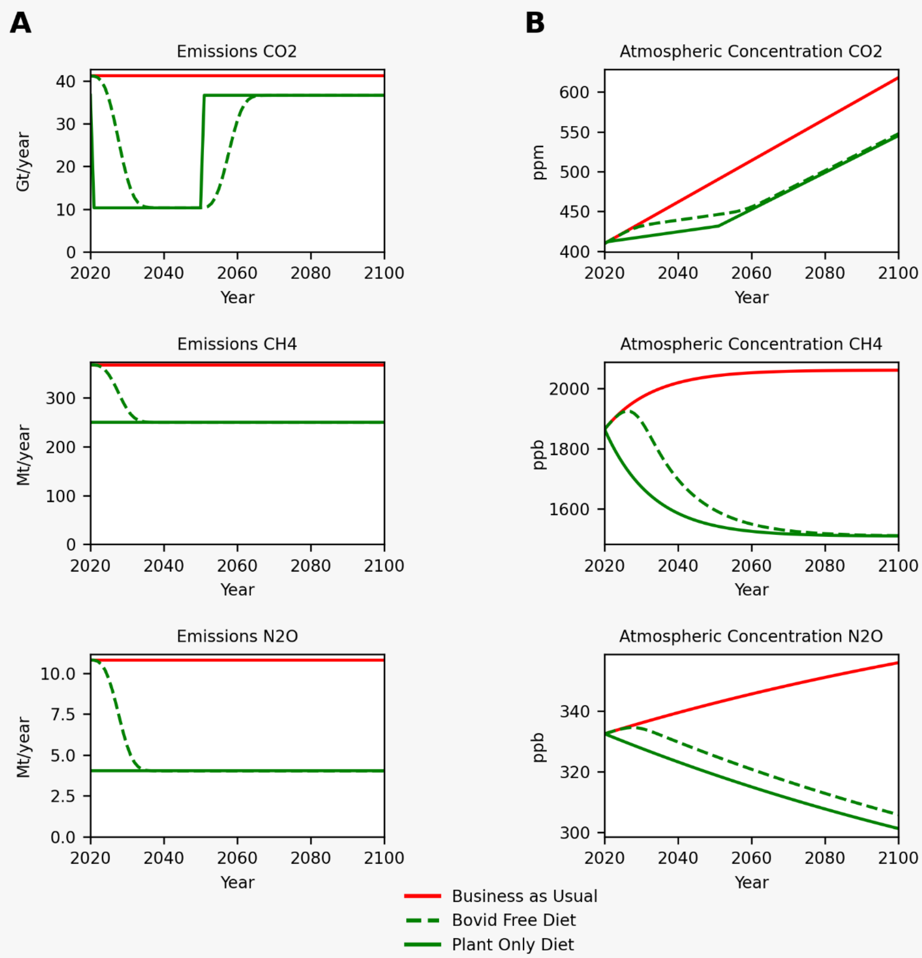


Figure 2. Impact of ending animal agriculture on atmospheric greenhouse gas levels.

(A) Projected annual emissions of CO_2, CH_4 and N_2O for Business as Usual and Plant Only Diet assuming an immediate cessation (solid lines) or 15 year transition (dashed line) to new diet. (B) Projected atmospheric concentrations of CO_2, CH_4 and N_2O under each emission scenario.

To capture the combined global-warming impact of the changing levels of these GHGs, we estimated radiative forcing (RF), the amount of solar energy absorbed by Earth and not radiated back into space, using the formulae described in (Myhre et al., 1998; Shine, 2000).

This analysis reveals a massive and previously unrecognized opportunity: if animal agriculture were phased out globally over the next 15 years, there would effectively be no net increase in

RF between 2030 and 2060 (Figure 3). And even after that 30-year pause in the previously monotonically increasing global warming potential of the atmosphere, the difference in RF between the POD and BAU scenarios would continue to increase, due to the absence of direct emissions from animal agriculture and the continuing decay of previously emitted CH_4 and N_2O towards lower steady-state values.

The end result is a dramatically lower RF at the end of the century: 3.9 Wm^{-2} for POD compared to 5.1 Wm^{-2} for BAU. To put this difference in perspective, phasing out animal agriculture over the next 15 years would reduce RF in 2100 by the same amount as eliminating 1,950 gigatons of CO_2 emissions, the equivalent of 39 years of current anthropogenic emissions.

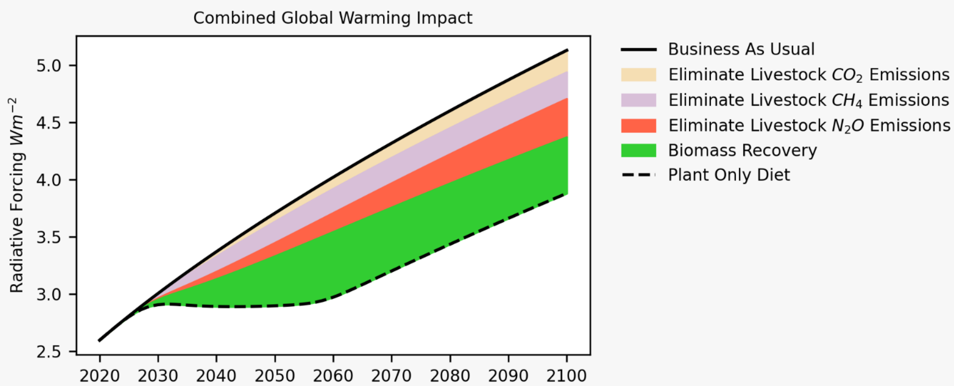


Figure 3. Phaseout of Animal Agriculture Reduces Global Warming Potential of Atmosphere.

Effect of eliminating emissions linked to animal agriculture and of biomass recovery on land currently used in animal agriculture on Radiative Forcing (RF), a measure of the instantaneous warming potential of the atmosphere. RF values computer from atmospheric concentrations in by formula of (Myhre et al., 1998; Ramaswamy et al., 2001) as modified in MAGICC6 (Meinshausen et al., 2011) with adjustment for gasses other than CO_2, CH_4 and N_2O as described in text.

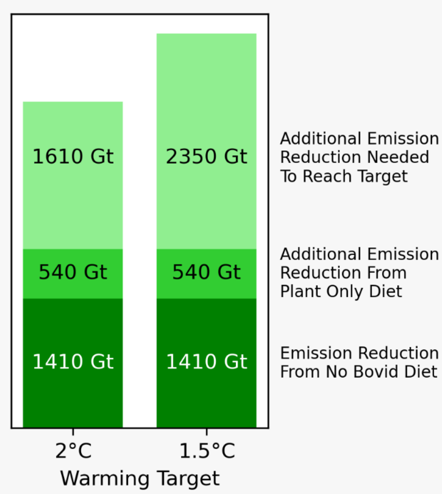
Eliminating animal agriculture would achieve half of the emission reductions needed to meet Paris Agreement GHG targets

In 2010, the climate modeling community defined a series of four "Representative Concentration Pathways" that capture a wide range of future warming scenarios, leading to 2100 RF levels of 8.5, 6.0, 4.5 and 2.6 Wm^{-2}, respectively (Moss et al., 2010; van Vuuren et al., 2011). These model pathways were extended after the Paris Agreement to include a target of 1.9 Wm^{-2}. Although the exact relationship between RF and global warming is complicated and incompletely understood, 2100 RF values of 1.9 and 2.6 Wm^{-2} are generally used as targets for limiting warming in this century to 1.5˚C and 2.0˚C, respectively, over the baseline pre-industrial global average temperature (IPCC, 2018).

The 1,950 gigaton CO_2eq reduction in RF from eliminating animal agriculture, would, without any other intervention to reduce GHG emissions, achieve around 55 percent of the net GHG emissions reductions necessary to reach the 2100 RF target of 2.6 Wm^{-2} and 45 percent of the emissions reductions necessary to reach the 1.9 Wm^{-2} target 4 and Figure 4-S1).

Figure 4. Significance of dietary transition in curtailing global warming.

Using projected CH_4 and N_2O levels in 2100 under business as usual diet as a baseline for RF calculation, we computed the CO_2 reductions necessary to reduce RF from the business as usual diet level of RF=5.13 to the bovid-free diet level of RF=4.26 (1410 Gt CO_2), the plant-only diet level of RF=3.88 (1950 Gt CO_2), the 2.0˚C global warming target of RF=2.6 (3560 Gt CO_2) and the 1.5˚C global warming target of RF=1.9 (4300 Gt CO_2). For this analysis we used a corrected RF that accounts for the absence of other gases in our calculation by training a linear regression model on published MAGICC6 output to estimate from CO_2, CH_4 and N_2O levels the residual RF impact of other gases.



Eliminating animal agriculture would negate half of anthropogenic GHG emissions through 2100

While widely used, such single point estimates of radiative forcing tell an incomplete story, as temperature change, and other climate impacts, depend cumulatively on the temporal trajectories of changing atmospheric greenhouse gas levels.

To capture these dynamic effects, we computed, for different dietary scenarios, the cumulative change in RF relative to BAU, between 2021 (the start of the intervention in this model) and each subsequent year through 2200. We designate this "cumulative RD difference" for year *y* $CRFD^y$. We then determined, for each intervention and year *y*, the sustained reductions in CO_2 emissions relative to BAU between 2021 and year *y* that would be required to achieve the same $CRFD^y$.

This annualized CO_2 equivalent is analogous to the commonly used global warming potential (GWP)-based CO_2 equivalents (Myhre et al., 2013), except that we consider sustained changes to emissions, whereas GWPs look at the impact of emission pulses. Because it represents the cumulative warming impact over an interval during which the RF impact of the hypothesized reductions in livestock systems varies over time, the value is also time dependent, and we therefore designate it aCO_2eq^y.

The aCO_2eq^{2100} for a 15-year phaseout of animal agriculture is 26.1 Gt/year, and the 2,063 Gt total CO_2eq equivalent emission reductions are slightly more than half of all emissions expected under BAU.

The full opportunity cost of continued animal agriculture is equivalent to 2,500 Gt of CO_2 emissions through 2100

Although it is unlikely to happen this rapidly, analyzing the impact of an immediate cessation of animal agriculture paints the clearest picture of the climate costs of its continuation. Unsurprisingly, a model in which all animal agriculture linked emissions are eliminated beginning in 2021, and the 30-year carbon recovery period begins on all land currently used in animal agriculture simultaneously, amplifies the effects seen with a 15-year phaseout (Figure 2-S1).

Crucially, the 2,550 Gt effective total emission reduction through 2100 arising from the immediate elimination of animal agriculture represents the full 21st century carbon opportunity cost of continuing to use animal agriculture as a source of food production.

The climate impact of animal agriculture is dominated by ruminants, especially cattle

To analyze the climate impact of specific animal products, and to attribute these impacts on a per unit basis, we ran models in which individual animal products were eliminated independently, using the species- and product-specific emissions and land use values described above (Figure 5; see also Table 1).

We use aCO_2eq^{2050}, the atmospheric warming potential through 2050, as our primary measure of product-specific effects. Although they account for only 50 percent of animal-derived protein, ruminants (cattle, buffalo, sheep and goats) collectively account for 86 percent of the aCO_2eq^{2050}, with the greatest effect coming from beef (46 percent) and cow milk (23 percent).

Because aCO_2eq compares the effects of persistent changes in animal agriculture to persistent changes in CO_2 emissions, it can be interpreted on a per unit basis. Ruminant meat has, by far, the greatest per-unit climate impact (Figure 5B and 4C), with a production-volume weighted average of 475 kg aCO_2eq^{2050} per kg of consumer product, and 2104 kg aCO_2eq^{2050} per kg protein. While milk has relatively low equivalent emissions per unit volume, 15.5 kg aCO_2eq^{2050} per liter, its per-protein equivalent emissions are also high at 460 kg aCO_2eq^{2050} per kg protein.

To put these numbers in perspective, the 30-year climate impact of a kg of beef is the same as that of driving a typical car 2,250 km (1,400 miles). Corresponding comparative values for other animal products are shown in Figure 5B and 4C.

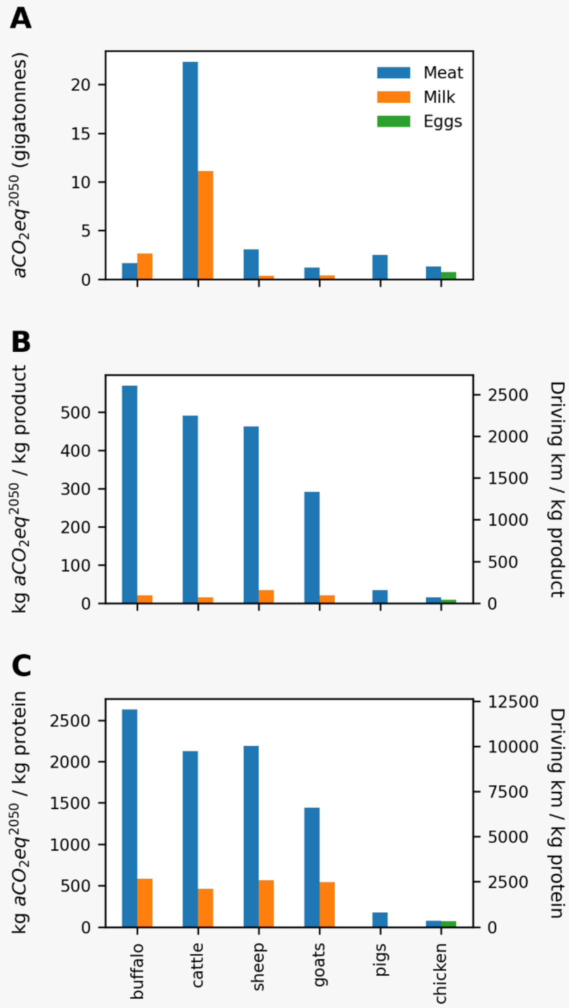


Figure 5. Annualized CO_2 equivalents of animal agriculture.

We calculated the (A) total annualized CO_2 equivalents through 2050, aCO_2eq^{2050}, for all tracked animal products, and the aCO_2eq^{2050} per unit production (B) or per unit protein (C). For (B) and (C) we also convert the values to driving equivalents, assuming cars that get 10.6 km per liter of gas (the average of new cars in the United States).

Caveats and Considerations

Although our general conclusions are robust to a wide range of assumptions about emissions, carbon fixation, diet and climate responses, there are many potential sources of error and uncertainty in these scenarios that could lead to either over and under-estimation of the impact of eliminating animal products from the human diet.

First, this analysis only considered consumption of terrestrial animal products, neglecting the considerable emissions and land use associated with seafood capture and aquaculture. While the land and emissions impact of seafood consumption has received comparably little attention, several studies have pointed to at least 500 Mt of CO_2 equivalent emissions per year from seafood (MacLeod et al., 2020; Parker et al., 2018; Poore and Nemecek, 2018). Recent work has also suggested that the disruption of carbon storage due to seafood harvesting via trawling has an effect equivalent of approximately 1.0 Gt of CO_2 emissions per year (Sala et al., 2021). Based on these published estimates, accounting for seafood consumption would increase the impact of animal food consumption measured in 2100 by an additional approximately 120 Gt CO_2 equivalents.

There are several sources of uncertainty in estimating carbon sequestration on land repurposed from animal agriculture. We use the mean values calculated by (Hayek et al., 2021) of a difference between BAU and POD of 863 Gt CO_2eq, but their estimates range from 670 to 1207, depending on land use details and future agricultural yields, without accounting for the unquantified uncertainty in soil carbon.

Some studies of biomass recovery on previously degraded lands suggest that our assumption that biomass carbon stores would fully recover to pre-livestock levels within 30 years may be optimistic (Lennox et al., 2018; N'Guessan et al., 2019; Poorter et al., 2016), or at least inconsistent. Deliberate, active management of ecosystem recovery to optimize for carbon sequestration could accelerate and increase the magnitude of carbon storage on land transitioning from intensive agricultural use, while providing livelihoods for the farmers and ranchers currently working on that land, and continuing to support the associated rural communities. Further research is required to define optimal management practices for recovery of ecosystems currently impacted by animal agriculture and to estimate the rate and magnitude of their impact on climate and biodiversity.

Our estimates of the emissions and land use associated with a BAU diet are conservative, as they fail to account for the continuing increases in population and per capita meat and dairy consumption in developing economies. It's worth noting that substantial reductions in land use and net greenhouse gas emissions could be achieved by switching meat consumption from ruminants, especially cattle, to non-ruminants like pig and chicken, although even non-ruminant livestock systems would still have substantially greater destructive impact on land use, water consumption and pollution, biodiversity and climate than plant-only diets.

Discussion

Our analysis has revealed the magnitude of the potential climate impact of a hypothetical, radical global change in diet and agricultural systems. These results should put replacement of animal agriculture at the forefront of climate-defense strategies, and inspire more research into the environmental, public health, food security, economic, political and social consequences of such a shift.

How such a transformation might come about is not within the scope of this report, but we believe it is eminently feasible. Although animal products currently provide, according to the most recent data from FAOSTAT, 18 percent of the calories, 40 percent of the protein and 45 percent of the fat in the human food supply, they can be readily replaced by calories, protein and fat from existing crops, with a vastly reduced land, water, GHG and biodiversity impact and only minor adjustments to optimize nutrition (Springmann et al., 2018). Indeed, the protein yield (assuming 37% yield of soy protein as concentrate) of the 2019 global soybean crop alone, grown on less than 1% of Earth's ice-free land surface, was equivalent to 264% of the total protein in all the bovine meat and milk produced globally in 2019 (FAO, 2021) after correction for digestibility and amino acid composition (Schaafsma, 2000).

The contemplated transition away from animal agriculture would entail many political, economic, and social challenges. The economic and social impacts, if thoughtlessly managed, would be acute in many regions and locales. Substantial global investment would be needed to ensure that the people who currently make a living from animal agriculture are better off when it is replaced. But that investment, we believe, would be small in comparison to the economic and humanitarian disruptions we would face if we allow climate change to continue unchecked (Howard and Sylvan, 2021; Stehfest et al., 2019).

Current dietary trends are unsustainable. If today's per capita animal-product consumption in wealthy, highly industrialized countries (OECD) were extended to the global population, an additional 46 million km^2 - an area roughly equal to the combined area of Africa and South America - would be needed to support the required growth in livestock populations. The destruction of this much of Earth's critical remaining native ecosystems would have catastrophic impacts on the climate, environment, and human health (Clark et al., 2019; Maron et al., 2018; Oliver et al., 2015; Satija et al., 2017; Springmann et al., 2016; Strassburg et al., 2020; Tilman and Clark, 2014).

Given this reality, reiterated in numerous studies over the past several decades, we find it astonishing that changes in food production and consumption are not at the forefront of proposed strategies for fighting climate change. And it is disappointing that the most prominent plans put forth by governments and international organizations to limit global warming ignore or discount the potential impact of significant reductions in livestock systems. For example, none of the mitigation strategies presented as part of the recent Intergovernmental Panel on Climate Change (IPCC) report on steps needed to keep global warming below 1.5˚C propose even a reduction in per capita livestock consumption below current levels (Figure 6), let alone a planet free of livestock production. They rely instead on currently non-existent and unproven, hypothetical carbon capture and storage technologies being deployed in the second half of the century.

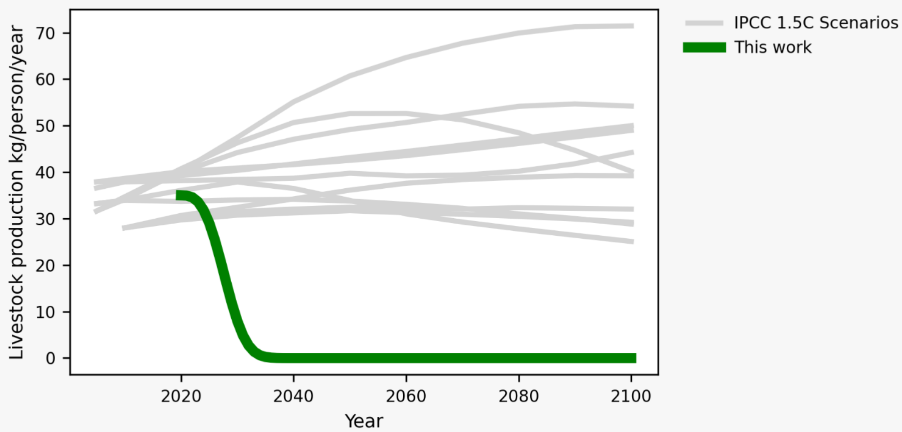


Figure 6. Projected per capita livestock production in SSP/IAM RF 1.9 scenarios.

We downloaded data for the Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017) from the SSP database (Version 2.0; last updated December 2018), and plot here the inferred per capita livestock production for scenarios meant to reach an RF target of 1.9 in 2100. While there is widespread acknowledgement of the impact that ongoing animal agriculture has on the climate, it is notable that most of these scenarios, which represent the most aggressive proposed mitigation strategies in this modeling framework, anticipate an increase in per capita livestock consumption, and none anticipate any significant reduction below current levels, in contrast to the complete elimination we propose here.

Although no plausible alternative would be comparably impactful, changes in our food-production system alone are not sufficient to stop and reverse climate change in this century. Transition to renewable energy systems, perhaps complemented by converting a fraction of the land once used for livestock production into carbon ranches (Clarke et al., 2014) will be essential to reach the goal of limiting global warming to 1.5˚C. But, crucially, phasing out consumption of animal products, especially those from cattle and buffalo, from the human diet today, could yield a three-decade pause in net accumulation of the greenhouse gasses that drive global warming. Such a pause would provide a window of opportunity to develop the renewable energy and carbon capture technologies required to achieve permanent net-zero emissions, along with the political will to implement them globally.

Species	Commodity	Primary Production	Protein Production	Emissions CO_2	Emissions CH_4	Emissions N_2O	Land Use	aCO_2eq	Emissions Intensity	Emissions Intensity	Driving Equivalents
		Metric tons	Metric tons protein	Mt	Mt	Mt	Mkm^2	Gt/year	kg aCO_2eq per kg	kg aCO_2eq per kg protein	km driven per kg
Buffalo	Meat	4,290,212	619,200	29	5.00	0.20	1.0	1.6	569	2630	2604
Cattle	Meat	68,281,663	10,493,839	616	49.30	2.41	17.2	22.3	491	2128	2244
Sheep	Meat	9,913,245	1,396,875	32	5.02	0.33	2.6	3.1	463	2192	2119
Goats	Meat	6,248,372	839,781	21	3.34	0.11	0.8	1.2	292	1446	1333
Pigs	Meat	110,102,495	14,456,458	359	7.19	0.62	1.6	2.5	34	175	157
Chickens	Meat	123,973,557	17,666,232	440	0.29	0.52	1.3	1.3	15	72	71
Chickens	Meat	7,363,110	1,049,243	36	0.02	0.05	0.1	0.1	18	83	81
Buffalo	Milk	133,752,296	4,510,017	121	10.87	0.45	1.2	2.6	20	584	90
Cattle	Milk	715,871,270	24,138,586	357	37.68	1.78	6.4	11.1	16	460	71
Sheep	Milk	10,587,020	642,183	10	1.72	0.12	0.1	0.4	34	569	158
Goats	Milk	19,910,379	745,972	10	1.74	0.06	0.2	0.4	20	544	93
Chickens	Eggs	88,431,696	10,965,530	221	0.57	0.35	0.6	0.7	8	66	38

Table 1. Product-specific Emissions, Land Use and Inferred Impacts

Primary production data aggregated from FAOSTAT for 2019. Protein production data calculated from primary production data and protein conversion factors inferred from GLEAM. Emissions data based on protein production data and emission intensities from GLEAM. Land use data calculated from FAOSTAT protein production data and product-specific land use data from (Poore and Nemecek, 2018). Annualized CO_2 equivalent emissions are for 2050 and calculated from atmospheric modeling results. Emissions Intensities are per kg retail product or per kg protein data calculated from production data and are for 2050. Driving equivalents calculated from per unit emissions intensities assuming 8.8 kg CO_2 per gallon of gas and 25 miles driven per gallon of gas.

Declaration of Conflict of Interest

Patrick Brown is the founder and CEO of Impossible Foods, a company developing a technology platform to replace the use of animals as a food-production technology, with the goal of ending the destructive impact of animal agriculture on our planet. Michael Eisen is an advisor to Impossible Foods. Both are shareholders in the company and thus might benefit financially from reduction or elimination of animal agriculture. Noting this conflict of interest, we have made all of the data and code used in this study available, inviting others to check and challenge our methods and conclusions. We intend for this work to provoke discussion and debate and to inspire other scientists to investigate the issues and opportunities we raise here.

Acknowledgements

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Methods

Data and Code Availability

Analyses were carried out in Python using Jupyter notebooks. All data, analyses and results presented here are available at github.com/meatlessmillennium.

Updating Estimates of Emissions from Animal Agriculture

We obtained country, species, herd and product type specific CO_2, CH_4 and N_2O emission data for terrestrial livestock from the public version of GLEAM 2.0 downloaded from http://www.fao.org/gleam/results/en/. GLEAM contains data for cattle, buffalo, sheep, goats, pigs and chickens, and attributes emissions to meat, milk and eggs. Although GLEAM further breaks down emissions based on herd type and production system, we used aggregate data for all herds and production types in the country.

We obtained livestock production data for 2019 (the most recent year available) from the "Production_LivestockPrimary" datafile in FAOSTAT. We extracted from Production_LivestockPrimary the amount (in tonnes), for all countries, of primary domestic production of meat from cattle, buffalo, sheep, goat, pig, chicken and duck, milk from cows, buffalo, sheep and goat, and eggs from poultry. We computed meat and protein yields from the carcass weight data reported by GLEAM.

We scaled the GLEAM emission data reported for entire herds based on carcass weight for meat, and production weight for milk and eggs. As GLEAM does not provide data for ducks, we used values for chicken. The scaling was done using country-specific livestock production data and regional data from GLEAM.

The emissions estimates from this analysis are 2.25 Gt CO_2, 122.2 Mt CH_4 and 6.98 Mt N_2O.

Estimating species-specific land use

We combined livestock production data (see above) with average species and product-specific land use data from (Poore and Nemecek, 2018) to estimate species, product and country-specific land use data associated with animal agriculture. We use data for cattle meat for buffalo meat, and cow milk for milk from buffalo, goat and sheep. The data are reported in m $m^2 (year)(100g\ protein)^{-1}$ except for milk which is reported in $m^2 (year)(liter)^{-1}$ which we convert to $m^2 (year)(kg\ primary\ production)^{-1}$ using conversion factors inferred from GLEAM which reports both protein and primary production data.

The total land use for animal agriculture inferred from this analysis is 33.7 million km^2, almost identical to the 33.2 million km^2 estimated by (Hayek et al., 2021) from satellite imagery.

Emissions from Agriculture

We used the Environment_Emissions_by_Sector_E_All_Data_(Normalized) data table from FAOSTAT, projecting from the most recent year of 2017 to 2018 by assuming the average annual growth from 2000 to 2017 continues. This yields an estimate of all agricultural emissions of 4.5 Gt CO_2, 142 Mt CH_4 and 7.8 Mt N_2O per yea.

Non-Agricultural Emissions

We extracted total emissions from FAOSTAT from the same data file as for Agricultural emissions, yielding an estimate for 2018 of 41.2 Gt CO_2, 368 Mt CH_4 and 10.8 Mt N_2O. Subtracting out agricultural emissions yields baseline non-agricultural emissions of 36.7 Gt CO_2, 226 Mt CH_4 and 2.99 Mt N_2O.

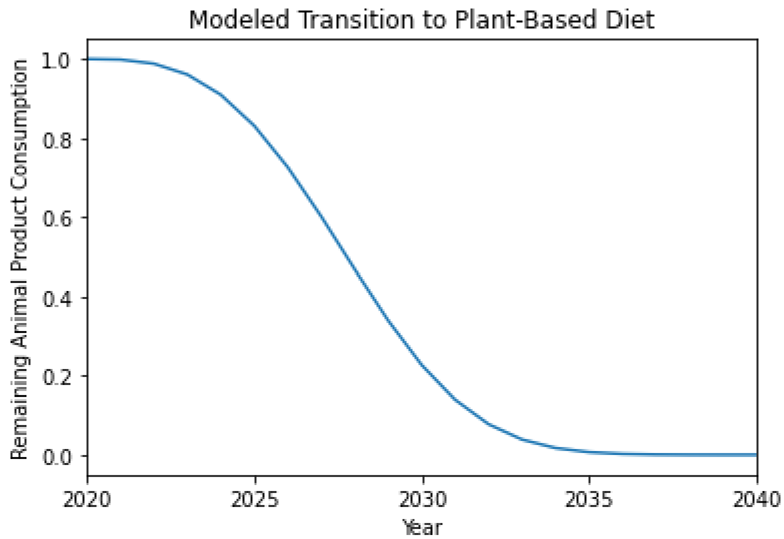
Diet-Linked Emissions

We assumed agricultural emissions under a business as usual (BAU) diet would remain at 2018 levels. For a plant-only diet (POD), we set CO_2 emissions to 0, as the carbon sequestration data from (Hayek et al., 2021) already accounts for increased land use required to produce a nutritionally balanced diet, and scaled remaining agricultural CH_4 and N_2O emissions after removing those from animal agriculture by 1.25 to account for the 20 percent of calories that currently come from animal agriculture products in the global diet). For diets involving the removal of one or more specific animal products, we scaled these dietary replacement emissions by the fraction of animal protein obtained from that product, and scaled biomass recovery by the fraction of animal agriculture land attributed to that product.

Emissions Projections

In all scenarios we assume annual non-agricultural emissions remain fixed at 2018 levels through 2100. For a BAU diet we added in agricultural emissions, effectively fixing total emissions at 2018 levels. For the POD we assumed a 15-year phaseout of animal agriculture with an accelerated rate of conversion from BAU to POD or BFD. The specific formula we use is $f(year) = e^{-5* \left(\frac{year - 2020}{15}\right)^3}$

yielding the conversion dynamics shown below:



We also include in the supplemental data a version of the analysis in which the hypothetical transition is instantaneous.

As the transition from BAU to POD or BFD occurs, agriculture linked emissions are set to

$$E_{food} = fE_{BAU} + (1 - f)E_{POD}$$

Where f is the fraction of the global diet that is still BAU.

We assume that, when animal-derived food consumption is reduced in a year by a fraction Δf, that carbon recovery on a corresponding fraction of land begins immediately and continues at a constant rate until it reaches 100 percent after 30 years (or, for the analysis depicted in Figure 2-S2, 50 years).

Converting between emissions and atmospheric concentrations of GHGs

The total mass of gas in the atmosphere is 5.136 * 10^{21} g, at a mean molecular weight of 28.97 g/mole (Walker, 1977), or is 1.77e+20 total moles of gas. Hence 1 ppb is 1.77*10^{11} moles and 1 ppm is 1.77 * 10^{14} moles.

We therefore use conversions from mass in Gt to ppb/ppm as follows:

$$CO_2\,ppm = CO_2\,Gt * \frac{10^{15} g}{Gt} * \frac{1\,mole}{44\,g} * \frac{1\,ppm}{1.77*10^{14}\,mole} * f_{sink}$$

$$CH_4\,ppb = CH_4\,Mt * \frac{10^{12} g}{Mt} * \frac{1\,mole}{16\,g} * \frac{1\,ppb}{1.77*10^{11}\ mole}$$

$$N_2O\,ppb = N_2O\,Mt * \frac{10^{12} g}{Mt} * \frac{1\,mole}{44\,g} * \frac{1\,ppb}{1.77*10^{11}\ mole}$$

We use an f_{sink} value of 0.50 reflecting the observation that approximately half of terrestrial CO_2 emissions end up in land or ocean sinks rather than the atmosphere (Houghton, 2003).

Estimating global non-anthropomorphic emissions

Both CH_4 and N_2O decay at appreciable rates, with half-lives of approximately 9 years for CH_4 (Morgenstern et al., 2017) and 115 years for N_2O (Prather et al., 2015), although these estimates are being continuously updated (Saunois et al., 2020). We balanced the corresponding decay equations against historical emissions and atmospheric levels, inferring unaccounted for and presumably non-anthropogenic sources leading to mole fraction equivalent increases of CH_4 of 25 ppb/year and N_2O of 1.0 ppb/year.

Projections of Atmospheric Gas Levels

We ran projections on an annual basis starting in 2020 and continuing through 2100. For each gas:

$$P_{gas}^{year+1} = P_{gas}^{year}(1 - A_{gas}) + E_{gas}^{year} + N_{gas}$$

where:

P_{gas}^{year} is the atmospheric concentration of *gas* in *year* in ppb for CH_4 and N_2O and ppm for CO_2

A_{gas} is the annual decay of *gas* and is equal to $(\frac{1}{2})^{\frac{1}{H_{gas}}}$ where H_{gas} is the half-life of *gas* (we assume that CO_2 does not decay)

$$H_{CH_4} = 9.0\,years \quad H_{N_2O} = 115.0\,years$$

E_{gas}^{year} is the emissions of *gas* in *year* converted to atmospheric ppb for CO_2 and N_2O and ppm for CO_2 as described above

N_{gas} is the constant term to account for emissions not captured in E

$$N_{CH_4} = 25.0\,ppb \quad N_{N_2O} = 1.0\,ppb$$

Starting conditions are:

$$P_{CO_2}^{2020} = 409.8\,ppm \quad P_{CH_4}^{2020} = 1863.9\,ppb \quad P_{N_2O}^{2020} = 332.5\,ppb$$

Radiative Forcing

We adopt the commonly used formula for radiative forcing (RF) which derives from (Myhre et al., 1998; Ramaswamy et al., 2001) as modified in the climate modeling program MAGICC6 (Meinshausen et al., 2011).

Given atmospheric concentration of *C* ppm CO_2, *M* ppb CH_4 and *N* ppb N_2O

$$RF(C, M, N) = \Delta F = \Delta F_{CO_2} + \Delta F_{CH_4} + \Delta F_{N_2O}$$

$$\Delta F_{CO_2} = \alpha_{CO_2} ln\frac{C}{C_0}$$

$$\alpha_{CO_2} = 5.35$$

$$\Delta F_{CH_4} = \alpha_{CH_4}(\,(1 + \beta_{CH_4})(\sqrt{M} - \sqrt{M_0}) + f(M, N_0) + f(M_0, N_0)\,)$$

$\alpha_{CH_4} = 0.036$ and $\beta_{CH_4} = 0.15$

$$\Delta F_{N_2O} = \alpha_{N_2O}(\sqrt{N} - \sqrt{N_0} + f(M_0, N\ ) + f(M_0, N_0)\,)$$

$$\alpha_{N_2O} = 0.12$$

The function $f(m, n) = 0.47ln(1 + 0.6356(\frac{mn}{10^6})^{.75} + 0.007(\frac{m}{10^3})(\frac{mn}{10^6})^{1.52}$ captures the overlap in spectra between CH_4 and N_2O.

C_0, M_0 and N_0 are the preindustrial levels of the corresponding gasses.

$$C_0 = 278\,ppm \qquad M_0 = 700\,ppb \qquad N_0 = 270\,ppb$$

Computing Emissions and Land Carbon Opportunity Cost

We define the combined emissions and land carbon opportunity cost (ELCOC) of animal agriculture as $2\Delta C$ where

$$RF(C_{BAU} - \Delta C, M_{BAU}, N_{BAU}) = RF(C_{POD}, M_{POD}, N_{POD})$$

The factor of 2 accounts for the half of CO2 emissions that go to terrestrial sinks.

Computing Carbon Budgets for RF 2.6 and 1.9

As RF calculations used in climate models account for other gasses and effects beyond the three gasses used here, we used multivariate linear regression as implemented in scikit-learn to predict the complete RF output of MAGICC6 using data data downloaded from the Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017). The model was trained on atmospheric concentrations of CO_2, CH_4 and N_2O to predict the difference between the MAGICC6 RF and the RF as calculated above. Then, for timepoints in our scenarios we computed RF as above from CO_2, CH_4 and N_2O concentrations, and add to this the adjustment from the linear regression model. We use this RF in Figures 3 and 4.

In the SSP file:

C = Diagnostics|MAGICC6|Concentration|CO_2
M = Diagnostics|MAGICC6|Concentration|CH_4
N = Diagnostics|MAGICC6|Concentration|N_2O

ΔF_{CO_2} = Diagnostics|MAGICC6|Forcing|CO_2

ΔF_{CF_4} = Diagnostics|MAGICC6|Forcing|CH_4

ΔF_{N_2O} = Diagnostics|MAGICC6|Forcing|N_2O

MAGICC6 RF = Diagnostics|MAGICC6|Forcing

aCO_2eq

We computed the CO_2 emission equivalents of perturbations to BAU emissions using the simulations described above to determine the RF of both BAU and the perturbation for years from 2020 through 2200. We then calculated the cumulative RF difference (CRFD) between the perturbation and BAU for each year, and determined, for each year, the equivalent annual reduction in CO2 emissions relative to BAU required to produce the same CRFD. This value, which we refer to as the annualized CO2 equivalent, abbreviated aCO2eq, is a function of the perturbation and reference year. In the text we report aCO2eq for 2050 (30 year time horizon), 2100 (80 year time horizon) and 2120 (100 year time horizon).

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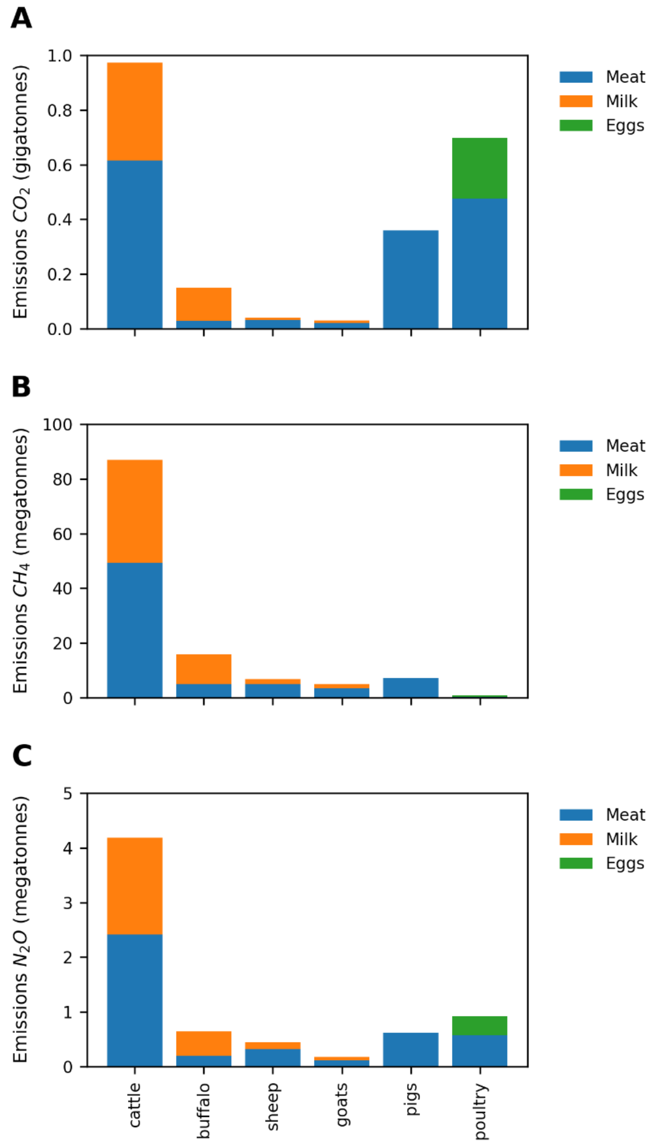

Figure 1-S1. Gas-specific emission footprints of animal agriculture.

Assembled from species, product and country-specific production data from FAOSTAT for 2018 and species, product, region and greenhouse gas-specific emissions data from GLEAM (MacLeod et al., 2018).

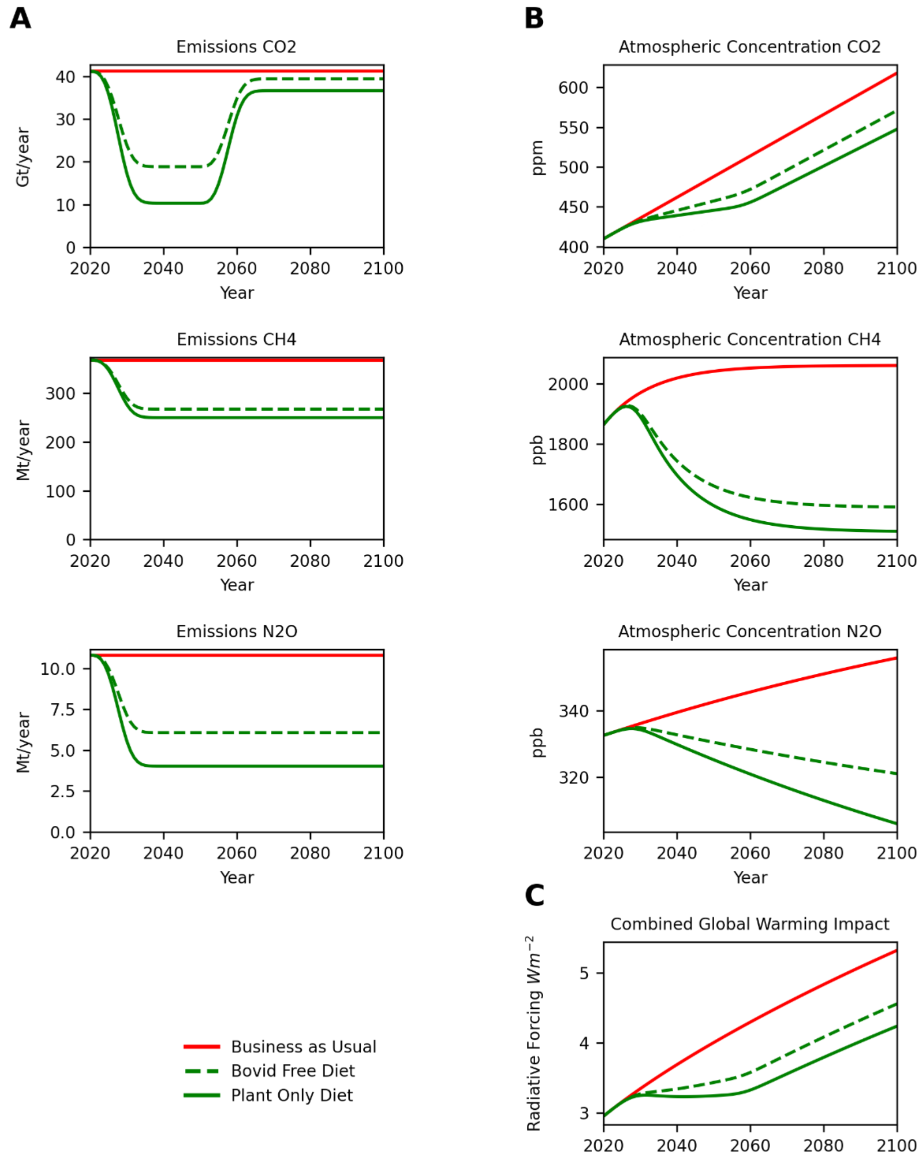

Figure 2-S1. Relative Contribution of Bovids.

(A) Projected annual emissions of CO_2, CH_4 and N_2O for Business as Usual, Plant Only and Bovid Free diets assuming 15 year transitions to new diets. (B) Projected atmospheric concentrations of CO_2, CH_4 and N_2O under each emission scenario. (C) Radiative Forcing (RF) inferred from atmospheric concentrations in (B) by formula of (Myhre et al., 1998; Ramaswamy et al., 2001) as modified in MAGICC6 (Meinshausen et al., 2011).

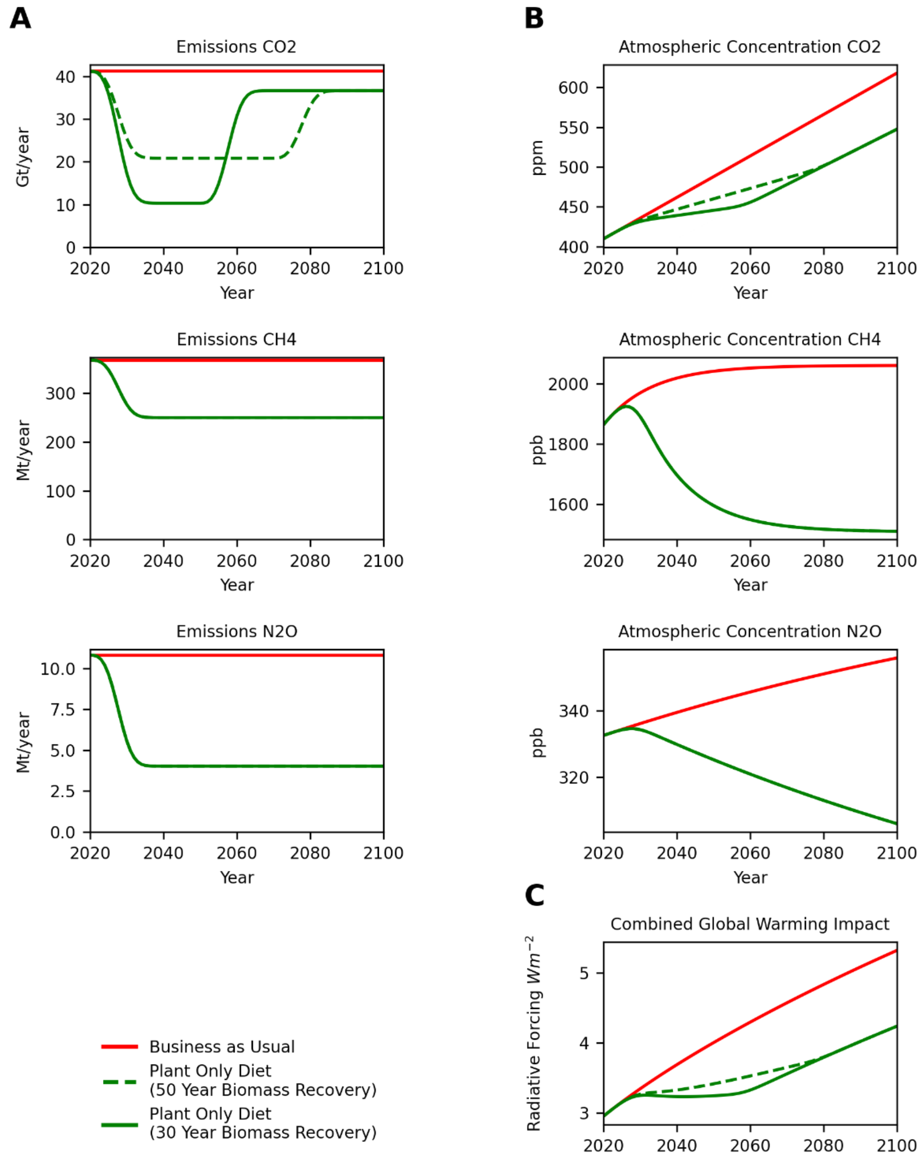

Figure 2-S2. Impact of slower biomass recovery on GHG levels.

(A) Projected annual emissions of CO_2, CH_4 and N_2O for Business as Usual Diet and Plant Only Diet assuming a 15 year transition to the new diet and either 30 or 50 year linear biomass recovery trajectory on freed land. (B) Projected atmospheric concentrations of CO_2, CH_4 and N_2O under each emission scenario. (C) Radiative Forcing (RF) inferred from atmospheric concentrations in (B) by formula of (Myhre et al., 1998; Ramaswamy et al., 2001) as modified in MAGICC6 (Meinshausen et al., 2011).

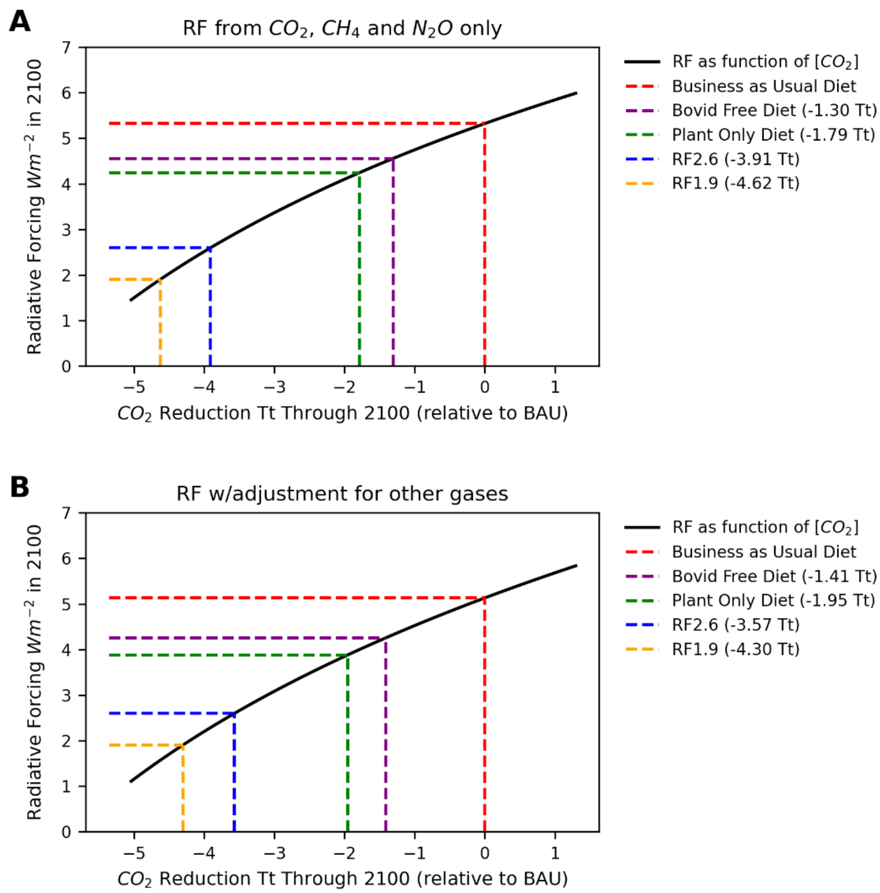

Figure 4-S1. Full carbon opportunity cost of animal agriculture.

We define the Emission and Land Carbon Opportunity Cost of animal agriculture as the total CO_2 reduction necessary to lower the RF in 2100 from the level estimated for a business as usual (BAU) diet to the level estimated for a plant only diet (POD). For these calculations we fix the CH_4 and N_2O levels in the RF calculation at those estimated for the BAU diet in 2100 and adjust CO_2 levels to reach the target RF. We also calculate ELCOC for just bovid sourced foods and determine the emission reductions necessary to reach RF's of 2.6 and 1.9, often cited as targets for limiting warming to 2.0˚C and 1.5˚C respectively. (A) Shows the results for RF directly calculated from CO_2, CH_4 and N_2O, while (B) shows an RF adjusted for other gases using multivariate linear regression on MAGICC6 output downloaded from the SSP database.