Ending animal agriculture would stabilize greenhouse gas levels for 30 years and offset half of anthropogenic emissions through 2100

Michael B. Eisen[1*] and Patrick O. Brown[2,3*]

[1] Department of Molecular and Cell Biology, Howard Hughes Medical Institute, University of California, Berkeley, CA 94720. [2] Department of Biochemistry (Emeritus), Stanford University School of Medicine, Stanford, CA 94305. [3] Impossible Foods, Redwood City, CA 94063.

* Address correspondence to mbeisen@berkeley.edu and pat.brown@impossiblefoods.com.

Preprint Server: This work has been deposited to bioRxiv and is available at https://www.biorxiv.org/content/10.1101/2021.04.15.440019v1

Classification: Physical Sciences: Sustainability Science

Keywords: Animal Agriculture, Livestock, Greenhouse Gases, Climate Change

Abstract

Animal agriculture contributes to global warming via ongoing emissions of the potent greenhouse gases methane and nitrous oxide, and displacement of biomass carbon on the land used to support livestock. We calculated the climate opportunity cost of the consumption of livestock products by modeling the combined effects of emission reduction and biomass recovery on atmospheric greenhouse gas levels under food-system scenarios ranging from "business as usual" to the complete elimination of animal agriculture. We found that, even in the absence of any other emission reductions, eliminating consumption of livestock products over the next 15 years would lead to rapid and persistent drops in atmospheric methane and nitrous oxide levels, and would dramatically slow carbon dioxide accumulation. These effects would yield a 30-year pause, from 2030 to 2060, in the rise of radiative forcing, a measure of the warming potential of the atmosphere, and a reduction in heat accumulation this century equivalent to a 25 gigaton decrease in annual carbon dioxide emissions, over half of current anthropogenic emissions. The magnitude and rapidity of these potential effects should place the reduction or elimination of animal agriculture at the forefront of strategies for averting disastrous climate change .

Significance Statement

The widespread use of animals to produce food has a massive negative impact on the climate and environment, but the benefits of a global switch to a plant based diet are underappreciated. In this paper we show that eliminating greenhouse gas emissions from livestock, and allowing native habitats to regrow on the roughly one third of Earth's land currently used to house and feed them, would reduce global warming for the rest of this century by the same amount as a 70 percent reduction in the use of fossil fuels in energy and transportation. We hope that putting a number on the "climate opportunity cost" of our continued use of animals as food will help policymakers and the public properly prioritize dietary change as a climate defense strategy.

Introduction

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

Major cuts in food-linked emissions are likely necessary by 2075 to limit global warming to 1.5°C, even in the context of large-scale reduction in emissions from other sources (Clark et al., 2020). Some reductions can likely be achieved by increasing agricultural efficiency, reducing food waste, limiting excess consumption, increasing yields, and reducing the emission intensity of livestock production (Hristov et al., 2013a, 2013b; Montes et al., 2013), although the magnitude of what such interventions can achieve is currently unknown. However, a recent analysis found that, of these options, a global transition to a plant-rich diet would be, by far, the most impactful (Clark et al., 2020)).

Nutritionally balanced plant-dominated diets (Agnoli et al., 2017; American Dietetic Association and Dietitians of Canada, 2003; Craig et al., 2009; Tilman and Clark, 2014; Willett et al., 2019) are common and diverse, and their global adoption 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).

Our goal here was to quantify the full impact that a transition to a global plant-based diet would have on the climate, taking into account both emission reductions and biomass recovery. We first curated publicly available, systematic data on livestock-linked emissions (FAO, 2021; MacLeod et al., 2018) and biomass recovery potential on land currently used to support livestock production (Hayek et al., 2021; Strassburg et al., 2020). We then used these data to predict how dietary shifts would affect net anthropogenic emissions, and used a simple climate model to project the resulting atmospheric GHG levels.

We calculated the combined impact of reduced emissions and biomass recovery for a range of dietary scenarios by comparing the cumulative reduction in the global warming potential of GHGs in the atmosphere for the remainder of the 21st century to reductions achieved by constant annual reductions in CO_2 emissions. Notably, we find that a global switch to a plant-only diet occurring over the next 15 years would have, through the end of the century, an effect equivalent to a 27-Gt annual reduction in CO_2 emissions, more than half of all current anthropogenic emissions.

Results

Modeling the effect of eliminating animal agriculture on GHG levels

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 1.6 Gt CO_2, due primarily to energy use (we excluded 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 four percent of CO_2, 35percent of CH_4 and 6 percent of N_2O emissions from all human activities.

To model the recovery of biomass on land currently used in livestock production, we used the median estimate 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, 216 Gt of carbon in plant and non-living biomass. A similar estimate was obtained by (Strassburg et al., 2020).

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 on 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; that food from livestock is replaced on a protein-equivalent basis by soybean; and that, when land is removed from livestock production, the conversion of atmospheric CO_2 into terrestrial biomass occurs linearly over the subsequent thirty years;

We emphasize that we are not predicting what will happen to global diets. Rather we are using simplified scenarios to characterize and quantify the climate impact of hypothetical changes to global dietary sources. Our climate model is also intentionally simple, considering only the partition of terrestrial emissions into the atmosphere, and the decay of methane and nitrous oxide, although it replicates the qualitative behavior of widely used MAGICC6 (Meinshausen et al., 2011).

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). In this scenario (replacement of animal-based food production over the next 15 years), 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.

To capture the combined global-warming impact of the changing levels of these GHGs, we estimated radiative forcing (RF), the reduction in radiative cooling by GHG absorption of infrared radiation, using the formulae described in (Myhre et al., 1998; Shine, 2000).

Figure 3 shows that, 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. 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.

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

By the end of the century the RF under the plant-only diet scenario would be 3.8 Wm^{-2} compared to 4.9 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 1,680 gigatons of CO_2 emissions, the equivalent of 32 years of current anthropogenic emissions.

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 1,680 gigaton CO_2 equivalent reduction in RF from eliminating animal agriculture, would, without any other intervention to reduce GHG emissions, achieve 53 percent of the net GHG emissions reductions necessary to reach the 2100 RF target of 2.6 Wm^{-2} and 44 percent of the emissions reductions necessary to reach the 1.9 Wm^{-2} target 4 and Figure 4-S1).

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 such dynamic effects, we computed, for different dietary scenarios, the integral with respect to time of the RF difference between each scenario and BAU, from 2021 (the start of the intervention in this model) to a given year "y". We designate this cumulative RF 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 explicitly consider the time-dependent impacts of emissions, whereas conventional CO_2eq GWPs represent 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.

Figure 5 shows the aCO_2eq for both phaseout and elimination of animal agriculture in reference years 2050 and 2100. The aCO_2eq^{2100} for a 15-year phaseout of animal agriculture is -25.0 Gt/year, and the -2,000 Gt total CO_2eq equivalent emission are slightly more than half of all emissions expected under BAU (see also Figure 5-S1 which compares the emissions, atmospheric levels, and cumulative RF differences with BAU of phaseout and a 25 Gt/year CO_2 decrease).

Although the immediate elimination of animal agriculture is not realistic, analyzing the impact of such a shift paints the clearest picture of the climate costs of its continuation and the climate opportunity unlocked by its reduction or elimination. Unsurprisingly, a model in which all animal agriculture linked emissions are eliminated beginning in 2021 (Figure 2-S1), and the 30-year carbon recovery period begins immediately on all land currently used in animal agriculture, amplifies the effects seen with a 15-year phaseout. This leads to a much higher aCO_2eq^{2050} for elimination (-45.0 Gt/year) than phaseout (-28.6 Gt/year).

The -2,300 Gt effective total emissions through 2100 inferred from the aCO_2eq^{2100} for immediate livestock elimination of -28.6 Gt/year represents our best estimate of the full 21st century carbon opportunity cost of continuing to use animal agriculture as a technology for 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 we considered the immediate elimination and 15 year phaseout of individual animal products or groups of related products, using the species- and product-specific emissions and land use values described above (Figure 5; see also Table 1).

Using aCO_2eq^{2050} , the atmospheric warming potential through 2050, as our primary measure of product-specific effects, beef accounts for 47 percent of the benefits of phasing out all animal agriculture, and cow milk 24 percent. Collectively, meat and milk from bovids (cattle and buffalo) produce 80 percent of the benefits. Although they account for only 50 percent of animal-derived protein, ruminants (cattle, buffalo, sheep and goats) collectively account for 90 percent of the aCO_2eq^{2050} of all livestock.

Because aCO_2eq for elimination 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 (Figure 6). Ruminant meat has, by far, the greatest per-unit climate impact, with a production-volume weighted average of 456 kg aCO_2eq^{2050} per kg of consumer product, and 2019 kg aCO_2eq^{2050} per kg protein. While cow milk has relatively low equivalent emissions per unit volume, 15.2 kg aCO_2eq^{2050} per liter, its per-protein equivalent emissions are also high at 450 kg aCO_2eq^{2050} per kg protein.

To put these numbers in perspective, we converted the aCO_2eq to the distance one would have to drive a typical car to produce the same emissions (Figure 6C). The aCO_2eq^{2050} for a kg of beef of 469 kg per year, for example, is equivalent to driving 1,905 km in a typical US car (Bureau of Transportation Statistics, 2021).

Discussion

Caveats and Considerations

This analysis only considered consumption of terrestrial animal products, neglecting the considerable emissions and land use (via feed production) 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 the equivalent of an additional approximately 120 Gt CO_2.

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) for carbon opportunity in living biomass of 152.5 Gt and soil and litter of 63 Gt, but there is large uncertainty in these estimates, especially around 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 intentionally conservative, as we chose not to account for projected continuing increases in population and per capita meat and dairy consumption. It is 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 impact on land use, water consumption and pollution, biodiversity and climate than plant-only diets.

Widely used climate models consider temporal and spatial variation in emissions; feedback between a changing climate and anthropogenic and natural emissions, carbon sequestration, atmospheric chemistry and warming potential; the impact of climate on human social, political and economic behavior. Ours does not. We compared our outputs to those from several such models using publicly available data from (Riahi et al., 2017) and found them to be in broad qualitative agreement. Thus, while other models could provide more precise estimates, we do not believe they would alter our major conclusions.

Perspective

Our analysis has provided a quantitative estimate of the potential climate impact of a hypothetical, radical global change in diet and agricultural systems. The impact is far greater than has previously been recognized. Unlike solutions aimed at replacing fossil-fuel combustion, which would merely abate further increases in carbon dioxide, reducing or eliminating the use of animals as food technology would actually “turn back the clock” on agricultural emissions, through decay of methane and nitrous oxide, and carbon fixation by photosynthesis, restoring biomass and biodiversity on the vast land areas currently impacted by grazing and feed-crop cultivation. Reductions in animal agriculture should therefore move to the forefront of climate-defense strategies, along with research to define and optimize the environmental, public health, food security, economic, political and social consequences of such a shift.

Animal products currently provide, according to the most recent data from FAOSTAT, 17 percent of the calories, 35 percent of the protein and 45 percent of the fat in the human food supply. These could be 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). The protein yield of the 2019 global soybean crop alone, grown on 0.92 percent of Earth’s ice-free land surface, was equivalent to 137% of all protein obtained from terrestrial livestock (FAO, 2021).

A transition away from animal agriculture would entail many challenges. The economic and social impacts, if ignored or 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 must be compared 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).

The scale of global animal agriculture continues to grow, along with its destructive impact on climate and biodiversity, driven by rising incomes (OECD-FAO Agricultural Outlook 2020-2029).

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 these realities, it is surprising that changes in food production and consumption are not at the forefront of proposed strategies for fighting climate change. 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 7). They rely instead on currently non-existent and unproven carbon capture and storage technologies being deployed in the second half of the century.

Although dietary change would be hugely 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 (Clark et al., 2020). But, crucially, phasing out consumption of animal products, especially those from cattle, 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 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
		tonnes	tonnes protein	Mt	Mt	Mt	Mkm^2	Gt/year	kg aCO2 per kg	kg aCO2eq per kg protein	km driven per kg
Buffalo	Meat	4,290,212	619,200	29	5.00	0.20	1.0	1.6	554	2557	2248
Cattle	Meat	67,893,363	10,435,590	236	49.30	2.41	17.1	21.2	469	2036	1905
Sheep	Meat	9,648,245	1,354,398	32	5.02	0.33	2.5	2.9	445	2105	1806
Goats	Meat	6,128,372	821,383	21	3.34	0.11	0.8	1.2	284	1410	1154
Pigs	Meat	110,102,495	14,447,438	278	7.19	0.62	1.6	2.6	35	177	142
Chickens	Meat	123,898,557	17,393,440	306	0.29	0.52	1.3	1.3	16	77	67
Chickens	Meat	7,363,110	1,044,797	27	0.02	0.05	0.1	0.1	20	95	83
Buffalo	Milk	133,752,296	4,510,017	119	10.87	0.45	1.2	2.6	20	584	80
Cattle	Milk	712,883,270	23,889,273	338	37.63	1.78	6.3	10.8	15	450	62
Sheep	Milk	10,172,020	624,048	10	1.72	0.12	0.1	0.4	35	575	142
Goats	Milk	18,752,379	702,585	10	1.74	0.06	0.2	0.4	21	554	84
Chickens	Eggs	88,361,696	10,982,733	159	0.57	0.35	0.6	0.7	8	67	34

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 technologies to replace the use of animals as a food-production technology. Michael Eisen is an advisor to Impossible Foods. Both are shareholders in the company and thus stand to 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, to enable others to check and challenge our methods and conclusions.

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/mbeisen/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 (MacLeod et al., 2018) 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 did not include CO2 emissions linked to land-use change, as this is associated with increases in livestock production which are explicitly not considered by our model.

We obtained livestock production data for 2019 (the most recent year available) from the "Production_LivestockPrimary" datafile in FAOSTAT (FAO, 2021). 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.

Estimating species-specific land use

We combined livestock production data 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.

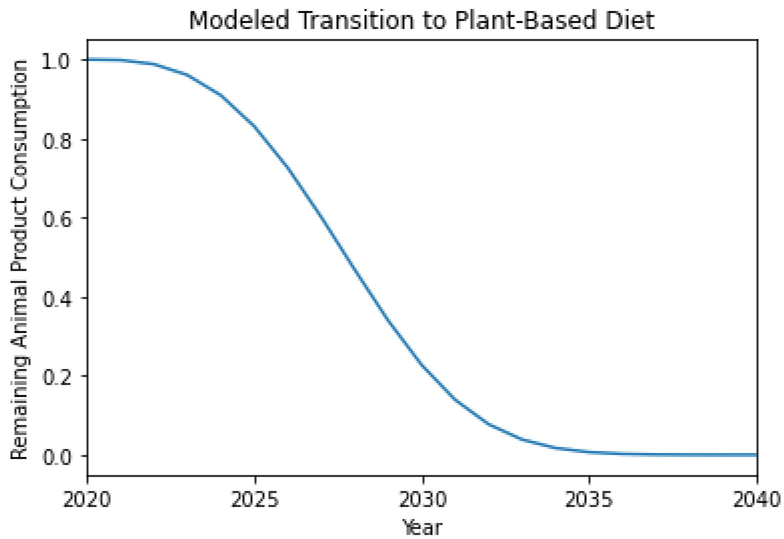
Diet-Linked Emissions

We assumed agricultural emissions under a business as usual (BAU) diet would remain at 2019 levels. For a plant-only diet (POD), we set emissions to those for protein-replacement with soybeans using emissions data from (Behnke et al., 2018). 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 2019 levels through 2100. For a BAU diet we added in agricultural emissions, effectively fixing total emissions at 2019 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).

<u>Converting between emissions and atmospheric concentrations of GHGs</u>

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.

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

<u>Computing Emissions and Land Carbon Opportunity Cost</u>

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

<u>aCO_2eq</u>

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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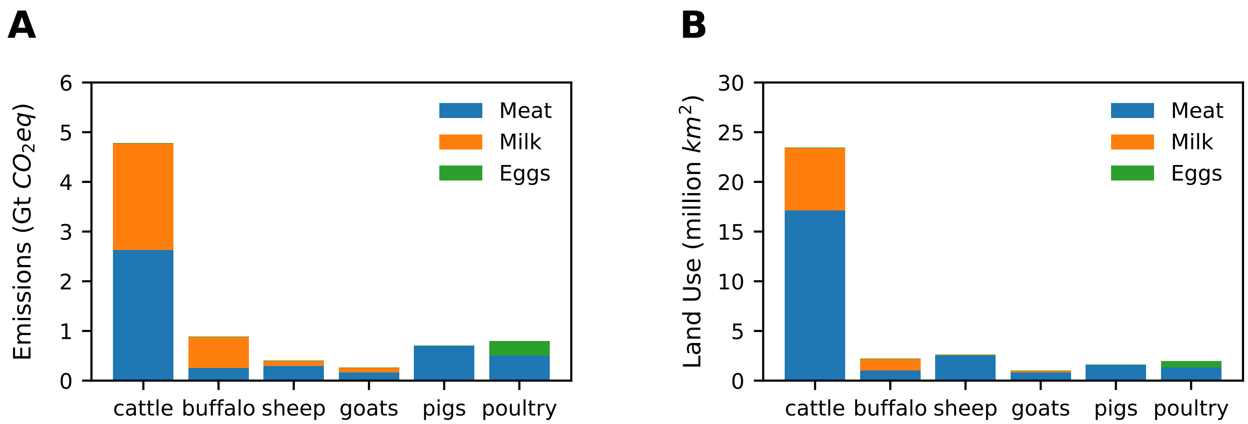

Figure 1. Global emissions and land use footprints of animal agriculture.

Total CO_2 equivalent emissions (A) assembled from species, product and country-specific production data from FAOSTAT for 2019 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 2019 and species and product specific land use data from (Poore and Nemecek, 2018).

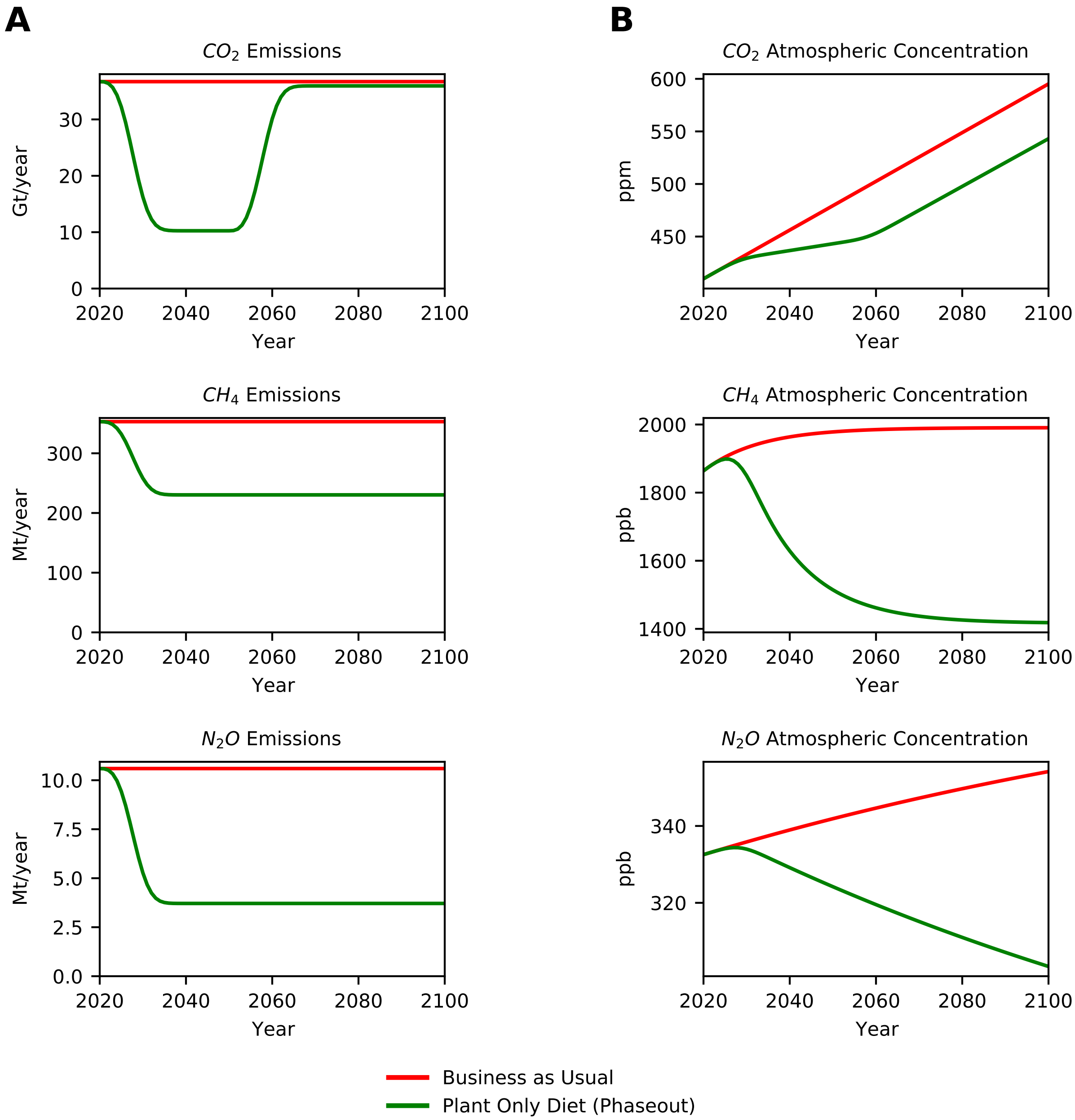

Figure 2. Impact of 15 year phaseout of animal agriculture on atmospheric greenhouse gas levels.

(A) Projected annual emissions of CO_2, CH_4 and N_2O for Business as Usual (red) and Plant Only Diet (green) assuming a 15 year transition to new diet. (B) Projected atmospheric concentrations of CO_2, CH_4 and N_2O under each emission scenario.

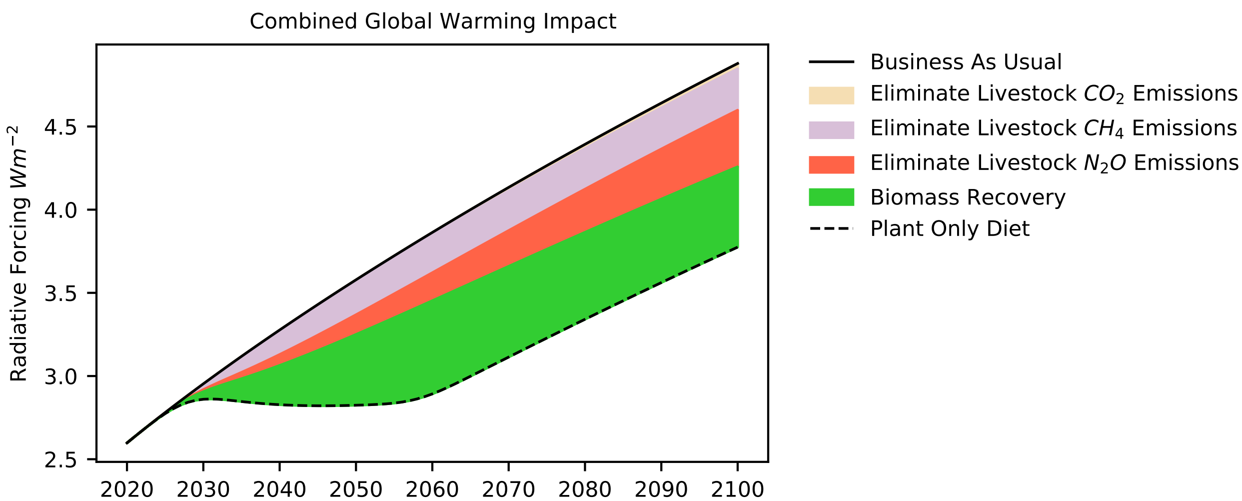

Figure 3. Phaseout of Animal Agriculture Reduces Global Warming Impact of Atmosphere.

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 computed 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.

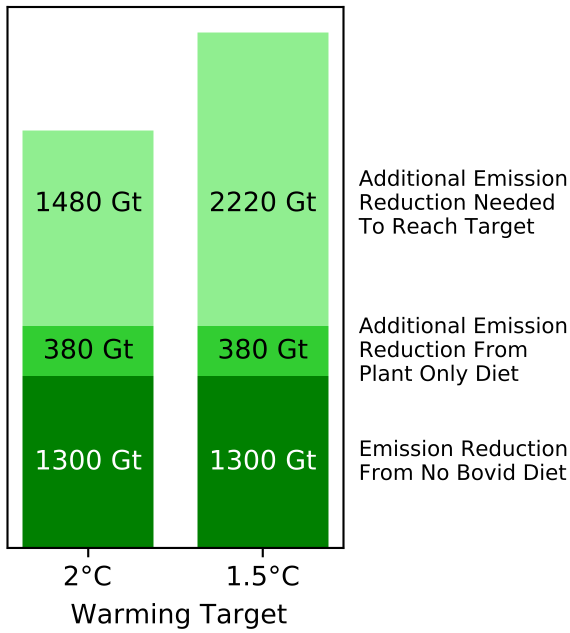

Figure 4. Impact of dietary transitions in curtailing global warming.

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=4.88 to the bovid-free diet level of RF=4.05 (1300 Gt CO_2), the plant-only diet level of RF=3.77 (1680 Gt CO_2), the 2.0˚C global warming target of RF=2.6 (3160 Gt CO_2) and the 1.5˚C global warming target of RF=1.9 (3900 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.

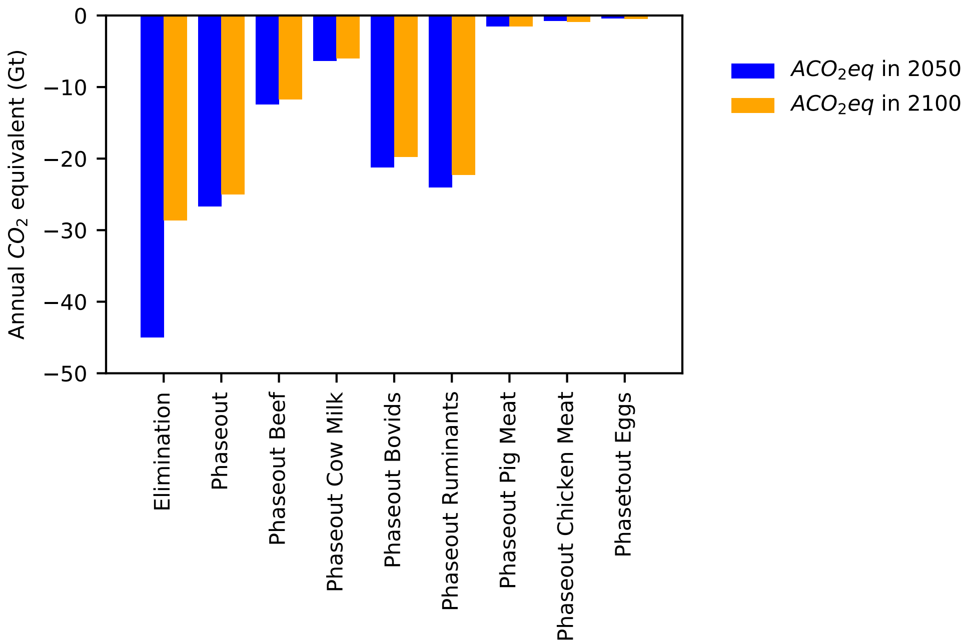

Figure 5. Annual CO_2 equivalents (ACO_2eq) of different dietary scenarios

For each scenario we calculated the constant annual reduction in CO_2 emissions starting in 2021 that would produce the same cumulative radiative forcing as the scenario in the period from from 2021 to 2050 (blue bars), or from 2021 to 2100 (orange bars).

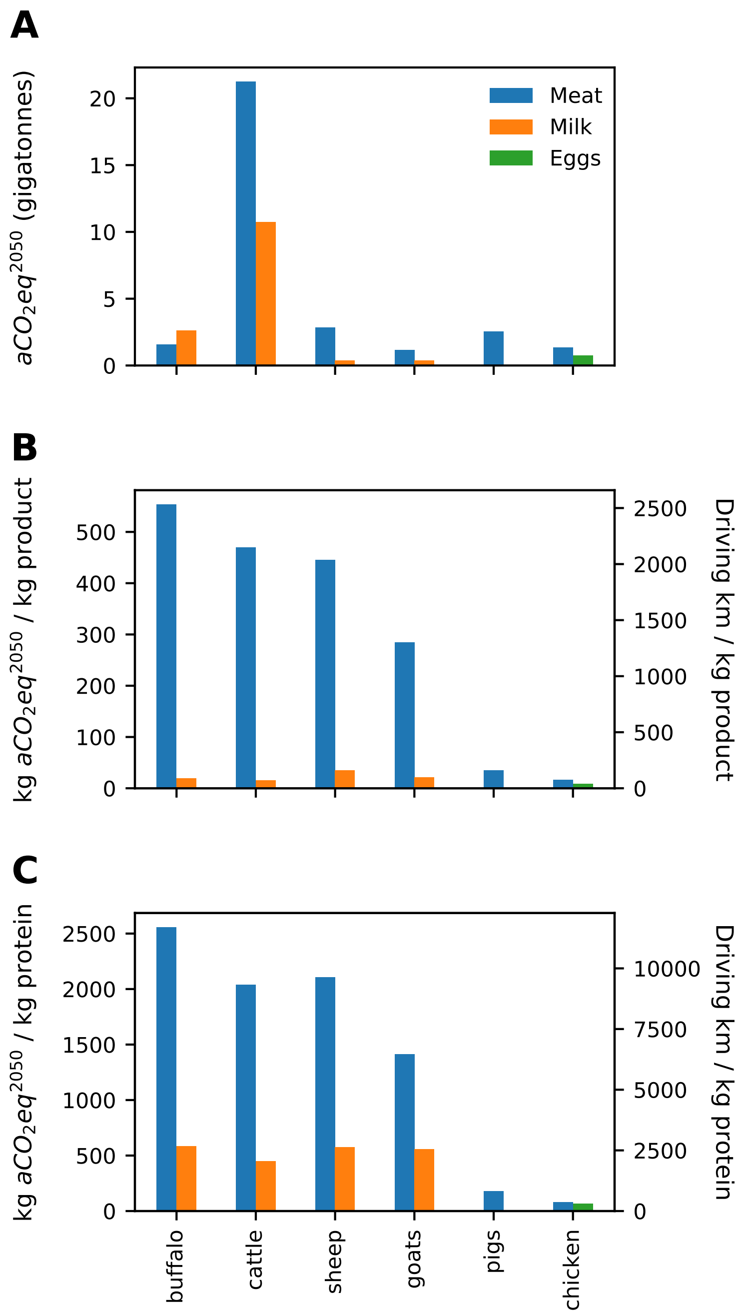

Figure 6. Annualized CO_2 equivalents of livestock species.

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).

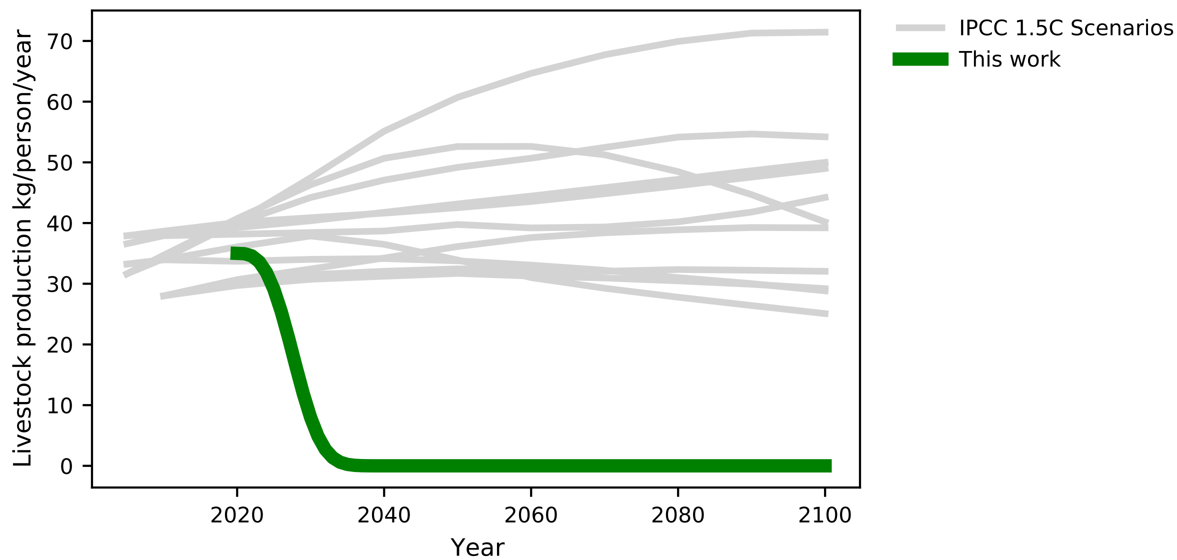

Figure 7. Projected per capita livestock production in SSP/IAM RF 1.9 scenarios.

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.