Eliminating Animal Agriculture Would Offset 35 Years of Greenhouse Gas Emissions

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Animal Agriculture is Destroying The Planet

The raising and harvesting of animals for food has had, and continues to have a profoundly negative impact on our climate and environment. The reduction in steady-state biomass associated with the transformation of native ecosystems by introduction of grazing livestock or cultivation of feed and forage crops is responsible for a third of anthropogenic CO_2 emissions to date (Hayek et al., 2021; Strassburg et al., 2020), and is the primary driver of the catastrophic biodiversity loss that has occurred over the past 50 years (Newbold et al., 2015). 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 based diet is practical (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 (Tilman and Clark, 2014), and could play an important role in climate-change mitigation (Gerber et al., 2013). However the potential overall impact on atmospheric greenhouse gases and climate remains poorly quantified and illustrated, and, as a result, underappreciated.

Using satellite imagery of biomass and geographically-resolved agricultural data, Hayek et al. recently estimated 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 plants, soil microbes, 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, and obtain a full accounting of the COC of animal agriculture, here we use public data on livestock production and associated release of CO_2, CH_4 and N_2O to obtain updated estimates of emissions linked to animal agriculture. We then combine these results and data from (Hayek et al., 2021) to evaluate how the complete 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.

We show that a global switch to a plant based diet would offset all human emissions for the next 30 years, and result in an effective elimination of 1,800 gigatons of CO_2 emissions this century, or approximately half of the reductions necessary to prevent global warming from exceeding 2˚C.

The Full Carbon Opportunity Cost 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.

We estimate that, in 2018 (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). These are consistent with other recent estimates (Gerber et al., 2013; Steinfeld et al., 2006) correspond, respectively, to five percent of global CO_2 emissions, 32 percent of CH_4 emissions and 64 percent of N_2O emissions.

Applying a simple model of the relationship between changes in emissions and atmospheric levels of CO_2, CH_4 and N_2O, we projected the impact of the combined elimination of animal agriculture-linked emissions and carbon recovery on the evolution of these gasses for the remainder of the 21st century.

We assumed that non-agricultural emissions remain constant, that the global transition to a plant based diet occurs over 15 years, and that, following (Hayek et al., 2021), the most intense period of carbon recovery occurs in the thirty years following a return to an undisturbed state. We also examine the effects of eliminating only emissions and land use associated with cattle and buffalo. Additional scenarios are explored in the supplemental figures and in the associated computational notebook.

Figure 2 shows the projected CO_2, CH_4 and N_2O emissions for the “business as usual” (BAU), “plant only diet” (POD) and “bovid free diet” (BFD) scenarios, and their modeled impact on atmospheric greenhouse gas levels. The global warming potential of these scenarios is captured via Radiative Forcing (RF), a measure of the combined warming potential of CO_2, CH_4 and N_2O (Myhre et al., 1998; Shine, 2000).

These projections have two important features. First, during the period of peak carbon recovery, in this case the period leading up to 2050, there is effectively no increase in radiative forcing (RF), a measure of the combined warming potential of CO_2, CH_4 and N_2O. This effect is due roughly equally to carbon sequestration on land previously occupied by livestock or feed crops, and to decay of atmospheric CH_4 and N_2O.

Second, even after the ongoing effects of carbon fixation end, the difference in RF between a business-as-usual diet and a plant-based diet continues to increase with ongoing CH_4 and N_2O decay, leading to a significantly lower RF in 2100 for either of the diet intervention models relative to baseline.

To further quantify this effect, we extend the concept of COC (Hayek et al., 2021) to include both emissions and land use changes. We define the “emissions and land carbon opportunity cost” (ELCOC) of dietary interventions as the cumulative reduction in CO_2 emissions necessary to reduce the RF projected in a BAU scenario in 2100 to the RF projected following intervention.

We estimate the ELCOC of animal agriculture to be approximately 1.9 Tt of CO_2 emissions (Figure 3-S1), the equivalent of around 38 years of total anthropogenic emissions at 2020 levels, and the ELCOC of bovids to be approximately 1.5 Tt of CO_2 emissions, or approximately 30 years of total emissions at 2020 levels.

Limiting Global Warming By Eliminating Animal Agriculture

In 2010, the climate modeling community defined a series of four “Representative Concentration Pathways” that capture a wide range of future warming scenarios, and are characterized by the RF levels reached in 2100 of 8.5, 6.0, 4.5 and 2.6 (Moss et al., 2010; van Vuuren et al., 2011). These were extended after the Paris Climate Accord in 2014 to include a target of 1.9 Wm^{-2}. Although the exact relationship between RF and global warming is complicated and uncertain, reaching 2100 RFs of 1.9 and 2.6 are generally used as targets for limiting warming to 1.5˚C and 2.0˚C respectively (IPCC, 2018).

Our BAU model, which assumes emissions remain constant at current levels through the end of the century, reaches an RF due to CO_2, CH_4 and N_2O of 5.3 Wm^{-2}. Reaching RF 2.6 by 2100 will require removing the equivalent of approximately 3.7 Tt of CO_2 emission, and RF 1.9 approximately 4.4 Tt of CO_2 emission.

Eliminating animal agriculture without any other intervention already achieves the moderate target of maintaining RF below 4.5 in 2100, and achieves 51 percent of the reduction necessary to reach RF 2.6 and 43 percent respectively of the emission reductions necessary to reach RF 1.9, greatly increasing the probability that we can limit global warming to 2.0˚C or even 1.5˚C. And nearly 80 percent of this potential would be realized simply by eliminating cattle and buffalo products from human diets.

Caveats and Considerations

Although the general trends discussed above are robust to a wide range of assumptions about emissions, carbon fixation, diet and climate responses, there are many potential sources of error in these scenarios that would lead to both over and underestimation of the magnitude of the impact of eliminating animal agriculture.

First, this analysis only included livestock, while there are also 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 recent 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). Another recent study suggested that the disruption of carbon storage due to seafood harvesting via trawling is the equivalent of approximately 1.0 Gt of CO_2 per year (Sala et al., 2021). Stipulating these estimates, accounting for seafood consumption would increase the ELCOC measured in 2100 of animal food consumption by approximately 120 Gt CO_2 equivalents.

There are several sources of uncertainty associated with carbon sequestration on land converted 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_2 equivalent carbon, but their estimates range from 670 to 1207, depending on land use details and future agricultural yields, and this is without accounting for the unquantified uncertainty in soil carbon.

Some data on carbon recovery on previously degraded lands suggests that the assumption of complete carbon recovery without 30 years may be optimistic (Lennox et al., 2018; N'Guessan et al., 2019; Poorter et al., 2016), or at least inconsistent. We note however that there is limited data on whether explicit management of recovery for carbon storage could accelerate and increase the magnitude of carbon storage on land transitioning from intensive agricultural use.

Our assumptions about the emissions and land use associated with a BAU diet are conservative, as they do not completely capture the combined increase in livestock consumption that will occur of current trends in population and in per capita animal agriculture product consumption in developing economies continue. We also are somewhat overestimating emissions linked to the POD diet as current all agriculture data includes crops not raised for food or feed, especially bioenergy.

Finally, temperature change and most other consequences of changing atmospheric greenhouse gas levels are a product of the temporal trajectories of atmospheric gas levels, as well as other factors. Thus single point estimates in 2100 tell an incomplete story. One likely advantage of eliminating animal agriculture is that this can be done now with its greatest impact prior to 2050, whereas other mitigation strategies are likely to be implemented later with effects restricted to the later half of the century. The resulting accelerated reduction in RF from eliminating animal agriculture would thus likely limit warming more than other strategies with similar RF endpoints.

Discussion

The elimination of animal products from the human diet represents the only climate mitigation strategy of large effect that could be implemented immediately without the invention or introduction of any new technologies or significant disruptions of the global economy.

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 protein in the human food supply, they can be readily replaced by calories, protein and fat from existing crops, with only minor adjustments to optimize nutrition (Springmann et al., 2018). While there are obviously logistical challenges at many levels to such a transition, and the economic impacts would be acute in many regions and locales, these are trivial in comparison to the looming economic disruptions of allowing unchecked climate change to continue.

While we focus here exclusively on the climate impacts, and end to the widespread raising and harvesting of animals for food would have profound positive impacts: ending the decimation of biodiversity due to habitat loss and greatly facilitating its recovery (Maron et al., 2018; Newbold et al., 2015; Strassburg et al., 2020), removing a major consumer of fresh water supplies and source of water pollution (Kim et al., 2020; Mekonnen and Hoekstra, 2012), improving human health via dietary improvement (Tilman and Clark, 2014) and reductions in foodborne illnesses (Li et al., 2019) and zoonotic diseases (Klous et al., 2016), and even the weather (Lawrence and Vandecar, 2014).

It is also clear that current dietary trends are unsustainable. If the current per capita animal product consumption and agricultural practices of wealthy, highly industrialized countries (OECD) were extended to the total population of the planet today, an additional 46 million km2 would be required to house and feed the expanded livestock populations. This is roughly equal to the combined area of African and South America. The destruction of this much of Earth's remaining native habitats would have catastrophic impacts on the climate, environment, and human health.

Given this reality, reiterated in numerous studies over the past several decades, it is astonishing that dietary change is 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 as unfeasible, or discount the potential impact of, significant reductions in livestock consumption.

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 4), let alone a planet free of livestock production. They rely instead on as of yet non-existent and unproven carbon capture and storage technologies coming on line in the second half of the century.

Dietary shifts are not sufficient to stop climate change. It is still essential that we transition to renewable energy and implement some form of carbon capture to reach the goal of limiting global warming to 1.5˚C. But, crucially, if we begin to phase out the consumption of animal products, especially those from cattle and buffalo, from the human diet today, we would in effect pause global warming for nearly four decades, providing crucial time to develop and scale renewable energy and carbon capture technologies, and to develop the political and economic cultures necessary to support their implementation.

Figures

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).

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. 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, 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. (D) 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-S1. Impact of immediate cessation of animal agriculture on atmospheric greenhouse gas levels.

(A) Projected annual emissions of CO_2, CH_4 and N_2O for Business as Usual Diet and Plant Only Diet assuming an immediate dietary transition and 30 year linear carbon fixation trajectory. (B) Projected atmospheric concentrations of CO_2, CH_4 and N_2O under each emission scenario. (D) 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 15 year transition to plant only diet on atmospheric greenhouse gas 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 30 year linear carbon fixation trajectory on freed land. (B) Projected atmospheric concentrations of CO_2, CH_4 and N_2O under each emission scenario. (D) 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-S3. Impact of slower carbon fixation on atmospheric greenhouse gas 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 50 year linear carbon fixation trajectory on freed land. (B) Projected atmospheric concentrations of CO_2, CH_4 and N_2O under each emission scenario. (D) 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-S4. Impact of bovid-free diet on atmospheric greenhouse gas levels.

(A) Projected annual emissions of CO_2, CH_4 and N_2O for Business as Usual Diet and Bovid Free Diet assuming a 15 year transition to the new diet and 30 year linear carbon fixation trajectory on freed land. (B) Projected atmospheric concentrations of CO_2, CH_4 and N_2O under each emission scenario. (D) 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 3. Significant contribution of dietary transition to emissions reductions needed to curtail 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=5.11 to the bovid-free diet level of RF=4.19 (1.47 Tt CO_2), the plant-only diet level of RF=3.88 (1.91 Tt CO_2), the 2.0˚C global warming target of RF=2.6 (3.71Tt CO_2) and the 1.5˚C global warming target of RF=1.9 (4.43 Tt CO_2) .For this analysis we used a corrected RF that accounts for the absence of other gasses 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 gasses.

Figure 3-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. The ELCOC in ppm is converted to emissions according to the following formula:

$$CO_2 Tt = \Delta CO_2 ppm * \frac{1\ Tt}{10^{18} g} * \frac{44\ g}{mole} * \frac{1.77*10^{14}\ mole}{ppm} * \frac{1}{f_{sink}}$$

Where $f_{sink} = 0.5$ to account for the half of emissions that go to terrestrial or oceanic sinks. We also calculate ELCOC for just bovid sourced foods (cattle meat, cow milk and buffalo meat and milk) 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 gasses using multivariate linear regression on MAGICC6 output downloaded from the SSP database.

Figure 4. Projected livestock production in Shared Socioeconomic Pathways

We downloaded data from the Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017), which are a "framework that the climate change research community has adopted to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation" from the SSP database (Version 2.0; last updated December 2018). We plot here the inferred per capita livestock production (the ratio of the 'Agriculture|Livestock Production' and 'Population' fields) 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.

Declaration of Conflict of Interest

Patrick Brown is founder and CEO of, and Michael Eisen is a long-time consultant for, Impossible Foods, a company founded to produce plant-based alternatives to meat and other animal products with the goal of ending the destructive impact of animal agriculture on the planet. Both are shareholders in the company and thus stand to benefit financially from a shift away from animal agriculture. While we acknowledge this clear conflict of interest, we have made all of the data and code available for others to check and criticize, and we hope this work encourages other scientists to address the issues we raise here.

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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 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 2018 (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 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.

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

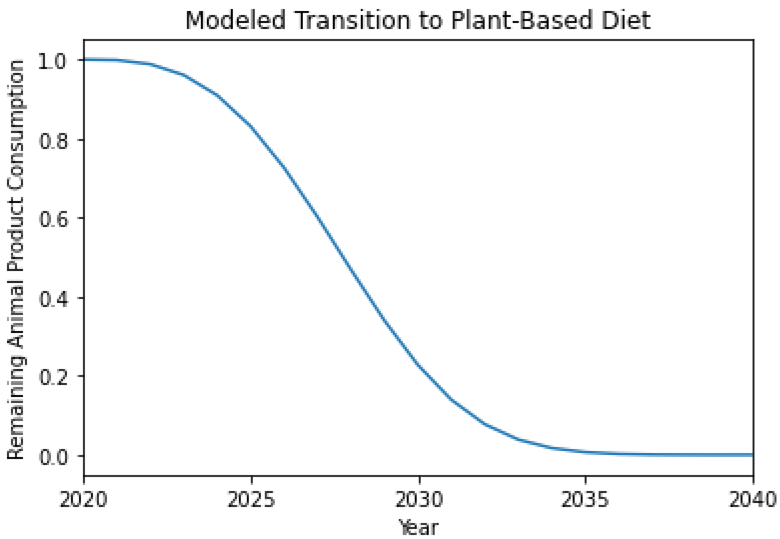
We assumed agricultural emissions under a business as usual (BAU) diet would remain at 2018 levels. For a plant only diet (POD), we set CO_2 emissions to 0, as the carbon sequestration data from (Hayek et al., 2021) already accounts for increased land use required to produce a nutritionally balanced diet, and set CH_4 and N_2O emissions to 1.25 times the difference between current agricultural emissions and animal agriculture linked emissions (the factor of 1.25 is to account for the 20 percent of calories that currently come from animal agriculture products in the global diet). For a bovine free diet (BFD) we used the same calculation except removed only emissions linked to cattle and buffalo and used a multiplier of 1.15.

Emissions Projections

In all scenarios we assume 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 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 agriculture 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 in one supplemental analysis 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 run 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 $f(m, n) = 0.47 ln(1 + 0.6356(\frac{mn}{10^6})^{.75} + 0.007(\frac{m}{10^3})(\frac{mn}{10^6})^{1.52}$ 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 the $2\Delta C$ 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 CO2, CH4 and N2O 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 CO2, CH4 and N2O concentrations, and add to that the adjustment from the linear regression model. We use this RF to calculate (Figure 3-S1, panel B) the carbon opportunity costs and emission reductions necessary to reach RF targets shown in Figure 3.

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

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