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RESEARCH ARTICLE

Model-based scenarios for achieving net negative emissions in the food system

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Abstract

Most climate mitigation scenarios point to a combination of GHG emission reductions and CO_2 removal for avoiding the most dangerous climate change impacts this century. The global food system is responsible for ~1/3 of GHG emissions and thus plays an important role in reaching emission targets. Consumers, technology innovation, industry, and agricultural practices offer various degrees of opportunity to reduce emissions and remove CO_2. However, a question remains as to whether food system transformation can achieve net negative emissions (i.e., where GHG sinks exceed sources sector wide) and what the capacity of the different levers may be. We use a global food system model to explore the influence of consumer choice, climate-smart agro-industrial technologies, and food waste reductions for achieving net negative emissions for the year 2050. We analyze an array of scenarios under the conditions of full yield gap closures and caloric demands in a world with 10 billion people. Our results reveal a high-end capacity of 33 gigatonnes of net negative emissions per annum via complete food system transformation, which assumes full global deployment of behavioral-, management- and technology-based interventions. The most promising technologies for achieving net negative emissions include hydrogen-powered fertilizer production, livestock feeds, organic and inorganic soil amendments, agroforestry, and sustainable seafood harvesting practices. On the consumer side, adopting flexitarian diets cannot achieve full decarbonization of the food system but has the potential to increase the magnitude of net negative emissions when combined with technology scale-up. GHG reductions ascribed to a mixture of technology deployment and dietary shifts emerge for many different countries, with areas of high ruminant production and non-intensive agricultural

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systems showing the greatest per capita benefits. This analysis highlights potential for future food systems to achieve net negative emissions using multifaceted "cradle-to-grave" and "land-to-sea" emission reduction strategies that embrace emerging climate-smart agro-industrial technologies.

Introduction

Balancing the planet's resource base with the growing nutritional demands of an expanding human population in a just, equitable and inclusive way, while simultaneously reducing GHG emissions from the world's food system, represents one of the biggest, most complex challenges of the 21st century. Current estimates suggest that the food system–a cradle-to-grave global network that grows, distributes, recycles, consumes, and disposes of resources for food production–generates 21–37% of GHG emissions each year (CO_2 equivalent (eq)) [1,2]. The unmitigated effects of the global food system on GHG emissions could grow by ~50–80% by 2050 [3,4], which, along with unmitigated fossil fuel emissions, portend unconscionable risks on the agricultural sector, including systemic crop failures, dilution of the nutritional quality of food for human and animal consumption, and especially profound impacts on small shareholder farms in developing economies [5–8]. Alternatively, the food system has been identified as a key sector for climate mitigation and aggressive action, particularly via the deployment of technologies that reduce GHG emissions and increase C sequestration in agricultural systems [9–13]. Whether the future food system adds to or reduces GHG emissions, and thereby contributes to global climate targets, hinges on a mix of consumer decisions, technology deployment, management practices, and policies.

Food system transformation has the capacity to radically reduce GHG emissions and could possibly achieve sector-wide net negative emissions, which is defined as the point wherein gross GHG emissions are lower than gross GHG removal (i.e., carbon dioxide removal, carbon dioxide equivalent removal, and C sequestration, referred to as CDR hereafter). Several studies have analyzed scenarios under which GHG emissions can be reduced through consumer decisions, particularly a switch in the foods consumed and their consequent effects on agricultural GHG emissions [9–12]. When consumers rely more heavily on plant sourced foods grown under conventional practices [9,12], for example, the amount of land required to support human nutrition may be reduced [9,13], potentially increasing natural ecosystem CDR via land sparing and vegetation recovery. Furthermore, sheep, cattle, and goats emit methane (CH_4), a potent GHG. Current estimates ascribe 14% of global GHG emissions to livestock, which include emissions from feed production, enteric fermentation, manure management, processing, and transportation [1]. Plant-based diets have in principle been suggested to lower such emissions through connections back to agricultural commodities and their growing practices. While much has been written on human dietary effects on GHG emissions [9–12], it is less clear whether consumer effects alone can cascade to global net negative GHG emissions in the food system, which is urgently needed to reverse the role of agriculture in GHG emissions and climate change.

Technology deployment and new land management practices offer an alternative if not synergist path for GHG emission reductions and CDR, with the potential to achieve sector wide net negative GHG emissions [13,14]. Some of the more promising technological interventions include those related to fertilizer production, agricultural and land management practices, and post-processing of farmland biomass and waste recycling [15–17]. CDR in the agricultural sector spans bioenergy carbon capture and storage (BECCS), agroforestry, land conservation, organic and rock dust soil amendments, and strategies to mitigate and upcycle food-loss and -waste through the soil [13]. These emerging technologies span the research and development spectrum as climate mitigation tools [18], however, further research is needed to overcome implementation barriers and understand known feedback effects and potential unintended consequences.

Previous studies [10,13] have suggested that a mix of technologies, growing practices, consumer effects, and waste reduction strategies can reduce gross GHG emissions alone and in certain combinations; however, a complete assessment across the permutation and combinations of possibilities with a focus on the capacity for sector-wide net negative GHG emissions is needed to make additional science-based advancements on food system solutions to climate change. Given the recognition for deep decarbonization and GHG neutrality/negativity goals by mid-century [19], the question of how the 2050 food system can contribute to sector wide net negative emissions, and the pathways to achieve this ambition, is a relevant issue for decision makers. Addressing the capacity for the future food system to achieve sector-wide net negative emissions requires a comprehensive analysis that includes emissions reductions and CDR, separately and in combination, from global to regional scales.

Here, we use a global food system model used in the EAT-Lancet analyses (see Methods; [11]) to examine an array of conditions and scenarios for which gross GHG reductions, gross CDR and net negative GHG emissions can be achieved in the 2050 food system. These scenarios include changes in dietary choice, land use changes, technology deployment levels, and food loss and waste reductions, thus alternating the land, fertilizer, and energy GHG emissions that are tied to the food demands of 10 billion people by 2050 (see Methods). We combine a 'business as usual' (BAU) scenario with a global food system model to ascribe GHG emissions to the production of different foods [11]. We focus on agro-industrial technologies representative of food system emissions sourcing, spanning cradle-to-grave and land-to-sea, including hydro-powered fertilizer production, improved livestock feed, anaerobic digesters, soil amendments, agroforestry, seaweed farming, and reduced trawling (Table 1, Fig 1). Our analyses include both discrete categories (Fig 2) and a continuous spectrum (Fig 3) of dietary,

Table 1. Brief definitions of the 11 technologies explored in this analysis, and whether they are emission reduction or carbon dioxide removal technologies. Biochar is listed twice as it was applied in the model as a technology that reduces nitrous oxide emissions and also increases soil carbon. Enteric fermentation is listed twice as we considered two different improved feed technologies for grass and grain fed livestock.

Technology	Definition
Trawling management[ER]	Reduced seafloor trawling in seafood production
Manure digestion[ER]	Digestion of manure to produce fertilizer and biogas
Renewable fertilizer production[ER]	Fossil fuel free production of nitrogen fertilizer
Enteric fermentation (grass)[ER]	More digestible forage
Enteric fermentation (grain)[ER]	Seaweed or microalgae feed supplements
Biochar[ER]	Biochar incorporation in soil to reduce nitrous oxide
Biochar[CDR]	Biochar incorporation to increase soil carbon
Compost[CDR]	Organic matter applications to increase soil carbon
Rock[CDR]	Silicate soil applications to increase inorganic soil carbon
Agroforestry[CDR]	Forest regeneration on abandoned agricultural lands
Seaweed farming[CDR]	Deep ocean seaweed burial

[ER]Emission reduction technologies.

[CDR]Carbon dioxide removal technologies.

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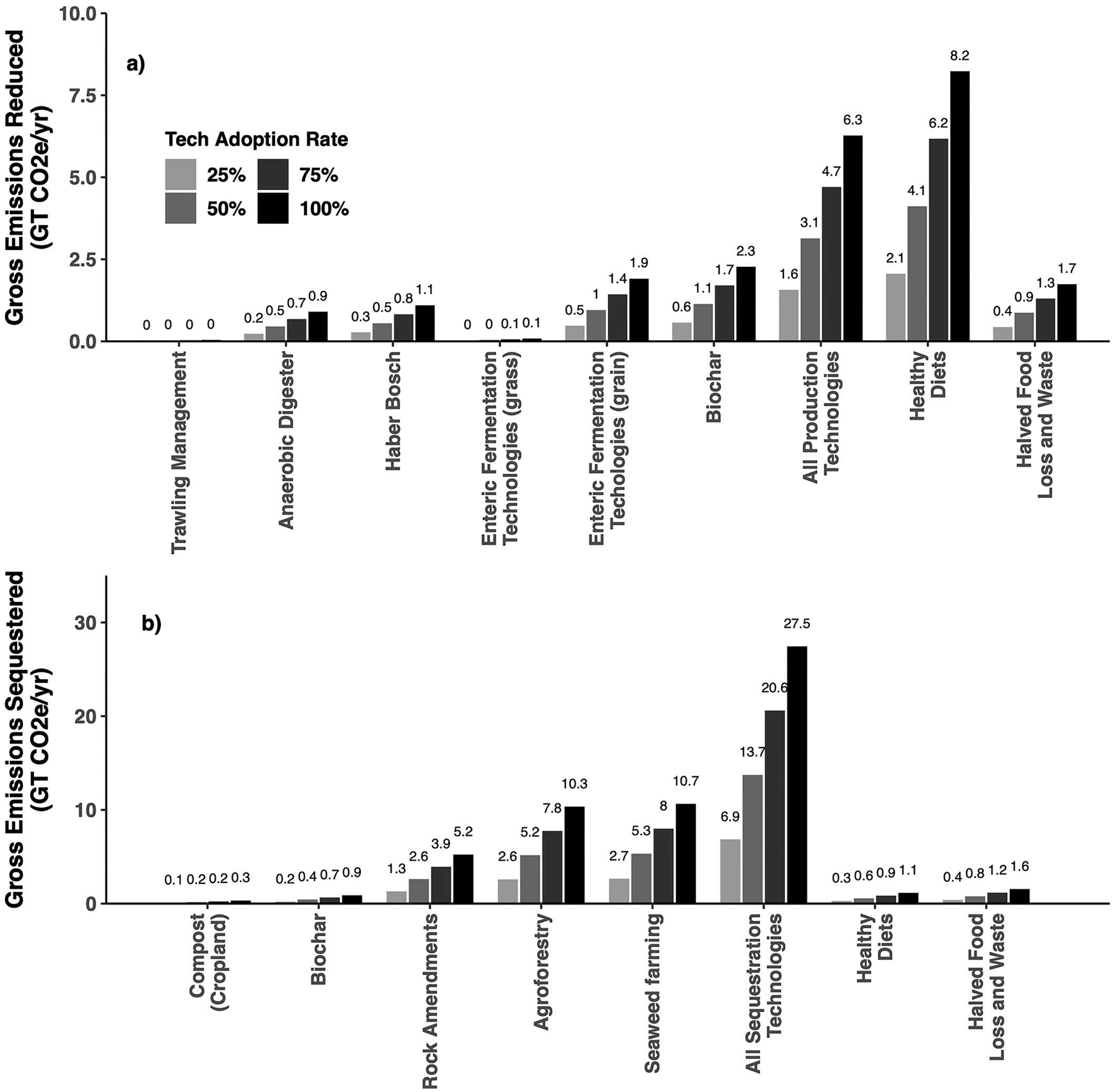

Fig 1. 2050 food system technologies targeting gross GHG emissions reductions (top) and gross carbon dioxide removal (CDR; bottom). Note the range difference on the y-axis. Rates of adoption are based on global capacity in year 2050 under a 'business as usual' scenario. Larger bars indicate greater reductions of greenhouse gases expressed as CO_2eq. 'All technologies' include the additive effects of each technology at a given level of adoption. Yield gaps are closed, BAU caloric consumption. Values provided in Supplemental Material (Table A and Table B in S1 Text).

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technological, and food loss and waste reduction scenarios, and include both global and country-wide scenarios (Figs 4 and 5). We aim to explore which levers offer the most potential for achieving food system emission targets. We argue that systematic investigation of the technologies we selected to explore, in combination with dietary change and food waste scenarios, will provide immediate policy-relevant foresight and help prioritize research and practice.

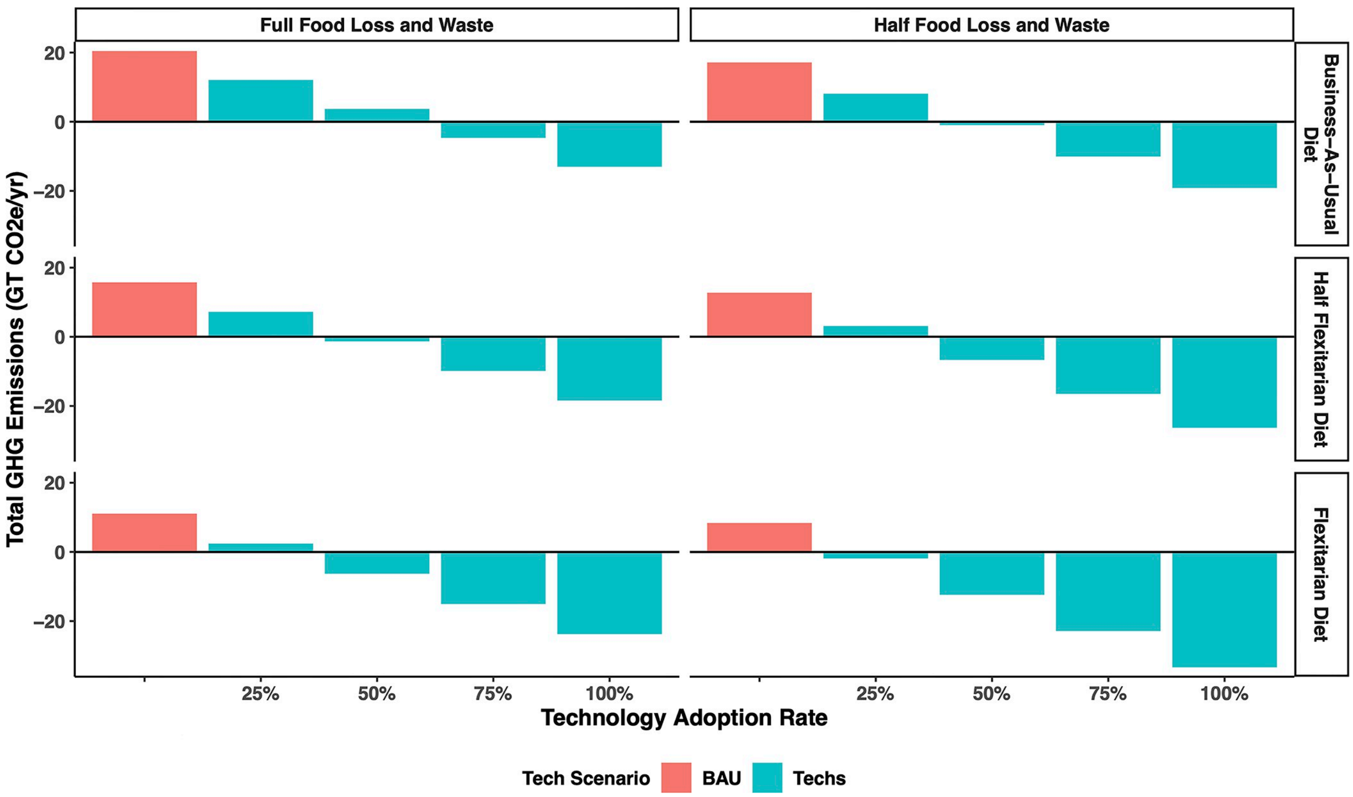

Fig 2. Net food sector GHG emissions from technology adoption scenarios (0%, 25%, 50%, 75% and 100% adoption) across global dietary transitions from business as usual (top) to 50% (middle) to 100% flexitarian adoption (bottom) with (right) and without (left) reductions in food loss and waste in 2050. All scenarios assume full closure of yield gaps by 2050. Technological adoption rate is based on the global additive effects of all technologies in Fig 1. BAU caloric consumption. Values provided in Supplemental Material (Table C in S1 Text).

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Methods

Approach

We examine the global-scale capacity for technologies, dietary transitions, and reductions in food waste to create agricultural systems with net negative GHG emissions using the global food system model used in the EAT-Lancet analysis (see section titled 'Modelling food system emissions' for more information). We account for the GHG emissions, CDR, and agricultural land cover change by examining historic spatial patterns of agricultural land cover and maps of C in organic biomass and soils. In addition, we examine how food system GHGs might be reduced by consumer-driven dietary transitions, reductions in food loss and waste, closing crop yield gaps (assumed in all scenarios), and the introduction of technologies that reduce emissions from food production or that increase rates of CDR on agricultural lands. Our focus is on 1) diets that vary in the proportion of plant to animal products [11], given that animal products generally produce more emissions than plant derived products, 2) emission reduction and CDR technologies representative of food system wide intervention, spanning cradle-to-grave and land-to-sea (Table 1), and 3) reductions in food discarded by retailers and consumers, which have been shown to have very high mitigation potential [1].

We selected technologies for which there was peer reviewed literature and potential to scale this century, acknowledging, however, that most climate smart technologies in the agricultural sector currently remain limited in their uptake. All estimates of climate change mitigation potential (i.e., combined C benefits from both emission reduction and CDR strategies) were

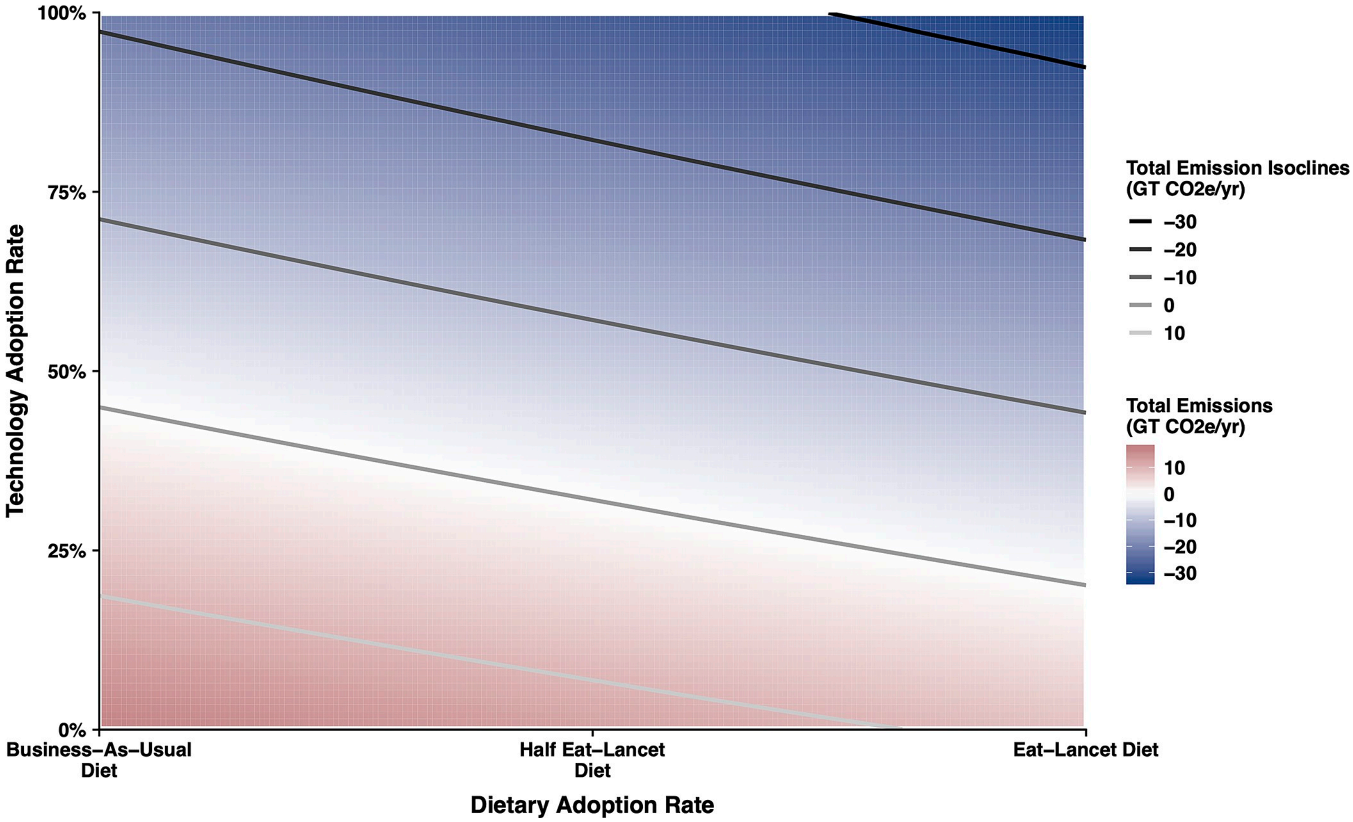

Fig 3. The option space for net GHG emissions from the 2050 food system. Shaded regions represent net GHG emissions. The isoclines track the shaded regions in increments of 10 billion tons of CO_2eq/yr. All scenarios assume closed yield gaps by 2050 and a halving of food loss and waste. Values provided in Supplemental Material (Table D in S1 Text).

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reported in tons CO_2 per hectare. If available, we also reported nitrous oxide (N_2O) and CH_4 (reported as CO_2eq). We provide estimated climate change mitigation potential based on a select suite of technologies, however additional development of more novel technologies, for which there is great potential [18], will increase the climate change mitigation potential of this lever.

Technologies were categorized according to whether they were reducing GHG emissions or acting as CDR strategies (Table 1). We carefully evaluated potential redundancies to avoid the double-counting of climate change mitigation potential. For each technology, we then modelled four scenarios based on a 25, 50, 75, and 100% global adoption rate and assessed the life cycle of agricultural GHG emissions from now to 2050 (see below for a more in-depth description of the model; Table 4). We chose these adoption rates because they give a range of the climate change mitigation potential of different strategies at various intervals of adoption, ranging from no adoption (0%, the 'business-as-usual' scenario) to complete adoption (100% adoption). Ultimately, the exact intervals we chose (25%, 50%, 75%, and 100%) are arbitrary, but having five rates of adoption of food system strategies provides enough resolution for readers, policy-makers, and the like to (a) understand the relative effectiveness of different strategies when implemented at the same adoption rate, but also (b) to compare the GHG benefit of different strategies when adopted at different rates (e.g., is adding biochar at 25% adoption rate more or less effective than a 50% adoption of a flexitarian diet?). Furthermore, providing a range of adoption rates is an advance beyond other food system emission modeling studies, which typically apply an adoption rate of 100%.

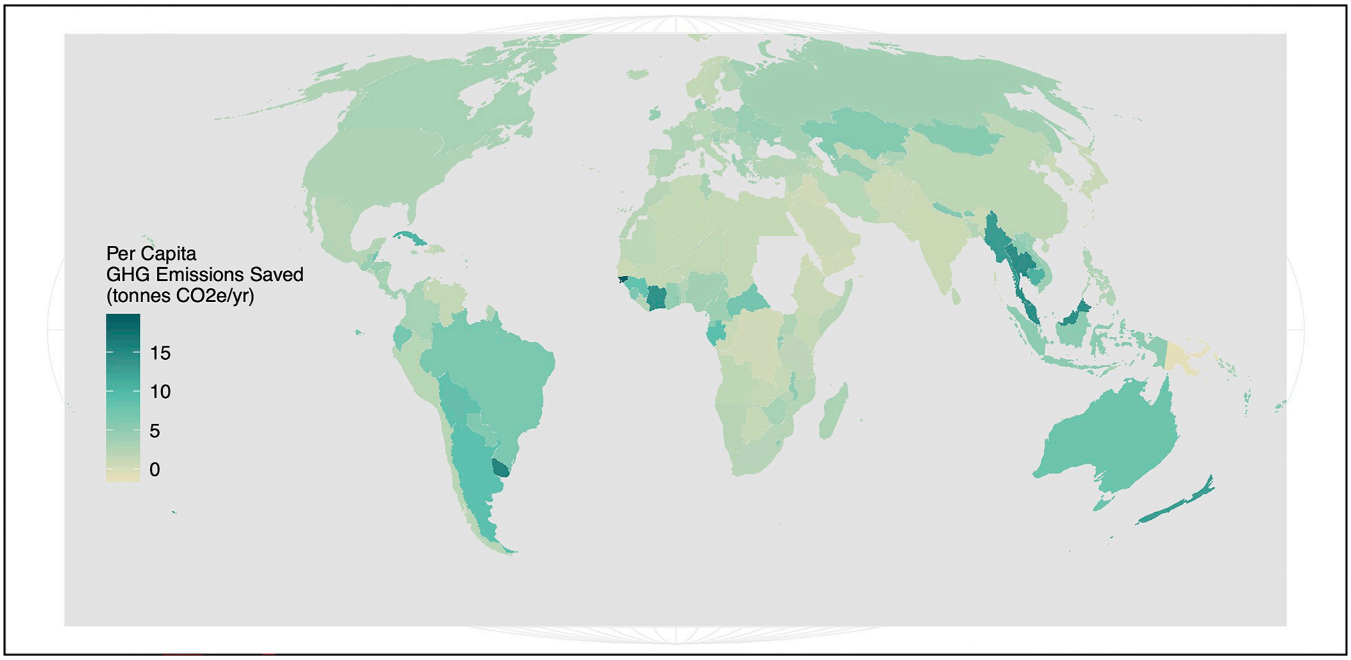

Fig 4. Climate change mitigation potential per capita (tonnes CO_2eq/yr) of simultaneously closing yield gaps, halving food loss and waste, transitioning halfway to a flexitarian diet, and implementing all technologies at 50% of their potential adoption rate. Emissions benefits do not include carbon dioxide removal on pasturelands or in oceans because these are treated as global goods in our model. The map was created in R version 3.6.0. The base layer of the map is the TM-World Borders 3.0 shape file, which is available at https://thematicmapping.org/downloads/world_borders.php. The licensing on the map is CC-BY 3.0 –SA. Values provided in Supplemental Material (Table E in S1 Text).

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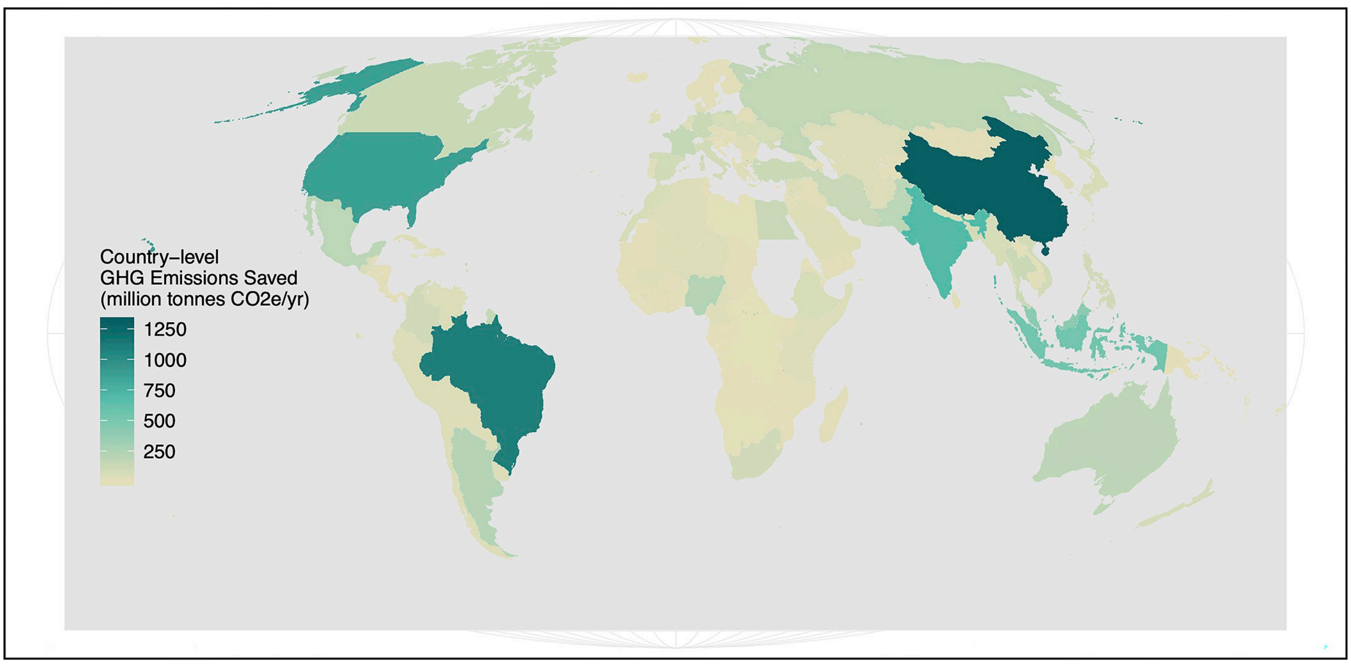

Fig 5. Estimated country-level climate change mitigation potential (million tonnes CO_2eq/yr) of simultaneously closing yield gaps, halving food loss and waste, transitioning halfway to a flexitarian diet, and implementing all technologies at 50% of their potential adoption rate. Emissions benefits do not include carbon dioxide removal on pasturelands or in oceans because these are treated as global goods in our model. The map was created in R version 3.6.0. The base layer of the map is the TM-World Borders 3.0 shape file, which is available at https://thematicmapping.org/downloads/world_borders.php. The licensing on the map is CC-BY 3.0 –SA. Values provided in Supplemental Material (Table E in S1 Text).

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The food system model

We used outputs from the projections resulting from the EAT-Lancet food system model, which connects food consumption across regions [11]. The EAT-Lancet model is based on the partial equilibrium multi-market food system model named International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), which is a network of economic, crop, livestock, and water models [11,20]. It projects food demand, food production, and crop land for >40 commodities in >150 regions (that are approximately equivalent to countries, it does not provide subnational estimates) from 2010 to 2050 based on associations with changes in income and population. The EAT-Lancet food system model (henceforth referred to as the "food system model") reformulates IMPACT such that food demand is an input parameter and food production is an output parameter. Equations used in this model are detailed in the appendix of Willett et al. [11]. The food system model adjusts relationships such as trade flows, processing, feed requirements, and demand for other associated commodities (i.e., oils, sugar, etc.) based on dietary changes. These data are translated into climate impacts based on country specific analyses of CH_4 and N_2O emissions for crops and livestock, and CO_2 emissions for seafood. We used this model for two primary reasons. First, the crop production, crop yield, crop land use, and diet demand projections are publicly available. Second, the EAT-Lancet analysis has gained widespread use and attention in the academic and policy spheres. Using the EAT-Lancet food system model, which has been extensively published and is widely known in the food system and policy spheres, provides more robust estimates than would creating our own food system model, whilst also ensuring the results of our analysis are more comparable to those published previously.

The BAU scenario assumes a middle-of-the-road pathway (i.e., Shared Socioeconomic Pathway 2) for economic growth, dietary trends, and rates of population increase. Projected increase in crop yields reflect potential rates of technology change and interactions between commodities and countries, whilst international food trade continues along gradients of comparative advantage in producer and consumer surplus. In this scenario, global population is projected to grow to 9.2 billion individuals in 2050, from 6.9 billion individuals in 2010. Similar to other analyses, diets transition to include more calories in total (an ~88% estimated increase in global food production from 2010 to 2050) as well as more calories from animal-sourced foods as populations become more affluent.

We also used the other food system scenarios analyzed in the EAT-Lancet report to investigate how changes to food supply and demand might interact with CDR technologies. These scenarios included different assumptions on dietary transitions (both amount of food consumed and type of food consumed), amounts of food loss and waste, and faster than BAU trends in crop yield increases. We analyze these scenarios to examine the potential climate change mitigation potential of technological implementation relative to other food system changes, as well as how the climate change mitigation potential of technology implementation might increase or decrease as other parts of the food system change. A further description of these scenarios is in the following paragraphs.

The alternative diet scenario we also analyzed is where the population slowly transitions to a flexitarian diet by 2050. The flexitarian diet (as described in the EAT-Lancet report, and also known as the EAT-Lancet diet), is where dietary composition meets best recommendations for human health as described in epidemiological and nutrition literature. This diet is predominantly plant-based and contains moderate amounts of dairy, eggs, meat, and fish.

Currently, it is estimated that one third of all food production is lost or wasted [21]. To examine the climate change mitigation potential of reductions in food loss and waste, and the interaction this may have with CDR technologies on agricultural landscapes, we included two food loss and waste scenarios: the first is the BAU scenario, or where current rates of food loss and waste continue into the future; and the second is where rates of food loss and waste throughout the entire food supply chain are reduced by 50% by 2050.

We assumed that yield gaps, or the difference between current yields and potentially attainable yields (as estimated in Mueller et al 2012; [22]), are closed by 2050. This assumption is intended to show that climate mitigation can be achieved in concert with increases in food production, however, we acknowledge that closing yield gaps is a more complicated aim than this scenario reflects. We assume the GHG impact per unit of food produced for potentially attainable yields is identical to current yields, which is a commonly used assumption in food system models, including Tilman and Clark (2014); Balzelj et al (2014); Springmann et al (2016); Springmann et al (2018); and Willett et al (2019). We made this assumption to increase comparability to other analyses but acknowledge that yield increases could both potentially increase (e.g., through excess fertilizer application and increased irrigation) and decrease (e.g., through better fertilizer management, land sparing, and increases in soil organic matter) GHG emissions per unit of food produced [23,24].

We used these diet, loss and waste, and yield scenarios to illustrate how different food system transformations affect overall food system GHG emissions and the potential emissions reductions of implementing CDR technologies at a global scale. We recognize that some of these scenarios may be challenging to implement and will have knock affects (and feedbacks) that permeate throughout the food system. For example, diet transitions towards lower-meat diets could reduce the cost of meat in the short-term resulting from surplus supply, which could have a rebound effect of increasing meat consumption. Similarly, rapid increases in crop yields could decrease the cost of food and result in increased diet demand, while also influencing the countries in which commodities are produced by affecting the relative economic costs of agricultural production across commodities and countries. While understanding these knock-on and rebound effects of food system transformation is integral to implementing them in real-life, they are beyond the scope of the current analysis.

All food system scenarios were implemented uniformly on a country-by-country basis. As such, for example, in the half flexitarian diet scenario, half the population of each country adopts the flexitarian diet whereas half the population continues to consume the BAU diet.

Estimating food system GHG emissions from production and land use change

We estimated the GHG emissions from the global food system for each of the diet, crop yield, and food loss and waste scenarios. This includes GHG estimates from agricultural production, as well as potential GHG emissions resulting from agricultural expansion into natural habitats and GHG sequestration from abandoning agricultural land.

To estimate emissions from agricultural production, we paired estimates of food production, consumption, and land use provided in the supplements of the EAT-Lancet analysis with results from an agro-environmental meta-analysis of life cycle assessments (LCAs) that estimated the GHG emissions per unit of food produced for different agricultural commodities [25]. The LCA meta-analysis used here has a system boundary of cradle to retail store, and provides GHG estimates from five agricultural activities: 1) fertilizer application, 2) manure management, 3) enteric fermentation, 4) methane from rice production, and 5) on-farm energy use. We then estimated emissions from food production, at both the national and global scale, by pairing estimates of the GHG emissions per unit of food produced with estimates of food production. Using this approach, we estimate global food production emissions were 10.08 Gt

CO_2eq yr^{-1} in 2010, which is similar to existing estimates of GHG emissions from food production [26,27].

To estimate GHG emissions from cropland expansion and cropland abandonment, we paired the estimates of changes in cropland use for each country with estimates of below and above ground biomass. To do this, we first estimated spatial changes in cropland extent at a 2.25 km^2 resolution using satellite data from 2002 to 2012 (MODIS; [28]). We then overlaid this historic spatial change in cropland extent with estimates of above-ground and below-ground C stores in natural land covers based on IPCC Tier 1 methodology [29,30], further 40% of soil organic C stores are lost following conversion to agriculture, which is in line with recent estimates of the proportion of soil organic C stores lost following conversion from forest to cropland [31]. This allowed us to derive country-specific estimates of average C stores per hectare in areas that experienced cropland expansion or abandonment in the ten years between 2002 and 2012 (i.e., a different value for cropland expansion and cropland abandonment for each country).

We validated this approach using current estimates of GHG emissions from cropland expansion into natural habitats. We did so by pairing historic changes in cropland extent from 2006–2010 as reported by the Food and Agriculture Organization (FAO) with the derived country-level average C stores described above. Using this approach, we estimated land use change (LUC) GHG emissions from changes in cropland extent and location to be an average of 4.0 Gt CO_2eq yr^{-1} from 2006 to 2010. This is within the range of existing estimates of agriculture-related land cover change emissions [26,32]. We do not estimate LUC emissions associated with changes in pastureland because satellite images often cannot differentiate pasturelands from nature grasslands or savannahs.

We used the same approach to project LUC GHG emissions in each food system scenario. Specifically, we paired the country-specific estimates of cropland LUC GHG emissions per hectare with the country-specific projections of cropland demand from the food system scenarios. In doing so, we amortized the potential GHG sequestration on abandoned croplands over a 100-year period because the full sequestration potential of abandoned agricultural lands is often only realized over a period of several decades to a century. This approach provides a conservative estimate of the GHG sequestration in abandoned croplands because we only account for the GHG sequestration potential that occurs during the time period of the analyses (e.g., before 2050).

Estimating the climate change mitigation potential of implementing climate smart technologies in agriculture

We estimated the climate change mitigation potential of incorporating technologies to the food system for each food system scenario. We included two broad types of technologies: ones that reduce emissions from food production, and ones that increase the rate of CDR on croplands and pasturelands.

We incorporated six technologies that reduce emissions from food production (see description of the technologies above and Table 1), which resulted in 63 unique emission reduction technology combinations (Table F in S1 Text). These technologies reduce food production GHG emissions from specific GHG emissions sources in food systems (e.g., microalgal feed additives in cattle rations reduce methane emissions from enteric fermentation). To account for the climate change mitigation potential of each technology, we therefore paired the individual technologies with the emissions source they target (e.g., microalgal feed additives in cow rations reduce enteric emissions) and then estimated climate change mitigation potential from this emissions source.

The technologies targeting emissions from food production reported their climate change mitigation potential as the percent of emissions from a specific source they reduce (e.g., 46% average reduction in methane emissions for enteric fermentation in the case of microalgal additives in cattle feed). As such, we calculated the climate change mitigation potential of a given tech as GHG emissions * (1 –tech benefit), where GHG emissions denotes the GHG emissions in the food system from the given source before technology is applied, and tech benefit is a value between 0 and 1 that denotes the extent to which the tech reduces food production emissions. In this case, values of 0.25, 0.5, 0.75, and 1 would reducing emissions from the targeted source by 25%, 50%, 75%, and 100%, respectively.

We incorporated five technologies that increase rates of CDR on existing or abandoned croplands and pasturelands, resulting in a total of 31 unique CDR technology combinations (Table G in S1 Text). The CDR benefit of many of these technologies scale linearly with land use. For these technologies, the total CDR benefit was thus calculated as the product of estimated CDR per hectare and total cropland area and was assumed to remain consistent over time.

In contrast to the other CDR technologies, we implemented agroforestry as a CDR practice only on abandoned agricultural lands to avoid competition with food production. Agroforestry is only possible in locations with adequate precipitation, with potential implementation only occurring in locations that receive >1 meter of precipitation per year (which is approximately equivalent to the precipitation threshold needed for establishment of trees). We therefore assumed that agroforestry would only be implemented in locations with cropland abandonment and in locations where annual precipitation is estimated to be at least 1 meter per year under both current and projected climates in Representative Concentration Pathway (RCP) 4.5 and 8. 5 [33]. To avoid double-counting CDR on abandoned croplands, we do not include natural rates of GHG sequestration on abandoned agricultural lands (as described above) in the locations and scenarios where agroforestry is implemented on abandoned croplands.

Technologies targeting CDR on agricultural lands are often economically profitable if applied infrequently (every five years at most). We thus assumed that technologies increasing rates of CDR were applied once every five years (as opposed to annually). Similarly, we assumed that agroforestry is at most implemented on 1/5 of the area potentially suitable for agroforestry. The total CDR benefit of these technologies would be larger if applied more frequently, for instance once every three years, or alternatively across a larger geographic area. Biochar, compost, and rock amendments use different mechanisms for C sequestration (biochar adds stable forms of organic C to the soil which increases organo-mineral associations and subsequent C storage, compost promotes plant growth and photosynthesis which transforms atmospheric CO_2 into soil organic matter, and silicate rock weathering converts atmospheric CO_2 into inorganic C in soils or soil pore water), and thus we assumed additive effects when co-implemented, however, this assumption remains to be tested in the field [34].

We paired every possible combination of technologies reducing emissions from food production with the technology combinations that increase rates of CDR while accounting for technologies that are not mutually compatible. We further assume technology is implemented at four different rates: 25%, 50%, 75%, and 100%. Note that because of economic limits on implementation of technologies targeting CDR, 100% adoption for these technologies corresponds with application of the technologies once every 5 years (or for agroforestry, that 1/5 of abandoned cropland is converted to agroforestry). We further assumed that implementing these technologies does not affect yields in either crop or livestock systems, and that they do not affect total cost of agricultural production. All analyses were performed using R version 3.6.0.

Model parametrization for technology data

We examined the peer-reviewed literature to estimate the efficacy of each of the chosen technologies (Table 1). When meta-analyses or comprehensive literature studies were available, we used the reported mean values of climate change mitigation potential. For technologies where no meta-analysis or literature review had been conducted, we either a) used data from individual studies in instances where published literature were scarce (e.g., seaweed farming and hydrogen powered fertilizer production) or b) conducted literature syntheses and calculated mean values in instances where published literature were plentiful but meta-analyses were lacking (e.g., biochar and rock amendments). For each technology (Table 1), we collected literature values on GHG emissions reductions (% reduction) and CDR (metric tonnes CO_2/ha), or related values that can be converted to emission reduction or CDR units. When multiple values were collected, we used the mean value in our analysis. For technologies that reduced only CH_4 or N_2O, we converted these emission values to CO_2eq. Technology values applied in the model can be found in Tables 2 and 3). We constrained soil amendment applications based on the global availability of source material (e.g., biomass availability limited compost applications to croplands as opposed to croplands and pasture lands).

We conducted a literature survey to determine the CDR rate of rock amendments. Peer-reviewed journal articles of enhanced silicate weathering studies were compiled using the search term "enhanced silicate weathering" in Google Scholar, and additional papers were obtained by following citations and by the suggestion of colleagues. Paleoclimate studies or those solely focused on nutrient liberation from rock amendments were omitted, as were laboratory studies of dissolution rates in suspended solution. This is a nascent field; therefore, studies were not excluded based on mineral used, cropping system, or other study design factors. If different rock types or application rates were used in a single publication, these were treated as separate studies. This yielded a total of 8 discrete studies from 5 papers, including five modeled estimates and three from mesocosm studies, from which CDR data were extracted. If only visual results were included, numerical values were extracted using WebPlotDigitizer [35]. Carbon dioxide removal on a per soil mass or per unit area basis was converted to Gt of CO_2 storage per year on a global scale.

Biochar can both remove CO_2 from the atmosphere and reduce N_2O emissions and was thus treated as both a CDR and GHG reduction technology (Table 1). We conducted a meta-analysis to determine biochar's emission reduction in croplands. A literature search for biochar studies that examined N_2O emission reductions was conducted in Google Scholar using the search terms "biochar" and "N_2O" or "greenhouse gas". Only studies on cropping systems and with study durations longer than 14 days were extracted for data. Different types of biochar showed no significant effects on emission reduction performance, but biochar application rates were weighted. In total, the N_2O emission data of 248 experimental treatments from 31 peer-reviewed articles were selected. Numerical data given by figures were extracted using WebPlotDigitizer [35]. The gas emission reduction percent was calculated by

$$\frac{\textit{gas emission without biochar amendment} - \textit{gas emission with biochar amendment}}{\textit{gas emission without biochar}} \times 100\%$$

, which generated a mean GHG reduction of 42.44% (Table 2). Biochar CDR data were obtained by Mayer et al. [17], which synthesizes data from multiple sources. CDR rate was reported in gigatonnes CO_2eq and converted based on application area; Mayer et al. report a CDR rate of 1.05 Pg C/yr, which converts to 3.89 Gt CO_2eq/yr. Dividing this by current cropland area (~1.27 billion hectares), results in 3.06 metric tonnes CO_2/ha (Table 3).

Table 2. Emission reduction technology land use applications, emissions form, mean emissions reductions (%) and source used in food system model.

Technology	Land type	Emissions source	Number of studies	Mean emissions reductions (%)	Low emissions reductions (%)	High emissions reductions (%)	Source
Trawling management	Coastal oceans	CO2 (energy use)	48	59			Meta-analysis (Hilborn et al. 2018)
Manure digestion	Grain-fed livestock	CH4 (manure management)	30	79	35	100	Meta-analysis (Miranda et al. 2015)
Renewable fertilizer production	Crops and grain-fed livestock	CO2 (energy use)	1	47			Michalsky et al. 2012
Enteric fermentation (grain)	Grain-fed livestock	CH4 (enteric fermentation)	Review	46	17	80	Meale et al. 2012
Enteric fermentation (grass)	Pasture-fed livestock	CH4 (enteric fermentation)	Review	35	25	45	Meale et al. 2012
Biochar	Croplands	N2O (fertilizer use)		42			Meta-analysis (Zhou et al. in prep)

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Literature on the impact of compost application on CDR rates was obtained from a review paper by Martinez-Blanco et al. [36] who synthesized the results from 90 articles. The review found that in croplands, compost amendments sequestered 2% to 53% of C applied in compost, depending on the time period being considered (100 years and 1 year, respectively) [36]. We used mean estimates of compost C content (30.61%) [37] to calculate CDR in metric tonnes CO_2eq/ha, based on the California Department of Food and Agriculture recommended cropland compost application rate of 4 tons/ha, which provided a range of 0.082–2.16 metric tonnes CO_2eq/ha from which we used the mean (1.12 metric tonnes CO_2eq/ha; Table 3).

Agroforestry (defined here as a natural resource management system that deliberatively integrates woody perennials (trees, shrubs, palms, bamboos, etc.) on farms and in the agricultural landscapes [38]) can increase both above and below ground C, including soil C. Since we include agroforestry on abandoned agricultural lands adjacent to farms, we consider this agroforestry as trees are deliberately planted within agricultural landscapes. Agroforestry data for combined above ground biomass and below ground soil C was sourced from Kim et al. [39] who synthesized the results of 56 papers and 109 observations on the climate change mitigation potential of agroforestry. This comprehensive study was used to extract mean CDR rate for agroforestry of 7.2 t C/ha, which was converted to 26.42 metric tonnes CO_2/ha (Table 3).

The impact of improved feed on reductions of CH_4 from enteric fermentation in both grass fed and grain fed livestock were obtained from a review paper by Meale et al. [40] For grain fed livestock, we selected feed supplements with the highest impact, including microalgae [40],

Table 3. Carbon sequestration technology land use applications, mean carbon sequestration (tonnes CO_2/ha) and source used in food system model.

Technology	Land type	Number of studies	Mean carbon sequestration (tonnes CO2/ha)	Low carbon sequestration (tonnes CO2/ha)	High carbon sequestration (tonnes CO2/ha)	Source
Biochar	Croplands	2	3.06	1.71	3.18	Mayer et al. 2018
Compost	Croplands	90	1.12	0.08	2.16	Meta-analysis (Martínez-Blanco et al. 2013)
Rock	Croplands	5	18.10	0.29	125	Literature survey (Holzer et al. in prep)
Agroforestry	Croplands	56	26.42	4.77	55.4	Meta-analysis (Kim et al. 2016)
Seaweed farming	Coastal oceans	1	11.10	1.07	2.13	Froehlich et al. 2020

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which ranged from a 25–80% reduction in CH_4, and seaweed feed, which ranged from a 17–63% reduction in CH_4 [41], we thus used a mean reduction value of 46.25%. For grass fed livestock, while a variety of forage strategies were identified, that included early season forage, leguminous forage, and genetically modified forage, these strategies were similar in that increased digestibility (higher nitrogen to lignin ratio) was key to reductions in CH_4 emissions [40]. Such strategies were applied for pasture only, rather than rangelands, as pastures are more likely to be managed and/or planted. Alfalfa pastures (78% alfalfa (*Medicago sativa* L.), 22% meadow bromegrass (*Bromus biebersteinii*)) were found to reduce emissions 25% compared to grass pastures, while early season pasture was found to reduce methane emissions up to 45%, thus we used a mean reduction value of 35%. We assume that emissions reductions on early-season pasture and alfalfa-grass pasture represent improvements that can be achieved through intensive grazing and pasture management to increase forage digestibility. Due to uncertainty over the split between pasture-based and grain-based cattle production systems, we further assumed that the average benefit of enteric fermentation technologies was equivalent to the average benefit of pasture-based and grain-based technologies (e.g., a 40.625% reduction overall, with a 35% reduction in pasture-based and 46.25% reduction in grain-based systems; Table 2). This assumption provides an absolute upper bound of the potential emission reductions, which is aligned with the approach we took on all other technologies. There is a need for further research, given that a linear assumption may not translate, given seasonal effects and lifecycle feeding dynamics for both grain- and grass-fed livestock.

Greenhouse gas emissions reductions from the adoption of anaerobic dairy manure digestion were obtained from a meta-analysis conducted by Miranda et al. [42] based on 30 studies, primarily located in Europe. The authors stated that components of emissions calculations varied by paper, but they included emissions from anaerobic digesters, storage, field application, offset of fossil fuels, and offset of mineral fertilizers. Percent relative changes in CH_4, CO_2, and N_2O emissions were evaluated, with nearly all emissions reductions resulting from changes in CH_4 production (78.5% reduction for CH_4 [n = 20] and 76.0% reduction for all GHGs [n = 24]; calculated as best estimates using the Kernal density distribution). Because these values were nearly comparable, only CH_4 was selected for use in our model analysis (Table 2).

Reduced trawling consists mainly of converting trawling equipment to pot fishing technology, thereby reducing the impact on ocean floors and energy costs from drag incurred on the fishing vessel as a result of trawling. We sourced data on reduced trawling from a literature synthesis of 148 animal based food studies by Hilborn et al. [43], 29 of which were for capture fisheries. In 2010, fish production was assumed to be 40% non-trawling fisheries, 10% trawling fisheries, and 50% aquaculture (FAO State of Fisheries 2018) [44]. We estimated the CO_2 emission reductions of decreasing trawling by assuming that all trawling fish (if 100% management was 100% adopted) was instead substituted by an equivalent amount of fish caught via non-trawling technologies, which resulted in a emission reduction value of 58.97% (Table 2).

Haber-Bosch (HB) nitrogen fertilizer production accounts for ~1% to 2% of the world's energy usage translating to 1.4% of energy-based CO_2 emissions or 0.5 Gt CO_2/yr [45]. Developing industrial-scale processes to synthesize C neutral fertilizers via hydrogen generation from renewables (solar, wind, and hydropower) can reduce the upstream GHG emissions and cut energy costs [15,16]. Given the projected doubling of HB fertilizer production from 100 Tg N/yr (in 2000) to 200 Tg N/yr by 2050 [46], we estimate that HB fertilizer production will result in 1 Gt of CO_2 emissions by 2050 under BAU practices. We assumed that the climate change mitigation potential of electrified HB production scales linearly against this value, with an emission reduction factor of 47% (Table 2), or 0.47 Gt CO_2 emissions reductions compared to the baseline.

At the time of analysis, only one study was known to have analyzed the CDR potential of seaweed farming [47]. Using current global oceanographic, biological, and production data, Froehlich et al. [47] explore the potential of seaweed aquaculture to offset C emission through CDR now and in the future. We extracted a CDR value of 11.1 metric tonnes CO_2eq/ha directly from the text (Table 3).

Results

Dietary transition effects on gross and net GHG emissions worldwide

We compared a baseline BAU against which the climate change mitigation potential of different interventions can be examined. Our BAU scenario assumes that diets, agricultural systems, and the global population continue to shift along historic middle-of -the-road development trajectories. The model results point to a 75% increase in GHG emissions from food production between 2010 to 2050, or an increase of 10.5 Gt CO_2eq/year in 2010 to 18.4 Gt CO_2eq/year in 2050 under the BAU case (see *Methods*). This increase in GHG emissions from food production is similar to past estimates and reflects a combination of land-use change, CH_4 and nitrous oxide (N_2O) emissions from agriculture and food waste [1,3].

Previous research suggests that such GHG emissions can be reduced by ~50–70% via worldwide adoption of diets with smaller contributions of animal sourced foods than average diets, such as a Mediterranean, pescatarian, or vegetarian diet [11,12]. Our model suggests a similar magnitude of global GHG emissions abatement via the adoption of a flexitarian diet, which is higher in fruits, vegetables, legumes, whole grains, and nuts, and lower in red meat, eggs, and starchy vegetables (potatoes) than the current average global diet (see the EAT-Lancet report for more details) [11]. In terms of the maximum capacity, if the entire human population adopted a flexitarian diet by 2050, we estimate a reduction in gross GHG emissions of 8.2 Gt CO_2eq, which is separated between 2.4 Gt CO_2eq of reductions in N_2O, 3.4 Gt CO_2eq of reductions in CH_4, and 2.4 Gt CO_2eq of reductions in production-related CO_2 emissions annually (Fig 1). Our model also suggests a maximum capacity of 1.1 Gt CO2/yr of gross CDR with 100% adoption of flexitarian diets with full crop yield gaps closure (Fig 1B), reflecting the magnitude of land savings and increased terrestrial C sinks compared to the BAU case. However, it is important to note these CDR benefits will only be realized if abandoned agricultural lands remain outside of human use in the long term and the C sinks remains resilient to climate impacts.

Our findings do not reveal an obvious pathway through which adoption of flexitarian diets can achieve net negative GHG emissions in the future food system. Net negative emissions are not apparent under dietary shifts in the model because gross CDR potential does not eclipse the magnitude of gross GHG emissions with the adoption of flexitarian diets, absent any other mitigation approaches (Fig 1). However, that dietary transitions would happen in the absence of new management practices and technology deployment is highly unlikely–and so we address the ensemble of possibilities involving technology and consumer decisions, both singly and systematically across scenarios, below.

Gross and net GHG emissions from global technology deployment

We examine the potential for technology deployment to alter gross GHG emissions reductions and gross CDR under the assumption that diets follow BAU trajectories (see *Methods*; Table 1). We distill our analysis into interventions that can reduce gross GHG emissions (Fig 1A) from those involved in gross CDR (Fig 1B), both singly and in combination (i.e., 'All Technologies'). We estimate that technologies aiming to reduce gross GHG emissions during agricultural production could mitigate between 1.5 (25% adoption, which corresponds with application on 25% of agricultural lands every 5 years) and 6.0 (100% adoption) Gt CO_2eq /yr in 2050 (Fig 1A), or ~2.2 Gt CO_2eq /yr fewer gross GHG reductions estimated for 100% adoption of flexitarian diets by 2050 (cf. Fig 1). The benefit of individual production technologies ranged from marginal (i.e., <0.1 Gt CO_2eq /yr) in the case of new seafood farming practices (i.e., trawling management), to substantial (>1.0 Gt/yr) for converting Haber-Bosch nitrogen fertilizer production to hydrogen-power (1.1 Gt CO_2eq /yr), supplementing feed with additives that reduce methane emissions in livestock systems (1.7 Gt CO_2eq /yr), and applying biochar to cropland soil that reduce N_2O emissions (2.3 Gt CO_2eq /yr). Anaerobic manure digesters are estimated to have a moderate GHG benefit (0.9 Gt CO_2eq/yr) (Fig 1A).

For technologies that increase CDR in croplands, we estimate climate change mitigation potential ranging from 6.9 (25% deployment) to 27.5 (100% deployment) Gt CO_2eq/yr when all technologies are implemented and whilst assuming that yield gaps—the difference between current yields and potentially attainable yields—are fully closed (Fig 1B; Table 4). The low-end gross CDR estimate is ~ six times greater than the land sparing benefits of dietary changes; the high-end estimate is ~27 times greater. At 25% deployment potential, organic soil amendments (i.e., compost and biochar) sequester 0.3 Gt CO_2eq/yr globally, assuming applications occur once every five years in cropland soil. Amending cropland soil every five years with silicate rock dust (known as enhanced weathering), which accelerates the formation of long-lived carbonates, results in 1.3 (25% deployment) to 5.2 (100% deployment) Gt CO_2eq/yr [48]. Seaweed farming, whereby seaweed is farmed at the ocean's surface and buried in the deep ocean, removed between 2.7 (25% deployment) to 10.7 (100% deployment) Gt CO_2/yr. In addition, our model projects unrivaled CDR capacity via agroforestry (tree planting in farmlands, which can sequester above and below ground C), varying between 2.6 (at 25% adoption) to 10.3 (at 100% adoption) Gt CO_2eq/yr (Fig 1B). We assume that any cropland abandoned that is presently suitable to tree growth is available for agroforestry thereby avoiding conflict between land needed for food production to meet human nutritional demands and land set aside for CDR. The magnitude of CDR from agroforestry would potentially be higher if extended into lands currently used for food production through practices such as hedgerows or intercropping.

Simultaneously implementing technologies that reduce GHG emissions and remove C from the atmosphere demonstrates a capacity for food systems to result in net negative emissions of 13 Gt CO_2eq /yr in 2050 if fully deployed. This scenario assumes BAU diets, no change in food loss or waste, and 50% of technology deployment at scale. This contrasts with the dietary lever, for which our model indicates that complete de-carbonization of the agricultural sector is not possible and that net negative emissions cannot be achieved if not paired with technological implementation. However, because neither dietary choice nor technology deployment operate in isolation, and further because relying on any single intervention whilst

Table 4. Adoption rate scenario (technology, dietary change, and food loss and waste reduction global adoption rate) data generated (gross or net GHG benefit), and assumptions (caloric consumption, yield gaps) organized by figure. BAU stands for business-as-usual, ER stands for emissions reduction, CDR stands for carbon dioxide removal, and GHG stands for greenhouse gas.

Figure	Climate change mitigation	Technology adoption rate (%)	Flexitarian diet adoption rate (%)	Food loss and waste adoption rate (%)	Caloric consumption	Yield gaps
1	Gross ER; Gross CDR	25, 50, 75, 100	25, 50, 75, 100	25, 50, 75, 100	BAU	Closed
2	Net GHG emissions	25, 50, 75, 100	0, 50	0, 50, 100	BAU	Closed
3	Net GHG emissions	0–100	0–100	50	BAU	Closed
4	GHG emissions saved	50	50	50	BAU	Closed
5	GHG emissions saved	50	50	50	BAU	Closed

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ignoring others increases the potential risk of not meeting global GHG targets, we therefore examine the climate change mitigation potential of simultaneously implementing technologies and dietary transitions below.

Scenarios for achieving net negative GHG emissions in the future food system

We examine the option space for joint implementation of dietary, technological, and food loss and waste changes to result in a food system with net negative emissions, recognizing the common pitfalls in either and barriers to regional decision making (see *Discussion*). We examine the model across both a discrete set (Fig 2) and full ensemble (Fig 3) of global modeling scenarios. The BAU diet scenario combined with closed yield gaps and with >50% adoption in combination with ensemble of technologies results in C neutrality by 2050 (Fig 2); additionally, halving food loss and waste, which could involve a set of policies, technologies and consumer habits [49], results in 6.7 Gt of net negative GHG emissions under the same assumptions (see *Methods*). Full scale-up of technological interventions (100%), combined with a halving of food loss and waste and closing yield gaps, results in net negative emissions of >20 Gt CO_2eq/yr from the world's food system in 2050 (BAU diet scenario) which increases to >30 Gt CO_2eq/yr with 100% adoption of a flexitarian diet (Fig 2). Although our model does not simulate net negative GHG emissions from the food system under dietary shifts, uptake of flexitarian diets increases the magnitude of net negative GHG emissions under all technology deployment scenarios (Fig 2), while also offering co-benefits to other aspects of environment and health that would not be realized with technological interventions singly (see *Discussion*).

Beyond these discrete simulations, we examine the full option-space for net negative GHG emissions from the 2050 food system, spanning +20 to -33Gt CO_2eq emissions annually on a global scale (Fig 3). It should be noted that technologies such as agroforestry and seaweed farming have a substantial influence on these findings given their high CDR potential (~10 Gt CO_2eq/yr). For example, removing seaweed farming from this analysis would effectively move the isoline for net-zero emissions (Fig 3) from ~45% adoption to ~70% adoption under a BAU diet scenario. The climate change mitigation potential of agricultural interventions are in some cases strongly affected by dietary choice: technologies targeting GHG emissions from animal sourced foods become less important as consumers shift to flexitarian diets and the global production of livestock decreases. While interventions that reduce CH_4 emissions from livestock (e.g., feed alternatives), and those targeting manure emissions (i.e., anaerobic digesters) and fertilizer N_2O emissions are sensitive to dietary choice, those targeting C sequestration through soil interventions, ocean trawling, and agroforestry are more reliant on the rate at which agricultural yields are increased and food loss and waste is decreased. It is important to note, however, that the GHG sequestration benefits of technologies that sequester C in soils or biomass (e.g., biochar applications, agroforestry) were based on primary analyses that examined these benefits in the short (several years) to medium (25 years) time durations. It is possible that in the longer term (> several decades), the annual emissions benefits of these technologies might reduce as C in living biomass and in soils saturates.

Spatial patterns across countries

While global analyses help to identify the total potential benefit of different strategies, it is important to downscale results, because food policies are often implemented at country or regional scales. We therefore explore the climate change mitigation potential in each country in a scenario with 50% adoption of technology and flexitarian diets by 2050, combined with a halving of food loss and waste (Figs 4 and 5). We focus on this middle path scenario as a reasonable compromise between tractability and complexity in our country-scale analysis, recognizing that there are vast numbers of options with varied amounts of dietary change, reductions in food loss and waste, and technological interventions, and further that full implementation of any single lever might not be possible due to taste preferences, sociocultural values, and the economics of dietary transitions and technology implementation.

We estimate the largest climate change mitigation potential per capita in: (1) areas with high rates of ruminant production and caloric consumption, especially New Zealand, Brazil, and the United States; (2) countries where ruminant abundance is moderate to high, with high GHG emissions per unit of production, such as central Asia; and (3) areas with yield gaps where agricultural intensification can reduce land use change emissions, benefiting natural CDR, principally parts of West Africa and Southeast Asia. In contrast, our findings highlight smaller per capita benefits in countries that consume smaller amounts of meat in general (and ruminant meat in particular), or where meat consumption might increase when transitioning to a flexitarian diet (as occurs in some low-income countries) (Fig 4).

Across regions, we estimate the largest national climate change mitigation potential in countries with large populations and a large amount of land devoted to agricultural production, such as China, Brazil, the US, India, and Indonesia. Many of these countries have high GHG emissions, with food sector innovations contributing to overall curbing GHG emissions. For instance, in China we estimate over 1 Gt CO_2eq/yr in GHG savings by halving food loss and waste, transitioning halfway to a flexitarian diet, and implementing all technologies at 50% of their potential adoption rate (Fig 5). Importantly, given the potential for unwanted outcomes to emerge with either/or strategies, it's critical that decision makers consider a mix of options that are locally anchored in a co-benefit space that considers human and environmental health, economic livelihoods, and climate mitigation and adaptation.

Discussion

Our analysis suggests diverse pathways and considerable options for realizing gross GHG reductions, gross CDR, and sector-wide net negative GHG emissions in the future food system worldwide. We build on previous work through (i) the specificity of technologies examined, (ii) analysis of capacity for net negative GHG emissions to occur in the global food system, and (iii) explicit investigation of a limited set of interactions between dietary shifts and technology and management approaches at a variety of adoption rates in a global model, spanning fundamental issues for achieving the climate stabilization targets of "1.5 degree world [13]". This holistic approach adds robustness to previous findings and our working conclusions. We explore a variety of levers, however, further investigations that include additional interactions could build upon our analysis, for instance, how both producer and consumer behaviors change as prices change in response to shifts in production dynamics. While adoption of flexitarian diets and deployment of technologies can in principle reduce upstream emissions (for example fertilizer production) as well as direct GHG emissions from croplands and agriculture, net negative GHG emissions in the food system can be achieved through a mix of technology interventions and dietary transitions. The right blend of approaches will depend on local factors and how the different interventions offer localized co-benefits beyond the global GHGs benefits [50].

Feed-additives, manure digesters, agroforestry, and soil amendments can all be implemented without the need for major changes to global infrastructure or supply chains. Supply chains that have originated for decades have focused on delivering agricultural inputs, such as fertilizer, pesticides, and seeds, enabling a built-in pathway through which other materials can be added to the agricultural pipeline and distributed globally. Many of the technologies we examine offer local economic and environmental co-benefits (via enhanced efficiencies of agricultural production and conversion of waste products into economic value; Table 2). Carbon pricing, such as Cap and Trade and voluntary offset markets, has the potential to accelerate adoption and, in the case of soil nutrient interventions and C sequestration, even raise farmer revenues beyond the local benefits of adoption. Still, the question remains as to where exactly adoption of such practices might occur. The likelihood of adoption of new technologies or diets also depends on complex and localized sets of economic, political, and cultural conditions. Capital costs can also limit scale-up, suggesting a role for financing and venture funding; for example, the purchase of manure digesters might prevent farmers from utilizing this technology in the absence of government-based incentives [51]. Future work on the regional and contextual boundary conditions, and consideration of other technologies that may be under development, would help decision makers create conditions that promote the best alternatives in a given jurisdiction, including culture, food-security, values, available financing, and economic conditions.

Barriers to and co-benefits of food-system transformation, whether consumer- or technology- driven, may be separate or overlapping (Fig 3). A principal barrier to technology deployment is economics, thus we describe costs associated with the climate mitigation levers we explored. Agroforestry is both the least costly and the most impactful strategy for CDR, owing to a greater potential for widespread adoption, however, it's worth noting that trees introduce an additional complication and potential barrier to adoption in terms of land tenure, since they involve multi-year claims on resources [52,53]. Although seaweed farming can produce substantial CDR (10.7 Gt CO_2eq/yr at 100% adoption), current cost barriers are substantially prohibitive ($543 USD/ton of CO_2eq) [47]. A reasonable way to appraise cost barriers considers the social costs of GHGs, which varies widely across regions and scenarios, approaching a median value of US$417 per tonnne of CO_2 [54]. Technologies that offer mitigation below this value can be seen as generally in line with damage estimates, although its critical to understand that markets are far from this level of C pricing. The costs of climate mitigation technologies vary widely, spanning more than two orders of magnitude, from $10 to $543 USD/ton of CO_2eq [47,55,56], but are generally well below the median social cost of CO_2. Moreover, even the higher end costs are lower than direct air capture, which currently varies between $610-$1000 USD/ton of CO_2eq [57,58]. The costs to individual adopters, particularly smallholder farmers, are critical and often a prohibitive factor in climate mitigation. Future research could examine how to reduce costs for technologies with high climate change mitigation potential and the influence of down-scaled social GHG costs on pathways for C pricing and deployment.

We examine a subset of possible technologies here; but climate mitigation through agricultural technology may involve an even larger suite of technologies, some of which have yet to be actualized in the market [18]. Any intervention has the potential for unwanted side-effects to occur at scale. Our analysis focuses on technologies that have demonstrated high impact potential, as supported by the peer-reviewed literature, rather than more futuristic options such as indoor farming or microalgal and fungal foods [59,60]. These technologies might also contribute to reducing food system emissions, although more research is needed to identify their scalability and potential role in mitigating climate change. While a large suite of emerging agricultural technologies exist, further field and modeling research on CDR potential and spatial extent is needed to improve estimates of their climate change mitigation potential.

We did not consider no-till or cover cropping effects, which could add several billion tonnes of global CO_2 sequestration to our estimates [61,62]. Nor did we analyze synergistic effects among interventions given the paucity of such data. Annual soil amendment applications in croplands coupled with expansion of interventions into global pasturelands and rangelands would dramatically increase our estimates for global CDR in the agricultural sector.

Furthermore, while the climate change mitigation potential of BECCS could be important [63], this approach has the potential to interfere with food-production for a growing world population, among other limitations [64]. Neither did we address time-lags of social change or technological adoption and the potential influence of soil C saturation [65–67]. While many cropland soils have been depleted of organic C supplies, limitations to C sequestration can include texture, drainage characteristics, plant root proliferation and turnover, C quality, and microbial respiration [68].

Further exploration into areas where technologies cannot be combined should be considered, such as agroforestry and other cropland interventions, or biochar and no-till practices. Experiments, preferably at scales that represent various combinations of technologies that farmers and ranchers find reasonable, could reveal impacts on crop yields, bottom line economics, co-benefits, and additive or even synergistic effects of combined practices for improving soil health. Additionally, monitoring technologies after they have been implemented in food systems is necessary to ensure that the technologies are effectively reducing GHG emissions without resulting in unintended environmental or health consequences.

A variety of the technological strategies hold co-benefits: soil amendments have been shown to increase yields, soil health and crop quality [69,70]; manure digestion can reduce nutrient runoff to waterways and produce fertilizer or biogas [55]; and agroforestry can promote biodiversity. Alternatively, new or emergent technologies can create negative or unforeseen impacts; for instance, organic amendments have been found to promote nutrient leaching [71], and agroforestry and BECCS can compete with resources to grow food [64,72]. Furthermore, strategies that affect unintended nutrient pollution from agriculture, either positively or negatively, can also have indirect effects on human health [73]. Moreover, some forms of agriculture, such as seaweed farming [47], are novel CDR strategies that have not yet been vetted for their potential negative impacts. Given the novelty of these technological strategies, further field and modeling studies will be necessary to better understand the social, environmental, and economic implications of the co-benefits and negative consequences associated with these climate change mitigation tools.

Our findings demonstrate that technological deployment offers an array of climate change mitigation potential and net negative emissions capacity in the world's food system, with flexitarian diets adding additional emissions reductions across interventions in all cases but livestock emissions approaches; assuming livestock numbers decrease proportionately to reduced meat consumption with flexitarian diets, the benefits of interactions that reduce CH_4 emissions from livestock no longer yield a return on deployment. Shifts and reductions in food loss and waste can promote environmental co-benefits, including for biodiversity, soil and water quality, and land conservation [9]. Transitions to flexitarian diets are suggested to hold health and other environmental benefits [74–76]. Lack of access to nutrient-dense foods, including those enriched in micronutrients, is a widespread challenge and needs to be considered when considering options for dietary shifts. This is especially true in the case of poor and vulnerable populations in developing economies, where people rely on a diverse mix of livestock and crops [77]. Quantitatively analyzing the costs and benefits of consumer choice and technologies, their unintended consequences, and known feedback effects is beyond the scope of our present study. Such analysis could help decision makers and resource managers craft down-scaled plans to create net negative GHG emissions, while considering culture, economics, and rural livelihoods.

Conclusions

The global food system can generate substantial net negative GHG emissions, singly via technology deployment but with greater potential realized through a combination of dietary transitions, technology interventions and reductions in food loss and waste, which can be regionally down-scaled according to local culture, economics, technology readiness, and agricultural management capacities. This makes agriculture a unique economic sector and reiterates that it should be a key focus when discussing climate targets. Context-specific policies that could achieve the GHG mitigation and sequestration benefits in fair, just, and equitably ways need to be identified, implemented, and then monitored to ensure the policies have the intended climate benefit without negatively impacting the health and wellbeing of human populations, food system resilience, and economic development. We suggest that alignment of climate-smart incentives with extant global agriculture infrastructure could accelerate net negative GHG emissions for the future food system, offering a wide path of options for decision-makers that can be tailored regionally. Importantly, however, a holistic food-system perspective that involves a thoughtful blend of interventions will often yield the greatest local outcomes for human health, environment, climate mitigation and resilience, and economic development.

Supporting information

S1 Text. Table A. Model outputs for Fig 1A. BMK = business as usual, full_w = full waste (no reduction in waste), waste_# = % reduction in waste, FLX_# = % adoption of flexitarian diets. Table B. Model outputs for Fig 1B. BMK = business as usual, full_w = full waste (no reduction in waste), waste_# = % reduction in waste, FLX_# = % adoption of flexitarian diets. Table. C Model outputs for Fig 2. Table D. Model outputs for Fig 3. Table E. Model outputs for Figs 4 and 5. Table F. Full list of emission reduction scenarios. Table G. Full list of carbon dioxide removal scenarios.
(XLSX)

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