Pace of adoption of alternatives to animal-source foods and climate goals

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Abstract

The global food system is an important contributor to greenhouse gas emissions that lead to climate change. Animal agriculture is responsible for a large share of the food-system emissions, both directly and through the production of animal feed. Limiting global warming to the goals set forth by the international community will not be possible without rapid phasing out of a substantial share of animal-source food. We show that the rapid adoption of alternatives to animal-source foods, such as plant-only diet, or plant-based, cultured, or fermentation-derived analogs to animal products, can be consistent with climate goals. Importantly, the longer the delay in the adoption of alternatives, the larger the share of diet they will have to represent in 2050 for the food system to stay within its carbon budget.

The world economy is not on track to reach climate goals.(1) In recent years it has become evident that constraining global temperature increase will require not only changes in energy production and transportation but also changes in the food system. Food systems are responsible for as much as a third of global anthropogenic greenhouse gas (GHG) emissions.(2) Therefore, the Paris Agreement climate goals cannot be achieved without changing the food system.(3; 4) The main change needed is a reduction in reliance on animal-source food.(5; 6; 7) A global switch to plant-based diets is a potential solution, but resistance to reducing consumption of animal-source foods (ASF) is well documented (8) and an upward trend in global consumption of ASF continues. Thus, it is unlikely that consumers will shift to plant-only diets fast enough to achieve climate goals and therefore there is a role for alternatives to ASF that rely on new technologies that will make products more acceptable to consumers than most products in the market today. These technologies, while not emission-free, have potential for substantially lower emissions than ASFs, especially given projected

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energy transition towards clean power. We contribute to the growing literature on these issues by providing a dynamic quantitative analysis of the global cumulative GHG emissions from the food industry under different dietary scenarios, taking into account possible consumer adoption paths for these scenarios.

Research has emphasized the need to increase the share of plants and reduce the share of animal-source products in the average diet to achieve climate goals and preserve biodiversity.(9)(10)(11) Eliminating greenhouse gas emissions from livestock and allowing native ecosystems to regrow on the land currently used to house and feed livestock, would be equivalent to a 68% reduction in carbon dioxide emissions.(12) Replacing just 50% of main animal products with alternatives by 2050 is estimated to reduce land use GHG emissions by 31% compared to 2020.(13) However, we cannot simply eliminate an important food source without replacing it with an alternative technology that also has a GHG footprint. While dietary changes are a partial solution,(14) such changes tend to be slow without an introduction of alternatives that are attractive to consumers in terms of price, taste, texture, nutritional value, and other attributes that consumers value.

We group alternatives to animal-source food products into two categories: plant-based, which are available to consumers and are already increasing their market share (15) and "cultured," which includes new technologies for protein production such as cellular agriculture (or cultivated alternatives), precision fermentation, biomass fermentation, molecular farming, and potentially other innovations, which are, with few exceptions, still mostly in the development stage or awaiting regulatory approvals. Production of these alternatives, especially when powered by clean energy, has a much lower GHG footprint than ASF(16)(17)(18) We consider scenarios in which ASF are replaced by such alternatives to evaluate the potential for this transition to lead to sustainable food system when compared to business-as-usual, plant-only diet, and healthy diet scenarios without introduction of these alternatives to ASFs.

Our approach to the dynamics of food system transition is distinct in that we model transition based on consumer acceptance models rather than pathways derived from emission reduction needs from climate scenarios. Thus, we provide calculations of cumulative emissions between 2024 and 2050 under conventional assumptions about the dynamics of consumer acceptance of new products. We find that compared to the business-as-usual scenario in which most of the global diets converge to the western diet by 2050 (19), a substantial reduction in cumulative food sector GHG emissions can be achieved with shifts to alternatives to ASFs or plant-only diet. The emission reduction crucially depends on the starting point of the transition: the longer the delay before the transition begins, the larger the share of the ASFs needs to be replaced by 2050 for the same target cumulative emissions.

If the goal is to keep global temperature rise under 2 degrees C with a probability 67%, IPCC estimates the remaining carbon budget of 1170 GtCO2e. Assuming that the food sector will continue contributing about a third to global GHG emissions (2), this leaves a carbon budget of 390 GTCO2e for the food sector, which we can allocate to the period up to 2050, since most climate models reach net zero by that time. In our benchmark calculations, this goal can be achieved in the following cases: With alternatives to ASFs, rapid adoption starting before 2028 with 60% of ASFs replaced by 2050, if rapid adoption starts as late as 2034, 100% of ASFs will need to be replaced, later start dates or 2050 replacement under 60% will not keep the food system within 390 GTCO2e budget. Transition to plant-only diet, without alternatives to ASFs, due to slower adoption rates will need to start no later than 2026 with 60% substitution of ASFs with plants by 2050 and no later than 2033 with convergence to 100% plant-only diet by 2050. EAT-Lancet Healthy Diets scenario, regardless of the start date and transition pace, is not able to stay within 390 GTCO2e budget.(20) This is because GHG emissions from animal-source foods in EAT-Lancet Healthy Diets substantially exceed that of plant production.(21)

Our estimates for the reduction in GHGs resulting from the substitution of ASF are on the conservative side because we do not factor in the potential for carbon sequestration resulting from restored biomass due to reduced agricultural land use.(12)(22) This is because the benefits of land use change may take decades to manifest, whether it is done through soil carbon sink or through reforestation, and because these benefits are quite uncertain given the uncertainty around climate change trajectory and other factors.(23)(22)

Our calculations correspond to the reduction of global food system GHG emissions relative to the business-as-usual scenario by 43-52% if the alternatives to ASFs are used, and by 45-51% if the replacement is with standard plant products. This impact compares favorably with other ideas proposed for reducing GHG emissions of the global food system, such as major shifting of cattle production areas, compositions of current feeds, and land restoration (estimated reduction of 34–85% annually)(24). Other approaches include reduction of food waste (leading to 15% reduction of emissions from the food system) as well as yield improvements and other technological changes (1-2%) (25)(26)(27)(3)(28)(29)(30).

1 Results

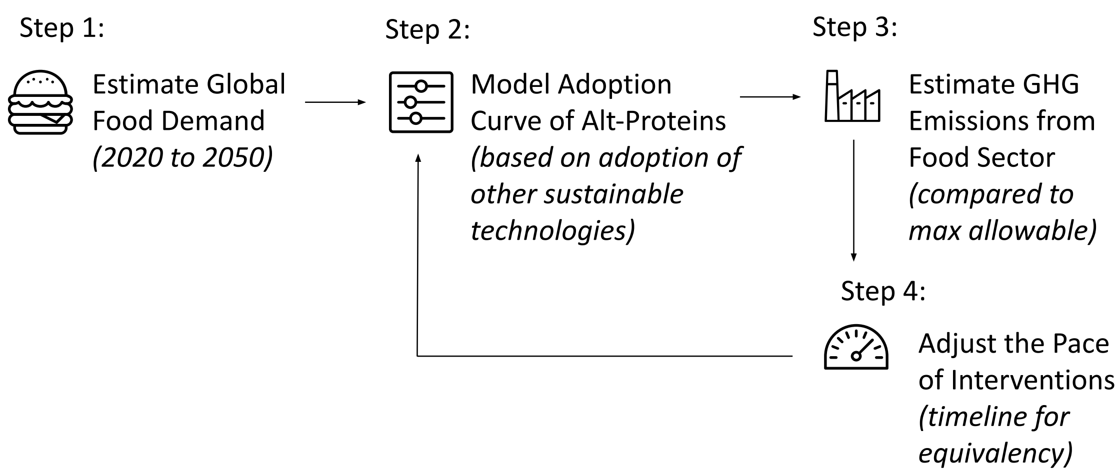
We organize our results in three main components (Figure 1). Two factors contribute to global caloric demand — population growth and income growth. These factors together contribute to the growing demand for calories, and disproportionately for calories from ASF. This results in a substantial increase in emissions from the food system, given business-as-usual (BAU) projections, for a total of 639 GtCO2e in the 2020-2050 time period. This amount is not compatible with most estimates of the emission budget for achieving climate goals.(3)

Any changes involving consumer behavior do not occur linearly. Across a variety of products, initial adoption is slow, but it turns into mass adoption after reaching certain threshold. This path is well approximated by Gompertz curves.(31)(32)(33)(34) For dietary changes to occur on a large scale, alternatives need to achieve the equivalency point, which, most importantly, means reaching parity with ASF in terms of price and taste, but also satisfying additional consumer attributes.

This equivalency point is still in the future and the timing of reaching it is key in determining cumulative food industry emissions.

Given substantially lower emissions from alternatives to ASF and from plants in general, cumulative food industry emissions can be substantially reduced by replacing ASF with alternatives or with a plant-only diet. Incremental reduction in the share of ASF in the diet, as proposed by EAT-Lancet REF, is not sufficient to reach the needed reduction of the food sector emissions. Obviously, a combination of approaches proposed, including transition to healty diets, reduction in food waste, and improvements in agricultural technologies, as well as alternatives to ASFs together will produce the best results. However, none of the individual interventions are estimated to be as large in magnitude as a switch to alternatives to ASFs or plant-only diets.

Figure 1: Analysis steps

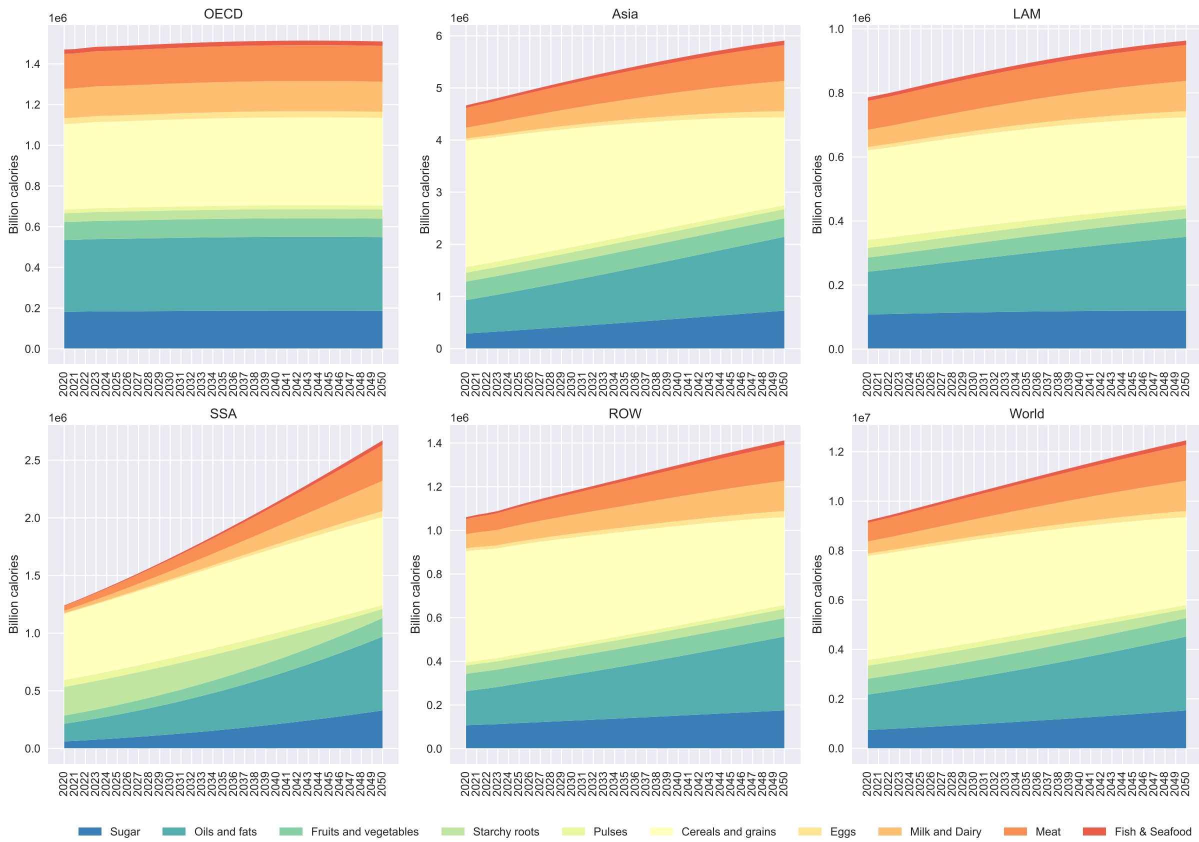


Notes: Components of evaluating the emissions from food industry in different scenarios.

1.1 Business as usual means increasing global emissions from the food industry

Population and income growth both contribute to the growing demand for calories. However, as incomes increase, there are also changes in diet compositions in the direction of the current ASF-heavy "western" diet (Figure 2) (19). Consumption of calorie-dense foods, including oils and fats, dairy, and meat, increases with growing income while the share of cereals and grains declines. The largest increases in both total calories as well as in the share of calorie-dense foods are in Sub-Saharan Africa (SSA). As a result, for the world as a whole, we estimate an increase in total calorie demand by 35% in 2050 compared to 2020, with the amount of calories obtained from all ASF (eggs, milk and dairy, meat, fish and seafood) more then doubling with an increase of 116%, and amount of calories obtained from meat specifically increasing by 93%. This corresponds to an increasing share of ASF in total calories consumed from 15.6% in 2020 to 24.9% in 2050, of which meat products share increases from 8.2% of total calories consumed in 2020 to 11.6% in 2050.

Figure 2: Global demand projections by food group and region



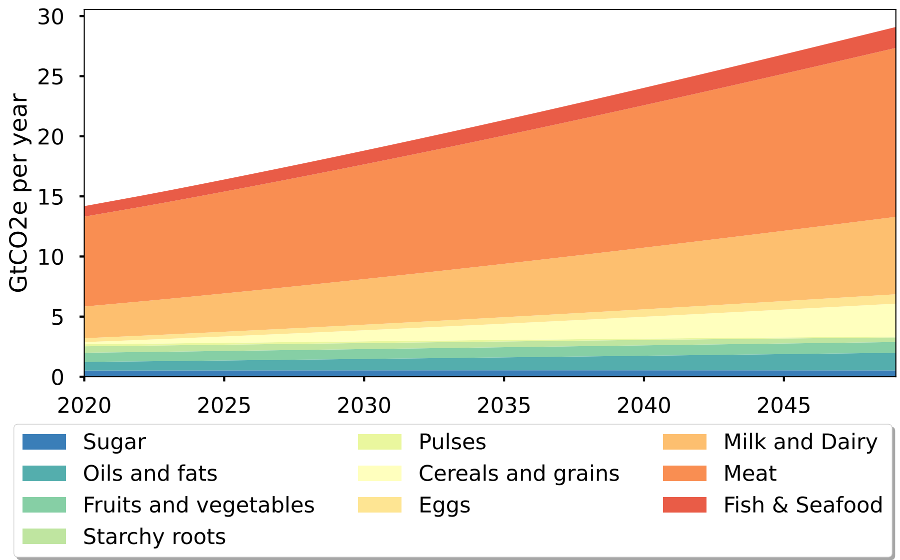
Notes: Projection of caloric demand by food group and the region. OECD includes all EU economies, LAM is Latin America, SSA is Sub-Saharan Africa, ROW is the rest of the world not included in other regions. Population projections are from the United Nations. Dietary projections are authors' calculations and are based on observed trends and the estimated relationship between income and dietary compositions.

Given substantially larger emissions from ASF than from plant sources with even the lowest-impact ASF on GHG emissions exceeding that of vegetable production (21), this change in diets as well as overall growth in calorie demand results in a substantial upward trend in annual emissions from the global food system (Figure 3), doubling between 2020 and 2050, with an increase driven almost entirely by the ASFs. These calculations are in line with prior results obtained with different methodologies (35).

1.2 Consumer choice does not follow a linear path

There is high uncertainty about the path of consumer behavior. However, a consensus in the literature is that it does not follow a linear path, but a path that is well approximated by Gomperz curves.(31)(32)(33)(34) Gompertz curves show that upon reaching the equivalency point — the point at which the new product matches consumer attributes of the product it is designed to replace — there is an initial slow period of adoption, with "early adopters" helping increase awareness and

Figure 3: Annual emissions by food group



Notes: Annual emissions are computed based on the world diet projections in Figure 2, with emissions by food group aggregated based on data in (21).

scale up the production therefore lowering the costs due to economies of scale. This slow initial period is followed by rapid adoption until a substantial share of replacement is reached. Once the adoption share approaches a final replacement share (which need not be 100%), the adoption rate slows down again. This pattern is illustrated in Figure 4. The Figure plots an extreme case of 100% replacement of ASF with alternatives, as an example, with an equivalency point set to 2026 and an additional adoption delay of 2 years.

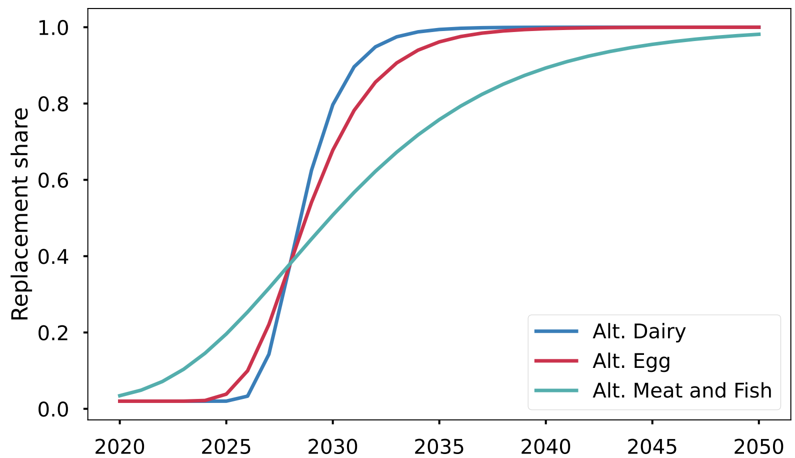
For our analysis, we vary final adoption share and equivalency point, but we assume throughout that the adoption pace is fastest for alternative milk and dairy, medium pace for alternative eggs, and slow for meat and fish, as reflected in Figure 4. Our robustness analysis shows that the impact of the adoption pace on the results is not nearly as large as that of the final adoption share and the equivalency point. Thus, specific assumptions of the adoption pace are not material to the outcomes.

1.3 Transition timing is key to cumulative emissions

Cumulative emissions from the food industry crucially depend on the path of the transition (Figure 5). Even a fast transition to 100% EAT-Lancet Healthy Diets starting in 2024 results in cumulative emissions exceeding 500 GtCO2e (a 22% decline relative to BAU) (20). By most estimates, this is still not compatible with reaching climate goals, which allocate 390 GtCO2e to the food sector, and therefore more substantial substitution away from ASF is needed.

To stay within the 390 GtCO2e budget, the scenario with only plant-based alternatives to ASF

Figure 4: Sample dynamics of adoption of alternatives



Notes: The following equation is plotted $S_{altj,t} = S_{altj,2020} + FA * \mathrm{e}^{-\mathrm{e}^{(-\alpha_j(t_j-(t_j^*+\delta t^*)))}}$, where S is the share of alternative j in year t, FA is the final adoption share, set in this example to 1, $\alpha_{alt.meat} = 0.18$, $\alpha_{alt.dairy} = 0.73$, $\alpha_{alt.egg} = 0.46$, which are based on the lowest, highest, and average adoption rates for solar and wind technology. Equivalency point is $t_j^* = 2026$ for all food groups, delay in adoption δt^* is 2 years. Current share $S_{altj,t}$ is 0.02 for all food groups.

through 2032 and cultured and fermentation-based alternatives increasing to 27% of all the alternatives by 2050 and no delay after the equivalency point is reached, requires 70% replacement of ASF with the alternatives by 2050 if equivalency point is reached in 2024, and 80% replacement if equivalency point is delayed by as long as 2030 (90% if the protein demand rather than caloric demand is matched).[1] Delay till 2032 will result in the need for 100% replacement by 2050 to stay within the carbon budget. Delay past 2023 means that a switch to alternatives alone will not be sufficient to satisfy global food demand without exceeding the cumulative emission budget.

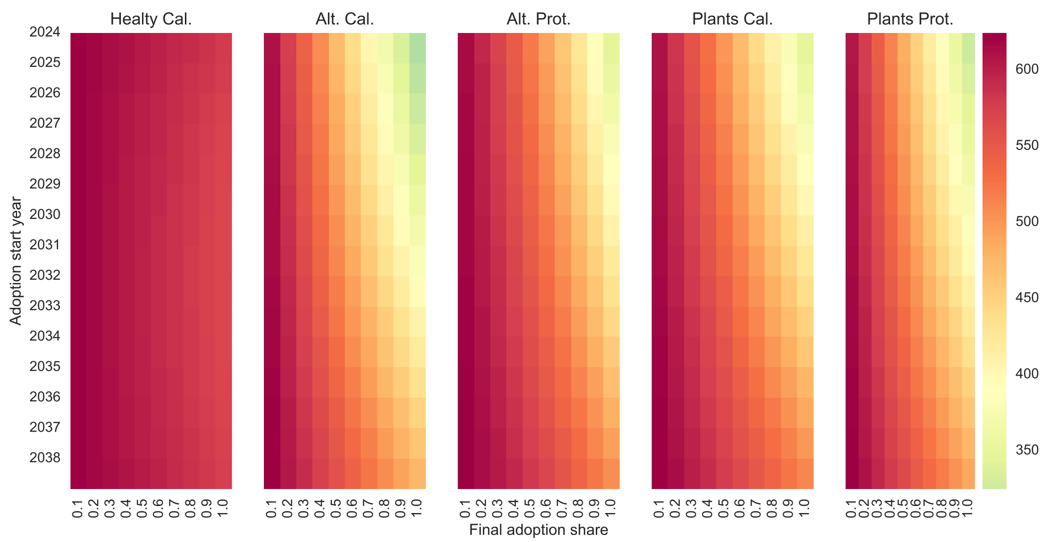
Because of the slower transition to plant-only diets without alternatives to ASF, as much as 90% of ASF need to be replaced with plants by 2050 if the transition starts before 2028 to stay within the 390 GtCO2e budget (80% to match protein rather than caloric demand). Delaying the transition to plant-only diets until 2030 will result in exceeding the emission budget even with 100% plant-only diets globally in 2050.

2 Discussion

Our results show that alternatives to ASF, if they are developed or improved to match consumer preferences, can go a long way in helping reduce GHG emissions from the food system to the levels

[1] Over time, technological innovation may increase protein content in staple crops used for alternatives to ASF, but we do not incorporate this into our calculations because of the high degree of uncertainty.

Figure 5: Cumulative emissions in different scenarios as a function of final adoption share and equivalency point



Cumulative emissions are computed for 2020-2050 time period. Healty Cal. is the convergence to EAT-Lancet diets globally. Alt. Cal. is the replacement of ASF with alternatives to match caloric value; Alt. Prot. is the replacement of ASFs with alternatives to match the total protein demand of the BAU scenario. Plants Cal. is the replacement of ASF with plants to match caloric value; Plants Prot. is the replacement of APS with plants to match protein demand in the BAU scenario. The adoption start year corresponds to the equivalency point in the Gompertz curves model. Scenario plotted is based on no adoption delay and slow introduction of cultured and fermentation-based alternatives to ASF to allow for various adoption barriers (36). The final adoption share is the 2050 target. Healthy Diets transition is assumed to have fast transition parameter $\alpha_{HD} = 0.73$, while the transition to plant-only diet is assumed to be slow with $\alpha_{Plants} = 0.18$ (37; 38; 39). The center color of the color bar is set to 390 GtCO2e, the estimated emission budget for the food industry, and is the same across panels.

that are consistent with global climate goals.

2.1 Adoption of alternatives to ASF leads to larger GHG emission reduction than other approaches

Replacing all animal-source foods with alternatives by 2050 without changing the composition of the average diet can reduce food system emissions from 519 Gt CO2e to 348 Gt CO2e in our benchmark scenario (a 171 Gt CO2e reduction) and to 291 Gt CO2e (a 228 Gt CO2e reduction) in the most optimistic scenario. This is a substantially larger reduction that can be obtained by food waste reduction, yield improvements, or the shift to plant-rich diets (65-92 Gt CO2e in Project Drawdown calculations) or 90 Gt CO2e impact of the transition to EAT-Lancet Healthy Diets in our calculations that do not involve the shift to alternatives.(30)(20) Thus, alternatives to animal-source foods are likely the most promising path to food system sustainability. Importantly, these reduction calculations are based on the full replacement of animal-source foods by 2050, the equivalency of alternatives reached by 2025, and the relatively short 3-year lag between the time full equivalency is reached and the demand takes off. Because cumulative emissions are key, delays in equivalency point, take-off, or limited ultimate replacement reduce the impact substantially. Thus, innovation in the alternatives to animal-source foods needs to be rapid and needs a supportive regulatory environment and private and public sector investment. In particular, policies similar to those that supported the development of alternative energy sources are necessary for the rapid food system transition.

It is clear that shifting global diets away from ASFs is key to reaching climate goals. Moreover, the change needs to be sufficiently drastic — incremental changes such as shifting to a healthier diet in developed countries is not likely to be sufficient due to the continuing growth of ASF consumption in developing countries because of continuing population growth and increasing wealth.(19) Can this shift occur without new technologies and products offering alternatives to ASF? It is possible, but the pace of transition to predominantly plant-based diets is likely to be insufficient: our calculations show that the transition will have to start now and reach 90% plant-based consumption globally by 2050. Given current trends of increasing share of ASF, this is not very likely.(37) (39; 38)

2.2 Policy interventions needed to speed up the adoption of alternatives to ASF

Alternatives to ASF are designed to make transition away from ASF more feasible for consumers, as the goal is to have a minimal change in consumer behavior but rather substitute the ASF inputs with new technologies: plant-based or cultured (including fermentation-based). This would allow for a faster adoption pace and therefore more realistic scenarios that are consistent with climate goals. Even with alternatives to ASF, however, the shift is unlikely to begin soon enough without intervention. Our adoption curve parameters are based on alternative energy transition which received substantial incentives from the governments worldwide. Now that the pace of adoption of electric vehicles and solar panel generation are exceeding forecasts,(40) policy interventions to help jump-start the transition away from ASF is likely to be highly impactful for reaching climate goals. Such interventions could include both supply-side incentives, such as research grants and R&D subsidies for quality improvement and subsidized loans that would allow for rapid scaling to match growing demand, and demand-side, such as incentives for food companies, retailers, and the food service industry to reduce their climate impact.

2.3 Other considerations beyond the scope of this study

It is worth reminding the reader that we do not include in our calculations CO2 sequestration through the restoration of ecosystems on the land that is freed from pasture and animal feed production, which could be as high as 332-547 GtCO2 by 2050, making cumulative GHG emissions from the land currently used for agriculture negative on net.(12)(41) If these effects are added, there is potential for reaching climate goals with lower final replacement of ASFs.(13)(42) That said, the exact timeline of the carbon sequestration potential prior to 2050 is highly uncertain, which is why we are not including these considerations in our benchmark analysis.

In this analysis, we do not address the financial aspects of diet transitions. Obviously, alternatives to ASF are in the early stage of development and need substantial investment. That said, given the lower demand for resources by plants and alternatives to ASF compared to those of animal agriculture, diet transition consistent with climate goals is likely to result in lower overall spending on food production. The analysis of the financial costs of this abatement strategy and its comparison with other emission-reduction approaches could be conducted along the lines of marginal abatement cost curves,(43) but is beyond the scope of the current study.

3 Methods

As discussed in Section 1, we've structured the analysis in three components. First, we estimate the global calorie consumption by food group between 2020 and 2050, then we model the adoption of alternatives to animal-source food categories, including both pure plant and manufactured alternatives. Finally, we calculate GHG emissions under different scenarios.

3.1 Two global demand scenarios to project total food consumption

We estimate the global food demand using population forecasts, daily per capita caloric intake, and estimates of the share of caloric intake sourced from proteins.

We segregate protein consumption into food groups based on relevant sources of protein — plants, eggs, dairy, fish, animal-source meat, and alternative meat. Plants consist of the following subcategories: sugar, oils and fats, fruits and vegetables, starchy roots, pulses, cereals and grains. We quantify the weight of each source through analysis of existing dietary patterns using Food and Agriculture Organization of the United Nations (FAO) individual consumption data and National Geographic "What the World Eats"data.

We first calculate 2020 caloric consumption by food group by country using FAO individual consumption data by country then aggregated this data into five regions with distinct consumption patterns: OECD90+EU, Asia, Latin America (LAM), Sub-Saharan Africa and Middle East and North Africa (MEA).

For the projections, we consider a 30 years time frame, from 2020 until 2050. This is the same time frame considered by the IPCC's assessment of the emissions budget required for limiting temperature rise to 1.5°C.(44). We model global food demand (GFD) for each year t, focusing on main food sources indexed j.

$$GFD_{jt} = 365 * N_t * C_t * S_j.$$

For C_t, daily caloric intake per person, we consider two scenarios. "Current Consumption" scenario (CC) assumes that there is a global convergence in both average daily calories consumed per individual and food group breakdown to the 2020 OECD90+EU numbers. In other words, for OECD90+EU the overall calories per individual and food group breakdown remain unchanged between 2020 and 2050, while for the other regions the calories per individual and breakdown by food source converge to the same numbers as for OECD90+EU. Overall, this means that globally the global caloric intake per person per day increases from 3220 kcal in 2020 to 3515 kcal in 2050. Alternatively, we consider the EAT Lancet "Healthy Diet" (HD) scenario, linearly decreasing per person caloric intake to 2500 per person by 2050 across all regions.(20)(45). We construct trends for shares to converge by 2050 to upper limits for animal-source food products (eggs, dairy, meat) recommended by EAT Lancet. We also use these two scenarios for the shares of food sources S_j. While CC scenario is consistent with commonly accepted projections corresponding to the second most optimistic scenario of the Share Socio-Economic Pathways (SSP2), total growth in caloric demand is lower under HD.(46)

Global caloric demand is the product of global population projections and per-person caloric intake for each food group. The global population is from the United Nation's projections for medium fertility and constant mortality scenarios (published by the Department of Economic and Social Affairs) and grows to 9.71 billion in 2050 and is evaluated as of July 1 for each year.

In 2020, around 82% of the protein demand globally was met by plants. animal-source meat provides 8%, dairy provides 7%, and fish provides 1% of the global caloric requirements. Overall consumption of alternative animal-source foods is negligible in 2020. However, as alternatives to animal-source foods start achieving parity in terms of taste, texture, and price with animal-source foods, their consumption is likely to grow.

3.2 Two scenarios for the shift to alternatives to animal-source foods

Next, to model the projected shift in consumption from animal-source foods to alternative sources, we develop a model of consumer adoption for each alternative meat category, plant-based eggs, plant-based milk and dairy, plant-based meat, and cultured meat.

We model the shift from animal-source foods to alternative protein sources from the initial market share of alternatives observed in 2020 to 100% by 2050.[2] To model transition dynamics, we rely on the Gompertz adoption model, which is commonly used for modeling new product adoption dynamics.(31)(32)(33)(34)

Gompertz adoption model allows us to create scenarios for alternative sources replacing animal-source foods:

$$S_{altj,t} = S_{altj,2020} + FA * \mathrm{e}^{-\mathrm{e}^{(-\alpha_j(t_j-(t^*+\delta t^*)))}},$$

[2]This is a baseline assumption that simplifies our calculations. Our baseline results, therefore, should be viewed as the best possible case for alternative proteins. In the sensitivity analysis, we also show the results for an ultimate market share of 50%.

where $S_{altj,t}$ is the share of food type j substituted for an alternative in year t, $S_{altj,2020}$ is such share observed in 2020, 1 represents the asymptote of full substitution, α_j is the speed of adoption, t_j^* is the year when alternative source achieves perceived taste, texture, other attributes, and price parity (we refer to it as "equivalency point"), and δt^* is the delay between equivalency point and the take-off of consumer adoption that might be due to needs for marketing, production increase, and market penetration.

Since alternative foods are still an emergent product and technology, we rely on previous technology adoption experience to calibrate the speed of adoption α_j of an alternative for each product category. In particular, we rely on observed adoption speed for recently matured sustainable technologies in energy generation, wind and solar.(31) We choose the following values for our benchmark scenario: $\alpha_{alt.meat} = 0.18$, $\alpha_{alt.dairy} = 0.73$, $\alpha_{alt.egg} = 0.46$, which are the lowest, highest, and average adoption rates for solar and wind technology. We set $\delta t^* = 3$. We set equivalency point $t^*_{alt.meat} = 2028$, $t^*_{alt.dairy} = 2023$ $t^*_{egg} = 2025$. We set the current market share for al alternative products to 2%.

Currently, there are two main types of technologies for producing analogs to animal-source foods: plant-based alternatives, which are broadly available in some countries for a number of animal-source product categories, and "high-tech" alternatives that include cultured alternatives (also known as cultivated alternatives or cellular agriculture), which focus primarily on meat products, and precision fermentation and molecular farming, targeting meat as well as dairy products.(47) Some precision fermentation products are available with very limited distribution, while cultured alternatives are not generally available.

For our scenario building, we combine all high-tech alternatives into one group — "cultured" alternatives, because of their similar impact on GHG emissions.(16)(17) We keep plant-based technologies separate. For our analysis, we construct two scenarios for the composition of alternatives to animal food sources: rapid shift to cultured (RS) scenario, which is based on projections in which consumer adoption of cultured products starts in 2026 and reaches two-thirds of the alternative meat market by 2050;(48) mostly plant-based (PB) scenario, instead, keeps the share of plant-based alternatives at 100% until 2033 and then assumes a quarter of an annual rate of increase of cultured alternatives in RS scenario, achieving the 100% substitution of animal-source foods through larger production of plant-based alternatives than in RS scenario.

3.3 GHG emissions by food group

We estimate the total reduction in annual GHG emissions from food consumption due to the introduction of alternative protein sources, based on adoption scenarios and emissions factors per food source.

To translate food demand to emissions impact, we compute the emissions factors in terms of CO2e GHGs per 1000 Kcal or per 100g of protein for each type of food (e.g. grains within plants).(21)

Using these factors for individual food items within each food source category, we aggregate them to the food source level as a weighted average to derive total category emissions factors. We then aggregate emissions by food source as a weighted average to compute total emissions from food consumption.

To translate food demand to emissions impact, we compute the emissions factors in terms of CO2e GHGs per 1000 Kcal or per 100g of protein for each type of food (e.g. grains within plants),(21). Using these factors for individual food items within each food source category, we aggregate them to the food source level as a weighted average to derive total category emissions factors reported in Table 1. We then aggregate emissions by food source as a weighted average to compute total emissions from food consumption. For the GHG emissions from plant-based alternatives to egg, dairy, and meat, we compute a weighted average of plants that are ingredients in such alternatives. Implicitly, this assumes clean energy sources for food processing up to the stage that is equivalent to animal-source foods. For cultured alternatives, we use mid-range values of GHG emissions per 100 Kcal.(49) This value of GHG emissions is higher than projected in recent LCA reports by cultivated meat companies.

Table 1: GHG Emissions by Food Source (Gt CO2e)

	Sugar	Oils & fats	Fruits & vegetables	Starchy roots	Pulses	Cereals & grains	ASFs				Plant-based			Cultured
							Eggs	Dairy	Meat	Fish	Eggs	Dairy	Meat/Fish	Meat/Fish
per 100g protein	0	0	5.4	7.2	0.6	3.5	4.2	9.7	13.6	7.2	1.6	1.8	1.6	2.5
per 1000 kcal	0.7	0.5	1.2	1.0	0.4	0.8	3.2	5.4	9.9	9.5	0.7	0.7	0.8	1.2

Notes: CO2e GHG emissions per 1000 Kcal or per 100g of protein for each food source.(21) (49)

We use two scenarios for the substitution of animal-source foods with alternatives. The first one is a caloric-equivalent (CE) scenario with GHG emissions based on substituting alternatives for animal-source foods 1-to-1 in terms of total calories. The second one is the protein-equivalent (PE) scenario. While protein can be obtained from a variety of plants, a common perception is that animal-source foods are an important source of protein. Indeed, the ratio of protein to calories in animal-source foods is generally higher than that of plants, even though some novel plant-based alternatives to ASFs have higher protein per calorie ratio than ASFs they are replicating. To reflect this, we convert GHG emissions per Kcal to GHG emissions per gram of protein and keep the total protein consumption in the alternative sources scenarios to be the same as in business-as-usual scenarios. This results in a higher amount of alternatives in total consumption compared to the caloric equivalent model.

3.4 Carbon budget assumptions

There is a wide variety of estimates of the total carbon budget remaining to achieve 1.5°C with a probability of 66% or 50% .(50) Given limited progress on emission mitigation, we are looking at the 2-degree goal instead.

Our ultimate question is how much GHG emission savings from the food system can we achieve by substituting ASFs with alternatives. It is best to answer this question in the context of the total carbon budget available to the food system. This number relies on two assumptions with a high degree of uncertainty: the exact magnitude of the impact of GHG concentration on temperature change is fundamentally uncertain; transition paths of other emission sources, especially energy and transportation are subject to multiple sources of uncertainty. With this in mind, we invite the reader to use their own preferred estimate for the carbon budget that we can allocate to the food system in the coming decades. Our preferred estimate is 390 GtCO2e which corresponds to a third of the total GHG budget of 1170 GtCO2e which we take from IPCC6. This is the budget to contain global warming to 2 degrees C with 67% probability. We extrapolate the estimate that in 2015 food system contributed 34% to the GHG emissions to arrive at the food sector budget of 390 GtCO2e.(2) While the CO2 budget is usually reported between 2020 and 2100, most of the paths underlying the calculations have net zero achieved by 2050 followed by net negative emissions. Thus, we allocate all the budget between 2020 and 2050.

4 Data availability

Calculations for the projections in this analysis are conducted in Python and Excel are shared at Figshare

`https://doi.org/10.6084/m9.figshare.22120541`

The shared file includes all the data inputs and formulas as well as links to data sources.

5 Code availability

All calculations for the projections in this analysis are conducted in Python Excel that is shared at Figshare

`https://doi.org/10.6084/m9.figshare.22120541`

The shared file includes all formulas.

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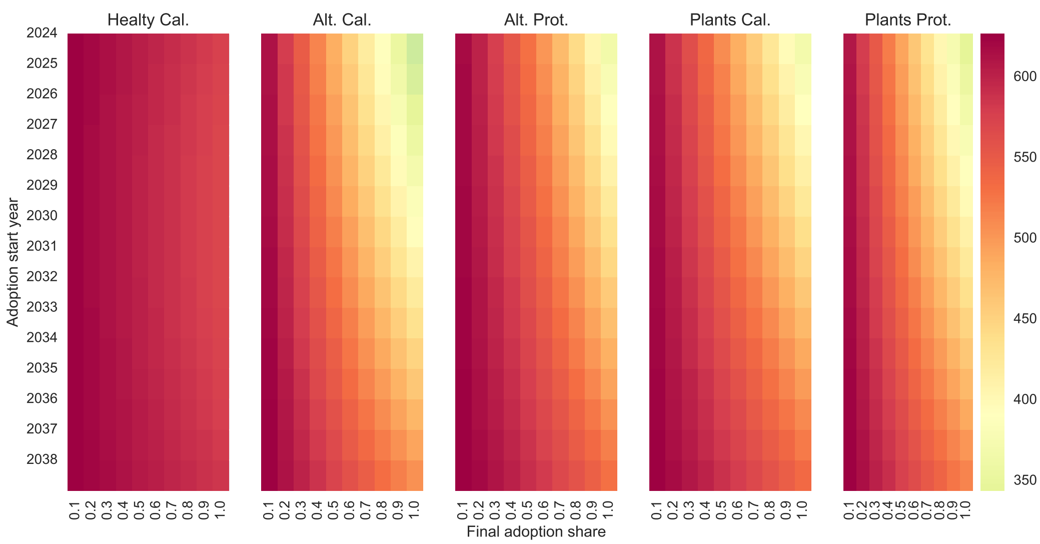
6 Supplement: Sensitivity to assumptions

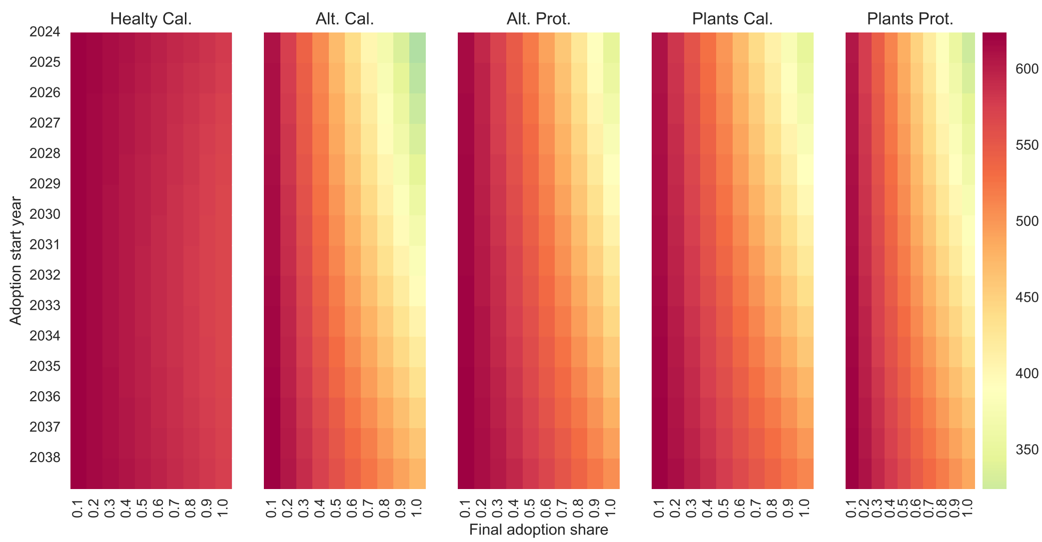
Our results do not change substantially when we use different assumptions on the delay in mass adoption (from 0 years in Figure 5 to 2 years) and when we shift from the mostly plant-based alternatives to ASFs to rapid adoption of cultured alternatives. Figures 6- 8 demonstrate calculations for extreme values of these assumptions relative to benchmark reported. The share of cultured alternatives does not make much impact on the calculations due to similar emissions from plant-based and cultured alternatives to ASFs. Delay in adoption has a linear impact on the calculation, which each delay year corresponding to a shift of the equivalency point by one year.

Figure 6: Cumulative emissions in different scenarios as a function of final adoption share and equivalency point: 2-year delay



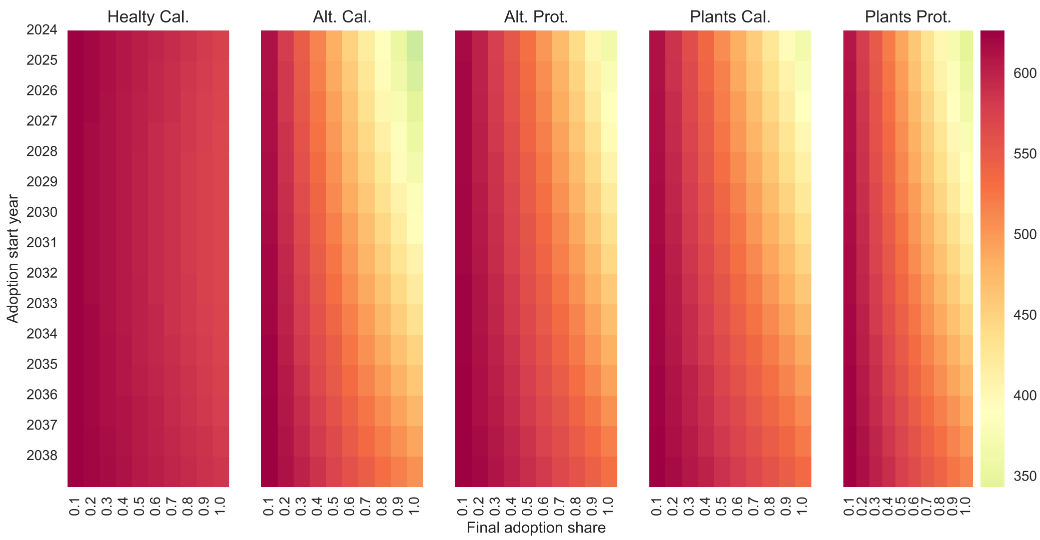
Cumulative emissions are computed for 2020-2050 time period. Healty Cal. is the convergency to EAT-Lancet diets globally. Alt. Cal. is replacement of ASFs with alternatives to match caloric value; Alt. Prot. is replacement of ASFs with alternatives to match total protein demand of BAU scenario. Plants Cal. is replacement of ASFs with plants to match caloric value; Plants Prot. is replacement of ASFs with plants to match protein demand in BAU scenario. Adoption start year corresponds to equivalency point in Gompertz curves model. Scenario plotted is based on adoption delay δ of 2 years and slow introduction of cultured alternatives to ASFs to allow for various adoption barriers (36). Final adoption share is the 2050 target. Healthy Diets transition is assumed to have fast transition parameter $\alpha_{HD} = 0.73$, while transition to plant-only diet is assumed to be slow with $\alpha_{Plants} = 0.18$ (37; 38; 39). The center color of the color bar is set to 390 GtCO2e, estimated emission budget for the food industry and is the same across panels.

Figure 7: Cumulative emissions in different scenarios as a function of final adoption share and equivalency point: rapid shift to cultured alternatives



Cumulative emissions are computed for 2020-2050 time period. Healty Cal. is the convergency to EAT-Lancet diets globally. Alt. Cal. is replacement of ASFs with alternatives to match caloric value; Alt. Prot. is replacement of ASFs with alternatives to match total protein demand of BAU scenario. Plants Cal. is replacement of ASFs with plants to match caloric value; Plants Prot. is replacement of APSs with plants to match protein demand in BAU scenario. Adoption start year corresponds to equivalency point in Gompertz curves model. Scenario plotted is based on no adoption delay and fast introduction of cultured alternatives to ASFs to allow for various adoption barriers (36). Final adoption share is the 2050 target. Healthy Diets transition is assumed to have fast transition parameter $\alpha_{HD} = 0.73$, while transition to plant-only diet is assumed to be slow with $\alpha_{Plants} = 0.18$ (37; 38; 39). The center color of the color bar is set to 390 GtCO2e, estimated emission budget for the food industry and is the same across panels.

Figure 8: Cumulative emissions in different scenarios as a function of final adoption share and equivalency point: 2-year delay and rapid shift to cultured alternatives



Cumulative emissions are computed for 2020-2050 time period. Healty Cal. is the convergency to EAT-Lancet diets globally. Alt. Cal. is replacement of ASFs with alternatives to match caloric value; Alt. Prot. is replacement of ASFs with alternatives to match total protein demand of BAU scenario. Plants Cal. is replacement of ASFs with plants to match caloric value; Plants Prot. is replacement of ASFs with plants to match protein demand in BAU scenario. Adoption start year corresponds to equivalency point in Gompertz curves model. Scenario plotted is based on adoption delay δ of 2 years and fast introduction of cultured alternatives to ASFs to allow for various adoption barriers (36). Final adoption share is the 2050 target. Healthy Diets transition is assumed to have fast transition parameter $\alpha_{HD} = 0.73$, while transition to plant-only diet is assumed to be slow with $\alpha_{Plants} = 0.18$ (37; 38; 39). The center color of the color bar is set to 390 GtCO2e, estimated emission budget for the food industry and is the same across panels.