Carbon Performance assessment of food producers: note on methodology

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Transition Pathway Initiative

LSE

Grantham Research Institute on Climate Change and the Environment

About the LSE Transition Pathway Initiative Centre

The Transition Pathway Initiative Centre (TPI Centre) is an independent, authoritative source of research and data on the progress of corporate and sovereign entities in transitioning to a low-carbon economy.

The TPI Centre is part of the Grantham Research Institute on Climate Change and the Environment, which is based at the London School of Economics and Political Science (LSE). It is the academic partner of the Transition Pathway Initiative (TPI), a global initiative led by asset owners and supported by asset managers. As of December 2023, 148 investors globally, representing around US$60 trillion combined Assets Under Management and Advice, have pledged support for TPI. Using companies' publicly disclosed data, as well as CDP responses where necessary, the TPI Centre:

- Assesses the quality of companies' governance and management of their carbon emissions and of risks and opportunities related to the low-carbon transition, in line with the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD).
- Assesses whether companies' current and planned future emissions are aligned with international climate targets and national climate pledges, including those made as part of the Paris Agreement.
- Provides the data for the Climate Action 100+ Net Zero Company Benchmark.
- Publishes its methods and results online and fully open access at www.transitionpathwayinitiative.org and on GitHub.

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Contents

1. TPI's Carbon Performance assessment: the Sectoral Decarbonisation Approach (SDA)

The TPI Centre's Carbon Performance assessments to date have been predominantly based on the Sectoral Decarbonisation Approach (SDA).[1] The SDA translates greenhouse gas emissions targets made at the international level (e.g. under the 2015 UN Paris Agreement) into appropriate benchmarks, against which the performance of individual companies can be compared.

The SDA recognises that different sectors of the economy (e.g. food production, electricity generation and automobile manufacturing) face different challenges arising from the low-carbon transition, including where emissions are concentrated in the value chain and how costly it is to reduce emissions. Other approaches to translating international emissions targets into company benchmarks have applied the same decarbonisation pathway to all sectors, regardless of these differences. [1] Such approaches may result in suboptimal insights, as not all sectors have the same emissions profiles or face the same challenges: some sectors may be capable of faster decarbonisation, while others require more time and resources.

Therefore, the SDA takes a sector-by-sector approach, comparing companies within each sector against each other and against sector-specific benchmarks, which establish the performance of an average company that is aligned with international emissions targets.

The SDA can be applied by taking the following steps:

- A global carbon budget is established, which is consistent with international emissions targets, for example keeping global warming below 2°C. To do this rigorously, some input from a climate model is required.
- The global carbon budget is allocated across time and to different regions and industrial sectors. This typically requires an Integrated Assessment Model (IAM), and these models usually allocate emissions reductions by region and by sector according to where it is cheapest to reduce emissions and when. Cost-effectiveness is, however, subject to some constraints, such as political and societal preferences, and the availability of capital. This step is therefore driven primarily by economic and engineering considerations, but with some awareness of political and social factors.
- In order to compare companies of different sizes, sectoral emissions are normalised by a relevant measure of sectoral activity (e.g. physical production or economic activity). This results in a benchmark path for emissions intensity in each sector:

$$\text{Emissions intensity} = \frac{\text{Emissions}}{\text{Activity}}$$

[1] The Sectoral Decarbonisation Approach (SDA) was created by CDP, World Resources Institute (WRI) and the World Wide Fund for Nature (WWF) in 2015. See Science-Based Targets Initiative [SBTi]: https://sciencebasedtargets.org/resources/files/Sectoral-Decarbonization-Approach-Report.pdf

- Assumptions about sectoral activity need to be consistent with the emissions modelled and therefore should be taken from the same economy–energy modelling where possible.
- Companies' recent and current emissions intensity is calculated, and their future emissions intensity is based on emissions targets they have set (this assumes companies meet their targets).[2] Together, these establish emissions intensity pathways for companies.

Companies' emissions intensity paths are compared with each other and with the relevant sectoral benchmark pathway.

[2] Alternatively, companies' future emissions intensity could be calculated based on other data provided by companies on their business strategy and capital expenditure plans.

2. Applying the SDA to the food sector

2.1. The food sector's role in climate change

The food sector is of global importance, with the combined market capitalisation of the 26 largest food producers amounting to around US$930 billion in 2022.[3] In addition to its financial importance to investors, the sector is a crucial driver of economic development, poverty alleviation and rural employment. [2] For example, the Agriculture, Forestry, and Other Land Use (AFOLU) (or 'managed land') sector, which has considerable overlap with the food sector, accounted for 3.7% of global GDP in 2017. [3]

Food producers are one of the most important actors in the global land use system. The food sector is associated with high greenhouse gas emissions, as well as other negative environmental impacts including biodiversity loss. While global emissions from the food sector are uncertain, estimates range from 19–32% [4–9], placing the food sector's contribution to global emissions on a par with that of the oil and gas industry. Agriculture constitutes 80% of total food sector emissions, [7] [8] with the remainder associated with the processing, transportation and disposal of food products. The largest single contributor to agricultural emissions is enteric fermentation – a digestive process that occurs within ruminant animals – which accounts for 40% of total agricultural emissions, followed by manure (25%) and emissions associated with the use of synthetic fertilisers (13%). [10]

To contain global temperature rise to well below 2°C, the food sector must dramatically reduce its emissions, which necessitates a fundamental transformation. [11–14] Supply-side mitigation relies heavily on efficient land use, livestock management and enhanced carbon removals. [15] [16] Reducing agricultural emissions driven by land use and land-use change (LULUC) – which account for around 30% of total food sector emissions – is also integral to mitigating impacts at the level of the farm. [6] [17] Supply-side mitigation actions outside of the farm itself include switching from fossil fuels to renewable energy and improving energy efficiency. [8] Demand-side strategies are also important for reducing the food sector's emissions. For example, large-scale switches to plant-based diets could reduce emissions from food production by almost 50%. [9]

The food sector is not only one of the greatest contributors to climate change, but it is also one of the sectors most vulnerable to the adverse impacts of climate change, further highlighting the importance of both climate mitigation and adaptation in this sector.

2.2. Defining the food sector: food producers

To apply the SDA methodology to the food sector, a definition of the sector is required. We follow the categorisation of the 'food producers' sector (3570) by the Industry Classification Benchmark (ICB) v2.6 [17], which is nested within 'consumer goods' and consists of the subsectors 'food products' (3577) and 'farming, fishing, and plantations' (3573). The food products subsector includes companies that manufacture meat, fruit, dairy and frozen seafood products – along with pet food and dietary supplements – but excludes producers of beverages. The farming subsector includes companies that own non-tobacco plantations, grow crops, raise livestock or operate fisheries.

The largest companies in the food producers' sector by free float market capitalisation, which are the focus of our assessment, are found within the food products subsector. However, the assessments also reflect the greenhouse gas emissions of the 'farming' subsector, owing to the inclusion of upstream Scope 3 emissions in the benchmarks and company assessments.

[3] Based on data provided by FTSE-Russell.

2.3. Deriving the benchmark pathways

The key inputs to calculating benchmark pathways in any sector are:

- A timeline for greenhouse gas emissions that is consistent with meeting a particular climate target (e.g. limiting global warming to 1.5°C)
- A breakdown of this economy-wide emissions path into emissions from key sectors (the numerator of sectoral emissions intensity), including the sector in focus
- Consistent estimates of the timeline of physical production from, or economic activity in, these key sectors (the denominator of sectoral emissions intensity).

A key challenge in assessing the food industry is to estimate emissions and physical production consistently, both for the benchmarks and for the companies being compared with those benchmarks. This challenge mainly stems from the high complexity of the sector, in particular the transformation of inputs at various stages, as well as co-products from the same basic agricultural commodity. One practical problem it creates is that the IAMs we depend on for future food-sector emissions pathways do not provide emissions and production figures on a basis that is consistent with the boundary most suitable for measuring company emissions (see Section 2.5). Neither do these IAMs provide a high level of product differentiation.

We overcome these challenges by calculating the benchmark pathways in two steps. First, the initial or base value of the food sector's emissions intensity is determined, which for food sector sources is 2019. The calculation uses data from the United Nations Food and Agriculture Organization (FAO) and various emissions factors obtained from a major literature review (see Section 2.4). Second, IAM scenarios are used to estimate the change in emissions intensity from the initial or base year as the sector's low-carbon transition progresses. We use scenario data from three IAMs (IMAGE, REMIND-MAgPIE and MESSAGE-GLOBIOM) to estimate the appropriate emissions reduction pathways to apply to the base year emissions intensity (see Section 2.5). These IAMs differentiate themselves from others by including detailed land use modules. Due to their close link between agricultural production and land use, they can provide relatively detailed projections of agricultural emissions and output.

Using this approach, we derive three benchmark emissions paths linked to the goals of the Paris Agreement on climate change, against which companies are evaluated by the TPI Centre:

1. 1.5 Degrees.
2. Below 2 Degrees.
3. 2 Degrees.

2.4. Base year emissions intensity

General approach

To estimate our base year (2019) emissions intensity, we combine data on global food-related agricultural production by commodity obtained from the FAOSTAT database with global emissions factor data from Poore and Nemecek, [9] [19] and supplement this with a number of additional sources (see Appendix 4). This means that our estimates are based on the most comprehensive global agricultural production dataset (which is also an input to the IAMs used) and the largest emissions factor literature review in the agricultural sector to date.

To determine the base year intensity, we use a denominator of the total volume of agricultural commodities produced in 2019 and a numerator of total emissions from these products. We favoured agricultural commodities produced over final, processed food products because there is better data availability on the total production of raw commodities than final food product volumes, with the former being provided by the FAO. Furthermore, most of the emissions factors used in this study to estimate the base year emissions value correspond to unprocessed agricultural commodities.

Base year production weight

We use global production data for all agricultural products from the FAOSTAT Crops and Livestock Products database to estimate total global food production in metric tonnes consistently with the emissions factors applied at a later stage. [9] Since only a portion of total crops and animal products ultimately become human food, we make several adjustments to the dataset to arrive at the final base year production volume.

For example, we exclude non-food items such as cotton and tobacco, alcoholic beverages, and a small number of other commodities with low production quantities, due to the lack of credible emissions factors.[4] Duplicate values are also excluded. For example, the FAO reports both the volume of egg production and the number of eggs produced, so only the former is included in our dataset. A list of all excluded commodities is given in Appendix A.

The commodity production values are also adjusted to reflect the proportion of total commodities that are destined to become human food by calculating the share of total production of edible commodities accounted for in human food use using the FAO's Supply Utilization Accounts (SUA).[5] [6] [18] [19] [21] Further details of these adjustments are available in Appendix 2.

To calculate a base year emissions intensity, it is important to ensure the production units align with the emissions factor functional units. Following Poore and Nemecek [9], who use the dry matter content of commodities as the basis of their functional unit, we adjust the volume of these commodities to account for this conversion. These authors also made several further smaller adjustments which we do not account for.[7] For example, we do not adjust meat production volumes, as these figures relate to 'fat and bone-free meat', conforming with Poore and Nemecek's functional unit. We also make no adjustment to grain, oilseed, pulse or soybean production quantities, as FAO production data are already reported in terms of clean, dry weight. [22]

This method yields a base year production value of 4.9 billion (metric) tonnes.

Base year emissions

Base year emissions from agricultural food production are estimated by multiplying the adjusted total production volumes of each of the commodities included in the base year production value with a global emissions factor. Most emissions factors are taken from Poore and Nemecek, [9] who estimated the lifecycle emissions of 43 staple food commodities and products, representing around 90% of global protein and calorie consumption. The authors conducted a meta-analysis of over 1,500 studies to estimate the emission factors covering the majority of lifecycle stages for these food products across different geographies. (For more information on life cycle emissions factor boundaries, see Appendix 6). They then use these emission factors to calculate an estimated 12 gigatonnes (billion metric tonnes) of carbon dioxide equivalent ($GtCO_2e$) of total global emissions from the food sector. We use the median emissions factors estimated by Poore and Nemecek (see Appendix 3). For commodities not covered by

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[4] While such omissions are likely to cause our base year value to understate the total greenhouse gas emissions resulting from food production, we are confident that the downward bias will be relatively modest, as the excluded commodities are all produced in small quantities. The impact is likely (not certain) to cause downward bias in our base year value as several excluded commodities are spice crops derived from perennial woody plants that tend to have negative emissions factors.

[5] The SUA provides aggregate national data on the following consumption categories: exports; livestock feed; seed use; processing for food use; processing for non-food use; losses during storage and transportation; and food supplies available for human consumption. The SUA also include the following production categories for the same commodities: production; imports; and change in stocks.

[6] We take two approaches to making these adjustments, depending on whether processed versions of the commodity are included in the dataset. When only the unprocessed form of the commodity (e.g. potatoes) is included, we calculate the relative proportion of the commodity used for processing for food use and food supplies available for human consumption, as per the SUA data. This approach is implemented for wheat, for example, as no processed form of the commodity (such as wheat flour) exists in the base year production dataset. When both the unprocessed and processed forms of the commodity are included in the dataset (e.g. SUA data shows that 2.3% of soybeans produced are used for food in their unprocessed form and 53.2% of soybean oil is used for food directly or is processed further for food-related use), we modify our approach to prevent double-counting: we calculate the relative proportion of the unprocessed commodity (e.g. soybeans) and the processed commodity(e.g. soybean oil) and use this to derive the base year production values.

[7] Poore and Nemecek (2018) adjust milk quantities across different species to standardize the fat and protein content, which is an item that we may address in subsequent versions of the benchmark.

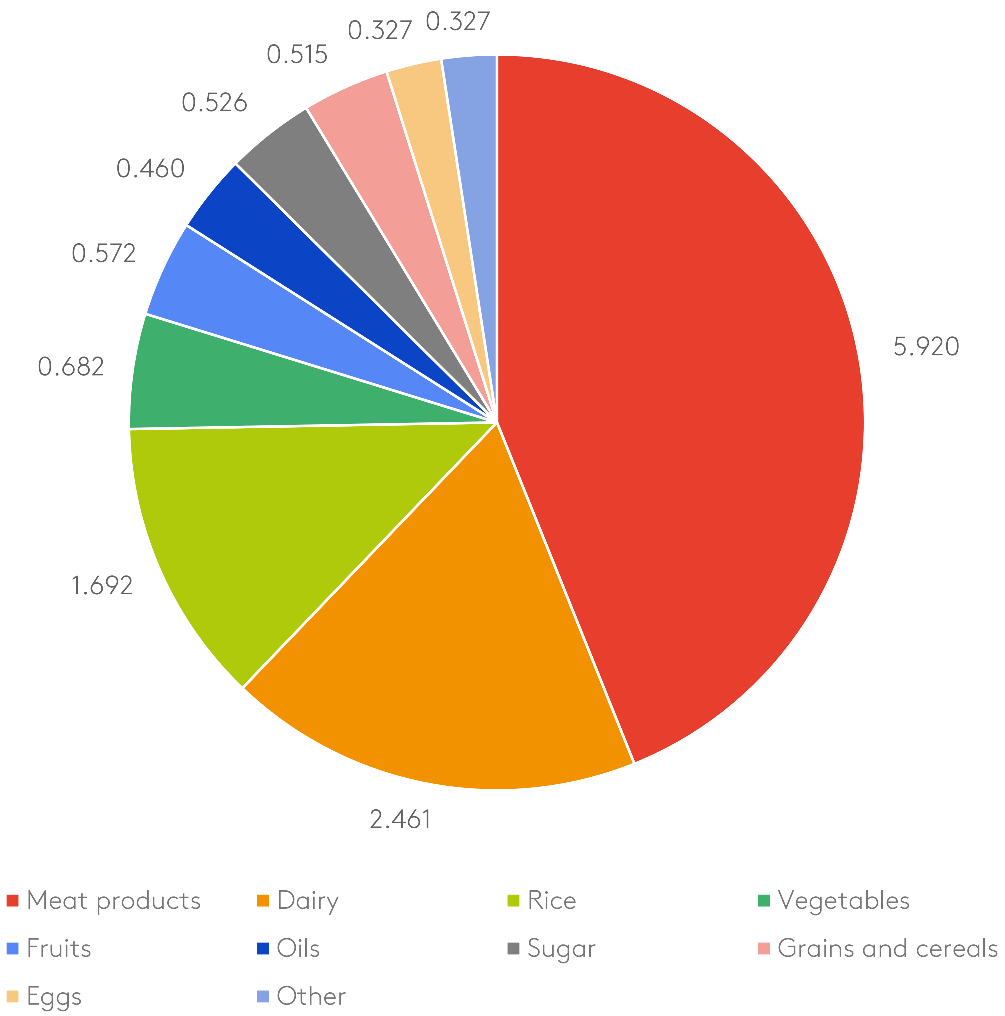
the 43 emissions factors in that study, we use emissions factors provided by a limited number of supplementary sources (Appendix 4).

This method yields a base year emissions value of 13.483 $GtCO_2e$, leading to a base year emissions intensity of 2.751 $GtCO_2e$ per billion (metric) tonnes of product in 2019. The estimated absolute base year emissions are corroborated by other sources, including 13.7 $GtCO_2e$ (Poore and Nemecek in 2017), 14.6 $GtCO_2e$ (Crippa et al. in 2015) and around 13 $GtCO_2e$ (IPCC in 2019; including all AFOLU but excluding food processing emissions). [6] [9] [23] Although a direct comparison between our data and these sources is not possible due to differing assessment boundaries, available data confirms a high degree of agreement with recent studies, especially when contrasted with the large variation of estimates of greenhouse gas emissions from food products. Table 1 and Figure 1 below provide further details of base year quantities and emissions by type of commodity.

Table 1. Quantities of and emissions from agricultural products in 2019

Commodity group	Weight (Gigatonnes)	Emissions (Gigatonnes CO_2e)
Meat products	0.272	5.920
Dairy	0.830	2.461
Rice	0.454	1.692
Vegetables	1.140	0.682
Fruits	0.806	0.572
Oils	0.100	0.460
Sugar	0.182	0.526
Grains and cereals	0.719	0.515
Eggs	0.078	0.327
Pulses and beans	0.065	0.066
Molasses	0.030	0.094
Root vegetables	0.186	0.074
Coffee	0.007	0.059
Legumes	0.005	0.018
Cocoa	0.005	0.016
Soybeans	0.008	0.010
Seeds	0.002	0.002
Honey	0.001	0.001
Seafood and fish	0.000	0.000
Spices	0.000	0.000
Nuts	0.011	-0.014
Total	**4.9013**	**13.483**

Figure 1. Estimated emissions from agricultural products in 2019 ($GtCO_2e$)



2.5. Benchmark emissions reduction pathways

We estimate changes over time in the emissions intensity of food producers for Scope 1, 2 and upstream Scope 3 emissions separately. Changes in Scope 1 and 2 emissions are estimated using low-carbon modelling scenarios produced by the International Energy Agency (IEA), whereas changes in food producers' upstream Scope 3 emissions intensity are estimated using data from three IAMs with detailed land use modules, compiled in the IAMC AR6 Scenarios Database. [24]

To calculate how Scope 1 emissions from food producers should evolve over time in each benchmark scenario, we take the direct emissions budget allocated to industry as a whole and subtract direct emissions allocated to the five principal high-carbon sectors: aluminium, cement, chemicals, paper and steel. The rates of change in the resulting residual industrial emissions are used to forecast direct Scope 1 emissions from food producers.

To forecast Scope 2 emissions, the TPI Centre multiplies a sector's electricity consumption by the emissions intensity of the electricity grid, along each of the IEA scenario paths. Since there is no electricity consumption allocated to food producers specifically, we calculate residual industrial power consumption in a similar way by subtracting the electricity allocated to aluminium, cement, chemicals, paper and steel from total industrial electricity consumption. This is then multiplied by the carbon intensity of the electricity grid over time in the three scenarios.

Upstream Scope 3 emissions account for 94.9% of emissions from the food sector considered in this analysis, and therefore changes in these emissions are the main determinant of the benchmark pathways. [9] To estimate changes in these emissions, we use scenario outputs from the following IAMs:

IMAGE, MESSAGE-GLOBIOM, and REMIND-MAgPIE.[8] Just using these three models, the AR6 Scenarios Database contains simulation results from 574 distinct model–scenario combinations (henceforth referred to as 'scenarios'), of which we selected 223 for our analysis.[9]

The 223 scenarios were grouped into the three benchmark scenarios linked to the Paris Agreement goals, using the same approach as Dietz et al.: [25]

- A 1.5 Degrees scenario, comprising the IPCC scenarios: 'Below 1.5°C' (limiting peak warming to below 1.5°C throughout the 21st century with a 50–66% likelihood); and '1.5°C with low overshoot' (limiting median warming to below 1.5°C in 2100; and with a 50–67% probability of temporarily overshooting that level earlier).
- A Below 2 Degrees scenario, comprising the IPCC scenarios: '1.5°C with high overshoot' (limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier); and 'lower 2°C' (limiting peak warming to below 2°C throughout the 21st century with greater than 66% likelihood).
- A 2 Degrees scenario, comprising the IPCC scenario in which average global warming is limited to 2°C (limiting peak global temperature rise to 2°C with a probability greater than 50%).

Table 2 summarises the number of scenarios that underpin our calculations for each warming scenario, and their distribution across models.

Table 2. Number of scenarios included in Scope 3 benchmark calculation by warming scenario and IAM

Warming scenario	Model			Total
	IMAGE	MESSAGE-GLOBIOM	REMIND-MAgPIE	
1.5°C	7	10	18	35
Below 2°C	28	69	47	144
2°C	9	29	6	44

The scenarios in our analysis provide projections for livestock, non-energy crop and energy crop production separately. To isolate food-specific agricultural production (i.e. the denominator of the benchmark trajectories), all livestock production is assumed to be used for food, and the proportion of non-energy crops used for food is assumed constant at 92.15%. This share excludes energy related non-food uses of crops.[10]

Modelled production values are all reported in dry matter quantities. By contrast, the FAO data used to calculate the base year production value are reported on a fresh-weight basis for all commodities except

[8] We use the following versions of these models: IMAGE 3.0, 3.0.1, 3.0.2 and 3.2; REMIND-MAgPIE 2.0-4.0, 2.1-4.2 and 2.1-4.3; MESSAGE-GLOBIOM 1.0; MESSAGEix-GLOBIOM 1.0, 1.1 and 1.2 and MESSAGEix-GLOBIOM_GEI 1.0.

[9] Of the 574 scenarios available from the three IAMs, 218 were unsuitable because the scenarios were incompatible with limiting warming to 2°C or below. Additionally, 48 scenarios lacked an IPCC climate category classification, which we use to classify scenarios into warming categories, leaving 308 remaining scenarios. Sixty-six of the remaining 308 scenarios were unsuitable as they did not provide results on agricultural production. IAMs with land use components differ in their treatment of bioenergy expansion. As a result, projected energy crop production varies widely across scenarios, with some projecting 10 billion tonnes and higher (26 times the average modelled production in 2020). The feasibility of such large bioenergy expansion is debated and, therefore, to mitigate the impact of outlier scenarios on the calculated benchmarks, scenarios whose projected energy crop production in 2100 falls into the upper 5% of the distribution were excluded. This criterion excludes 19, leaving a final group of 223 scenarios.

[10] The 92.15% figure is derived from Cassidy et al. [30], who show that crops used for industrial uses, including biofuels, make up 9% of crops by mass. The authors are not able to provide the share of all crops allocated to industrial uses excluding biofuels, so this is estimated by calculating 9% of the sum of energy and non-energy crop production in 2010 (the closest year in the scenario output data to that of Cassidy et al.), subtracting energy crop production, and expressing the residual amount as a share of non-energy crop production. The mean value of this calculation across the 67 scenarios considered is 7.85% and the residual share used for food is 92.15%.

grains, oilseeds, pulses and soybeans. We align the denominator of the benchmark pathways with that of the base year value by dividing the modelled quantities by the conversion factors shown in Table 3.[11] More details on the conversion factor calculations are provided in Appendix 5.

Table 3. Agricultural production conversion factor by IAM and product category

Model	Conversion factor	
	Crops	Livestock products
IMAGE	0.680	0.523
MESSAGE-GLOBIOM	0.688	0.534
REMIND-MAgPIE	0.680	0.523

The scenarios in our analysis provide projections for total CO_2, methane (CH_4) and nitrous oxide (N_2O) from the AFOLU sector.[12] The following assumptions are used to isolate emissions attributable to food producers:

- AFOLU CH_4 emissions are solely due to food-related agricultural production. This is justified by the observation that 99% of anthropogenic CH_4 emissions from agriculture are due to enteric fermentation by livestock (67%), manure management (8%) and flooded rice cultivation (24%). [26]
- AFOLU N_2O emissions due to food crop and livestock production are directly proportional to the share of food crops and livestock in total agricultural production. This is justified by FAO data [20] that show manure left on pasture and manure management account for approximately the same amount of N_2O emissions as synthetic fertilisers, manure applied to soils, crop residues and crop residue burning.
- AFOLU CO_2 is entirely attributable to food processors. As the vast majority of AFOLU CO_2 emissions are due to land-use change,[13] this inclusion is justified by agriculture's major role in driving land conversion. [28] [29]

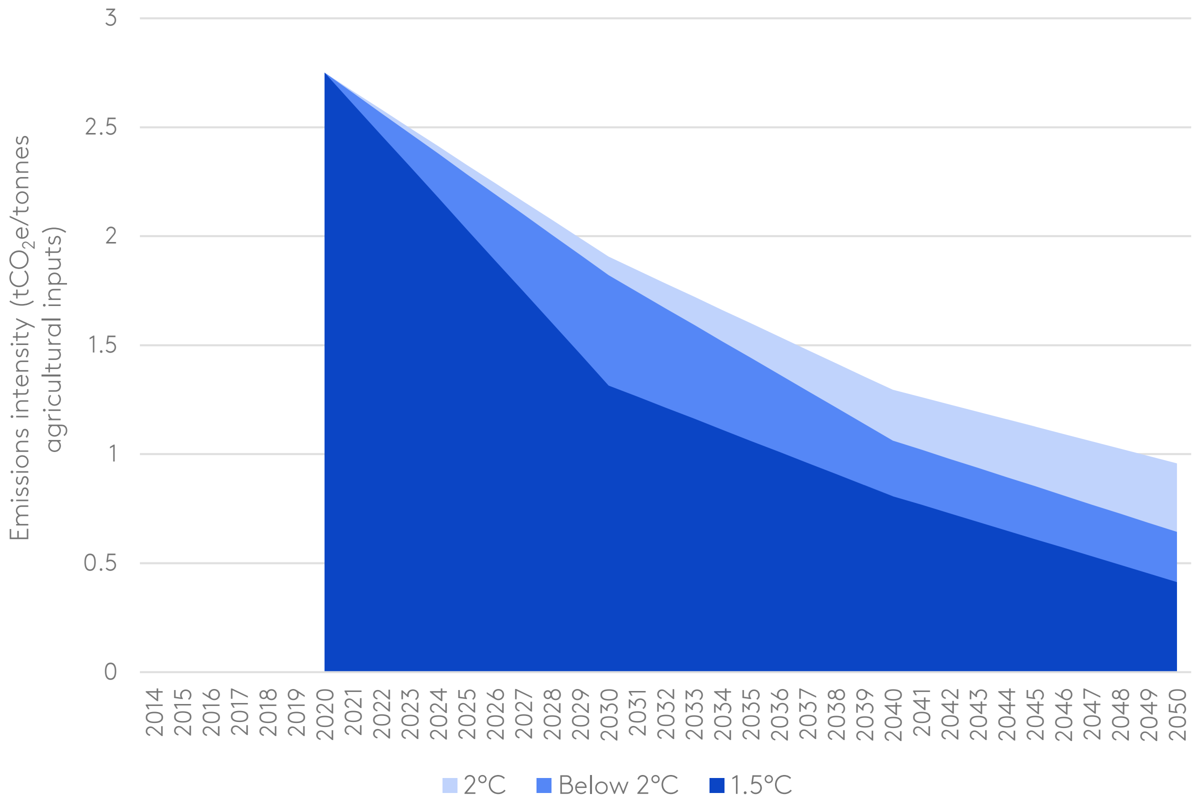
For each scenario, upstream Scope 3 emissions are combined with food processor's Scope 1 and 2 emissions and divided by agricultural production quantities (all calculated using the methods described above). These scenario-specific emissions intensities are converted into a pathway for each warming scenario using the averaging approach developed in Dietz et al.[14] and calculating the change in intensity from 2020 (the closest modelled year to 2019, which is the year used to calculate a baseline emissions value). The resulting benchmark pathways are shown in Table 4 and Figure 2 below.

[11] The conversion factors are a weighted mean across the agricultural commodities modelled by each IAM. The factors are taken as 1 for cereal crops, oilseeds, pulses, and soybeans and the dry matter percentage for other crops and livestock products. The weights are calculated using FAO production data as commodity production values in 2019 expressed as a share of all production across modelled commodities, calculated separately for crops and livestock products. The conversion factors are the same for IMAGE 3.0.1 and REMIND-MAgPIE 1.7-3.0 as these models simulate essentially the same suite of agricultural commodities.
[12] CH_4 and N_2O emissions are converted to CO_2e using the 100-year Global Warming Potentials from the IPCC Sixth Assessment report. [27]
[13] See Figure 7.3.a in IPCC AR6 WGI Chapter 7. [27]
[14] Specifically, the emissions intensities were first averaged across scenarios within IAM and warming category. The warming scenario value of these variables was then calculated as a weighted mean of the within-IAM averages, using equal weights across IAMs.

Table 4. Emissions intensity benchmark pathway by warming scenario (tCO_2e/tonne agricultural inputs)

Warming scenario	2020	2030	2040	2050
1.5°C	2.751	1.315	0.807	0.414
Below 2°C	2.751	1.821	1.063	0.643
2°C	2.751	1.906	1.295	0.958

Figure 2. Emissions intensity benchmark pathway by warming scenario



3. Carbon Performance assessment of food producers

3.1. Measuring companies' emissions intensities

In some cases, food producing companies do not publicly disclose the data necessary to calculate their emission intensities according to TPI's sectoral benchmarks. The most common related issues and how we address them are described as follows:

- Emissions from purchased agricultural goods may not be disclosed by the company (i.e. when Scope 3 category 1 emissions are not broken down into further sub-categories). In this case, Scope 3 emissions category 1 - purchased goods and services are used as a proxy. By adopting this approach, emissions due to non-agricultural inputs and purchased services are also included in a company's emissions intensity, along with purchased agricultural goods. However, data from companies that disclose both emissions categories show that purchased agricultural inputs account for the vast majority of total Scope 3 purchased goods and services emissions. Thus, although this approximation causes a minor upward bias in our calculated emissions intensity relative to the scope of emissions covered in the benchmark pathways, we are confident that the magnitude of this bias is negligible.
- Emissions from land use, land use change and forestry (LULUCF) are required to be explicitly included in company's reports. This provides insights regarding the reporting accuracy of companies. Where this is not provided, the TPI Centre analyses on a case-by-case basis whether a company's disclosure is suitable for a Carbon Performance assessment.
- Sourced agricultural inputs may not disclosed by the company. Broadly, few companies disclose raw input materials by weight (excluding packaging materials), which is required to calculate an emissions intensity metric comparable to the benchmark pathways. Where this metric is unavailable, we are unable to estimate the emissions intensity of the company.

3.2. Emissions reporting boundaries

Companies disclose emissions using different organisational boundaries. There are two high-level approaches: (i) the equity share approach and (ii) the control approach, within which control can be defined as financial or operational. Companies are free to choose which organisational boundary to set in their voluntary disclosures, and there is variation across the companies assessed by TPI.

The TPI Centre accepts emissions reported using any of the above approaches to setting organisational boundaries, as long as:

- The boundary that has been set appears to enable a representative assessment of the company's emissions intensity; and
- The same boundary is used for reporting company emissions and activity, to obtain a consistent estimate of emissions intensity.

Currently, limiting the assessment to one particular type of organisational boundary would severely restrict the breadth of companies that can be assessed.

When companies report historical emissions or emissions intensities using both equity share and control approaches, a reporting boundary is chosen based on which method provides the longest available time series of disclosures or is the most consistent with disclosure on activity and any targets.

3.3. Data sources and validation

All TPI Centre's data are based on companies' own disclosures. The sources for the Carbon Performance assessment include responses to the annual CDP questionnaire, as well as companies' own reports, e.g. sustainability reports.

Given that TPI's Carbon Performance assessment is both comparative and quantitative, it is essential to understand exactly what the data in company disclosures refer to. Company reporting varies not only in terms of what is reported, but also in terms of the level of detail and explanation provided. The following cases can be distinguished:

- Companies that provide data in a suitable form and with enough detail for analysts to be confident that appropriate measures can be calculated or used.
- Companies that provide enough detail in their disclosures, but not in a form that is suitable for the assessment (e.g. they do not report the measure of company activity needed). These companies cannot be included in the assessment.
- Companies that do not provide enough detail on the data disclosed (e.g. the company reports an emissions intensity estimate, but does not explain precisely what it refers to). These companies are also excluded from the assessment.
- Companies that do not disclose their carbon emissions or activity.

Once a preliminary Carbon Performance assessment has been made, it is subject to the following procedure to provide quality assurance:

- Internal review: the preliminary assessment is reviewed by an analyst that was not involved in the original assessment.
- Company review: the reviewed assessment is sent to the company, which has the opportunity review it and confirm the accuracy of the disclosures used. This review includes all companies, including those who provide unsuitable or insufficiently detailed disclosures.
- Final assessment: feedback from the company is reviewed and incorporated if it is considered appropriate. Only information in the public domain can be accepted as a basis for any change.

3.4. Responding to companies

Giving companies the opportunity to review their Carbon Performance assessments is an integral part of the TPI Centre's quality assurance process. Each company receives its draft assessment and the data that underpins the assessment, offering them the opportunity to review and comment on the data and assessment. We also allow companies to contact us at any point to discuss their assessment.

If a company seeks to challenge its result or representation, our process is as follows:

- The TPI Centre reviews the information provided by the company. At this point, additional information may be requested.
- If it is concluded that the company's challenge has merit, the assessment is updated and the company is informed.
- If it is concluded that there are insufficient grounds to change the assessment, the original assessment is published.
- If the company requests an explanation regarding its feedback after the publication of its assessment, the TPI Centre explains the decisions taken.
- If a company requests an update of its assessment based on data publicly disclosed after the research cut-off date communicated to the company, the new disclosure is noted on the company's profile on the TPI Centre website.

If a company chooses to further contest the assessment and reverts to legal means to do so, the company's assessment is withheld from the TPI Centre website and the company is identified as having challenged its assessment.

3.5. Presentation of assessment on the TPI Centre website

The results of the Carbon Performance assessments are posted on TPI Centre's online tool (https://www.transitionpathwayinitiative.org/tpi/sectors). On each company page, its emissions intensity path is plotted on the same chart as the benchmark paths for the relevant sector. Different companies can also be compared on the toolkit main page, with the user free to choose which companies to include in the comparison.

4. Company emissions disclosures

4.1. Measure of emissions intensity

In applying the SDA to the food sector, the specific measure of emissions intensity is:

- Scope 1, 2 and 3 (purchased agricultural goods) emissions, in units of tonnes of CO_2 equivalent per tonne of agricultural inputs.

Recognising that most emissions stem from the sourcing of food producers' agricultural inputs, the scope of the assessment includes emissions from purchased goods – including emissions due to land use change – plus the contribution from direct and indirect operational emissions (i.e. Scope 1 and 2). The denominator in the intensity measure is agricultural inputs rather than food products, as the former aligns more closely with the commodities modelled by the IAMs used to derive the benchmark pathways.

4.2. Coverage of targets

Companies disclose various types of emissions reduction targets, but they can be broadly categorised into absolute emissions targets and emissions intensity targets. Absolute emissions targets are expressed in terms of a decrease in total company emissions. In contrast, emissions intensity targets are expressed in terms of company emissions per unit of output or activity and make no direct reference to total emissions. To convert an absolute emissions target into an intensity target, an assumption is made about the future growth of agricultural inputs purchased by the company. Consistent with the approach adopted in other TPI sectors, our food sector assessment assumes that a company's agricultural inputs grow in line with projected agricultural production calculated using the IAMs described above. If both an absolute and intensity target are disclosed, we verify that they are consistent with each other. If so, we prefer the intensity target. If not, further research is needed to accurately reflect a company's decarbonisation pathway.

Targets can cover different scopes of emissions and apply either to specific operations or to the whole organisation. When company targets do not cover the full scope of our analysis, assumptions are required to calculate how emissions outside the scope of the target evolve. Consistent with the approach used in other sectors, we assume that the emissions intensity of activities outside the scope of the target remains constant at the level of the latest disclosure year. In the food sector, companies' targets typically include more Scope 3 categories than solely purchased agricultural goods. In this case, we assume that emission reduction efforts are uniform across all scopes covered (i.e. ruling out that some emissions categories are reduced at a faster rate than others).

Some companies disclose net targets. Unlike gross targets, net targets include offsets or carbon removals, either within company boundaries or outside of them. Currently, the TPI Centre accepts both types of targets and does not make an explicit distinction between them. Although we recognise additional risks related to relying heavily on offsetting, it is in principle, a cost-effective mechanism for reducing emissions. Only a few companies currently disclose in detail the contribution of offsets to their overall targets.

Furthermore, some companies disclose a target range. In this case, the upper bound value is used. Finally, most companies express targets relative to emissions in a base year. However, some companies disclose targets without disclosing the base year. The TPI Centre then assumes that the base year is the latest year of disclosure prior to the publication of the target.

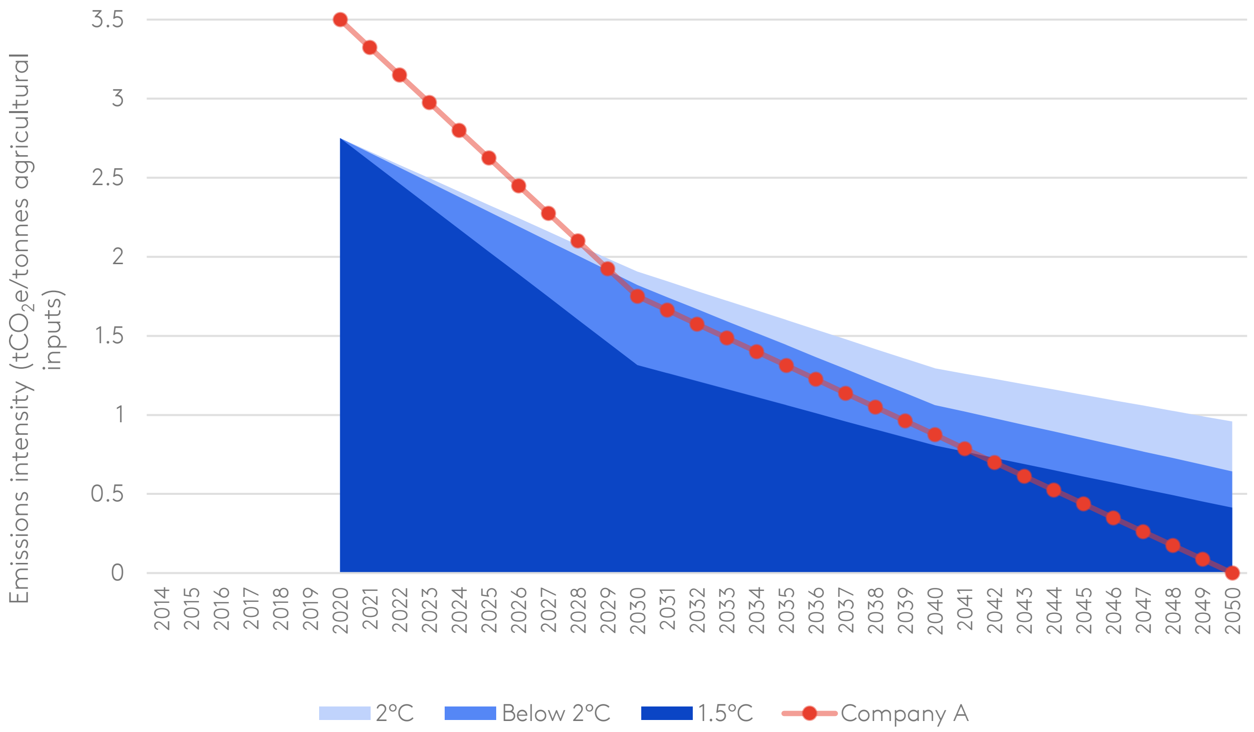
4.3. Worked examples

Company A: a straightforward calculation

Company A reports its emissions intensity in the required metric, i.e. Scope 1, 2 and 3 (from purchased agricultural inputs) in carbon dioxide equivalent per unit of agricultural input. For example, in 2020 it was 3.5 tCO_2e/tonne of agricultural input. These figures are used directly without adjustment.

Company A has also set a target to reduce its emissions intensity to 1.75 tCO_2e/tonne of agricultural input by 2030 and to 0 tCO_2e/tonne of agricultural input by 2050. After verifying that the target emissions intensities are expressed in a manner consistent with the historical emissions intensity disclosures, the target figures are used without adjustment.

Figure 3. Company A's emissions-intensity pathway compared to sectoral benchmarks



Company B: emissions reported in a consistent unit and target reported on an absolute emissions reduction basis

Company B reports its absolute Scope 1, 2 and 3 greenhouse gas emissions (from purchased goods and services) in carbon dioxide equivalent and discloses its yearly used agricultural inputs in tonnes. For example, Company B discloses that its Scope 1, 2 and 3 greenhouse gas emissions (from purchased goods and services) were 29.50 $MtCO_2e$ in 2020. Aggregating its input portfolio mix, it used 10 million tonnes of agricultural inputs in 2020.

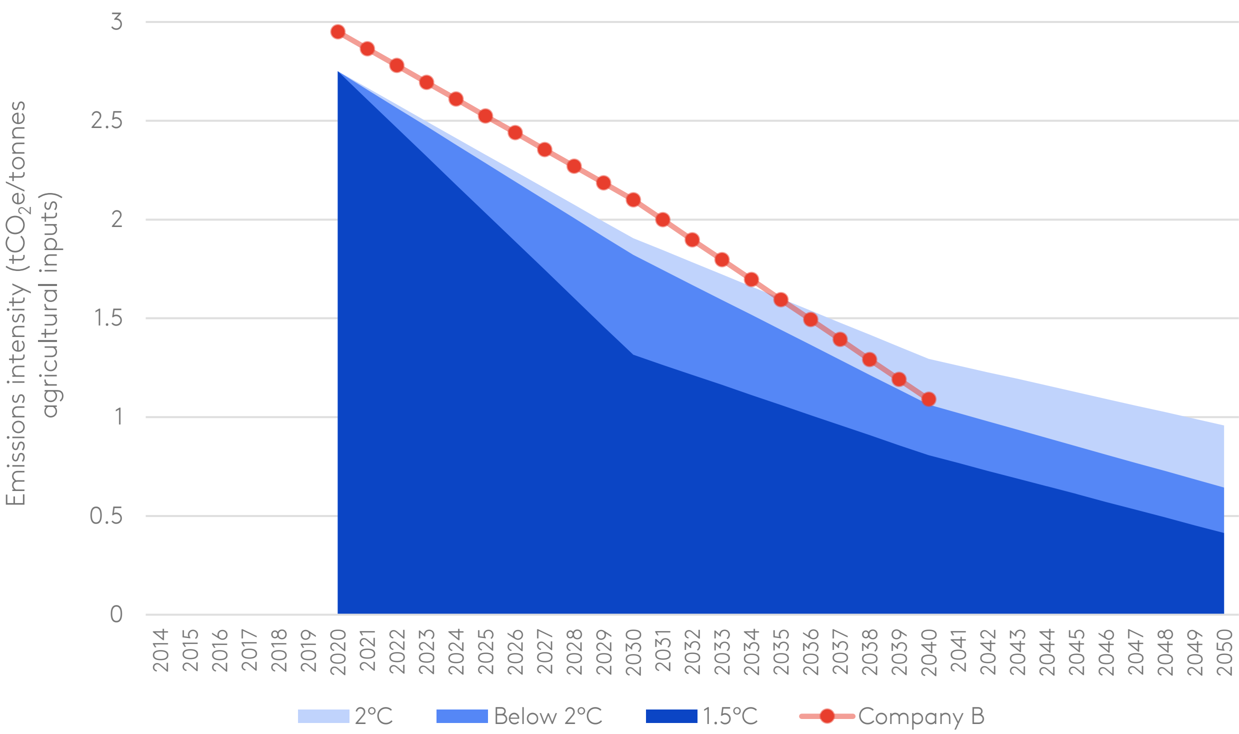
Company B also has a target to reduce its Scope 1, 2 and 3 (from purchased goods and services) emissions by 25% compared with 2020 levels by 2030 and 60% by 2040. We assume this target applies uniformly to the company's Scope 3 emissions from sourced agricultural inputs. In order to translate this information into an estimate of emissions intensity between 2020 and 2040, the following steps are taken:

- First, using TPI's food producers' benchmarks, the emissions intensity for the year 2020 is calculated as equivalent to 2.95 tCO_2e/tonne of agricultural input (29.5 $MtCO_2e$ / 10 million tonnes of agricultural inputs).
- Second, the 2020 emissions from Scope 1, 2 and 3 emissions (from purchased goods and services) are 29.5 $MtCO_2e$. The company's target is understood to cover 100% of all such emissions. Hence,

the targeted absolute emissions for Company B in 2030 and 2040 will be: 22.13 MtCO2e (29.5 x [1 – 25%]) and 11.8 MtCO2e (29.5 x [1 – 60%]) respectively.

- Third, as the company does not provide an intensity target, its sourced agricultural inputs between 2020 and 2040 are assumed to grow according to the global agricultural input production forecasts from several IAMs under a business-as-usual scenario. In this scenario, global agricultural production grows cumulatively by 5.5% between 2020 and 2030 and 8.7% between 2020 and 2040. The company's used agricultural inputs in 2020 totalled 10,000,000 tonnes, and its used agricultural inputs in 2030 and 2040 can be estimated at 10,550,000 tonnes (10,000,000 x [1 + 5.5%]) and 10,870,000 tonnes (10,000,000 x [1 + 8.7%]) respectively.
- Fourth, dividing the company's estimated 2030 and 2040 absolute emissions by these estimates of agricultural inputs for the same years gives estimated intensities of 2.10 tCO_2e ÷ tonne of agricultural inputs (22.13 $MtCO_2e$ / 10,550,000) for 2030, and 1.09 tCO_2e / tonne of agricultural inputs (11.8 / 10,870,000 tonne of agricultural inputs) for 2040.

Figure 4. Company B's emissions-intensity pathway compared with sectoral warming benchmarks



5. Discussion

This methodology note has described the methodology followed by the TPI Centre in carrying out the Carbon Performance assessment of food producing companies.

The Carbon Performance assessment is designed to be robust yet easy to understand and use. There are inevitably many nuances surrounding each company's individual performance, how it relates to the benchmarks, and why. Investors may wish to dig deeper into companies' assessments in their engagements with them to better understand these.

5.1. General issues

The Carbon Performance assessment of food producing companies follows the Sectoral Decarbonisation Approach (SDA), which involves comparing companies' emissions intensity with sector-specific benchmark emissions intensities that are consistent with international targets (i.e. limiting global warming to 1.5°C, well below 2°C and a 2°C scenario).

The TPI Centre uses IAMs from the academic literature to calculate the benchmark pathways, as compiled by IPCC. The models used have a number of advantages, but they are also subject to limitations. In particular, model projections often turn out to be wrong, which means that comparisons between companies and the benchmark pathways may also be inaccurate. However, there is no way to escape the need to make projections of the future in forward-looking exercises like this. Models tend to be regularly updated with the aim of improving their accuracy, and the TPI Centre updates its benchmark pathways accordingly.

The TPI Centre uses companies' self-reported emissions and activity data to derive emissions intensity paths. Therefore, companies' paths are only as accurate as the underlying disclosures.

Estimating the recent, current and especially the future emissions intensity of companies involves making a number of assumptions. Therefore, it is important to bear in mind that the emissions pathway drawn for each company is an estimate made by the TPI Centre, based on information disclosed by companies, rather than the companies' own estimates or targets. In other cases, the information disclosed by companies alone is sufficient to completely characterise the emissions intensity pathway.

5.2. Issues specific to food producers

In applying the SDA methodology to food producers, a key consideration is that the vast majority of emissions stem from the food producers' agricultural inputs. Therefore, the scope of the assessment should include emissions from purchased goods, including emissions due to land use change and the contribution of direct and indirect operational emissions (i.e. Scope 1 and 2).

We have chosen agricultural inputs, rather than food products, to serve as the measure of physical production and denominator of the sector's emissions intensity. The former aligns more closely with the commodities that are modelled by the IAMs used to derive the benchmark pathways. Hence, the specific measure of emissions intensity developed by the TPI Centre for food producers is Scope 1, 2, and 3 (purchased agricultural goods) emissions in units of tonnes of CO_2 equivalent per tonne of agricultural inputs.

Food producing companies do not always publicly disclose the data necessary to calculate this measure. Companies often do not disaggregate Scope 3 Category 1 emissions (from purchased goods and services) into sub-categories that contain specific data on emissions attributable to sourced agricultural inputs. In such cases, we use the former to approximate emissions (Scope 3, Category 1). This causes a slight upward bias in the calculated emissions intensity for food producers, but this is negligible. On the other hand, the quantity of sourced agricultural inputs in physical units is rarely disclosed by companies. In cases where this metric is not provided, we are unable to provide an assessment.

Food producing companies typically describe the methodology used to estimate their Scope 3 emissions from purchased goods and services in their CDP disclosures. In several instances, changes to these methodologies lead to large year-on-year increases in disclosed emissions, which are implausible given changes in production over the same period. In these instances, we adjust the disclosed emissions values to be consistent using an average ratio of emissions calculated over the period for which the methodology is constant.[15]

Supply chains are complex in the food industry, with many ingredients feeding into diverse product portfolios. Food producers' product portfolios are likely to be a principal driver of their emissions intensities, depending on the emissions factors of the commodities they predominantly produce. Meat and dairy producers are expected to be the highest emitters given the high lifecycle emissions of these products [9]. Companies that are taking early action to diversify their product portfolio to include more plant-based alternatives with lower emissions factors are expected to make a faster transition to a 1.5°C-aligned pathway.

For companies sourcing agricultural commodities (especially beef, soy and palm oil), a major driver of their emissions outside of direct operations is often linked to agriculturally induced land-use change and deforestation. To date, the lack of reporting from food producers around agricultural input use has prevented more companies from being included in the analysis of food-producing companies and a more in-depth analysis of the drivers of emissions intensity across the supply chain. Food producing companies also vary widely in their business structures, due to the stages of food production included in their direct operations. For example, a predominantly vertically integrated firm that owns farms and produces and processes food products itself, should be in a better position to accurately report its Scope 3 emissions, as it should be able to exercise more significant and direct control over its supply chains.

[15] Production volume is used if this is disclosed, and revenue if it is not.

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Appendix 1. Food commodities excluded from the assessment

Reason for exclusion	FAO item name	FAO item code
Alcoholic beverage	Beer of barley	51
	Wine	564
Duplicate	Offals, edible, buffaloes	948
	Butter and ghee, sheep milk	983
	Butter, buffalo milk	952
	Butter, cow milk	886
	Butter, goat milk	1022
	Cheese, buffalo milk	955
	Cheese, goat milk	1021
	Cheese, sheep milk	984
	Cheese, skimmed cow milk	904
	Cheese, whole cow milk	901
	Cream fresh	885
	Ghee, buffalo milk	953
	Ghee, butteroil of cow milk	887
	Milk, dry buttermilk	899
	Milk, skimmed condensed	896
	Milk, skimmed cow	888
	Milk, skimmed dried	898
	Milk, skimmed evaporated	895
	Milk, whole condensed	889
	Milk, whole dried	897
	Milk, whole evaporated	894
	Whey, condensed	890
	Whey, dry	900
	Yoghurt	891
	Eggs, hen, in shell (number)	1067
	Eggs, other bird, in shell (number)	1092
	Chillies and peppers, dry	689
	Maize, green	446
	Offals, edible, camels	1128
	Offals, edible, cattle	868
	Offals, edible, cattle	868
	Offals, edible, goats	1018
	Offals, horses	1098

	Offals, pigs, edible	1036
	Offals, sheep, edible	978
	Fat, buffaloes	949
	Fat, camels	1129
	Fat, goats	1019
	Fat, sheep	979
	Margarine, short	1242
	Oil palm fruit	254
	Oil, maize	60
	Oilseeds n.e.s*	339
	Rapeseed	270
	Rice, paddy	27
	Safflower seed	280
	Sugar beet	157
	Sugar cane	156
	Sugar crops n.e.s	161
	Onions, dry	403
	Peas, dry	187
	Palm kernels	256
Non-food product	Triticale	97
	Agave fibres n.e.s	800
	Bastfibres, other	782
	Beeswax	1183
	Canary seed	101
	Castor oil seed	265
	Chicory roots	459
	Coir	813
	Cotton lint	767
	Cottonseed	329
	Fibre crops n.e.s	821
	Flax fibre and tow	773
	Hemp tow waste	777
	Hempseed	336
	Hides, buffalo, fresh	957
	Hides, cattle, fresh	919
	Jojoba seed	277
	Jute	780
	Kapok fruit	310
	Linseed	333
	Lupins	210
	Manila fibre (abaca)	809
	Melonseed	299

	Oil, cottonseed	331
	Oil, linseed	334
	Pyrethrum, dried	754
	Ramie	788
	Rubber, natural	836
	Seed cotton	328
	Silk-worm cocoons, reelable	1185
	Silk, raw	1186
	Sisal	789
	Skins, goat, fresh	1025
	Skins, sheep, fresh	995
	Tallow	1225
	Tallowtree seed	305
	Tobacco, unmanufactured	826
	Vetches	205
	Wool, greasy	987
Small production value and no credible emissions factor	Areca nuts	226
	Meat, camel	1127
	Meat, game	1163
	Meat, horse	1097
	Meat, mule	1111
	Meat, other camelids	1158
	Meat, other rodents	1151
	Meat nes	1166
	Meat, ass	1108
	Poppy seed	296
	Cloves	698
	Mustard seed	292
	Anise, badian, fennel, coriander	711
	Spices nes	723
	Vanilla	692
	Maté	671
	Hops	677
	Fat, cattle	869
	Fat, pigs	1037
	Lard	1043
Subsistence product	Bambara beans	203

*n.e.s = not elsewhere specified

Appendix 2. Adjustments made to commodity weights

SUA adjustment type	FAO item name	FAO item code	Weight (tonnes)	SUA adjustment factor	Other ad hoc weight adjustment	Final weight (tonnes)	Source for ad hoc weight adjustments
Food as % of production	Groundnuts, with shell	242	48756790	0.156	Shell removed from weight	5321348	https://openknowledge.fao.org/server/api/core/bitstreams/133abe54-26f6-48a5-afeb-e512bcc37ebb/content
	Coconuts	249	62455084	0.339		21144677	
	Dates	577	9075446	0.849		7708168	
	Rice, paddy (rice milled equivalent)	30	503901025	0.900		453738111	
	Sesame seed	289	6549725	0.306		2003270	
	Soybeans	236	333671692	0.023		7803089	
	Sunflower seed	267	56072746	0.007		395622	
Food and processed as % of production	Meat, goat	1017	6252564	0.953	Bone removed from carcass weight	4689423	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4093053/
	Sugar, raw centrifugal (sugar beet portion)	162	182166152	0.972	Total centrifugal sugar divided into sugar cane portion	36433230	https://www.isosugar.org/sugarsector/sugar
	Sugar, raw centrifugal (sugar cane portion)	162	182166152	0.972	Total centrifugal sugar divided into sugar cane portion	145732922	https://www.isosugar.org/sugarsector/sugar

	Brazil nuts, with shell	216	70256	0.985	Shell removed from weight	38051	https://openknowledge.fao.org/server/api/core/bitstreams/133abe54-26f6-48a5-afeb-e512bcc37ebb/content
	Cashew nuts, with shell	217	3960680	1.054	Shell removed from weight	990170	https://openknowledge.fao.org/server/api/core/bitstreams/133abe54-26f6-48a5-afeb-e512bcc37ebb/content
	Hazelnuts, with shell	225	1125178	0.944	Shell removed from weight	531041	https://openknowledge.fao.org/server/api/core/bitstreams/133abe54-26f6-48a5-afeb-e512bcc37ebb/content
	Walnuts, with shell	222	4498442	0.929	Shell removed from weight	2384174	https://openknowledge.fao.org/server/api/core/bitstreams/133abe54-26f6-48a5-afeb-e512bcc37ebb/content
	Meat, turkey	1080	5991771	0.971	Bone removed from carcass weight	4361741	https://www.e3s-conferences.org/articles/e3sconf/pdf/2021/49/e3sconf_interagromash2021_02019.pdf
	Meat, cattle (beef herd)	867	68313894	0.982	Total cattle herd divided into beef herd portion Bone removed from carcass weight	57436970	https://www.ciwf.org.uk/media/5235182/Statistics-Dairy-cows.pdf; https://www.diva-portal.org/smash/get/diva2:943348/FULLTEXT01.pdf https://www.ers.usda.gov/webdocs/publications/41880/33132_ah697_002.pdf
	Meat, cattle (dairy herd)	867	68313894	0.982	Total cattle herd divided into dairy herd portion Bone removed from carcass weight	4087239	https://www.ciwf.org.uk/media/5235182/Statistics-Dairy-cows.pdf; https://www.diva-portal.org/smash/get/diva2:943348/FULLTEXT01.pdf https://www.ers.usda.gov/webdocs/publications/41880/33132_ah697_002.pdf
	Meat, rabbit	1141	883936	1.013	Bone removed from carcass weight	751346	https://www.canr.msu.edu/resources/rabbit_tracks_meat_quality_and_carcass_evaluation#:~:text=Sometimes%20they%20go%20to%20market,percent%20of%20the%20dressed%20weight
	Meat, pig	1035	110109911	1.094	Bone removed from carcass weight	71571442	https://livestock.extension.wisc.edu/articles/how-much-meat-should-a-hog-yield/
	Meat, goose and guinea fowl	1073	2760973	1.005	Bone removed from carcass weight	2207557	https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.821.8091&rep=rep1&type=pdf

	Wheat	15	765769635	0.694	Convert grain weight to flour equivalent	420275992	https://www.fao.org/fileadmin/templates/ess/documents/methodology/totdoc.pdf
	Coffee, green	656	10035576	0.906	Converted to roasted coffee equivalent	7274396	https://pubs.acs.org/doi/pdf/10.1021/acs.jafc.7b03310
	Apples	515	87236221	0.915		79814977	
	Apricots	526	4083861	0.906		3699662	
	Artichokes	366	1594385	0.896		1428890	
	Asparagus	367	9432062	0.944		8905404	
	Avocados	572	7179689	0.882		6335105	
	Bananas	486	116781658	0.831		97094033	
	Barley	44	158979610	0.272		43223348	
	Beans, dry	176	28902672	0.737		21302340	
	Beans, green	414	26981784	0.954		25753614	
	Berries nes	558	922681	0.841		776059	
	Blueberries	552	823328	1.023		842483	
	Broad beans, horse beans, dry	181	5431503	0.532		2891863	
	Buckwheat	89	1612235	0.261		420962	
	Cabbages and other brassicas	358	70150406	0.868		60866898	
	Carobs	461	46604	0.173		8047	
	Carrots and turnips	426	44762859	0.856		38332593	
	Cashewapple	591	1324050	0.706		331013	
	Cassava	125	303568814	0.838		254312367	
	Cauliflowers and broccoli	393	26918570	0.897		24159049	
	Cereals nes	108	7909001	0.805		6366391	
	Cherries	531	2595812	0.862		2238126	
	Cherries, sour	530	1411608	0.922		1301336	
	Chestnut	220	2406903	0.936		2253480	
	Chickpeas	191	14246295	0.737		3561574	
	Chillies and peppers, green	401	38027164	0.922		9506791	
	Cinnamon (cannella)	693	242635	0.884		214589	
	Cocoa, beans	661	5596397	0.904		5060761	
	Cow peas, dry	195	8903329	0.511		2225832	

	Cranberries	554	687534	0.882		606704	
	Cucumbers and gherkins	397	87805086	0.911		21951272	
	Currants	550	647815	0.973		161954	
	Eggplants (aubergines)	399	55197878	0.935		13799470	
	Eggs, hen, in shell	1062	83483675	0.866		72301491	
	Eggs, other bird, in shell	1091	6039581	0.893		5396194	
	Figs	569	1315588	0.941		328897	
	Fonio	94	700501	0.377		264289	
	Fruit, citrus n.e.s	512	14496484	0.909		13172565	
	Fruit, fresh n.e.s	619	39505413	0.916		36171033	
	Fruit, pome n.e.s	542	127620	0.840		107150	
	Fruit, stone n.e.s	541	608431	0.743		451969	
	Fruit, tropical fresh n.e.s	603	25331691	0.921		23329436	
	Garlic	406	30708243	0.928		7677061	
	Ginger	720	4081374	0.568		1020344	
	Gooseberries	549	80014	0.975		78037	
	Grain, mixed	103	3416985	0.207		706999	
	Grapefruit (incl. pomelos)	507	9289462	0.902		8382702	
	Grapes	560	77137016	0.973		75028495	
	Honey, natural	1182	1852598	0.803		1487200	
	Karite nuts (sheanuts)	263	759764	0.670		509370	
	Kiwi fruit	592	4348011	0.912		3966675	
	Kola nuts	224	306415	0.902		276369	
	Leeks, other alliaceous vegetables	407	2192476	0.921		548119	
	Lemons and limes	497	20049630	0.902		18092487	
	Lentils	201	5734201	0.792		4539206	
	Lettuce and chicory	372	29134653	0.886		25825065	
	Maize	56	1148487291	0.199		186268979	

	Mangoes, mangosteens, guavas	571	55853238	0.900		50275783	
	Meat, buffalo	947	4290212	0.745		3195464	
	Meat, chicken	1058	118017161	0.927		109396656	
	Meat, duck	1069	4858137	0.979		4755612	
	Meat, sheep	977	9922238	0.964		9567764	
	Melons, other (incl. cantaloupes)	568	27501360	0.823		22629735	
	Milk, whole fresh buffalo	951	133752296	0.928		124065560	
	Milk, whole fresh camel	1130	3111462	0.834		2594578	
	Milk, whole fresh cow	882	715922506	0.947		678229684	
	Milk, whole fresh goat	1020	19910379	0.917		18251777	
	Milk, whole fresh sheep	982	10587020	0.901		9535328	
	Millet	79	28371792	0.735		20841226	
	Molasses	165	63705325	0.465		29591840	
	Mushrooms and truffles	449	11898399	0.890		10585314	
	Nutmeg, mace and cardamoms	702	141700	0.734		104025	
	Nuts n.e.s	234	997225	0.836		834015	
	Oats	75	23104147	0.214		4939408	
	Oil, coconut (copra)	252	3278258	0.869		2849742	
	Oil, groundnut	244	5551574	0.865		4802379	
	Oil, olive, virgin	261	3574336	1.027		3670659	
	Oil, palm	257	71468153	0.468		33472777	
	Oil, palm kernel	258	7842084	0.572		4488274	
	Oil, rapeseed	271	24579588	0.444		10908443	
	Oil, sesame	290	1059146	0.782		761701	
	Oil, soybean	237	56912719	0.533		30313431	
	Oil, sunflower	268	18409217	0.696		12813083	
	Okra	430	9953537	0.792		2488384	
	Olives	260	19464495	0.922		4866124	
	Onions, shallots, green	402	4491246	0.972		4363374	

	Oranges	490	78699604	0.911		71674438	
	Papayas	600	13735086	0.900		12366892	
	Peaches and nectarines	534	25737841	0.933		24018394	
	Pears	521	23919075	0.883		21111426	
	Peas, green	417	21766060	0.947		5441515	
	Peppermint	748	74232			74232	
	Persimmons	587	4270074	0.961		4105535	
	Pigeon peas	197	4425969	0.866		3831983	
	Pineapples	574	28179348	0.868		24464250	
	Pistachios	223	911829	0.706		643998	
	Plantains and others	489	41580022	0.902		37512648	
	Plums and sloes	536	12601312	0.938		11817964	
	Potatoes	116	370436581	0.716		265263030	
	Pulses n.e.s	211	4553029	0.609		1138257	
	Pumpkins, squash and gourds	394	22900826	0.850		19473889	
	Quinces	523	666589	0.920		166647	
	Quinoa	92	161415	0.787		126972	
	Roots and tubers n.e.s	149	9871094	0.626		6182696	
	Rye	71	12801441	0.408		5218372	
	Sorghum	83	57893378	0.519		30024788	
	Spinach	373	30107231	0.943		28400304	
	Strawberries	544	8885028	0.903		8022564	
	String beans	423	1387667	0.888		1231626	
	Sweet potatoes	122	91820929	0.631		73456743	
	Tangerines, mandarins, clementines, satsumas	495	35444080	0.887		28355264	
	Taro (cocoyam)	136	10541914	0.590		8433531	
	Tea	667	6497443	0.815		5197954	
	Tomatoes	388	180766329	0.893		144613063	
	Tung nuts	275	332447	0.656		265958	
	Vegetables, fresh n.e.s	463	311823678	0.805		249458942	

	Vegetables, leguminous n.e.s	420	1566331	0.898		1253065	
	Watermelons	567	100414933	0.811		80331946	
	Yams	137	74321821	0.543		59457457	
	Yautia (cocoyam)	135	481199	0.708		120300	
Food and processed as % of use categories	Almonds, with shell	221	3497148	0.960	Shell removed from weight	1846331	https://openknowledge.fao.org/server/api/core/bitstreams/133abe54-26f6-48a5-afeb-e512bcc37ebb/content
	Meat, bird n.e.s	1089	19197	1.000		19197	
	Oil, safflower	281	95728	0.536		47188	
	Pepper (piper spp.)	687	1103024	0.918		1012638	
	Raspberries	547	822493	0.935		768867	
	Snails, not sea	1176	20164	1.000		20164	

Appendix 3. Emissions factors and functional units of commodities

(from Poore and Nemecek)

Commodity	Functional unit	Median global emissions factor
Apples	1 kg of fresh fruit or vegetable	0.4
Bananas	1 kg of fresh fruit or vegetable	0.8
Barley (Beer)	1 litre of beer	1.2
Beet Sugar	1 kg of raw/refined sugar	1.8
Berries & Grapes	1 kg of fresh fruit or vegetable	1.4
Bovine Meat (beef herd)	1 kg fat and bone-free meat and edible offal	60.4
Bovine Meat (dairy herd)	1 kg fat and bone-free meat and edible offal	34.1
Brassicas	1 kg of fresh fruit or vegetable	0.4
Cane Sugar	1 kg of raw/refined sugar	3.2
Cassava	1 kg soil free tuber	1.1
Cheese	1 kg cheese	18.6
Citrus Fruit	1 kg of fresh fruit or vegetable	0.3
Coffee	1 kg of ground, roasted beans	8.2
Crustaceans (farmed)	1 kg of head-free meat (shell-free for large shrimp)	14.7
Dark Chocolate	1 kg of dark chocolate	5.0
Eggs	1 kg eggs	4.2
Fish (farmed)	1 kg edible fish	7.9
Groundnuts	1 kg shell free, roasted nut	3.3
Lamb & Mutton	1 kg fat and bone-free meat and edible offal	40.6
Maize (Meal)	1 kg meal (for polenta)	1.2
Milk	1 litre of pasteurized milk (4% fat)	2.7
Nuts	1 kg shell free, dry nut	-1.3

Oats	1 kg rolled oats	2.6
Olive Oil	1 litre of refined/filtered oil	5.1
Onions & Leeks	1 kg of fresh fruit or vegetable	0.4
Other Fruit	1 kg of fresh fruit or vegetable	0.7
Other Pulses	1 kg dry pulse without pod	1.4
Other Vegetables	1 kg of fresh fruit or vegetable	0.4
Palm Oil	1 litre of refined/filtered oil	7.2
Peas	1 kg dry pea without pod	0.8
Pig Meat	1 kg fat and bone-free meat and edible offal	10.6
Potatoes	1 kg soil free tuber	0.5
Poultry Meat	1 kg fat and bone-free meat and edible offal	7.5
Rapeseed Oil	1 litre of refined/filtered oil	3.5
Rice	1 kg full grain white or brown rice	3.7
Root Vegetables	1 kg of soil free tuber	0.4
Soybean Oil	1 litre of refined/filtered oil	3.9
Soymilk	1 litre of soymilk	0.9
Sunflower Oil	1 litre of refined/filtered oil	3.5
Tofu	1 kg tofu (16% protein)	2.6
Tomatoes	1 kg of fresh fruit or vegetable	0.7
Wheat & Rye (Bread)	1 kg bread (variable protein wheat)	1.3
Wine grapes	1 litre of wine	1.6

Appendix 4. Supplementary emissions factors used in this study

FAO item name	FAO item code	Emissions factor (Clune)	Emissions factor (Other source)	Other sources
Cinnamon (cannella)	693	-	0.87	https://assets.wwf.org.uk/downloads/how_low_report_1.pdf
Soybeans	236	-	1.3	https://pubs.acs.org/doi/pdf/10.1021/acs.jafc.7b03310; https://link.springer.com/article/10.1007/s10584-014-1169-1/tables/4
Cocoa, beans	661	-	3.22	https://www.sciencedirect.com/science/article/pii/S0959652607002429
Milk, whole fresh goat	1020		4.94	Authors' calculations using: https://www.fao.org/3/i3461e/i3461e04.pdf https://ec.europa.eu/jrc/sites/default/files/BISO-EnvSust-Food-and-Feed-Milk_141020.pdf https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7492176/
Milk, whole fresh sheep	982	-	5.66	Authors' calculations using: https://www.fao.org/3/i3461e/i3461e04.pdf https://ec.europa.eu/jrc/sites/default/files/BISO-EnvSust-Food-and-Feed-Milk_141020.pdf https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7492176/
Rye	71	0.41	-	
Fonio	94	0.47	-	
Millet	79	0.47	-	
Barley	44	0.49	-	
Grain, mixed	103	0.50605689	-	
Buckwheat	89	0.53391128	-	
Honey, natural	1182	0.795	-	
Sorghum	83	0.88	-	
Sesame seed	289	0.88	-	

Quinoa	92	1.15	-	
Sunflower seed	267	1.41	-	
Oil, coconut (copra)	252	2.1	-	
Meat, duck	1069	3.085	-	
Oil, safflower	281	3.525	-	
Oil, sesame	290	3.525	-	
Milk, whole fresh buffalo	951	3.75	-	
Meat, bird nes	1089	3.7745566	-	
Meat, rabbit	1141	4.7	-	
Oil, groundnut	244	4.717	-	
Meat, turkey	1080	6.04063592	-	
Meat, goat	1017	23	-	
Meat, buffalo	947	55.3956835	-	

Appendix 5. Agricultural production conversion factor calculations

Product	Models	Dry matter share	Factor to apply	FAOSTAT production 2010	Factor weight (share of production across modelled crops)	
					IMAGE; REMIND-MAgPIE	MESSAGE-GLOBIOM
Temperate cereals (wheat, rye, oats, barley, triticale)	IMAGE; REMIND-MAgPIE	0.89	1	960614319	0.16	0.00
Rice	MESSAGE-GLOBIOM; IMAGE; REMIND-MAgPIE	0.89	1	499709669	0.08	0.08
Maize	MESSAGE-GLOBIOM; IMAGE; REMIND-MAgPIE	0.87	1	1141359868	0.19	0.19
Tropical cereals (millet, sorghum)	IMAGE; REMIND-MAgPIE	0.895	1	85695849	0.01	0.00
Pulses	IMAGE; REMIND-MAgPIE	0.91	1	50273736	0.01	0.00
Temperate roots and tubers	IMAGE; REMIND-MAgPIE	0.25	0.25	403982633	0.07	0.00
Tropical roots and tubers	IMAGE; REMIND-MAgPIE	0.33	0.33	464734169	0.08	0.00
Sunflower	MESSAGE-GLOBIOM; IMAGE; REMIND-MAgPIE	0.923	1	56020665	0.01	0.01
Soybean	MESSAGE-GLOBIOM; IMAGE; REMIND-MAgPIE	0.91	1	336329392	0.06	0.06
Groundnut	MESSAGE-GLOBIOM; IMAGE; REMIND-MAgPIE	0.91	1	49544191	0.01	0.01
Rapeseed	MESSAGE-GLOBIOM; IMAGE; REMIND-MAgPIE	0.923	1	71838655	0.01	0.01
Sugarcane	MESSAGE-GLOBIOM; IMAGE; REMIND-MAgPIE	0.32	0.32	1955307695	0.32	0.33
Barley	MESSAGE-GLOBIOM	0.89	1	158462601	0.00	0.03
Dry beans	MESSAGE-GLOBIOM	0.91	1	26095060	0.00	0.00
Cassava	MESSAGE-GLOBIOM	0.33	0.33	299028225	0.00	0.05
Chickpea	MESSAGE-GLOBIOM	0.91	1	14184449	0.00	0.00
Cotton	MESSAGE-GLOBIOM	0.935	1	45377342	0.00	0.01
Millet	MESSAGE-GLOBIOM	0.9	1	28333094	0.0	0.00
Potatoes	MESSAGE-GLOBIOM	0.25	0.25	354812093	0.00	0.06
Sorghum	MESSAGE-GLOBIOM	0.89	1	57362755	0.00	0.01

Sweet potatoes	MESSAGE-GLOBIOM	0.33	0.33	91490303	0.00	0.02
Wheat	MESSAGE-GLOBIOM	0.89	1	764980821	0.00	0.13

Product	Models	Dry matter share	Factor to apply	FAOSTAT production 2010	Factor weight (Share of production across modelled livestock products)		
					IMAGE	REMIND-MAgPIE	MESSAGE-GLOBIOM
Bovine meat	MESSAGE-GLOBIOM; IMAGE	0.39	0.39	67915624	0.06	0.00	0.06
Bovine milk	MESSAGE-GLOBIOM	0.54	0.54	708264265	0.00	0.00	0.62
Small ruminant meat	MESSAGE-GLOBIOM; IMAGE	0.65	0.65	15550194	0.01	0.00	0.01
Small ruminant milk	MESSAGE-GLOBIOM	0.54	0.54	30684320	0.00	0.00	0.03
Pig meat	MESSAGE-GLOBIOM; IMAGE; REMIND-MAgPIE	0.59	0.59	109635731	0.10	0.10	0.10
Poultry meat	MESSAGE-GLOBIOM; IMAGE; REMIND-MAgPIE	0.25	0.25	123630097	0.11	0.11	0.11
Eggs	MESSAGE-GLOBIOM; IMAGE; REMIND-MAgPIE	0.767	0.767	84363316	0.07	0.07	0.07
Ruminant meat	REMIND-MAgPIE	0.595	0.595	83465818	0.00	0.07	0.00
Milk	IMAGE; REMIND-MAgPIE	0.54	0.54	738948585	0.65	0.65	0.00
Bovine meat	MESSAGE-GLOBIOM; IMAGE	0.39	0.39	67915624	0.06	0.00	0.06

Appendix 6. Agricultural production conversion factor calculations

Value chain stage	Included	Excluded
Land use change	Above ground C Stock Change (CO_2) Below ground C Stock Change (CO_2) Forest burning (CH_4, CO_2) Organic soil burning (CO_2, CH_4, N_2O)	Leaching, runoff and induced non-CO_2 emissions.
Crop production	Seed nursery Inputs production Machinery Greenhouse and trellis infrastructure Electricity and fuel Fertiliser and retained crop residue (N_2O, NH_3, NO_2, NO_3, NH_4+, P, N) Urea and lime (CO_2) Flooded rice (CH_4) Residual burning (CH_4, N_2O, NH_3, NO_2) Cultivation of drained organic soils (CO_2, CH_4) Drying/grading Irrigation water consumptionLand use: seed; fallow; arable and permanent crops	Soil emissions (CH_4) Organic fertiliser application (CH_4) N fixation emissions C sequestration in crop residue Runoff (N) Residue burning indirect emissions (N_2O) Human labour
Livestock/Aquaculture	Pasture management (same as for food/feed) Feed processing Housing energy use Enterica fermentation (CH_4) Manure management (N_2O, NO_x, NH_3, CH_4) Aquaculture ponds (N, P, N_2O, NO_x, NH_3, CH_4) Drinking and service water Land use: permanent pasture; temporary pasture; aquaculture ponds	Infrastructure Pasture residue (emissions or burning) Pasture N fixation emissions Pasture runoff (N) Manure management (P) Human labour
Processing	Energy (CO_2, NO_x, SO_2) Wood burning (CH_4, N_2O, NO_x, SO_2) Wastewater (CH_4, N_2O, P, N, COD) Incineration (CH_4, N_2O, NO_x, SO_2) Processing water consumption	Miscellaneous inputs Human labour Infrastructure Land use
Packaging	Materials Material transport End of life disposal	Human labour Infrastructure Land and water use
Retail	Energy use	Human labour

		Infrastructure Land and water use
Losses (L) and Transport (T) (CO_2, NO_x, SO_2)	L_1 - Storage and transport L_2 - Processing and packaging L_3 - Wholesale and retail	T_1 - Feed T_2 - Food T_3 - Processed foods

Source: Poore and Nemecek (2018)

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