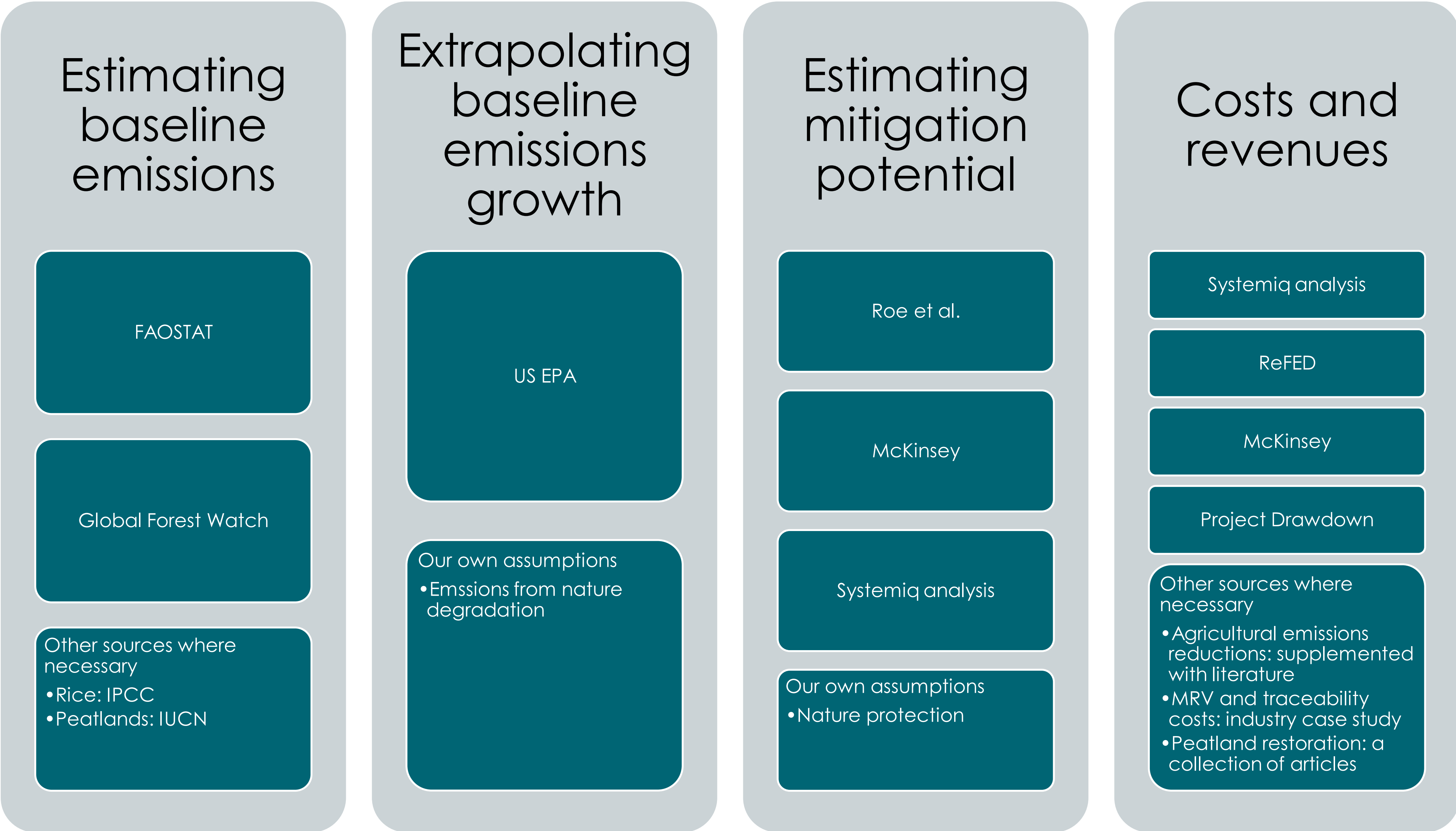
Future Fit Food and Agriculture: Technical Appendix

Contents

This Technical Appendix accompanies the Future Fit Food and Agriculture report series, co-authored by FOLU, WBCSD and We Mean Business. The analysis behind the series is all derived from the same model. The steps of how the model was built are laid out below in their simplest form in Figure 1. The following chapters will expand upon the analysis that makes up each step.

Figure **1**: Model map outlining the key steps and sources used in the modelling for the Future Fit Food and Agriculture reports. The model works through the steps below from left to right. There are 37 agricultural solutions, 2 solutions to protect nature and 38 demand-side solutions. The Future Fit reports recognise that this set of solutions is not exhaustive but are priority solutions for food and agriculture companies to implement to mitigate the majority of their agriculture and land-use change emissions.



1. Estimating baseline emissions

Land based emissions within food and agriculture value chains

The first step was to calculate food and agriculture emissions in 2020, which was chosen as a common, relatively recent date for which comprehensive data could be obtained. Several assumptions were made to estimate the agricultural and land use change emissions (summarized as land-based emissions) that fall within and outside of food and agriculture value chains. Table 1 provides a summary of the relevant information and assumptions made per emission category.

Data sources

First, most emission sources were estimated using data from the Food and Agriculture Organization (FAO). FAOSTAT 'Emissions Totals' provides data on a range of on-farm and land use change emissions sources per year and by country.

To estimate emissions from forest loss the authors used Global Forest Watch (GFW) and Curtis et al. (2018). GFW provide gross deforestation emissions rather than the net emissions given by FAOSTAT, and helpfully, GFW provide data on emissions from deforestation by country, by year. These were then combined with the regional drivers of deforestation from Curtis et al[1] to estimate deforestation emissions by country, year and driver. The five identified drivers of deforestation are:

- Commodity-driven deforestation – Large-scale deforestation linked primarily to commercial agricultural expansion.
- Shifting agriculture – Temporary loss or permanent deforestation due to small- and medium-scale agriculture.
- Forestry – Temporary loss from plantation and natural forest harvesting, with some deforestation of primary forests.
- Wildfire – Temporary loss, does not include fire clearing for agriculture.
- Urbanization – Deforestation for expansion of urban centres.

Given the relatively low net emissions from peatland degradation in FAOSTAT, data from the International Union for Conservation of Nature (IUCN) published in 2021 was used to estimate peatland emissions.[2] Whilst the IUCN Issues Brief does not specify the year of these emissions, we took these as a proxy for annual peatland degradation emissions.

Similar to emissions from peatland degradation, FAOSTAT's rice cultivation emissions appeared to be low in comparison to other credible sources. Emissions from rice cultivation were therefore estimated using data from the Intergovernmental Panel on Climate Change

(IPCC)'s Working Group 3 contribution the Sixth Assessment Report (2021).[3] According to the IPCC (2021), rice cultivation emissions contributed to 8% of total AFOLU emissions in 2019, which equals approximately 1Gt CO_2e. Similarly, analysis from the Global Environmental Facility (GEF) in 2019 suggests that methane emissions from rice cultivation were 12% of global methane emissions, which corresponded to approximately 1Gt CO_2e. For the purposes of our analysis, we assumed that rice cultivation emissions in 2020 were similar to the IPCC estimate for 2019.

Estimating land-based emissions within food and agriculture value chains

This analysis looks at land-based emissions (i.e. emissions that occur before the farm gate or are caused by land use change) that occur within the value chains of food and agriculture companies. For each emission category, assumptions were made to calculate the percentage of emissions that are attributable to the formal food and agriculture sector. The informal food sector relates to production of food for subsistence or for sale in the informal economy.[4] This never enters company value chains, which instead is considered part of the formal economy and the focus of our work.

Estimating land-based emissions within food and agriculture value chains - Nature degradation

Deforestation: we assumed that emissions from commodity-deforestation, defined as *large-scale deforestation linked primarily to commercial agricultural expansion,*[5] sit within formal food and agriculture value chains, while deforestation emissions from shifting agriculture, defined as *temporary loss or permanent deforestation due to small- and medium-scale agriculture*,[6] sit outside of formal value chains but still contribute to food system emissions. Other drivers of deforestation were considered outside of food systems.

Peatland degradation: whilst it was not possible to derive the exact percentage of peatland degradation that is not caused by agriculture, agricultural expansion forms the main driver of peatland degradation.[7] Therefore, it was assumed that all emissions from peatland degradation sit within food and agriculture value chains.

Estimating land-based emissions within food and agriculture value chains – On-farm production

To estimate the share of emissions from on-farm production that are attributable to the formal food and agriculture sector it was necessary to consider what share of production can be classified as subsistence farming or destined to be exchanged in the informal economy. The Consultative Group for International Agricultural Research (CGIAR)'s Research Programme on Climate Change, Agriculture and Food Security estimated that smallholder farms (<2ha) globally are responsible for 32% of emissions from the agriculture sector.[8] This estimate was fact checked using existing Food and Land Use (FOLU) analysis on Nature-based Solutions for

Kenya,[9] Colombia[10] and India.[11] From this analysis we find that globally 73% of agricultural production sits within formal company value chains, which is close to the CGIAR's estimate of 68%. Table 1 outlines the description, sources and assumptions used to estimate land-based emissions within food and agriculture value chains, broken down by source of emissions.

Table 1: Emission sources within food and agriculture value chains in India, Kenya and Colombia

Emission category	**Description and assumptions made**	**Total emissions (Gt)**	**Percentage within food and agriculture value chain**	**Land based emissions within formal value chains (Gt)**	**Data sources**
Enteric fermentation	Emissions from enteric fermentation, manure management, manure left on pasture and manure applied to soils, manure left on pasture, manure applied to soils and fertilizer use in 2020 were taken from FAOSTAT's FAOSTAT's 'Climate Change: Agrifood systems emissions'.	2.9	59%	1.7	FAOSTAT 'Climate Change: Agrifood systems emissions: Emissions totals' (2023)
Manure management, manure left on pasture and manure applied to soils		1.3	84%	1.1	
Fertilizer use		0.6	76%	0.5	
Forest loss emissions: commodity-driven deforestation	Deforestation emissions in 2020 per country were taken from Global Forest Watch and combined with drivers of forest loss per region from Curtis et al. (2018). The sum of country's gross emissions from forest loss multiplied by the regional percentage of forest loss that is commodity-driven was taken for 2020.	3.1	100%	3.1	Global Forest Watch (2023); Curtis et al. (2018)
Forest loss emissions: shifting agriculture	The sum of country's gross emissions from forest loss in 2020 was multiplied by the regional percentage of forest loss that is driven by shifting agriculture.	3.3	0%	0	
Forest loss emissions: forestry	Taking a similar approach, the sum of country's gross	2.8	0%	0	

	emissions from forest loss in 2020 was multiplied by the regional percentage of forest loss that is driven by forestry.				
Forest loss emissions: urbanization and wildfires	Taking a similar approach, the sum of country's gross emissions from forest loss in 2020 was multiplied by the regional percentage of forest loss that is driven by shifting agriculture, urbanization or wildfires.	1.8	0%	0	
Peatland degradation	Emissions from drained peatlands in 2020 were estimated using an estimate of yearly peatland emissions from IUCN (2021).	1.9	100%	1.9	IUCN (2021)
Rice cultivation	Emissions from rice cultivation in 2020 were based on the Intergovernmental Panel on Climate Change (IPCC)'s Working Group III Report.	1	75%	0.8	IPCC (2022)
Crop residues	Emissions categorized as 'other' include emissions from crop residues, burning crop residues and savanna fires, and were taken from FAOSTAT's 'Climate Change: Agrifood systems emissions'.	0.5	100%	0.5	FAOSTAT 'Climate Change: Agrifood systems emissions: Emissions totals' (2023)
Burning crop residues					
Savanna fires					

Estimating emissions per commodity within food and agriculture value chains

Box 1 in 'Future Fit Food and Agriculture: The financial implications of mitigating agriculture and land use change emissions for businesses' highlights six production and consumption hotspots. This section outlines how we estimated these key priority areas.

Beef

Estimating beef related deforestation emissions

- *Brazil*: Pendrill et al. (2019)[12] breaks down commodity-driven deforestation emissions per country and commodity. From that we estimate that 65% of commodity-driven deforestation emissions in Brazil are related to beef production. This percentage was multiplied by total commodity-driven deforestation emissions from Brazil based on data from Global Forest Watch (2023) and Curtis et al. (2018).
- *Other countries*: Similarly, using Pendril et al. (2019) we find that 24% of commodity-driven deforestation emissions in countries other than Brazil are related to beef production. Again, this percentage was multiplied by total commodity-driven deforestation from Global Forest Watch (2023) in all other countries.

Estimating beef related emissions from enteric fermentation, manure management, manure left on pasture and manure applied to soils

Emissions from enteric fermentation and manure management, manure left on pasture and manure applied to soils were taken from FAOSTAT's Emissions from Livestock[13] database. This database separates emissions from enteric fermentation and manure management, manure left on pasture and manure applied to soils by commodity and country. As discussed before, only emissions within formal food and agriculture company value chains were considered.

Estimating 'other' emissions from beef production

Other emissions include emissions from feed. According to Poore & Nemecek (2018), feed emissions from beef production are 155 $MtCO_2e$. FAO's[14] global assessment of emissions and mitigation opportunities offers an overview of emission categories that contribute to beef emissions, including feed related emissions. According to the FAO's assessment, feed emissions contribute to 35% of global emissions from beef supply chains. Nearly 30% of this 35% is driven by energy-related on-farm emissions and we have excluded these energy-related emissions from our analysis. This component of feed emissions was thus excluded from Poore & Nemecek's 155 $MtCO_2e$ of feed emissions. This results in a remaining 111 $MtCO_2e$ of feed emissions, primarily from the production of maize and soybean.

Dairy

Estimating dairy related deforestation emissions

- *Brazil:* According to a study from Chain Reaction Research,[15] up to 80% of deforestation in the Brazilian Amazon is caused by cattle pasture. Further to this, Pendrill et al. (2020) estimate that 65% of deforestation emissions in Brazil originate from beef production. We assumed that the remaining 15% of commodity-driven deforestation emissions caused by cattle pasture in Brazil originate from dairy production. This percentage was multiplied by total commodity-driven deforestation emissions from Brazil.

- *Deforestation emissions from countries other than Brazil*: Based on data from Poore & Nemecek (2018), we estimate that land use change emissions from dairy production are 342 $MtCO_2e$ per year. By excluding the emissions from dairy production in Brazil (calculated above), we estimate that the remaining deforestation emissions from dairy production amount to 174 $MtCO_2e$.

Estimating dairy related emissions from enteric fermentation and manure management, manure left on pasture and manure applied to soils

As before, emissions from enteric fermentation and manure management, manure left on pasture and manure applied to soils were taken from FAOSTAT's Emissions from Livestock[16] database.

Estimating 'other' emissions from dairy production

- *Feed*: Using the same methodology outlined in section 1.2.1.3 above, we exclude energy-related emissions from feed production. Thus, amending Poore & Nemecek's 168 $MtCO_2e$ of feed-related dairy emissions we are left with 116 $MtCO_2e$ of feed emissions.

Rice

Estimating rice cultivation emissions

- *China*: As previously highlighted, we assumed FAOSTAT rice cultivation emissions are an underestimate. Therefore, we used alternative sources for country-specific rice cultivation emissions. Rice cultivation emissions from China are estimated at 219 $MtCO_2e$, taken from Liang et al. (2021).[17] This estimate was then multiplied by the relevant percentage from Table 1 to estimate the emissions that sit within formal company value chains.
- *India*: Climate TRACE[18] estimates rice cultivation emissions from India to be 213 $MtCO_2e$ per year. We multiplied this figure by the relevant percentage from Table 1 to estimate the emissions that sit within formal company value chains.
- *Other countries*: According to the IPCC's Working Group III Contribution to the Sixth Assessment Report (2022),[19] methane emissions from rice cultivation contribute to 8% of Agriculture, Forestry and Land Use (AFOLU) emissions, or 1.7% of global total emissions (59 $GtCO_2e$). Taking the average of these two estimates, total rice cultivation emissions are estimated at 1.02 $GtCO_2e$. Subtracting rice cultivation emissions from China and India from this total estimate, and correcting for subsistence farming based on Table 1, allows us to estimate rice cultivation emissions from countries other than China and India.

Estimating emissions from fertilizer use related to rice production

Nitrogen fertilizer emissions from rice production are approximately 11% of global agricultural CH_4 emissions Gupta et al. (2021).[20] Using data from the World Bank (2023),[21] 11% of 2.23 $GtCO_2e$

is 250 $MtCO_2e$. This estimate was then corrected using Table 1 to estimate emissions within formal company value chains.

Estimating 'other' emissions from rice production

Using data from Poore & Nemecek (2018), on-farm emissions from rice can be estimated at 1.46 $GtCO_2e$. Other emissions are therefore the remaining emissions from this 1.46 $GtCO_2e$ that aren't captured by any of the other emission sources for rice.

Palm oil

Estimating palm oil related deforestation emissions

- *Indonesia and Malaysia*: Using data from Pendrill et al. (2020), 48% of Indonesia commodity-related deforestation emissions are attributable to palm oil. This percentage was multiplied by total commodity-driven deforestation emissions from Indonesia based on data from Global Forest Watch (2023). We used the same approach for Malaysia.
- *Other countries*: According to data from Pendrill et al. (2020), 14.3% of commodity-driven deforestation emissions can be traced back to palm oil production. Subtracting the estimates from Indonesia and Malaysia, this results in 187 $MtCO_2e$.

Estimating palm oil related emission from peatland degradation

- *Indonesia*: We estimated total emissions from peatland degradation in Indonesia to be 520 $MtCO_2e$ (Systemiq Analysis). This number is close to the estimate published by the Global Green Institute, who approximate that 40% of total greenhouse gas emissions from Indonesia are caused by peatland degradation.[22] Using data from Pendrill et al. (2020), we estimated that 40% of these emissions are caused by palm oil production.
- *Malaysia*: According to Cooper et al. (2020),[23] between 16.6% and 27.9% of total GHG emissions in Malaysia are caused by peatland degradation. Taking the average (22.3%), this results into 58 $MtCO_2e$ emissions from peatland degradation. Using data from Pendrill et al. (2020), we estimated that 67% of these emissions can be traced back to palm oil production.
- *Other countries*: Based on data from Pendrill et al. (2020), we assumed that Indonesia's palm oil driven peatland emissions account for 43% of commodity-driven peatland degradation emissions from palm oil. Using this statistic, we were able to estimate palm oil related emissions from peatland degradation in other countries (excluding Indonesia and Malaysia).

Chicken, eggs and pork

Estimating emissions from deforestation related to chicken, eggs and pork production

Poore & Nemecek (2018) gives an estimate for land use change emissions attributable to chicken, eggs and pork production. Considering that gross deforestation emissions were used in this paper as opposed to net deforestation emissions, we increased these estimates by

70.2% to account for larger gross deforestation emissions. The 70.2% is based on comparing total commodity-driven deforestation emissions from Pendrill et al. (2020) to total (gross) commodity-driven deforestation emissions in 2020 from Global Forest Watch (2023).

Estimating 'other' emissions from chicken, eggs and pork production

According to Poore & Nemecek (2018), feed emissions from chicken and egg production are 314 MtCO_2e. Using FAO (2013)'s global assessment of emissions and mitigation opportunities, 47% of feed emissions are caused by on-farm energy use. Excluding these emissions, feed emissions can be estimated at 172 MtCO_2e. The same approach was used to estimate feed emissions from pork production.

Estimating emissions from manure management, manure left on pasture and manure applied to soils related to chicken, eggs and pork production

As before, emissions from enteric fermentation and manure management, manure left on pasture and manure applied to soils were taken from FAOSTAT's Emissions from Livestock[24] database.

Wheat and maize

Estimating wheat and maize related land use change emissions

Land use change emission from wheat and maize were taken from Poore & Nemecek (2018). These estimates may incorporate emissions from on-farm practices such as tillage and may therefore be a slight overestimate of land use change when compared to alternative estimations of LUC emissions from wheat/maize presented in World Wildlife (2022).[25]

Estimating wheat and maize related emissions from fertilizer use

The International Fertilizer Association (2023)[26] provides data on fertilizer use by crop and by country. It was assumed that fertilizer emissions are proportional to fertilizer use. Accordingly, the percentages of fertilizer use for wheat and maize by country were multiplied by emissions from fertilizer use by country, available from FAOSTAT (2023). Similarly, emissions from fertilizer use from wheat and maize at a global level were calculated by multiplying the global fertilizer use by crop from The International Fertilizer Association (2023) with total fertilizer emissions from FAOSTAT (2023).

Estimating 'other' wheat and maize related emissions

On-farm emissions mainly originate from crop residue, organic fertilizer, and drying & grading. Following Poore & Nemecek (2018), on-farm emissions from wheat and maize production are 426 $MtCO_2e$ and 177 $MtCO_2e$ respectively. Using analysis from World Wildlife Fund (2022),[27] approximately one third of these emissions were categorized as emissions from input production and electricity, and these were therefore subtracted from the on-farm emissions. This resulted in 284 $MtCO_2e$ and 149 $MtCO_2e$ of on-farm emissions for wheat and maize respectively. Subsequently, fertilizer emissions from wheat and maize production were subtracted from these estimates to calculate the remaining farm emissions.

Soy

Estimating soy related deforestation emissions

Using data from Poore & Nemecek (2018), land use change emissions from applied soy products (soybean oil, soymilk and tofu) equal 139 $MtCO_2e$. Increasing this by 70.2% based on comparing total commodity-driven deforestation emissions from Pendrill et al. (2020) to total (gross) commodity-driven deforestation emissions in 2020 from Global Forest Watch (2023) leads to an estimated 237 $MtCO_2e$ of emissions. Using Pendrill et al. (2020), we estimate that two-thirds of those emissions originate from Brazil and one-third from other countries.

Estimating 'other' soy related emissions

Following Poore & Nemecek (2018), on-farm emissions from applied soy products are 69 $MtCO_2e$. Based on World Wildlife Fund (2022),[28] we estimate that 30% of those emissions originate from electricity/diesel. The remaining on-farm emission are therefore 48 $MtCO_2e$. On-farm emissions from applied soy products primarily originate from fertilizer use and crop residue.

Table 2: Emissions split by commodity, country and source of emissions

Commodity	Geography	Enteric Fermentation	Deforestation	Manure	Fertilizer	Rice Cultivation	Peatland Degradation	Other
Beef	Brazil	187	726	73				
Beef	USA	74	-	35				
Beef	China	38	-	20				
Beef	India	64	-	18				
Beef	Other	547	487	286				111
Dairy	USA	20	-	16				
Dairy	India	149	-	53				

Dairy	Brazil	21	168	7				
Dairy	China	38	–	19				
Dairy	Pakistan	51	–	18				
Dairy	Other	204	174	115				116
Rice	China				190	164		
Rice	India					160		
Rice	Other					442		
Pork	China			35				
Pork	USA			23				
Pork	EU			26				
Pork	Other		296	58				143
Soy	Brazil		158					
Soy	Other		79					48
Palm oil	Indonesia		254				201	
Palm oil	Malaysia		38				39	
Palm oil	Other		187		76		227	
Wheat	China				17			
Wheat	India				17			
Wheat	Other		50		51			171
Maize	US				24			
Maize	China				25			
Maize	Other		117		46			24
Chicken & Eggs	China			19				
Chicken & Eggs	Brazil			5				
Chicken & Eggs	USA			7				
Chicken & Eggs	Other		498	66				172

Estimating emissions from the consumption of commodities

The last piece in the hotspot analysis in the second report of this series was to look at where consumption of specific commodities related could be linked to particular hotspots. For this, data was taken from FAOSTAT's 'Food Balances'. For each commodity, the domestic supply quantity was considered as a proxy for consumption. The domestic supply quantity is defined as 'production + imports- exports + changes in stocks (decrease or increase). Consequently, percentages of global commodity consumption per key country or geography were estimated using the domestic supply quantities. These percentages were multiplied by the emissions per commodity presented in Table 2 to get to the estimated consumption commodity emissions hotspots.

2. Extrapolating baseline emissions growth

The next step in the model is to estimate what emissions will be in the future in a Business-As-Usual (BAU) scenario. Several assumptions were made to extrapolate emissions from 2020 to 2030.

Extrapolating on-farm emissions

To estimate how all agricultural on-farm emissions grow from 2020 to 2030 (e.g. from livestock, rice and other crops), estimates from a study by the United States Environmental Protection Agency (EPA) (2019)[29] were used. The EPA uses "globally available growth rate or activity data specific to each source" to estimate emissions growth until 2050. The EPA's growth rates in emissions take into account projected increases in production and consumption, as well as the area used for crops or livestock. The EPA focuses on non-CO_2 emissions (i.e. N_2O and CH_4), which for on-farm emissions are the most relevant emission sources (e.g. methane emissions from rice cultivation and enteric fermentation, nitroxide emissions from fertilizer use).

Extrapolating emissions from conversion of natural ecosystems

For emissions from the conversion of natural ecosystems (deforestation and peatland degradation) we assumed that emissions would remain constant in the BAU scenario, not changing from the 2020 baseline.

3. Mitigation potential, costs, cost-savings and revenues

To estimate the mitigation potential, as well as the costs, costs-savings and revenues of food and land-use mitigation solutions, the authors drew on a number of sources.

First, to determine the mitigation potential we identified what change in practice is relevant to address key emissions sources. Then we needed to determine the abatement or sequestration potential of that solution and the extent to which that solution can be applied and how quickly. Second, the area of incremental implementation and/or the mitigation potential was used to understand the costs, cost-savings and revenues that can be obtained through implementing the solution. For each solution, these financial estimates were calculated either based on a cost, cost-saving or revenue per tCO_2e or per hectare implemented. The full list of solutions are outlined in Table 6, along with the sources used for their mitigation potential. Similarly, all sources used to estimate the costs, cost savings and revenues for different mitigation solutions are summarized in Table 7.

Data sources

A combination of sources was used to determine the mitigation potential, costs, cost-savings and revenues for different solutions in this paper. These include Roe et al. (2019)[30] and Roe et al. (2021),[31] McKinsey (2023)[32] and McKinsey (2020)[33], Project Drawdown[34] and variety of other sources. For carbon sequestration solutions, mitigation potential was taken from Roe et al. (2019) and Roe et al. (2021). These two papers estimate the mitigation potential from several land based measures between 2020 and 2050. Whilst Roe et al. (2019) and (2021) are credible sources, there are some challenges with exclusively relying on this data that encouraged us to seek alternative sources to augment the analyses in this series of papers. First, whilst Roe et al. (2019) and (2021) provide a credible, clear overview of land based mitigation potential between 2020 and 2050, the data presented is not granular enough to understand how several levers contribute to the mitigation potential of each solution. For example, though they provide an estimate of enteric fermentation mitigation potential between 2020 and 2050, it does not offer understanding on the various levers (e.g. feed additives versus improved genetic stock selection) that contribute to reduced enteric fermentation. Second, the assumptions used about ending nature degradation in Roe et al. (2019) and (2021) are not in alignment with recent nature frameworks (i.e. they allow some level of land conversion to continue), and therefore lead to an underestimate of the mitigation potential from protecting natural ecosystems. Recent frameworks such as the Science Based Targets Initiative (SBTi) and Science Based Targets Network (SBTN) call for a complete elimination of deforestation by 2025. Additionally, more than 100 global leaders pledged to end deforestation by 2030. It is therefore important to be more ambitious and demonstrate what the mitigation potential from ending nature degradation by 2030 can be. Similarly, Roe et al. assumes that emissions reductions from on-farm solutions only begin in 2030. Given the importance of emissions reductions to

2030, this was another assumption that was amended in this report. Third, Roe et al. (2019) and (2021) do not provide any estimates on costs, cost-savings and revenues for each of the mitigation solutions. Therefore, by definition, other sources needed to be considered to estimate the investment required, and potential cost-savings and revenues obtained when implementing these mitigation solutions.

On-farm solutions

On-farm emissions reductions

On-farm emissions reductions – Mitigation potential

For the following on-farm mitigation solutions: *enteric fermentation, manure management, manure left on pasture and manure applied to soils, rice cultivation, synthetic fertilizer use* McKinsey (2023) was used to calculate the mitigation potential (complemented by McKinsey (2020) as needed). These two reports provide detailed estimate of mitigation potential, as well as net costs, for 28 on-farm decarbonization levers. Comparing the McKinsey estimates to Roe et al. (2021), the McKinsey estimates are more ambitious and assume that mitigation potential can be unlocked from today, whereas Roe assumes that on-farm emissions reductions start from 2030. The McKinsey papers provide estimates of the mitigation potential of each solution based on technical mitigation potential (as a percentage of emissions) and assumptions on feasible implementation by 2050. We used the various on-farm emission reduction levers from McKinsey (2023) and McKinsey (2020) to calculate the mitigation potential of each on-farm emission reduction solution. It was assumed that feasible implementation follows a linear growth rate from 2020 to 2050. Doing so allowed us to estimate the mitigation potential between 2020 and 2030.

On-farm emissions reductions – Costs, cost-savings and revenues

For most on-farm emissions reduction solutions, McKinsey (2023) estimates were used to estimate the costs and potential cost-savings/revenues. McKinsey (2023) provides estimates per t/CO_2e per solution that, combined with the mitigation potential estimates described previously, can be used to calculate total costs or potential cost savings/revenues obtained by 2030. Importantly, McKinsey (2023) only provides a net cost or cost-saving in \$/tCO_2e per mitigation lever. This net number is therefore the product of the investment required and the potential cost-savings or revenues obtained. Thus, it was necessary to do additional literature research for each solution to understand if the net number is equal to: (a) total investment required without any potential cost-savings and/or revenues; (b) total cost-savings and/or revenues that can be obtained without any investment required; (c) the sum of costs, costs-savings and revenues that are relevant for implementing this solution. For on-farm emission reduction solutions that fall under scenario (c), additional sources needed to be considered to separate the investment required with the cost-savings and/or revenues that can be obtained. These solutions are detailed below.

Scenario (a) and (b): Using McKinsey (2023) to estimate incremental costs or cost-savings

- Animal feed mix optimization, decreased forage-to-concentrate ratio and animal feed additives. These solutions require making changes in feed processes of ruminant animals to reduce methane emissions, for which McKinsey (2023) estimates the costs of implementation. According to Hegarty et al. (2021),[35] research demonstrates that there is insufficient evidence of increased production from animal feed additives. Similarly, for animal feed mix optimization and forage-to-concentrate ratio, there is high variability in and unclear evidence of cost-savings/revenues obtained through feed mix optimization.[36]
- Heat stress management. According to Edwards-Callaway et al. (2021), providing shade can require minimal capital investments, which is why the McKinsey (2023) net number was used to estimate cost savings.
- Small and large-scale anaerobic manure digestion. The installation of small and large-scale anaerobic manure digesters can require significant capital investment and annual operation and maintenance costs. There are limited to no reported cost-savings or increases in productivity from anaerobic manure digesters.[37]
- N-inhibitors on pasture. Whilst nitrogen inhibitors on pasture can reduce nitrogen losses and improve soil health, the effects on pasture biomass yields are mixed and not significant.[38,39]
- Improved fertilization practices in rice cultivation. The total net cost estimate from McKinsey (2023) was taken as a cost estimate, provided that there is insignificant evidence of yields improvements as a result of higher sulphate content to reduce methane emissions from rice cultivation.[40]
- Improved rice paddy water management, expand adoption of dry direct seeding in rice cultivation, improve rice straw management, optimal rice varietal selection, reduced nitrogen overapplication. Evidence suggests that reducing methane emissions from rice cultivation through alternate wetting and drying, improving dry direct seeding and straw management, selecting different, more sustainable rice varieties and limiting the application of nitrogen can be done with marginal investments required [41,42,43,44]. Therefore, McKinsey (2023) net negative cost estimate was taken to calculate cost savings.
- Incorporation of cover crops. Whilst yield increases are possible with the incorporation of cover crops[45], yield declines have also been reported[46]. Given that the McKinsey (2023) cost estimate is relatively low ($10 per t/CO2) and yield evidence is inconclusive, it was assumed that the net cost estimate was not substantially affected by possible yield increase or decreases.

- Biologicals. Whilst biologicals reportedly can increase crop yields[47], the mitigation potential derived from these solution is less than 20 $MtCO_2e$ and so any effect here is marginal.
- Specialty fertilizer. The McKinsey (2023) net number is interpreted as only referring to incremental costs needed to implement based on their description of the methodology of this measure and additional research that indicates insufficient data to quantitatively assess the cost-savings from specialty fertilizers at global scale. [48]

Scenario (c). Using different sources to estimate costs, cost-savings and revenues

- GHG focussed selection and breeding. According to McKinsey (2023), the combined cost and cost-savings of implementing GHG focussed genetic selection and breeding are $0 per t/$CO_2$e. According to several authors, such as OECD (2015)[49] and Beauchemin et al. (2020)[50], the costs of implementing GHG focussed genetic selection and breeding are close to zero, given that incremental costs for artificial insemination and/or natural selection for genetic improvement should be no significant cost increase. This paper assumed that costs for GHG focussed selection & breeding are $1.7 per t/CO2e, based on Rowe et al. (2022).[51] Rowe et al. (2022) provide an estimate of the costs to implement a national breeding scheme in sheep to reduce methane emissions using actual farm gate data.
- Animal health monitoring. Similarly, McKinsey (2023) estimates the combined costs and cost-savings of improved animal health monitoring solutions at $0 per t/$CO_2$e. Therefore, additional research was performed the understand the potential costs and cost-savings associated with this solution. Defra (2015) [52] offers a comprehensive overview of 30 different measures related to animal health monitoring, as well as the volume abated (ktCO_2e), cost effectiveness (converted to $ per t/CO_2e). Using both volume abated, and costs and cost-savings in $ per t/CO2e, a weighted average of costs and cost savings for animal health monitoring measures was calculated.
- Increased livestock production efficiencies. For technologies that increase livestock production efficiencies, the cost estimate from McKinsey (2020) and the cost-savings estimate from McKinsey (2023) was used to estimate costs and cost-savings. Whilst both net estimates may include costs and cost-savings, these estimate were used in absence of more detailed sources.
- Variable rate fertilizers. Variable fertilization, according to McKinsey (2023) can be implemented at a net cost of -$64 per t/CO2e. These figures are in line with other studies.[53] According to IIASA (2015)[54], potential costs from implementing variable rate fertilizers can include an increase in costs per acre based on increased human capital needed and because of the potential to administer the incorrect amount of fertilizer. IIASA (2015) estimates the implementation costs of variable rate fertilization to be between $40 and $60 per tonne applied. For the analysis in this paper, $50 was

multiplied by 115 million tonnes of nitrogen[55] to determine the total cost of implementation. This estimate was multiplied by the feasible implementation rate to get to an annual, feasible cost estimate. Both the McKinsey and IIASA figures were then used to give a better estimate of implementation costs and savings.

On-farm sequestration

On-farm sequestration – Mitigation potential

Biochar, and soil organic carbon sequestration in croplands and grasslands

For biochar, and soil organic carbon sequestration in croplands and grasslands, a combination of Roe et al. (2019) and Roe et al. (2021) was used to determine the mitigation potential of these solutions. Roe et al. (2019) outlines the adoption rate of the 20 Natural Climate Solutions these two papers assume. This was combined with data from Roe et al. (2021) to determine how the cost-effective mitigation potential of each solution scales from 2020 to 2050.

Agroforestry

To calculate mitigation potential from agroforestry solutions, we used data from Roe et al. (2019 & 2021) and Project Drawdown (2020). First, we used Roe et al. to estimate growth of agroforestry solutions by area. Subsequently, this estimate was broken down into three agroforestry solutions, in line with Project Drawdown (2020) definitions. Project Drawdown distinguishes between three agroforestry solutions:

- Multistrata agroforestry. This is defined as a "*perennial cropping system that features layers of carbon-sequestering vegetation*."
- Silvopasture. This incorporates "*integrating trees and pasture into a single system for raising livestock*".
- Tree intercropping. This refers to "*intermingling trees and crops on agricultural land*".

For each of the solutions, Project Drawdown provides estimates for the current extent of implementation (in hectares), along with projections for potential expansion in additional areas under both a lower and higher ambition scenario. The proportions of agroforestry mitigation potential that can be achieved through each of the three solutions from Project Drawdown were applied to the total area from Roe et al. (2019 & 2021), which was translated back into mitigation potential to arrive at mitigation potential per agroforestry solution. This provides more granularity than the overall mitigation potential estimate from Roe et al. (2019) & (2021) and allows us to estimate the costs, cost-savings and revenues associated with implementing agroforestry solutions.

On-farm sequestration – Costs, cost-savings and revenues

Biochar

To estimate the costs of increasing the use of biochar, a combination of Roe et al. (2019 & 2021) and Dickinson et al. (2015)[56] were used. First, the total area covered by increased biochar from Roe et al. (2019, 2021) was considered per country. Subsequently, Dickinson et al. (2015) provides data on costs per ton applied biochar for North Western Europe and Sub-Saharan Africa, which was converted into costs per hectare. The costs per hectare for North Western Europe or Sub-Saharan Africa were then applied to countries based on region categories from Roe et al. (2021):

- North Western Europe: Developed Countries
- Sub-Saharan Africa: Africa and Middle East, Asia and Developing Pacific, Latin America and Caribbean, Asia and Developing Countries, Eastern Europe and West-Central Asia

Soil organic carbon sequestration in croplands and grasslands, and agroforestry

To calculate total costs and revenues from agroforestry solutions, we used data from Roe et al. (2019 & 2021) and Project Drawdown (2020). The total potential area (in hectares) covered by agroforestry solutions from Roe et al. (2019 & 2021) was broken down into three agroforestry solutions (as explained above). Project Drawdown provides estimates of the difference in establishment, implementation costs and revenues between business-as-usual agriculture production and the various agroforestry solutions. These cost and revenue estimates were converted to $/ha estimates and combined with the estimated hectares per agroforestry solution as outlined above to create estimates for: (i) net first costs to implement, (ii) operational costs, (iii) increased revenues.

Similarly, total costs and revenues for soil organic carbon sequestration in croplands and grasslands was calculated by combining $/ha estimates from Project Drawdown with total area (in hectares) under management from Roe et al. (2019 & 2021).

Protect nature

Protect nature – Mitigation potential

In the BAU scenario we assume that the conversion of natural ecosystems (i.e. commodity-driven deforestation and peatland degradation) continues at current rates. The mitigation potential from ending the conversion of natural ecosystems is therefore equal to the avoided emissions, and zero-conversion is achieved by 2025.

Protect nature – Costs, cost savings and revenues

To estimate the costs of ending commodity-driven deforestation and peatland degradation within value chains we looked at two solutions.

Traceability, monitoring and certification costs

We was assumed that the primary cost for ending commodity-driven land conversion that sits within food and agriculture value chains relate to monitoring, traceability and certification to ensure sourcing of deforestation-free (and peatland conversion) commodities. Chain Reaction Research (2020)[57] and (2022)[58] provide estimates of the costs per tonne produced ($) of top food and agriculture companies to execute No Deforestation, Peat and No Exploitation (NDPE) policies. These include costs for traceability, certification and implementation of NDPE policies.

Second, it was assumed that the primary commodities that are contributing to commodity-driven land conversion are palm oil, beef, soy and dairy. Chain Reaction Research (2020) and (2022) offer estimates of the costs of NDPE policies for palm oil, beef and soy. It was assumed that the cost per tonne for dairy is similar to beef and soy. The costs per tonne produced were multiplied by the tonnes produced in 2020 for each of these four commodities.

According to research from Polaris Market Research (2023)[59], the food traceability market share is expected to grow at 9% per year between 2020 and 2030. Whilst demand for this market is expected to grow, the costs are likely to decrease in the forecast period as a consequence of new technologies, which reduces the cost required from food and agriculture companies to implement NDPE policies. We assume that the overall effect is that total cost to the food and agriculture sector remains constant, even if it becomes cheaper for individual companies.

Forest-positive business models

Another solution we investigated was the investment needed to expand forest-positive business models in forest frontier communities. Partnerships for Forests is a technical assistance facility that catalyses investment into sustainable businesses at the forest frontier across the tropical belt.[60] Using data provided by them we were able to estimate the $/ha investment needed per year in such businesses and applied that cost to the total forest frontier area (600 million hectares) to determine the investment needed per year globally.

Revenues

Whilst nature protection can require significant costs, there are also sizable market opportunities that can be unlocked through forest-positive businesses. In particular, non-food-nontimber forest products (NTFPs) were considered to be an important source of revenue. NTFPs are naturally produced in forests, with minimal damage to natural ecosystems, and include products like oils, medicinal plants, nuts and saps. Using analysis from AlphaBeta

(2020)[61], as well as internal analysis, it was assumed that the market value of NTFPs follows a linear growth rate from 2016 to 2030 and reaches a future value of $145 billion in 2030.

Demand-side shifts

Shift to sustainable diets

Shift to sustainable diets – Mitigation potential

To estimate the mitigation potential from healthy diets we adapted the Roe et al. methodology to include a more recent definition of the sustainable diet. The Roe et al. 2019 and 2021 papers draw on Project Drawdown[62] as their source. Their methodology is outlined below:

"We calculated impacts of increased adoption of the Plant-Rich Diets solution from 2020 to 2050 by comparing two growth scenarios with a reference scenario in which the food demand reflects future "business-as-usual" dietary changes based on projected regional growth factors (Alexandratos et al., 2012).

To meet our definition of plant-rich, a diet must include:

- *consuming 2,300 kilocalories per day*
- *consuming reduced quantities of animal-based protein (particularly red meat, which is constrained to 57 grams per day)*
- *purchasing locally produced food when possible (a 5 percent localization factor is applied globally).*

The caloric breakdown comes from Bajželj et al. (2014). It takes projected regional data and optimizes it according to a number of nutritional studies to create a "healthy" diet.

Adoption scenarios in this model grow linearly over time starting from the base year of 2014, and are considered "complete" in 2050. Linear growth trends were chosen because of the lack of country or regional data; additional behavioral research at more granular scales can reveal more representative adoption estimates.

The following scenarios were considered:

- *Scenario 1: 50 percent of people adopt a plant-rich diet by 2050.*
- *Scenario 2: 75 percent of people adopt a plant-rich diet by 2050."*

To adapt the Project Drawdown methodology, the model for this analysis uses two different sources for the diet scenarios. The first, to replace the Alexandratos et al. 2012 paper, is the FAO's 'Future of Food and Agriculture – Alternative pathways to 2050'.[63] This work details current and future Business-As-Usual (BAU) consumption at a global and regional level and is a more recent study for the model to use. The second adaptation was to use the EAT-Lancet

Commission's 'Food in the Anthropocene' report[64] as the basis for the sustainable diet. This was chosen as it is a more recent, more widely studied and debated analysis.

Scenario 1 above, which is adopted as Roe et al.'s 'cost-effective' scenario, is then used by the model in the same way and so adoption grows linearly over time, starting from the base year in 2014 and 'complete' in 2050.

In order to calculate the mitigation potential from this change in diets, we multiplied the 2020 emissions by commodity (calculated in the commodity emissions analysis described above in chapter 1.2) by the projected change in global consumption in the two different scenarios to calculate the change in emissions associated with the changing diet.

For example, if in the BAU scenario red meat consumption is projected to grow from 146 million tonnes in 2020 to 166 million in 2030 – a growth of 14%, then emissions from red meat will also grow by 14% over the same period. This is in comparison to the sustainable scenario, where red meat consumption only grows by 0.5% over the same period. The associated difference in emissions is then attributed to the change in diet.

Global consumption from the model is shown below for comparison:

Table 3: BAU consumption of different food groups, globally, in million metric tonnes per year.

Food group	Year										
	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Vegetables	765	777	788	800	812	824	836	848	860	871	883
Fruits	447	454	460	467	474	481	488	495	502	509	516
Sugar & Sweeteners (HFCS)	119	121	122	124	126	128	130	132	134	136	138
Vegetable oils	60	61	62	62	63	64	65	65	66	67	68
Red meat	146	148	150	152	154	156	158	160	162	164	166
Poultry	82	83	85	86	87	88	90	91	92	94	95
Eggs	41	42	43	44	44	45	46	47	48	48	49
Dairy	494	499	504	510	516	522	528	533	539	545	551
Fish	107	108	109	109	110	110	111	112	112	113	113
Wheat products	347	351	354	357	360	364	367	371	374	377	381
Rice	289	292	296	299	303	307	310	314	318	321	325
Maize	95	96	97	98	99	100	101	102	103	104	106
Other grains	60	61	62	63	65	66	68	69	71	72	74
Roots	367	373	379	385	391	398	404	411	417	424	431
Pulses	50	51	52	53	54	55	56	57	58	59	60
Other crops	72	73	74	75	76	77	78	79	80	81	82

Table 4: *Scenario 1* consumption of different food groups, globally, in million metric tonnes per year.

Food group	**Year**										
	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Vegetables	733	739	744	750	755	760	765	769	773	777	780
Fruits	448	454	460	467	474	480	487	493	499	505	511
Sugar & Sweeteners (HFCS)	114	115	116	116	117	118	119	120	120	121	121
Vegetable oils	63	64	65	66	67	69	70	71	72	73	75
Red meat	137	137	138	138	138	138	138	138	138	138	138
Poultry	80	81	82	82	83	84	85	85	86	87	87
Eggs	40	41	41	42	42	43	43	43	44	44	45
Dairy	493	498	503	508	514	519	525	530	535	540	546
Fish	103	103	103	102	102	102	102	102	102	101	101
Wheat products	337	339	340	341	343	344	346	347	348	349	351
Rice	284	286	288	291	293	296	298	300	303	305	307
Maize	87	87	86	86	85	85	84	84	83	83	82
Other grains	55	55	55	56	56	56	56	57	57	57	57
Roots	355	358	362	366	369	373	376	380	383	386	389
Pulses	62	65	68	71	74	77	80	84	87	90	94
Other crops	70	70	71	72	72	73	74	74	75	75	76

Shift to sustainable diets – Cost, cost-savings and revenues

Though shifting to healthy and sustainable diets will require significant effort and investment from multiple stakeholders, for example from national and local legislators, health experts and NGOs, the critical solution that must be implemented by the private sector is investment to support the growth of alternative proteins. While it is true that companies will also have to spend money on advertising and marketing, changing store layouts to promote different products and pivot to new products with their R&D spend, for the purpose of this analysis we assumed this would involve repurposing existing budgets and so would come at no additional cost.

Growth in alternative proteins

This considers how meat- and dairy-mimicking products might disrupt traditional animal-sourced protein consumption and draws from Systemiq analysis that projected the growth of alternative protein consumption globally to 2050. The analysis used FOLU's Tipping Points framework,[65] using the tipping points identified, namely price parity, performance parity, and social contagion, to predict when exponential growth in the consumption of alternative proteins will occur. Food price data was then collected to estimate the value of production at this scale, resulting in a market size of over $200 billion in 2030. This is used as an estimate of the business opportunity in alternative proteins.

For the associated costs of alternative proteins, the Systemiq analysis estimates the manufacturing and processing capacity required to produce alternative proteins at the scale projected, and then calculates the investment needed to build facilities of that scale. This results in over $100 billion needed to build alternative protein production facilities up to 2030 in order to meet the projected demand.

Reduced food loss & waste

Reduced food loss & waste – Mitigation potential

To estimate the mitigation potential from reduced food loss & waste, a combination of data from Lipinski et al. (2013)[66] and Roe et al. (2019 & 2021) was used. The mitigation potential from Roe et al. (2021) is defined as:

"Emissions reductions from diverted agricultural production (excluding land-use change) from reduced food loss and wastage from all stages of production, distribution, retail, and consumption through the implementation of measures such as improved storage and transport systems, generation of public awareness, and changing consumer behaviors."

Combining the Roe et al. papers we calculated the mitigation potential in 2030 from reduced food loss & waste. Then, using Lipinski et al. (2013) which defines the regional variation by which food lost or wasted occurs in different parts of the value chain we were able to disaggregate the mitigation potential by stage in the value chain (consumption, distribution & market, process & packaging, handling & storage, production).

Reduced food loss & waste – Cost, cost-savings and revenues

Subsequently, for each stage, a number of specific solutions were selected that contribute to reduced food loss & waste within that stage of the value chain. For each solution, the ReFED[67] data provides a total cost estimate of annual investment required, as well as the potential emissions reductions that can be realized. These numbers were used to create a costs per t/CO_2e per solution. In addition, for solutions at the production stage, FAO (2018a)[68] and FAO (2018b)[69] were used to determine cost estimates for 'training and capacity building' and 'hermetic cocoon'.

Production

- *Buyer specification expansion.* This refers to expanding purchasing specifications that allow for a greater variety of product grades into sales and recipes to reduce on-farm waste.
- *Training and capacity building.* This includes training and capacity building for farmers to reduce on-farm waste.
- *Hermetic cocoon.* This refers to type of hermetic storage that can help reduce post-harvest food loss

Handling and storage

- *Milk coolers.* Milk coolers can be used to reduce food loss and waste in the dairy industry by storing milk at low temperatures.
- *Rented plastic crates.* This includes the use of plastic crates for the handling and storage of agricultural products to reduce food loss and waste.

Processing & packaging

- *Manufacturing line optimization.* This refers to identifying opportunities to reduce food waste from manufacturing and processing operations, such as in product line changeovers.
- *Manufacturing byproduct utilization.* This includes converting food by-products that would otherwise not go to human consumption into a new ingredient or edible food products.

Distribution & market

- *Decreased transit time.* This includes reducing time in transit by team driving to extend the distance product can move each day from farm to distribution.

- *Intelligent routing.* This refers to intelligent routing of products based on near time data on impacts to freshness, such as cold chain maintenance so that shorter-life product is routed to closer destinations.
- *First expired first out.* This includes designing processes to move products based on what will expire first, rather than when it was received.
- *Temperature monitoring.* This refers to the use of measurement and alert technology and other systems for pallet- or truck-level temperature tracking to identify areas for improved cold chain compliance, third-party issue identification, and real-time detection and resolution.
- *Increased delivery frequency.* This includes increasing the frequency of delivery from suppliers to stores, restaurants, facilities, or other food destinations to reduce dwell time in distribution centres.

Consumption

- *Consumer education campaigns.* This includes conducting large-scale advocacy campaigns to raise awareness and educate consumers about ways to prevent food waste in their homes.
- *Portion sizes.* This involves creating smaller size options for menu items to reduce over-portioning and plate waste.
- *Meal kits.* This incorporates the assemblies of pre-measured ingredients to cook specific meals, marketed as a way to save time and minimize waste of raw ingredients purchased individually.
- *Waste tracking.* This includes technology-enabled tracking of food loss and waste to highlight opportunities for reduction.
- *Active & intelligent packaging.* This refers to packaging to slow spoilage through technologies such as ethylene absorption, modified atmospheres, moisture absorption, etc., or adaptive materials that inform as to the quality/safety of the contents.
- *Standardized date labels.* This includes standardizing the wording of food label dates to two phrases, one to indicate quality and another for dates which indicate safety risk, in order to reduce consumer misinterpretation.
- *Markdown alert applications.* This refers to applications that alert consumers to markdowns or excess food at retailers or restaurants.
- *Package design.* This refers to optimizing food packaging size and design to ensure complete consumption by consumers and avoid residual container waste.
- *Assisted distressed sales.* This refers to assistance, e.g. through third-party companies, in selling salvaged, overstocked, and out of date food at a discounted rate.
- *Standardized date labels.*. This includes standardizing the wording of food label dates to two phrases, one to indicate quality and another for dates which indicate safety risk, in order to reduce consumer misinterpretation.

- *Trayless.* This involves eliminating trays in all-you-can-eat dining facilities to reduce over-portioning by consumers.
- *Minimized on hand inventory.* This includes reducing product dwell time in distribution centres by not holding safety stock and excess days on-hand.
- *Temperature monitoring.* This refers to the implementation of measurement and alert systems within foodservice cold storage units to detect out of range temperatures and notify automatically.
- *Small plates.* This refers to using plates with a smaller diameter in all-you-can-eat dining establishments to provide visual appeal of abundance while minimizing portion sizes to reduce plate waste.

A weighted average cost per t/CO_2e per stage was calculated based on the total costs and mitigation offer by each solution per stage. This was multiplied by the mitigation potential per stage to calculate the overall costs of food loss and waste solutions. The table below summarizes the cost estimates per t/CO_2e, as well as the sources used.

Table 5: Estimates of costs for reduced food loss & waste solutions in different stages of the value chain.

Stage	Weighted Average Costs ($ per t/CO_2e)	Global Mitigation Potential (Mt Co2e)	Total Cost ($ billion)	Sources Used
Production	43.4	96	4.2	ReFED ; FAO (2018)
Handling & Storage	66	92	6.1	ReFED
Process & Packaging	219.4	16	3.1	ReFED
Distribution & Market	129.6	48	7.5	ReFED
Consumption	41.7	140	6.7	ReFED
Total	70.4	391	27.5	

Table 6: Sources of mitigation potential estimates by solution.

Source of emissions	Solution	Source for mitigation potential

Enteric Fermentation	GHG focussed genetic selection and breeding	McKinsey, 2023
Enteric Fermentation	Animal health monitoring and illness prevention	McKinsey, 2023
Enteric Fermentation	Animal feed mix optimization	McKinsey, 2023
Enteric Fermentation	Animal feed additives	McKinsey, 2023
Enteric Fermentation	Feed-grain processing for improved digestibility	McKinsey, 2023
Enteric Fermentation	Heat stress management	McKinsey, 2023
Enteric Fermentation	Decrease forage-to-concentrate ratio	McKinsey, 2023
Enteric Fermentation	Increased livestock production efficiencies	McKinsey, 2020
Manure Management	Large-scale anaerobic manure digestion	McKinsey, 2023
Manure Management	Small-scale anaerobic manure digestion	McKinsey, 2023
Total manure	Animal health monitoring and illness prevention	McKinsey, 2023
Total manure	Livestock Nutrient Effiency	McKinsey, 2020
Manure left on pasture	N-inhibitors on pasture	McKinsey, 2023
Total manure	GHG focussed genetic selection and breeding	McKinsey, 2023
Total manure	Increased livestock production efficiencies	McKinsey, 2023
Rice Cultivation	Improve fertilization practices in rice cultivation	McKinsey, 2023
Rice Cultivation	Improve rice paddy water management	McKinsey, 2023
Rice Cultivation	Expand adoption of dry direct seeding in rice cultivation	McKinsey, 2023
Rice Cultivation	Improve rice straw management	McKinsey, 2020
Rice Cultivation	Optimal rice varietal selection	McKinsey, 2020
Synthetic fertilizers	Reduce nitrogen overapplication	McKinsey, 2023

Synthetic fertilizers	Expand adoption of controlled-release and stabilized fertilizers	McKinsey, 2023
Synthetic fertilizers	Variable rate fertilization	McKinsey, 2023
Synthetic fertilizers	Specialty fertilizers	McKinsey, 2023
Synthetic fertilizers	Incorporation of cover crops	McKinsey, 2023
Synthetic fertilizers	Biologicals	McKinsey, 2023
Synthetic fertilizers	Improved fertilization timing	McKinsey, 2020
Conversion and degradation of natural ecosystems	Nature protection	*Authors' assumption*
Increased sequestration	Silvopasture	Project Drawdown and Roe et al. 2019 & 2021
Increased sequestration	Tree intercropping	Project Drawdown and Roe et al. 2019 & 2021
Increased sequestration	Multistrata agroforestry	Project Drawdown and Roe et al. 2019 & 2021
Increased sequestration	Soil organic carbon sequestration in croplands	Roe et al. 2019 & 2021
Increased sequestration	Soil organic carbon sequestration in grasslands	Roe et al. 2019 & 2021
Increased sequestration	Biochar	Roe et al. 2019 & 2021
	Shifting to sustainable diets	EAT-Lancet and Roe et al. 2019
	Reduce food loss and waste	Lipinski et al. and Roe et al. 2019

Sources: McKinsey (2020)[70] and McKinsey (2023)[71] Roe et al. (2019)[72] and Roe et al. (2021),[73] EAT-Lancet[74], Project Drawdown[75] and Lipinski et al.[76]

Table 7: Full list of mitigation solutions and the sources used to estimate costs, cost savings and revenues

Mitigation category	Mitigation lever	Source
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	GHG focussed genetic selection and breeding	Rowe et al., 2022
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	Animal health monitoring and illness prevention	Defra, 2015
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	Animal feed mix optimization	McKinsey, 2023
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	Animal feed additives	McKinsey, 2023
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	Feed-grain processing for improved digestibility	McKinsey, 2023
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	Heat stress management	McKinsey, 2023
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	Decrease forage-to-concentrate ratio	McKinsey, 2023
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	Increased livestock production efficiencies	McKinsey, 2023

Enteric fermentation & manure management, manure left on pasture and manure applied to soils	Large-scale anaerobic manure digestion	McKinsey, 2023
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	Small-scale anaerobic manure digestion	McKinsey, 2023
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	Livestock Nutrient Effiency	McKinsey, 2023
Enteric fermentation & manure management, manure left on pasture and manure applied to soils	N-inhibitors on pasture	McKinsey, 2023
Rice cultivation	Improve fertilization practices in rice cultivation	McKinsey, 2023
Rice cultivation	Improve rice paddy water management	McKinsey, 2023
Rice cultivation	Expand adoption of dry direct seeding in rice cultivation	McKinsey, 2023
Rice cultivation	Improve rice straw management	McKinsey, 2023
Rice cultivation	Optimal rice varietal selection	McKinsey, 2020
Nutrient management	Reduce nitrogen overapplication	McKinsey, 2023
Nutrient management	Expand adoption of controlled-release and stabilized fertilizers	McKinsey, 2020 & 2023
Nutrient management	Variable rate fertilization	McKinsey, 2023
Nutrient management	Specialty fertilizers	McKinsey, 2023

Nutrient management	Drip or sprinkler irrigation	McKinsey, 2023
Nutrient management	Incorporation of cover crops	McKinsey, 2023
Nutrient management	Biologicals	McKinsey, 2023
Nutrient management	Improved fertilization timing	McKinsey, 2020
Agroforestry	Silvopasture	Project Drawdown
Agroforestry	Tree intercropping	Project Drawdown
Agroforestry	Multistrata agroforestry	Project Drawdown
Soil organic carbon in croplands	Soil organic carbon in croplands	Project Drawdown
Soil organic carbon in grasslands	Soil organic carbon in grasslands	Project Drawdown
Biochar	Biochar	Dickinson et al., 2014
Shift to sustainable diets	Shift to sustainable diets	Systemiq analysis
Reduced food loss & waste	Reduced food loss & waste	Refed US (2023) and additional sources
Reduced deforestation and commodity-driven peatland degradation	Reduced deforestation and commodity-driven peatland degradation	Systemiq Analysis (methodology outlined above)

4. Estimating the cost of non-compliance in report 1

In *Future Fit Food and Agriculture: Developments in voluntary frameworks and standards and their influence on legislation for businesses*, Section 3, we estimate the cost of compliance with the EUDR for a large European coffee manufacturer. This fictitious company archetype was composed using publicly available data for real European companies and adjusting numbers where necessary. For this fictitious company, we assume revenues are €5 billion per year and they operate with a profit margin of 20%. This means that costs amount to €4 billion, 25% of which we assume are for the purchase of coffee (or €1 billion). We find that the premium for certified deforestation-free coffee ranges between 1-6%,[77,78] resulting in an increase in costs of between €10-65 million per year. This is compared to the 4% penalty on the company's European revenues (i.e. 4% of €5 billion), which equals €200 million.

5. Cost of mitigating emissions for company 'archetypes'

In *Future Fit Food and Agriculture: The financial implications of mitigating agriculture and land use change emissions for businesses*, Section 5, we outline 3 company archetypes and explore how the cost of mitigating 30% of their agricultural production and land use change emissions – in line with SBTi FLAG targets[79] – compares to their revenues.

Our company archetype analysis was composed of three parts:

1. Company financials
2. Company emissions
3. Cost of abatement

For each of the 3 archetypes that we developed, we used publicly available information from a number of different companies and integrated these findings to develop an overall picture of a generic and anonymous archetypal company. Sources for step (1) varied, while the Carbon Disclosure Project[80] was used as a source for step (2). For the beef farmer we used Systemiq analysis, which modelled an archetypal beef farm in Brazil. The aim for our archetypal companies was to outline their annual costs, revenues and Scope 1, 2 and 3 emissions by source commodity. We then tested these assumptions with relevant experts.

Once we had put together this profile, the average $/t$CO_2$e costs/returns calculated from the analysis outlined in the sections above were used to calculate the cost of abatement for each commodity. The necessary emissions reductions followed the same percentage reduction identified in our model, with any remaining mitigation achieved through an appropriate mix of solutions to sequester emissions and manage demand.

As an example, consider the beef farm.

Revenues: $2.6 million

Emissions: 27,000 tonnes CO_2e

Breakdown of emissions by source	Emissions (tCO_2e)
Enteric fermentation	9,000
Manure	12,000
Deforestation	4,300

Emissions reductions:

Solution	Percent reduction *(by 2030)*	Cost ($/$tCO_2e$)
Reduced enteric fermentation	18%	46.9
Improved manure management	16%	165.3
Reduced deforestation	100%	15.2

Combining the two tables above; (e.g. *emissions source* x *percent reduction* x *cost per tCO_2e*)

Emissions source	Total reduction (tCO_2e)	Total cost
Enteric fermentation	1,620	$75,000
Manure	1,920	$320,000
Deforestation	4,300	$65,000
Total mitigated	**7,840**	**$460,000**

Even mitigating 7,840 tCO_2e, the farmer still has a further 260 tCO_2e to mitigate to reach the 30% target outlined. This will be achieved through a range of appropriate on-farm carbon removals (e.g. agroforestry and soil organic carbon sequestration in grasslands).

This methodology was applied to each of the archetypal companies and across all the commodities in their portfolio.

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