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CODEX PLANETARIUS

Key Impacts, Metrics, and Minimum Performance Standards for Greenhouse Gases in Food Production

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About *Codex Planetarius*

Codex Planetarius is a proposed system of minimum environmental performance standards for producing globally traded food. It is modeled on the *Codex Alimentarius*, a set of minimum mandatory health and safety standards for globally traded food. The goal of *Codex Planetarius* is to measure and manage the key environmental impacts of food production, acknowledging that while some resources may be renewable, they may be consumed at a faster rate than the planet can renew them.

The global production of food has had the largest impact of any human activity on the planet. Continuing increases in population and per capita income, accompanied by dietary shifts, are putting even more pressure on the planet and its ability to regenerate renewable resources. We need to reduce food production's key impacts.

The impacts of food production are not spread evenly among producers. Data across commodities suggest that the bottom 10-20% of producers account for 60-80% of the impacts associated globally with producing any commodity, even though they produce only 5-10% of the product. We need to focus on the bottom.

Once approved, *Codex Planetarius* will provide governments and trade authorities with a baseline for environmental performance in the global trade of food and soft commodities. It won't replace what governments already do. Rather, it will help build consensus about key impacts, how to measure them, and what minimum acceptable performance should be for global trade. We need a common escalator of continuous improvement.

These papers are part of a multiyear proof of concept to answer questions and explore issues, launch an informed discussion, and help create a pathway to assess the overall viability of *Codex Planetarius*. We believe *Codex Planetarius* would improve food production and reduce its environmental impact on the planet.

This proof-of-concept research and analysis is funded by the Gordon and Betty Moore Foundation and led by World Wildlife Fund in collaboration with a number of global organizations and experts. For more information, visit www.codexplanetarius.org

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Abstract

The food system is responsible for a large proportion of global greenhouse gas (GHG) emissions, the majority of which originate on farms. For a given agricultural product, the GHG footprint, or the emissions per unit of product, varies greatly, due to both location and production practices. For the majority of products, there is strong evidence that relatively few GHG-intensive farms are responsible for an outsized proportion of GHG emissions, relative to their (low) production of food. Thus, a global threshold prohibiting the trade of the most GHG-intensive products can deliver high levels of GHG mitigation while having relatively minor reductions in food production. Potentially, this could result in a 15-20% reduction of GHGs from food production with a 2-5% reduction in food produced. However, enforcing these thresholds across products with very different average emissions intensity could result in disproportionate impact to some foods and thus nutrient sources, suggesting that a tiered threshold (for example, for vegetal and animal source foods) may be preferable from an economic and nutrition standpoint. Tiered thresholds can produce similar GHG reductions to a universal threshold, with only 2-3% reductions while allowing for more balanced production across food groups.

In this study, we explore the potential ramifications of these thresholds on both GHG emissions and food production as well as how these performance thresholds could be set and measured at scale.

Introduction

Why food system change is necessary to tackle climate change

The food system, from cradle-to-grave, is responsible for an estimated 21-37% of the global greenhouse gas emissions (about 17 GtCO_2e/yr).[1, 2] These emissions come from diverse sources: the production of inputs; nitrous oxide emissions related to fertilizer; crop residue; soil organic carbon stock change; carbon loss from land clearing; fuel use for transport; refrigerant releases from cold-chain components; and methane release from ruminants, rice, and waste decay.

Limiting warming to 1.5°C above pre-industrial levels[3] requires tackling the massive amount of total emissions from the food sector. Modeling work affirms this; even if fossil fuel emissions were eliminated today, the biogenic emissions from the food sector alone would preclude limiting temperature rises to 1.5°C.[4] The Koronivia Joint Work on Agriculture, in which the United Nations Framework Convention on Climate Change (UNFCCC) calls for interrelated topics in agriculture including food-security to be considered as part of climate solutions, underscores the increasing recognition of this nexus.[5]

Role of food sector in 1.5°C pathways

Quantifying the necessary emissions reductions over time from different sectors in order to limit warming to 1.5°C requires modeling both how sectoral emissions might evolve (in a way that is economically, politically, and physically reasonable) and how those emissions influence temperature. Sophisticated climate models called integrated assessment models include simulation of both physical processes of how the planet warms and economic processes like how agriculture will expand to meet food demand. To limit warming to 1.5°C, emissions from the global food system need to decline from a 2020 baseline by an absolute 80% by 2050, while we produce more food for a growing human population, which means emissions intensity must decline by more than 80%[6] for many products even while production increases. Because food production has numerous emissions sources with different impacts and mitigation potential, the degree of mitigation needed and time frame for those changes differ **(see Figure 1[7], page 16)**.

Specifically, the food-system is responsible for the following:

1. Commodity-driven deforestation and non-forest conversion needs to quickly decline and reach zero by 2030, with all other agriculturally driven conversion[8] going to zero by approximately 2035.
2. On-farm emissions from sources like soil nitrous oxide emissions or enteric methane need to decline by about 40% by 2050.[9]
3. Significant changes in soil management (tillage, cover cropping, silvopasture, etc.) will need to sequester about 1.3 Gt CO_2e/yr (up from about 0 or even positive emissions currently) and about the same amount through agroforestry or other restoration on agricultural lands.
4. Emissions from fossil-sources (energy, industry, and waste) both on- and off-farm will need to decline by over 85% from current levels by 2050.

Two roadmaps, the FAO & SBTi 1.5°C roadmaps, provide additional breakdowns of the sources of emissions and of the specific commodities that contribute to the necessary mitigation. See **Annex I (page 7)**. These roadmaps quantify what aggregate emissions rates are acceptable or not.

In short, 2050 net emissions from the food sector are below 4GtCO₂e/yr, having fallen at a roughly linear rate of about 3% per year starting in 2020 from a 2020 baseline.[10, 11, 12]

Overview of food system emissions

For the food system as a whole, emissions are roughly split between (1) non-CO_2 emissions from agricultural production, (2) CO_2 emissions from land-use and land-use change, and (3) all other supply-chain emissions. A rough breakdown of magnitude:[13]

- **Land use and land-use change (LUC)** for agriculture (including deforestation and conversion of other natural ecosystems such as grasslands, peatlands, mangroves, and others, as well as the emissions from degradation, e.g., from drained organic soils): 5.9 $GtCO_2e$/yr
- **Methane** from agriculture (ruminants, manure, and rice): 4.0 $GtCO_2e$/yr
- Nitrous oxide from **fertilized soils and manure:** 2.2 $GtCO_2e$/yr
- **Upstream & on-farm fossil emissions:** 1 – 1.5 $GtCO_2e$/yr
  - **Embedded in input production:** 0.6 $GtCO_2e$/yr
  - **Electricity and fuel use:** 0.7 $GtCO_2e$/yr
- **Transport:** 0.8 $GtCO_2e$/yr
- **Processing & packaging:** 1.4 $GtCO_2e$/yr
- **Retail & consumption:** 1.2 $GtCO_2e$/yr
- **Waste:** 1.5 $GtCO_2e$/yr

If we break these emissions into some of the common categories we get the following results **(Table 1, page 14)**, also broken down into industrialized and developing countries.

Variability in food production emissions

The total emissions from food production come from many processes that are used to produce many different foods. The emissions intensity, or the emissions per unit of product or per area of farmland, varies dramatically across different products; when these different intensities are multiplied by the (also variable) amounts of products grown, the total contribution by different foods is markedly different. This distinction is critical when thinking about the differences between the most emissions-intense products inclusive of all foods (which might disproportionately come from a few commodities) versus the most intense products within a commodity.

This emissions intensity across and within foods is large, as **Figure 2 (page 18)** illustrates.

In either case, it is the variability in the individual processes that contribute to a food's total footprint; low emissions from each process will result in a low total footprint, whereas high emissions from each process will result in a high total footprint. Because the mechanism for *Codex Planetarius* is to set thresholds for minimum performance, it is the aggregate high-intensity emissions that we are interested in detecting.

Table 2 (page 14) shows a variety of relevant processes and the variability observed for that individual process, alongside the total global emissions for that process across all products for context. The variability estimates are derived from a literature review **(Annex II, page 8)**, which goes into detail for these different emissions sources and what drives that variability. Production processes with high variability are more likely to contribute to high footprints that would be excluded from trade in the *Codex Planetarius* system.

Variability across and within foods

From farm to table, the life cycle of any given food product can be characterized as going through several of the processes in Table 2. The average GHG footprint of that product will be the sum of the average emissions during each process. An average GHG footprint, however, would obscure the wide range of values that emissions can take in each process. Compare the top and bottom panels of Figure 2, for example: while the average steak results in 40kg-CO_2e/kg steak, the serving on a plate could have emitted anywhere from 12 to 144 $kgCO_2e$/kg steak.

Across products, a disproportionate amount of the GHG emissions originate from a minority of production (by volume). Almost 50% of the total GHG emissions from each product is produced by the least efficient 25% of that product; the least efficient 5% produce almost 15% of the total impact.

If we consider different potential thresholds (e.g., at a threshold of 1 $kgCO_2e$/kg product, anything above 1 $kgCO_2e$/kg product is considered unacceptably high; here we assume this production is removed from the system for analytical ease, but it could, alternatively, be produced and exported using improved practices or sold domestically with the same intensity), this would lead to different amounts of food systems emissions avoided and different amounts of food not produced. **Figure 3**[35] **(page 19)** shows the proportion of the food system production and proportion of food system GHG emissions implicated at these different thresholds. When the threshold is 0 $kgCO_2e$/kg product (top right point), all emissions from traded food would be avoided (19%) but there would also be a 16% reduction in total food production. However, at higher thresholds (going southwest in the chart), most traded food emissions are still avoided while most traded food is not "lost".

Note that the products implicated are disproportionately meat, seafood, and vegetal oil products. Tiered, or commodity-specific, thresholds could also be employed and show broadly similar patterns. For example, **Figure 4 (page 20)** shows a threshold of 1, 3, and 5 $kgCO_2e$/kg product for non-animal products and an increasing threshold for animal-source products.

In short, this suggests that thresholds targeting the most heavily emitting products could greatly reduce emissions while not significantly impacting the food supply. However, the choice of what threshold(s) are used does determine the magnitude of the trade-off and which foods are more or less affected by the policy.

Role of trade

The previous sections explored the variability in emissions across and within products. However, as alluded to in Figures 3 and 4, not all of those products are embodied in internationally traded foods. Currently, most analyses of agricultural emissions embedded in trade assume that a nationally representative footprint (per food) is exported. Some of the results from these types of analyses are discussed below, along with a numerical illustration of why these assumptions are likely insufficient.

Using national-level trade data, researchers find about 16% of emissions from both non-LUC on- farm emissions and agriculturally driven LUC emissions are traded globally.[36, 37] Inclusive of LUC, this is about 1.9 $GtCO_2e$/yr, with one-quarter of those coming from the trade of plant-based foods and the rest from animal-based foods.[38] **Figure 5 (page 20)** shows some of these results by geography. Both of these estimates suggest that proportionally to the amount of production, less GHG emissions (approx. 16% of farm-gate emissions) are traded than food is traded (approximately 25%).

However, it should be noted that these estimates are based on national-level statistics. So, the heterogeneity in total emissions per crop at the national scale is captured, but within country heterogeneity is not.

It is likely that these differences are significant. For example, if we look at Brazilian beef production in 2020, FAO-STAT estimates 10 million tonnes of total production, of which 2.6 million tonnes were exported. Beef production was associated with about 1.9 million ha of forest loss per year during that time.[39] One of the few datasets that lets us disaggregate exported from domestic production is Trase's deforestation data for Latin America; using this data lets us explore whether the assumption that exported product has a similar footprint to domestically consumed product in a small case-study. Data from Trase for Brazilian beef suggests that about 1 million ha of embedded deforestation was exported. Thus, while only about 25% of Brazilian beef was exported, about half of the total deforestation from cattle pasture was exported.

For different importing countries, these differences may be more stark depending on the local sourcing patterns. **Figure 6 (page 20)** shows for the same Trase dataset the heterogeneity in imported deforestation footprint for cattle by importing country; it varies over 30-fold.

This suggests that the assumption that national-level emissions intensity for products is equal across domestically consumed and exported products is likely false. However, this type of analysis is limited; Trase, for example, has only 19 subnational commodity-country datasets, and the subnational cropland ecosystem transition data from Mapbiomas is similarly restricted to only a few countries. And this accounts for the variability in land-use change alone. The differences sub-nationally in all the other GHG emissions, which we know are significant spatially,[40] and how those emissions are embodied in traded foods, is unknown. There is no standard dataset currently available to quantify this more broadly.

As subnational-level estimates of GHG footprints have revealed large heterogeneity in footprints, it is likely that as future analyses start to develop regional values for crop production and trade flows, the values for how much embedded emissions travel internationally will be substantially revised.

However, these existing analyses do suggest that significant GHG emissions are embedded in the international trade of food and that, in some cases, subnational data may reveal that more emissions are implicated than is currently thought. **Annex V (page 11)** explores heterogeneity at different spatial scales, which is suggestive of how farm-level, subnational, and national-level variability may influence how large of an effect *Codex Planetarius* would have for different actors.

Measurement & Accounting

Measuring the GHG emissions associated with agricultural production and, subsequently, setting performance thresholds requires making several decisions about scoping and methods. Below, we explain each methodological decision and make a recommendation.

Emissions sources

Recommended emissions sources – fossil fuel and non-fossil fuel emissions: In the climate science community, agriculture, forestry, and other land use emissions are grouped as AFOLU emissions. These may be aptly considered "land-sector" emissions, as they comprise the biogenic emissions arising from terrestrial processes associated with land-use, land-clearing, and the rearing of crops or livestock on those lands.[41] For the purposes of *Codex Planetarius*, AFOLU emissions include some emissions sources that are not relevant — in particular those relating to forestry — and exclude sources that should be included — in particular those related to fossil emissions sources, like fuel use for tractors on farms. While there are relevant differences to the rate at which AFOLU and fossil-fuel emissions must decrease in 1.5C scenarios (see Annex I), both emissions sources are significant in food production.

Accounting focus (product, entity, or area)

Recommended accounting focus – product: Greenhouse gas accounting can be conducted with different foci. For example, entity-level accounting (e.g., corporate accounting) tabulates emissions associated with that entity and product-level accounting that tabulates emissions associated with the life cycle of that product.[42] In the *Codex* context, we could imagine calculating emissions for each farm (entity) and comparing that footprint against a threshold or calculating emissions per product. In the former case, determining the threshold at an entity level would be challenging without scaling it by farm area, revenue, or production; if a farm produces 1,000 tonnes of CO_2e per annum, this could well be very efficient for a large, productive farm or high for a very small farm. Scaling by revenue would be challenging as prices fluctuate frequently and relative footprints could decrease as prices rise without any change in behavior, which is not desirable. Scaling by area could be promising; however, it could perversely incentivize more extensive production. In addition, focusing on entity accounting raises the issue of whether the embedded emissions in farming inputs should be included. This is particularly salient for livestock, as the majority of the footprint comes from feed, which may be produced on-farm for some entities and purchased for others; excluding these emissions would inherently create an uneven scope for comparison between farms. Normatively, including emissions from inputs is desirable as it gives farmers sourcing feed an incentive to buy low-carbon products.

Product-level accounting is already "scaled" by the functional unit of the product and including the embedded emissions of inputs is standard. As production becomes more efficient, footprints decrease, which is normatively desirable. For *Codex*, product level accounting is the most relevant because it pertains to the goods that are transported through trade.

Life cycle stages

Recommended life cycle stages – cradle-to-farm-gate: Life cycle stages that are included are typically defined by their "start" and "end." Cradle-to-grave analyses, for example, include all raw materials and follow the product to disposal; gate-to-gate analyses restrict the analysis to what enters and exits a single facility. The life cycle stage included should match the intended use of the analysis. Given the recommended product footprint focus, the life cycle accounting should start with the raw materials that are input – the "cradle." *Codex Planetarius* is intended to monitor the health of renewable resources impacted by food production, intervening at the point of trade. This may naturally suggest an endpoint at the point of export.[43] Retail, consumption, and disposal primarily occur after trade, leaving them outside the scope of *Codex*. However, the point in a product's life cycle at which it is traded differs across products. For example, some livestock are traded prior to slaughter while others are cooked and packaged as ready-to-go meals prior to export; some feeds may be traded internationally while others are "traded" only after being incorporated into the muscle of a sold animal. Therefore, it would be difficult to determine thresholds for products at the point of export at differing levels of final processing unless each threshold is product specific. Emissions to farm-gate comprise a little over 70% of cradle-to-grave food emissions, while processing and transport comprise a little over 10%.[44] Setting thresholds for emissions up to the farm-gate thus captures the majority of emissions, including the emissions sources that are most likely to cause an outlier high value **(see Table 3, page 15)**. The major exception to this point is food transport by air freight, which can have an outsized impact when it is used, but other policy levers are likely more suited to address these emissions than the *Codex Planetarius* framework.

Measurement approach and tools

Recommended measurement approach – simplified calculators with automated data collection:

Modeled versus physically measured emissions: One critical distinction between GHG assessments is the method of measurement. At its coarsest scale, we can consider the differences between physical and modeled estimates.

Physical measurements of GHGs are typically in the form of gas concentrations and fluxes. For the atmosphere as a whole, this may be from dedicated observatories (e.g., Mauna Loa observation time series). Emissions at farm-scales often use devices like flux-towers or smaller-scale devices to monitor emissions from individual animals (e.g., with mouthpieces to detect methane emissions from cattle). This measurement infrastructure is typically expensive and requires specialized expertise and often laboratory analysis. Due to this, these farm-scale measurements are sparse and often part of efforts to build models that can predict the emissions or to better understand the underlying relationships that drive the dynamics.

Physical measurements of carbon stocks are also common, especially for soil carbon and the live biomass of native vegetation. For soil carbon, physical soil core samples are then analyzed for carbon content in a laboratory. Like atmospheric measurements, these in situ ground-truth measurements are typically time, resource, and expertise intensive.

In many cases, physical measurements serve as a ground truth around which models can be built to estimate emissions using other information. For example, in situ carbon measurements of ecosystem carbon content could be used to calibrate satellite monitoring of land-cover types. Measurement of enteric fermentation for selected cattle can be linked to models of diet and metabolism for those animals.

Many models also rely on the physical relationships — like chemical reactions — that occur in these processes to estimate emissions. These models may be relatively simple, like multiplying the amount of fertilizer by an emissions factor, or very complicated biophysical simulations of nitrogen and carbon cycling.

Given the spatial extent of farmland implicated, requiring physical measurements of emissions for *Codex* is infeasible. So, we must turn to modeled estimates of emissions, which at the farm scale are typically called GHG "calculators."

Tools for measuring agricultural product GHG emissions: There are hundreds of different GHG calculators available for farm or product level estimations; some are generic for many crops and geographies, while others are tailored for particular countries. These calculators require some input data about farming practices, geography, and/or purchases in order to estimate the associated GHG emissions.

The time and opportunity cost to farmers for collecting sustainability and other regulatory compliance data is a major concern. At the same time, the reliability of collected data is also often of concern. Using remote sensed data (e.g., for monitoring land-use change or for practices like cover cropping), auditable data from other sources (e.g., electricity bills or purchase receipts), etc., have been proposed as ways to address both issues; streamlining data collection across *Codex* environmental variables and through remote sensed data will be critical for feasibility.

Often, farm calculators are intended to track specific sustainability interventions (e.g., FAO's EX-ACT calculator) or to estimate emissions for both typical and farms that are leading in sustainability practices. Because the goal of this measurement tool is to detect emissions above the threshold, it is the opposite suite of practices that we are most interested in (i.e., the highest emitting practices). Given the analysis shown in Figures 3 and 4, emissions thresholds from 3-10 kgCO_2e/kg product tends to balance high (about 15% emissions reductions) with low food production loss (2-3%), any process that is likely to add emissions of 1kgCO_2e/kg product or more is particularly salient to be measured. Table 3 shows the processes that are individually likely to cause a product footprint to exceed a threshold of 0.5 kgCO_2e/kg product and what minimum data are needed to estimate the GHG footprint.

Selecting tools that meet these minimum requirements and are compatible with the thresholds will be challenging. Right now, farm-level calculators measuring the same farm often produce results that vary by many factors[45]; this variability could both encourage "tool shopping" for better results and mean that measurement variability obscures real differences among farms. Beyond assessing the methodologies used by a tool and their adherence to specific accounting standards, there is not a framework for assessing the accuracy and precision of these tools, or of their suitability to specific geographies or production systems. To ensure tools are fit-for-purpose in comparing to thresholds, we recommend the following approach:

- A tool should be developed (or altered from an existing tool) that meets the data-collection and estimation recommendations for the final version of the *Codex Planetarius* climate chapter; this calculator should be built in concert with threshold development to en sure that the numerical thresholds are well-calibrated. This will likely necessitate creating an expert-mediated test dataset of farm characteristics that can be used for both fine-tuning thresholds and tool development. This tool and the underlying farm datasets will be the benchmark for other tools' performance.
- If other tools (i.e., for specific commodities, regions, etc.) will be used, the following due diligence should be conducted:
  - Methodologies for calculating emissions should be aligned with IPCC guidance.
  - For calculators tailored to a specific geography or product, emissions sources may be dropped (e.g., methane from rice paddies for non-rice products) but the guidance on when the tool may be used must be followed.

- Output of the tool on test farms should reconcile closely with the outputs of the benchmark tool; additional regional or commodity specific data may be used to assess this reconciliation.
- The tool should qualitatively rank the farms from the benchmark test dataset as above or below the threshold.

As the field of GHG calculator assessment matures[46], further refinement should take place.

Detailed accounting preferences

In addition to the aforementioned measurements, several accounting decisions also must be made. These accounting decisions determine how emissions are assigned over time and to which products. These accounting recommendations follow life cycle assessment best practice and standard guidance where appropriate.

In order to compare GHG footprints, the same functional unit must be used; other methodological choices like allocation should also be consistent both across all footprints as well as between the calculated thresholds and the footprints. Several of these key decisions are listed below:

- **Functional unit – recommended per kg of live-weight or fresh-weight sold:** Assignment of emissions to products is closely related to the functional unit being considered. The functional unit is the denominator in the GHG intensity — kg CO_2e per kg of what? Often mass is used (kilograms) because this is comparable across many different foods and products, and is relatively straightforward to measure. Mass is often further specified, for example, as kilograms of live weight or kilograms of edible weight or kilograms of fillet. Given that emissions are not assigned to waste products, but can be assigned to co- or by-products, these distinctions are very important, as many crops have inedible portions or portions that are used as animal feed, fertilizer, etc. The definition of what comprises edible weight may be locally different and may also be operation specific (for example, different achieved dressing percentages).

  Other functional units are used, including mass of protein (or other nutrient) to convey the nutritional benefit of the food. For some foods, like milk, there are explicit corrections to help harmonize these functional units when they differ greatly between areas and production systems. However, basing the functional unit on more complicated nutritional units makes assessment difficult for food items with very different nutritional purposes (e.g., vegetables versus fish) and requires additional data for converting easily measured mass to those units.

  Because mass is easily measured and corresponds with farm-relevant concepts like yields (crops) or weight gains (animals) this is a good choice for functional unit for *Codex*. Using the live weight or fresh weight that is sold is recommended to avoid allocation amongst co-products downstream.

- **Exclusion threshold:** As detailed in the previous section, including more processes increases the burden on the farmer and cost for data collection. Higher quality data on the processes likely to cause a product to exceed (or fall below) the threshold is likely more valuable than additional information on low-emissions processes. If a process is unlikely, even at the 95th percentile of worst performance, to cause 1/n of the threshold in emissions, where n is the number of processes relevant for that product, it can be excluded; the exclusion process should be conducted at the commodity- and tool-level, not the farm-level.

- **Land-use change:** Emissions from land-use change should be included, and should include emissions from any non-agricultural land to agricultural use or shifts between agricultural land-use classes (e.g., permanent crops to annual crops). If an increase in carbon is expected from a transition, see bullet below on removals. Emissions from land-use change are a significant driver of heterogeneity in product footprints.

  - **Direct vs. induced/indirect land-use change: Direct.** Direct, statistical, and indirect land-use change are often discussed. Direct land-use change is that which occurred in a particular land-unit that produced a crop. Statistical land-use is a proxy estimate for land-use change when traceability or monitoring of conversion cannot be conducted. Indirect land-use change is that which was economically induced by changed land-use elsewhere.[47] While all three are relevant in different contexts,[48] the focus of *Codex Planetarius* is to identify outlier emissions, so direct land-use change emissions are the most relevant because they describe the emissions for the particular product.
  - **Plot vs. farm-level: Maximum between plot- and farm-level emissions.** Plot-level accounting for land-use change focuses on the homogenous area within a property to assess deforestation risk for the commodity(ies) produced there. It is used in the European Union Deforestation Regulation as the relevant unit for deforesttion assessment[49]; this approach is consistent with measurements driven by remote sensing that look to crop identity to assess whether deforesttion occurred. However, many frameworks, like the Accountability Framework Initiative[50] and Greenhouse Gas Protocol[51], define the farm (or production unit) as the relevant scale as this unifies the economic pressures and management of the farm, prevents leakages between plots, and better accounts for practices like crop rotations, fallows, and shifting what is grown over time across plots. The risk with plot-level compliance is that other plots on the same farm might be non-compliant, allowing the farm to reap economic benefit from clearing *and* from being perceived as conversion free. However, allocating the carbon footprint of clearing to all products on a farm may artificially lower the footprint for the products on a cleared plot, especially in large properties. To balance these issues, the following is proposed:

    Farm-level calculation: the amortized emissions from LUC are allocated on a production (mass) basis to all products leaving the farm in that year.

    Plot-level calculation: the amortized emissions from LUC are allocated on a production (mass) basis to all products produced in that plot during the year that are sold into an international market (i.e., co-products that sold domestically or used on farms cannot be allocated emissions).

    The maximum value between these two is selected for comparison against the threshold. This makes it more likely that LUC emissions are assigned to a product, which is a normative choice in line with detecting outlier poor practices.
  - **Carbon pools: the four biomass pools** (above-ground, below-ground, necromass, and soil carbon) should all be considered, following IPCC guidance and draft GHG protocol land-sector guidance.

  - **Amortization time-frame — 20 years or length of crop rotation:** National GHG accounting amortizes emissions from LUC over 20 years and this is also the norm in corporate and product-level accounting. For agricultural products, a longer amortization period can be used for products (like some permanent crops) that have a production cycle longer than 20 years.

  - **Linear vs. equal amortization — small preference for linear, but either is acceptable as long as thresholds are calculated with the same amortization.** Across the amortization timeframe, the emissions may be allocated equally (e.g., 5% each year for a 20-year period) or in a linear decrease (e.g., starting at 10% and declining to 0% over 20 years). The latter case penalizes recent clearing, and may align incentives better with cut-off dates made in deforestation- and conversion-free commitments.[52] The SBTi FLAG guidance recommends the linearly decreasing amortization[53], the draft GHGP land sector guidance allows both[54], while many product standards like the European Union Product Environmental Footprint Category Rules require equal amortization. Equal amortization is slightly easier to calculate, but either is trivial to compute when the date of land clearing is known, which is almost universally feasible using historical satellite imagery. However, for *Codex Planetarius* purposes the most critical consideration is that the threshold against which the footprint is compared uses the same amortization.

  - **Carbon estimates for original and crop land:** Carbon content of cleared ecosystems is variable, even among the same land type (e.g., forests) and the carbon content can be difficult to estimate from historical satellite imagery, especially for non-forest ecosystems and for belowground biomass pools. The carbon estimates for ecosystems should be conservative (high-end).

- **Soil carbon:** Excluding emissions from land-use change, changes in soil carbon should not be included as part of the GHG footprint. Soil carbon measurements and modeled estimates are incredibly variable. For both losses and sequestration potential, the magnitude of changes on a per crop basis are typically small (i.e., a 0.5 tC / ha / yr); allowing products to reduce an outlier foot print by soil carbon sequestration (which is highly uncertain even when measured directly) is likely not normatively desirable. This stance could be revised as better modeling and measurement comes online.

- **Primary data requirements:** Primary data is often required for "foreground" systems, or those systems that are within operational control of the assessed group, which in this case would be for the farm(s) where the product is produced. However, given the goal of this analysis is not to generate an accurate footprint, but rather to assess whether the footprint exceeds a threshold, a two-step process could be employed. The footprint can first be estimated with external data and, for processes that are not able to be estimated with those data (for example, direct N2O emissions), a conservative estimate of the 95%-confidence-level worst case for that crop can be used; if the sum of these conservative estimates is below the threshold, primary data would not be required (or only required at a slower cadence); for any case where the threshold is in questions with those conservative estimates, primary data pertaining to the key emissions sources would be required **(See Figure 7, page 21)**.

- **Removals – only allowed with primary data:** Carbon sequestration on agri cultural lands is likely necessary to meet climate goals.[55] Removals would be, by default, excluded from any estimations of the footprint. If the farm wishes to include removals, for example from agroforestry, etc., they would be required to monitor these removals yearly (i.e., as if they were in the "above the threshold" use case). Following the draft GHG Protocol guidance, ongoing monitoring would need to detect any reversals (including from natural disasters) and if monitoring stops, a reversal is assumed. For farms below the threshold, accounting for removals is unnecessary in the *Codex Planetarius* framework because they are not at risk of being excluded.

- **Assessment period — three year rolling average:** Yearly assessment would capture the full dynamics of annual crops (or multiple crops grown within a year). However, temporal heterogeneity is also high, and interannual variability can be higher than subnational and smaller scale heterogeneity.[56] Intraseason variability can also be pronounced.[57] Averaging across several years would avoid penalizing farmers for a bad meteorological year when they have otherwise good practices. For farms growing perennial crops and livestock, a multiple year look-back to account for the product's life cycle will be required regardless of the assessment frequency. Assessing the footprint each year but having a three-year rolling average should smooth across some weather variability.

- **Allocation:** Economic allocation should be used. This both aligns with leading standards like the European product environmental footprint category rules, but typically is also closer aligned to footprints coming from climate models that assign emissions to primary products. In line with ISO 14044, because the amount of co-products cannot be easily altered, this is a preferable approach.[58]

Threshold Setting

For climate stabilization, we have globally agreed aggregate targets for reductions,-summarized for the food system in Role of Food Sector in 1.5 C Pathways and **Annex I: Roadmaps (page 7)**. Recall that the rough goal is that 2050 net emissions from the food sector are below 4 GtCO_2e/yr, having fallen at a roughly linear rate of about 3% per year starting in 2020 from a 2020 baseline. Reductions of this magnitude will likely require a combination of dietary shift, changes in production practices on all farms, and, per the *Codex Planetarius* model, the improvement or elimination of production beyond a particular threshold through global trade standards. Improving or eliminating those exceptional farms is not a viable stand-alone strategy for achieving a 1.5C future for two reasons: first, global trade only addresses roughly a quarter of food production and at most 20% of food systems emissions, and second, even if it applied to both traded and non-traded food, an exclusion threshold that results in the required 80% absolute reductions would reduce the global food supply by about 10%, while increased production is likely needed for a growing population. Thus other mitigation tools are needed in addition to the *Codex Planetarius* approach.

As shown in Figures 3 and 4, the trade-off between the emissions avoided and production reduced is a continuum. The shape of that trade-off will be influenced by producer responses: if farmers above the threshold, rather than stopping production, improve to the threshold, emissions reductions will be slightly smaller than expected but production reduction will also be less; if instead, producers shift who supplies domestic versus export markets, it is possible that no emissions reductions would occur at all.

The decision, then, of how to set the threshold should be informed by the global climate targets referenced above and ultimately balance what is seen as an acceptable trade-off between emissions reductions and potentially lost food production.

Several key methodological considerations on setting thresholds are detailed below:

- **Alignment of measurements and thresholds:** The thresholds should be set using the same methodological choices as the measurements (e.g., using the same allocation rules); **Annex IV (page 11)** illustrates the importance of this issue.
- **Tiered thresholds:** Given the huge difference in emissions ranges between animal source and non-animal source foods, different thresholds will likely need to be set for those two categories (at a minimum); if not, thresholds would either fully exclude some foods or be set so high as to lack impact. See Figures 3 and 4.
- **Regional thresholds:** Some climate targets, like those from SBTi-FLAG, are regionally specific, accounting for different initial emissions rates and potentially accounting for differences in potential productivity and natural resource constraints in the future. One can also imagine normative justification for different regional thresholds to account for historical inequities, other development constraints, or even trade-offs with other environmental impacts.
- **Annual performance assessment:** Inter-annual or seasonal variability can be very large both for yields (which tend to drive GHG footprints for many crops) and for determining which interventions (irrigation, tillage, etc.) are used to ensure production. For perennial crops, annual crop rotations, and livestock, information from multiple years is already necessary when calculating footprints even for a single-year's production. Annual fluctuations in inputs used, practices responding to changing conditions, etc. will likely cause foot prints to fluctuate over time, for most farms still well-below the threshold; averaging over longer-period decreases the ability to detect and respond to high-emissions products by essentially allowing farms to offset a bad-performing year with a good one.
- **Dynamic threshold:** Given the agricultural sector needs to consistently reduce emissions over time, setting an initial threshold(s) that captures a reasonable balance between emissions addressed and food potentially lost from trade should be revisited every 3-5 years to ensure that balance remains. Changing climatic conditions will change crop yields and practices; in addition, de pending on action from other sectors may alter the "budget" available for emissions from the agricultural sector. In addition, if methodological improvements in measurement change sufficiently, it is likely that thresholds should be altered to be comparable with those measurements.

Annex I: Roadmaps

There is widespread agreement at the international level that GHG emissions can be used to express the status of and progress in mitigating climate change (e.g. United Nations Framework. Convention on Climate Change (UNFCCC) reporting). Budgets for GHG emissions over the 21st century may be expressed in aggregate (e.g., approx. 250 GtCO₂e emissions from 2023 for a 50% chance of 1.5°C limited warming[59]), over time (e.g., 4.2% reduction each year from a baseline for corporations setting 1.5°C targets[60]), or with greater resolution on specific sectors or gases. Date targets are often set for specific endpoints like "net-zero" without specifying the trajectory over time, despite the ambiguity in total emissions this represents; in the limit of delaying all action to the penultimate year, total emissions are two times larger than a linear decrease from current to target emissions.

There are two Roadmaps that quantify the emissions reductions necessary from the food system specifically.

FAO 1.5°C food roadmap

At COP28, the FAO unveiled the first part of a roadmap linking SDG 2 (no hunger) with climate: "Achieving SDG 2 without breaching the 1.5°C threshold: a global roadmap."[61, 62] It is informed by both the current issues with mal- and under-nutrition affecting billions of people globally and projected yield decreases due to a changing climate. The necessary mitigation, as seen in **Figure 8 (page 21)**, is broken down by emissions source, which in some cases (e.g., livestock and manure) implicate specific food products.

Note that these rates of mitigation are well aligned with what is listed above. This roadmap has received criticism,[63] in particular for a lack of ambition on dietary shift and unclear assumptions around seafoods.

SBTi FLAG roadmap

The Science Based Targets initiative Forestry, Land, and Agriculture 1.5°C roadmap is, to our knowledge, the only roadmap that creates emissions pathways for specific key commodities and for the sector as a whole.[64] These targets are for farm-gate fresh weight emissions. These targets were built using results from the IMAGE 3.0 model and land-sector mitigation goals from Roe et al. (2019). This is in contrast to the FAO Food Roadmap, which is more general in target reduction areas.

The SBTi FLAG roadmap focuses on nine high-emitting commodity products: Maize, Rice, Soy, Wheat, Dairy, Beef, Pork, Chicken, and Palm Oil. For 2020, across these nine commodities **(see Figure 9, page 22)**, total emissions are estimated at 8 GtCO₂e/yr (or about half of all food system emissions) of which about 3 GtCO₂e/yr comes from deforestation.[65] In 2050, the total emissions are less than 4 GtCO₂e/yr, which is in line with both the FAO Roadmap and ensemble integrated assessment model outcomes.[66]

For commodities not on this list, the SBTi FLAG framework prescribes 3.03% absolute yearly reductions from a near 2020 baseline. Note that this rate is similar to and often lower than the effective absolute reduction rate for the nine high-emitting commodities.

Annex II: Sources of emissions in food production

Non-CO₂ on-farm emissions

Non-CO₂ emissions from agriculture (i.e., from methane and nitrous oxide) come from various sources, including methane from enteric fermentation, manure, and rice production; nitrous oxide emissions from fertilizer, agriculture residues, and livestock manure and urine. These emissions are mediated by bacteria and are dependent on environmental variables like temperature and moisture of the media (manure, soil, compost). They comprise roughly half of agriculture's AFOLU emissions. However, unlike land conversion, we expect that to reach zero in most 1.5°C or net-zero scenarios, there will still be about 4GtCO₂e of non-CO₂ emissions from farms.

Enteric fermentation

Ruminants like cattle produce methane as part of their digestion. When feed digestibility is low, they produce more methane. Thus, both the quality of food and how long the animal is alive strongly influence the amount of methane produced within the same animal species and breed.

Species differences

Different ruminants have different methane production rates. The amount of methane produced is strongly related to animal size and feed intake, although as **Table 4 (page 15)** shows, the amount of methane production per animal weight does appear to differ by species.

Dietary differences

Methane production rates as a function of diet vary by roughly a factor of two (i.e., two animals fed for the same period of time different diets could produce two-times different amounts of methane), although this scenario is unlikely; an animal fed a more digestible, higher quality diet is also more likely to attain a higher weight or more milk, changing its metabolic needs and necessitating a different feed ration. Feed conversion efficiency is therefore a critical measure of sustainability of any animal agriculture production system.

Lifespan differences

Differences in the age at first reproduction (typically ranging 15-27 months for cattle versus 6-9 months for goats) and the time to slaughter (typically ranging 18 months to over 3 years for cattle versus 3-5 months for goats) greatly influence the overall time animals spend on farms before producing meat or milk. We should expect roughly two-times variability from life-cycle differences in cattle alone, although they are likely to covary significantly with diet and thus be magnified. Note that animal mortality also strongly influences these results, as animals that perish and are not consumed add emissions, but not edible products.

Summary

Different combinations of these factors lead to differences in methane per kg of edible weight varying over 10-fold. For example, across geographies, FAO's GLEAM tool reports values from 11-76 kgCO₂e/kg edible meat[67], while a meta-analysis of different farms yields 17-102 kgCO₂e/kg edible meat for beef cattle and 2.5-35 kgCO₂e/kg edible meat for dairy cattle (some emissions are allocated to milk for dairy herds, thus the stark difference).[68]

In general, pasture-fed animals produce more methane because the feed conversion rates are lower and the amount of cellulose in grazed fodder is greater. While feed additives can drastically decrease enteric methane emissions, there does appear to be a non-zero amount of methane produced by ruminants regardless of diet. Converting cellulose to digestible sugars requires anoxic microbial metabolism, which produces methane.

Manure decomposition

Release of methane occurs during anaerobic decomposition of organic matter, while nitrous oxide is mainly generated during ammonia decomposition. There are different manure management systems practiced across the world, and they lead to different emission levels.

The emission quantity is correlated to type of management, environmental conditions, and the manure composition. For example, the methane conversion factors for selected management practices (which essentially multiply the amount of manure):[69]

- 1-2% for pasture depending on temperature
- 2-5% for solid storage
- 3-30% for pit storage less than one month
- 10% for burned as fuel

These differences can be magnified by temperature and residence times. Effective manure management involves controlling how manure decomposes in order to reduce emissions.[70] Thus, for the same amount of waste, management practices yield 10- to 100-fold differences.

Manure can also be used in biodigesters to produce biogas; in these systems, manure management could displace fossil fuel emissions from fuel gas.

Fertilized soils (direct & indirect)

Nitrous oxide (N_2O) emissions occur from soils when Nitrosomonas and other bacteria convert amine nitrogen (organic and inorganic) to nitrate (NO_3) (or NO_3 to N_2), but do not have adequate oxygen to complete the process. These emissions depend on soil type, climate conditions, fertilizer type and application method and are roughly proportional to the amount of nitrogen added. Soils that have nitrogen added to them from fertilizers or crop residues and high water content (thus low oxygen) can emit significant fractions of the available nitrogen as NO_2 in a single day. Generally, the default N_2O emission factor widely assumed in the agricultural LCA is 1% of the N-applied to soil.[71] The Intergovernmental Panel on Climate Change (IPCC) recommends a default emissions factor of about 4 CO_2e/kgN for direct emissions from applied nitrogen but the range for this emission factor is large (1.3-13), in part because N_2O has such a high CO_2 equivalent impact (273 times over 100-year period).

However, the rate of N_2O emissions is quite variable in time and is strongly influenced by the water retention and flow through soils. The conditions that lead to N_2O emissions are well known but the frequency and duration of those conditions in the field are not well known because they emerge and subside so rapidly. Synthetic and organic fertilizers also produce different amounts of nitrous oxide. Complicated models of carbon, water, and soil dynamics are required to predict local fertilizer emission rates. Wet climates tend to have higher emissions per kg of applied nitrogen than dry; synthetic nitrogen inputs tend to have higher emissions than organic.

To understand the effect of fertilizer on the footprint of a product, the balance between yield boost from fertilizer and the emissions from that fertilizer need to be considered; if one is over-fertilizing, yield will not be increasing as quickly as emissions from fertilizer; if one is under-fertilizing, the increase in production on the land outpaces the increased emissions.

For example, without fertilizer, Indonesian yields of oil palm per ha are about 10 tonnes of fresh-fruit bunches (~2 t crude palm oil (CPO); this is like the yield in Cameroon (~2.4 tCPO/ha) which has low fertilizer use); every 10kg of fertilizer adds about 0.5 tCPO.[72] At current fertilization levels, many plantations could increase yields while improving emissions intensity per fresh-fruit bunch. This illustrates the tension between land use intensity and crop yield intensity. Increasing crop yield potentially reduces total pressure on land conversion but increases total GHG emissions per production cycle.

Aquaculture pond emissions

Emissions of methane and nitrous oxide may be significant contributors to overall GHG emissions from aquaculture ponds and cages; these emissions largely result from decomposing faeces and uneaten feed.[73] Direct greenhouse gas emissions from aquaculture are rarely measured or even estimated as part of aquaculture LCAs; when these emissions are added, they may add from 0.1 to 61 kgCO_2e/kg edible meat, depending on local climate, pond depth, and amount of waste in the pond.[74] Direct measurements from ponds suggest that fluxes may be much lower in some shrimp systems[75] (as the anoxic conditions that produce methane would be deadly for fish) or aerated ponds[76]; however, there is a dearth of information about these emissions.

Other organic effluent

Vegetable crops also produce organic effluents as waste products, which when they decay release greenhouse gases. These emissions are typically considered as outside the farm-gate, as they often occur during processing, although the effluents may be returned to farms as fertilizer. For example, palm oil mill effluent (POME) is an organic pollutant resulting from the oil palm processing. When POME is left to degrade with no treatment, the emissions of methane range between about 1-2 kgCO_2e/kg CPO[77]; better practice is to either use POME as fertilizer or to generate electricity from the methane, which can potentially displace fossil fuel use.[78] These effluents are also commonly generated for crops like coffee that require a husk-separation process.

Land use and land-use change

Emissions from land use and land-use change comprise emissions from the conversion of natural lands into croplands, from the degradation of natural lands, as well as other emissions or sequestration from the management of agricultural or natural lands (note that the latter is quite small!). Currently, the emissions from the conversion of natural lands into croplands (a type of land-use change) dominate this category, although emissions from degradation or use (for example, emissions from organic soils are a large contributor to palm oil carbon footprints) may be significant for some commodities or regions. Typically, discussion of degradation or management emissions are those that occur due to ongoing decisions and actions (most often in non-optimal forest harvest management); in the case of agriculture on drained organic soils, the ongoing emissions from those soils are typically considered separately from the emissions from the initial forest loss, although some academic studies differ.

Ecosystem conversion (land-use change)

Land-use change describes the transition of land from one land-use class to another. The conversion of a wetland to housing or housing to a forest would both be considered land-use change. In agricultural systems, the conversion of natural lands to crop or pasture is the primary transition of concern, as agriculture is the leading driver of loss of forests and other natural ecosystems.

Different ecosystems store different amounts of carbon in four "pools"—above-ground biomass (tree trunks, leaves, etc.), below-ground biomass (roots), necromass (leaf litter, fallen branches, etc.) and soil carbon.

When these ecosystems are converted, the carbon stored in biomass (e.g., trees, shrubs, grass) is released as carbon dioxide, and much of the carbon stored in the soil is also released. The total amount of GHGs contributed when these ecosystems are converted is determined by the density of carbon per area and the total area converted.

This impact is typically calculated using a "stock change approach" wherein the total loss of carbon is calculated by comparing the initial biomass in above-ground, below-ground, surface litter, and soil carbon to that after conversion; however, other approaches like the opportunity cost approach are gaining traction. Different habitats have very different amounts of carbon stored. Whether the land is converted to annual or permanent crops also influences the carbon storage post-conversion, with permanent crops tending to have higher carbon storage. Because this carbon is typically lost within a decade of clearing (often much faster), a consensus has emerged for emissions from the clearing event to be amortized across 20 years.[79] This 20-year amortization is typical for both corporate, product, and national-level accounting.

However, it should be noted that this stock change approach can both underestimate and overestimate the true impacts of habitat conversion, due to both local climatic feedbacks from vegetated areas and the loss of potential increases in biomass sinks on these natural lands over time.

Even for the foods that are the main drivers of habitat conversion, the amount of total production area that has been cleared that same year is small; for oil, palm, soy, pasture, cocoa, and coffee, it is about 1% of the total production area of each product.[80] However, over the 20-year amortization window, these numbers are much higher, with 61% of oil palm areas converted in that period, about 25% for coffee and cocoa, 9% for soy, and about 2% for pasture. Note that these are lower-bound estimates, as they quantify direct conversion of forest; market mediated induced LUC (sometimes called "indirect" LUC) estimates can be twice as high as speculative clearing that does not end up in cultivation. These estimates exclude conversion of non-forest ecosystems, which is often over 20% of total emissions.[81]

Deforestation

While overall rates of deforestation have been decreasing, the rate of deforestation driven by commodity agriculture has stayed relatively constant (about 5.2 million ha per year, comprising 2.8 GtCO_2e/yr).[82] Seven commodities drive most deforestation: beef, soy, palm oil, coffee, cocoa, rubber, and timber for pulp and paper.[83] Loss of forest cover is also driven by shifting agriculture, which is typically presumed to be caused primarily by subsistence agriculture, causing about 1.1-2.2 GtCO_2e/yr;[84] it is also typically assumed that these lands will have the opportunity to recover to a natural state, unlike commodity driven deforestation.

When deforestation occurs, the footprint per unit of production typically dwarfs other sources. **Table 5[85] (page 15)** shows the additional emissions compared with typical emissions on-farm.

Non-forest conversion

Similar to forest clearing, the destruction of other habitats for pasture or cropland releases large amounts of carbon from biomass and from soils. Globally, non-forest ecosystem conversion accounted for about 27% of total global emissions from agriculturally driven land use change between 2009 and 2018,[86] and this percentage continues to rise.

The amount of carbon implicated depends on the soil type, climate, and local vegetation. **Table 6 (page 16)** shows some illustrative values for the three best-characterized (and typically largest) pools of carbon for several different ecosystems.

Peatland loss and degradation

Peat forests have both a large amount of biomass above-ground and below-ground but also a huge store of organic matter in the soils; globally, peat soils store over 550Gt of carbon. When peat soils are drained, they directly emit CO_2, N_2O, and methane for at least 100 years. Globally, damaged peatlands emit about 1.9Gt CO_2e/yr;[92] tropical peatlands converted for agriculture (of which oil palm plays a large role) are estimated at 0.4 Gt CO_2e/yr.[93] Unless water levels are managed, drained peatlands continue emitting greenhouse gases in addition to 'normal' land-use change emissions from forest removal.

Sequestration

Sequestration of GHG in agricultural lands refers to carbon stock enhancement on agricultural lands through agricultural soil carbon or vegetation (i.e. agroforestry).

Soil organic carbon loss and gain on agricultural lands

Soil carbon sequestration transfers atmospheric carbon dioxide into long-term pools of carbon storage such that the carbon is not immediately re-emitted into the atmosphere through decomposition. Plants play a major role in the soil carbon sequestration process by converting atmospheric carbon dioxide to biomass through photosynthesis. What is not needed for growth can be exuded from roots to feed soil organisms or contribute to leaf litter.[94] The decomposition of plant and animal biomass over time converts into biologically inactive humus.

While current practices result in a net carbon loss from agricultural soils there is strong evidence that management practices that focus on soil carbon sequestration can be effective. Under long-term cultivation, the IPCC estimates that between 18% and 42% of the near-surface soil carbon is lost over 20 years (depending on climate). In contrast, with low-till, high-manure inputs, increases of over 40% over this period can occur.[95]

Low- or no-till farms often have higher concentrations of soil-organic carbon in the upper soil layer.[96] Well-managed grazing lands can also sequester carbon over time; how much and how quickly depends on local conditions including how degraded the soil is currently. Measuring this sequestration is still nascent. In addition, grazing lands that are converted to row crops release carbon, so keeping cattle on natural grasslands can be an important part of habitat (and carbon) maintenance.

Enhanced soil carbon sequestration in agricultural lands could provide about 1.3 $GtCO_2e$/yr when deployed globally at reasonable rates,[97] although the biophysical limits are 4-5 times higher.[98] On an areal basis, this translates to 2-4 tCO_2e/ha/yr (0.6-1.2 tC/ha/yr up until the soil saturates, which happens on the order of decades);[99] per food product, this will then be divided by yield per hectare and will vary by orders of magnitude depending on the crop and local efficiency.

Non-AFOLU Emissions

Inputs & on-farm fuel

On-farm emissions also include fossil-based GHG emissions, typically falling into two major categories: electricity and fuel use on the farm, and the embedded emissions from producing inputs for farm use.

Electricity and fuel use

Electricity produced from the burning of fossil fuels is responsible for significant greenhouse gas emissions. Typically, the GHG intensity of electricity is determined regionally because the local grid's usage of different fossil and non-fossil energy sources influences the GHG intensity; this value will vary over time (even over hours) as different power sources come online to meet demand. Across countries, it ranges from about 0.1 to over 1.4 $kgCO_2$/kWh; subnational variation can also be significant.[100] Electricity is used on farms to run machinery, heat and cool buildings, etc. Emissions from electricity are often present in the processing phase (to run slaughter, filleting, etc.)

The combustion of diesel and gasoline fuels also emits GHG. The emissions from these fuels are proportional to the amount of fuel used. The emissions factor for diesel is about 2.7 kg CO_2e/L and for gasoline about 2.4 kg CO_2e/L.[101]

The emissions from these sources are often high for systems like recirculating or aerated aquaculture, which use pumps. Fishing vessels use fuel; these fuels release GHGs (primarily CO_2) when burned. The total amount of GHG emitted per tonne of tuna is thus a function of how much fuel is used to catch each tonne of tuna. This fuel-use intensity is typically expressed in liters of fuel per tonne of fish caught; the fuel use varies from about 0.1 to well over 10 $kgCO_2e$/kg of fish caught.

Inputs

The production of (non-feed) inputs for agriculture are often small per unit product but are globally significant. About 1 $GtCO_2e$/yr is generated from input production, of which about 0.3-0.6 $GtCO_2e$/yr is for fertilizer alone.[102] The production of synthetic nitrogen fertilizer is particularly GHG intensive, although technologies to run the Haber-Bosch process with renewable energy are emerging. Different fertilizers (e.g., urea vs. ammonium nitrate) have different emissions during their production.[103] For some products, other inputs like machinery production or trellis infrastructure are non-negligible.

Overall, these emissions can be near zero for low-input / infrastructure foods and close to 1 $kgCO_2e$/kg product for others.

Downstream emissions

These emissions mostly occur outside the scope of what is considered for *Codex*, excepting when they pertain to farm inputs like feed. These are provided mostly for context.

Transport

The emissions from transport depend on the distance and mode of travel. Aviation is over 10x more GHG-intense for the same distance-tonnage than trucking or watercraft. Emissions from transport typically range over 100x different when considered across destinations and transport mode.[104] An average or typical value is not typically helpful, as the actual value is highly variable based on origin of production, destination, and transit mode.

Processing & packaging

Emissions from processing vary widely depending on the final form of the product. These emissions might be from simple processes like drying that may or not use any electricity or fuels. These processes may occur on-farm, off-farm but in the country of production, or at the destination. The largest differences in processing emissions seem to arise across foods (relative to different methods for processing the same food), although data are limited. The yield or production of co-products can have a high impact on the footprint of the processed product.

Emissions from packaging may similarly occur domestically or in the country of import. The emissions from packaging are typically dominated by the emissions used to produce the packaging material. Thus, the amount and type of packaging used are critical. For the same type of packaging, smaller portions will have a higher per unit impact because more packaging is used. For example, small metal tins for fish, like sardines, often have footprints of 2.5$kgCO_2e$/kg fish, while larger tins for tuna are closer to 1.6$kgCO_2e$/kg fish. However, light plastic pouches might only have a footprint of 0.2-0.5$kgCO_2e$/kg fish.

Packaging is a significant source of emissions for several products, including fish and for products like coffee.

Annex III: Smallholder Production

Smallholder & subsistence

The *Codex* framework targets food exports. While for some commodities like palm oil, cocoa, tea, and coffee, the products of smallholder farms are known to enter commodity and international markets, farm size is often used as a proxy for subsistence agriculture (which would not be influenced by the *Codex* thresholds). As can be seen with the current debates on the European Union's Deforestation Regulation's impact on smallholders and historically different criteria in certification schemes for these farms, the impact of potential standards on smaller farms is of great political and popular interest.

Smallholder on-farm emissions are estimated to contribute about 2.5 $GtCO_2e/yr$, of which 0.8 $GtCO_2e/yr$ is from deforestation; most of the non-LUC emissions are from China, India, and Indonesia, while LUC emissions are from Brazil, Indonesia, Congo DRC, and Cameroon.[105] **Table 7 (page 16)** shows the top 10 countries by net yearly emissions from smallholder agriculture, split into on-farm, non-LUC emissions and LUC emissions, along with the proportion of key commodities that are exported for each country. While the proportion of smallholders likely varies between commodities and may also differentially enter domestic and international markets, this does suggest that a non-insignificant proportion of exported emissions may come from smallholders. Therefore, disaggregation of export-related emissions to farms of different sizes merits greater attention.

Annex IV: Importance of Methodological Alignment in Setting and Implementing *Codex* Thresholds

The issues for supply chains using different GHG accounting are facially obvious; using different methods to calculate a footprint will result in different results. However, these issues are perhaps even more relevant when implementing potential thresholds. When thresholds are set using different assumptions – whether from top-down modeling of targets necessary for 1.5°C or through an analysis of the distribution of performance – any measurement against that threshold needs to be comparable or the threshold is meaningless. This comparability is outcome determinative.

Let's go through a concrete example. The Science Based Targets initiative set the Forestry, Land, and Agriculture guidance,[106] which for 11 key commodities includes intensity-based targets. This hugely impressive work built on the integrated assessment model, IMAGE, through the work of Smith et al. (2016)[107] and incorporated the necessary land-sector mitigation for a 1.5°C future from Roe et al.[108]

This modeling work essentially assigned the appropriate GHG emissions to each food and how much they need to decline to keep within the GHG limits for 1.5°C. The result is a set of target GHG intensities ($kgCO_2e$/kg fresh weight product) that declines over time. Companies need to contract to or stay below this target intensity over time in order to do their fair share of climate mitigation for that commodity.

As we can see from **Table 8 (page 17)**, when we multiply these greenhouse gas intensities by the amount of production (in this case, for the year 2015), these results align with the results of other estimates; that is, it accounts for most farm-gate food system emissions (9.7 $GtCO_2e$ for these nine foods, versus an estimated 11-13 $GtCO_2e$ for *all* foods from other models).

However, if we use different accounting, that alignment is broken. In **Figure 10 (page 22)**, we show how the whole animal emissions from cattle are allocated to the carcass (which is the unit used in the FLAG model) depending on the method.

Note that the mass allocation essentially offers half the footprint of all emissions being allocated to the carcass and nearly half to economic. Because the edible part of animals is typically much less than the live weight, this calculation methodology produces particularly large differences for meat products.

So how big of an issue is this?
If we assume that all the livestock producers used the allocation method (mass) that gives their main product the lowest footprint, then the footprint of livestock in 2015 would be 9 $GtCO_2e$ for cattle, pork at 1.1 $GtCO_2e$, and chicken at 1.2 $GtCO_2e$. This gives us a farm-gate footprint of 11.3 $GtCO_2e$ for only those 3 products and of 14.8 $GtCO_2e$ for all nine products; **this is higher than the total for *all foods* from the IPCC!** (see table 8) Seen the other way, this means that many companies could report their current, business-as-usual as achieving FLAG intensity targets and continue to claim this for years to come. They would in reality be emitting far more than we meant to allocate them; that means we'd be going far over the GHG budget necessary for a 1.5°C future. Clearly, emissions accounting and allocation should not be able to hide or shield emissions,[113] so care must be taken to ensure that the measurements and thresholds are well matched.

There are many other areas of accounting that have similarly large effects – the assignment of LUC emissions at different spatial scales and with different crop rotations is another decision that can have several-fold differences in total footprint. In fact, direct versus indirect LUC accounting often is two-fold different, largely because indirect LUC also captures dynamics of shifting crops and cleared lands that never end up in production.

Annex V: Variability across different spatial scales

While much attention is given to variability in separate "named" production systems (e.g., conventional vs. organic), differences between these separate types of production systems are often small (with exceptions — e.g., pasture-raised cattle tend to produce more emissions than feedlot cattle) because these designations often do not align with the major drivers of emissions footprints.[114] Using the exceptional case above, the difference between pasture- and feedlot-raised cattle is easily dwarfed by the differences of cattle raised on pasture with or without land-use change.

Here, we consider four scales: field-level, farm-level, subnational regional, and national to illustrate how the variability in each agricultural process (Table 2 and Annex II) contributes to differences at larger scales.

At each of these scales, the natural resource endowment may differ, creating differences in both what crops or livestock can effectively grow there and what practices are best suited to production. Either driven by these constraints or others (e.g., availability of inputs or local customs), some practices may be more or less common within each scale; these practices may be effectively locked-in by regional infrastructure like roads and electricity lines or by local infrastructure like irrigation.

Field-level
Farms are not homogenous, although the degree of variability in conditions will be a

function both of farm-size and its local geography. For example, a similar sized farm situated in a flat prairie may have less heterogeneity than a farm in a riparian area.

This can often be seen in terms of yields within a farm, even when input applications are similar. For maize and soybeans in the US, differences of over 2x in profitability were observed as scales below 1km^2; differences between profitability and loss were also seen at those scales.[115] Similar differences were observed for potato production in Denmark, with standard deviations of about 20% of yield occurring within farms.[116] While studies of within-field variability tend to be local, these values do not seem atypical.[117] How these differences manifest in GHG emissions depends on the management practices; with identical practices (and soil dynamics), a yield difference of 20% will also lead to GHG emission intensity differences of 20%. If practices are varied between or within fields — for example, more inputs are used or asymmetrical water application due to irrigation equipment placement — these differences could be much larger.

In some farms, this heterogeneity may be exploited by planting different crops or leaving some land as natural buffers.

Note that if deforestation or other conversion occurs at a field-scale, this can drive even larger differences of 10-fold or more depending on the crop yield and the carbon content of the previous habitat. Historically, the loss of habitat would have been accounted for at a larger spatial scale and allocated to all the crops within the farm and/or region, but with the advent of precision satellite mapping and GIS systems, industry players are looking to assign those emissions to individual crops within farms.

Farm-level

Farm-level differences may be more or less pronounced than field-level differences, although it may be more likely that there are differences in management practices across than within farms. Multi-fold yield differences are common across farms using similar production practices (e.g., rain-fed wheat) in the same region.[118] (These differences often translate to multi-fold differences in GHG intensity for products produced on those farms.) In other cases, like the potato farms in Denmark described above, variability was larger across fields within a farm than across farms. For studies across multiple regions, management practices seem to drive yield differences between farms.[119]

Across farms, more analyses have been conducted. Much higher differences are also described, especially when many farms are explicitly surveyed to determine emissions footprints. For example, for 370 farms using the Cool Farm Tool in Colombia, while average emissions were 1.2kgCO_2e/kg green coffee, some farms had emissions over 30 kgCO_2e/kg.[120] However, we have not seen any analyses that explicitly look at the trends in this variable across large spatial scales and for multiple crops, so it is difficult to generalize.

Sub-national

State or province level agricultural data are often the smallest unit of data collection, although some countries like the US provide those data within smaller regions; the availability of GHG intensity estimates at this high resolution is rarely available. In some cases, this level of aggregation may capture meaningful differences in natural resource endowment; in other cases, it may not. These analyses seem to be driven by reporting convenience, and studies of the implications of variability at smaller and larger scales relative to sub-national are sparse.

Because at this scale, the average impact has already incorporated differences across many farms, differences of several factors (rather than 10-fold) seems to be more common.[121]

National

Differences in footprints at national levels have received great attention in the academic and policy literature.[122] The difference between countries' footprints for producing the same products is highly variable, as **Figure 11 (Page 22)** and **Table 9 (Page 17)** illustrate; national footprints for a product typically vary by a factor of approximately 4, but can range as high as a factor of 30 (Fig. 11).

The differences between countries' average footprint is widely considered important. In one analysis across 26 crops (row, fruits, herbs, and vegetables) of non-LUC related on-farm emissions, differences of 10-fold or more for the footprints of the same crop were found, and country-specific differences, including biophysical and regulatory differences, drove much of the variability.[123]

Note that LUC impacts are often calculated at a national scale, which is particularly suitable for capturing induced land-use change but is likely very different from direct land-use change estimates, especially at a farm-scale. ■

Peer Reviewers

1. **Hans Blonk**, Janjoris van Diepen, and Nicolo Braconi, Blonk Sustainability
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Tables

Table 1. Emissions aggregated by source for roughly 2015-2018 period. Note that estimates are a composite of multiple sources, so some constituent values may not add exactly to the whole. The rows in blue highlight agriculture, forestry, and other land-use (AFOLU) emissions associated with agriculture versus agriculture emissions that include fossil fuel sources as well up through the farm-gate. The last row (green) gives the mass of all agricultural production across industrialized and developing countries to contextualize their respective emissions.

	Estimate in GtCO$_2$e/yr[14]	Industrialized countries[15]	Developing countries[16]
LULUC	4.9[17] - 5.9	0.7	5
Non-CO$_2$ ag. emissions	6	1.6	4.4
Ag. emissions from fossil fuels	1[18]	0.4	0.6
AFOLU ag. emissions (LULUC + non-CO$_2$e ag)	11.9	2.3	9.4
All farm-gate emissions (LULUC + non-CO$_2$ ag. + fossil ag.)	12.8	2.7	10
Total food system emissions	**18**[19]	**4.8**	**12.9**
Total agr. products (Gt)[20]		**2.5**	**5.3**

Table 2. Summary of observed variability in GHG intensity for different relevant food production processes and the overall contribution of that process towards global emissions across foods.

	Difference (multiplied) in emissions per kg edible product *	Total emissions from agriculture (GtCO$_2$e/yr)
Enteric fermentation	> 10x	3[21]
Manure management	10x **	0.4[22]
Aquaculture ponds	50x[23]	0.2-0.6[24, 25]
Vegetal effluents[26]	>2x **	?
Land-use change	> 10x	>3[27]
Drained organic soils	>100[28]	0.7[29]
Soil carbon management	>2x **	?
Agricultural direct & indirect N$_2$O	>10x	1.5[30]
Inputs	>20x	0.3-0.6[31, 32]
Agricultural soil sequestration	>100x	0
Transport	10; 100x ***	0.9[33]
Processing & packaging	10x	1.4[34]

* Note that this variability excludes 0; 10x indicates a ten-fold difference in intensity has been reported for non-zero values.
** Indicates that emissions can be negative, which is not factored into the variability range.
*** First value is for mode of transit differences only; second is in combination with distance.

Table 3. Processes that often cause large (over 0.5kgCO$_2$e/kg product) emissions and associated principal data need for estimation. Bolded entries indicate the data can be collected by satellite. Processes were selected using the frequency of occurrence in the Poore & Nemecek dataset above 0.5 kgCO$_2$e/kg at 95th percentile and 1 kgCO$_2$e/kg at 99th percentile. Note that this is a heuristic measure given that the number of entries is idiosyncratic per product and some entries do not have a value for a particular process.

LUC emissions	**Occurrence within 20 yrs.; cleared ecosystem type**
Fertilizer & pesticide (input)	Amount used
Electricity and fuel use (on farm)	Amount used; location (electricity grid)
Direct N_2O emissions from fertilizer	Amount nitrogen applied
CH_4 from rice	Wet-dry periods
Organic soil emissions	Presence on drained organic soil
Animal housing (inputs)	**Building size and age**
Feed (input)	Amount used; typical footprint of feed
Enteric fermentation	Pasture vs. grain fed; age to slaughter
Manure emissions	**Storage type**
Product produced	Amount

Table 4. Data from IPCC 2019 refinement tables 10.11, 10.12, 10.A.5.

	Methane production (kgCH$_4$/head/yr)	Methane production (kg) per kg animal live weight
Sheep	5-9	11-14%
Goats	5-9	18%
Camels	46	8%
Deer	20	17%
Dairy cattle	62-138	21-22%
Beef cattle	41-64	16-20%

Table 5. Table 5: GHG footprint (kgCO$_2$e/kg product) from land-use change, assuming average 2020 yield and carbon content for deforestation from Global Forest Watch[85] and from conversion from IPCC 2006 default. [ ] show the average emissions to farm-gate without LUC from Poore & Nemecek, supra. These estimates assume the entire area (or area for feed) was deforested.

	Green coffee	Oil palm fruit	Soybean	Beef
Footprint from deforestation	27 [8]	1.8 [0.5]	9.6 [0.7]	525 [57]

Table 6. Carbon storage in different ecosystems (tC per ha)

Land-cover	Above ground C	Below ground C	Soil C
Peat swamp[87]	182 (26)	25 (12)	?
Mangrove[88]	115 (7)	741 (29)	
Lowland forest[89]	147 (76)	24 (13)	120 (6)
Rainforest[90]	168 (6)	37	77 (6)*
Grassland[91]	6 (4)	8 (5)	?

When land is cleared for crops, the carbon stored in plants both above and below-ground and in the soil emitted to the atmosphere. The above and below-ground biomass are expected to release their carbon relatively quickly; soil carbon may take longer to decay. Carbon storage in tonnes C / ha, with standard deviation in ( ). * indicates soil carbon to 50cm, otherwise to 1m.

Table 7. Estimated emissions from agriculture & LUC from smallholders in MtCO$_2$e/yr from Vermeulen et al. (2017) for top 10 countries in each category. The percent of national agricultural emissions from smallholders (assumed as the percentage of land under smallholders; this is likely not true, but better data on this relationship are sparse and inconclusive) is also listed. The proportion for bovine meat, cocoa, coffee, maize, palm oil, pigmeat, poultry meat, rice, soya, and wheat from 2015-2021 (FAO-STAT) that is exported per product is also shown. Export ratios were capped at 1; values beyond that likely indicate import and re-exports. Values above 10% are highlighted in blue.

	Smallholder ag.	% small	Bovine	Cocoa	Coffee	Maize	Palm	Pig	Poultry	Rice	Soya	Wheat
China	804	98	0.03	0.00	1.00	0.00	0.17	0.01	0.05	0.01	0.01	0.01
India	287	44	0.39	0.46	1.00	0.07	0.00	0.00	0.00	0.11	0.01	0.02
Indonesia	86	55	0.01	0.60	1.00	0.01	0.66	0.00	0.00	0.00	0.01	1.00
Ethiopia	54	60	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.44	0.00
Bangladesh	51	69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.04
Tanzania	39	88	0.00	0.82	1.00	0.03	1.00	0.00	0.00	0.09	0.73	0.80
Pakistan	21	15	0.03	0.00	0.00	0.03	0.00	0.00	0.00	0.51	0.00	0.03
Egypt	16	58	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.01	0.07
Colombia	16	28	0.04	0.30	0.99	0.04	0.35	0.00	0.00	0.00	0.00	1.00
Nepal	14	69	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00

	Smallholder LUC	% small	Bovine	Cocoa	Coffee	Maize	Palm	Pig	Poultry	Rice	Soya	Wheat
Brazil	203	36	0.22	0.30	0.75	0.33	0.10	0.29	0.29	0.11	0.63	0.16
Indonesia	112	49	0.01	0.60	1.00	0.01	0.66	0.00	0.00	0.00	0.01	1.00
DRC	48	80	0.00	1.00	0.18	0.00	0.03	0.00	0.00	0.00	0.02	0.49
Cameroon	46	57	0.00	1.00	0.70	0.00	0.01	0.00	0.05	0.06	0.06	1.00
Venezuela	43	36	0.00	0.15	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.40
Tanzania	38	57	0.00	0.82	1.00	0.03	1.00	0.00	0.00	0.09	0.73	0.80
Myanmar	36	84	0.00	0.00	0.51	0.36	0.00	0.00	0.00	0.09	0.04	0.04
Argentina	34	39	0.17	0.00	0.00	0.58	0.00	0.02	0.09	0.41	0.14	0.64
Bolivia	29	36	0.04	0.00	0.06	0.03	0.00	0.00	0.00	0.00	0.01	0.03
Ecuador	28	36	0.00	1.00	1.00	0.00	0.46	0.00	0.00	0.02	0.00	1.00

Table 8. GHG totals from the agriculture sector from different models. All values in $GtCO_2e$. Note that for the FLAG model estimate, we avoided double-counting emissions from feed fed to animals by subtracting a correction to the sum for the proportion of crops used for feed. Note that the two columns in green are the emissions for only the nine foods included in the FLAG model. The other columns are for all foods (inclusive or exclusive of seafood as noted).

Emissions category	FLAG Model (9 foods only, 2015)	P&N (9 foods only)[109]	P&N (excl. seafood) Gt	IPCC AR6 CH 12 (2018; incl. aquaculture)[110]	IPCC AR6 Ch 7 (2010-2019 avg; excl. seafood)	Crippa (incl. aquaculture, 2015)
Agricultural	5.9	5.8	8.1	6.3	6.0 (+/- 1.7)*	7.1
LUC	3.7	1.6	2.6	4.0	5.9 (+/- 2.7)	5.7
Total FG	**9.7**	**7.4**	10.7	10.3	11.9 (+/- 4.4)**	12.8
Total food system (including post-farm)	---	9.1	13.1	17	--	18

* Indicates AFOLU only, while other ‘agriculture’ emissions include non-AFOLU sources like tractors and electricity use on-farm.

** This is total AFOLU.

Table 9. Standard deviation divided by average footprints (or coefficient of variation) for the SBTi-FLAG commodities across the 26 IMAGE regions for 4 datasets: the FLAG model, the Global Feed LCA Institute (GFLI), Global Livestock Environmental Assessment Model (GLEAM), and Poore & Nemecek (supra). These ratios include LUC, but note that for some datasets the definitions are inconsistent (e.g., GLEAM only calculates LUC for soy and pasture in Latin America). GFLI data excludes LUC because the data was sparse for LUC availability.

LUC	FLAG (2020)	GFLI	GLEAM	Poore & Nemecek
Beef	2.1		1.3	4.7
Dairy	1.7		1.1	4.2
Pork	5.2		0.4	0.4
Chicken	3.6		0.5	1.1
Rice	8.3	2.0		0.4
Wheat	21.7	0.5		7.2
Maize	6.3	1.0		8.2
Palm Oil	2.4			3.6
Soya	7.5	0.9		6.0

Figures

Figure 1. Breakdown of Food Sector GHG Emissions. Food sector emissions under business-as-usual (left, 2020) and for 2°C and 1.5°C with a breakdown of gross emissions into agricultural non-CO_2 sources; energy, industry, and waste; conversion of natural lands into agricultural lands and land degradation; and sequestration in agricultural lands.

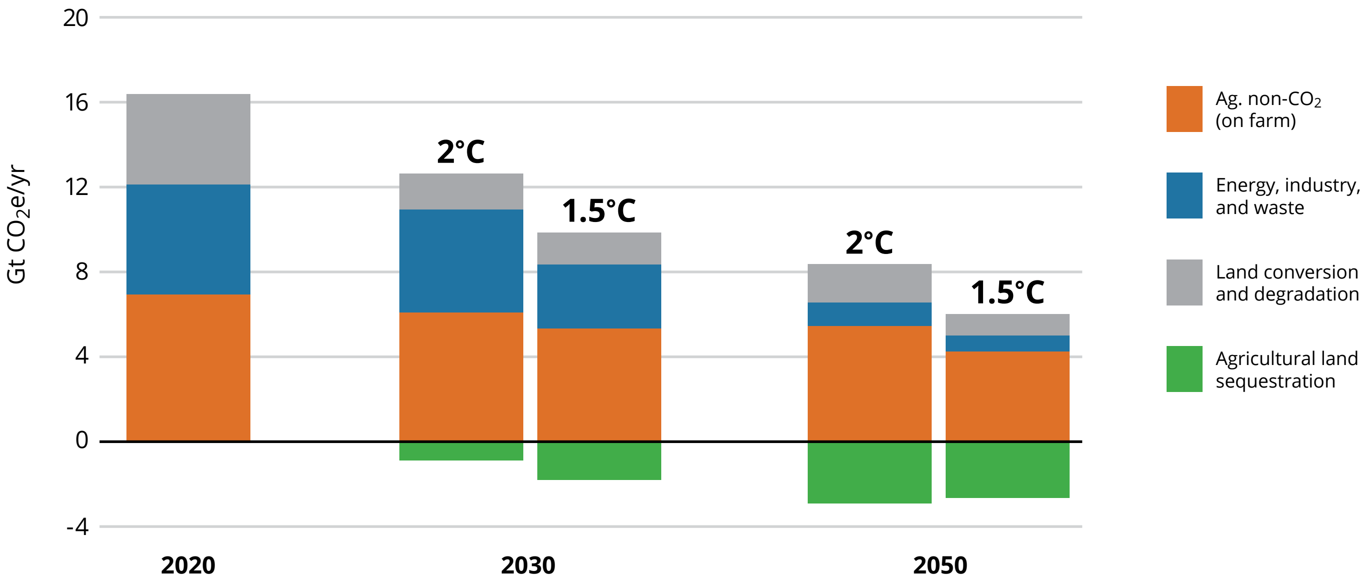


Figure 2. Variability across and within plates. ***Top:*** GHG footprint of the shown plate with average emissions intensity for each food product. ***Bottom:*** GHG footprint of that plate with the highest (left) and lowest (right) emissions intensity for producing those same foods. *Data principally from Poore & Nemecek to minimize accounting differences in estimates (supra).*

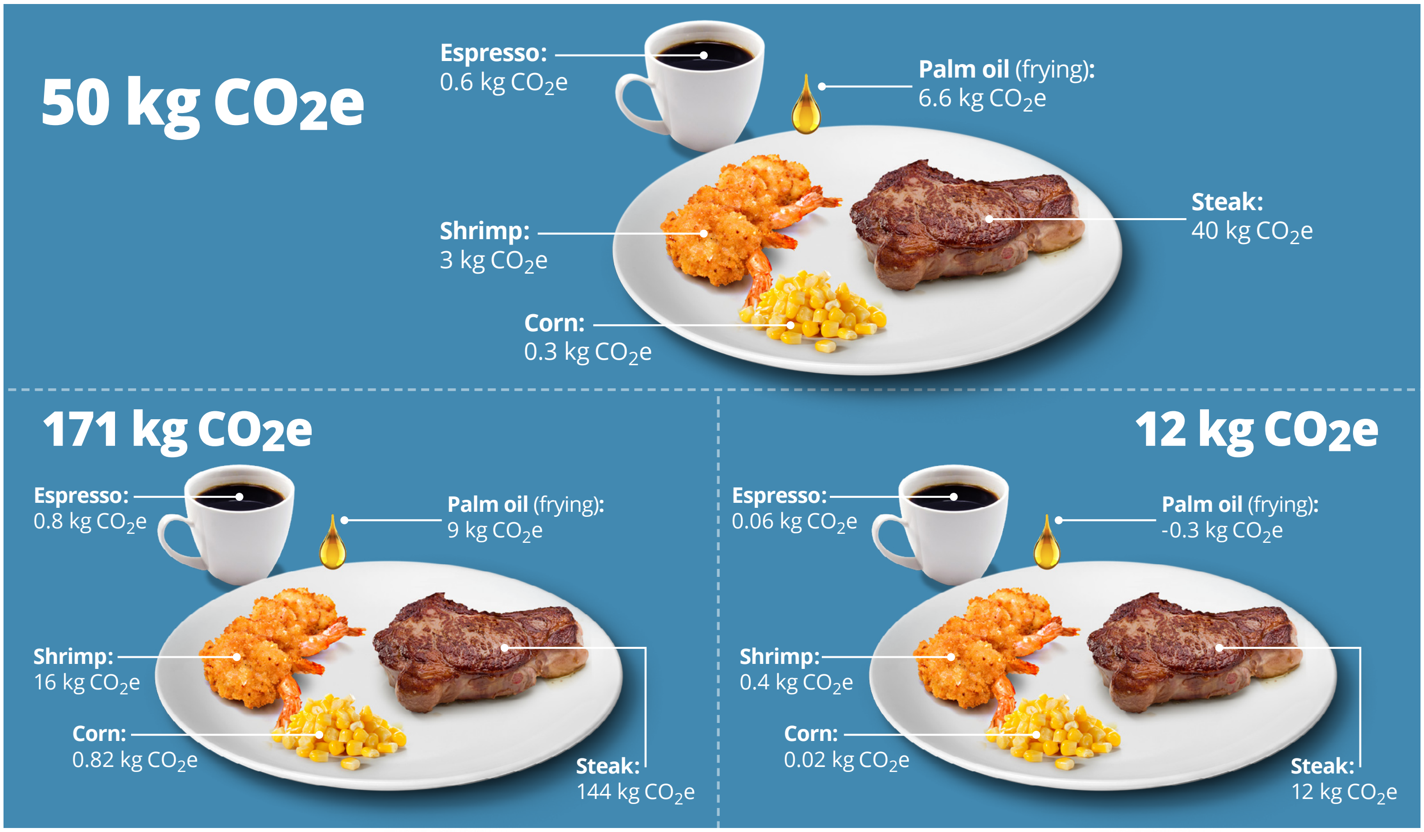
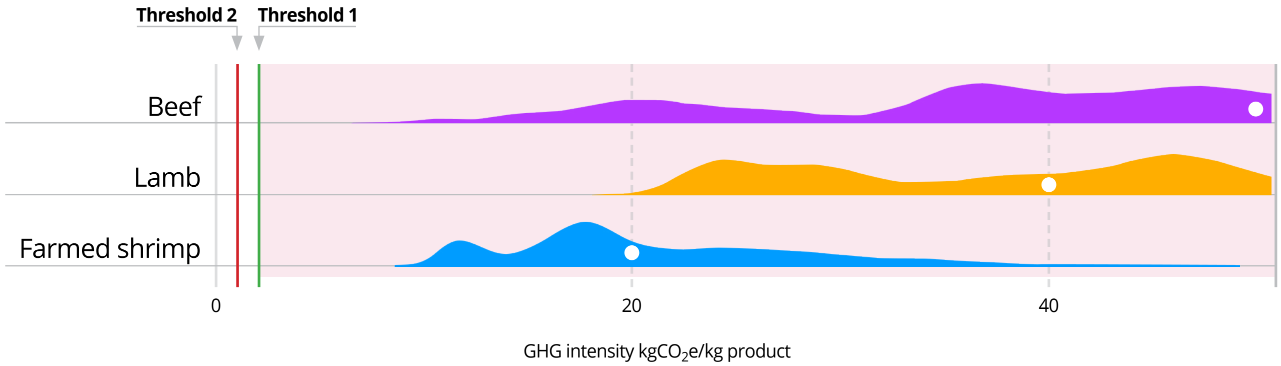
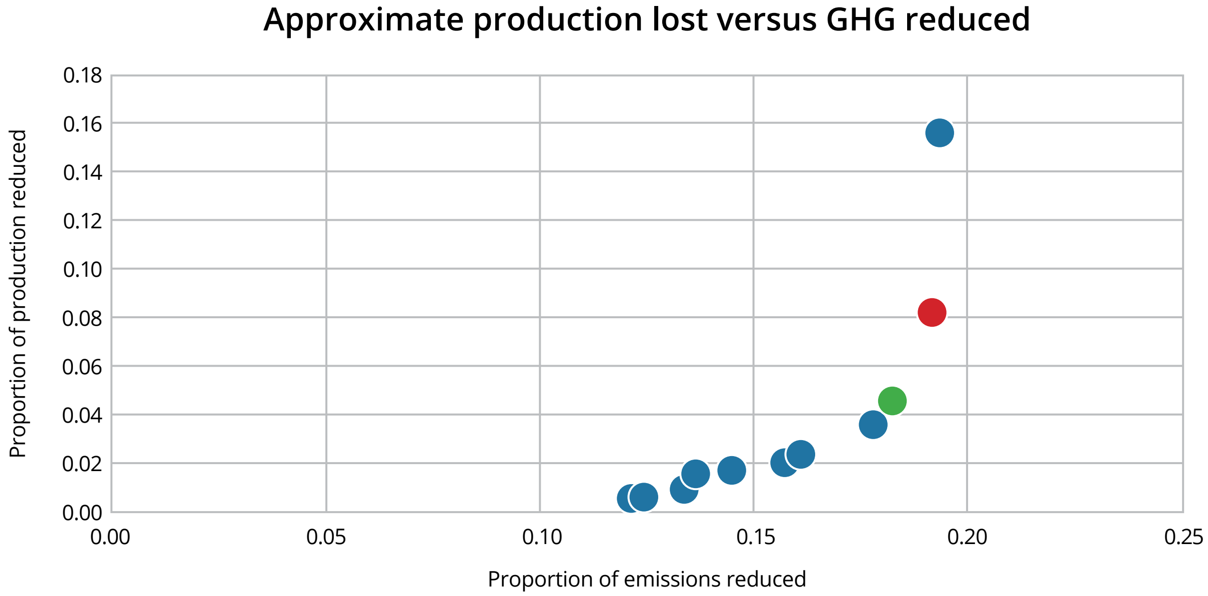


Figure 3.[35] ***Top:*** Illustration of the distribution of GHG intensity for different products and the proportion of each production that exceeds two potential thresholds (thresholds shown in green and red; pink shading shows the proportion of production excluded). ***Bottom:*** For several potential thresholds, the proportion of GHG emissions and food production lost (if that production no longer exists, as we assume here) are plotted. A red and green dot are highlighted to show, as in the top panel, how a higher and lower threshold influence the trade-off between emissions avoided and food reduced. The lowest threshold (0 kgCO_2e/kg product) is in the top right; the highest (13 kgCO_2e/kg product) is in the bottom left. Note that these effects are only considered within traded product; product specific export to production rates were taken from FAO-STAT for 2020. *Other data from Poore & Nemecek, supra.*





The chart above ("Approximate production lost versus GHG reduced") shows the proportion of the food system production and proportion of food system GHG emissions implicated at these different thresholds. When the threshold is 1kgCO_2e/kg product (top right point), nearly all emissions from traded food would be avoided (19%) but there would also be a 16% reduction in total food production. However, at higher thresholds (going southwest in the chart), most traded food emissions are still avoided while most traded food is not “lost”.

Note that the products implicated are disproportionately meat, seafood, and vegetal oil products. Tiered, or commodity-specific, thresholds could also be employed and show broadly similar patterns. For example, **Figure 4** (next page) shows a threshold of 1, 3, and 5 kgCO_2e/kg product for non-animal products and an increasing threshold for animal-source products.

Figure 4. Threshold for vegetal products. Proportion of GHG emissions and food production implicated across variable GHG intensity thresholds for animal-source products; the threshold for plant products is 1, 3, and 5 kg CO_2e/kg product. The lowest threshold (5 kgCO_2e/kg product) is in the top right; the highest (70 kgCO_2e/kg product) is in the bottom left. Note that these effects are only considered within traded product; product specific export to production rates were taken from FAO-STAT for 2020. *Other data from Poore & Nemecek, supra.*

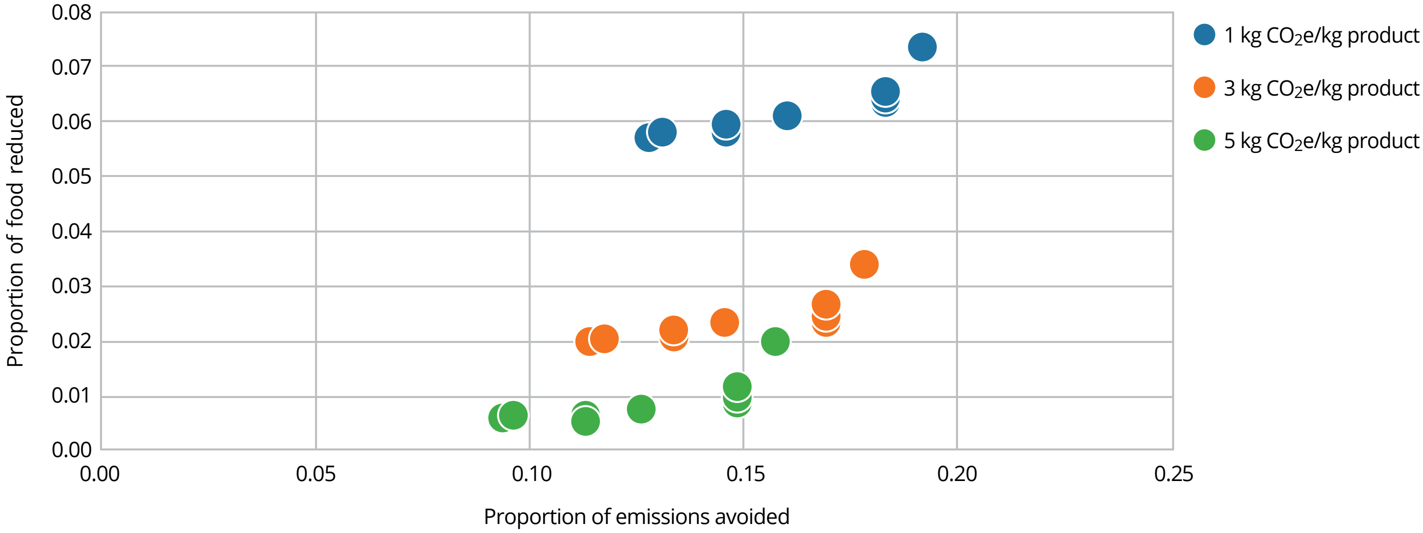


Figure 5. Imported and exported food emissions by region. Note that these estimates exclude emissions from savannah burning and drained peat. *From Xu et al. (2021) supra.*

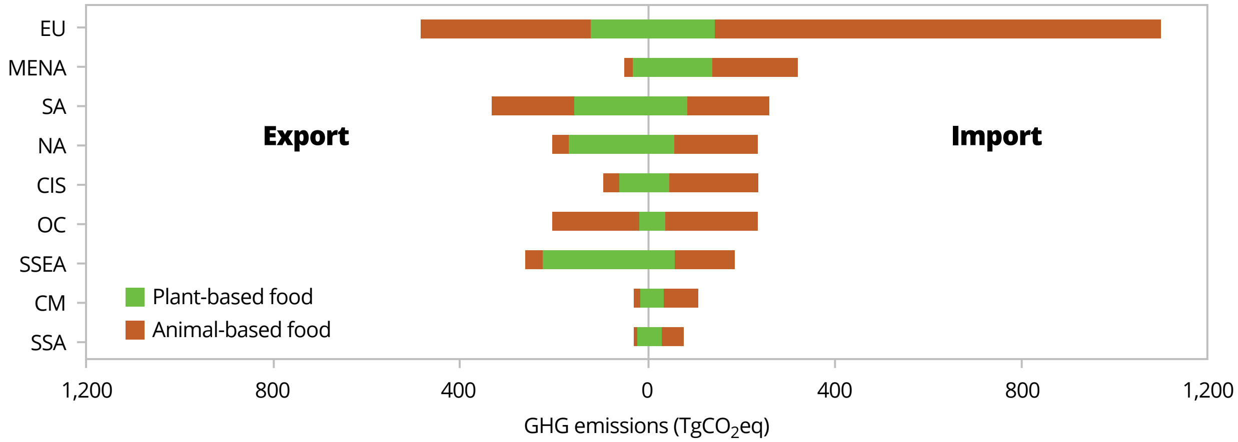


Figure 6. Deforested area imported from Brazilian beef. Frequency of different amounts of imported deforestation for beef imported from Brazil. Note that several countries' imports of Brazilian beef implicated less than 0.11 ha of deforestation per tonne of product, while several had over 4x that rate in their imports.

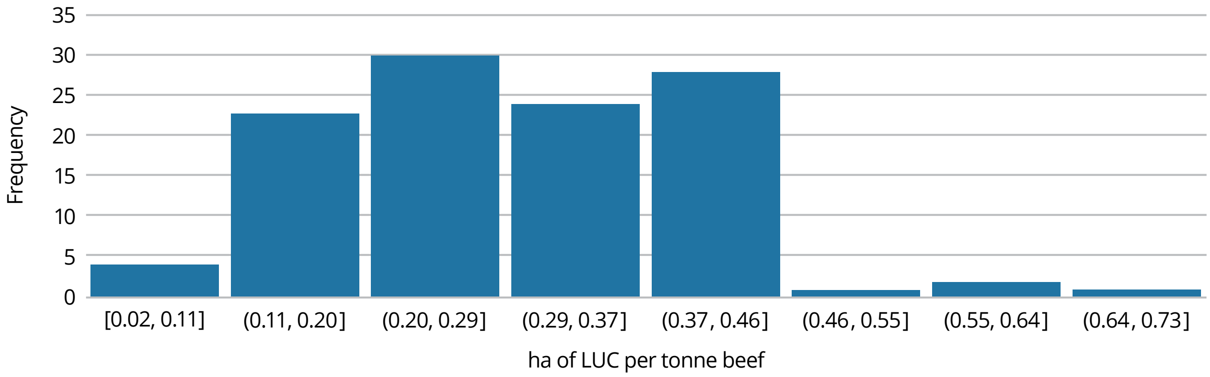


Figure 7. Schematic showing potential logic for required primary data. To minimize the data collection burden, primary data from the farm would only be required in cases where, within a 95% confidence band from the emissions for that emissions source, after emissions are estimated using external data like satellite imagery the potential footprint lies outside the threshold.

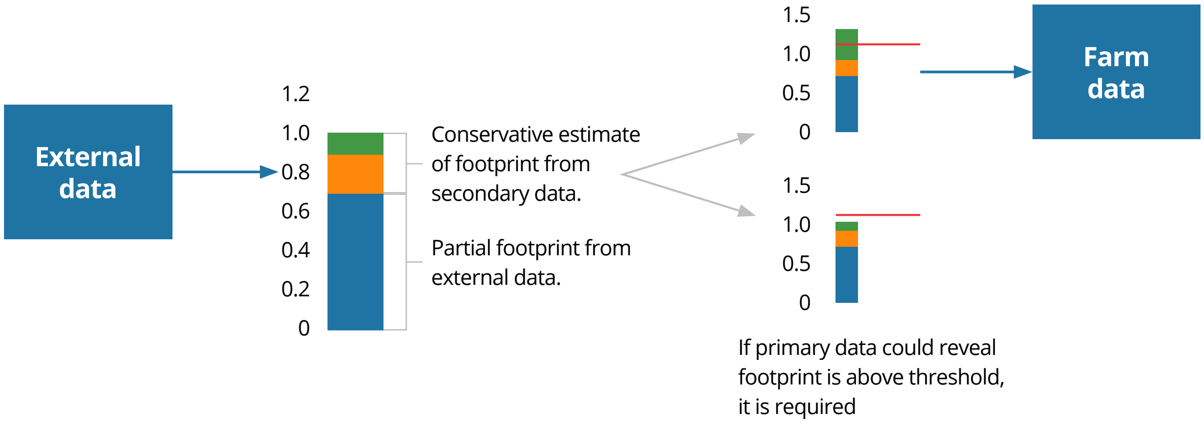


Figure 8. FAO 1.5°C food roadmap. Note that the removals from bioenergy with carbon capture and storage fall outside of the definition of food production used in this chapter. It is unclear what the scope of the ecosystem restoration refers to.

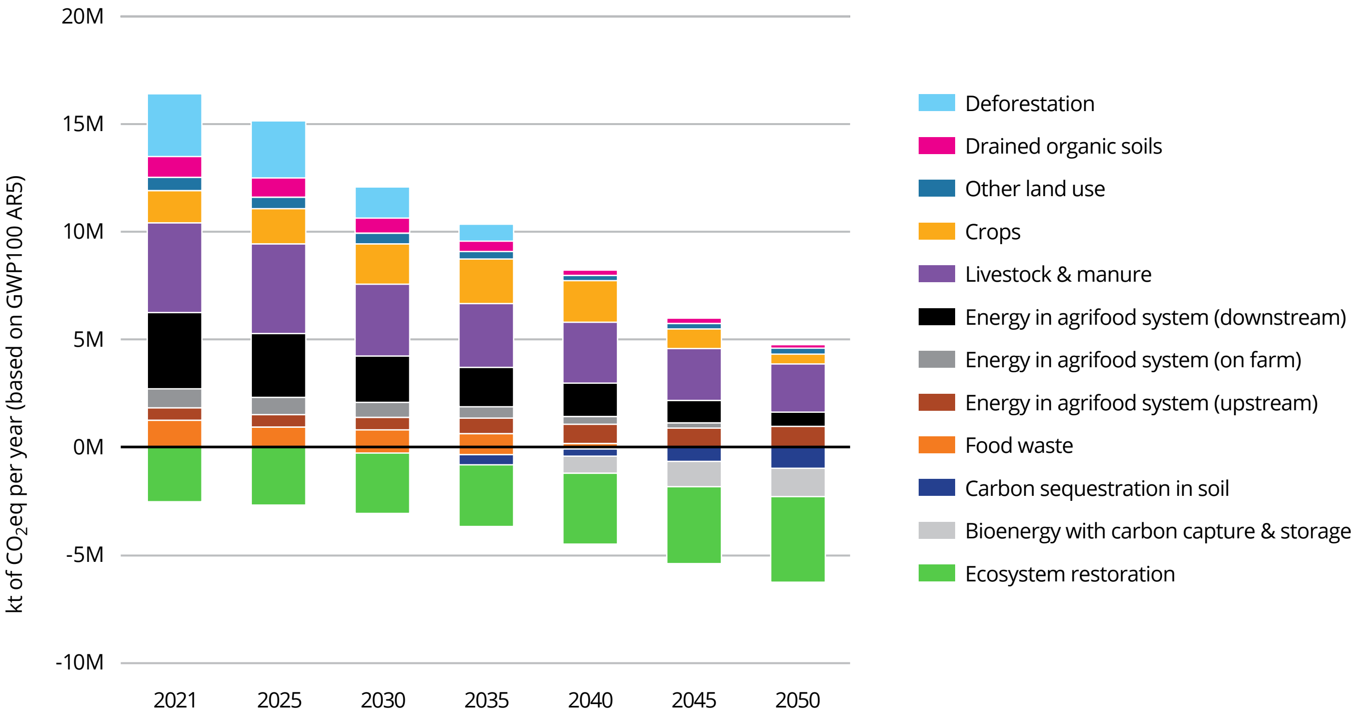


Figure 9. Global SBTi FLAG targets. Emissions intensity targets for the nine specifically modeled SBTi FLAG commodities. These targets include reductions in on-farm emissions, elimination of deforestation and conversion, and enhanced soil carbon sequestration. These emissions targets assume growth in each commodity's production, which is also modeled in IMAGE 3.0. Region-specific targets are also available for the 26 modeled regions in IMAGE.

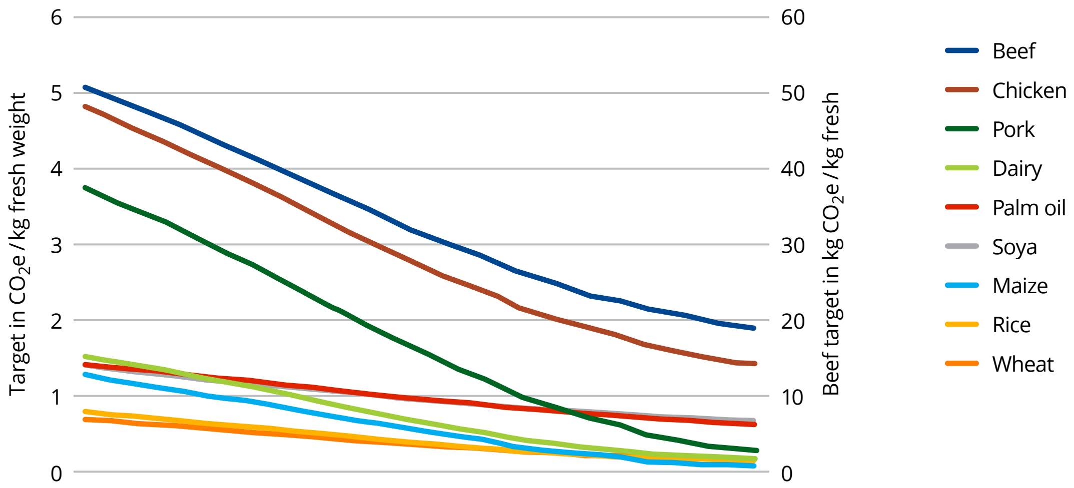
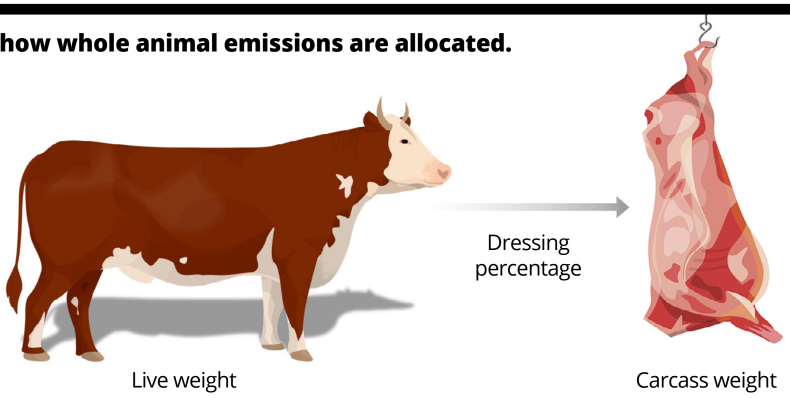


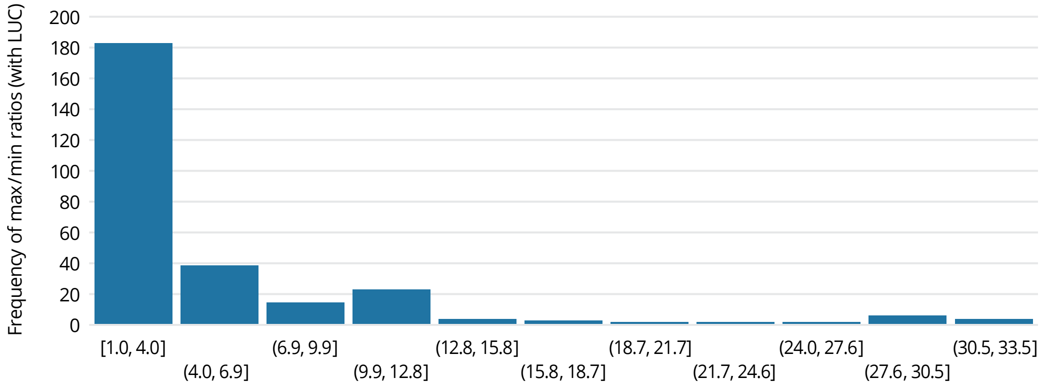
Figure 10. Schematic of how whole animal emissions are allocated.



Animal emissions: 10 tons CO_2e **Dressing percentage:** 50%

Allocation method	Emissions to carcass	Carcass emissions intensity
All animal emissions to carcass	10 t	10 t / 0.5 = **20 t CO_2e/t CW**
Economic allocation (90% value)	10 t * 0.90 = **9 t**	9 t / 0.5 = **18 t CO_2e/t CW**
Mass allocation	10 t / 0.5 = **5 t**	5 t / 0.5 = **10 t CO_2e/t CW**

Figure 11. Frequency of the ratio between the maximum reported footprint for the same product and minimum by country in Agrifootprint 5.0 database. The average ratio was 4.9 with LUC included; it was 2.8 without LUC. Note that the majority of these items are crops or feed ingredients.



Footnotes / Citations

[1] Babiker, M., G. Berndes, K. Blok, B. Cohen, A. Cowie, O. Geden, V. Ginzburg, A. Leip, P. Smith, M. Sugiyama, F. Yamba, 2022: Cross-sectoral perspectives. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA

[2] Crippa et al. (2021) “Food Systems Are Responsible for a Third of Global Anthropogenic GHG Emissions.” Nature.

[3] For the remainder of this document, 1.5C temperature increase or 1.5C future refers to limiting temperature rises to 1.5C degrees above pre-industrial levels. Where overshoot is relevant, it will be specified.

[4] Clark, M. A., Domingo, N. G., Colgan, K., Thakrar, S. K., Tilman, D., Lynch, J., ... & Hill, J. D. (2020). Global food system emissions could preclude achieving the 1.5 and 2 C climate change targets. *Science,* 370(6517), 705-708.

[5] https://unfccc.int/topics/land-use/workstreams/agriculture/KJWA#COP-27-November-2022

[6] Summarized here: https://wwfint.awsassets.panda.org/downloads/dcf_critical_for_1_5_pathway___summary_and_techincal_methods.pdf

[7] https://wwfint.awsassets.panda.org/downloads/dcf_critical_for_1_5_pathway___summary_and_techincal_methods.pdf

[8] Non-commodity driven conversion includes clearing for subsistence agriculture.

[9] This is an approximate average across IAMs; see WWF resource on Why DCF is Critical for a 1.5C Future, supra

[10] https://www.fao.org/interactive/sdg2-roadmap/en/

[11] https://www.fao.org/3/cc9113en/cc9113en.pdf

[12] https://sciencebasedtargets.org/sectors/forest-land-and-agriculture

[13] IPCC Special Report on Climate and Land Use (2019); Poore & Nemecek (2018), Vermeulen et al. (2012; Crippa et al. (2021); FAO 1.5°C roadmap supra

[14] IPCC AR6 Chapter 7

[15] Crippa et al. (2021) infra; total LULUC for Crippa is 5.7 GtCO2e/yr

[16] Crippa et al. (2021) infra

[17] IPCC Special Report on Land and Climate Change https://www.ipcc.ch/srccl/chapter/summary-for-policymakers/

[18] Crippa et al. (2021) all production sources listed as “energy” or “industry”

[19] Crippa et al. infra

[20] From FAO-STAT 2019-2021 Food Balances (new method) production, using same country categories as Crippa et al. Foods were inclusive of cereals, eggs, fish, fruits, meat, milk, oilcrops, pulses, vegetables; some of these products may end up in non-food uses.

[21] Crippa et al. infra

[22] Crippa et al.

[23] Poore & Nemecek, supra

[24] Hu et al. (2012) Nitous oide emission from aquaculture: a review. Env. Sci. Tech.

[25] Rosentreter et al. (2021) Nature Geoscience

[26] Effluents from the processing of crops like oil palm and coffee; these effluents produce methane and nitrous oxide under traditional disposal.

[27] FAO 1.5°C roadmap

[27] FAO 1.5°C roadmap

[28] Poore & Nemecek, supra

[29] FAO-STAT, drained organic soils in croplands, average 2019-2021 using 273 GWP for N2O

[30] Crippa et al.

[31] Crippa et al.

[32] FAO 1.5°C roadmap (supra)

[33] Crippa et al.

[34] Crippa et al.

[35] Graph modified from https://ourworldindata.org/less-meat-or-sustainable-meat, footprint for farmed shrimp re-normalized with protein content from Poore & Nemecek supplement.

[36] Niu, B., Peng, S., Li, C., Liang, Q., Li, X., & Wang, Z. (2020). Nexus of embodied land use and greenhouse gas emissions in global agri cultural trade: A quasi-input–output analysis. Journal of cleaner production, 267, 122067. They found 0.7 GtCO2e/yr embodied in trade, corresponding to 4.9 GtCO2e/yr emissions from the food system, which is roughly in line (albeit low) with farm-level, non-LUC emissions.

[37] Xu, X., Sharma, P., Shu, S. et al. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. *Nat Food* 2, 724–732 (2021). https://doi.org/10.1038/s43016-021-00358-x

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[39] MAPBIOMAS land transitions data using Level 2 transitions to pasture from 2018-2022, amortized over 4 years.

[40] Halpern, B. S., Frazier, M., Verstaen, J., Rayner, P. E., Clawson, G., Blanchard, J. L., ... & Williams, D. R. (2022). The environmental footprint of global food production. *Nature Sustainability*, 5(12), 1027-1039.

[41] AFOLU emissions sources include: enteric fermentation, manure management, synthetic fertilizer application, rice cultivation, changes in soil carbon stocks, and conversion between land classes (e.g., deforestation, peatland conversion, coastal conversion, grass land conversion; af-/re-forestation).

[42] See, for example, GHG Protocol Corporate Protocol (https://ghgprotocol.org/corporate-standard) versus their product standard (https://ghgprotocol.org/tags/product-standard).

[43] This was suggested by some reviewers of the first draft of this chapter. The author does not think that this is feasible in totality but wanted to highlight that the choice of life-cycle stages is not trivial.

[44] Note that when transport or waste emissions occur on the farm or prior to the farm-gate, they are included within the scope of the farm-gate footprint.

[45] https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=20967%0A

[46] E.g., https://coolfarm.org/three-major-farm-carbon-calculators-outline-a-roadmap-to-harmonisation/

[47] Greenhouse Gas Protocol Draft Land Sector and Removals Guidance Part I: https://ghgprotocol.org/sites/default/files/2022-12/Land-Sector-and-Removals-Guidance-Pilot-Testing-and-Review-Draft-Part-1.pdf

[48] Jannick H. Schmidt, Bo P. Weidema, Miguel Brandão, A framework for modelling indirect land use changes in Life Cycle Assessment, Journal of Cleaner Production, Volume 99,2015, Pages 230-238,ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2015.03.013.

[49] EUDR guidance: https://green-business.ec.europa.eu/deforestation-regulation-implementation/traceability-and-geolocation-commodities-subject-eudr_en

[50] https://accountability-framework.org/fileadmin/uploads/afi/Documents/Resources/Assessing_Compliance_at_the_Production_Unit_Level.pdf

[51] Greenhouse Gas Protocol Draft Land Sector and Removals Guidance Part I: https://ghgprotocol.org/sites/default/files/2022-12/Land-Sector-and-Removals-Guidance-Pilot-Testing-and-Review-Draft-Part-1.pdf

[52] A cut-off date is a date of land-clearing past which it is non-compliant. 2020 is the international standard for deforestation and conversion free supply-chains, although some geographies and commodities may have earlier standard dates.

[53] https://sciencebasedtargets.org/sectors/forest-land-and-agriculture

[54] Greenhouse Gas Protocol draft guidance, supra

[55] Roe, S., Streck, C., Obersteiner, M. et al. Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Chang*. 9, 817–828 (2019). https://doi.org/10.1038/s41558-019-0591-9

[56] E.g., Ravensbergen, A. P. P., van Ittersum, M. K., Silva, J. V., Maestrini, B., Kempenaar, C., & Reidsma, P. (2023). Yield variability across spatial scales in high input farming: Data and farmers' perceptions for potato crops in the Netherlands. European Journal of Agronomy, 150, 126925.

[57] E.g., Apdini, T., Al Zahra, W., Oosting, S.J. et al. Understanding variability in greenhouse gas emission estimates of smallholder dairy farms in Indonesia. *Int J Life Cycle Assess* 26, 1160–1176 (2021). https://doi.org/10.1007/s11367-021-01923-z

[58] From ISO 14044: ""Physical allocation can be applied when a physical, i.e. causal, relationship can be identified between the inputs, outputs and co-products of the multifunctional process. Such a relationship exists when the amounts of the co-products can be independently varied. How the amounts of inputs and outputs (emissions and waste) change following such a variation can be used to allocate the inputs and outputs to the varied co-product."

[59] Lamboll, R.D., Nicholls, Z.R.J., Smith, C.J. et al. Assessing the size and uncertainty of remaining carbon budgets. *Nat. Clim. Chang.* 13, 1360–1367 (2023). https://doi.org/10.1038/s41558-023-01848-5

[60] Science Based Targets Initiative rate of decrease from base year: https://sciencebasedtargets.org/step-by-step-process

[61] https://www.fao.org/interactive/sdg2-roadmap/en/

[62] https://www.fao.org/3/cc9113en/cc9113en.pdf

[63] For example, Verkuijl, C., Dutkiewicz, J., Scherer, L. et al. FAO's 1.5 °C roadmap for food systems falls short. *Nat Food* (2024). https://doi.org/10.1038/s43016-024-00950-x

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[65] Data from the SBTi-FLAG model tool. The sum is corrected for feed inclusion by only including the proportion of crops going to non-feed uses, estimated from FAOSTAT. FAOSTAT global totals for production were used to estimate the total emissions using the FLAG emissions intensities.

[66] Roe, S., Streck, C., Obersteiner, M. et al. Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Chang*. 9, 817–828 (2019). https://doi.org/10.1038/s41558-019-0591-9

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[69] From Table 4.13 of the GLEAM 2018 documentation (2.0): "Resources | Global Livestock Environmental Assessment Model (GLEAM) | Food and Agriculture Organization of the United Nations."

[70] Musengezi et al., "U.S. Beef Supply Chain: Opportunities in Fresh Water, Wildlife Habitat, and Greenhouse Gas Reduction. The Nature Conservancy."

[71] IPCC, "2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Chapter 5," IIPCC., 2006, http://www.ipcc-nggip.iges.or.jp/public/2006gl/ (accessed 1 Nvo. 2024): 1% kgN as N2O as applied N, rescaled to CO2e using 28/44 kgN:kgN2O and GWP of 273 for N2O.

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[74] Poore and Nemecek, "Reducing Food's Environmental Impacts through Producers and Consumers."

[75] Ping Yang et al., "Fluxes of Greenhouse Gases at Two Different Aquaculture Ponds in the Coastal Zone of Southeastern China," *Atmospheric Environment* 115 (2015): 269–77, https://doi.org/10.1016/j.atmosenv.2015.05.067.

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[81] From Gasser et al. considering cumulative ELUC and LASC (227 PgC) from deforestation for cropland and cumulative "other natural land appropriation" (76 PgC). https://bg.copernicus.org/articles/17/4075/2020/.

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[83] Estimating the Role of Seven Commodities in Agriculture-Linked Deforestation: Oil Palm, Soy, Cattle, Wood Fiber, Cocoa, Coffee, and Rubber: https://www.wri.org/research/estimating-role-seven-commodities-agriculture-linked-deforestation-oil-palm-soy-cattle

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