



**JNCC Report 746**

**Technical documentation for an official statistic in development estimating the  
global environmental impacts of consumption: 2023 Version**

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## Summary

The Outcome Indicator Framework for the UK Government's 25 Year Environment Plan called for the development of an indicator to measure the "overseas environmental impacts of UK consumption of key commodities." Its more recent update in the form of the Environmental Improvement Plan continues to acknowledge the importance of understanding the global environmental impacts of consumption. This report describes the methodologies used to produce an official statistic in development that is published as UK Biodiversity Indicator A4, that feeds into Outcome Indicator Reporting as indicator K1 and that has been included as a component indicator within the Kunming-Montreal Global Biodiversity Framework. This includes:

- An overview of the modelling framework, which is based on hybrid multi-regional input-output modelling using data from the [Food and Agriculture Organisation \(FAO\) of the United Nations](#) and [EXIOBASE](#), which are combined within the Stockholm Environment Institute's IOTA (Input-Output Trade Analysis) framework (Croft *et al.*, 2018).
- An explanation of the treatment of commodities that differed in methods and data from the other commodities analysed, namely cattle and timber.
- An explanation of the data sources used for each impact metric type, how they were integrated into the modelling, and any known data update plans. In brief:
  - Cropland area harvested was based on FAO data on land areas harvested.
  - Deforestation and associated carbon emissions were based on methods originally developed in Pendrill *et al.* (2019a, b) which have subsequently been updated with methodological enhancements to improve spatialised crop-specific attribution and forest-loss coverage and to include in non-tropical regions (Singh & Persson, 2023).
  - Water footprint metrics were based on annualised [Water Footprint Network](#) data, with a water scarcity metric combining this data with [AWARE](#) factors (relative Available WATER REmaining per area in a watershed, Boulay *et al.*, 2018).
  - Two separate methods were used for estimating biodiversity loss:
    - Characterisation factors provided by Chaudhary and Kastner (2016) were used to predict regional species loss.
    - [MapSPAM](#) data was used alongside species richness information from the [International Union for the Conservation of Nature \(IUCN\)](#) and [BirdLife International](#) to estimate species richness-weighted extent of crop production.

Supplementary results to the main indicator release are included in Annex 1. A discussion of alignment with related metrics is given in Annex 2. Where the methodology has been updated since the indicator's original release, changes are described in Annex 3. Detailed concordances between data sources used are provided in Annex 4.

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# 1. Introduction

This report constitutes the technical and methodological documentation for the [official statistic in development](#) estimating the global environmental impacts of UK consumption for a range of impact metrics, and the associated [interactive dashboard](#). An official statistic in development is a newly developed or innovative official statistic that is undergoing evaluation, produced under the [Code of Practice for Statistics](#). In order to facilitate user involvement in the development of this indicator, we would welcome any feedback, particularly on the usefulness and value of these statistics, via [enviro.statistics@defra.gov.uk](mailto:enviro.statistics@defra.gov.uk). Further information can be found on the [Office for Statistics Regulation website](#).

Since its [original publication in 2021](#), the official statistic in development has been updated twice. The [2022](#) and 2023 releases of the indicator follow the same methodology outlined in this documentation, except for those differences detailed in Annex 3. In the 2022 release, the updates included the addition of reptile data to the biodiversity metric and a clarification of which subset of an underlying data set has been used. In this [2023 release](#), updates include the addition of data on deforestation outside of the tropics and associated improvements in the spatial granularity of the deforestation metric. In both the 2022 and 2023 releases, the time series was extended, with the latest release providing updated data for 2005 to 2021 (note that as data was updated for the full time series, data in the current version may differ from data in the previous versions). Methodological changes relating to the addition of data on more consumption countries/territories to the associated dashboard in 2023 (building on the original 44 countries/territories published in previous years) are detailed on the [dashboard website](#). This does not form part of the UK data release but will be of interest to international users of the data.

The report provides an explanation of the datasheets published and the methods used (main report), as well as a range of supplementary information in the Annexes (supplementary graphs for 2023 in Annex 1; consideration of alignment and consistency with the UK Carbon Footprint and UK Material Footprint in Annex 2; 2022 and 2023 methods' updates in Annex 3; concordances in Annex 4).

## 1.1 Policy context

Around [45% of direct UK food supply](#) (based on the farm-gate value of unprocessed food) is met from production in other countries/territories (Defra, 2018). The UK is also heavily reliant on imports for many other commodities, such as minerals and fuels. Commodities embedded within products (directly as an ingredient such as palm oil in cosmetics, or indirectly such as soy used as feed in the production of meat) are more difficult to trace, but also make up a substantial proportion of UK consumption. Therefore, addressing the sustainability of UK consumption considering products and commodities produced overseas is at least as important as those produced in the UK.

Globally, consumption of commodities is a major driver for natural habitat loss and degradation of ecosystem services, such as biodiversity, resilience to hazards, and climate change mitigation and adaptation. For example, [9–14% of global annual greenhouse gas \(GHG\) emissions](#) come from the gases emitted and sequestration potential lost when land is converted for food and fibre commodity production (reviewed in Harris *et al.*, 2020). The issue has been highlighted recently in multiple high-profile reports, such as the [National Food Strategy](#) and the [Dasgupta Review](#), as well being the focus of Target 16 in the [Convention on Biological Diversity \(CBD\)'s Kunming-Montreal Global Biodiversity Framework](#).

The Government's [25 Year Environment Plan](#) (25YEP) and its first revision, the [Environmental Improvement Plan 2023](#), recognise the need to better understand the UK's contribution to such impacts. The associated Outcome Indicator Framework sets out a series of indicators to track delivery of progress. One of these indicators (K1) seeks to track the "overseas environmental impacts of UK consumption of key commodities" and is designed to enable government to measure the environmental risks and impacts associated with UK consumption. The official statistic in development for which the methodologies are presented here feeds into Outcome Indicator Reporting for K1. It is also the basis for [UK Biodiversity Indicator A4](#) "Global biodiversity impacts of UK economic activity / sustainable consumption", and was included as a component indicator for Target 16 of the CBD's Kunming-Montreal Global Biodiversity Framework, as the "Global Environmental Impacts of Consumption (GEIC) indicator".

## 1.2 Previous publications

The methods in this document build on previous work contracted and conducted by JNCC on behalf of Defra, including an investigation of best practices in the field of measuring consumption impacts (Route2 and Carbon Smart, 2019), an investigation of the feasibility of an indicator originally proposed to act as K1 (Harris *et al.*, 2019) and a research output detailing interim methods for a draft version of the statistic (Croft *et al.*, 2021).

## 1.3 Explanation of datasheets published

The datasheets detailing the underlying data behind the indicator are published on the [JNCC Resource Hub](#) and include:

- [results-total-annual](#) – aggregated results showing the total estimate for each impact type associated with all UK consumption (of all commodities and from all countries/territories combined) for each year;
- [producing-country-results](#) – results showing the total estimate for each impact type associated with UK consumption, broken down by the producing country/territory in which the impact took place (but aggregated across all commodities produced within that country/territory) for each year;
- [commodity-results](#) – results showing the total estimate for each impact type associated with UK consumption, broken down by the commodity responsible for the impact (but aggregated across producing countries/territories from which the commodities came) for each year;
- [uk-results-disaggregated](#) – results showing the estimate for each impact type associated with UK consumption for each commodity in each country/territory of production for each year;
- Additional datasheets, including those relevant to other consuming countries/territories assessed, can be downloaded from the [associated dashboard](#).

Descriptions of column headings can be found in Section 2.4.6 of this report (Table 1).

## 2. Overview of modelling framework

### 2.1 Background

The results are produced from a specially updated version of SEI's Input-Output Trade Analysis (IOTA) modelling framework (Croft *et al.*, 2018).

Traditional production and bilateral trade statistics detail production quantities of commodities and their flows from country/territory to country/territory. However, the 'point of import' viewpoint that such data provide can be, and often is, quite different from that obtained from 'final consumption' profiles that aim to understand the dependencies of products associated with the final purchases and consumption of materials and services. This is especially true for commodities with long and complex supply chains, where consumption of the commodity is indirect and embedded within other consumption activities (for example most soy is "consumed" as feed within meat products).

MRIO approaches overcome this limitation by offering a representation of the entire global economy, which captures the full breadth (all sectors) and depth (all tiers of the supply chain from point of production to point of consumption) of global supply chains. MRIOs detail financial transactions between different sectors of the economy, and final purchases from the economy for consumption. Standard MRIO methods allow for consumption activities to be linked not just to outputs associated with direct purchases, but also all up-stream outputs throughout the entire supply chain. This means that footprints of consumption can be linked to points of origin of raw commodity production, regardless of how many trade, processing or utilisation steps there are between these points of origin and the final consumption.

However, traditional MRIOs offer this breadth and depth at the sacrifice of resolution. This applies to both geographic and commodity fidelity; whilst physical data will often detail commodity-specific production and country-to-country trade, typical MRIO representations will cover purchases between (often broad) economic sectors and a mix of countries/territories and geographic regions (MRIOs contain some countries/territories, while other countries/territories are aggregated together into 'rest of world' regions). Not only does this limit the resolution of results, but it can be especially problematic when looking at impacts which can be highly heterogeneous within sectors and regions.

IOTA is an environmentally extended hybridised MRIO model. IOTA's hybridised approach attempts to overcome the limitations of both approaches by adopting a modelling framework comprising a hybrid of commodity- and country/territory-specific physical production and trade data with the sector- and regional- level representation of the global economy offered by MRIOs. The result is a model that links individual commodity production, resolved to country/territory level, via commodity-specific country/territory-level trade flows and the sector/regional financial flows, to final consumption behaviour at the MRIO regional-level. That is, it retains the production-end resolution of commodity and country/territory specificity but allows for full length supply chain modelling through to final consumption activities, and thus a better understanding of specific production footprints driven by final demand. Environmental extensions allow for any production-linked impacts to be likewise linked through to consumption.

Results are generated for the years 2005 to 2021 inclusive, in line with the current availability of underlying data (Singh & Persson, 2023) for the primary indicator of tropical deforestation.



## 2.2 Physical production and trade data

The country/territory-level commodity-specific data are taken from FAOSTAT. The main source of FAOSTAT trade data is official country/territory statistics compiled by UNSD (the United Nations Statistics Division) and Eurostat.

For crop and cattle products, production data are sourced from the FAOSTAT “Production - Crop and livestock products” data set, and bilateral trade data from the “Trade - Detailed trade matrix” data set.

For forestry products, production data are sourced from the FAOSTAT “Forestry - Forestry Production and Trade” data set, and bilateral trade data from the “Forestry - Forestry Trade Flows” data set.

## 2.3 MRIO data

In this work, IOTA utilises the EXIOBASE 3.8.1 MRIO model (<https://zenodo.org/record/4588235>). EXIOBASE comprises 44 countries/territories plus five rest-of-world (ROW) regions, and 163 industries.

There are multiple MRIO models available for use, each with relative strengths and weaknesses. This includes geographic and sectoral resolution, temporal coverage and lag, as well as licensing constraints and considerations around future availability. There is no clear “correct” or “best” option that can be adopted when selecting an MRIO for consumption-based accounting, but EXIOBASE was chosen for this work primarily for a combination of temporal coverage, alignment with UK Carbon/Material Footprints (see Annex 2), and for its track record within research applications.

From 2023, results from a Global Trade Analysis Project (GTAP) version of the model will also be available via the [associated interactive dashboard](#) (see details in Section A3.1.3, Annex 3), though these results do not form part of the official version of the UK indicator under development.

## 2.4 Implementation

### 2.4.1 Re-exports

*Challenge: trade data often don't actually represent origin-to-destination flows. MRIO modelling is therefore required to resolve origin to destination flows.*

Bilateral trade data often contain records pertaining to the re-export of goods; that is the report of exporting a good that has previously been imported. This is problematic since such records are not providing a direct link between point of origin and destination, and instead contain records e.g. A -> B and B -> C, when the information that is desired is the resolved flow A -> C. This issue is resolved by running the production and trade data through an algorithm which takes countries'/territories' supply (production + imports) into account and reassigns exports accordingly to estimate their true origin. Supply constrains possible exports, and so the system fully resolves whilst preserving total inputs (e.g. all production), and forbids the exports of goods from a country/territory which does not have sufficient supply (be it domestic production or imports from other countries/territories) to meet, i.e. the whole system is balanced (see Croft *et al.*, 2018 for more technical detail).

*Outcome: a trade data set corrected for intermediate flows to give origin-to-destination flows.*

### 2.4.2 Concordance of FAO countries/territories and commodities to EXIOBASE countries/territories/regions and sectors, respectively

*Challenge: the physical and monetary data sets use different geographic and commodity classification schemes.*

The re-export algorithm provides a best estimate of where (at the country/territory level) a country's production of a commodity has been distributed to after all trade activity associated with the raw commodity has been conducted. To align this with the MRIO database, all of the countries/territories in the FAO data need to be concorded to EXIOBASE's countries/territories and regions. This is a one-to-one mapping for countries/territories within the MRIO, and an aggregation of countries/territories for the ROW regions. This allows the country/territory of origin to country/territory of destination results from the re-export algorithm to be transformed into a country/territory of origin to MRIO country/territory/region of destination array.

Likewise, to understand which sectors within the MRIO database the production of a given commodity is associated with (which is important for allocation within the MRIO; see below), the FAO commodities need to be concorded to appropriate producing sectors within the MRIO database (Annex 4, Table S4). In some cases, this is a one-to-one mapping (e.g. "Rice, paddy" within the FAO database maps to the "Cultivation of paddy rice" sector within EXIOBASE), but typically it is an aggregating process (e.g. "Barley", "Maize", "Rye", "Oats" etc. all map to the "Cultivation of cereal grains nec" sector).

*Outcome: the different data sets have a "mapping" to join them together, allowing one to be aligned with the other.*

### 2.4.3 Hybridisation of FAO-derived re-exports data and EXIOBASE MRIO database

*Challenge: merging the two data sets still requires action on how to apportion disaggregated values from one to the other.*

The concorded results of the re-export algorithm provide the MRIO countries/territories/regions to which each countries' traded production of a given commodity needs to be allocated. However, each country/territory/region within the MRIO comprises multiple sectors across which this needs to be further allocated. This is done by taking the relative expenditure by sectors within an importing country/territory/region on outputs of the concorded sector responsible for the production. Below is an example of this allocation process (note "Country/territory *B\_c*" in the example below could be a country/territory or region within the MRIO database).

*Example:*

From re-exports results:

Country/territory *A* exports *X* tonnes of Commodity *Y* to Country/territory *B*

Concordance relationships:

Country/territory *A* concords to Country/territory *A\_c*

Country/territory *B* concords to Country/territory *B\_c*

Commodity *Y* concords to Sector *Y\_c*

(i.e. Sector *Y\_c* is the sector associated with production of Commodity *Y*)

Concorded results:

$X$  tonnes of Country/territory  $A$ 's production of Commodity  $Y$  allocated to Country/territory  $B_c$

Disaggregation of Country/territory  $B_c$ 's allocation to sectors:

Take relative expenditure by all sectors within Country/territory  $B_c$  on outputs from Sector  $Y_c$ , and distribute concorded results proportionally

After this process, the production of a given commodity within a given country/territory has been allocated to the importing countries/territories/region and sectors within the MRIO.

*Outcome: a simple but robust approach is in place to handle splitting national-level values across sub-sectors of its economy.*

#### 2.4.4 Calculation of “physical $L$ matrix”

*Challenge: we want to understand the total upstream material requirements associated with economic outputs.*

In traditional MRIO methods, the  $L$  matrix (or Leontief inverse/“total requirements” matrix) allows the calculation of all financial outputs required across the entire economy (all sectors in all countries/territories/regions) for the purposes of enabling a given sector within a given country/territory/region to produce a unit of output. By allocating the physical quantities of traded commodities to the appropriate sectors of import (see above), a “physical  $L$  matrix” can be constructed which allows the estimation of the amount of these physical flows embedded in the final consumption from different sectors within different countries/territories or regions. This means that final consumption within a given country/territory can be linked back to the country/territory within which its component commodities were produced.

This is achieved by normalising the sector allocations by total sector monetary outputs (i.e. converting the total allocations into intensities, e.g. unit mass of commodity per unit value of output) and multiplying the monetary  $L$  matrix. A unique matrix is constructed for each individual commodity.

*Outcome: we produce a matrix of values for each commodity which captures the upstream material requirements for economic activity across each and all countries/territories and sectors.*

#### 2.4.5 Compiling results for final demand

*Challenge: we want to calculate total material requirements associated with consumption.*

Multiplying the “physical  $L$  matrix” for a given commodity by the final demand vectors for a consuming country/territory/region (the UK in this case), calculates the physical quantities of that commodity embedded within this final demand. This process works by taking the value of purchases from a given sector in a given country/territory/region, and accounting for all required outputs from all other sectors for the given sector to meet this demand. By way of the “physical  $L$  matrix”, these “outputs” take the form of physical flows of the commodity associated with each possible point (i.e. country/territory) of production.

*Outcome: a list of total material requirements, including country/territory of origin, associated with localised consumption activities.*

## 2.4.6 Applying indicator metrics

*Challenge: we want to know the values of different metrics associated with these material requirements.*

The indicator metrics (Table 1, with methodological details in sections below) are transformed into per-unit-mass intensities. This is done by taking e.g. total deforestation linked to a country/territory's production of a given commodity in a given year and dividing this by total mass produced of that commodity in that country/territory/year. This is then simply applied as a scaling factor to the embedded production (mass) results to convert these mass-flow results into results for the different indicator metrics in their appropriate units.

**Table 1.** Summary of indicators used in this study that are applied within the IOTA framework.

<b>Indicator (commodities applied to)</b>	<b>Units</b>	<b>Brief description</b>	<b>Report section providing further detail</b>
Production (all commodities)	tonnes	Tonnes of commodity production embedded within consumption activities	2, 3
cropland_area_ harvested (crops)	hectares (ha)	Area of cropland used to produce materials embedded in consumption. If the same crop is sown and harvested more than once per year in the same area, the area is counted as many times as harvested.	4
tropical_deforestation (all commodities)	hectares (ha)	Area of tropical deforestation associated with the production of materials embedded in consumption	5
def_emissions_incl_ peat_drainage (all commodities)	tonnes of CO <sub>2</sub> (tCO <sub>2</sub> )	Net tonnes of CO <sub>2</sub> emissions (above-, below-ground and change in soil organic C stocks) associated with the area deforested to produce materials embedded in consumption, including due to the drainage of peatlands	5
def_emissions_excl_ peat_drainage (all commodities)	tonnes of CO <sub>2</sub> (tCO <sub>2</sub> )	Net tonnes of CO <sub>2</sub> emissions associated with the area deforested, excluding due to the drainage of peatlands	5
blue_water (crops)	metres cubed (m <sup>3</sup> )	Ground and surface (blue) water used to produce materials embedded in consumption	6
green_water (crops)	metres cubed (m <sup>3</sup> )	Rain (green) water used to produce materials embedded in consumption	6
scarcity_weighted_blu e_water (crops)	metres cubed (m <sup>3</sup> )	Ground and surface (blue) water used, adjusted for water scarcity in the country/territory of production, to produce materials embedded in consumption	6

Indicator (commodities applied to)	Units	Brief description	Report section providing further detail
predicted_species_ loss (crops)	species lost	Number of species predicted to become extinct within an ecoregion due to conversion of land for the production of commodities embedded in consumption	7
species_richness_ area (crops)	species- hectares (species_ha)	An estimate of biodiversity loss in terms of a species richness-weighted extent of crop production embedded in consumption	8

*Outcome: a measure of impact/risk for each indicator is assigned to each point of material use.*

### 3. Further details on inclusion of different commodity types

Whilst for crops the treatment is consistent throughout the framework, with production and trade data from FAOSTAT used for the individual commodities, and the individual commodity identity preserved through to final results, for cattle and forestry products bespoke approaches were adopted.

#### 3.1 Cattle (and buffalo) meat and leather

To align with the Pendrill *et al.* (2020) deforestation data sets (see below), for which cattle (specifically meat and leather) is a key component of impact, the appropriate FAO commodities associated with cattle need to be handled slightly differently to FAO crop data.

Whilst the production of crops can be easily represented within the IOTA framework by the harvest of the raw primary commodity due to simple seasonal cycles, cattle “production” is a more complex matter. Herd sizes do not provide an appropriate analogy for annual output given cattle live for multiple years and also are used for e.g. dairy production, so instead the mass of production of derived products from slaughter, from FAOSTAT, are used as the measure of material production. As a result, it is not just one single commodity which is considered at the point of production (as with a crop), but rather four commodities linked to the production of cattle (meat, offal, fats and hides). Such data are also available for buffalo, which are included alongside cattle for alignment to the Pendrill *et al.* (2020) dataset.

These individual cattle/buffalo-linked commodities are initially run through the IOTA framework following the same logic as the crop commodities, with the flows of the individual commodities modelled independently through the trade stages and the MRIO within the indicator framework. In the preparation of results, they are then aggregated together under a title of “Cattle and buffalo meat, plus associated co-products”, ready for the application of indicator extensions. Since this is no longer aligned with the FAOSTAT classification scheme, it is assigned a commodity code of “XXXX”.

#### 3.2 Forestry

Unlike the other commodities above, for forestry products the data within FAOSTAT are not consistent in terms of the commodity classifications adopted within the distinct production and trade data sets. In this application, production and trade of forestry products, in physical terms within the IOTA framework, is limited to the treatment (i.e. production and trade of) “industrial roundwood”.

Within the production data sets, relevant commodities are:

- 1601 Sawlogs and veneer logs, coniferous
- 1604 Sawlogs and veneer logs, non-coniferous
- 1602 Pulpwood, round and split, coniferous (production)
- 1603 Pulpwood, round and split, non-coniferous (production)
- 1623 Other industrial roundwood, coniferous (production)
- 1626 Other industrial roundwood, non-coniferous (production)

Within the trade data sets, the associated commodities are:

- 1651 Industrial roundwood, coniferous (export/import)
- 1657 Industrial roundwood, non-coniferous tropical (export/import)

## 1670 Industrial roundwood, non-coniferous non-tropical (export/import)

These two sets of commodities are aggregated and concorded as “Industrial roundwood, coniferous” and “Industrial roundwood, non-coniferous” to create two equivalent commodity types within both the production and trade data sets. Another distinction between forestry products and the others implemented is units reported, with the forestry commodities above all listed in volume (cubic metres) rather than mass. To make this consistent with the other commodities (and allow them to be counted in biomass flows), the volumes are converted to mass utilising conversion factors of 0.52 tonne/m<sup>3</sup> for coniferous industrial roundwood, and 0.68 tonne/m<sup>3</sup> for non-coniferous industrial roundwood (values adopted from Stadler *et al.*, 2018).

Following this conversion, the commodities are aggregated to form an “Industrial roundwood” commodity, in mass units, before being run through the framework and having indicators applied. Since this is no longer aligned with the FAOSTAT classification scheme, it is assigned a commodity code of “YYYY”.

## 4. Cropland area harvested

### 4.1 Overview

This indicator provides an estimate of the land area harvested in order to produce the commodities embedded in UK consumption. The data are sourced from the same FAOSTAT “Production – Crop and livestock products” data sets as the crop production data.

### 4.2 Methodological summary

Along with production masses, the FAOSTAT “Production – Crop and livestock products” data set provides associated land use (ha) and yield (hectograms/hectare) values. We create land use intensities (ha/tonne) from this data, which can equivalently be done by either taking the area harvested values and dividing by associated production mass, or multiplying the inverse of the yield value by 10,000.

### 4.3 Application in IOTA framework

The country/territory-commodity specific land use intensities (ha/tonne) are multiplied by the associated calculated mass flows to provide the estimates of cropland use embedded within these flows. Where no data are available, entries are left as zero.

This indicator is applied to all crop commodities in the data set.

### 4.4 Data update plans

The relevant FAOSTAT data sets are updated annually and often revised and improved in between (e.g. updated reporting, replacing inferred data with official data, improved methodologies applied etc.). For entries where no land use/yield data are available, we could look to fill these data gaps by e.g. utilising global average values, checking other reference years, and looking at nearest neighbour yields, but this has not been attempted in this release.



## 5. Deforestation and associated carbon emissions

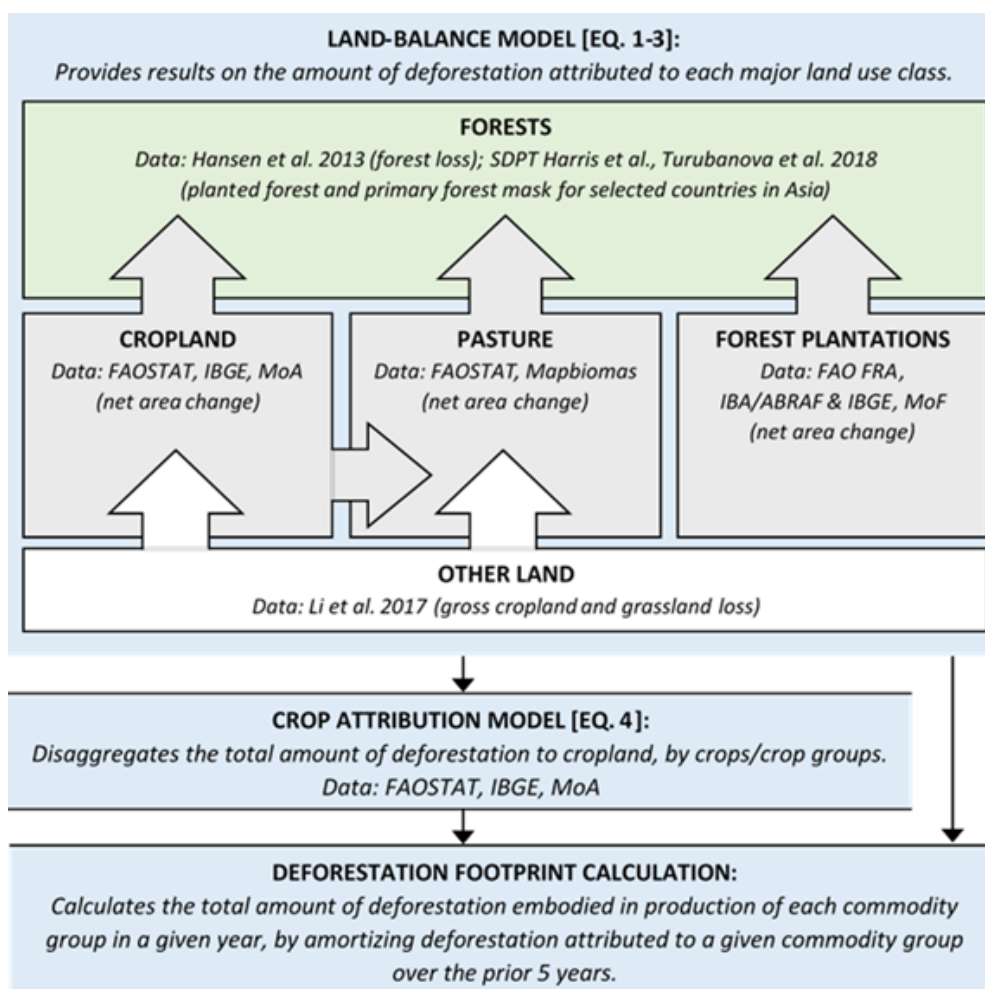
### 5.1 Overview

This extension for the UK indicator framework was originally based on a data set which contains estimates of tropical and subtropical deforestation embodied in the production, exports, imports and consumption of agricultural and forestry commodities by country/territory, year, and commodity, in the time period 2005 to 2017. The data was an update on the results presented in Pendrill *et al.* (2019a, b), using a land-balance model to attribute deforestation across 135 countries/territories in the tropics and subtropics to expansion of cropland, pastures and forest plantation and the commodities produced on this land. The 2022 indicator release incorporated an updated data set, but methods used to create these estimates were equivalent. In this latest (2023) release, the methods utilised for estimating deforestation and associated carbon emissions have been substantially revised with the incorporation of additional spatial data (where available) to allow spatially-explicit attribution of forest loss to commodities, plus concurrent extension of the data set to non-tropical forests via the use of deforestation-driver information (Singh & Persson, 2023). Elements of the prior methodology are still incorporated into the new methods so below we retain the original methodological summary for the indicator (Section 5.2), but this should now be read alongside details in Annex 3 which provide an account of the new methods utilised.

### 5.2 Methodological summary

A detailed description of methods for this extension can be found in Pendrill *et al.* (2019a, b) (which should also be referred to for more detail of the more granular treatment of deforestation in Brazil and Indonesia in comparison with the treatment of other included countries/territories). A visual summary of the source data and methodology is provided in Figure 1.

Observed forest loss, from remote sensing data (from [GLAD](#)/Hansen – at 30m resolution, with a threshold of 25% canopy cover used to define forest, and complete loss per pixel defined as ‘forest loss’), is attributed to agricultural and forest commodities using a relatively simple land-balance model implemented at national scale (apart from for Brazil and Indonesia, where it is implemented at subnational scale). In this land-balance model, cropland expansion (data for which is sourced from FAO, except Brazil and Indonesia which use national statistics) takes place first into pastures (in cases where there is gross pasture loss), and then into forests (where there is gross forest loss). This assumption is deemed to robustly reflect typical landscape dynamics. In essence, in the model, forest loss is attributed across expanding cropland, pasture and forest plantations based on their area increase, but capped at total estimated forest loss in the focal region. Forest loss attributed to cropland expansion is then further attributed to individual crops or crop groups in proportion to their relative expansion in harvested area (also from FAO, except Brazil and Indonesia which use national statistics). Forest loss attributed to pasture is linked to cattle grazing for meat and (to a lesser extent) leather production. Note that, whilst data on forest loss is spatially specific (as it is derived from remote sensing), attribution to individual crops/crop groups is conducted non-spatially based on overall planted areas and not the physical location/expansion of specific crops (data on which is not globally available at this stage).



**Figure 1.** Overview of the main steps of the analysis linking deforestation to agricultural and forestry production as well as the main data sources used for the analysis. Revised from Pendrill *et al.*, 2019a to reflect latest updates to data set; provided by and reproduced with permission of Florence Pendrill.

### 5.2.1 Deforestation data

Deforestation occurring in one year is not linked immediately to commodity production in another, because a transition period which can span several years between clearance and resource production is typical. To account for this, the change in area of cropland, pastures and plantations over a three-year period following forest loss is used in the attribution step. This effectively accounts for ‘lag time’ between conversion of land and conversion to productive use in order to adequately identify which land uses caused the deforestation.

Furthermore, because land may be productive many years following conversion (and thus production in subsequent years can be validly attributed to previous land use change), an amortisation period of five years is adopted, meaning that the total amount of deforestation embodied in production of a given commodity in a given year is calculated as the total deforestation attributed to the land use producing that commodity in the five previous years, divided by five. This amortisation step ensures that ‘responsibility’ for the original conversion is distributed over a number of subsequent years of production (which is a practice commonly applied to other metrics, including those used e.g. in greenhouse gas inventories).

### 5.2.2 Carbon emissions data

Carbon emissions from deforestation are estimated by quantifying the changes in carbon stocks resulting from forest loss and subsequent land use, considering above-ground biomass (AGB), below-ground biomass (BGB) and soil organic carbon (SOC). A separate component of the data adds emissions associated with the drainage of peatland. Estimates of above-ground carbon loss are derived geospatially by combining forest loss data with estimates of carbon stocks prior to forest loss (in the year 2000), compiled at 30m resolution. Carbon loss is attributed only to forest loss (which means that, where carbon loss may have taken place due to earlier degradation, it is possible over-estimates are present). BGB estimates are more uncertain, but follow a typically-adopted approach of assuming a ratio between AGB and BGB. In this data set, vegetation-specific ratios are adopted following 2006 IPCC guidelines. Stocks of AGB and BGB in resultant land uses (crops, pastures, plantations) were based on existing literature. SOC estimates are estimated from a tropical meta-analysis (Don *et al.*, 2011 cited in: Pendrill *et al.*, 2019b). Emissions estimates are attributed to commodities in the same way as deforestation rates (i.e. a commodity attributed 10% of deforestation will be attributed 10% of emissions).

Emissions from peatland drainage (excl. Indonesia) are based on a single study which provides country-level data on carbon emission from peatlands drained for agriculture and forestry for the years 1990 and 2008 (see Pendrill *et al.*, 2019b for full details), which allow emissions per unit of land drained to be estimated (note that there is some requirement for interpolation and extrapolation to achieve this, with an assumption made that the share of cropland occupying peat/non-peatland remains constant over time). Estimates for Indonesia (which accounts for nearly two-thirds of tropical peatland carbon) are based on more specific, province-level data.

### 5.3 Data update plans

The authors are looking for opportunities to ensure that continued data updates are possible. Updates approximately yearly (or as soon as the underlying data sets are updated) are therefore considered likely.

### 5.4 Source(s)

This dataset is managed by the Chalmers University of Technology, Sweden. The key contact point is Martin Persson, who is an active collaborator with the SEI York team.

The data are available, open source at: <https://zenodo.org/record/4250532> . Publications using this data (including as applied within the UK indicator framework) should properly reference this resource (and associated papers).

Citation of original data source (users should refer to details in Annex 3 regarding the updated data sets used in the 2022 and 2023 data releases): Pendrill, Florence, Persson, U. Martin, & Kastner, Thomas. (2020). Deforestation risk embodied in production and consumption of agricultural and forestry commodities 2005-2017 (Version 1.0) [Data set]. Zenodo. <http://doi.org/10.5281/zenodo.4250532>

### 5.5 Application in IOTA framework

Attribution data from the Zenodo data set is utilised. This allows for the addition of the production linked deforestation and emissions estimates directly into the IOTA framework (to FAO production categories) which are then translated, via our modelled trade-and-

consumption system, into footprint indicators (for units refer to results sheets). The following notes are relevant to the application of this data set in IOTA:

- The raw data are classified already into FAO production categories. We have created a library to ensure the correct matching where any alternative product labels are used (which occurs in a handful of cases). One crop (Guarana produced in Brazil) in the Pendrill data set is not associated with FAO production/trade data and is therefore not included in the footprint;
- The data set contains two listings relating to cattle production: “cattle meat” and “leather”. These impacts are both aggregated together and then assigned to the individual FAO commodities associated with cattle production (see above) in proportion to relative mass produced, before being aggregated post-modelling to form the “Cattle and buffalo meat, plus associated co-products” impact;
- The impacts are divided by associated commodity production quantities to create a set of impact per tonne intensities. These are then multiplied by the resolved mass flows to extend these to estimates of embedded impacts within those flows;
- These are applied to all commodities within the current database. Where any country/territory/commodities have no data within a given year/the time series, these are left empty.

## 6. Water footprint and water scarcity

### 6.1 Overview

Our indicator for water consists of three metrics: ‘blue water’, which estimates the surface and groundwater consumed (i.e. not returned to the basin due to evaporation, inter-basin transfer, product integration or release to the sea) as a result of production; ‘green water’, which estimates rainwater consumed; and ‘water-availability-adjusted blue water’ (aka. Blue water scarcity), which scales the blue water footprint according to water availability in a region after human and aquatic ecosystem demands have been met. These indicators are applied only to crop products at the current time. A more detailed explanation of the differences between blue and green water can be found on the [Water Footprint Network website](#).

### 6.2 Methodological summary

Tamea *et al.* (2021) details an approach to creating an annualised water footprint for crop products; expressed as a volume of water per unit weight (unit water footprint; uWF). As its basis, the uWF approach utilises the well-established ‘Water Footprint Network’ (WFN) crop-specific water-footprint data (Hoekstra and Chapagain, 2007; Mekonnen and Hoekstra, 2010). However, given that WFN data provide estimates solely for a single reference period, a ‘fast track’ method is utilised to provide water footprints of production (uWFP) that vary over time.

The uWFP is based on a function of evapotranspiration calculated for the growing period of the crop and the crop yield. In Tamea *et al.* (2021), annualised uWFP’s are created using the ‘fast track’ method introduced and substantiated in Tuninetti *et al.* (2017) that are in turn based on the use of the WaterStat database (Mekonnen and Hoekstra, 2010) for expressing the *spatial variations* in evapotranspiration and on a ratio of agricultural yields for expressing the *temporal variability* of the unit water footprint:

$$uWFP_{c,p,t} = \overline{uWFP_{c,p,T}} \cdot \frac{Y_{c,p,t}}{\overline{Y_{c,p,T}}},$$

where  $\overline{uWFP_{c,p,T}}$  is the reference unit water footprint provided by WaterStat (Mekonnen and Hoekstra, 2010) corresponding to an average in the period  $T = 1996–2005$ ,  $\overline{Y_{c,p,T}}$  is the average crop yield over the same period  $T$ , and  $Y_{c,p,t}$  is the annual crop yield in a generic year  $t$  in the range 1961–2016. The average crop yield is obtained as an average of the annual yields in the years 1996–2005, weighted by the harvested areas across the years in country/territory  $c$ , based on FAOSTAT data. Effectively this function is estimating annual water consumption by taking the average yield over the reference period and scaling water consumption based on yield in a particular year.

Because data released in Tamea *et al.* (2021) is present only to 2016 and only for aggregated (green and blue) water footprints, we use the equation above, along with the original WaterStat and FAO (FAOSTAT crop production statistics) sources to compile our own timeseries for both blue and green water footprints to match the availability of IOTA data (2005-2017) and to allow us to readily update the data in future. An important limitation is that, in the absence of additional information, we retain the green:blue water requirement

ratios of the original WaterStat reference period when annualising results, e.g. this assumes that increases in yield over time are achieved by proportionally fixed increase in both blue and green water requirements.

The blue water footprint refers to the volume of surface and groundwater consumed as a result of the production of a crop. Green water footprint refers to the rainwater consumed. The blue water footprint is then additionally scaled by a factor (from WULCA; Boulay *et al.*, 2018) which represents the relative Available wATER rEmaining per area in a country/territory (or watershed), after the demand of humans and aquatic ecosystems have been met. AWARE factors for use alongside agricultural water use are available and these are adopted in our indicator set.

### 6.2.1 Water Footprint Network data

The Water Footprint Network's 'product water footprints for crops' is utilised, which is described in full detail within Mekonnen and Hoekstra (2010 & 2011). This data set contains an estimate of water footprint of crops based on a water-balance model applied at a 5 by 5 arc minute grid. This model computes a daily soil water balance and calculates crop water requirements, actual crop water use (both green and blue) and actual yields, and is used to estimate the crop water use of 126 primary crops, with requirements of an additional 20 minor crops estimated by application of the [CROPWAT 8.0](#) model. For rain-fed crop production, blue water use (as irrigation) is zero and the green water use (m<sup>3</sup>/ha) is calculated by summing up daily evapotranspiration values over the length of crop growing periods and compared to precipitation to derive the water consumption of crops. For irrigated crops, green and blue water use is calculated via a combination of two soil-balance scenarios: a first scenario is based on the modelled assumption that the soil receives no irrigation and uses crop parameters of irrigated crops (e.g. the same rooting depth as in an irrigated condition), with the calculated evapotranspiration in this scenario equalling the green water footprint estimate. A second scenario assumes actual irrigation sufficient to meet water requirements, applying the same parameters as in the first scenario, with the blue water use calculated as the difference between water use across the two scenarios. Crop growth is also modelled, accounting also for water stress, to provide estimates of actual yields which are scaled according to national FAO yield data. The green and blue water footprints of primary crops (m<sup>3</sup>/ton) are then calculated by dividing the total volume of green and blue water by the quantity of production per year. The data provided by Water Footprint Network has a reference year of 2000, but represents the average over a period 1996-2005.

### 6.2.2 uWFp (unit water footprint of production) data

Tamea *et al.* (2021) present 'annualised' water footprint data based upon changes in productivity of crops over time. The authors apply annualised water footprints to the trade of agricultural commodities, as part of a European project: CWASI ('Coping with wATER Scarcity In a globalized world'), but the method for creating 'unit water footprints of production' (uWFp) are in turn based on a 'fast track' method for incorporating the *temporal* variability of water footprints into studies (Tuninetti *et al.*, 2017; which also describes the suitability of this approach for creating a simple but appropriate evaluation of a time-varying crop water footprint). The fast track method employed in Tamea *et al.* (2021) is replicated here with original data sources, with an annualised water footprint for each crop calculated by taking a reference water footprint value (obtained from the Water Footprint Network database) and multiplying this by the average yield (from FAO) for the crop for the same reference period (1996-2005), before dividing through by the crop yield (again from FAO) for the target year (see equation above). This fast track method effectively keeps the rates of evapotranspiration per crop (as estimated originally by the Water Footprint Network model)



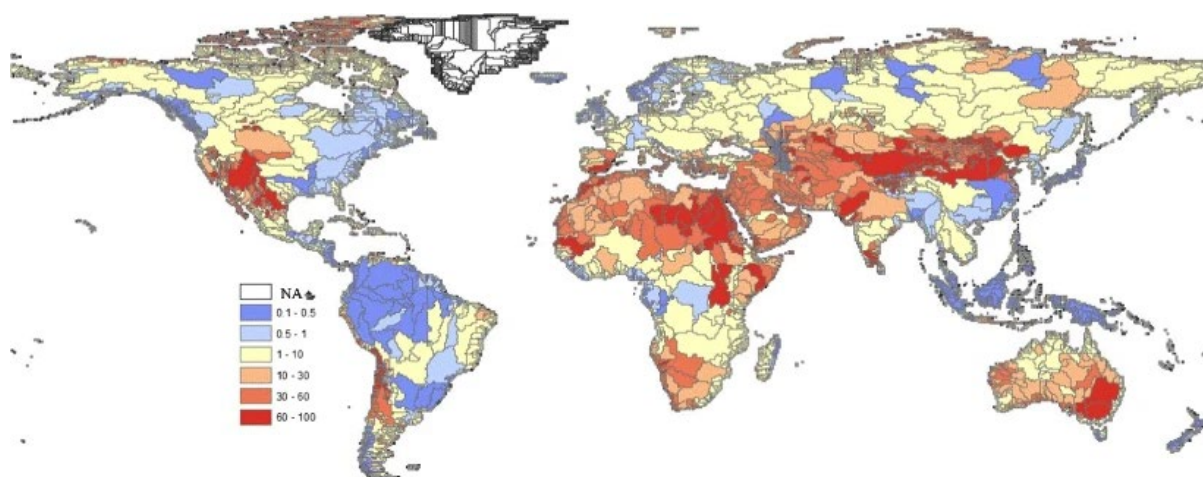
constant, and thus it has monitored changes in yield which determine changes in the water volumes used. When linking to trade data, a problem arises when a country/territory was not a crop producer in the 1996-2005 reference period and therefore does not have an associated reference water footprint. Tamea *et al.* (2021) resolve this issue by adopting reference footprint values from the nearest country/territory within 10 degrees of the focal countries/territories and in cases where no alternative country/territory-value is available the global average value is adopted.

### 6.2.3 AWARE data

**AWARE** factors represent the relative Available wATER rEmaining per area in a river basin, after the demand of humans and aquatic ecosystems have been met (Boulay *et al.*, 2018). They are a result of a 2-year consensus building process by 'Water Use in Life Cycle Assessment' (WULCA), a working group of the UNEP-SETAC (United Nations Environment Programme— Society of Environmental Toxicology and Chemistry) Life Cycle Initiative, on the development of a water scarcity method for use in LCA (Life Cycle Assessment) and water scarcity footprint assessments (Boulay *et al.*, 2018). AWARE factors assess the water deprivation potential, to either humans or ecosystems, with the assumption that the less water remaining available per area, the more likely another user will be deprived. Water availability minus demand (AMD) of humans and aquatic ecosystems is first calculated in terms of  $\text{m}^3$  per  $\text{m}^2$  per month. Values are then normalised with a world average result ( $\text{AMD} = 0.0136\text{m}^3.\text{m}^{-2}.\text{month}^{-1}$ ) and inverted, to derive the relative value in comparison with the average  $\text{m}^3$  consumed in the world.

The indicator is limited to a range from (i.e. subjected to thresholds between) 0.1 to 100, with a value of 1 corresponding to the world average, and a value of 10, for example, representing a region where there is 10 times less available water remaining per area than the world average. Data is calculated at the sub-watershed scale and for monthly timesteps, but is available aggregated to country/territory, with an annual average. Aggregations can be conducted differently to better represent an agricultural water use or a domestic/industrial use, based on the time and region of water use. Characterization factors for agricultural and non-agricultural use are therefore provided.

To calculate AWARE factors (see Figure 2), actual water availability was obtained from the WaterGAP2.2 (Müller Schmied *et al.*, 2014) model for more than 11,000 global watersheds (with the largest watersheds divided into sub-watersheds), using climatic data over the period 1960–2010 to model runoff based on precipitation and evapotranspiration. Current human water consumption (the fraction of water withdrawal not returning to the watershed after use) represents human demand, with data obtained from the WaterGAP model (Florke *et al.*, 2013). This includes domestic, industrial, agricultural, livestock and energy production sectors modelled for the year 2010 on a 0.5 degree global resolution. Water requirements for freshwater ecosystems are used as a proxy for ecosystem demand, with a monthly model from Pastor *et al.* (2013) chosen that evaluates minimum water requirements as a fraction of the available flow to ecosystems in "fair" conditions. Water requirements of terrestrial and groundwater-dependent ecosystems are not included since the link between blue water consumption (for which AWARE is used) and water deprivation of terrestrial ecosystems is unclear at the current time.



**Figure 2.** Annualised AWARE characterization factors for non-agricultural use in  $\text{m}^3$  world eq./ $\text{m}^3$ . Reproduced from Boulay *et al.*, 2018.

### 6.3 Data update plans

Water Footprint Network baseline water footprint statistics, and AWARE scarcity factors present ‘snapshots’ around baseline periods of 1996–2005, and 2010 respectively. The authors are unaware as to whether there are any plans to update these reference data sets at the time of writing.

The ‘fast-track’ method presented above represents a credible attempt to develop annualised water footprint statistics from baseline WFN data.

The simplicity of the fast-track method means that it is relatively easy to provide annual water footprint data for future years as this is only dependent on the release of FAO crop production data. However, at the present time an important limitation is that the original reference ratio of blue:green water use is retained in our annualised results. Future work could scope out whether improvements to this approach could be made (e.g. via consideration of recorded rainfall or information on national irrigation rates).

In addition to exploring the opportunities to update water scarcity data going forward, it is also worth noting that future developments may allow the utilisation of basin-specific water footprint and water-scarcity metrics, that may be combined with geographically specific crop-production data to provide more granularity. At the present time, only national averages have been deployed.

### 6.4 Source(s)

Water footprint estimates from the Water Footprint Network are sourced from: <https://waterfootprint.org/en/resources/waterstat/product-water-footprint-statistics/>

Statistics necessary to annualise these factors are sourced from FAO: <http://www.fao.org/faostat/en/#data/QCL>

AWARE factors are sourced from WULCA country/territory-level values: <https://wulca-waterlca.org/aware/download-aware-factors/>

All sources are currently publicly, and freely, available.



## 6.5 Application in IOTA framework

Unit water footprint data for crop production are compiled for all crops present in the IOTA data set. Water footprints of crop production are then converted, via our modelled trade-and-consumption system, into consumption-based footprint indicators (for units refer to results sheets). The following notes are relevant to the application of this data set in IOTA:

- National average estimates are extracted for the reference period 1996-2005 for each available crop from the WFN data set.
- From FAOSTAT production statistics the mean yield is calculated for the same reference period by summing total production values over that period and dividing through by total land use requirements for that period. In line with Tamea *et al.* (2021), for each year of crop production relevant to the current UK indicator timeseries (2005–2017), the yield is extracted from FAO. The reference yield is divided by the focal-year yield and then multiplied by the reference water footprints to estimate water intensities (unit water per unit production). Reference water footprints are used for blue and green water individually, in order to calculate annualised results for both blue and green water. An important limitation is that the ratio of blue:green water used in the annualised data is fixed to that of the reference period.
- Cross-referencing the new annualised water footprint data against the crop production data sets reveals gaps in the data.
  - For those cases where reference period water footprint data are not available, a country-to-country distance matrix is utilised (based on country/territory centroids) to identify the next-nearest countries/territories within the equivalent of ten angular degrees at the equator (1,110 km) of the focal country/territory;
  - If annualised water footprint data are available for at least one of these countries/territories, the water footprint value of closest 'replacement' country/territory is then adopted;
  - If no substitute country/territory is identified with annualised information, the analyst checks for non-annualised data, starting with focal country/territory and then again with the nearest neighbours within the specified range (1,110 km);
  - If no substitute is found the global average water footprint value for the crop for the original reference period is adopted;
  - Only values where both blue and green water values are available from the same source are adopted. If a global average value is not found for the crop, no water footprints are provided.
- This process provides annualised green and blue water intensities for each year, crop and country/territory. The blue water footprints are also then multiplied by country/territory-level AWARE characterisation factors for agricultural use to provide an estimate of the scarcity-weighted blue water footprint. A handful of small producing countries/territories (mainly Oceanic island states) do not have water scarcity values in the AWARE database. No attempt was made to provide scarcity estimates for these countries.
- These indicators are only applied to crop commodities within the data set.

## 7. Biodiversity 1 – Predicted species loss

### 7.1 Overview

Using the countryside species area relationship (cSAR) model, biodiversity impacts can be estimated as the number of regional species lost as a result of agricultural land use. Chaudhary and Kastner (2016) provide crop- and country-specific characterisation factors to estimate the impact per tonne of production for 152 crops/crop groups in 171 countries/territories (Table S1 in Chaudhary & Kastner, 2016). For the UK indicator, these were linked to respective crop production statistics within the IOTA framework to estimate the 'predicted regional species loss' associated with consumption activities.

### 7.2 Methodological summary

Countryside SAR can be used to predict the final level of species extinctions per ecoregion but does not specify the timing of extinctions. In other words, SARs provide an estimate of species 'committed to extinction' in the absence of habitat restoration (Chaudhary & Kastner, 2016). The extinction risk associated with land use change and occupation was estimated for each of the 804 terrestrial ecoregions for mammals, birds, amphibians and reptiles (Chaudhary *et al.*, 2015). These were then allocated to different land use types according to the relative area of each land use within the ecoregion and the estimated species 'affinity' for that land use. This provides characterisation factors per ecoregion and broad land use type, that Chaudhary and Kastner (2016) then further disaggregated to specific crops using crop maps and yields from Monfreda *et al.* (2008), which modelled harvested area at 5 minute pixel resolution for, nominally, the year 2000. For the indicator, these country/territory and crop specific characterisation factors (in terms of 'predicted regional species loss per tonne') were applied directly to IOTA to estimate biodiversity losses.

See Chaudhary and Kastner (2016) and references therein for more detailed descriptions of data sources and methods.

### 7.3 Data update plans

The Chaudhary and Kastner (2016) data set was released as an application of the cSAR-based approach to estimating potential species loss alongside crop-specific production and trade (at FAO commodity level). More recently, the methods have been developed (e.g. Chaudhary and Brooks, 2018) and applied in the preparation, for example, of characterisation factors for use in life cycle assessment (LCA) e.g. within LC-IMPACT. The LC-IMPACT factors were those previously applied within a JNCC study in conjunction with a non-hybridised EXIOBASE model in the precursor to the application of the IOTA modelling framework but are not currently prepared for use with FAO data and the IOTA model. Future work could explore the application of the Chaudhary and Brooks (2018) factors alongside FAO production statistics. However, it should be noted that these still depend on land use information from the Monfreda *et al.* (2008) data set with reference year 2000. With additional effort, it may be possible also to create a cSAR-based biodiversity metric using more recent crop production data.

### 7.4 Source(s)

Characterisation factors are taken from the Supplementary Information (Table S1) of Chaudhary and Kastner (2016), which is not currently an open access publication, and has been accessed via an institutional licence.

## 7.5 Application in IOTA framework

Characterisation factors for “Total regional species lost per ton” were taken from Table S1 of Chaudhary and Kastner (2016). These were first cleaned to remove duplicated entries for ‘Chillies and peppers, green’ and then a concordance table was constructed to map the country/territory and commodity names to their respective FAO codes for joining to IOTA.

The characterisation factors are already in a production intensity form (i.e. per unit mass), and so the mass flows resolved by the framework are simply multiplied by the corresponding factor to provide estimates of regional species loss embedded in these flows.

If no value is available, it is left as zero. This indicator is applied only to crop commodities within the dataset.

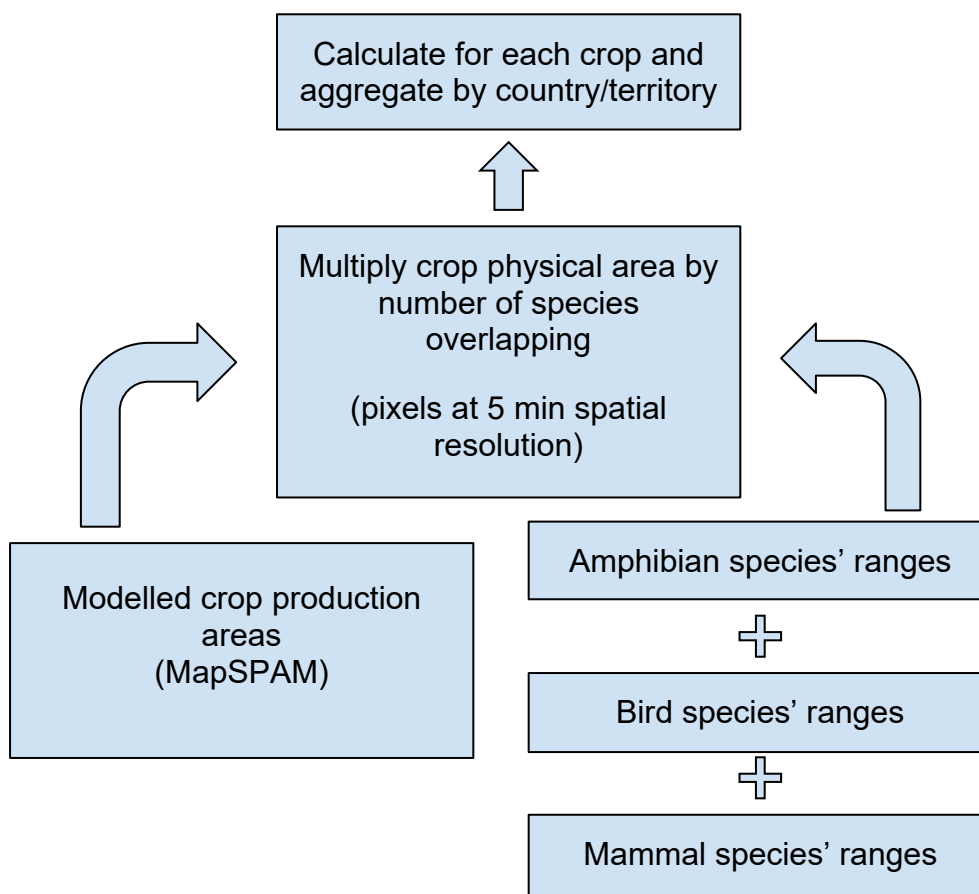
## 8. Biodiversity 2 – Species richness weighted hectares

### 8.1 Overview

This metric is based on the global mapped ranges of 11,145 bird species (BirdLife 2020), 6,707 amphibians and 5,537 terrestrial mammals (IUCN 2020). These can be used as a proxy for biodiversity importance across the world's terrestrial surface. We intersected these biodiversity layers with 42 modelled crop production layers from [MapSPAM](#) (IFPRI & IIASA 2016; IFPRI 2019) for the relevant (see below) reference years of 2005 and 2010 to estimate, for each crop, the number of hectares of production (physical hectares) within each species' range. This is then summed across all species to estimate the biodiversity loss from the production of each crop in terms of 'species-hectares' i.e. the species richness-weighted extent of crop production. The measure accounts for the high degree of spatial variation in species richness, and can also respond to information on agricultural expansion.

### 8.2 Methodological summary

Data on species' ranges are a mainstay of global biodiversity mapping and analyses. Detailed information on the data are provided by Birdlife International and the International Union for Conservation of Nature (BirdLife International and Handbook of the Birds of the World, 2020; IUCN, 2020). Figure 3 describes how species-hectares are calculated.



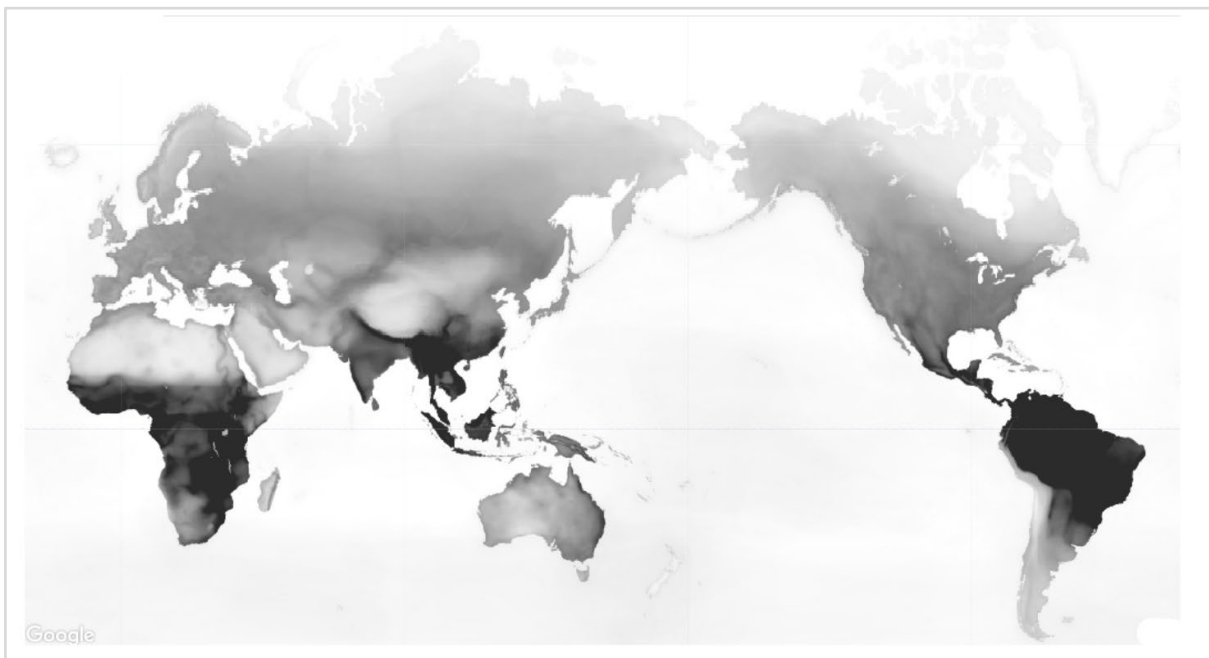
**Figure 3.** Visual summary of the method for calculating species-hectares.

We conducted the integration of data illustrated in Figure 3 and described below in the [Google Earth Engine](#) platform.

### 8.2.1 Species data

Species range polygons are available from Birdlife International and IUCN's online data portals. These delineate the geographical limits to species' ranges, also known as a species' extent of occurrence, but are not refined by known habitat preferences or altitudinal limits, so will contain commission errors. These polygons therefore contain the smallest area that encompasses all known or inferred species occurrences and can include large extents of habitat which are unsuitable for species. However, these data are highly useful for showing the potential biodiversity value in terrestrial areas, relative to global biodiversity (Figure 4).

The spatial data are associated with information on the species' threat status, presence, origin, and seasonality (Annex 4, Table S3). We therefore estimated biodiversity loss by filtering the original data according to specific criteria. This included using all extant species (i.e. presence is "Extant" and they are not listed as "Extinct" or "Extinct in the Wild") and species that are either native to the area or originate from reintroductions or assisted colonisation (i.e. conservation interventions). All parts of seasonal ranges were included (BirdLife, n.d.; IUCN, 2018).



**Figure 4.** Global map of species richness based on summing raw IUCN and BirdLife species ranges for amphibians, birds and mammals. Darker areas signify higher species richness.

### 8.2.2 Crop data

Outputs from the Spatial Production Allocation Model ([MapSPAM](#)) (IFPRI & IIASA 2016; IFPRI 2019) were used to estimate the distribution of cropland under each of 33 crops and 9 crop aggregates (Table S1, Annex 4). Physical area was used, which refers to the actual area where a crop is grown; measured in hectares. Use of physical area means that pressures associated with, for example, double-cropping activities are not explicitly captured, i.e. we provide a species richness-weighted *extent* of crop production which does not account for the differing impacts associated with different production systems and land use intensities. Data are provided globally at 5 minute resolution nominally for 2000, 2005 and

2010 (data from 2000 falls outside our indicator period). In practice these data are compiled by MapSPAM authors from a variety of sources and timestamps centred, where possible, on the three years around the nominal date.

### 8.2.3 Calculating species-hectares

For the two years that align with the IOTA timeseries for which crop models were available (2005 and 2010), Google Earth Engine was used to create a global species richness layer across mammal, amphibian and bird data sets. For each crop/crop group, the physical area of cropland in every pixel (5 min resolution) was multiplied by this combined species richness layer i.e. number of species range polygons that overlapped it. This, then, is the estimated 'species-hectares' measure for that crop in that pixel. Summing these pixel values for each country/territory using the simplified Large Scale International Boundaries data set (LSIB; USDS, 2017), allows an estimate of how many 'species-hectares' are impacted by the production of that crop in the reference year.

## 8.3 Data update plans

The species range data hosted by IUCN and BirdLife International are one of the most important conservation data sets globally. These are regularly updated on an annual basis and up to date information added. MapSPAM has data for 2000, 2005 and 2010 with more recent data available for specific regions of the world but the authors are unaware of any plans to update global data sets for later years. Species and crop data used in calculating species impacts are freely available for non-commercial purposes with the requisite citations.

## 8.4 Source(s)

Species ranges for birds are sourced from: <http://datazone.birdlife.org/species/requestdis>

Species ranges for mammals and amphibians are sourced from: <https://www.iucnredlist.org/>

Crop-distribution estimates for reference years 2005 and 2010 are sourced from: <https://www.mapspam.info/data/>

All sources are currently publicly, and freely, available.

## 8.5 Application in IOTA framework

- Summed species richness data for mammals, birds and amphibians was compiled from source data within Google Earth Engine.
- For each crop/crop group, species richness per pixel is multiplied by the associated estimate of physical area of crop production. Resulting 'species-hectares' are then aggregated to country/territory level. This step is conducted using both 2005 and 2010 crop extents.
- The IOTA timeseries provides a consumption to production data set for 2005 to 2017. [MapSPAM](#) provides crop models for 2005 and 2010. Therefore, for those years without an associated crop model, the closest available was used, so that 2005-2007 rely on the species-hectares data compiled from [SPAM 2005](#), whereas 2008-17 rely on species-hectares data compiled from [SPAM 2010](#).
- Of the 42 crop layers mapped in MapSPAM, nine are aggregate crop groups:

- If the indicator data concurs to a single commodity within the FAOTAT classification, that impact is assigned directly to the production of that commodity.
- If the indicator data concurs to multiple commodities, the impact is distributed across the production of those commodities in proportion to the relative land area used in their production. If no land area data are available within FAOSTAT for a given country/territory/commodity/year, then an estimate is derived based on global average yields, and this is then used to apportion the share of the indicator data to the crop.
- Once total impacts have been assigned to the production of corresponding crops, they are converted to intensities by dividing through by associated annual FAOSTAT-provided crop production masses. The resolved mass flows are then multiplied by the corresponding factors to estimate the species richness-weighted hectares embedded within those flows.
- This indicator is only applied to the crop commodities within the data set.

A concordance was developed (Table S1, Annex 4) to provide alignment between the commodities provided by MapSPAM and those used in IOTA. A concordance is also necessary to align countries/territories/regions covered by the two data sets.

To map the impacts calculated per country/territory using LSIB (USDS, 2017), a table was developed to provide concordance between the country/territory names resulting from the application of the LSIB country/territory boundaries used to derive country/territory-level species-hectares estimates, and those countries/territories used within IOTA. This is provided in Table S2 in Annex 4.

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## Annex 1: Supplementary Graphs (2023)

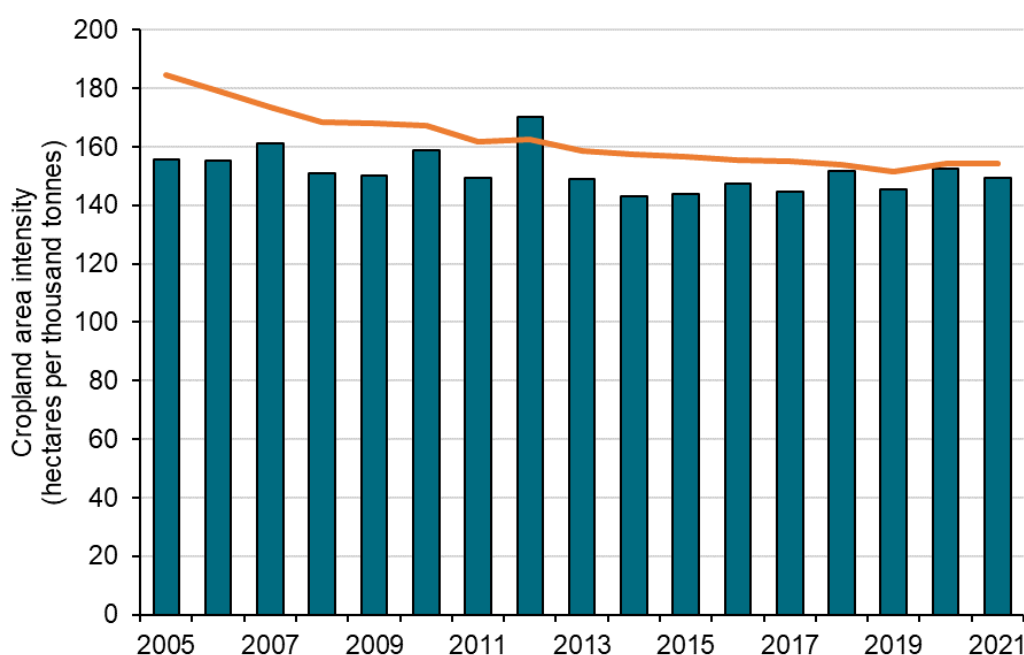
The [official statistic in development](#) itself includes basic graphs on total estimates for:

- area of deforestation risk associated with UK consumption (headline result);
- predicted regional species loss associated with UK consumption (biodiversity metric 1);
- species richness-weighted crop area associated with UK consumption (biodiversity metric 2);
- deforestation linked GHG emissions (excluding peatland drainage) associated with UK consumption;
- scarcity-weighted blue water use associated with UK consumption;
- cropland area harvested associated with UK consumption;
- material footprint associated with UK consumption.

However, it was not possible to include all graphs produced in the [indicator fiche](#) itself. This Annex presents additional graphs, showing intensities related to each of the above rather than totals, as well as emissions including peatland drainage, blue water footprint and green water footprint.

### Cropland

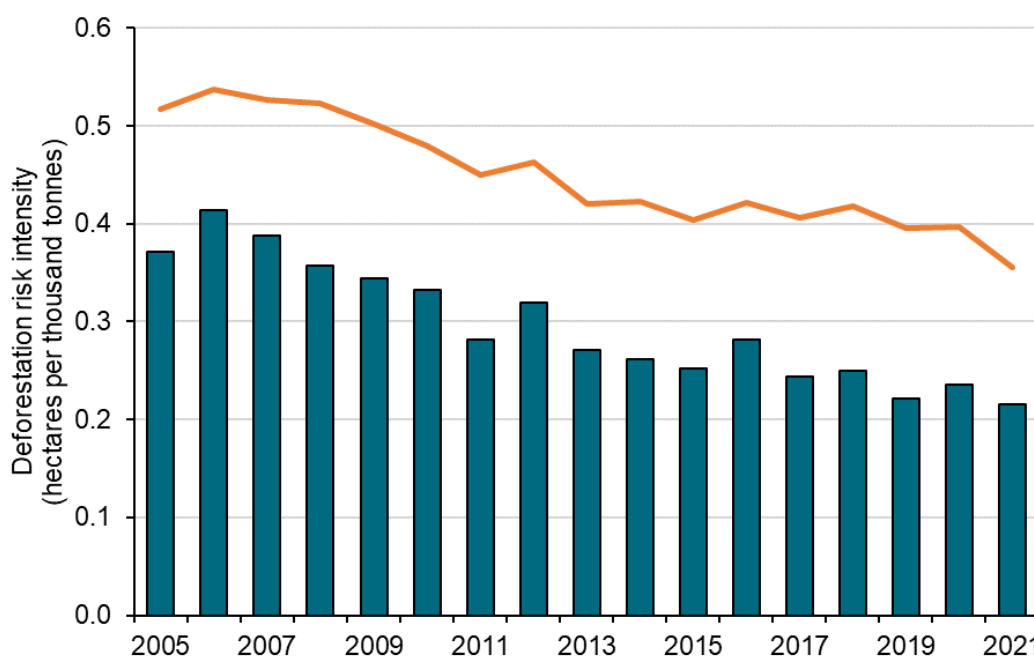
UK consumption of crop commodities in 2021 was associated with an estimated total land use footprint intensity of 149 ha per thousand tonnes of embedded production, a decrease of 4.2% since 2005 (Figure 5). Comparing the 2021 footprint with 2016 reveals a short-term increase of 1.2% (five years is the standard short-term comparison used for the UKBIs). Although the metrics presented here do not officially form part of the UKBI itself, the same comparisons are made for consistency with the rest of the data set.) For the latest year (2021) a 2.2% decrease is observed. UK consumption-based intensities are below that of the global average (orange line) for all years except 2012. Estimates refer to crop commodities only.



**Figure 5.** Cropland area intensity (hectares per thousand tonnes) associated with UK consumption. The (orange) line compares this to intensities associated with global consumption.

## Deforestation

UK consumption of **crop, cattle-related and timber** commodities in 2021 was responsible for an estimated agriculture-driven deforestation intensity of 0.21 ha per thousand tonnes of embedded production, a decrease of 42.2% since 2005. Comparing the 2021 footprint with 2016 reveals a short-term decrease of 23.7% (Figure 6). For the latest year (2021) a decrease is observed (8.7% decrease). UK consumption-based intensities are below that of the global average (orange line) for all years in the timeseries. Estimates refer to deforestation as a result of crop, cattle-related and timber commodities only.

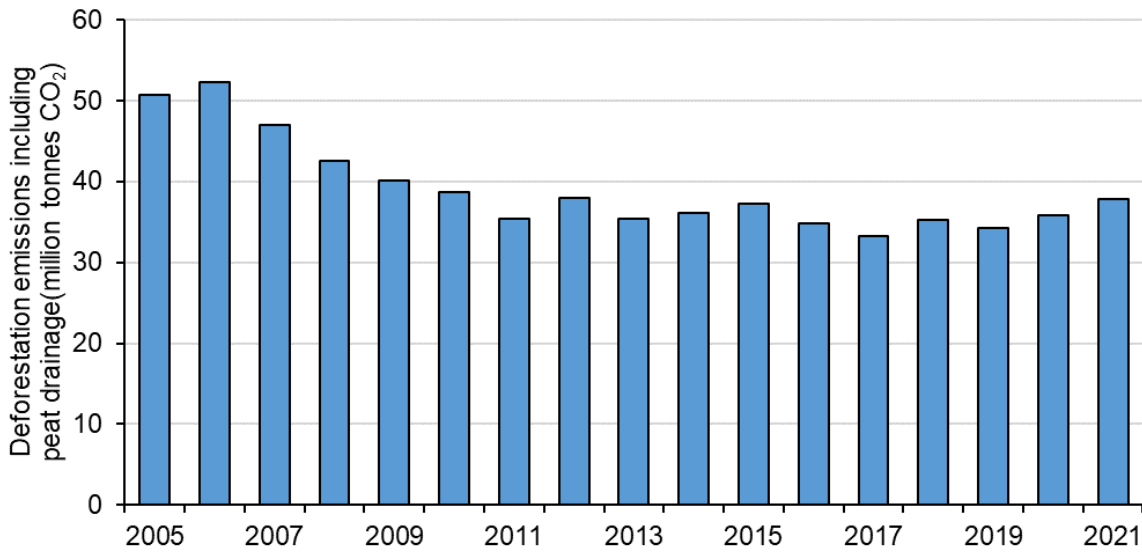


**Figure 6.** Deforestation intensity (hectares per thousand tonnes) associated with UK consumption. The (orange) line compares this to intensities associated with global consumption.

## Deforestation linked emissions

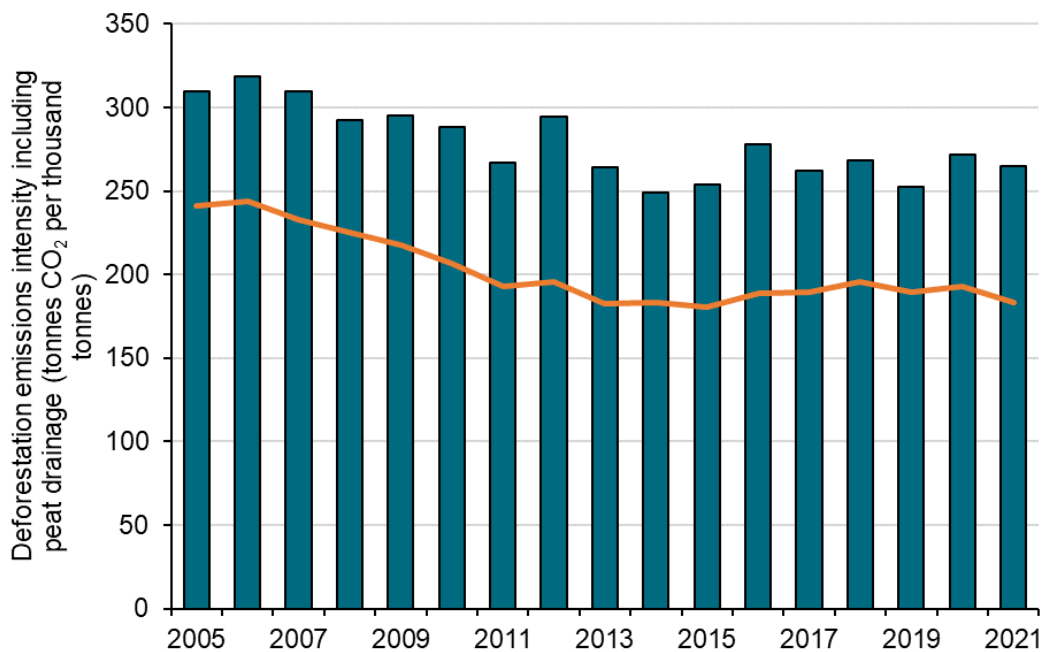
Note that the results presented in this section should be treated with caution, due to current limitations associated with the deforestation linked emission calculations (see details and references in Section A3.1.5, Annex 3). In brief, methods developed to estimate emissions linked to tropical forest loss are followed and the assumptions inherent in this approach are applied now for both tropical and non-tropical forest loss. For example, treatment of emissions from drained peatlands utilises tropical factors and therefore are likely to be inaccurate for non-tropical regions. Future updates on the results presented in this section will aim to improve upon this current limitation.

UK consumption of **crop, cattle-related and timber** commodities in 2021 was responsible for an estimated 37.8 million tonnes of CO<sub>2</sub> emissions linked to deforestation worldwide, inclusive of peat drainage, a decrease of 25.5% since 2005 (Figure 7). Comparing the 2021 footprint with 2016 reveals a short-term increase of 8.5%. For the latest year (2021) an increase is observed (5.6% increase). Estimates refer to deforestation as a result of crop, cattle-related and timber commodities only.



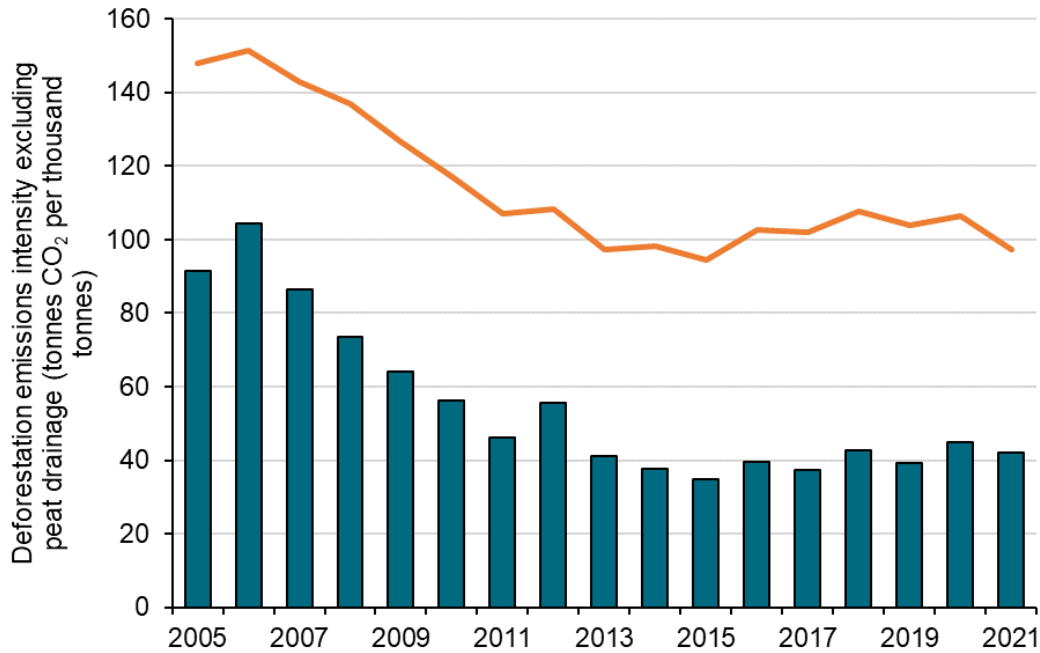
**Figure 7.** Deforestation emissions (including peat drainage) associated with UK consumption (million tonnes CO<sub>2</sub>)

UK consumption of **crop, cattle-related and timber** commodities in 2021 was responsible for an estimated deforestation linked emissions intensity, inclusive of peat drainage, of 265 tonnes of CO<sub>2</sub> per thousand tonnes of embedded production, a decrease of 14.5% since 2005 (Figure 8). Comparing the 2021 footprint with 2016 reveals a short-term decrease of 4.6%. For the latest year (2021) a decrease is observed (2.6% decrease). UK consumption-based intensities are higher than that of the global average (orange line) for all years in the timeseries. Estimates refer to deforestation as a result of crop, cattle-related and timber commodities only.



**Figure 8.** Deforestation emissions intensity (including peat drainage) associated with UK consumption (tonnes CO<sub>2</sub> per thousand tonnes). The (orange) line compares this to intensities associated with global consumption.

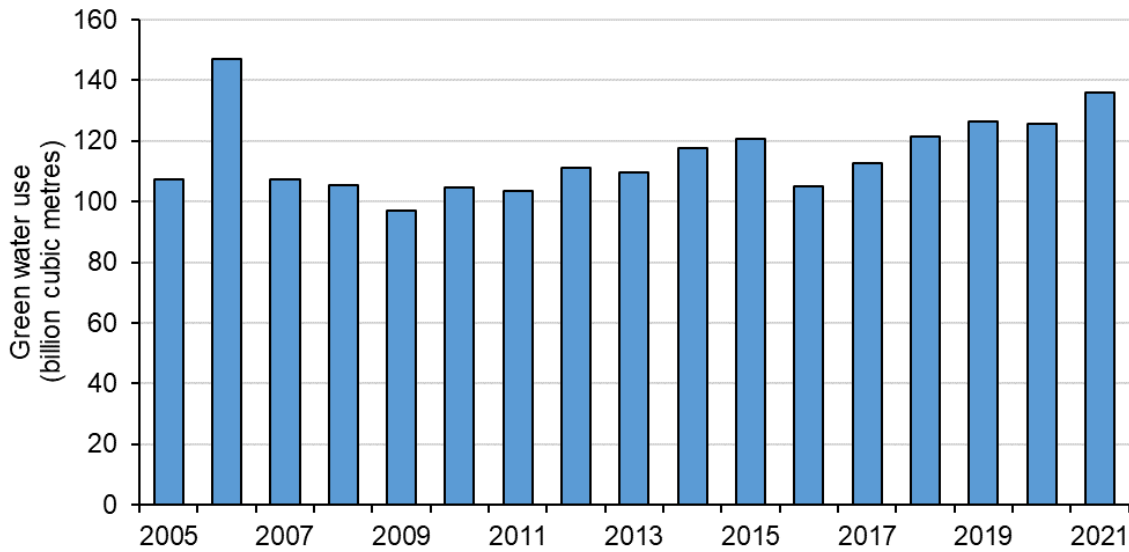
UK consumption of **crop, cattle-related and timber** commodities in 2021 was responsible for an estimated deforestation linked emissions intensity, excluding peat drainage, of 42 tonnes of CO<sub>2</sub> per thousand tonnes of embedded production, a decrease of 54.2% since 2005 (Figure 9). Comparing the 2021 footprint with 2016 reveals a short-term increase of 5.8%. For the latest year (2021) a decrease is observed (6.3% decrease). UK consumption-based intensities are below that of the global average (orange line) for all years in the timeseries. Estimates refer to deforestation as a result of crop, cattle-related and timber commodities only.



**Figure 9.** Deforestation emissions intensity (excluding peat drainage) associated with UK consumption (tonnes CO<sub>2</sub> per thousand tonnes). The (orange) line compares this to intensities associated with global consumption.

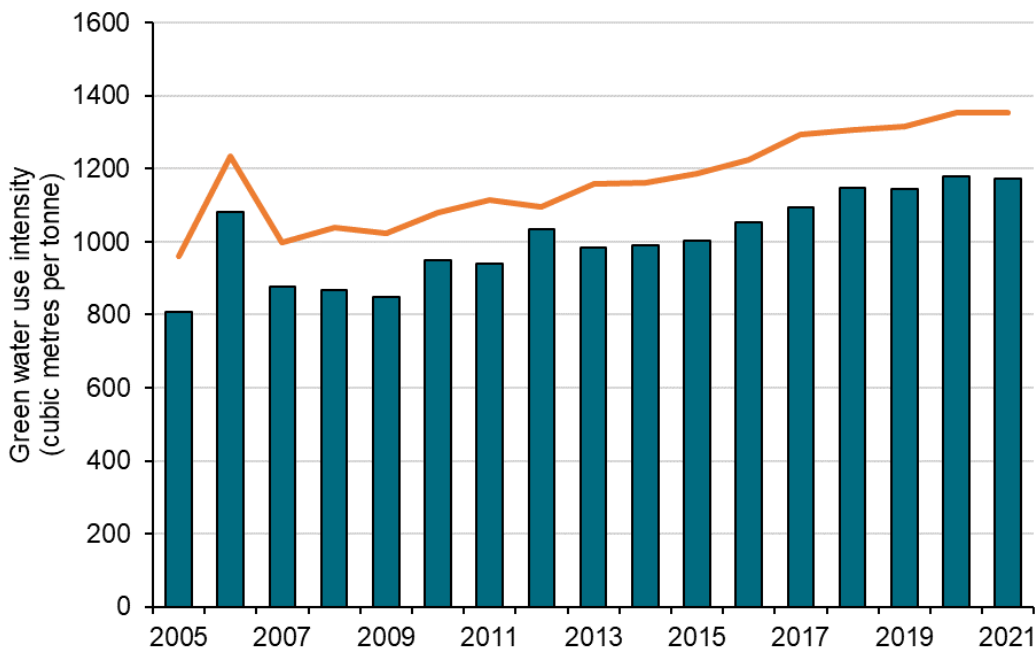
### Green water use

UK consumption of **crop** commodities in 2021 was responsible for an estimated 136.16 billion cubic metres of green water use worldwide, an increase of 26.8% since 2005 (Figure 10). Comparing the 2021 footprint with 2016 reveals a short-term increase of 29.4%. For the latest year (2021) an 8.2% increase is observed. Estimates refer to crop commodities only.



**Figure 10:** Green water use associated with UK consumption (billion cubic metres)

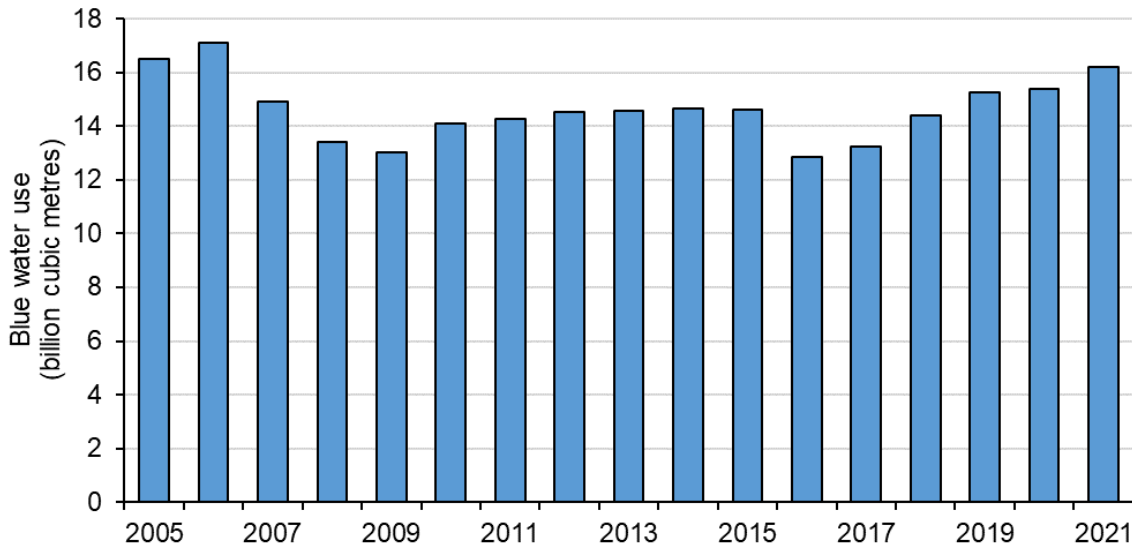
UK consumption of **crop** commodities in 2021 was responsible for an estimated green water use intensity of 1,174 cubic metres per tonne of embedded production, an increase of 45.4% since 2005 (Figure 11). Comparing the 2021 footprint with 2016 reveals a short-term increase of 11.6%. For the latest year (2021) a 0.5% decrease is observed. UK consumption-based intensities are below that of the global average (orange line) for all years. Estimates refer to crop commodities only.



**Figure 11:** Green water intensity (cubic metres per tonne) associated with UK consumption. The (orange) line compares this to intensities associated with global consumption.

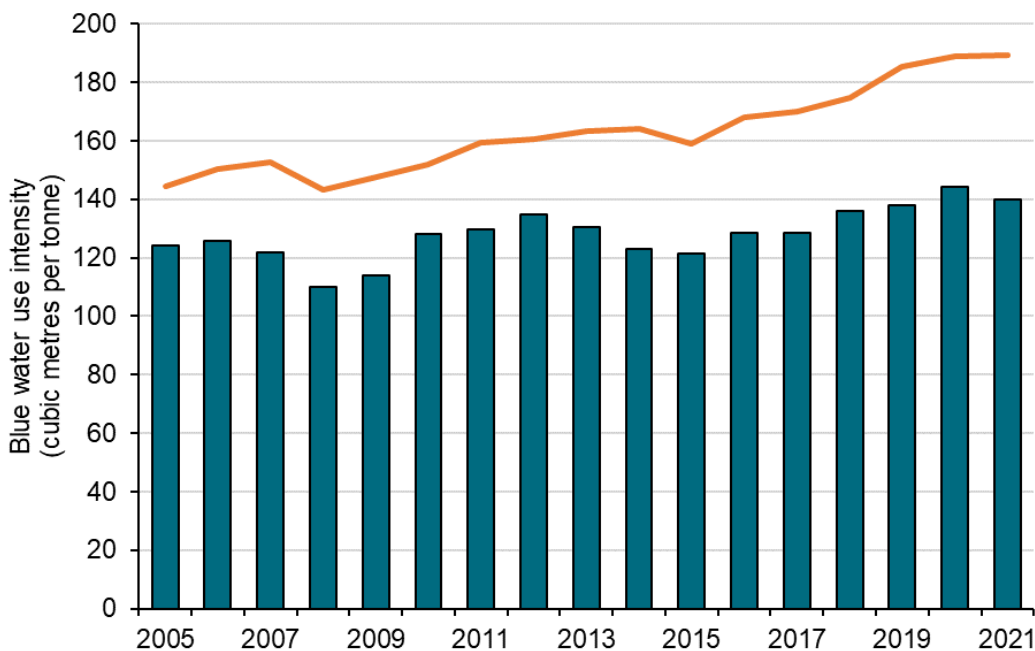
## Blue water use

UK consumption of **crop** commodities in 2021 was responsible for an estimated 16.2 billion cubic metres of blue water use worldwide, a decrease of 1.8% since 2005 (Figure 12). Comparing the 2021 footprint with 2016 reveals a 26.2% increase. For the latest year (2021) a 5.5% increase is observed. Estimates refer to crop commodities only.



**Figure 12:** Blue water use associated with UK consumption (billion cubic metres).

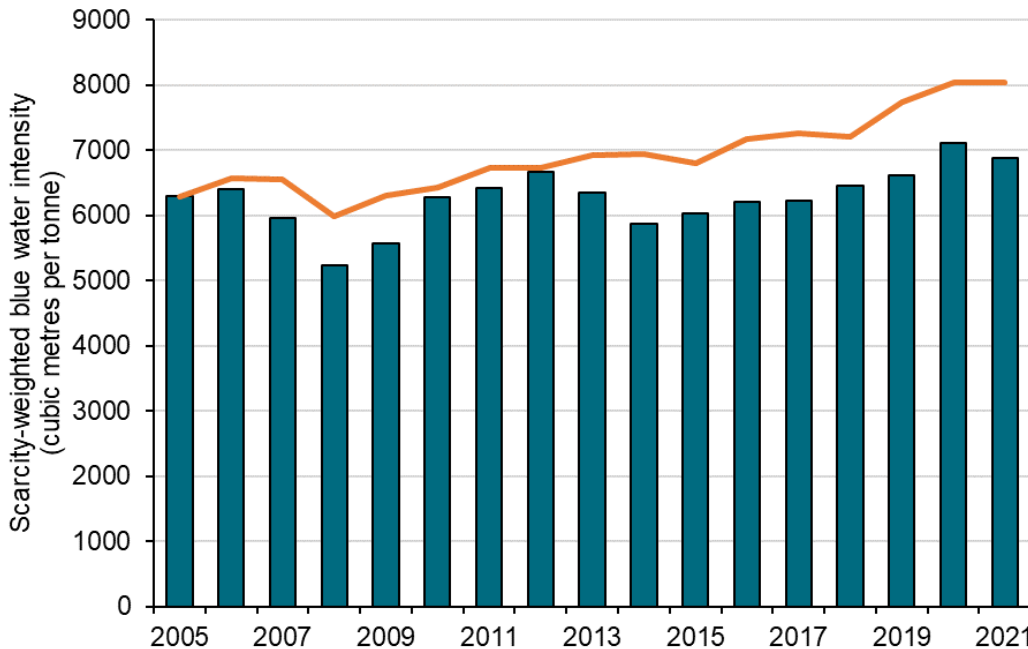
UK consumption of **crop** commodities in 2021 was responsible for an estimated blue water use intensity of 140 cubic metres per tonne of embedded production, an increase of 12.7% since 2005 (Figure 13). Comparing the 2021 footprint with 2016 reveals a short-term increase of 8.8%. For the latest year (2021) a 3.0% decrease is observed. UK consumption-based intensities are below that of the global average (orange line) for all years in the timeseries. Estimates refer to crop commodities only.



**Figure 13:** Blue water intensity (cubic metres per tonne) associated with UK consumption. The (orange) line compares this to intensities associated with global consumption.



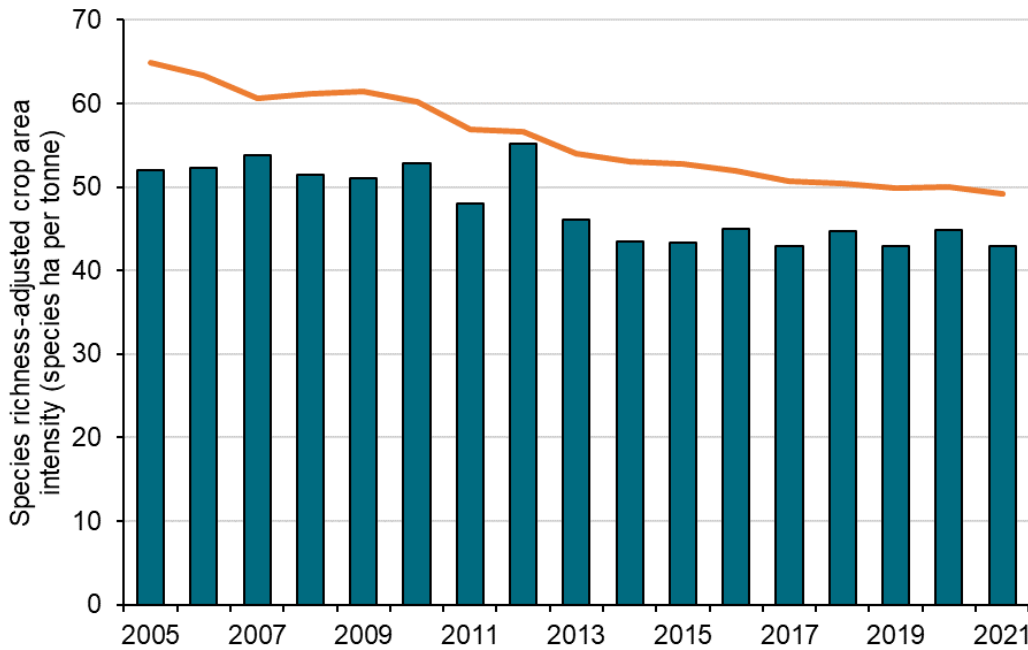
UK consumption of **crop** commodities in 2021 was responsible for an estimated scarcity-weighted blue water use intensity of 6,877 cubic-metres per tonne of embedded production, an increase of 9.3% since 2005 (Figure 14). Comparing the 2021 footprint with 2016 reveals a short-term increase of 10.6%. For the latest year (2021) a 3.4% decrease is observed. UK consumption-based intensities are below that of the global average (orange line) for all years across the timeseries. Estimates are for crop commodities only.



**Figure 14:** Scarcity-weighted blue water intensity (cubic metres per tonne) associated with UK consumption. The (orange) line compares this to intensities associated with global consumption.

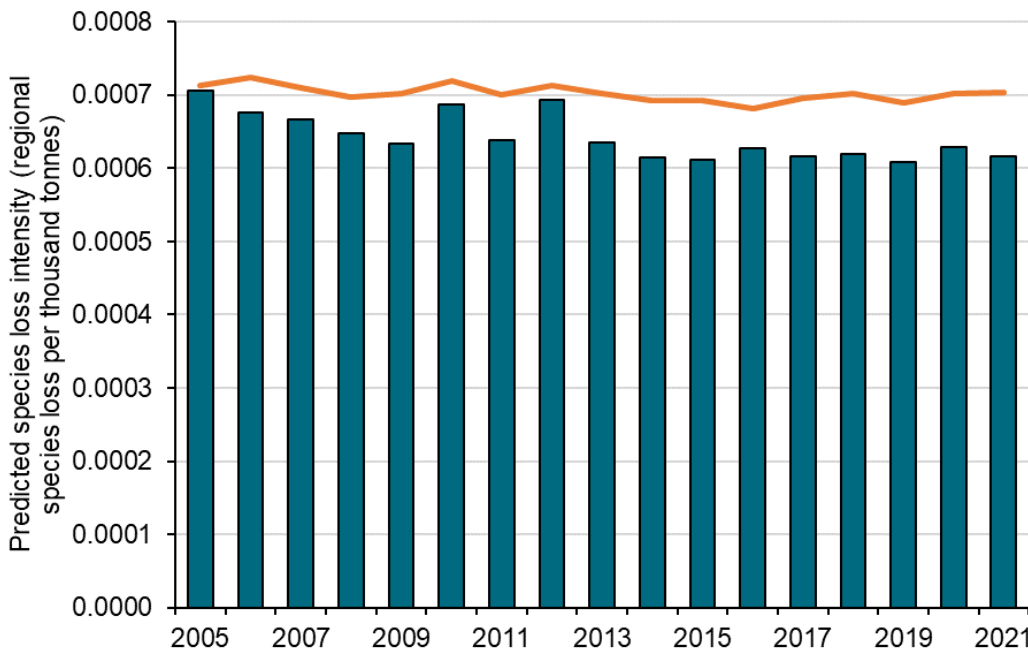
## Biodiversity

UK consumption of **crop** commodities in 2021 was responsible for an estimated intensity of 42.9 species richness-weighted hectares per tonnes of embedded production (Figure 15), a 17.7% decrease since 2005. Comparing the 2021 footprint with 2016 reveals a short-term decrease of 4.9%. For the latest year (2021) a 4.5% decrease is observed. UK consumption-based intensities are below that of the global average (orange line) for all years in the timeseries. Estimates refer to crop commodities only.



**Figure 15:** Species richness-weighted crop area intensity (species-hectares per tonne) associated with UK consumption. The (orange) line compares this to intensities associated with global consumption.

UK consumption of **crop** commodities in 2021 was responsible for a predicted regional species loss intensity of 0.00062 species per thousand tonnes of embedded production, a decrease of 12.8% since 2005 (Figure 16). Comparing the 2021 footprint with 2016 reveals a short-term decrease of 1.8%. For the latest year (2021) a 2.0% decrease is observed. UK consumption-based intensities are below that of the global average (orange line) for all years in the timeseries. Estimates refer to crop commodities only.



**Figure 16:** Predicted species loss intensity (regional species loss per thousand tonnes) associated with UK consumption. The (orange) line compares this to intensities associated with global consumption.

## Annex 2: Consideration of alignment and consistency with the UK Carbon Footprint and UK Material Footprint

The University of Leeds already compile an MRIO-based indicator about two aspects of the UK's consumption impacts, in the form of the [UK Carbon Footprint](#) and the [UK Material Footprint](#). The project recognised the potential for alignment as it could be useful if other environmental indicators developed in this body of work are produced in a consistent and comparable way with existing UK indicators. In particular, this project is producing a material footprint of its own, on which the impact metrics are based, and a GHG emissions from deforestation indicator (an aspect of GHG emissions not currently included within the UK Carbon Footprint). The project team, therefore, met with those who work on the UK Carbon Footprint in February 2021 to discuss potential alignment opportunities.

However, the nature of the UK Carbon/Material Footprints does not allow for a detailed breakdown in terms of commodities and countries/territories of origin, unlike the indicator developed under this project. For example, carbon emissions linked to agricultural commodities are presented at an aggregate 'agricultural' sector level, which cannot be broken down into specific commodities such as soy, wheat, palm oil, etc., and geographic resolution is limited to that of the MRIO. This is because the Carbon/Material Footprints aim to quantify the overall pressure that the UK is exerting, whilst the work within this project aims to understand in greater detail the location of impacts and their associated drivers, to inform action. As understanding countries/territories and commodities of impact is key to many of the current indicator's use cases across both the steering group and the stakeholder group, it was decided that in this case alignment would not be immediately beneficial. GHG emissions are also less sensitive to spatial heterogeneity compared to impacts such as deforestation and biodiversity.

It should therefore be flagged that the results from these two indicators will not be directly comparable. They are not in the same format, and they also use separate methodologies. However, the project team will keep channels of communication open with Leeds as future use cases may emerge where direct harmonisation in approaches is useful. One such use case would be in an instance where the land-use emissions estimates resulting from the work conducted for this report could be considered as a 'supplement' to UK GHG accounts (which currently do not include LULUCF (Land Use, Land Use Change and Forestry) emissions).

## Annex 3: Methodology updates for the 2022 and 2023 releases of UK Biodiversity Indicator A4

The 2022 and 2023 releases of the indicator follow the same methodology outlined in this documentation, except for those differences detailed in this Annex. As well as extending the time series (with data up to 2021 included in the 2023 release), these changes include the addition of reptile data to the biodiversity metric, the addition of data on deforestation outside of the tropics along with revised methods for attributing forest loss to commodity expansion, and modifications to and clarifications around the underlying data sets used. In the 2023 release, data were also added to the associated dashboard for a wider range of consumption countries, via the use of an alternative MRIO model. This is described in the [Methodology section of the associated dashboard website](#) as this does not form part of the UK official statistic in development.

Due to the amendments to the methodology, the 2022 release recalculated data for its full time series (2005-2018), rather than simply adding 2018 data to the time series calculated previously. Similarly, this 2023 release provides updated data for the full time series (2005-2021). Those who have been using the data in analyses to this point should be aware that data in the current version may differ from data in the previous versions and should ensure that they are now using the most up to date version. Previous versions of the UK Biodiversity Indicators can still be accessed from the [JNCC website](#) if required.

As an official statistic in development in only its third year of publication, there are many further improvements that could be made to the underlying methodology. Indicator development work is planned until at least March 2025. Users can therefore expect the methodology to continue to change and improve throughout this time period. A brief overview of expected developments and likely timelines is provided in Section A3.2. Users can contact [ukglobalimpacts@jncc.gov.uk](mailto:ukglobalimpacts@jncc.gov.uk) if they have enquiries or ideas related to this.

### A3.1 Methodological differences and clarifications

#### A3.1.1 Use of IUCN data (2022 onwards)

In the 2021 release, the 'Species richness-weighted crop area associated with UK consumption' indicator made use of IUCN data, which included information on birds, mammals and amphibians (IUCN 2012, 2018 and 2020). From the 2022 release onwards (for the entire time series published), additional data are included on reptiles, which were not previously comprehensively covered, yet have recently undergone a global assessment, the data for which are also available from the IUCN (IUCN 2021). These reptile data have been used in addition to the data for other taxa and (via inclusion of these data) simply serve to increase the counts of species present per pixel. A result of this is that estimates of 'species hectares' provided are inflated compared to the previous release as more species are accounted for. For other taxa, the same data as in the 2021 release have been used in the 2022 and 2023 releases.

#### A3.1.2 Use of the amortised version of the Pendrill data set (2022 onwards)

In the 2021 release, the Pendrill deforestation data set (Pendrill *et al.*, 2020) provided deforestation attributions to crops derived from a method that amortised impacts over a five-year period (spreading the impact over this time to recognise that the cause for the impact was not an instant and independent event). From 2022 onwards, these data are termed 'deforestation risk' embodied in agricultural commodities by the authors. The later Pendrill *et al.* datasets also include an unamortised version of the data, termed 'deforestation

attribution' to land use. The 2022 and 2023 indicator releases use the amortised 'deforestation risk' data, which is of the same type as that used in the 2021 release, both for consistency with the previous release and in recognition that the cause of the impact is not an instant and independent event. Our selection of the amortised version is therefore not a methodology change, but is a point that requires clarification in terms of which data from the Pendrill *et al.* (2022) source (and subsequent releases from the Chalmers University of Technology; Singh & Persson, 2023) have been used, as now this would be unclear from the previous documentation. From 2022, data releases make use of updated input data for deforestation attribution, and thus some of these attribution values differ from previous releases.

### A3.1.3 Availability of the GTAP version of the model to complement EXIOBASE (2023 onwards)

Extension of the model to include additional MRIO data sets in the results is covered in detail in the [Methodology section of the associated dashboard website](#). These results do not form part of the official version of the UK indicator under development, but this may be an interesting data set to compare against and will be of use to other countries/territories for which EXIOBASE data are not available.

### A3.1.4 Change in forest-product trade data (2023 onwards)

For the 2021 and 2022 publications, FAO's "Forestry Trade Flows" data set was used to provide the bilateral trade data for the timber products represented within the indicator. However, this resource is currently marked as "temporarily discontinued 2018", with no data available for 2019 onwards. To circumvent this restriction and provide supply chain results for timber products in the 2023 update (adding years 2019-2021 to the existing 2005-2018 results), a change in data sources has been necessitated, with the choice made to use trade data from UN Comtrade. For consistency across the time series, this change has been made to the full time series (i.e. the entire dataset published in 2023 is based on Comtrade and no FAO data are used).

Comtrade provides a similar data structure to FAO (namely reporter-partner trade flows) but reports commodities according to the HS6 (Harmonised System) classification scheme. From FAO's own literature (<https://www.fao.org/3/i0750m/i0750m01.pdf>), the corresponding HS codes were identified as mapping onto the respective FAO timber classifications used previously:

44032X: 1651 Industrial roundwood, coniferous (export/import)

44034X, 44039X: 1657 Industrial roundwood, non-coniferous tropical (export/import), 1670 Industrial roundwood, non-coniferous non-tropical (export/import)

Note: the latter two HS codes/FAO commodities need to be mapped as aggregate pairs (i.e. all non-coniferous timber) since the HS code 440399 is an unspecified mix of tropical and non-tropical non-coniferous goods, and thus it is not possible to disentangle the reporting to tropical and non-tropical type.

For the most part, this change of data source has no effect on the core methodology; it simply represents a change of input data set. That said, there have been two changes in the way that timber products have been handled within the modelling process compared to previous versions:

1) Previously, coniferous and non-coniferous products were aggregated together, with all trade treated as simply that of “industrial roundwood” as a whole. Now, these two commodity types are kept separate throughout the modelling process, and only aggregated for the sake of reporting results.

2) FAO report their timber data in volume units of m<sup>3</sup>, whilst Comtrade provide volume and mass. Previously, this required applying conversion factors to convert the FAO production and trade volumes into mass units. Now, the mass values are used for the trade data, with just the conversion of production values required. The method of performing this conversion has changed slightly, with new factors applied. The items used from within FAO’s forestry production data are as follows:

1601; Sawlogs and veneer logs, coniferous

1604; Sawlogs and veneer logs, non-coniferous

1602; Pulpwood, round and split, coniferous (production)

1603; Pulpwood, round and split, non-coniferous (production)

1623; Other industrial roundwood, coniferous (production)

1626; Other industrial roundwood, non-coniferous (production)

Conversions are applied (again, based on FAO’s own literature; <https://www.fao.org/3/i0750m/i0750m01.pdf>) such that coniferous products are converted at 1.43 m<sup>3</sup>/tonne, with non-coniferous from fully tropical countries/territories at 1.37 m<sup>3</sup>/tonne, from non-tropical countries/territories at 1.25 m<sup>3</sup>/tonnes, and partially tropical countries/territories at the average of 1.31 m<sup>3</sup>/tonne (with tropical status based on <https://worldpopulationreview.com/country-rankings/tropical-countries>).

### **A3.1.5 Updated version of the deforestation data (2023 onwards)**

The deforestation (and associated deforestation linked emissions) metrics rely on data provided by the Chalmers University of Technology. As described in Section 5 of the report, historically these have been based on a ‘land-balance’ approach where spatialised forest loss information was aggregated at the country scale and then attributed to commodity expansion based on overall (non-spatial) pasture, plantation and cropland (and crop) expansion statistics. In this release, deforestation-attribution methods have been substantially revised by the Chalmers University of Technology, with the outcome of enhancing the data set (via the use of spatialised land use and commodity data sets for certain regions and commodities) and expanding its coverage to estimate non-tropical deforestation for the first time (Singh & Persson, 2023).

Conceptually, the process of allocating forest loss to agricultural production remains similar in the revised data set compared to its previous iteration. Firstly, forest loss is categorised according to drivers. The methodological approach behind this step has been revised in the 2023 data release to incorporate certain spatially explicit crop and forest plantation data sets, as well as spatially explicit land use information where available. It has also been expanded to include information on specific drivers of forest loss (in addition to the three broad categories of cropland expansion, pasture expansion, and forest plantation expansion). Secondly, attribution of crop-land expansion to specific commodities then takes

place. Thirdly, in addition to the deforestation estimates, associated emissions from land use change are estimated. In comparison with the previous methods, however, there are differences at each of these three stages as follows:

**Forest loss categorisation:** The methods to classify forest loss according to its proximate drivers (and allow eventual classification to commodity level) have been improved. Firstly, more data sets have been utilised. Tree cover loss data (from – as before – the Hansen *et al.* data set) is overlaid with a number of data sets including the MapBiomass (MapBiomass 2022) collection (covering various Latin American countries, plus Indonesia), individual spatial commodity-expansion data (for soy (Song *et al.*, 2021) and plantations (Du *et al.*, 2022)), plus other spatialised classifications of forest-loss drivers (fire (Tyukavina *et al.*, 2022) and other drivers (Curtis *et al.*, 2018)). These different data sets provide varying levels of detail regarding the deforestation drivers for each pixel globally. Therefore, for each pixel, the spatial data set with the highest levels of detail with respect to a specific driver of forest loss is prioritised. Specific commodity-expansion data (e.g. soy extent), therefore, takes precedence over more broadly-classified land use data (e.g. cropland or pasture), followed by data on dominant forest loss drivers (e.g. commodity-driven deforestation).

Certain processing details require assumptions/decisions to be made: i) Forest is defined as areas with 25% or greater tree cover density for each 30m pixel; ii) Where multiple MapBiomass data sets cover the same pixel, priority is given to data with higher specificity; for example forest loss in a pixel which can be linked to ‘oil palm’ will take precedence over a broad land use category; iii) Potential time lags between detected forest loss and establishment of agricultural land are accounted for by applying a four-year time window from the year of deforestation. For example, if forest loss occurs in 2001 and a data set (e.g. MapBiomass) suggests cropland exists in that pixel in 2003 then that forest loss is attributed to cropland expansion. Within this four-year time window if the same pixel experiences different land uses then attribution to plantations is prioritised, followed by pasture, perennial crops, then temporary crops; iv) Any forest loss in agricultural land systems established prior to 2001 is excluded; v) After forest loss data has been attributed to commodities or other categories of land use, forest loss due to (spatio-temporally defined) fire (a dominant driver in temperate and boreal regions) is excluded from the analysis; vi) For any areas not covered by aforementioned data/assumptions the data set provided by Curtis *et al.* (2018) which identifies forest loss drivers – complemented by a global forest management data set to differentiate between managed and undisturbed forests for the year 2000 (Lesiv *et al.*, 2022) – is used to determine remaining agricultural-commodity driven and forestry-related deforestation post year-2000.

In some cases, results indicate that forest-loss is attributed to land use categories which cover multiple activities (e.g. ‘mosaics’). Here a statistical attribution approach is utilised using annual land use data from FAOSTAT. Land use data from FAO are available to 2020, allowing statistical expansion to be determined until 2019. To fill gaps in 2020 and 2021, therefore, the last three-year average (i.e. 2017-2019) expansion data are used to apportion forest loss in later years. In cases where mosaics are identified to be a mix of cropland and pasture, forest loss is divided based on relative areas of FAO-defined land expansion (equivalent to methods in Pendrill *et al.*, 2019a). When forest loss is categorised into broad-driver classifications or spatially unclassified regions, a cap is applied by selecting the lowest of either the proportionally distributed forest loss or land-use expansion estimates.

The final step in the forest loss categorisation stage is to sum spatial and statistical attributions associated with each individual land class, which results in the determined forest loss attributed to cropland, pasture and forest plantation expansion.



Two particularly important changes arise from the methods described above in comparison to the previous methods. Firstly, the use of spatially explicit land use and commodity information should markedly improve the attribution of forest loss to agricultural and forestry-driven deforestation, where this spatially explicit information is available. Secondly, the utilisation of data on dominant drivers of forest loss means that, in comparison with prior data sets, non-tropical forest loss can be allocated to commodity-production. However, it should be noted that the information on dominant forest-loss drivers is coarse (approximately in a 10-by-10 km pixel) and operates in a 'binary' manner (i.e., pixels are designated by their dominant driver of forest loss, meaning that forest loss within a pixel could potentially be a mix of several drivers – across space and time – which may include agriculture, but this may not be apparent). The important consequence of this is that the data quality for forest-loss attributions varies across the data set, with better estimates existing for Latin America and Indonesia where spatially-explicit land use and certain crop-extent information is available.

**Commodity attribution:** In the new methods, attribution of deforestation to individual crops depends on combinations of spatial and statistical attribution. It is assumed that remote sensing products utilised provide accurate estimates of crop-specific deforestation. These crop-specific products are i) oil palm in Indonesia, ii) soybeans in Argentina, Bolivia, Brazil, Chile, Paraguay and Uruguay, and iii) sugarcane, rice, coffee and citrus fruit in Brazil. Spatially-specific attribution to forest loss is conducted first, where data are available, and statistical attribution is then employed to allocate any remaining forest loss to cropland expansion in a manner parallel to the land balance approach utilised in prior releases (i.e. based on relative crop expansions compared to total cropland expansion). Because FAO crop product data are available to 2021, this allows statistical crop-attribution to 2020, with data to 2021 calculated using a similar 'nowcasting' method as described above. If there is a surplus in forest loss attributed to cropland expansion compared with FAO's records of cropland expansion, then this surplus is allocated proportionally based on annual harvested areas. As with the previous methods, attributed deforestation for each commodity is spread over a 5-year amortisation period.

**Carbon emissions:** Carbon emissions are calculated using analogous methods to the prior release, with the primary difference being that the use of more detailed spatialised land use information improves attribution of forest loss to particular commodities. It is important to note that the methods of Pendrill *et al.*, 2019b are followed and that assumptions inherent in this approach are applied now for tropical and non-tropical forest loss. For example, carbon sequestration potential (resulting from forest transition to higher-carbon stock land uses) uses values obtained for tropical forest, and therefore is likely associated with some error when applied to non-tropical forests. Future results will seek to improve upon this limiting assumption. Similar limitations arise with regard to treatment of emissions from drained peatlands, which also utilise tropical factors and therefore are likely to be inaccurate for non-tropical regions. Again, future results will aim to improve upon this current limitation.

We expect further revisions to these deforestation-attribution methods (and associated data) in the coming months. Future revisions are likely to include improvements to deforestation-emissions estimates for peatlands, and also associated 'flag' information to help identify the underpinning data quality associated with particular commodity/country/territory deforestation estimates. For this release, data were supplied to the indicator team directly by the authors (Singh & Persson, 2023).

### A3.1.6 Modification to the trade balancing methods (2023 onwards)

For the re-export algorithm (which takes multi-stage bilateral trade flows and “stitches” them together to link origin with destination, via trade intermediaries) to operate within the framework, it is important that reported exports from a given country/territory do not exceed the available supply in that country/territory (i.e. production plus imports). This constraint is sometimes not satisfied by the *reported* production and trade data. Thus, a balancing step is required. Previously, this balancing step was done in a very simple way: where exports exceeded available supply for a given country/territory, all exports from this country/territory were scaled down to be equal to their supply. Since this would reduce other countries/territories’ imports, potentially making supply less than reported imports plus production, the process would then run iteratively until all constraints were satisfied.

A new approach to this balancing step has been adopted. The idea is to find an adjusted set of trade data that is ‘as close as possible’ to the reported data, among all possible sets that satisfy the constraint that exports do not exceed production plus imports in any country/territory. Here, “close” is measured as the statistical “divergence” between the resolved data set and the original reported data set, specifically, the Kullback-Liebler divergence (Kullback & Leibler, 1951; Többen & Schröder, 2018; Golan & Vogel, 2010). By definition, this results in the creation of no new trade relationships, and rather only adjusts reported trade flows. Reported trade can be split into disjoint “trade blocks” (i.e., groups of countries/territories with no trade between groups), which can be solved in isolation. Where possible, an additional constraint is imposed that the total resolved trade within each trade block is equal to the total reported trade in that trade block.

### A3.1.7 Modification to the water indicator methods (2023 onwards)

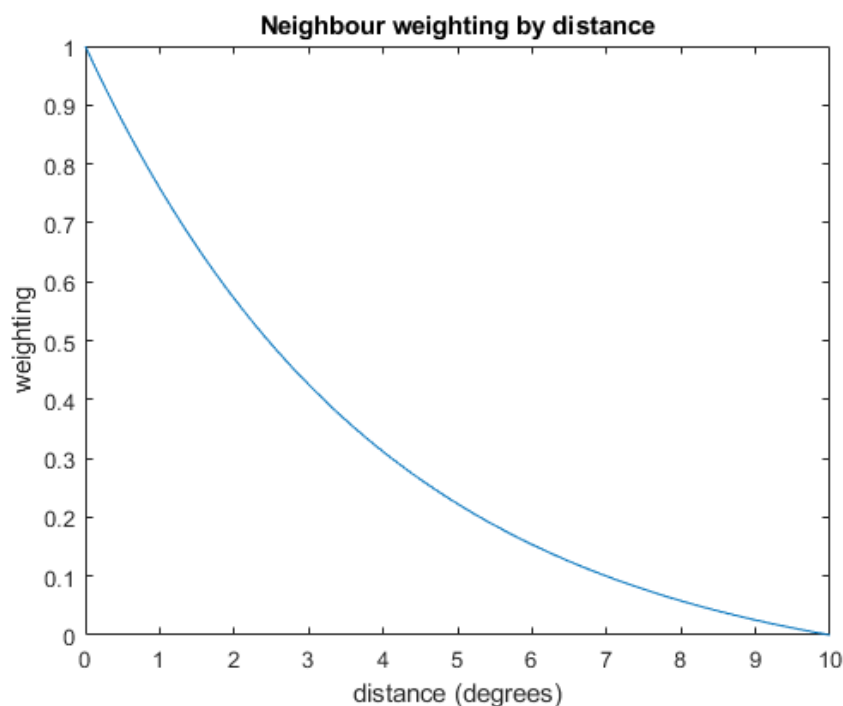
The core methods for developing the water indicator data remain unchanged, with the same input data used and the same basic method of establishing a baseline for the recorded reference years, and annualising this by scaling based on relative annual yield compared to the yield from the reference period. This baseline yield is now established against the latest FAO production and cropland use area data, but the method remains the same as before.

However, the method by which data from neighbouring countries/territories are used to fill data gaps has been modified. Previously, as per Tamea *et al.* (2021), gaps in country/territory data were filled using the value of the “nearest neighbour” within a distance threshold of 1110km (approximately equivalent to 10 degrees of latitude). In this release, the approach adopted is instead to calculate a weighted average of neighbours within this same distance threshold, with weighting exponentially decaying with increasing distance.

Specifically, the weighting for each neighbour is calculated via the equation:

$$w_x = \frac{\exp(-0.25 \cdot d_x)}{1 - \exp(-2.5)} + \left(1 - \frac{1}{1 - \exp(-2.5)}\right),$$

where  $w_x$  is the weighting for country/territory  $x$ , which is an angular  $d_x$  from the focal country/territory (calculated as the Euclidean distance between coordinates). Figure 17 shows a plot of this decay function, demonstrating how the function takes maximum weighting (i.e. 1) at zero distance, before decaying to no weighting (i.e. 0) beyond the threshold distance of 10 degrees.



**Figure 17:** Exponential decay function utilised to establish relative weighting of neighbours in the calculation of weighted averages to fill gaps within the water indicator data set.

The weighted average is then calculated over all neighbours based on these weightings. Where no data exist for a country, and no suitable value is established via the above neighbour-based routine, the global average is adopted as was previously the case.

### A3.1.8 Treatment of changed jurisdictional classifications (2023 onwards)

Within the time series covered by this work, there are two instances of changing jurisdictional classifications, namely 'Serbia and Montenegro' splitting to become 'Serbia' and 'Montenegro' in 2006, and 'Sudan (former)' splitting in 2012 to form 'Sudan' and 'South Sudan'. These changes are reflected appropriately in the production and trade data used within the framework, however for some input indicator files this is not the case due to time stamps or classification choices. In these instances, separate entries have had to be aggregated to form entries for the pre-split jurisdictions, or pre-split entries disaggregated/extrapolated to apply to post-split jurisdictions, as appropriate on a case-by-case basis.

## A3.2 Planned development work

In 2024-25, development work is planned to:

- Integrate higher geographic resolution data.
- Scope out the potential to add agri-chemical related impact metrics, such as nitrogen and phosphorous pollution.
- Scope out the potential to add marine commodities.

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## Annex 4: Concordances

This Annex provides concordance information between MapSPAM crops and FAO/IOTA data (Table S1); concordance information between LSIB country/territory names and FAO country/territory names (Table S2); attributes associated with spatial data adapted from IUCN (2012, 2018) and BirdLife International (n.d.) (Table S3); and concordance information between FAO commodities and appropriate producing sectors within the MRIO database (Table S4).

**Table S1.** MapSPAM crops and concordance with FAO/IOTA.

<b>MapSPAM NAME</b>	<b>FAO ITEM NAME</b>	<b>FAO ITEM CODES</b>	<b>FAO GROUP</b>
WHEAT	WHEAT	15	CEREALS
RICE	RICE	27	CEREALS
MAIZE	MAIZE	56	CEREALS
BARLEY	BARLEY	44	CEREALS
PEARL MILLET	MILLET	79	CEREALS
SMALL MILLET	MILLET	79	CEREALS
SORGHUM	SORGHUM	83	CEREALS
OTHER CEREALS	OTHER CEREALS ++	71; 75; 89; 92; 94; 97; 101; 103; 108;	CEREALS
POTATO	POTATO	116	ROOTS&TUBERS OR STARCHY ROOTS
SWEET POTATO	SWEET POTATO	122	ROOTS&TUBERS OR STARCHY ROOTS

<b>MapSPAM NAME</b>	<b>FAO ITEM NAME</b>	<b>FAO ITEM CODES</b>	<b>FAO GROUP</b>
YAMS	YAM	137	ROOTS&TUB ERS OR STARCHY ROOTS
CASSAVA	CASSAVA	125	ROOTS&TUB ERS OR STARCHY ROOTS
OTHER ROOTS	YAUTIA ++	135; 136; 149	ROOTS&TUB ERS OR STARCHY ROOTS
BEAN	BEANS; DRY	176	PULSES
CHICKPEA	CHICKPEA	191	PULSES
COWPEA	COWPEA	195	PULSES
PIGEONPEA	PIGEON PEA	197	PULSES
LENTIL	LENTILS	201	PULSES
OTHER PULSES	BROAD BEANS ++	181; 187; 203; 205; 210; 211	PULSES
SOYBEAN	SOYBEAN	236	OILCROPS
GROUNDNUT	GROUNDNUT; WITH SHELL	242	OILCROPS
COCONUT	COCONUT	249	OILCROPS
OILPALM	PALMOIL	254	OILCROPS
SUNFLOWER	SUNFLOWER SEED	267	OILCROPS



<b>MapSPAM NAME</b>	<b>FAO ITEM NAME</b>	<b>FAO ITEM CODES</b>	<b>FAO GROUP</b>
RAPESEED	RAPESEED	270; 292	OILCROPS
SESAMESEED	SESAME SEED	289	OILCROPS
OTHER OIL CROPS	OLIVES ++	260; 261; 263; 265; 268; 271; 275; 277; 280; 281; 290; 296; 299; 305; 310; 329; 331; 333; 334; 336; 339;	OILCROPS
SUGARCANE	SUGAR CANE	156	SUGAR CROPS
SUGARBEET	SUGARBEET	157	SUGAR CROPS
COTTON	SEED COTTON	328	FIBRES
OTHER FIBRE CROPS	OTHER FIBRES ++	773; 777; 778; 780; 782; 788; 789; 800; 809; 813; 821;	FIBRES
ARABICA COFFEE	COFFEE	656	STIMULANT
ROBUSTA COFFEE	COFFEE	656	STIMULANT
COCOA	COCOA	661	STIMULANT
TEA	TEA	667	STIMULANT
TOBACCO	TOBACCO LEAVES	826	STIMULANT
BANANA	BANANA	486	FRUITS
PLANTAIN	PLANTAIN	489	FRUITS

MapSPAM NAME	FAO ITEM NAME	FAO ITEM CODES	FAO GROUP
TROPICAL FRUIT	ORANGES ++	490; 495; 497; 507; 512; 567; 568; 569; 571; 572; 574; 577; 587; 591; 600; 603;	FRUITS
TEMPERATE FRUIT	APPLES ++	515; 521; 523; 526; 530; 531; 534; 536; 541; 542; 544; 547; 549; 550; 552; 554; 558; 560; 592; 619;	FRUITS
VEGETABLES	CABBAGES AND OTHER BRASSICAS ++	358; 366; 367; 372; 373; 388; 393; 394; 397; 399; 401; 402; 403; 406; 407; 414; 417; 420; 423; 426; 430; 446; 449; 459; 461; 463;	VEGETABLES
REST OF CROPS	ALL INDIVIDUAL OTHER CROPS (EG SPICES; TREE NUTS; OTHER SUGAR CROPS; MATE; RUBBER)	161; 216; 217; 220; 221; 222; 223; 224; 225; 226; 234; 671; 677; 687; 689; 692; 693; 698; 702; 711; 720; 723; 748; 754; 767; 836; 839;	

**Table S2.** To align the species-hectare indicator calculated per country/territory using the LSIB country/territory boundaries (USDS, 2017) to IOTA, we developed a table to provide concordance between the LSIB country/territory names to those names and codes used by the FAO.

LSIB NAME	FAOSTAT NAME	FAOSTAT CODE
Afghanistan	Afghanistan	2
Akrotiri	Cyprus	50
Albania	Albania	3
Algeria	Algeria	4
American Samoa	American Samoa	5
Andorra	Andorra	6

<b>LSIB NAME</b>	<b>FAOSTAT NAME</b>	<b>FAOSTAT CODE</b>
Angola	Angola	7
Anguilla	Anguilla	258
Antarctica	Antarctica	30
Antigua & Barbuda	Antigua and Barbuda	8
Argentina	Argentina	9
Armenia	Armenia	1
Aruba	Aruba	22
Australia	Australia	10
Austria	Austria	11
Azerbaijan	Azerbaijan	52
Bahamas, The	Bahamas	12
Bahrain	Bahrain	13
Bangladesh	Bangladesh	16
Barbados	Barbados	14
Belarus	Belarus	57
Belgium	Belgium	255
Belize	Belize	23
Benin	Benin	53

<b>LSIB NAME</b>	<b>FAOSTAT NAME</b>	<b>FAOSTAT CODE</b>
Bermuda	Bermuda	17
Bhutan	Bhutan	18
Bolivia	Bolivia (Plurinational State of)	19
Bosnia & Herzegovina	Bosnia and Herzegovina	80
Botswana	Botswana	20
Bouvet Island	Bouvet Island	31
Brazil	Brazil	21
British Virgin Is	British Virgin Islands	239
Brunei	Brunei Darussalam	26
Bulgaria	Bulgaria	27
Burkina Faso	Burkina Faso	233
Burma	Myanmar	28
Burundi	Burundi	29
Cabo Verde	Cabo Verde	35
Cambodia	Cambodia	115
Cameroon	Cameroon	32
Canada	Canada	33
Cayman Is	Cayman Islands	36

<b>LSIB NAME</b>	<b>FAOSTAT NAME</b>	<b>FAOSTAT CODE</b>
Central African Rep	Central African Republic	37
Chad	Chad	39
Chile	Chile	40
China	China, Mainland	41
Christmas I	Christmas Island	42
Cocos (Keeling) Is	Cocos (Keeling) Islands	43
Colombia	Colombia	44
Comoros	Comoros	45
Cook Is	Cook Islands	47
Coral Sea Is	Australia	10
Costa Rica	Costa Rica	48
Cote d'Ivoire	Côte d'Ivoire	107
Croatia	Croatia	98
Cuba	Cuba	49
Curacao	Curaçao	279
Cyprus	Cyprus	50
Czechia	Czechia	167
Dem Rep of the Congo	Democratic Republic of the Congo	250

<b>LSIB NAME</b>	<b>FAOSTAT NAME</b>	<b>FAOSTAT CODE</b>
Denmark	Denmark	54
Dhekelia	Cyprus	50
Djibouti	Djibouti	72
Dominica	Dominica	55
Dominican Republic	Dominican Republic	56
Dragonja River Mouth	Croatia	98
Dramana-Shakatoe Area	China, Mainland	41
Ecuador	Ecuador	58
Egypt	Egypt	59
El Salvador	El Salvador	60
Equatorial Guinea	Equatorial Guinea	61
Eritrea	Eritrea	178
Estonia	Estonia	63
Ethiopia	Ethiopia	238
Falkland Islands	Falkland Islands (Malvinas)	65
Faroe Is	Faroe Islands	64
Fed States of Micronesia	Micronesia (Federated States of)	145
Fiji	Fiji	66

<b>LSIB NAME</b>	<b>FAOSTAT NAME</b>	<b>FAOSTAT CODE</b>
Finland	Finland	67
France	France	68
French Polynesia	French Polynesia	70
French S & Antarctic Lands	French Southern Territories	71
Gabon	Gabon	74
Gambia, The	Gambia	75
Georgia	Georgia	73
Germany	Germany	79
Ghana	Ghana	81
Gibraltar	Gibraltar	82
Greece	Greece	84
Greenland	Greenland	85
Grenada	Grenada	86
Guadeloupe	Guadeloupe	87
Guam	Guam	88
Guatemala	Guatemala	89
Guernsey	Channel Islands	259
Guinea	Guinea	90



LSIB NAME	FAOSTAT NAME	FAOSTAT CODE
Guinea-Bissau	Guinea-Bissau	175
Guyana	Guyana	91
Haiti	Haiti	93
Heard I & McDonald Is	Heard and McDonald Islands	92
Honduras	Honduras	95
Hong Kong	China, Hong Kong SAR	96
Hungary	Hungary	97
Iceland	Iceland	99
India	India	100
Indonesia	Indonesia	101
Invernada Area	Brazil	21
Iran	Iran (Islamic Republic of)	102
Iraq	Iraq	103
Ireland	Ireland	104
Isla Brasilera	Uruguay	234
Isle of Man	Isle of Man	264
Israel	Israel	105
Italy	Italy	106

LSIB NAME	FAOSTAT NAME	FAOSTAT CODE
Jamaica	Jamaica	109
Jan Mayen	Svalbard and Jan Mayen Islands	260
Japan	Japan	110
Jersey	Jersey	283
Jordan	Jordan	112
Kalapani Area	India	100
Kazakhstan	Kazakhstan	108
Kenya	Kenya	114
Kiribati	Kiribati	83
Korea, North	Democratic People's Republic of Korea	116
Korea, South	Republic of Korea	117
Korean Is. (UN Jurisdiction)	Republic of Korea	117
Kosovo	Serbia*	272
Koualou Area	Benin	53
Kuwait	Kuwait	118
Kyrgyzstan	Kyrgyzstan	113
Laos	Lao People's Democratic Republic	120
Latvia	Latvia	119

<b>LSIB NAME</b>	<b>FAOSTAT NAME</b>	<b>FAOSTAT CODE</b>
Lebanon	Lebanon	121
Lesotho	Lesotho	122
Liberia	Liberia	123
Libya	Libya	124
Liechtenstein	Liechtenstein	125
Lithuania	Lithuania	126
Luxembourg	Luxembourg	256
Macau	China, Macao SAR	128
Macedonia	North Macedonia	154
Madagascar	Madagascar	129
Malawi	Malawi	130
Malaysia	Malaysia	131
Maldives	Maldives	132
Mali	Mali	133
Malta	Malta	134
Marshall Is	Marshall Islands	127
Martinique	Martinique	135
Mauritania	Mauritania	136

LSIB NAME	FAOSTAT NAME	FAOSTAT CODE
Mauritius	Mauritius	137
Mayotte	Mayotte	270
Mexico	Mexico	138
Moldova	Republic of Moldova	146
Monaco	Monaco	140
Mongolia	Mongolia	141
Montenegro	Montenegro*	273
Montserrat	Montserrat	142
Morocco	Morocco	143
Mozambique	Mozambique	144
Namibia	Namibia	147
Nauru	Nauru	148
Nepal	Nepal	149
Netherlands	Netherlands	150
Netherlands (Caribbean)	Netherlands Antilles (former)	151
New Caledonia	New Caledonia	153
New Zealand	New Zealand	156
Nicaragua	Nicaragua	157

<b>LSIB NAME</b>	<b>FAOSTAT NAME</b>	<b>FAOSTAT CODE</b>
Niger	Niger	158
Nigeria	Nigeria	159
Niue	Niue	160
Norfolk I	Norfolk Island	161
Northern Mariana Is	Northern Mariana Islands	163
Norway	Norway	162
Oman	Oman	221
Pakistan	Pakistan	165
Palau	Palau	180
Panama	Panama	166
Papua New Guinea	Papua New Guinea	168
Paraguay	Paraguay	169
Peru	Peru	170
Philippines	Philippines	171
Pitcairn Is	Pitcairn	172
Poland	Poland	173
Portugal	Portugal	174
Puerto Rico	Puerto Rico	177

LSIB NAME	FAOSTAT NAME	FAOSTAT CODE
Qatar	Qatar	179
Rep of the Congo	Congo	46
Reunion	Réunion	182
Romania	Romania	183
Russia	Russian Federation	185
Rwanda	Rwanda	184
S Georgia & S Sandwich Is	South Georgia and the South Sandwich Islands	271
Saint Lucia	Saint Lucia	189
Samoa	Samoa	244
San Marino	San Marino	192
Sao Tome & Principe	Sao Tome and Principe	193
Saudi Arabia	Saudi Arabia	194
Senegal	Senegal	195
Serbia	Serbia*	272
Seychelles	Seychelles	196
Sierra Leone	Sierra Leone	197
Sinafir & Tiran Is.	Saudi Arabia	194
Singapore	Singapore	200

<b>LSIB NAME</b>	<b>FAOSTAT NAME</b>	<b>FAOSTAT CODE</b>
Slovakia	Slovakia	199
Slovenia	Slovenia	198
Solomon Is	Solomon Islands	25
Somalia	Somalia	201
South Africa	South Africa	202
South Sudan	South Sudan*	277
Spain	Spain	203
Spain (Africa)	Spain	203
Spain (Canary Is)	Spain	203
Sri Lanka	Sri Lanka	38
St Barthelemy	Saint Barthélemy	282
St Helena	Saint Helena, Ascension and Tristan da Cunha	187
St Kitts & Nevis	Saint Kitts and Nevis	188
St Martin	Guadeloupe	87
St Pierre & Miquelon	Saint Pierre and Miquelon	190
St Vincent & the Grenadines	Saint Vincent and the Grenadines	191
Sudan	Sudan*	276
Suriname	Suriname	207

<b>LSIB NAME</b>	<b>FAOSTAT NAME</b>	<b>FAOSTAT CODE</b>
Svalbard	Svalbard and Jan Mayen Islands	260
Swaziland	Eswatini	209
Sweden	Sweden	210
Switzerland	Switzerland	211
Syria	Syrian Arab Republic	212
Taiwan	China, Taiwan Province of	214
Tajikistan	Tajikistan	208
Tanzania	United Republic of Tanzania	215
Thailand	Thailand	216
Timor-Leste	Timor-Leste	176
Togo	Togo	217
Tokelau	Tokelau	218
Tonga	Tonga	219
Trinidad & Tobago	Trinidad and Tobago	220
Tunisia	Tunisia	222
Turkey	Türkiye	223
Turkmenistan	Turkmenistan	213
Turks & Caicos Is	Turks and Caicos Islands	224



<b>LSIB NAME</b>	<b>FAOSTAT NAME</b>	<b>FAOSTAT CODE</b>
Tuvalu	Tuvalu	227
US Virgin Is	United States Virgin Islands	240
Uganda	Uganda	226
Ukraine	Ukraine	230
United Arab Emirates	United Arab Emirates	225
United Kingdom	United Kingdom of Great Britain and Northern Ireland	229
United States	United States of America	231
United States (Alaska)	United States of America	231
United States (Hawaii)	United States of America	231
Uruguay	Uruguay	234
Uzbekistan	Uzbekistan	235
Vanuatu	Vanuatu	155
Vatican City	Holy See	94
Venezuela	Venezuela (Bolivarian Republic of)	236
Vietnam	Viet Nam	237
Wake I	Wake Island	242
Wallis & Futuna	Wallis and Futuna Islands	243
Western Sahara	Western Sahara	205

LSIB NAME	FAOSTAT NAME	FAOSTAT CODE
Yemen	Yemen	249
Zambia	Zambia	251
Zimbabwe	Zimbabwe	181

\*Within the time series covered by this work, there are two instances of changing jurisdictional classifications, namely 'Serbia and Montenegro' splitting to become 'Serbia' and 'Montenegro' in 2006, and 'Sudan (former)' splitting in 2012 to form 'Sudan' and 'South Sudan'. These changes are reflected appropriately in the production and trade data used within the framework, however for some input indicator files this is not the case due to time stamps or classification choices. In these instances, separate entries have had to be aggregated to form entries for the pre-split jurisdictions, or pre-split entries disaggregated/extrapolated to apply to post-split jurisdictions, as appropriate on a case-by-case basis.

**Table S3.** Attributes associated with spatial data (adapted from IUCN (2012, 2018) and BirdLife International (n.d.)). Values indicated in bold and asterisked are those that were included in calculation of species-hectares. For more information on Red List classification criteria, see IUCN (2018).

Attribute	Value	Description
Threat classification	Extinct	No reasonable doubt that the last individual has died. Exhaustive surveys in known and expected habitat, at appropriate times and throughout its historic range have failed to record an individual
	Extinct in the Wild	As above, except that it survives in cultivation, in captivity or as a naturalized population(s) outside its past range.
	<b>Critically Endangered*</b>	<b>Considered to be facing an extremely high risk of extinction in the wild.</b>
	<b>Endangered*</b>	<b>Considered to be facing a very high risk of extinction in the wild.</b>
	<b>Vulnerable*</b>	<b>Considered to be facing a high risk of extinction in the wild.</b>
	<b>Near Threatened*</b>	<b>Close to qualifying for or is likely to qualify for a threatened category in the near future.</b>

Attribute	Value	Description
	<b>Least Concern*</b>	<b>Does not qualify as threatened or Near Threatened. Widespread</b>  <b>and abundant taxa are included in this category.</b>
	<b>Data Deficient*</b>	<b>Inadequate information to make an assessment of extinction risk based on its distribution and/or population status. A taxon in this category may be well studied, and its biology well known, but appropriate data on abundance and/or distribution are lacking. Data Deficient is therefore</b>  <b>not a category of threat.</b>
	<b>Not Evaluated*</b>	<b>Species has not yet been evaluated against the criteria.</b>
Presence	<b>Extant*</b>	<b>Species is known or thought very likely to occur currently in the area, which encompasses localities with current or recent records where suitable habitat at appropriate altitudes remains.</b>
	Probably Extant	Species' presence is considered probable, based on extrapolations of known records, or realistic inferences (e.g. distribution of suitable habitat at appropriate altitudes and proximity to areas where it is known to be extant). IUCN has discontinued use of this value for reasons of ambiguity.
	Possibly Extant	No record of the species in the area, but may occur, based on the  distribution of potentially suitable habitat at appropriate altitudes. The degree of probability of the species occurring is lower (e.g. because the area is beyond a geographic barrier, or because the area represents a considerable extension beyond areas of known or probable occurrence).
	Possibly Extinct	Species was formerly known or very likely to occur (post 1500 AD), but is most likely now extirpated from the area because of habitat loss and/or other threats, No confirmed recent records despite searches.

Attribute	Value	Description
	Extinct (post 1500)	Species was formerly known or very likely to occur (post 1500 AD), but extirpation confirmed through exhaustive searches alongside knowledge of the intensity and timing of threats that could plausibly have extirpated the species.
	Presence Uncertain	Record exists of the species' presence in the area, but it requires verification or is rendered questionable owing to uncertainty over the identity or authenticity of the record, or accuracy of the location.
Origin	<b>Native*</b>	<b>Species is/was native to the area.</b>
	<b>Reintroduced*</b>	<b>Species is/was reintroduced within its known historical range through either direct or indirect human activity.</b>
	Introduced	Species is/was introduced outside of its known historical distribution range through either direct or indirect human activity. Includes species intentionally moved outside of native range to perform a specific ecological function, but does not include species subject to assisted colonisation.
	Vagrant	Species is/was recorded once or sporadically, but it is known not to be native to the area.
	Origin Uncertain	Species' provenance in an area is not known (it may be native, reintroduced or introduced)
	<b>Assisted Colonisation*</b>	<b>Species intentionally moved and released outside its native ranges to reduce extinction risk.</b>
Seasonality	<b>Resident*</b>	<b>Species known or very likely resident throughout the year</b>
	<b>Breeding Season*</b>	<b>Species known or very likely to occur during breeding season and to breed and be capable of breeding.</b>
	<b>Non-breeding Season*</b>	<b>Species known or very likely to occur during non-breeding</b>

Attribute	Value	Description
		<b>season. In the Eurasian and North American contexts, this encompasses 'winter'.</b>
	<b>Passage*</b>	<b>Species known or very likely to occur during relatively short period(s) of the year on migration between breeding and non-breeding ranges.</b>
	<b>Seasonal occurrence uncertain*</b>	<b>Species present, but not known if it is present during part or all of the year.</b>

**Table S4.** Concordance table showing how FAO commodities were concorded to appropriate producing sectors within the MRIO database.

FAO Commodity Code	FAO Commodity	EXIOBASE Sector Code	Allocation Factor
15	Wheat	2	1
27	Rice, paddy	1	1
44	Barley	3	1
56	Maize	3	1
71	Rye	3	1
75	Oats	3	1
79	Millet	3	1
83	Sorghum	3	1
89	Buckwheat	3	1
92	Quinoa	3	1
94	Fonio	3	1
97	Triticale	3	1
101	Canary seed	3	1
103	Grain, mixed	3	1
108	Cereals nes	3	1
116	Potatoes	4	1
122	Sweet potatoes	4	1
125	Cassava	4	1
135	Yautia (cocoyam)	4	1
136	Taro (cocoyam)	4	1
137	Yams	4	1
149	Roots and tubers nes	4	1
156	Sugar cane	6	1
157	Sugar beet	6	1
161	Sugar crops nes	6	1
176	Beans, dry	4	1
181	Broad beans, horse beans, dry	4	1

FAO Commodity Code	FAO Commodity	EXIOBASE Sector Code	Allocation Factor
187	Peas, dry	4	1
191	Chick peas	4	1
195	Cow peas, dry	4	1
197	Pigeon peas	4	1
201	Lentils	4	1
203	Bambara beans	4	1
205	Vetches	4	1
210	Lupins	4	1
211	Pulses nes	4	1
216	Brazil nuts, with shell	4	1
217	Cashew nuts, with shell	4	1
220	Chestnut	4	1
221	Almonds, with shell	4	1
222	Walnuts, with shell	4	1
223	Pistachios	4	1
224	Kola nuts	4	1
225	Hazelnuts, with shell	4	1
226	Areca nuts	4	1
234	Nuts nes	4	1
236	Soybeans	5	1
242	Groundnuts, with shell	5	1
249	Coconuts	5	1
254	Oil palm fruit	5	1
260	Olives	5	1
263	Karite nuts (sheanuts)	5	1
265	Castor oil seed	5	1
267	Sunflower seed	5	1
270	Rapeseed	5	1
275	Tung nuts	5	1
277	Jjoba seed	5	1
280	Safflower seed	5	1
289	Sesame seed	5	1
292	Mustard seed	5	1
296	Poppy seed	5	1
299	Melonseed	5	1
305	Tallowtree seed	5	1
310	Kapok fruit	5;7	0.66;0.34
328	Seed cotton	5;7	0.63;0.37
333	Linseed	5	1
336	Hempseed	5	1
339	Oilseeds nes	5	1

FAO Commodity Code	FAO Commodity	EXIOBASE Sector Code	Allocation Factor
358	Cabbages and other brassicas	4	1
366	Artichokes	4	1
367	Asparagus	4	1
372	Lettuce and chicory	4	1
373	Spinach	4	1
378	Cassava leaves	4	1
388	Tomatoes	4	1
393	Cauliflowers and broccoli	4	1
394	Pumpkins, squash and gourds	4	1
397	Cucumbers and gherkins	4	1
399	Eggplants (aubergines)	4	1
401	Chillies and peppers, green	4	1
402	Onions, shallots, green	4	1
403	Onions, dry	4	1
406	Garlic	4	1
407	Leeks, other alliaceus vegetables	4	1
414	Beans, green	4	1
417	Peas, green	4	1
420	Vegetables, leguminous nes	4	1
423	String beans	4	1
426	Carrots and turnips	4	1
430	Okra	4	1
446	Maize, green	4	1
449	Mushrooms and truffles	4	1
459	Chicory roots	4	1
461	Carobs	4	1
463	Vegetables, fresh nes	4	1
486	Bananas	4	1
489	Plantains and others	4	1
490	Oranges	4	1
495	Tangerines, mandarins, clementines, satsumas	4	1
497	Lemons and limes	4	1
507	Grapefruit (inc. pomelos)	4	1

FAO Commodity Code	FAO Commodity	EXIOBASE Sector Code	Allocation Factor
512	Fruit, citrus nes	4	1
515	Apples	4	1
521	Pears	4	1
523	Quinces	4	1
526	Apricots	4	1
530	Cherries, sour	4	1
531	Cherries	4	1
534	Peaches and nectarines	4	1
536	Plums and sloes	4	1
541	Fruit, stone nes	4	1
542	Fruit, pome nes	4	1
544	Strawberries	4	1
547	Raspberries	4	1
549	Gooseberries	4	1
550	Currants	4	1
552	Blueberries	4	1
554	Cranberries	4	1
558	Berries nes	4	1
560	Grapes	4	1
567	Watermelons	4	1
568	Melons, other (inc.cantaloupes)	4	1
569	Figs	4	1
571	Mangoes, mangosteens, guavas	4	1
572	Avocados	4	1
574	Pineapples	4	1
577	Dates	4	1
587	Persimmons	4	1
591	Cashewapple	4	1
592	Kiwi fruit	4	1
600	Papayas	4	1
603	Fruit, tropical fresh nes	4	1
619	Fruit, fresh nes	4	1
656	Coffee, green	8	1
661	Cocoa, beans	8	1
667	Tea	8	1
671	Mate	8	1
677	Hops	8	1
687	Pepper (piper spp.)	8	1
689	Chillies and peppers, dry	8	1



FAO Commodity Code	FAO Commodity	EXIOBASE Sector Code	Allocation Factor
692	Vanilla	8	1
693	Cinnamon (cannella)	8	1
698	Cloves	8	1
702	Nutmeg, mace and cardamoms	8	1
711	Anise, badian, fennel, coriander	8	1
720	Ginger	8	1
723	Spices nes	8	1
748	Peppermint	8	1
754	Pyrethrum, dried	8	1
773	Flax, processed but not spun	7	1
777	Hemp tow waste	7	1
780	Jute	7	1
782	Bastfibres, other	7	1
788	Ramie	7	1
789	Sisal	7	1
800	Agave fibres nes	7	1
809	Manila fibre (abaca)	7	1
821	Fibre crops nes	7	1
826	Tobacco, unmanufactured	8	1
836	Rubber, natural	8	1
867	Meat, cattle	35	1
868	Offals, edible, cattle	35	1
869	Fat, cattle	35	1
919	Hides, cattle, fresh	49	1
947	Meat, buffalo	35	1
948	Offals, edible, buffaloes	35	1
949	Fat, buffaloes	35	1
957	Hides, buffalo, fresh	49	1
YYYY	Timber	18	1