Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Killian Davin

The limits of scale for biodiversity characterisation factors

Investigating the impacts of aggregation methods on biodiversity characterisation factors and biodiversity footprints

Master's thesis in Industrial Ecology
Supervisor: Edgar Hertwich
Co-supervisor: Maximilian Koslowski
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Master`s Agreement / Main Thesis Agreement

Faculty	**Faculty of Engineering**
Institute	**Department of Energy and Process Engineering**
Programme Code	**TEP4930**
Course Code	**TEP4930**

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The Master`s thesis

Starting Date	**15.01.2022**
Submission Deadline	**11.06.2022**
Thesis Working Title	**Detailed analysis of the biodiversity impacts embodied in agricultural and food products imported into the European Union, identifying the causal links between impacts, trade, and consumption.**
Problem Description	**Background and objective Following on from the fall semester project, where the results of the study on biodiversity losses driven by household consumption showed that products of agriculture and food were the dominant causes of biodiversity impacts embodied in trade. Several barriers prevent the completed analyses on supply chain biodiversity hotspots from being used in a substantial manner by stakeholders, looking to prevent future biodiversity impacts and advancing the cause of biodiversity conservation. Firstly, the analysis was cross-sectional in nature and failed to examine the evolution of trade impacts and supply chain trends over time. Secondly, the analysis suffered from the consequences of spatial aggregation both in the aggregation of ROW regions at the continental level, and of the LCIA characterisation factors at a national level. This gap, failed to consider the heterogeneity of biodiversity impacts**

	across regions at the subnational, national, and continental level, where aggregated regions and characterization factors masked internal divergences in biodiversity impacts. The analysis was incapable of taking advantage of the spatially explicit characterisation factors of the LC-IMPACT LCIA methodology due to the divergence in spatial detail between that of the MRIO database EXIOBASE and LC-IMPACT. The limitations of the spatial resolution in MRIO models for analysing environmental impacts that are heterogeneous in nature are well documented. Finally, the sector resolution in the food and agriculture sectors in EXIOBASE and the opaque nature of the product/commodity pertained in an aggregated agricultural sector driving impacts in the countries of origin was another prohibitive aspect limiting the application of the results in trade policy formation. Therefore, the master's thesis will look to improve aspects of these limitations experienced in the fall project by analysing the predominant biodiversity impact area identified in the results, agricultural and food products, in greater detail. The objective of the thesis will be to perform a spatial consumption-based biodiversity footprint assessment of imported agricultural and food products to the EU bloc for a timeframe of which the data will allow. The analysis will seek to assess the drivers of on the ground biodiversity impacts occurring outside the EU territory in a manner that is useful to policy makers and that could potentially contribute to the EU's Biodiversity strategy for 2030. The following tasks and methods will be performed but are not exhaustive: 1. Prepare the necessary data for demand side modelling of imported agricultural and food products to the desired spatial detail (national level at a minimum) using biophysical or monetary MRIO models. 2. Quantify biodiversity impacts for supply chain hotspots using life cycle impact methodology and spatially explicit characterisation factors where possible. 3. Apply new datasets coming on stream on the EXIOBASE platform to garner fresh perspectives on land management practices and the resulting impacts on biodiversity and supply chains. 4. Analyse the impacts of imported agricultural products into the EU for intermediate and endpoint consumption, assessing trends and discussing what it means for future EU strategies surrounding consumption and biodiversity.

This Master`s agreement must be signed when the guidelines have been reviewed.

Signatures

Killian Davin
Student

14.01.2022
Digitally approved

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14.01.2022
Digitally approved

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25.01.2022
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Disclaimer

The final thesis research topic deviated from the initial project description scope after much deliberation over previously published research articles and figuring out what was possible within the realms of a master thesis. Rather than focusing on demand side modelling of imported agriculture and food products to the EU, the paper focused on biodiversity characterisation factors (CFs) for Agriculture within LC-Impact. The paper instead looked at the reliability of current aggregated national CFs for land occupation and water consumption and investigated if a different aggregation approach of native scale CFs resulted in significantly different CFs. Finally it investigated whether diverging biodiversity CFs lead to changes in biodiversity impacts at a global level due to agricultural production. The direction of this work is explicitly defined in both the introduction and methodology sections that follow.

Preface

This master thesis was completed during the spring semester of 2022, within the Department of Industrial Ecology and under the Department of Energy and Process Engineering (EPT) umbrella at NTNU. The thesis is written in a research article format with the hope of eventual publishing in an academic journal. Hence, the thesis is written in a compact, concise manner with all superfluous information and data incorporated in the supplementary information instead.

The thesis was supervised by Professor Edgar Hertwich and Max Koslowski (PhD candidate), both from the Industrial Ecology department at NTNU. Edgar Hertwich acted as the main supervisor, providing guidance on the overall direction of the thesis work, the methodological scope and general progress on the project. Max Koslowski provided more hands on supervision and supervised the construction of the MRIO calculations and inspected the results form the characterisation factor (CF) disaggregation and resulting biodiversity impact results. Additionally, Martin Dorber provided feedback and advice on the construction of the LCIA characterisation factors, supplying relevant research papers to help with methodological choices which have been cited and referenced in the main body of the master thesis. He also helped focus the research question on a discussion of the limitations of national LCIA characterisation factors rather than constructing CFs as a replacement for the set of national CFs available in LC-Impact today due to the ecological limitations of merging two distinctly different spatial models in LC-Impact and the mapSPAM model. Konstantin Stadler gave his time to help with the execution of project code in python on the NTNU server when the MRIO tables were too large for execution on a local hardrive. MRIO tables from the Cabernard and Pfister (2020) resolved EXIOBASE-Eora database required such execution.

All persons listed above are affiliated with the Industrial Ecology department at NTNU, Trondheim at the time of writing. The thesis was written for readers with prior knowledge and competence on biodiversity footprinting with LCIA characterisation factors and MRIO methodology. However, the thesis is written in a clear and concise manner and is accessible to all when accompanied with a small level of background reading on the topic of MRIO and biodiversity endpoints. The following work is the independent work of the main author but as input and advice was received for sections in the project, the paper is written in the 'we' narrative when a passive form could not be preserved.

Acknowledgements

I would like to extend my sincerest gratitude to my supervisors Professor Edgar Hertwich and PhD candidate Max Koslowski. Edgar as my main supervisor provided valuable insights on the practicalities of my research topic, helping to focus the direction of my research and navigate any broad methodological challenges faced throughout the year. A special mention goes to Max for the overly charitable donation of his valuable time and guiding me through the troughs and crests of writing a master thesis. His encouragement and enthusiasm for the research topic was a constant source of inspiration. I enjoyed our weekly discussions that often deviated to discussions on life itself.

To Martin Dorber who ignored my coarse knowledge on LCIA endpoints and was always happy to help with my methodological misunderstandings and conceptual questions on biodiversity impact measurements. His insights were crucial for the realizing of this master thesis and for that I am very grateful.

To my parents who have guided me through 20 years of education and have been the constant backbone in my life. Without you none of this would be possible. To my friends and family who bring joy to life. And finally to my classmates in Industrial Ecology and Circular Economy both in NTNU and Chalmers. What a two years we had! A life time of inspiration and proof that we can solve the many environmental challenges facing us in the near future.

Abstract

The Anthropocene is increasingly affecting all aspects of the world today and it has had and continuous to have catastrophic impacts on biodiversity. Natural ecosystems have suffered a decline of 47% relative to their earliest predicted baseline (IPBES, 2019). Agriculture is the largest contributor to ecosystem impacts with agricultural land use, land transformations and blue water consumption for irrigation the primary drivers of global extinctions today (IPBES, 2019; IUCN, 2021b). Biodiversity impact studies where environmentally-extended multi-regional input-output (MRIO) modelling is merged with life cycle impact assessment (LCIA) methodology have continually pointed to the limitations of the regional scale of input-output tables for capturing the heterogeneous and inherently localised impacts of biodiversity (Moran et al., 2016; Verones et al., 2017). The availability of spatially explicit LCIA databases for application in life cycle analysis are hampered by the need for aggregating native scale characterisation factors (CFs) to the national/continental scale which introduces aggregation errors.

In the absence of spatial datasets for elementary stressor flows, CFs are aggregated to the national level via proxy of ecoregion land shares for land use and total blue water consumption at the watershed level for water stress. Koslowski et al. (2020) suggested that the largest source of uncertainty in biodiversity footprint results at the national level likely originate from the aggregated CFs and not the MRIO models themselves despite recent focus on improving the national resolution of MRIO tables (Bjelle et al., 2021; Cabernard & Pfister, 2020).

Here, we apply a global agricultural production model, mapSPAM (Yu et al., 2020), with the LCIA database, LC-Impact (Verones, Hellweg et al., 2020), to create crop-specific national CFs for agriculture and for the impact pathways of land use and blue water consumption. Our approach uses elementary stressor data available from MapSPAM for weighting of the native scale CFs to the national level, diverging from the approach used in LC-Impact for national aggregation. We investigated if the differing aggregation approaches and the increased spatial explicitness of the constructed CFs deviate substantially from those in LC-Impact and what the resulting consequences for national production and consumption-based biodiversity footprints are.

The results revealed an increase in global production based biodiversity impacts of 38% and 17.5% for land use and blue water consumption respectively. Large variations in CFs between crops and within countries demonstrate the pressing need for regionalization of MRIO models if the heterogeneity of biodiversity impacts are to be fully realized. The results clarified that broad cropland categories of land use, the absence of category distinctions for wetland multipliers and current upward aggregation techniques for native scale CFs are a poor proxy for describing country level ecosystem damage from agricultural production. The disparity in resulting national CF factors depending on the aggregation methodology used is evidence that modelling of national level CFs in LCIA databases must be reassessed if biodiversity footprint analysis with MRIO tables are to be improved at the national level.

Contents

List of Figures

List of Tables

List of Acronyms

CF Characterization Factor

CFs Characterisation factors

EE-MRIO Environmentally Extended Multi-Regional Input Output

FAO Food and Agriculture Organisation

GTAP Global Trade Analysis Project

IO Input-Output

IUCN International Union for Conservation of Nature

LCA Life Cycle Analysis

LCIA Life Cycle Impact Assessment

MapSPAM Spatial Production Allocation Model

MRIO Multi-Regional Input Output

PDF Potentially disappeared fraction of species

ROW Rest Of The World

SUT Supply and use tables

1 Introduction

Land systems are the critical underpinning of modern human civilisations. Amongst other ecosystem services, land systems service human needs via the provisioning of food, energy, and material resources. In 2019, global agricultural land area accounted for 37% of the available land surface of planet earth or approximately five billion hectares (FAO, 2021). Today's agricultural system is characterised by an integrated global system of production, with industrial inputs and feed from remote markets servicing local land systems to supply domestic demand and increasingly, demand in markets far removed from the locations of production (Kastner et al., 2021). If land systems service human needs, biodiversity can be defined as the infrastructure which underpins the ecological processes that provide such food security (Grooten & Almond, 2018). Agricultural production is responsible for significant biodiversity impacts globally, with agricultural land use, land transformations and blue water consumption for irrigation primary drivers of global species extinction today (IPBES, 2019; IUCN, 2021b). In parallel, the emerging impacts from climate change, of which agricultural emissions share a responsibility, is expected to become a major driver of change in the local richness of ecological communities in the coming decades (Newbold, 2018). While land impacts dominate and drive ecosystem deterioration, impacts on wetland habitats are of growing concern. Blue water consumption demand, defined as water from surface or groundwater resources which is either evaporated or incorporated into a product, has increased six fold since 1900, with 70% of all water withdrawals effectuated by agriculture (IPBES, 2019).

To stem the irrevocable slide towards ecosystem tipping points, several global political agreements for safeguarding biodiversity have been brokered (Krug et al., 2014; UN DESA, 2021). Agreements have failed to arrest the decline thus far and there is a need for a clear, effective, and comparable biodiversity indicator(s) that describes the state of nature and around which political will and public support can galvanize (Rounsevell et al., 2020). Despite recent studies incorporating several biodiversity indicators (BDIs) (Leclère et al., 2020), Life Cycle Assessment (LCA) practitioners today predominantly use 'species richness' as a measure for ecosystem health with assessment of overall system structure and function largely absent (Marques et al., 2017). Species-area relationships proposed by Chaudhary et al. (2015), measuring species loss to an area in terms of a potentially disappeared fraction (PDF) is the most popular measure of species richness. Inclusion of vulnerability scores for species endemism and geographical range, translates local PDF scores to globally comparable biodiversity indices (Verones, Hellweg et al., 2020)

LCA and environmental footprint studies are prominent tools for the assessment of biodiversity impacts of resource use. LCA is grounded at the product level, quantifying the environmental impacts of an individual product or service. For global studies, Environmentally-Extended Multi-Regional Input-Output analysis (EE-MRIO) is the preferred approach, reducing inventory requirements and avoiding supply chain truncation (Majeau-Bettez et al., 2011; Wiedmann et al., 2011).

Lenzen et al. (2012) was the first to model global biodiversity loss with EE-MRIO models, merging the MRIO database, Eora (Lenzen et al., 2013), with IUCN red list species to assess the impacts of global trade. Biodiversity impacts are heterogeneous and inherently local in scale and effect. Moran and Kanemoto (2016) built on Lenzen's study by improving the connection between global supply chains and spatially explicit biodiversity hotspots. In LCA, environmental burdens are characterised to biodiversity endpoint indices through the life cycle impact assessment (LCIA) method. To tackle the issue of variability and scale of ecosystem impacts, regionalized LCIA databases, like LC-Impact (Verones, Hellweg et al., 2020), were constructed with spatially explicit characterisation factors (CFs) for several impact pathways at the relevant scales of consequence. Verones et al. (2017) and Koslowski et al. (2020) merged LC-Impact with the MRIO database, EXIOBASE (Stadler et al., 2018), to analyse the ecosystem consequences of resource footprints and the connection between urbanity and affluence for interpreting levels of consumption-based biodiversity impacts.

EE-MRIO databases today are not of the required spatial detail to capture the variable nature of biodiversity impacts (Crenna et al., 2020; Winter et al., 2017). Economic data in Input-Output (IO) tables are constructed at the national level while ecosystem consequences occur at the regional level (ecoregion scale for land use impacts and watershed level for wetland impacts). Incomplete IO tables for countries with inadequate economic bookkeeping, requires the aggregation of nations into proxy continental regions further exacerbating the issue of scale. Previous biodiversity footprint studies have pointed to the need for sub-national MRIO accounts so that environmental variation of consequence can be captured (Moran & Kanemoto, 2016; Moran et al., 2016; Verones et al., 2017).

Recent work has focused on improving the national level detail of MRIO tables by disaggregating continental regions in EXIOBASE to improve the geographical explicitness of the footprint results (Bjelle et al., 2021; Cabernard & Pfister, 2020). However, the largest source of uncertainty in biodiversity footprint results at the national level likely originate from the aggregated CFs and not the MRIO models themselves (Koslowski et al., 2020). With the lack of sub-national production data, current footprinting work requires the aggregation of the native scale CFs to be normalized and weighted to the national level for analysis. The absence of global, spatially resolved agriculture data means that aggregation of land impact CFs are not completed by weighted averages of elementary flows as recommended (Mutel et al., 2019) but by proxy of ecoregion land shares (Verones, Hellweg et al., 2020). For wetland CFs, aggregation is completed using elementary flows of blue water, weighted by total blue water consumption per watershed but ignoring the spatial variation of crop locations and activity driving the demand.

Our aim is to contribute towards a more complete representation of the global consequences of consumption and production on biodiversity. We examine the reliability of current national and continental CFs for agricultural land use and water consumption in LC-Impact and whether differing aggregation approaches affect the results. The recent availability of a global agriculture production model, the Spatial Production Allocation Model (MapSPAM) from Yu et al. (2020), with spatially resolved production statistics for 42 crops, allows for the creation of crop specific CFs when combined with LC-Impact. Currently, two cropland CFs exist for land use and a single CF for blue water consumption. With the geospatial production data from MapSPAM, 8 individual crop CFs per impact pathway can be created. Aggregation from the native to the national scale can thus be completed based on explicit crop locations and elementary flows as recommended (Mutel et al., 2019). We combine the newly disaggregated CFs with the MRIO database, EXIOBASE, to calculate production-based accounts and consumption-based biodiversity footprints driven by the final demand for food and agriculture products for the year 2010. We compare results with previous accounts to analyse the effect of the regionalization method for national CF formation. The new CFs are not intended to replace the current set of national CFs in LC-Impact due to their amalgamation of differing spatial models in the construction process but are intended to act as a heuristic and a discussion on the current reliability of national CFs, interpreting whether further model development is required.

2 Methods

2.1 Overview

The procedure for calculating the biodiversity footprints of land use and water consumption for global agriculture and food production in the year 2010 is disclosed below. The database EXIOBASE 3 (Stadler et al., 2018) was used for the MRIO analysis, providing economic trade data and stressor detail for the two environmental pressures. The MRIO footprint results are then integrated with the LCIA method LC-Impact (Verones, Huijbregts et al., 2020) and the resulting environmental pressures are characterized to final endpoint biodiversity impacts. Prior to charactersation, we outline the steps for the formation of spatially explicit, crop specific, national and continental CFs in LC-Impact. The method details how the application of the MapSPAM model by Yu et al. (2020) allows for the harnessing of the fine sub-national spatial resolution of the LC-Impact database.

2.2 Multi-regional input-output analysis

IO models are constructed 'from observed data for a particular economic area' like a nation or state (Miller & Blair, 2009). IO addresses the economic transactions occurring within an economy, while multi-regional IO extrapolates the methodology to the global level, mapping the bilateral trade linkages between different economies. MRIO addresses the limitations of bottom-up life cycle approaches for global analysis, capturing the impacts of full supply chains while reducing the data intensity requirements and avoiding truncation errors (Majeau-Bettez et al., 2011; Wiedmann et al., 2011). MRIO models are constructed upon the economic data of national IO tables, themselves a derivative of national supply use tables (SUT) (Eurostat, 2008). IO tables capture the monetary flows of products and services between sectors in order to satisfy the final demand of a country's consumption (Miller & Blair, 2009). Environmentally-extended MRIO (EE-MRIO) models integrate environmental factors, tracking environmental burdens associated with the trade of goods and services. The approach has been widely disseminated in environmental research today and is one of the primary methods for linking consequences of consumption to environmental pressures and ecosystem deterioration (Ivanova et al., 2017; Lenzen et al., 2012; Peters & Hertwich, 2004; Verones et al., 2017).

2.3 MRIO database - EXIOBASE

The EE-MRIO database, EXIOBASE (Stadler et al., 2018), was selected based on its high suitability for environmental analysis. The database was constructed with the specific aim of providing a high level of detail for environmental stressors and a consistent level of sector detail across industries, particularly those that have significant environmental burdens such as agriculture and mining (Stadler et al., 2018). It has a superior level of product detail and superior number of environmental extensions when compared to competing MRIO databases like Eora (Lenzen et al., 2013) and the Global Trade Analysis Project (GTAP) (Corong et al., 2017). EXIOBASE lacks the level of spatial detail that Eora provides with only 49 regions accommodated to Eora's 189. However, a more comprehensive environmental systems of accounts is a worthwhile trade-off for the granular country level detail.

The developers of EXIOBASE combined the detailed production and trade data from FAO (Wood et al., 2014) with the detailed SUT coefficients of the AgroSAM model (Müller et al., 2012) to compile its high-resolution agriculture and food data. In this paper, we apply version 3.8.1 of EXIOBASE and the monetary 200 x 200 (product x product) monetary tables for the year 2010 (Stadler et al., 2021). Of the more than 1000 environmental stressors in EXIOBASE, eight cropland land use stressors and thirteen blue water consumption stressors are included in our analysis. All final demand categories are included but impacts of land use and blue water consumption due to global final consumption of primary agriculture and food products are considered only. EXIOBASE compromises of eight primary crop products, six animal products and twelve processed food products, including beverages. A list of the product categories and environmental stressors can be retrieved in the supplementary information (SI). EXIOBASE provides IO data for 44 countries, with a particular eurocentric focus, including the EU-27 member states plus the United Kingdom, Norway, Croatia and Switzerland. The 44 countries combine to account for 90% of the worlds GDP for the year 2014 (Stadler et al., 2018). The remaining 10% of the global economy is aggregated into 5 rest of the word (ROW) regions of Africa, the Americas, Middle east, Asia and Europe.

2.4 Leontief analytical calculus

The standardised methodology for IO analysis is that of the Leontief inverse calculus (Leontief, 1936, 1970) also known as the demand-pull quantity model. Letting upper case letters represent matrices and lower case letters represent vectors, IO tables are composed of a transaction matrix $\mathbf{Z}$, a final demand matrix $\mathbf{Y}$, and the satellite matrices of the economy, $\mathbf{F}$. The total industrial output requirements for a country/region, where n is the number of regions, and m the number of product sectors in the economy is given by

$$\mathbf{x} = \mathbf{Z}i + \mathbf{Y}i \tag{1}$$

For MRIO analysis, the transaction matrix **Z**, is a square $nm \times nm$ matrix describing the inter-industry trade of products and services across the global economy. The 200 × 200 product sector detail coupled with the 49 regions in EXIOBASE 3 (Stadler et al., 2021) creates a 9800 × 9800 square transaction matrix. The final demand matrix, **Y**, has a size $nm \times nk$, where k is the number of final demand categories considered (Miller & Blair, 2009). All non agriculture and food related product demand is set to zero in **Y**. All seven EXIOBASE final demand categories are included and therefore k = 7. The technology coefficient matrix, **A**, is derived from $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$, maintaining the square matrix shape $nm \times nm$. This leads to the formation of the defining IO equation, the Leontief inverse:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{2}$$

I is an identity matrix of shape $nm \times nm$ and $(\mathbf{I} - \mathbf{A})^{-1}$ is known as the Leontief inverse, **L**. Equation (2) dictates the total industrial output of the economy for an arbitrary vector of final demand, **y**, using the constant linear economy assumption (Leontief, 1936, 1970; Miller & Blair, 2009). **y** is the total aggregated final demand vector resulting from the matrix multiplication of the **Y** matrix with column vector i. The EE-MRIO database includes satellite accounts for emission flows. The satellite matrix, **F**, is of shape $s \times nm$, where s is the number of environmental stressors considered. 21 stressors from EXIOBASE are incorporated forming a matrix of size 21 × 9800. Given the total environmental pressure footprint, **F**, the stressor coefficient matrix, **S**, is the normalized environmental satellite showing the environmental inputs per unit of monetary output of a sector ($\mathbf{F}\hat{\mathbf{x}}^{-1}$). The diagonal blocks of **S**, **L** and **Y** represent the domestic economy while the off-diagonal blocks represent the traded parts of the economy in an MRIO system (the off-diagonal parts of the **S** matrix are zero as there are no traded impact multipliers of production). The consumption-based environmental footprint is calculated as:

$$\mathbf{E} = \mathbf{SLy} \tag{3}$$

Production-based environmental accounts are simply equal to the factors of production matrix **F**. To segregate the portion of imported and exported environmental pressure footprints, the domestically satisfied final demand is set to zero in the diagonalized square matrix **Y**. The traded portion of final demand is given by $\mathbf{Y}_t = \mathbf{Y} - \mathbf{Y}_{i,j}|(i = j)$ (Miller & Blair, 2009). The imported and exported environmental footprints are:

$$\mathbf{E}_{imp} = \mathbf{SLY}_t \tag{4}$$

$$\mathbf{E}_{exp} = \mathbf{F} - (\mathbf{E} - \mathbf{E}_{imp}) \tag{5}$$

2.5 Life cycle impact assessment database: LC-Impact

LCIA translates emission and resource inventories to impact endpoints based on the study objectives or their relative importance (ISO, 2006). Biodiversity multipliers are sourced from an LCIA database and there are several LCIA methods available with differing impact categories and value choices (Curran et al., 2011; Mutel et al., 2019). Databases covering ecosystem health include ReCiPe (Huijbregts et al., 2017) and IMPACT World+ (Bulle et al., 2019). LC-Impact version 1.3 (Verones, 2021; Verones, Hellweg et al., 2020) is selected here for its superior spatial explicitness of ecosystem impacts (Verones et al., 2017). LC-Impact measures biodiversity impacts in ”Potentially Disappeared Fraction of species” (PDF) units per m2 of land use or m3 of blue water consumption for the taxa considered. It is a measure of species richness and a proxy for ecosystem health/quality. The method includes weighted species vulnerability scores used to translate local species loss to global endpoint scores. Vulnerability scores point to endemic nature of a species via geographical ranges and IUCN threat levels (IUCN, 2021b). Land occupation impacts are only considered here with the impacts from land transformations negated. Land CFs are constructed at the ecoregion level using the countryside species area (c-SAR) model (Chaudhary et al., 2015). LC-Impact provides stressor characterisation for three agricultural land use types: ‘Annual’, ‘Permanent’ and

‘Pasture’ cropland. For water stress, CFs are constructed at the watershed ‘catchment’ level and impacts are modelled based on the change in wetland area due to water consumption (Verones, Hellweg et al., 2020).

2.6 Spatial Production Allocation Model - MapSPAM

In the absence of spatial detail on crop production, LC-Impact calculates aggregated regional multipliers for land occupation from weighted averages based on ecoregion land shares within a region’s boundaries. Native CFs for blue water consumption are aggregated by weighting total blue water consumption occurring per watershed independent of crop or activity. Regionalization and crop distinction was pursued by integrating geospatial crop production data from the MapSPAM model. MapSPAM provides georeferenced crop statistics (e.g harvested area, production quantity, and yield) for 42 agricultural crops globally, disaggregated by different farming systems and allocated into spatially gridded units at the 5 arc min resolution (Yu et al., 2020). To date, the model has been published for the year 2010. The rationalised spatial scale for LC-Impact’s land use CFs (the ecoregion) and water stress CFs (the watershed) allows for the tailoring of CFs when the similarly scaled elementary flow data from the MapSPAM model is applied for upward aggregation. The model is applied directly with LC-Impact for constructing land use CFs based on specific crop location and physical land areas while water CF construction requires the addition of a spatially explicit water dataset to translate crop production volumes in tonnes to blue water irrigation demands in m3 for the year 2010.

2.7 Disaggregation of LC-Impact characterisation factors

Discussions from LCA experts on regionalization of life cycle impact assessments concluded that regionalized LCAs should be comparable, reproducible, and transparent (Frischknecht et al., 2019). For the regionalization and subsequent aggregation of CFs, the standardised methodology proposed by Pfister et al. (2020) for overlaying country, watershed, and ecoregion data for LCIA was followed for comparability. In our case, 3 spatial layers, rather than the recommended 6 spatial layers were used due to the nature and scope of this study. The spatial layers are: (1) the political layer (Natural Earth, 2019), desired for the application of the global MRIO study; (2) terrestrial ecoregion layer, required for the analysis of biodiversity related land impacts (Jolliet et al., 2018; Olson et al., 2001) ; (3) global watersheds layer, the recommend spatial scale for analysing regional water stress impacts (Boulay et al., 2015; Müller Schmied et al., 2014; Pfister & Bayer, 2014, 2018).

The resulting shapefile was used to map the global crop production statistics for the year 2010 from MapSPAM on a 5 arcmin spatial resolution (International Food Policy Research Institute [IFPRI], 2019; Yu et al., 2020). Mapping of water consumption statistics for agricultural crops from Pfister and Bayer (2018) was carried out at the watershed level. CFs from LC-Impact (Verones, 2021) were overlayed at their respective native scales. The resulting polygons matched the area extents of the native scale boundaries but with internal crop statistics and native CFs included.

Missing CFs at the ecoregion level arising from the lack of data for isolated areas or for areas where it is reasonable not to have a CF like Antarctica are treated via differing techniques depending on the circumstance of the no data instance. If, according to MapSPAM, crop data was present in ecoregions with no data values, neighbouring ecoregion interpolation was used. For islands without neighbouring (touching) ecoregions, an averaged CF proxy of nearby islands of the same ecoregion biome and class was applied. An absence of crop data in ecoregions with missing CFs prompts regions to be treated as zeros and excluded from the weighted average analysis. Where EXIOBASE regions are not covered in LC-Impact, missing national CFs are replaced with a continental CF (e.g European continent water stress CF as a proxy for Malta) or with approximates from similar countries (Chinese CFs for Taiwan). The harmonizing steps follow the recommendations of Mutel et al. (2019) for the handling of no data values.

The water data provided by Pfister and Bayer (2018) has global coverage for 160 crops, with blue water consumption per tonne of crop produced and total blue water consumption datasets available for each crop in over 12'000 watershed units for the year 2000. The 42 aggregated crops of MapSPAM and 160 crops of Pfister and Bayer (2018) were merged into the following nine distinct agricultural categories according to the FAO and EXIOBASE categorization methodology: 'Paddy Rice', 'Wheat', 'Cereal grains Nec', 'Sugar', 'Oil seeds', 'Plant based fibers', 'Vegetables,fruit and nuts','Crops Nec.' and an extra 'Fodder crop' category for the water consumption data (MapSPAM does not contain production statistics for fodder crops but the water dataset has total blue water consumption data for the crop in the year 2000). Nec stands for 'Not elsewhere classified', and it represents cereal crops or other agriculture crops not already represented in individual categories.

We construct an individual CF for each EXIOBASE crop stressor category by resolving the two land use CFs for cropland and the single CF for water stress in LC-Impact currently (Verones, 2021; Verones, Huijbregts et al., 2020). Pastureland is excluded from the analysis due to the absence of production data in MapSPAM. Traditionally, applying the current LC-Impact CFs with EXIOBASE meant losing the stressor resolution afforded in EXIOBASE. An aggregation step was required prior to biodiversity footprint quantification to match the more detailed EXIOBASE stressor categories with those of the aggregated LC-Impact CFs. This negated and dampened the effects of spatial variation in environmental consequences which is so important for reducing uncertainty in biodiversity impact appraisals (Moran & Kanemoto, 2016; Verones et al., 2017)

The individual crop CFs are constructed by aggregating the native regional CFs to the national and continental scales using weighted averages based on annual elementary flow quantities in each native scale region as recommended by Mutel et al. (2019). The elementary flows are the resulting spatial footprints from MapSPAM and Pfister and Bayer (2018) after normalising to the required EXIOBASE crop categories. It forms the hypothesis that environmental impacts are more likely to materialize in areas where elementary stressors are already occurring. Aggregated land CF calculation for the eight disaggregated annual crop and permanent crop land use types were as follows.

$$LC_{jx} = \sum_{i=1}^{n} \frac{P_{ijx}}{\sum_{i=1}^{n} P_{ijx}} \times C_{ix} \tag{6}$$

Variable name	Description	Unit
C_{ix}	LC-Impact land use CF for polygon i	PDF/km^2
LC_{jx}	Land use CF for crop j in country/ROW region x	PDF/km^2
P_{ijx}	Physical production area of crop category j in polygon i	km^2
n	Number of polygons in country/ROW region x	

Table 1. Variables required in Equation (6) for the aggregation of native scale land use characterisation factors to the national level

The blue water consumption elementary flows were calculated by combining the blue water consumption per tonne of produced crop data for the year 2000 of Pfister and Bayer (2018) with the irrigated crop production quantities of MapSPAM for the year 2010 (IFPRI, 2019). The resulting data is to act as a proxy for elementary blue water crop consumption in the year 2010 in the absence of primary data sets for the elementary flow. For data gaps in polygons where MapSPAM assesses irrigated crop production to take place but no water consumption data exists, national average blue water consumption per tonne of crop produced data for the crop in question was applied. In contrast, if blue water data exists for a polygon but crop data in MapSPAM suggests no crop production to exist, it is concluded that no consumption occurs in the polygon for this crop. The calculation of national water CFs for the nine disaggregated annual and permanent crop types are presented in equation (7). For watersheds not covered in LC-Impact but present in the Pfister and Bayer (2018) dataset, existing national CFs were applied for missing watersheds within a country's boundaries. For the native scale CFs, only surface water consumption effects were considered due to the low level of robustness for groundwater-fed wetlands data in LC-Impact (Verones, Huijbregts et al., 2020).

$$WC_{jx} = \sum_{h=1}^{n} \frac{Q_{hjx} \times K_{hjx}}{\sum_{h=1}^{n} Q_{hjx} \times K_{hjx}} \times C_{hx} \tag{7}$$

Variable name	Description	Unit
C_{hx}	LC-Impact blue water consumption CF for polygon h	PDF/m^3
WC_{jx}	Blue water consumption CF for crop j in country/ROW region x	PDF/m^3
Q_{hjx}	Irrigated production volume of crop category j in polygon h	MT
K_{hjx}	Blue water consumption per tonne of crop j in polygon h	m^3/MT
n	Number of polygons in country/ROW region x	

Table 2. Variables required in equation (7) for the aggregation of native scale water stress characterisation factors to the national level

2.8 Biodiversity impact accounts

Transformation of the environmental pressures quantified via the Leontief calculus in section 2.4 is performed from both a consumption and a production-based perspective. However, we only detail the production-based accounts in the results section to emphasize country level CF divergence. Consumption-based results are included in the SI (SI.6). Consumption-based accounts allocate the impacts linked to final consumer demand to the country or region where the consumption takes place, whereas production-based accounts apportion impacts directly to the country or region where the impacts occur.

$$\mathbf{D}_{cba} = \mathbf{C} \odot \mathbf{SLy} \tag{8}$$

$$\mathbf{D}_{pba} = \mathbf{C} \odot \mathbf{F} \tag{9}$$

$\mathbf{D}_{cba}$ is the consumption-based biodiversity footprint resulting from the Hadamard product of the LCIA CF matrix, $\mathbf{C}$, and the environmental pressure matrix from equation (3), $\mathbf{SLy}$, generating a matrix of shape 21×9800. $\mathbf{C}$ is the subsequent matrix of the disaggregated CFs formed in equations (6) and (7). $\mathbf{D}_{pba}$, the production-based biodiversity impact matrix, is formed from the Hadamard product of the LCIA CF matrix and total environmental stressor flow matrix $\mathbf{F}$. Direct household impacts of consumption are not considered here.

2.9 Methodological limitations

The temporal mismatch between the primary water consumption data from Pfister and Bayer (2018) and the production year modelled in the study is acknowledged. Consequentially, the estimation of proxy blue water consumption values introduces a level of uncertainty to the constructed blue water CFs. The non-inclusion of groundwater effects due to large uncertainties in the modelled data points to an under representation of the wetland impacts. Land impacts from transformations are negated ignoring a primary ecosystem consequence of agricultural production which is farmland expansions into virgin ecosystem frontiers (Zabel et al., 2019). Fragmentation and land use intensities are not considered in the current LC-Impact database, potentially missing impacts due to increasing land use intensities or fragmenting habitat areas. A model proposing the inclusion of fragmentation in land use CF formation generally predicts higher per-area impacts of land use than the impacts estimated by the c-SAR (a median relative difference of +9%) (Kuipers et al., 2021).

In general, species richness as a biodiversity indicator fails to incorporate all elements of ecosystem health. It ignores the structural and functional aspects of biodiversity, and its incomplete assessment of nature must be recognized here (Curran et al., 2011). The absence of spatial detail on production is another limitation that has not been bridged. It is assumed that each product sector of a country has universal biodiversity impact intensities independent of the spatial distribution of the production systems. Oftentimes it leads to sectors being a poor approximation of its constituent flows. The lack of subnational trade data in the MRIO databases leads to a disregard for the spatial diversity of biodiversity impacts at a product level (Moran et al., 2016).

3 Results

3.1 The effect of spatial disaggregation on LC-Impact characterisation factors

3.1.1 Land characterisation factors

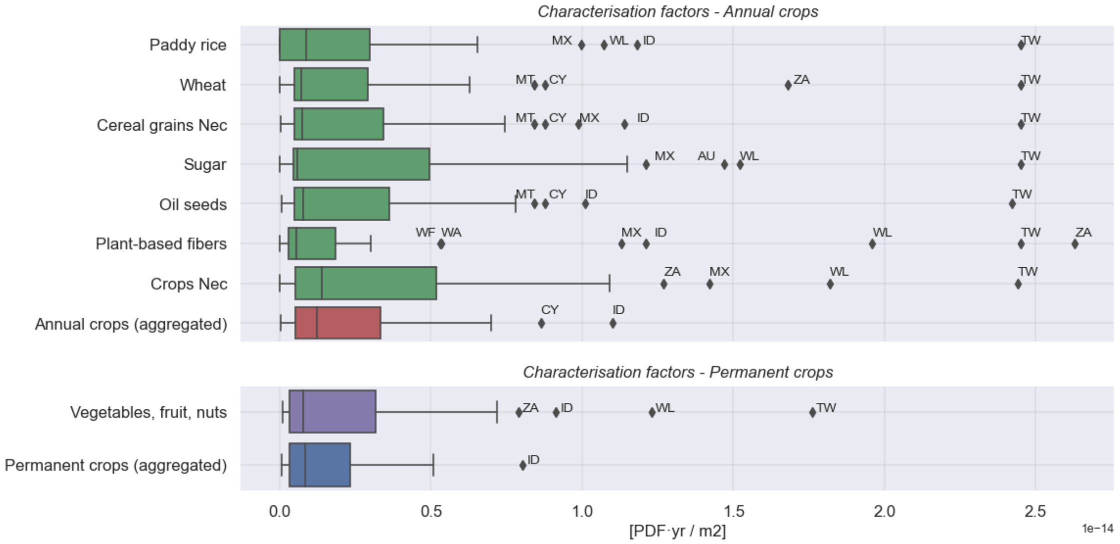
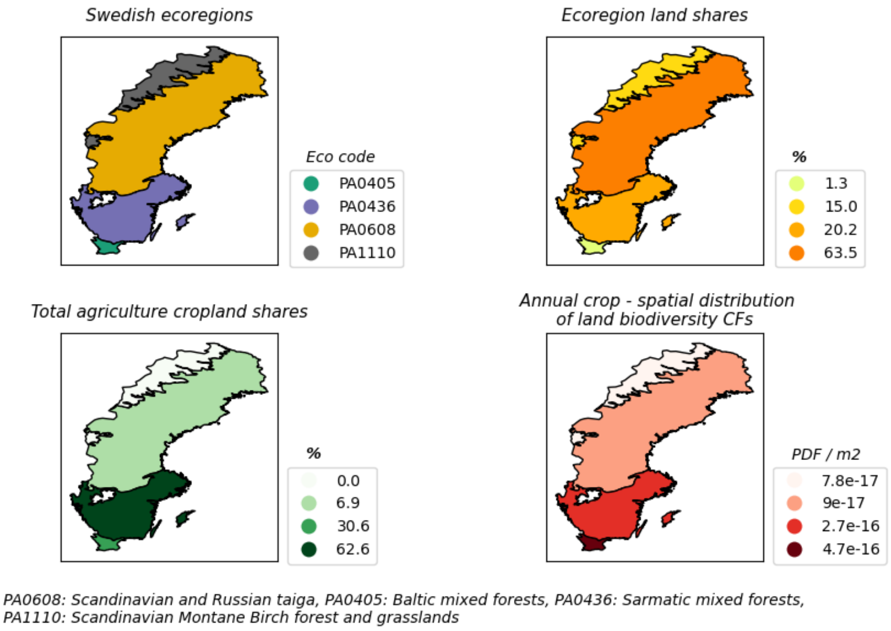


Fig. 1. Differences in national land use characterisation factor distributions post disaggregation for the Annual and Permanent crop categories in LC-Impact and for the 49 EXIOBASE regions. The ROW regions have the following ISO codes: RoW America = WL, RoW Asia = WA, RoW Africa = WF, RoW Middle-East = WM and RoW Europe = WE.

The distribution of the newly formed categories of cropland CFs for the 49 Exiobase regions are presented in Fig 1. The splintering of the two land use cropland categories Annual crops and Permanent Crops and the subsequent aggregation of ecoregion level CFs to the national/continental level via spatially explicit cropland elementary flows are displayed. The resulting CFs convey significant divergence from existing CFs aggregated via ecoregion land shares. The crop categories sugar, crops nec, and 'Vegetables, fruit, nuts' have wider distributions with a number of larger outliers in comparison to the pre-existing distributions. It suggests the ecological damage of land use for their production has been underrepresented in a number of countries to date. The production of sugar in Australia for instance is concentrated in ecoregions of greater sensitivity to land occupation than if predicted by ecoregion land shares. The Australian CF for sugar cropland is 1.47 E-14 PDF/m^2, the third highest for sugar globally. The Annual crop CF for Australia in LC-Impact is only the 18th largest however. The narrower distribution for plant-based fiber CFs, discounting the impact increases for several outliers, points to an overestimation of the crops' impacts.

Taiwan is a significant outlier in all crop categories. A certain level of uncertainty surrounds the Taiwanese CF results as national CFs are not provided in LC-Impact. This could owe to a large level of uncertainty in the ecoregion CFs in the region or to a lack of taxonomic coverage. We construct CFs for the country in any case and compare with the national CFs of China as a proxy. The northern transitory climate regions of Canada, Russia, Norway and Sweden all experience large increases in CFs across all crop categories grown in the respective countries. Russia experiences an 885 % increase in its CF for Paddy rice rising from a PDF/m^2 of 9.04 E-17 for annual cropland land use to a CF of 8.91 E-16 PDF/m^2 for tailored paddy rice production. The countries accommodate ecoregions with large land surface areas in their northern territories. The northern ecoregions have lower land CFs due to lower levels of species richness and endemism (Barry et al., 2013; IUCN, 2021a). Climate and terrain limiting factors restrict expansion of cropland to the north leading to the concentration of cropland in the southern regions where species richness rates are higher (Verones, 2021). Fig 2 displays the contrasting distributions of ecoregion and cropland land shares in Sweden and the relative sensitivity of species in each ecoregion to annual cropland occupation. A concentration is found in the south, where 93% of total annual cropland exists in the two southern ecoregions comprising of just 21.5% of the total Swedish land surface area. The ecoregions of greater crop concentration are also the ecologically more sensitive to annual cropland occupation.

The ROW regions of the Americas, Asia and Africa, shown to be the origins of the largest shares of impacts related to agricultural land use (Chaudhary & Kastner, 2016; Verones et al., 2017), see large variation in their respective spatially dissolved CFs. All three observe increases ranging from 67 % to 655 % for the categories of 'Vegetables,fruit, nuts', paddy rice and crops nec. Increases are not universal and where ROW Africa has increased wheat impacts, ROW Asia and ROW America experience a decline in theirs for example. Decreases in CFs for central European countries can broadly be observed and there's less divergence in the EU-27 in general when comparing the variance expressed in other regions.



PA0608: Scandinavian and Russian taiga, PA0405: Baltic mixed forests, PA0436: Sarmatic mixed forests, PA1110: Scandinavian Montane Birch forest and grasslands

Fig. 2. Four panel map of Swedish ecoregions analysing the share of total land surface area in each ecoregion and the spatial distributions of annual cropland characterisation factors and annual cropland area within the 4 ecoregion borders of Sweden.

3.1.2 Water characterisation factors

The application of the irrigated crop dataset from MapSPAM (IFPRI, 2019) allowed for the distinction between blue and green water consumption for agricultural production. If water requirements are fully met by green water consumption, blue water biodiversity impacts are assumed to be zero and this methodological reasoning was applied across all crop categories and countries. For example, wheat and paddy rice are extensively grown in rainfed regions around the world (Molden et al., 2011; Seck et al., 2012) and their production in a handful of countries produces no blue water related biodiversity impacts.

Significant variation in country/continental CFs are observed for the eight tailored crop categories. A single aggregated country/continent level CF based on shares of total blue water consumption

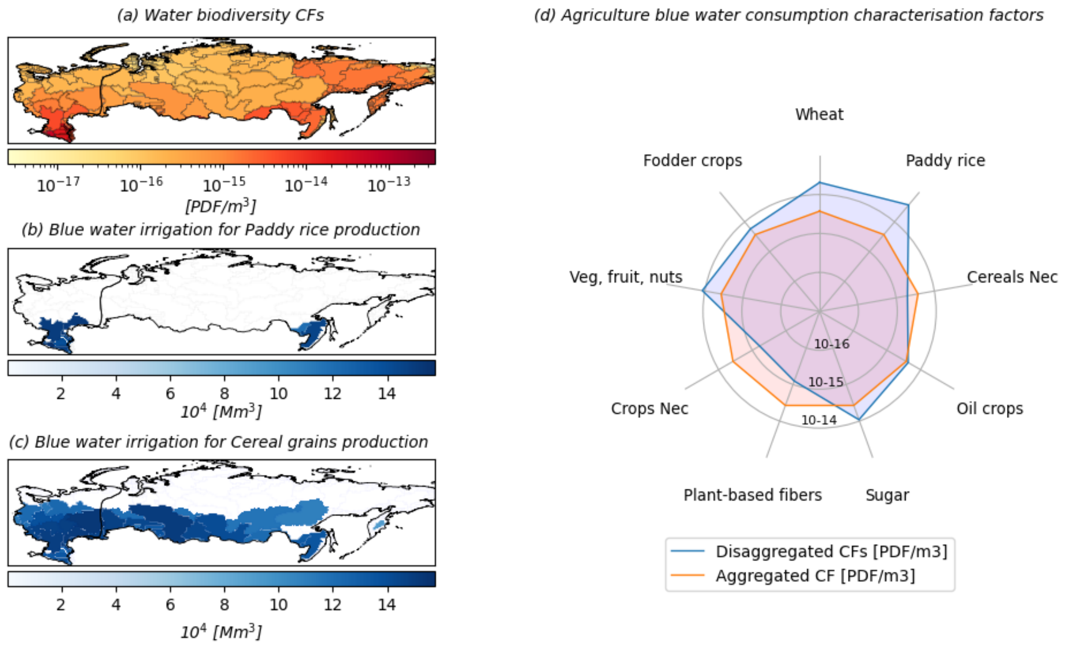


Fig. 3. Spatially explicit map distribution of (a) wetland characterisation factors, (b) blue water consumption for paddy rice production and (c) blue water consumption for cereal grain nec production, in Russia. (d) shows a radar plot of the resulting wetland characterisation factors for Russian crop categories after spatial disaggregation

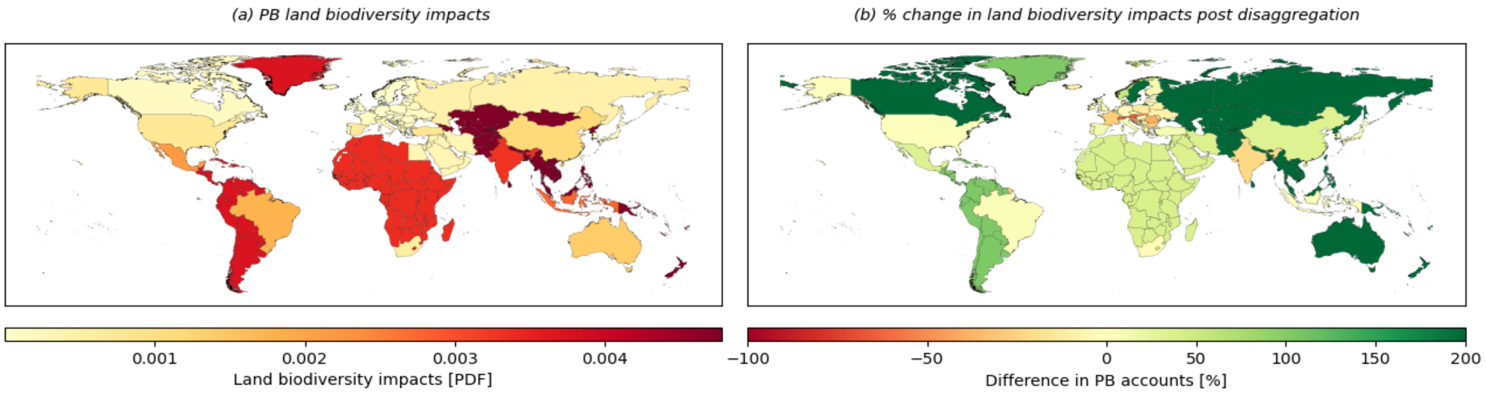
fails to effectively describe crop specific dynamics transpiring within a country's borders. Water impacts related to wheat and rice production have likely been overestimated to date due to the absence of explicit datasets on rain-fed and irrigated production. The US, a major producer of both crops, observes a reduction in impact intensities of 31% and 60% for wheat and rice production respectively based on where and to what degree irrigated crop production occurs. Changes to CF impact intensities in the US and Australia have global implications for biodiversity as their wetland habitats are affected by blue water withdrawals at greater rates that compare in orders of magnitude. The blue water CF in LC-Impact for the US is 1.15 E-12 PDF/m^2 in contrast to the average regional CF of 9 E-14 PDF/m^2. Post disaggregation, the two countries remain as ecological damage hotspots. In the US case, oil seed crops, sugar crops and crops nec see increased biodiversity impacts, with crops nec impacts deviating substantially to 7.41 E-12 PDF/m^2.

Spatially explicit blue water data is especially important in the Russian case with wheat, rice and 'vegetable, fruit and nuts' production impact intensities increasing by 445%, 884% and 210% respectively. However, oil seeds, plant based fibers and crops nec are grown in ecologically less sensitive regions in Russia and have declining impact intensities. Fig 3 visualises the spatial distribution of CFs and blue water consumption for two crop categories, cereal grains nec and paddy rice, within Russia. It details the large deviation in locations and blue water consumption intensities for both crops, exposing the issue with single aggregated impact factors for characterising pressure footprints.

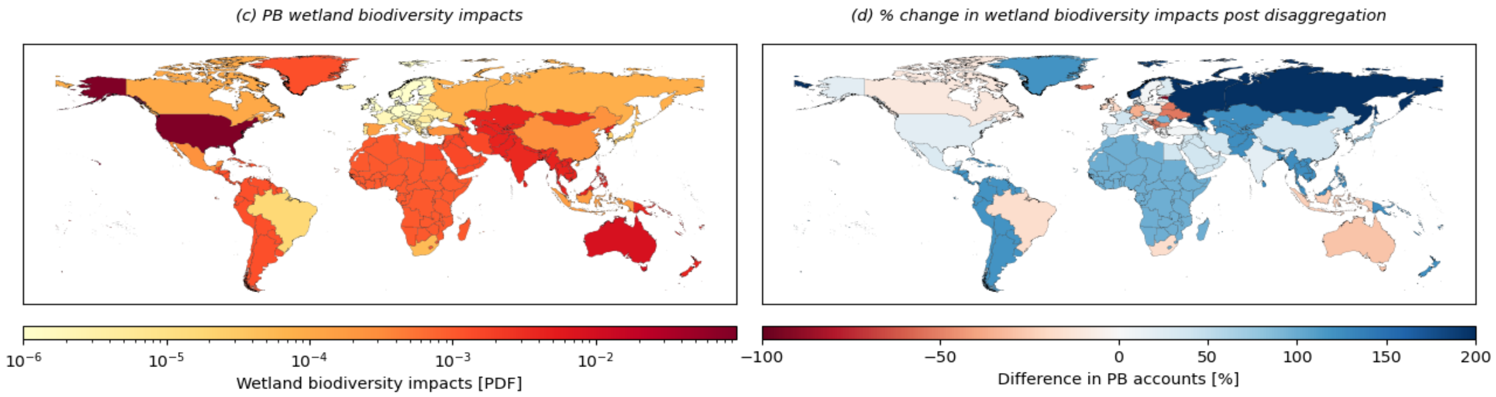
The large continental ROW regions suffer similarly from the lack of spatial and categorical detail in LC-Impact. In tropical ROW regions, crops recognized for drawing large irrigation footprints are significantly underrepresented in terms of biodiversity impact intensities. This goes for rice production in ROW Asia, vegetable and fruit production in ROW Americas and fodder crops in ROW Africa. The full set of crop specific CFs can be retrieved in the SI (SI.4).

3.2 Production-based accounts of biodiversity impacts

The biodiversity footprint results for land use and blue water consumption are presented categorically and independent of each other. The study acknowledges the possibility for harmonizing the biodiversity effects from land and water use within LCA (Verones et al., 2015). The research seeks


(a) PB land biodiversity impacts

(b) % change in land biodiversity impacts post disaggregation


(c) PB wetland biodiversity impacts

(d) % change in wetland biodiversity impacts post disaggregation

Fig. 4. Production-based (PB) impact accounts of nations resulting from the spatially resolved CFs are shown for (a) agricultural cropland occupation, and (c) crop blue water consumption. The panels to the right visualise the change in production-based impacts for (b) land occupation, and (d) water consumption, when characterization is completed with spatially resolved CFs in contrast to the current national CFs in LC-Impact. Individual country PDF scores are available in SI.5.

to outline differences in footprint results between spatially explicit and non-explicit CFs and does not attempt to delve into LCA trade-off style analysis of yield efficiencies and rainfed or irrigated production technologies. Normative assumptions for aggregating impacts from different stressors and taxa are avoided as a result.

3.2.1 Land impacts

The global land ecosystem consequences for servicing global final demand for agriculture products in 2010 was a PDF of 0.0295. Applying the spatially explicit CFs equates to an increase of 38% in global biodiversity footprints. Characterising with the existing LC-Impact multipliers, India and Indonesia are the largest contributors to agricultural production impacts but post aggregation they are replaced by the three ROW regions, ROW Asia, ROW America and ROW Africa as the leading contributors to ecosystem damage (Fig 4). India actually sees a reduction in its biodiversity footprint post disaggregation. ROW Asia climbs from 7th to 1st place overall, increasing its footprint by 260 % to 0.0048 PDF.yr.

For some regions, ecoregion land shares as a predictor of land impact intensities were valid with the EU-27, Brazil and the United States seeing minor changes to their footprints. The sizable increase in CFs for the northern temperate regions predictably translate to large increases in biodiversity footprints. Swedish land impacts due to cereals production trebled, while Russian impacts for paddy rice production were underestimated by a factor of 10 increasing from a PDF of 3.87 E-07 to 3.79E-06. Australia also absorbs large impact increases due to sugar and oil seed production occurring in ecoregions of greater sensitivity than predicted via ecoregion land shares.

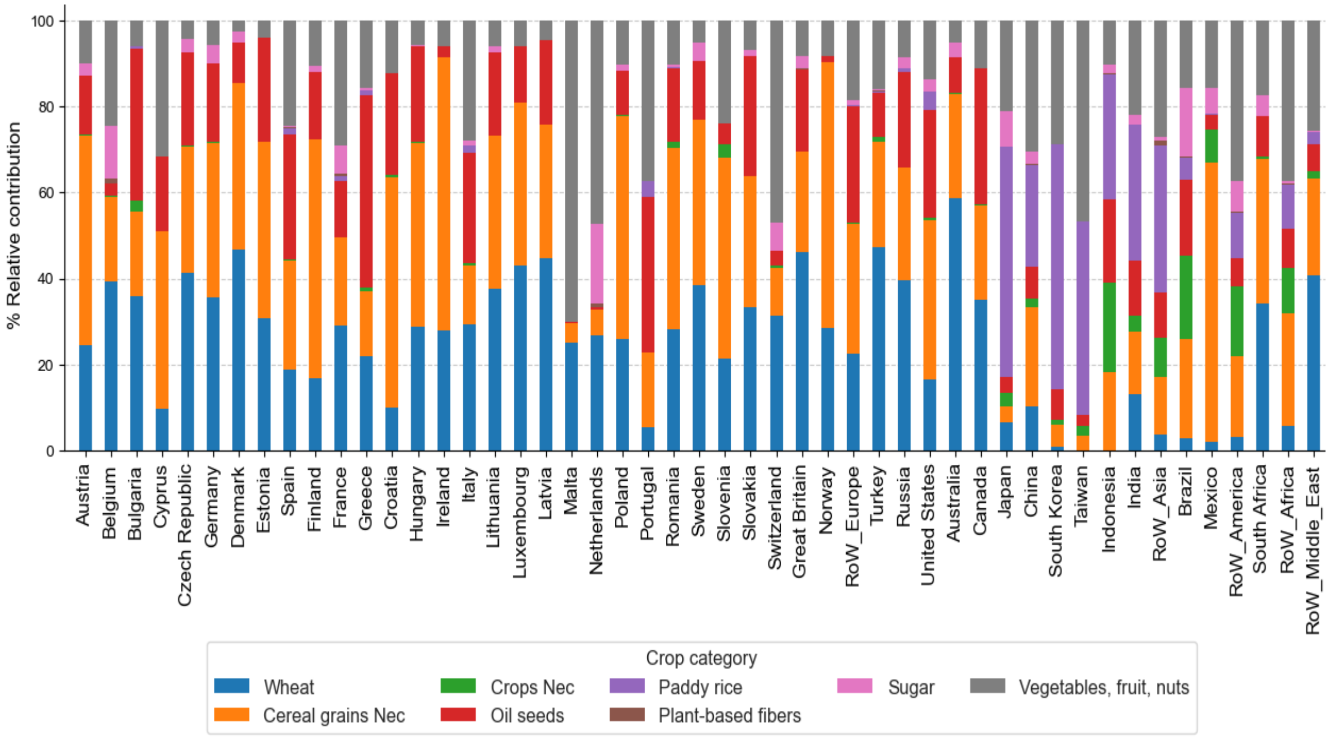


Fig. 5. Relative contributions of the eight EXIOBASE crop categories to the total production-based land impacts of agricultural crop systems in the year 2010 and for the 49 EXIOBASE regions. Note the variation of crop importance for describing land impacts between geographical regions of the world. Individual crop impacts can be retrieved from SI.5.

Globally, aggregated ecoregion share CFs substantially underestimate land related impacts from wheat, plant-based fibers and crops nec. Global impacts from oil seed and 'Vegetable,fruit and nut' production have been slightly overestimated but global outlooks mask large internal changes at the country level. Crop categories have regional trends in impacts, with cereals and oil seeds production accounting for over 80% of cropland ecosystem consequences in the majority of European countries, while Paddy rice is the dominant cropland stressor in Asia (Fig 5.). Impacts are diversified in ROW America and Africa with no single crop emerging as the main driver of ecosystem damage.

3.2.2 Wetland impacts

Partitioning the single CF into eight crop categories and aggregating via crop specific locations and elementary flows increases the global wetland biodiversity impacts of cropland by 17.5 %. Global burdens are driven by water consumption in the US, responsible for 81 % of global impacts. This is expected as its suite of wetland CFs are orders of magnitude higher than the majority of countries/regions included. The four regions of the US, Australia, ROW Asia and India are accountable for over 90% of impacts globally. The US's footprint increased from a PDF score of 0.08 to 0.096 for the year 2010. The increase was partly due to the acute impacts for the crops nec category after mapSPAM modeled growing regions to be concentrated in the highly sensitive wetland areas of the southeastern seaboard. The US, similar to many countries, experience large fluctuations between crop categories. While the impacts from crops nec were acute, the distribution and spatial demand for blue water irrigation in the US for wheat and 'vegetables, fruit and nuts' concluded that previous estimates of respective crop impacts were overstated. While diverging outcomes in the US resulted in broadly increasing wetland impacts overall, the opposite is true in Australia, where fluctuating crop impacts result in an overall decline in impacts.

Large spatial differences in crop locations and irrigation demands produce the largest divergence in Russia. Fig 3 illustrated the spatial distribution of blue water irrigation for paddy rice and cereals nec in Russia and the contrasting impacts on resulting Russian CFs. The outcome of greater spatial resolution in Russia's case is substantially increased wetland biodiversity consequences (Fig 4.). 'Vegetable,fruit and nuts' production is an extensive driver of impacts internationally, dominating biodiversity footprints in many countries. If irrigated rice production exists in a region then it is likely that the crop is the prevalent wetland stressor as is the case with South Korea, Japan, Russia and ROW Asia. Discounting the US impacts, wetland impacts from global wheat, rice, sugar and 'Vegetables, fruit and nuts' production have been underrepresented, while the impacts from fodder crops, oil seeds and crops nec have likely been overstated. ROW regions containing extensive land areas, traversing several climates, growing conditions and levels of aridity all displayed noticeable variation in their respective ecosystem consequences post disaggregation.

4 Discussion

4.1 Crop impacts

Similar to previous food impact studies of land occupation (Chaudhary & Kastner, 2016), our results reveal that extensive crops dominating global agricultural land footprints are responsible for the largest share of terrestrial ecosystem damage and this has amplified post disaggregation. Results for blue water consumption largely follow similar trends but there are acute impacts for crops with lesser footprints such as sugar and fodder also. Crop extensiveness describes land occupation dynamics but when included, land transformations can represent as much as 57% of total biodiversity impacts (Verones et al., 2015). Food crops linked to tropical deforestation such as oil seeds, coffee and cocoa will have significantly larger global impacts despite smaller pressure footprints because of the transformation of virgin ecosystems that occurs to establish their production (Kastner et al., 2021; Pendrill et al., 2019).

While the results point to extensively grown crops for describing global ecosystem impacts, internal country dynamics are much more opaque. Large CF fluctuations within countries and between crops show the importance of crop regionalization and category disaggregation for describing impact effects at the national level. Weighting regional CFs via ecoregion land shares or total blue water consumption, independent of crop or activity are imprecise proxies for true spatial production data and have possibly underestimated land and wetland impacts to date. The disparity between resulting land use national CFs when aggregating native scale CFs via ecoregion land shares or by cropland elementary flows demonstrates the need for improving LCIA modelling at the national level in existing databases. It makes transparent the limitations of scale within current MRIO analysis with biodiversity endpoints and the inherent uncertainty involved.

Such divergence in crop CFs amongst countries raises the potential of international trade for reducing certain crop related impacts if otherwise local demand was met by domestic production only. While numerous studies have concluded that international trade is responsible for between 20-30% of global biodiversity impacts (Bjelle et al., 2021; Lenzen et al., 2012; Wilting et al., 2017), Kastner et al. (2021) estimated that international trade has a net positive effect on biodiversity due to land sparing from the export of certain food crops from countries with higher yield capabilities and lesser biodiversity impact intensities. Such conclusions, when only considering one impact pathway (land use) need to be considered with caution. Take 'cereals nec' production in the US, the largest grain exporter globally in 2010 (Stadler et al., 2021). Comparing US production with that of the second largest exporting region in 2010, ROW America, the US land impact intensity per million euro of crop consumption is six times lower. However, wetland impacts in the US from 'cereals nec' production post CF disaggregation increase by 544% and its impact intensities per million euro of crop consumption are over 350 times greater than those of ROW America.

The land and water results are not directly comparable, but work has been completed in attempting to harmonize biodiversity effects from land and water use within LCA (Verones et al., 2015). It involves normative choices on what species should be prioritised for impact weighting. This is a challenge as beyond providing ecosystem services for food production, biodiversity is pluralistic in the benefits it provides across different groups in society (Pascual et al., 2021). The nexus of food production and biodiversity necessitates trade-offs where maximizing yield efficiencies for example requires the introduction of irrigation technology, increasing blue water consumption impacts but reducing land impacts through land sparing and vice versa. Potentially, a symbiotic relationship between the two is possible by optimizing the preferential growing locations for specific crops and merging with demand side policies as suggested in the scenario modelling by Leclère et al. (2020). However, specialisation and intensification bring further ecosystem concerns of water scarcity, eutrophication and land use intensity as well as a string of social and geopolitical concerns around food security (Fischer et al., 2017).

4.2 Spatial resolution of MRIO regions and national characterisation factors

Biodiversity footprint studies with MRIO have consistently pointed to the low level of regional data for countries not explicitly covered in the MRIO databases as a significant limitation (Cabernard & Pfister, 2021; Moran et al., 2016). ROW regions are responsible for the largest share of land related biodiversity impacts both from a production and consumption-based perspective owing to their higher rates of species richness and endemism (Bjelle et al., 2021; Lenzen et al., 2012; Verones et al., 2017). The issue of spatial resolution in MRIO models was tackled in papers by Bjelle et al. (2021) and Cabernard and Pfister (2021). Bjelle et al. (2021) applied a spatially disaggregated form of EXIOBASE, EXIOBASE 3rx (Bjelle et al., 2019), for investigating land use biodiversity impacts and concluded that regions in Asia and Africa in particular should be represented in a finer level of spatial detail to avoid aggregation errors. Cabernard and Pfister (2021) created a merged hybrid MRIO model of the Eora and EXIOBASE databases, increasing the country spatial resolution of EXIOBASE from 49 regions to the resolution of Eora (189) while maintaining the high sector detail of EXIOBASE.

Cabernard and Pfister (2021) found the EU consumption-based footprint for land use related biodiversity impacts to increase by between 2-6 % on footprints calculated using EXIOBASE 3 for the years 1995 to 2015. Our study observed an increase of 23.8% for EU consumption-based biodiversity footprints when applying the disaggregated CFs with EXIOBASE 3 for the year 2010.

Both sets of results have levels of uncertainty that are not quantified due to the complexity and lack of uncertainty probabilities attached to the source data. The disaggregated MRIO model by Cabernard and Pfister (2021) uses proxy data for ROW countries, disaggregating countries by weighted country and sector specific shares derived from Eora26 and FAOSTAT. The model does not apply matrix balancing calculations unlike EXIOBASE but balanced the total input based on residual value added (Cabernard & Pfister, 2021). Wiebe and Lenzen (2016) found diverging results for the contrasting balancing approaches but it was not clear which approach resulted in superior results. In MapSPAM, model confidence varies between crops and countries depending on the input data (Yu et al., 2020). Subjective uncertainty rating by the MapSPAM practitioners, rank the input data for several of the countries contained in the ROW EXIOBASE regions as highly uncertain (Yu et al., 2020). Combining an LCIA model with a more detailed and spatially explicit crop dataset, both with their independent set of modelling parameters and assumptions, raises the question of the scientific exactness of bridging the two models from an ecological perspective. The drive for more applicable national CFs should be initiated within the LCIA models themselves and ideally not remediated by merging two distinctly different models with differing intentions of use.

Uncertainties aside, Cabernard and Pfister (2020)'s spatially resolved MRIO database produces a noticeably lower divergence in footprint results in comparison to our merging of EXIOBASE 3 with disaggregated LC-Impact CFs. It appears that CFs and their construction have a larger influence on the final biodiversity footprints rather than the MRIO models themselves. Improvements in the national spatial detail of MRIO models are degraded when it is the national CFs that introduce the largest uncertainty in the footprint results. It identifies the urgent need for sub-national IO accounts to alleviate spatial aggregation concerns for both the MRIO and LCIA databases.

4.3 Limitations

It is imperative that pasture cropland be included in future analysis with previous work apportioning significant impacts to cattle rearing for example (Marquardt et al., 2019). The absence of explicit data for pastureland in MapSPAM prohibits CF construction and an incomplete picture of the effects of agricultural land use is formed as a consequence. Land fragmentation and land use intensity practices are not accounted for here. Research has shown that incorporating fragmentation dynamics predicts higher median per-area impacts of land use compared with the standard speices-area c-SAR model (Kuipers et al., 2021). Naturally there is land in EXIOBASE that differs in intensity of use (that is, yields per area of farmland use) and should be reflected in the localised PDF values for biodiversity's response to the varying levels of intensification. The availability of yield data in MapSPAM and farming inputs data from FAO (FAO, 2022) should allow for land management analysis but further development of biodiversity responses to such intensities is needed for specific agricultural land types and taxa beyond the novel work conducted by Chaudhary and Brooks (2018).

We acknowledge that combining two different data sets spanning two time periods to calculate elementary crop blue water consumption in 2010 adds a level of uncertainty to the results that is not quantified. Assuming primacy of the MapSPAM data over the Pfister and Bayer (2018) blue water dataset when mismatches occurred in crop locations was done mainly because it was constructed for the year of our analysis and is a newer spatial model and not necessarily because of the superior underlying scientific rigour of the model itself. The mismatch of crop categories between MapSPAM and EXIOBASE also introduced inaccuracies. MapSPAM includes nut crops in the aggregated 'crops nec' crop category, while EXIOBASE groups the crop in the 'Vegetables, fruit, nuts' category. This led to land areas for nut production being included in the crops nec category, overemphasising land use in certain ecoregions during weighting of the local PDF scores for 'crops nec'. However, nuts account for a small portion of total agricultural surface area and the inaccuracies are not expected to affect the national CF results in a meaningful way. The wide distribution of impacts between crop categories in the results suggest greater agricultural product and stressor detail in MRIO tables and in turn more detailed crop specific CFs in LCIA databases would improve the resolution of results. One approach would be to apply a biophysical MRIO databases, such as FABIO (Bruckner et al., 2019). FABIO provides superior agriculture product detail, capturing detailed supply chain information for 130 raw and processed agricultural and forestry products in physical rather than monetary flows.

5 Conclusion

Using a spatially resolved agricultural production allocation model, we disaggregated the number of LC-Impact cropland CFs available for land use and blue water consumption at the national level. The results revealed an increase in global production based biodiversity impacts of 38% and 17.5% for land use and blue water consumption respectively. It demonstrated that broad cropland categories of land use, the absence of category distinctions for wetland multipliers and current upward aggregation techniques for native scale CFs are a poor proxy for describing country level ecosystem damage from agricultural production. Large variations in CFs between crops and within countries demonstrate the pressing need for regionalization of MRIO models if the heterogeneity of biodiversity impacts are to be fully realized. At the national level it is the aggregated LCIA CFs rather than the aggregated MRIO models that introduce the largest uncertainty. The study has visualised the high level of uncertainty inherent in the existing national cropland CFs in LC-Impact and the recommendations set out by UNEP-SETAC (Frischknecht et al., 2016) for reducing overall uncertainty in biodiversity CFs for LCA are yet to be fundamentally addressed. Avoiding the aggregation of native scale PDF scores in future studies would remove many of the uncertainties discussed but LCIA practitioners must seek to improve national level CFs if biodiversity footprint analysis with current MRIO tables are to be improved. Species richness, while only covering one aspect of ecosystem health (Curran et al., 2011), is the most acceptable and navigable biodiversity indicator in use today. For greater effectiveness it is essential that all stressor pathways for species impacts are considered in the future (Mutel et al., 2019). Not least, the biodiversity impacts from climate change are expected to increase drastically as the consequences of global heating unfold (Newbold, 2018). Within the pathways of the current study, efforts must be made to incorporate fragmentation and land use intensity for land occupation CFs while groundwater effect models for wetland CFs must also be considered in the future.

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Supplementary Information

Contents

Tables

Figures

1. SI.1 - EXIOBASE

a. EXIOBASE - stressor tables

The eight cropland stressors for land occupation in Table S1 are included in the study. The fodder cropland stressors for land occupation which include fodder crops for cattle, meat animals nec, pigs, poultry, and raw milk, encompassing rows 450, 451, 452 and 453 in the F matrix were removed due to the lack of spatial production data for the relevant crops in MapSPAM. In the disaggregated LC-IMPACT categorization, the land occupation stressors of Vegetables, fruit, nuts, roots and tubers, and pulses are aggregated to a single `vegetables, fruit, nuts’ category. The current LC-IMPACT database has two characterisation factors (CFs) for cropland, ‘Annual cropland’ and ‘Permanent cropland’ and in the disaggregated form of the LC-IMPACT characterisation matrix, **C**, there are 8 tailored, crop-specific land occupation characterisation factors (CF) for cropland. There is a single blue water consumption CF in LC-IMPACT currently and the 13 blue water consumption stressors in EXIOBASE (F rows: 924- 936) are characterized by this single multiplier. In this study, the disaggregated LC-IMPACT matrix, **C**, provides 9 crop-specific CFs for the characterisation of the 13 blue water consumption stressors related to cropland irrigation. Like land occupation, water consumption for Vegetables, fruit, nuts, roots and tubers, and pulses are aggregated to a single `vegetables, fruit, nuts’ category. An individual CF is available for each stressor category in EXIOBASE as a result.

Table S1: Selected EXIOBASE stressor rows from the environmental pressure matrix, F, to be characterized by the two impact pathways of land occupation and water stress in LC-Impact.

No.	Stressor - EXIOBASE F matrix	F matrix - row	Unit	LC-IMPACT - Impact Category	Disaggregated LC-IMPACT category
1	Wheat	459	km^2	Land Occupation - annual crops	Wheat
2	Cereal grains nec	447	km^2	Land Occupation - annual crops	Cereal grains nec
3	Crops nec	448	km^2	Land Occupation - annual crops	Crops nec
4	Oil seeds	454	km^2	Land Occupation - annual crops	Oil seeds
5	Paddy rice	455	km^2	Land Occupation - annual crops	Paddy rice
6	Plant-based fibers	456	km^2	Land Occupation - annual crops	Plant-based fibers
7	Sugar cane, sugar beet	457	km^2	Land Occupation - annual crops	Sugar
8	Vegetables, fruit, nuts	458	km^2	Land Occupation - permanent crops	Vegetables, fruit, nuts
9	Agriculture - Paddy Rice	924	m^3	Blue water consumption	Paddy rice
10	Agriculture - Wheat	925	m^3	Blue water consumption	Wheat
11	Agriculture - Cereals nec	926	m^3	Blue water consumption	Cereals nec
12	Agriculture - Roots and tubers	927	m^3	Blue water consumption	Vegetables, fruit, nuts
13	Agriculture - sugar crops	928	m^3	Blue water consumption	Sugar crops
14	Agriculture - Pulses	929	m^3	Blue water consumption	Vegetables, fruit, nuts
15	Agriculture - Nuts	930	m^3	Blue water consumption	Vegetables, fruit, nuts
16	Agriculture - Oil seeds	931	m^3	Blue water consumption	Oil seeds
17	Agriculture - Vegetables	932	m^3	Blue water consumption	Vegetables, fruit, nuts
18	Agriculture - Fruits	933	m^3	Blue water consumption	Vegetables, fruit, nuts
19	Agriculture - Plant-based fibers	934	m^3	Blue water consumption	Plant-based fibers
20	Agriculture - Crops nec	935	m^3	Blue water consumption	Crops nec
21	Agriculture - Fodder crops	936	m^3	Blue water consumption	Fodder crops

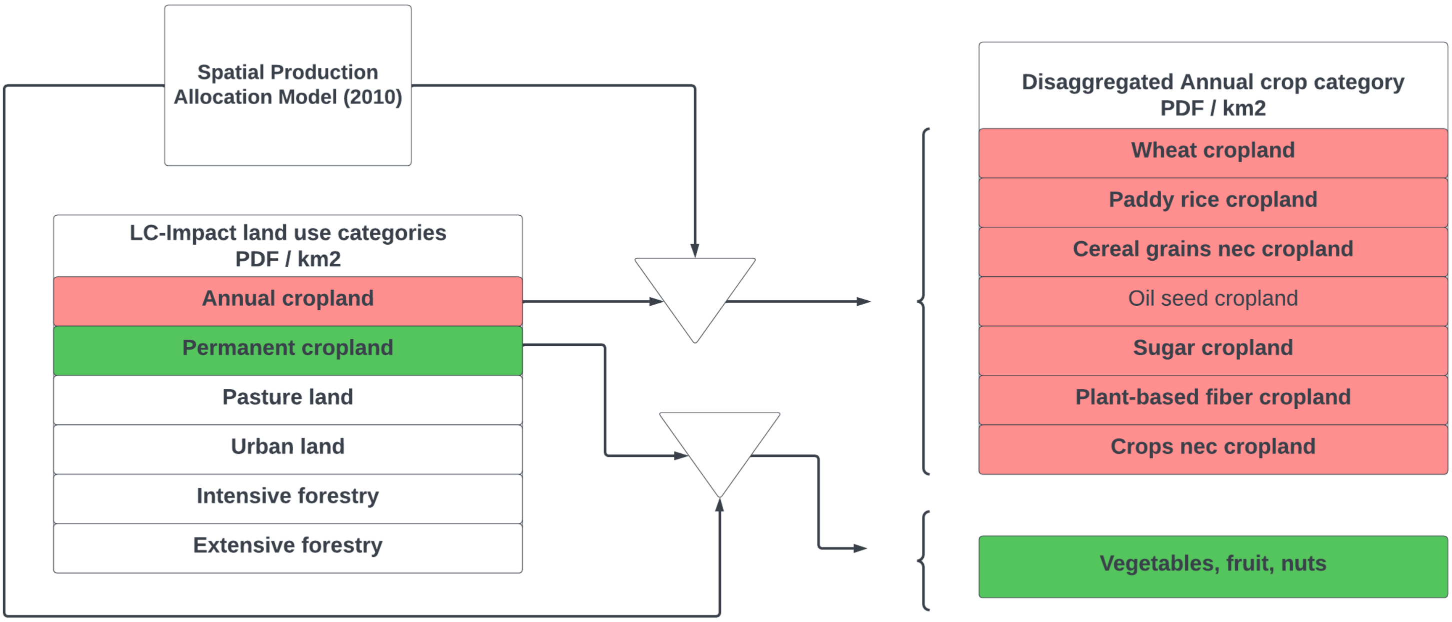

Figure S1. Overview of the intended category disaggregation in LC-IMPACT for the two cropland land use categories completed by incorporating geospatial data from the mapSPAM model.

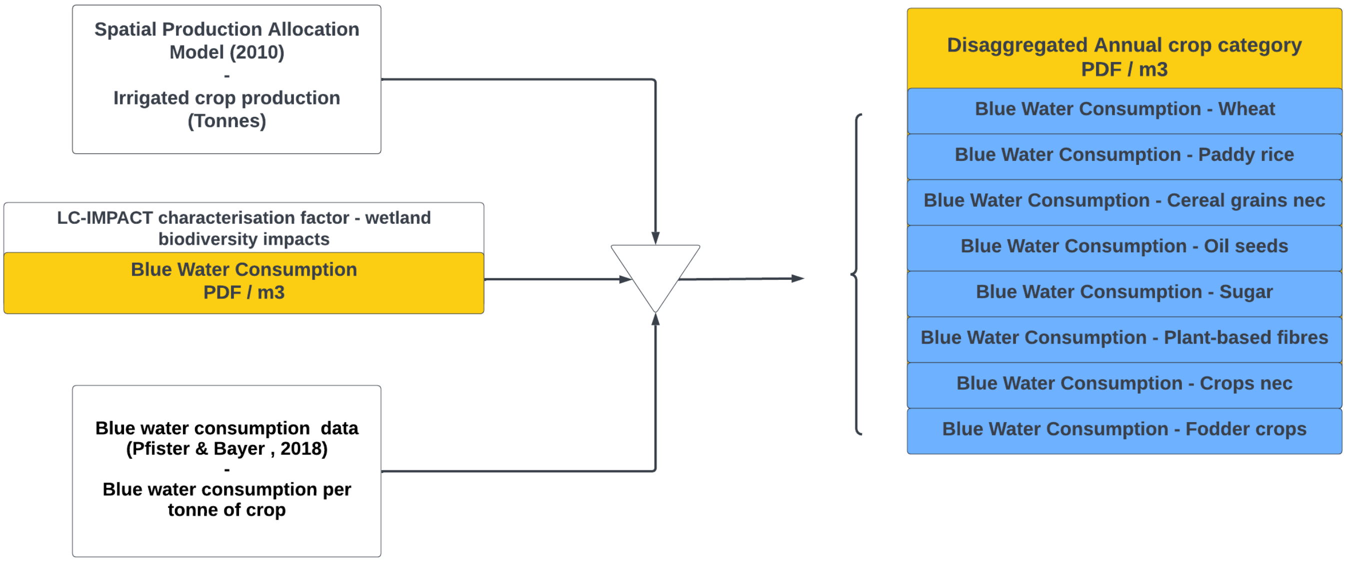

Figure S2. Overview of the intended category disaggregation in LC-IMPACT for the blue water consumption characterisation factor into eight constituent crop categories, completed by incorporating geospatial data from the MapSPAM model.

b. EXIOBASE - product categories

The study looked at the biodiversity impacts related to the demand for agricultural and food products only. Agricultural demand within other non-food product categories as an input to final product production (e.g., oil for soap, petfood) were ignored. We note that non-food products are responsible for about one-quarter of the EU's cropland footprint, a share which was constantly rising over the past 20 years (Bruckner et al., 2019). The main driver of cropland use is of course for human nutrition, and we thought it of more interest to focus on the aspects of biodiversity impacts that were caused directly by human food consumption demands here. EXIOBASE contains 12 primary agricultural commodity products, in that they are non-processed after the point of harvesting. Secondly, EXIOBASE contains 13 processed food products and includes any form from simple grinding of grain to complex industrial methods used for convenience foods. The product categories, excluding the explicit categories like 'wheat' and 'paddy rice' are aggregated product categories, containing merged monetary input-output data for several or more products per EXIOBASE category. We include a detailed breakdown of each EXIOBASE crop category, listing what FAO crop pertains to which EXIOBASE product category. The table is too large to be included here, but it is included in the accompanying excel sheet 'FAO_EXIOBASE_Prod' in the 'Supplementary_info_excel_sheet_1' excel attachment.

Table S2: List of final demand product categories from EXIOBASE included in the final demand matrix ***Y.***

No.	EXIOBASE Product Category	Product Type
1	Paddy rice	Primary Agricultural commodity
2	Wheat	Primary Agricultural commodity
3	Cereal grains nec	Primary Agricultural commodity
4	Vegetables, fruit, nuts	Primary Agricultural commodity
5	Oil seeds	Primary Agricultural commodity
6	Sugar cane, sugar beet	Primary Agricultural commodity
7	Plant-based fibers	Primary Agricultural commodity
8	Crops nec	Primary Agricultural commodity
9	Cattle	Primary Agricultural commodity
10	Pigs	Primary Agricultural commodity
11	Poultry	Primary Agricultural commodity
12	Meat animals nec	Primary Agricultural commodity
13	Animal products nec	Processed food
14	Raw milk	Processed food
15	Products of meat cattle	Processed food
16	Products of meat pigs	Processed food
17	Products of meat poultry	Processed food
18	Meat products nec	Processed food
19	products of Vegetable oils and fats	Processed food
20	Dairy products	Processed food
21	Processed rice	Processed food
22	Sugar	Processed food
23	Food products nec	Processed food
24	Beverages	Processed food
25	Fish products	Processed food

c. EXIOBASE - Final Demand categories

We include all seven EXIOBASE final demand categories to ensure discrepancies of consumption allocation between final demand categories amongst countries are avoided. National systems of account and Input-output (IO) tables are assembled by each country and broadly follow the UN Supply and Use tables (SUT) guidelines for compilation (UN, 2018) . However, allocation of consumption demand can vary between countries, where one country might consider a consumption activity to fall under final consumption expenditure by households, while another may group expenditure with government spending. It is also a matter of detail, resolution, and the level of scrutiny applied to consumption allocation during a country's construction of its SUT and IO tables. Therefore, rather than limiting the work to household final consumption, we incorporate all final demand categories to ensure all food related expenditure is captured and that discrepancies of accounting between countries are avoided.

Table S3: Categories of final demand existing in EXIOBASE – All seven are included in the study.

No.	EXIOBASE - Final Demand Categories - Y matrix	Unit
1	Final consumption expenditure by households	MEur
2	Final consumption expenditure by non-profit organisations serving households (NPISH)	MEur
3	Final consumption expenditure by government	MEur
4	Gross fixed capital formation	MEur
5	Changes in inventories	MEur
6	Changes in valuables	MEur
7	Exports: Total (fob)	MEur

d. EXIOBASE – Regions

The 5 rest of the world (ROW) regions of EXIOBASE are made up of a total of 214 aggregated regions (Wood et al., 2014). The list of regions in each EXIOBASE ROW region can be obtained from the excel sheet 'ROW_regions_EXIO' in the 'Supplementary_info_excel_sheet_1' excel attachment.

Table S4: List of the 49 EXIOBASE regions and their accompanying International Organization for Standardization (ISO) 3166-1 alpha-2 codes

No.	EXIOBASE Regions	ISO 3166-1 alpha-2 codes	No.	EXIOBASE Regions	ISO 3166-1 alpha-2 codes
1	Austria	AT	26	Slovenia	SL
2	Belgium	BE	27	Slovakia	SK
3	Bulgaria	BG	28	United Kingdom	UK
4	Cyprus	CY	29	United States	US
5	Czech Republic	CZ	30	Japan	JP
6	Germany	DE	31	China	CN
7	Denmark	DK	32	Canada	CA
8	Estonia	EE	33	South Korea	KR
9	Spain	ES	34	Brazil	BR
10	Finland	FI	35	India	IN
11	France	FR	36	Mexico	MX
12	Greece	GR	37	Russia	RU
13	Croatia	HR	38	Australia	AU
14	Hungary	HU	39	Switzerland	CH
15	Ireland	IE	40	Turkey	TR
16	Italy	IT	41	Taiwan	TW

17	Lithuania	LT	42	Norway	NO
18	Luxembourg	LU	43	Indonesia	ID
19	Latvia	LV	44	South Africa	ZA
20	Malta	MT	45	RoW Asia and Pacific	WA
21	Netherlands	NL	46	RoW America	WL
22	Poland	PL	47	RoW Europe	WE
23	Portugal	PT	48	RoW Africa	WF
24	Romania	RO	49	RoW Middle East	WM
25	Sweden	SE			

2. SI.2 – LC-IMPACT

a. Summary of considered pressures from the MRIO and the corresponding impact categories from LC-IMPACT

Table S5. Summary of considered pressures from the MRIO and the corresponding impact categories in LC-IMPACT (Verones, Hellweg, et al., 2020).

No.	Aggregated impact	Pressure	Impact pathway	Taxonomic coverage	Modelling approach	Key references
1	Water use	Blue water consumption (m3)	Water stress, [PDF·yr/m3] (0.05° × 0.05°)	Mammals, birds, reptiles, amphibians, vascular plants	Marginal	(Pfister & Bayer, 2014), (Pfister et al., 2009)
2	Land occupation	Agricultural Land area (Ha)	Land occupation, [PDF·yr/km2] (ER)	Mammals, birds, reptiles, amphibians, vascular plants	Average	(Chaudhary et al., 2015)

We chose an average modelling approach for Land occupation rather than a marginal approach. The study looked at the impacts of current agricultural land use in existence today and an average modelling approach reflects this perspective by applying the distance between the current state and a state of zero impacts (virgin ecosystems) to calculate the average impact per unit of intervention (Verones, Hellweg, et al., 2020; Verones, Huijbregts, et al., 2020). The marginal approach is more in line with consequentialist LCA approach, where a study focuses on the impacts of an additional unit increase in the environmental pressure. LC-IMPACT includes a method for the marginal approach only for water consumption impacts on ecosystems.

b. Value Choices

LC-IMPACT provides four sets of value choices based on cultural perspective theory (Huijbregts et al., 2017). The four sets are a resulting matrix combination based on the two key aspects of time horizon and level of evidence of impacts (Verones, Huijbregts, et al., 2020). There are no time horizon value choices to be made for the land occupation and blue water consumption impact categories as an infinite time horizon is assumed under steady-state conditions. In terms of evidence-based impacts, levels of robustness vary significantly between surface water-fed wetlands and groundwater-fed wetland models. Groundwater-fed wetlands are considered to have a much lower level of certainty due to the considerably less data available for the model construction (Francesca Verones et al., 2020). We chose to include impacts from groundwater-fed irrigation only. The data resolution for land occupation is considered to be of high quality and is based of the countryside species area relationship model by (Chaudhary et al., 2015). Therefore, no certainty choices are required for the impact method as the model is of a robust nature.

c. National & continental characterisation factors – LC-IMPACT

Table S6. Current national & continental LC-IMPACT characterisation factors for land occupation and water stress (Verones, 2021).

Pressure	**Stressor**	**Units**	**AT**	**BE**	**BG**	**CY**	**CZ**	**DE**	**DK**	**EE**	**ES**	**FI**	**FR**	**GR**
Land Occupation Average	Annual crops	[PDF-eq/m2]	1.81E-15	5.17E-16	1.10E-15	8.63E-15	5.29E-16	5.03E-16	4.43E-16	2.70E-16	5.68E-15	3.44E-17	1.34E-15	6.11E-15
Land Occupation Average	Permanent crops	[PDF-eq/m2]	1.25E-15	3.17E-16	6.49E-16	4.85E-15	3.26E-16	3.08E-16	2.79E-16	1.50E-16	3.60E-15	8.90E-17	7.95E-16	3.54E-15
Water Consumption - core	Water consumption - core	[PDF·yr/m3]	1.60E-14	3.31E-16	9.50E-15	5.51E-14	4.08E-15	4.21E-15	4.91E-16	2.82E-16	1.18E-14	3.68E-16	6.19E-16	5.52E-15
Water Consumption - extended	Water consumption	[PDF·yr/m3]	3.56E-13	3.31E-16	1.75E-14	5.51E-14	5.39E-15	5.12E-15	4.91E-16	2.95E-16	1.45E-14	8.99E-16	7.03E-16	5.54E-15
Pressure	**Stressor**	**Units**	**HR**	**HU**	**IE**	**IT**	**LT**	**LU**	**LV**	**MT**	**NL**	**PL**	**PT**	**RO**
Land Occupation Average	Annual crops	[PDF-eq/m2]	2.15E-15	5.51E-16	2.44E-16	5.15E-15	3.49E-16	4.63E-16	2.74E-16	6.37E-15	5.27E-16	6.37E-16	5.28E-15	1.15E-15
Land Occupation Average	Permanent crops	[PDF-eq/m2]	1.33E-15	3.39E-16	1.44E-16	3.18E-15	2.04E-16	2.76E-16	1.53E-16	3.92E-15	3.26E-16	4.11E-16	3.22E-15	7.79E-16
Water Consumption - core	Water consumption - core	[PDF·yr/m3]	8.66E-15	1.30E-14	7.59E-16	3.41E-15	2.74E-16	5.65E-15	2.42E-16	4.57E-15	5.24E-16	4.30E-16	4.23E-15	4.21E-15
Water Consumption - extended	Water consumption	[PDF·yr/m3]	1.34E-14	2.05E-14	5.48E-15	3.48E-15	2.74E-16	5.65E-15	4.32E-16	9.02E-15	5.32E-16	5.64E-16	5.99E-15	9.86E-15
Pressure	**Stressor**	**Units**	**SE**	**SI**	**SK**	**GB**	**US**	**JP**	**CN**	**CA**	**KR**	**BR**	**IN**	**MX**
Land Occupation Average	Annual crops	[PDF-eq/m2]	1.03E-16	1.52E-15	1.43E-15	2.89E-16	7.30E-16	3.34E-15	1.22E-15	9.49E-17	1.24E-15	3.58E-15	3.21E-15	6.98E-15
Land Occupation Average	Permanent crops	[PDF-eq/m2]	1.04E-16	9.76E-16	9.87E-16	1.80E-16	5.10E-16	2.24E-15	8.49E-16	9.13E-17	8.64E-16	2.49E-15	2.33E-15	5.08E-15
Water Consumption - core	Water consumption - core	[PDF·yr/m3]	4.63E-16	2.67E-14	1.07E-14	6.32E-16	1.15E-12	1.28E-14	2.32E-15	2.83E-13	3.99E-14	2.76E-15	1.12E-14	1.24E-14
Water Consumption - extended	Water consumption	[PDF·yr/m3]	5.11E-16	4.19E-14	1.67E-14	2.68E-15	1.15E-12	5.25E-14	2.35E-15	2.85E-13	4.75E-14	2.85E-15	1.12E-14	1.25E-14
Pressure	**Stressor**	**Units**	**RU**	**AU**	**CH**	**TR**	**TW**	**NO**	**ID**	**ZA**	**WA**	**WL**	**WE**	**WF**
Land Occupation Average	Annual crops	[PDF-eq/m2]	9.04E-17	1.67E-15	1.78E-15	3.95E-15	1.22E-15	5.53E-17	1.10E-14	5.93E-15	1.42E-15	3.98E-15	8.35E-16	1.67E-15
Land Occupation Average	Permanent crops	[PDF-eq/m2]	8.68E-17	1.06E-15	1.22E-15	2.39E-15	8.49E-16	5.49E-17	8.03E-15	3.63E-15	1.03E-15	2.89E-15	5.44E-16	1.15E-15
Water Consumption - core	Water consumption - core	[PDF·yr/m3]	3.74E-15	2.25E-12	7.66E-15	1.92E-14	2.96E-13	4.00E-16	2.92E-14	1.76E-14	1.46E-14	3.19E-14	4.57E-15	1.58E-14
Water Consumption - extended	Water consumption	[PDF·yr/m3]	3.75E-15	2.34E-12	7.73E-15	1.95E-14	2.96E-13	4.00E-16	2.92E-14	1.76E-14	2.24E-14	4.88E-13	1.68E-14	1.96E-14
Pressure	**Stressor**	**Units**	**WM**											
Land Occupation Average	Annual crops	[PDF-eq/m2]	1.42E-15											
Land Occupation Average	Permanent crops	[PDF-eq/m2]	1.03E-15											
Water Consumption - core	Water consumption - core	[PDF·yr/m3]	1.46E-14											
Water Consumption - extended	Water consumption	[PDF·yr/m3]	5.31E-14											

3. SI.3 - Detailed information for CF disaggregation

a. Divergence in crop categorization between MapSPAM and EXIOBASE

MapSPAM details geospatial production data for 42 crop categories for the year 2010 (Yu et al., 2020). While many of the crop categories are individual crops, several of the crop categories are a combination of several FAO crops merged under a single crop category and fall under product categories such as 'Temperate fruit', 'Vegetables', 'Rest of Crops', 'Other Oil crops' etc. Prior to merging the geospatial data from the agricultural model with the spatially explicit, native scale LC-IMPACT CFs, normalization of product categories between MapSPAM and the eight crop stressor categories of EXIOBASE was required. It enables the construction of crop-specific CFs which could be applied directly with the MRIO tables of EXIOBASE. The 42 crops of MapSPAM were aggregated into the 8 crop stressor categories of EXIOBASE: 'Paddy rice', 'Wheat', 'Cereals nec', 'Plant-based fibers', 'Vegetables, fruit, nuts', 'Oil seeds', 'Crops nec' and 'Sugar'. Table S3 titled 'SPAM2010 crop categories' in the supplementary information (SI) of (Yu et al., 2020) outlined the FAO crops contained within the aggregated MapSPAM categories while information on land use categories and their allocation to EXIOBASE's sectorial resolution was retrieved from table S6 in SI6 of (Stadler et al., 2018). We completed the normalization of the 42 crop categories of mapSPAM to the eight crop categories of EXIOBASE by following the detail in both tables. Table S7 outlines the crops not included in MapSPAM but contained within the EXIOBASE sectorial resolution. Detailed FAO, EXIOBASE and MapSPAM crop classifications are available in excel sheet 'FAO_EXIOBASE_Prod' in the accompanying excel sheet 'Supplementary_info_excel_sheet_1'. Table S7. Missing crops in MapSPAM but contained within aggregated EXIOBASE product category

Table S7. Missing crops in MapSPAM but contained within aggregated EXIOBASE product category

Exiobase Crop Category	Missing in MapSPAM	FAO codes
Plant-based fibers	Coir	813
Oil seeds	Jojoba seeds, Mustard seeds, Tallowtree seeds, cottonseed	277, 292, 305, 328
Vegetables, fruit, nuts	Carobs, Cassava leaves, Onions (dry)	461, 378, 403

Differences in allocation approaches of crops within product categories exist between EXIOBASE and mapSPAM. FAO crops already aggregated within one of the 42 mapSPAM crop categories were unable to be disaggregated and resolved into the desired EXIOBASE categories if they were allocated in a different manner in mapSPAM. These crops and their diverging categorization are listed in Table 9. The major conceptual discrepancy is the allocation of nut crops in the 'crops nec' category in mapSPAM and 'vegetables, fruit, nuts' category in EXIOBASE or the allocation of olives in the 'Oil seeds' category and not in 'Vegetables, fruit, nuts' as in EXIOBASE. When completing the weighting of native land CFs to the national level using the elementary flows of specific cropland shares in each ecoregion, discrepancies between crop categories will exist as a result. As mapSPAM provides the geospatial elementary flow data, land shares for the 'crops nec' category in ecoregions containing nut production will be overestimated and underestimated for the 'vegetables, fruit, nuts' product category. The discrepancies are not expected to affect the national CF results in a meaningful way as land use for nut production, olives and chicory root are only a small share of total agricultural crop land surface areas.

The issue does not arise when aggregating the watershed CFs to the national level because total blue water consumption data for individual crops exist in the Pfister (2018) water dataset for the year 2000. Therefore, instead of calculating crop blue water consumption by merging the crop production data from mapSPAM in 2010 (in tonnes) with the blue water irrigation per tonne of crop produced date (m3/tonne) from Pfister (2018) to calculate proxy blue water elementary flows for the year 2010, the total blue water consumption data (m3) available for the year 2000 for the misallocated crops were applied instead. The total blue water consumption data for nuts in 2000 for example was then merged with the calculated proxy blue water consumption for 2010 for the 'vegetables and fruit' category to form the desired 'Vegetables, fruit, nuts' EXIOBASE category. This was only possible due to the more resolved crop categories in the Pfister dataset, where it included geospatial blue water consumption data for over 160 crops. The calculation was as follows:

$$M_{vegetables,fruit,nuts,i} = B_{nuts,2000} + I_{avg}P$$

Table S8. Variable descriptions for equation S1

Variable	Description	Units
$M_{vegetables,fruit,nuts}$	Proxy blue water consumption for the year 2010 in watershed I for the EXIOBASE crop category of 'Vegetables, fruit, nuts'	*M^3*
$B_{nuts,2000}$	*Total blue water consumption for nut production in watershed I for the year 2000. (Pfister, 2018)*	*M^3*
I_{avg}	*Average blue water per tonne requirement for each FAO crop contained within the 'Vegetables and fruit' EXIOBASE crop category in the year 2000 for watershed i (Pfister, 2018)*	*M^3/tonne*
P	*Total production in tonnes of Vegetables and fruit in watershed I in the year 2010 (Yu et al., 2020)*	*Tonnes*

Table S9. Divergence between EXIOBASE and mapSPAM for allocating specific crops to a product category

CROP	EXIOBASE CATEGORY	MAPSPAM CATEGORY
OLIVES	Vegetables, fruit, nuts	Oil seeds
BRAZIL NUTS, WITH SHELL	Vegetables, fruit, nuts	Crops nec
CASHEW NUTS, WITH SHELL	Vegetables, fruit, nuts	Crops nec
CHESTNUT	Vegetables, fruit, nuts	Crops nec
ALMONDS, WITH SHELL	Vegetables, fruit, nuts	Crops nec
WALNUTS, WITH SHELL	Vegetables, fruit, nuts	Crops nec
PISTACHIOS	Vegetables, fruit, nuts	Crops nec
KOLA NUTS	Vegetables, fruit, nuts	Crops nec
HAZELNUTS, WITH SHELL	Vegetables, fruit, nuts	Crops nec
ARECA NUTS	Vegetables, fruit, nuts	Crops nec
NUTS, NES	Vegetables, fruit, nuts	Crops nec
CHICORY ROOTS	Crops nec	Vegetables, fruit, nuts

b. Country coverage in MapSPAM and Pfister (2018) Water Dataset

For the 214 countries aggregated into the 5 ROW regions, MapSPAM does not contain spatial production data for Netherlands Antilles in ROW America, Nauru in ROW Asia and Pacific, and for Zanzibar in ROW Africa. These regions were removed from the analyses and the ecoregions within these regions were not considered in the weighted aggregation of the land use ecoregion CFs to the continental ROW level.

The following countries are not included in Water dataset (Pfister & Bayer, 2014b) and needed treatment: Kosovo, Sint Maarten, Nauru, Seychelles, Hong Kong, Netherlands Antilles, Curacao, Bermuda, Zanzibar, Palau, Micronesia Fed. Sts., Marshall Islands, Macao, Maldives, Tuvalu, Cayman Islands, Palestine, South Sudan, Cook Islands, French Polynesia and Kiribati. However, according to MapSPAM, South Sudan is the only missing region in the water dataset with irrigated crop production according to its geospatial modelling data. Therefore, the countries above are eliminated from the water characterisation factor weighting and proxy data is applied in the South Sudan case. South Sudan was given averaged crop blue water per tonne data from an average of its neighbouring regions Ethiopia, Sudan, Central African Republic, Uganda, and DR Congo.

c. Treatment of no data values in LC-IMPACT

For missing ecoregions in LC-IMPACT we apply proxy ecoregion data if mapSPAM predicts agricultural land to exist within a missing ecoregion. We follow the recommendations outlined by (Mutel et al., 2019) for the handling of no data values in regionalized LCIA assessments. For missing ecoregions, we replace the missing data with the average CFs of its neighbouring (touching) ecoregions. If the missing ecoregion is an island, then regions in the locale with the same biome and ecoregion class are used to calculate an averaged set of CFs for the missing island ecoregion. See Table S10 for instruction on the calculated proxies for the missing ecoregions in LC-IMPACT.

The same approach is completed for missing CFs in the ecoregion dataset provided by LC-IMPACT. The list of missing ecoregion CFS and their resulting proxies are listed in Table S11. Ecoregions with no crop data according to MapSPAM, which assumes no crop production to take place and therefore no land related biodiversity impacts from cropland agriculture, are removed from the analysis and simply ignored. No proxies are provided for these ecoregions.

For missing watersheds in LC-Impact, we apply the national wetland CF for missing wetlands within a country’s boundaries if irrigated production occurs within the native boundary according to Pfister (2018) and the MapSPAM datasets.

Table S10. Missing ecoregions in LC-IMPACT and the proxy ecoregions applied as their replacement

Eco-code	**Eco_name**	**Equivalent ecoregion replacement**	**Notes**
AT1301	Aldabra Island xeric scrub		no crops located in ecoregion from SPAM model
NT0110	Cayos Miskitos-San AndrÃ©s and Providencia moist forests		no crops located in ecoregion from SPAM model
NA0301	Bermuda subtropical conifer forests		no crops located in ecoregion from SPAM model
NT0403	San Félix -San Ambrosio Islands temperate forests		no crops located in ecoregion from SPAM model
OC0104	Eastern Micronesia tropical moist forests	OC0110, AA0101, OC0112, AA0119, AA0126	Crops located in ecoregion from SPAM model
OC0102	Central Polynesian tropical moist forests		no crops located in ecoregion from SPAM model
OC0204	Yap tropical dry forests		no crops located in ecoregion from SPAM model
OC0116	Tubuai tropical moist forests	OC0110, AA0101, OC0112, AA0119, AA0126	Crops located in ecoregion from SPAM model
OC0107	Kermadec Islands subtropical moist forests		no crops located in ecoregion from SPAM model
AN1101	Marielandia Antarctic tundra		no crops located in ecoregion from SPAM model
AT0720	St. Helena scrub and woodlands		no crops located in ecoregion from SPAM model
OC0101	Carolines tropical moist forests	OC0110, AA0101, OC0112, AA0119, AA0126	Crops located in ecoregion from SPAM model
AN1104	Southern Indian Ocean Islands tundra		no crops located in ecoregion from SPAM model
NT1311	Malpelo Island xeric scrub		no crops located in ecoregion from SPAM model
AN1103	Scotia Sea Islands tundra		no crops located in ecoregion from SPAM model
NT0123	Fernando de Noronha-Atol das Rocas moist forests		no crops located in ecoregion from SPAM model
OC0703	Northwestern Hawaii scrub		no crops located in ecoregion from SPAM model
AN1102	Maudlandia Antarctic desert		no crops located in ecoregion from SPAM model
OC0111	Rapa Nui subtropical broadleaf forests		no crops located in ecoregion from SPAM model
OC0113	Society Islands tropical moist forests	OC0112	Crops located in ecoregion from SPAM model

Table S11. Missing ecoregion CFs in LC-IMPACT and their resulting ecoregion proxies if required

		Annual crops	Permanent crops	
eco_code	**proxy_eco_code**	**Median**	**Median**	**notes:**
AA0109	**not required**			no crops located in ecoregion from SPAM model
AA0114	**not required**			no crops located in ecoregion from SPAM model
AA0401	**AA0403, AA0414, AA0408, AA0405**	2.6667E-15	2.07103E-15	Crops located within ecoregion from Spam model
AA0701	**AA0704, AA0709, AA0706**	1.34147E-15	1.0248E-15	Crops located within ecoregion from Spam model
AA1101	**not required**			no crops located in ecoregion from SPAM model
AT0113	**not required**			no crops located in ecoregion from SPAM model
AT0703	**not required**			no crops located in ecoregion from SPAM model
AT0801	**PA1303, AT1306**	4.736E-16	3.41568E-16	Crops located within ecoregion from Spam model
AT0802	**not required**			no crops located in ecoregion from SPAM model
AT0803	**not required**			no crops located in ecoregion from SPAM model
AT1304	**AT1305**	8.33481E-16	5.87485E-16	Crops located within ecoregion from Spam model
AT1308	**not required**			no crops located in ecoregion from SPAM model
AT1315	**not required**			no crops located in ecoregion from SPAM model
IM0110	**not required**			no crops located in ecoregion from SPAM model
IM0148	**not required**			no crops located in ecoregion from SPAM model
NA0521	**NA0506, NA0514, NA0509, NA1106**	4.66086E-16	3.68451E-16	Crops located within ecoregion from Spam model
NA0526	**NA1310, NA1201, NA1301,**	3.62169E-15	2.13426E-15	Crops located within ecoregion from Spam model
NA0604	**not required**			no crops located in ecoregion from SPAM model
NA0611	**not required**			no crops located in ecoregion from SPAM model
NA0612	**not required**			no crops located in ecoregion from SPAM model
NA0615	**not required**			no crops located in ecoregion from SPAM model
NA0617	**not required**			no crops located in ecoregion from SPAM model
NA1103	**not required**			no crops located in ecoregion from SPAM model
NA1105	**not required**			no crops located in ecoregion from SPAM model

NA1109	**not required**			no crops located in ecoregion from SPAM model
NA1110	**not required**			no crops located in ecoregion from SPAM model
NA1112	**not required**			no crops located in ecoregion from SPAM model
NA1113	**not required**			no crops located in ecoregion from SPAM model
NA1114	**not required**			no crops located in ecoregion from SPAM model
NA1116	**not required**			no crops located in ecoregion from SPAM model
NA1118	**not required**			no crops located in ecoregion from SPAM model
NT0116	**not required**			no crops located in ecoregion from SPAM model
NT0216	**not required**			no crops located in ecoregion from SPAM model
NT0401	**not required**			no crops located in ecoregion from SPAM model
NT0705	**not required**			no crops located in ecoregion from SPAM model
NT1303	**NT1201, NT1406, NT1315**	1.12756E-14	7.98202E-15	Crops located within ecoregion from Spam model
OC0103	**not required**			no crops located in ecoregion from SPAM model
OC0108	**OC0105**	5.00048E-14	3.5541E-14	Crops located within ecoregion from Spam model
OC0109	**not required**			no crops located in ecoregion from SPAM model
OC0115	**not required**			no crops located in ecoregion from SPAM model
OC0117	**not required**			no crops located in ecoregion from SPAM model
PA0602	**PA0608**	3.09588E-17	8.95555E-17	Crops located within ecoregion from Spam model
PA0604	**PA0603**	6.6129E-17	9.60613E-17	Crops located within ecoregion from Spam model
PA0605	**PA0520**	5.40199E-17	4.66781E-17	Crops located within ecoregion from Spam model
PA0807	**not required**			no crops located in ecoregion from SPAM model
PA1101	**not required**			no crops located in ecoregion from SPAM model
PA1102	**not required**			no crops located in ecoregion from SPAM model
PA1104	**not required**			no crops located in ecoregion from SPAM model
PA1105	**PA0603**	6.6129E-17	4.50079E-17	Crops located within ecoregion from Spam model
PA1107	**not required**			no crops located in ecoregion from SPAM model
PA1108	**PA0608, PA0611**	2.77029E-17	4.50079E-17	Crops located within ecoregion from Spam model
PA1109	**not required**			no crops located in ecoregion from SPAM model

PA1111	**not required**			no crops located in ecoregion from SPAM model
PA1113	**not required**			no crops located in ecoregion from SPAM model
PA1114	**not required**			no crops located in ecoregion from SPAM model
PA1304	**PA0905, PA1321, PA1212**	7.9341E-16	4.16485E-16	Crops located within ecoregion from Spam model
PA1333	**PA1327, PA1329, AT0713**	1.04965E-16	6.67506E-17	Crops located within ecoregion from Spam model

4. SI.4 - Disaggregated CF results

a. Disaggregated LC-Impact characterisation factor results – Land Use

Table S12. Tailored, crop-specific CFs for land occupation

Environmental Pressure	**Stressor name**	**Units**	**AT**	**BE**	**BG**	**CY**	**CZ**	**DE**	**DK**	**EE**	**ES**	**FI**	**FR**	**GR**	**HR**
Land Occupation Average	Paddy rice	[PDF-eq/m2]	0	0	8.72E-16	0	0	0	0	0	6.53E-15	0	5.60E-15	4.63E-15	0
Land Occupation Average	Wheat	[PDF-eq/m2]	5.55E-16	5.33E-16	7.83E-16	8.78E-15	4.93E-16	4.88E-16	4.80E-16	2.74E-16	6.29E-15	3.55E-17	7.12E-16	5.88E-15	6.06E-16
Land Occupation Average	Cereal grains Nec	[PDF-eq/m2]	6.49E-16	5.34E-16	7.91E-16	8.78E-15	4.97E-16	4.90E-16	4.80E-16	2.74E-16	6.36E-15	3.78E-17	7.34E-16	6.06E-15	1.32E-15
Land Occupation Average	Sugar	[PDF-eq/m2]	5.20E-16	5.35E-16	1.72E-15	0	5.02E-16	4.98E-16	5.13E-16	2.74E-16	6.04E-15	4.81E-17	2.05E-15	4.87E-15	5.55E-16
Land Occupation Average	Oil seeds	[PDF-eq/m2]	5.94E-16	5.26E-16	7.79E-16	8.78E-15	4.97E-16	4.87E-16	4.78E-16	2.74E-16	6.49E-15	4.82E-17	6.77E-16	6.07E-15	1.54E-15
Land Occupation Average	Plant-based fibers	[PDF-eq/m2]	6.96E-16	5.34E-16	8.39E-16	0	4.88E-16	5.12E-16	0	2.74E-16	2.81E-15	0	8.89E-16	0	5.51E-16
Land Occupation Average	Crops Nec	[PDF-eq/m2]	5.64E-16	5.36E-16	8.64E-16	8.78E-15	5.10E-16	4.92E-16	5.23E-16	2.74E-16	6.31E-15	3.10E-17	1.61E-15	5.52E-15	1.68E-15
Land Occupation Average	Vegetables, fruit, nuts	[PDF-eq/m2]	3.72E-16	3.30E-16	5.28E-16	4.94E-15	3.10E-16	2.99E-16	3.14E-16	1.53E-16	4.31E-15	9.26E-17	1.80E-15	3.89E-15	1.05E-15
Environmental Pressure	**Stressor name**	**Units**	**HU**	**IE**	**IT**	**LT**	**LU**	**LV**	**MT**	**NL**	**PL**	**PT**	**RO**	**SE**	**SI**
Land Occupation Average	Paddy rice	[PDF-eq/m2]	5.51E-16	0	2.10E-15	0	0	0	0	0	2.98E-15	6.06E-15	7.63E-16	0	0
Land Occupation Average	Wheat	[PDF-eq/m2]	5.51E-16	2.61E-16	5.92E-15	3.47E-16	4.63E-16	2.74E-16	8.43E-15	5.36E-16	5.86E-16	6.15E-15	7.19E-16	3.13E-16	8.30E-16
Land Occupation Average	Cereal grains Nec	[PDF-eq/m2]	5.51E-16	2.60E-16	3.44E-15	3.38E-16	4.63E-16	2.74E-16	8.43E-15	5.36E-16	5.33E-16	4.73E-15	6.94E-16	3.12E-16	8.51E-16
Land Occupation Average	Sugar	[PDF-eq/m2]	5.51E-16	0	5.05E-15	3.74E-16	4.63E-16	2.74E-16	0	5.36E-16	5.18E-16	5.12E-15	9.34E-16	4.28E-16	5.51E-16
Land Occupation Average	Oil seeds	[PDF-eq/m2]	5.51E-16	2.60E-16	6.33E-15	3.31E-16	4.63E-16	2.74E-16	8.43E-15	5.36E-16	5.21E-16	6.02E-15	6.82E-16	3.27E-16	9.62E-16
Land Occupation Average	Plant-based fibers	[PDF-eq/m2]	5.51E-16	0	3.01E-15	4.72E-16	4.63E-16	2.74E-16	0	5.36E-16	6.04E-16	0	7.43E-16	0	2.94E-15
Land Occupation Average	Crops Nec	[PDF-eq/m2]	5.51E-16	2.61E-16	5.18E-15	3.53E-16	4.63E-16	2.74E-16	0	5.36E-16	5.89E-16	5.21E-15	7.20E-16	0	2.18E-15
Land Occupation Average	Vegetables, fruit, nuts	[PDF-eq/m2]	3.39E-16	1.51E-16	3.51E-15	2.03E-16	2.76E-16	1.53E-16	5.19E-15	3.32E-16	4.01E-16	3.17E-15	4.83E-16	1.83E-16	7.89E-16
Environmental Pressure	**Stressor name**	**Units**	**SK**	**GB**	**US**	**JP**	**CN**	**CA**	**KR**	**BR**	**IN**	**MX**	**RU**	**AU**	**CH**
Land Occupation Average	Paddy rice	[PDF-eq/m2]	0	0	2.05E-15	3.25E-15	1.89E-15	0	1.39E-15	2.97E-15	3.03E-15	9.97E-15	8.91E-16	1.44E-15	2.78E-15
Land Occupation Average	Wheat	[PDF-eq/m2]	8.14E-16	3.22E-16	5.95E-16	2.92E-15	1.38E-15	4.38E-16	1.40E-15	3.19E-15	1.88E-15	4.22E-15	5.19E-16	5.13E-15	5.16E-16
Land Occupation Average	Cereal grains Nec	[PDF-eq/m2]	6.86E-16	3.08E-16	6.18E-16	3.15E-15	1.30E-15	4.65E-16	1.54E-15	2.98E-15	2.19E-15	9.87E-15	5.17E-16	4.44E-15	6.10E-16
Land Occupation Average	Sugar	[PDF-eq/m2]	5.61E-16	3.22E-16	1.99E-15	9.02E-15	3.67E-15	4.34E-16	0	5.00E-15	2.63E-15	1.21E-14	6.14E-16	1.47E-14	5.78E-16
Land Occupation Average	Oil seeds	[PDF-eq/m2]	7.98E-16	3.22E-16	6.71E-16	3.28E-15	1.37E-15	4.56E-16	1.46E-15	2.36E-15	1.89E-15	7.79E-15	7.06E-16	6.24E-15	4.99E-16

Land Occupation Average	Plant-based fibers	[PDF-eq/m2]	9.87E-16	3.26E-16	3.67E-16	0	1.83E-15	4.35E-16	1.17E-15	1.74E-15	2.80E-15	1.13E-14	1.89E-16	0	4.63E-16
Land Occupation Average	Crops Nec	[PDF-eq/m2]	5.75E-16	3.27E-16	4.54E-15	5.33E-15	2.34E-15	6.49E-16	1.40E-15	9.51E-15	4.28E-15	1.42E-14	6.53E-16	4.48E-15	7.19E-16
Land Occupation Average	Vegetables, fruit, nuts	[PDF-eq/m2]	5.18E-16	1.92E-16	1.62E-15	2.43E-15	1.29E-15	3.11E-16	9.63E-16	3.37E-15	2.15E-15	5.60E-15	3.48E-16	2.22E-15	5.83E-16

Environmental Pressure	Stressor name	Units	TR	TW	NO	ID	ZA	WA	WL	WE	WF	WM
Land Occupation Average	Paddy rice	[PDF-eq/m2]	2.68E-15	2.45E-14	0	1.18E-14	2.71E-15	5.42E-15	1.07E-14	8.58E-16	4.67E-15	2.01E-15
Land Occupation Average	Wheat	[PDF-eq/m2]	4.11E-15	2.45E-14	1.11E-16	0	1.68E-14	7.06E-16	2.15E-15	7.53E-16	2.82E-15	2.15E-15
Land Occupation Average	Cereal grains Nec	[PDF-eq/m2]	4.39E-15	2.45E-14	7.64E-17	1.14E-14	3.28E-15	7.23E-15	7.44E-15	7.04E-16	1.43E-15	2.12E-15
Land Occupation Average	Sugar	[PDF-eq/m2]	3.49E-15	2.45E-14	0	1.15E-14	4.96E-15	6.83E-15	1.52E-14	5.67E-16	6.61E-15	1.00E-15
Land Occupation Average	Oil seeds	[PDF-eq/m2]	5.15E-15	2.42E-14	7.49E-17	1.01E-14	3.52E-15	4.86E-15	1.75E-15	7.72E-16	1.80E-15	3.64E-15
Land Occupation Average	Plant-based fibers	[PDF-eq/m2]	1.95E-15	2.45E-14	0	1.21E-14	2.63E-14	5.34E-15	1.96E-14	3.79E-16	5.32E-15	3.14E-16
Land Occupation Average	Crops Nec	[PDF-eq/m2]	4.33E-15	2.44E-14	0	1.09E-14	1.27E-14	1.07E-14	1.82E-14	1.73E-15	4.29E-15	2.40E-15
Land Occupation Average	Vegetables, fruit, nuts	[PDF-eq/m2]	2.95E-15	1.76E-14	8.99E-17	9.14E-15	7.89E-15	7.19E-15	1.23E-14	5.69E-16	1.93E-15	1.05E-15

Table S13. Relative divergence in national/continental land occupation CFs post-disaggregation compared with current LC-IMPACT CFs for Annual cropland and Permanent cropland.

	Vegetables, fruit, nuts	Paddy rice	Wheat	Cereal grains Nec	Sugar	Oil seeds	Plant-based fibers	Crops Nec
Austria	-70.24%	-100.00%	-69.34%	-64.14%	-71.27%	-67.18%	-61.55%	-68.84%
Belgium	4.10%	-100.00%	3.09%	3.29%	3.48%	1.74%	3.29%	3.68%
Bulgaria	-18.64%	-20.73%	-28.82%	-28.09%	56.36%	-29.18%	-23.73%	-21.45%
Cyprus	1.86%	-100.00%	1.74%	1.74%	-100.00%	1.74%	-100.00%	1.74%
Czech Republic	-4.91%	-100.00%	-6.81%	-6.05%	-5.10%	-6.05%	-7.75%	-3.59%
Germany	-2.92%	-100.00%	-2.98%	-2.58%	-0.99%	-3.18%	1.79%	-2.19%
Denmark	12.54%	-100.00%	8.35%	8.35%	15.80%	7.90%	-100.00%	18.06%
Estonia	2.00%	-100.00%	1.48%	1.48%	1.48%	1.48%	1.48%	1.48%
Spain	19.72%	14.96%	10.74%	11.97%	6.34%	14.26%	-50.53%	11.09%
Finland	4.04%	-100.00%	3.20%	9.88%	39.83%	40.12%	-100.00%	-9.88%
France	126.42%	317.91%	-46.87%	-45.22%	52.99%	-49.48%	-33.66%	20.15%
Greece	9.89%	-24.22%	-3.76%	-0.82%	-20.29%	-0.65%	-100.00%	-9.66%
Croatia	-21.05%	-100.00%	-71.81%	-38.60%	-74.19%	-28.37%	-74.37%	-21.86%
Hungary	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Ireland	4.86%	-100.00%	6.97%	6.56%	-100.00%	6.56%	-100.00%	6.97%
Italy	10.38%	-59.22%	14.95%	-33.20%	-1.94%	22.91%	-41.55%	0.58%
Lithuania	-0.49%	-100.00%	-0.57%	-3.15%	7.16%	-5.16%	35.24%	1.15%

Luxembourg	0.00%	-100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Latvia	0.00%	-100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Malta	32.40%	-100.00%	32.34%	32.34%	-100.00%	32.34%	-100.00%	-100.00%
Netherlands	1.84%	-100.00%	1.71%	1.71%	1.71%	1.71%	1.71%	1.71%
Poland	-2.43%	367.82%	-8.01%	-16.33%	-18.68%	-18.21%	-5.18%	-7.54%
Portugal	-1.55%	14.77%	16.48%	-10.42%	-3.03%	14.02%	-100.00%	-1.33%
Romania	-38.00%	-33.65%	-37.48%	-39.65%	-18.78%	-40.70%	-35.39%	-37.39%
Sweden	75.96%	-100.00%	203.88%	202.91%	315.53%	217.48%	-100.00%	-100.00%
Slovenia	-19.16%	-100.00%	-45.39%	-44.01%	-63.75%	-36.71%	93.42%	43.42%
Slovakia	-47.52%	-100.00%	-43.08%	-52.03%	-60.77%	-44.20%	-30.98%	-59.79%
Great Britain	6.67%	-100.00%	11.42%	6.57%	11.42%	11.42%	12.80%	13.15%
United States	217.65%	180.82%	-18.49%	-15.34%	172.60%	-8.08%	-49.73%	521.92%
Japan	8.48%	-2.69%	-12.57%	-5.69%	170.06%	-1.80%	-100.00%	59.58%
China	51.94%	54.92%	13.11%	6.56%	200.82%	12.30%	50.00%	91.80%
Canada	240.64%	-100.00%	361.54%	389.99%	357.32%	380.51%	358.38%	583.88%
South Korea	11.46%	12.10%	12.90%	24.19%	-100.00%	17.74%	-5.65%	12.90%
Brazil	35.34%	-17.04%	-10.89%	-16.76%	39.66%	-34.08%	-51.40%	165.64%
India	-7.73%	-5.61%	-41.43%	-31.78%	-18.07%	-41.12%	-12.77%	33.33%
Mexico	10.24%	42.84%	-39.54%	41.40%	73.35%	11.60%	61.89%	103.44%
Russia	300.92%	885.62%	474.12%	471.90%	579.20%	680.97%	109.07%	622.35%
Australia	109.43%	-13.77%	207.19%	165.87%	780.24%	273.65%	-100.00%	168.26%
Switzerland	-52.21%	56.18%	-71.01%	-65.73%	-67.53%	-71.97%	-73.99%	-59.61%
Turkey	23.43%	-32.15%	4.05%	11.14%	-11.65%	30.38%	-50.63%	9.62%
Norway	63.75%	-100.00%	100.72%	38.16%	-100.00%	35.44%	-100.00%	-100.00%
Indonesia	13.82%	7.27%	-100.00%	3.64%	4.55%	-8.18%	10.00%	-0.91%
South Africa	117.36%	-54.30%	183.31%	-44.69%	-16.36%	-40.64%	343.51%	114.17%
RoW_Asia_and_Pacific	599.81%	282.78%	-50.14%	410.60%	382.35%	243.23%	277.13%	655.67%
RoW_America	325.06%	168.67%	-46.02%	86.81%	281.66%	-56.06%	392.14%	356.99%
RoW_Europe	4.68%	2.74%	-9.83%	-15.70%	-32.10%	-7.55%	-54.62%	107.16%
RoW_Africa	67.83%	179.64%	68.86%	-14.37%	295.81%	7.78%	218.56%	156.89%
RoW_Middle_East	2.20%	41.95%	51.84%	49.72%	-29.38%	157.07%	-77.82%	69.50%
Taiwan	1973.03%	1908.20%	1908.20%	1908.20%	1908.20%	1883.61%	1908.20%	1900.00%

b. Disaggregated LC-Impact characterisation factor results – Water stress

Table S14. Tailored, crop-specific CFs for water stress of wetlands

Environmental Pressure	**Stressor name**	**Units**	**AT**	**BE**	**BG**	**CY**	**CZ**	**DE**	**DK**	**EE**	**ES**	**FI**	**FR**	**GR**
Blue water consumption - core	Agriculture - Wheat	[PDF·yr/m3]	1.87E-14	2.76E-16	3.77E-15	7.68E-14	0	5.98E-15	6.37E-16	0	1.53E-14	0	6.67E-16	4.18E-15
Blue water consumption - core	Agriculture - Paddy rice	[PDF·yr/m3]	0	0	3.32E-15	0	0	0	0	0	1.49E-14	0	0	3.74E-15
Blue water consumption - core	Agriculture - Cereals nec	[PDF·yr/m3]	1.87E-14	3.26E-16	6.36E-15	6.79E-14	0	3.13E-15	6.39E-16	0	1.35E-14	4.84E-16	9.13E-16	4.75E-15
Blue water consumption - core	Agriculture - Oil seeds	[PDF·yr/m3]	1.87E-14	4.50E-16	6.56E-15	0	0	5.98E-15	0	0	1.50E-14	0	7.74E-16	4.57E-15
Blue water consumption - core	Agriculture - Sugar	[PDF·yr/m3]	1.87E-14	2.71E-16	3.72E-15	0	6.84E-15	2.80E-15	6.86E-16	3.05E-16	9.49E-15	4.48E-16	6.86E-16	3.81E-15
Blue water consumption - core	Agriculture - Plant-based fibers	[PDF·yr/m3]	1.87E-14	4.06E-16	3.86E-15	0	0	1.48E-15	0	0	1.50E-14	0	7.58E-16	4.14E-15
Blue water consumption - core	Agriculture - Crops nec	[PDF·yr/m3]	1.87E-14	3.18E-16	5.15E-15	8.55E-14	7.57E-15	6.44E-15	0	0	9.00E-15	0	1.69E-15	3.66E-15
Blue water consumption - core	Agriculture - Vegetables, fruit, nuts	[PDF·yr/m3]	1.87E-14	3.09E-16	4.96E-15	7.20E-14	7.80E-15	2.59E-15	6.20E-16	0	1.46E-14	4.68E-16	1.02E-15	7.67E-15
Blue water consumption - core	Agriculture - Fodder crops	[PDF·yr/m3]	1.87E-14	4.23E-16	6.18E-15	6.93E-14	6.65E-15	2.94E-15	5.93E-16	2.57E-16	1.34E-14	5.37E-16	7.54E-16	5.42E-15
Environmental Pressure	**Stressor name**	**Units**	**HR**	**HU**	**IE**	**IT**	**LT**	**LU**	**LV**	**MT**	**NL**	**PL**	**PT**	**RO**
Blue water consumption - core	Agriculture - Wheat	[PDF·yr/m3]	0	0	0	4.50E-15	2.48E-16	0	2.47E-16	0	0	0	5.33E-15	0
Blue water consumption - core	Agriculture - Paddy rice	[PDF·yr/m3]	0	0	0	4.33E-15	0	0	0	0	0	0	5.90E-15	0
Blue water consumption - core	Agriculture - Cereals nec	[PDF·yr/m3]	4.93E-15	1.31E-14	0	3.87E-15	2.47E-16	0	2.47E-16	0	7.61E-16	4.09E-16	4.85E-15	1.26E-14
Blue water consumption - core	Agriculture - Oil seeds	[PDF·yr/m3]	0	1.31E-14	0	0	2.47E-16	0	2.47E-16	0	0	6.36E-15	5.22E-15	1.24E-14
Blue water consumption - core	Agriculture - Sugar	[PDF·yr/m3]	1.19E-14	1.31E-14	0	6.50E-15	2.40E-16	0	2.68E-16	0	9.82E-16	3.84E-16	4.18E-15	1.24E-14
Blue water consumption - core	Agriculture - Plant-based fibers	[PDF·yr/m3]	0	1.31E-14	0	3.61E-15	2.53E-16	0	0	0	0	4.18E-16	0	1.28E-14
Blue water consumption - core	Agriculture - Crops nec	[PDF·yr/m3]	1.19E-14	1.31E-14	0	4.09E-15	0	0	0	0	0	3.80E-16	5.16E-15	1.27E-14
Blue water consumption - core	Agriculture - Vegetables, fruit, nuts	[PDF·yr/m3]	7.65E-15	1.31E-14	6.07E-16	4.46E-15	2.47E-16	0	2.71E-16	4.57E-15	9.67E-16	3.98E-16	4.67E-15	1.24E-14
Blue water consumption - core	Agriculture - Fodder crops	[PDF·yr/m3]	7.63E-15	1.31E-14	6.81E-16	4.47E-15	2.54E-16	5.80E-15	3.02E-16	0	9.96E-16	4.07E-16	5.28E-15	1.23E-14
Environmental Pressure	**Stressor name**	**Units**	**SE**	**SI**	**SK**	**GB**	**US**	**JP**	**CN**	**CA**	**KR**	**BR**	**IN**	**MX**
Blue water consumption - core	Agriculture - Wheat	[PDF·yr/m3]	0	1.25E-14	1.37E-14	0	7.84E-13	8.25E-15	3.25E-15	3.34E-13	0	3.91E-15	1.69E-14	9.51E-15
Blue water consumption - core	Agriculture - Paddy rice	[PDF·yr/m3]	0	0	0	0	4.58E-13	2.04E-14	2.02E-15	0	4.65E-14	1.63E-15	1.12E-14	9.02E-15
Blue water consumption - core	Agriculture - Cereals nec	[PDF·yr/m3]	3.42E-16	7.02E-15	1.37E-14	0	1.63E-12	1.54E-14	3.32E-15	3.16E-13	4.80E-14	2.74E-15	1.27E-14	2.94E-14
Blue water consumption - core	Agriculture - Oil seeds	[PDF·yr/m3]	0	1.25E-14	1.37E-14	0	1.48E-12	0	2.76E-15	3.46E-13	0	2.89E-15	1.05E-14	1.79E-14
Blue water consumption - core	Agriculture - Sugar	[PDF·yr/m3]	4.72E-16	1.25E-14	1.37E-14	5.34E-16	2.48E-12	1.31E-14	2.15E-15	3.61E-13	0	2.75E-15	1.04E-14	9.87E-15

Blue water consumption - core	Agriculture - Plant-based fibers	[PDF·yr/m3]	0	0	0	0	9.68E-13	0	5.37E-15	1.81E-13	0	2.15E-15	1.18E-14	1.99E-14

Environmental Pressure	**Stressor name**	**Units**	**SE**	**SI**	**SK**	**GB**	**US**	**JP**	**CN**	**CA**	**KR**	**BR**	**IN**	**MX**
Blue water consumption - core	Agriculture - Crops nec	[PDF·yr/m3]	0	1.25E-14	1.37E-14	0	7.41E-12	0	1.45E-14	1.86E-13	4.68E-14	2.27E-15	1.19E-14	1.08E-14
Blue water consumption - core	Agriculture - Vegetables, fruit, nuts	[PDF·yr/m3]	5.04E-16	9.80E-15	1.37E-14	5.41E-16	9.41E-14	1.48E-14	3.49E-15	6.83E-14	4.70E-14	3.31E-15	1.37E-14	1.30E-14
Blue water consumption - core	Agriculture - Fodder crops	[PDF·yr/m3]	6.08E-16	1.13E-14	1.37E-14	5.75E-16	1.02E-12	1.84E-14	5.44E-15	2.69E-13	4.72E-14	3.05E-15	1.18E-14	1.56E-14

Environmental Pressure	**Stressor name**	**Units**	**RU**	**AU**	**CH**	**TR**	**TW**	**NO**	**ID**	**ZA**	**WA**	**WL**	**WE**	**WF**
Blue water consumption - core	Agriculture - Wheat	[PDF·yr/m3]	2.04E-14	1.23E-12	0	2.14E-14	0	0	0	3.04E-14	3.81E-14	2.63E-14	1.49E-15	1.34E-14
Blue water consumption - core	Agriculture - Paddy rice	[PDF·yr/m3]	3.68E-14	5.12E-13	0	1.56E-15	2.72E-13	0	2.33E-14	0	4.00E-14	5.98E-14	2.81E-15	4.11E-14
Blue water consumption - core	Agriculture - Cereals nec	[PDF·yr/m3]	1.98E-15	1.06E-12	5.36E-15	2.46E-14	0	1.02E-15	9.55E-15	2.37E-14	3.92E-14	5.82E-14	1.95E-15	1.51E-14
Blue water consumption - core	Agriculture - Oil seeds	[PDF·yr/m3]	4.29E-15	3.69E-12	0	2.24E-15	0	0	2.43E-14	5.52E-15	2.40E-14	1.35E-14	1.53E-15	9.59E-15
Blue water consumption - core	Agriculture - Sugar	[PDF·yr/m3]	9.19E-15	4.08E-12	3.89E-15	2.62E-14	0	0	2.03E-14	5.52E-15	3.74E-14	3.56E-14	3.62E-15	1.22E-14
Blue water consumption - core	Agriculture - Plant-based fibers	[PDF·yr/m3]	8.05E-16	1.25E-12	0	1.56E-15	0	0	0	7.43E-15	2.57E-14	6.61E-14	6.98E-16	5.58E-15
Blue water consumption - core	Agriculture - Crops nec	[PDF·yr/m3]	6.06E-16	0	7.72E-15	1.91E-14	3.22E-13	0	2.79E-14	3.79E-15	1.55E-14	7.75E-14	4.22E-15	5.68E-15
Blue water consumption - core	Agriculture - Vegetables, fruit, nuts	[PDF·yr/m3]	1.16E-14	1.85E-12	5.76E-15	2.36E-14	2.25E-13	1.18E-15	3.88E-14	1.11E-14	2.86E-14	9.75E-14	2.69E-15	3.36E-14
Blue water consumption - core	Agriculture - Fodder crops	[PDF·yr/m3]	5.84E-15	1.53E-12	6.99E-15	2.23E-14	2.47E-13	8.54E-16	0	2.70E-14	1.14E-14	3.95E-14	2.07E-15	4.77E-14

Environmental Pressure	**Stressor name**	**Units**	**WM**
Blue water consumption - core	Agriculture - Wheat	[PDF·yr/m3]	1.95E-14
Blue water consumption - core	Agriculture - Paddy rice	[PDF·yr/m3]	1.65E-14
Blue water consumption - core	Agriculture - Cereals nec	[PDF·yr/m3]	2.08E-14
Blue water consumption - core	Agriculture - Oil seeds	[PDF·yr/m3]	2.34E-14
Blue water consumption - core	Agriculture - Sugar	[PDF·yr/m3]	2.57E-14
Blue water consumption - core	Agriculture - Plant-based fibers	[PDF·yr/m3]	1.72E-14
Blue water consumption - core	Agriculture - Crops nec	[PDF·yr/m3]	5.66E-14
Blue water consumption - core	Agriculture - Vegetables, fruit, nuts	[PDF·yr/m3]	1.70E-14
Blue water consumption - core	Agriculture - Fodder crops	[PDF·yr/m3]	2.26E-14

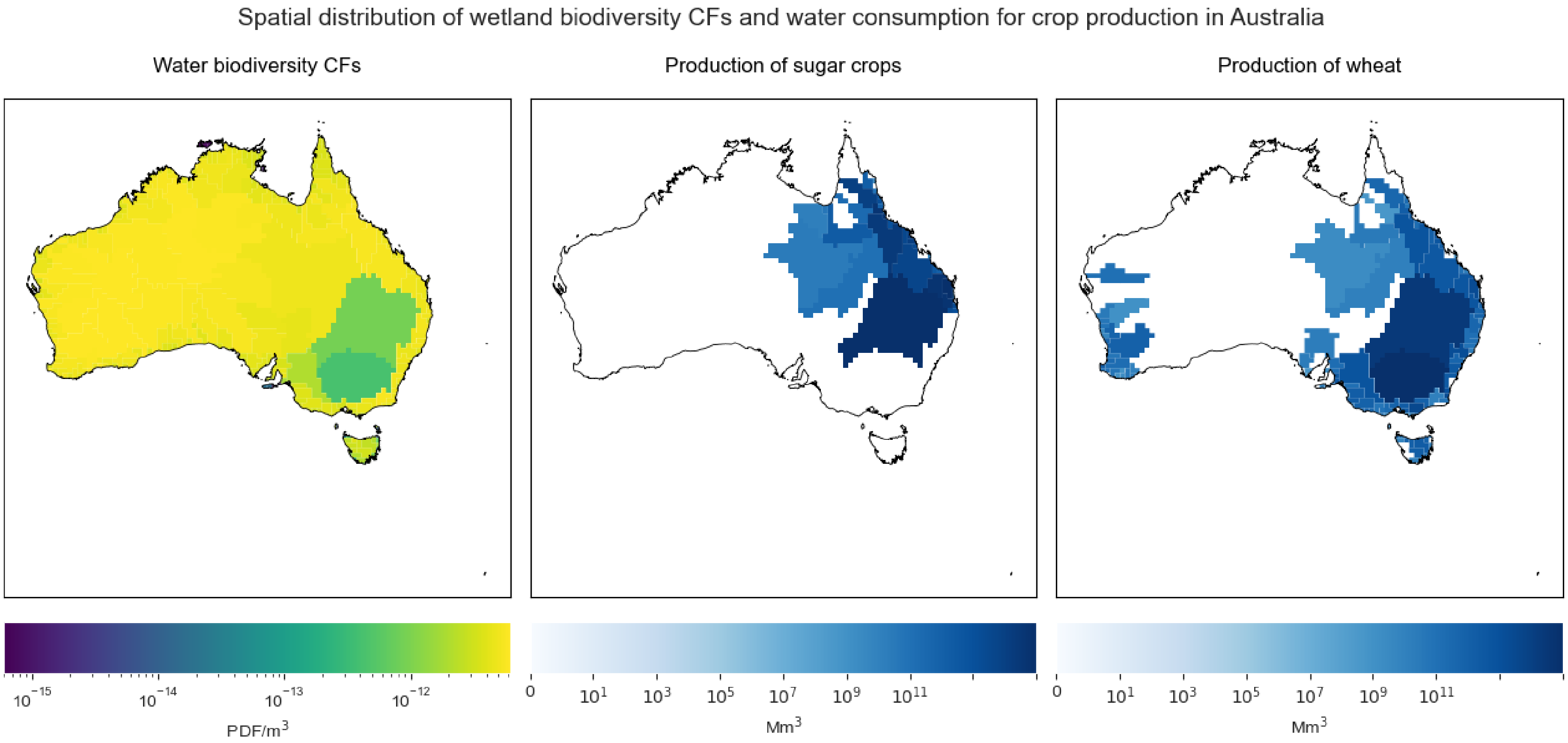

Figure S3. Three panel series of the Australian continent. The left panel maps the spatial distribution of LC-IMPACT wetland biodiversity impact CFs at the watershed level. The middle panel visualises the geographical distribution of sugar crop irrigation requirements for the year 2010 after merging of the mapSPAM model and the (Pfister & Bayer, 2014b) water dataset. The right panel displays the resulting distribution of wheat irrigation for the year 2010 on the continent.

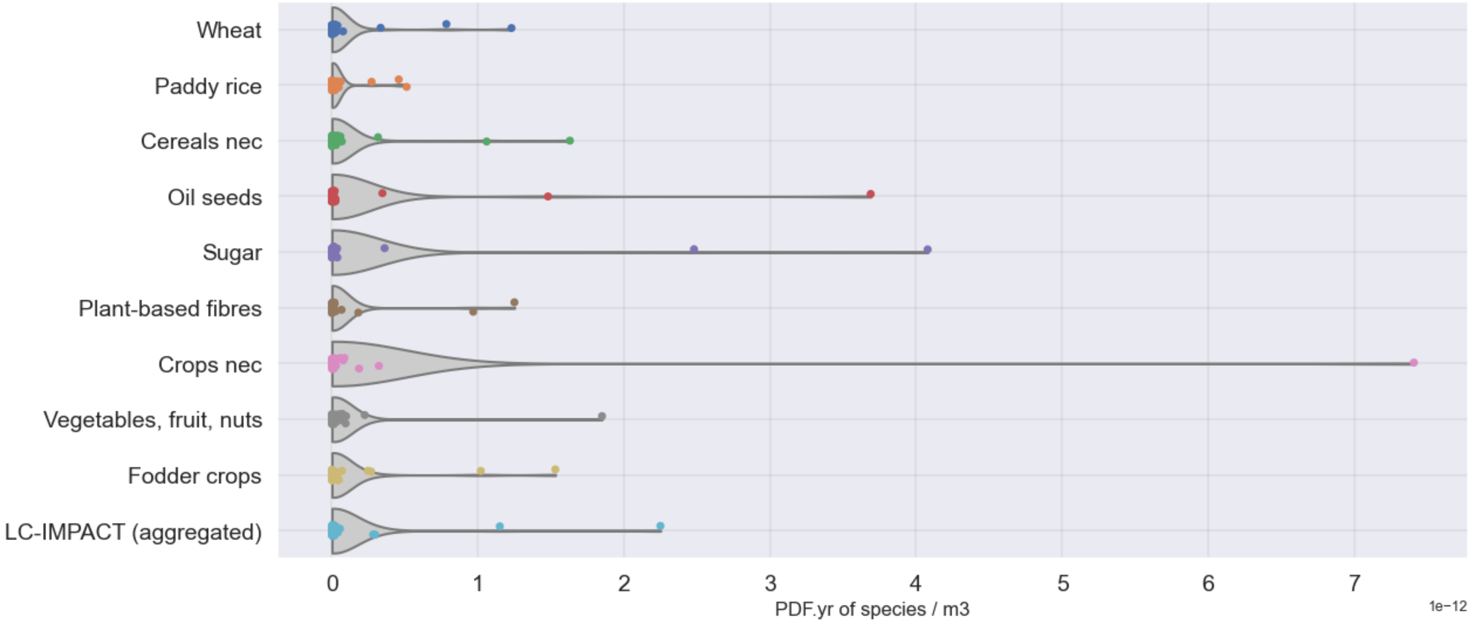

Figure S4. Violin plot of the distribution of LC-IMPACT wetland characterisation factors post disaggregation. The two consistent outliers across the crop categories are the national CFs for the US and Australia. Both have CFs orders of magnitude greater than most countries. Hence, the grouping of datapoints close to zero on this graph. The second plot below captures the distribution of the lower CF values in the violin plot for greater visualisation.

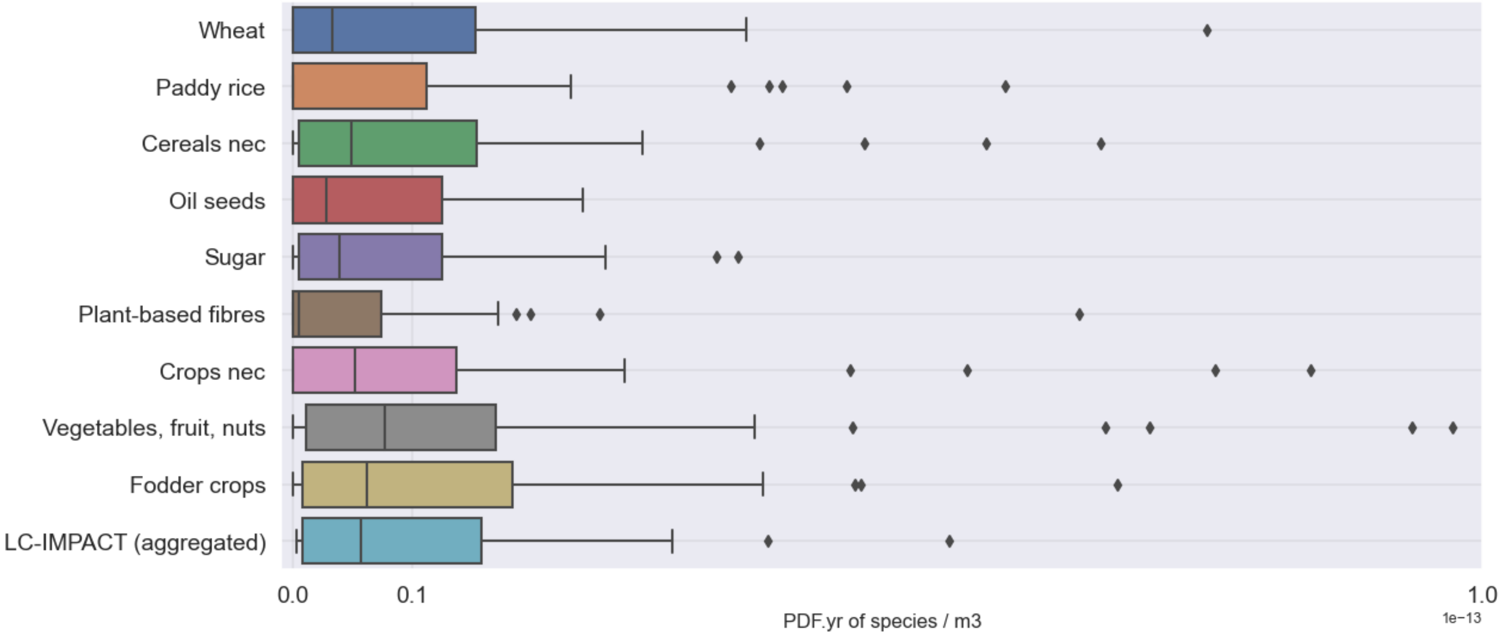

Figure S5. Distribution of the LC-IMPACT wetland characterisation factors post disaggregation minus the large outliers of Australia and the US. Many of the crop categories have a lower Inter-quartile at 0 and this is because a country's CF is assumed 0 if the crop is not grown in the region or if crop production is rainfed and does not require additional blue water irrigation.

Table S15. Relative divergence in national/continental wetland CFs post-disaggregation compared with current LC-IMPACT CF for blue water consumption.

	Wheat	Rice	Cereals nec	Oil seeds	Sugar	Plant-based fibers	Crops nec	Vegetables, fruit, nuts	Fodder crops
Austria	17%	-100%	17%	17%	17%	17%	17%	17%	17%
Belgium	-17%	-100%	-2%	36%	-18%	23%	-4%	-7%	28%
Bulgaria	-60%	-65%	-33%	-31%	-61%	-59%	-46%	-48%	-35%
Cyprus	39%	-100%	23%	-100%	-100%	-100%	55%	31%	26%
Czech Republic	-100%	-100%	-100%	-100%	68%	-100%	86%	91%	63%
Germany	42%	-100%	-26%	42%	-33%	-65%	53%	-38%	-30%
Denmark	30%	-100%	30%	-100%	40%	-100%	-100%	26%	21%
Estonia	-100%	-100%	-100%	-100%	8%	-100%	-100%	-100%	-9%
Spain	30%	26%	14%	27%	-20%	27%	-24%	24%	14%
Finland	-100%	-100%	32%	-100%	22%	-100%	-100%	27%	46%
France	8%	-100%	47%	25%	11%	22%	173%	65%	22%
Greece	-24%	-32%	-14%	-17%	-31%	-25%	-34%	39%	-2%
Croatia	-100%	-100%	-43%	-100%	37%	-100%	37%	-12%	-12%
Hungary	-100%	-100%	1%	1%	1%	1%	1%	1%	1%
Ireland	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-20%	-10%
Italy	32%	27%	13%	-100%	91%	6%	20%	31%	31%
Lithuania	-9%	-100%	-10%	-10%	-12%	-8%	-100%	-10%	-7%
Luxembourg	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	3%
Latvia	2%	-100%	2%	2%	11%	-100%	-100%	12%	25%
Malta	-100%	-100%	-100%	-100%	-100%	-100%	-100%	0%	-100%
Netherlands	-100%	-100%	45%	-100%	87%	-100%	-100%	85%	90%
Poland	-100%	-100%	-5%	1379%	-11%	-3%	-12%	-7%	-5%
Portugal	26%	39%	15%	23%	-1%	-100%	22%	10%	25%
Romania	-100%	-100%	199%	195%	195%	204%	202%	195%	192%
Sweden	-100%	-100%	-26%	-100%	2%	-100%	-100%	9%	31%
Slovenia	-53%	-100%	-74%	-53%	-53%	-100%	-53%	-63%	-58%
Slovakia	28%	-100%	28%	28%	28%	-100%	28%	28%	28%
Great Britain	-100%	-100%	-100%	-100%	-16%	-100%	-100%	-14%	-9%
United States	-32%	-60%	42%	29%	116%	-16%	544%	-92%	-11%
Japan	-36%	59%	20%	-100%	2%	-100%	-100%	16%	44%
China	40%	-13%	43%	19%	-7%	131%	525%	50%	134%
Canada	18%	-100%	12%	22%	28%	-36%	-34%	-76%	-5%
South Korea	-100%	17%	20%	-100%	-100%	-100%	17%	18%	18%

Brazil	42%	-41%	-1%	5%	0%	-22%	-18%	20%	11%
India	51%	0%	13%	-6%	-7%	5%	6%	22%	5%
Mexico	-23%	-27%	137%	44%	-20%	60%	-13%	5%	26%
Russia	445%	884%	-47%	15%	146%	-78%	-84%	210%	56%
Australia	-45%	-77%	-53%	64%	81%	-44%	-100%	-18%	-32%
Switzerland	-100%	-100%	-30%	-100%	-49%	-100%	1%	-25%	-9%
Turkey	11%	-92%	28%	-88%	36%	-92%	-1%	23%	16%
Taiwan	-100%	-8%	-100%	-100%	-100%	-100%	9%	-24%	-17%
Norway	-100%	-100%	155%	-100%	-100%	-100%	-100%	195%	114%
Indonesia	-100%	-20%	-67%	-17%	-30%	-100%	-4%	33%	-100%
South Africa	73%	-100%	35%	-69%	-69%	-58%	-78%	-37%	53%
RoW_Asia_and_Pacific	161%	174%	168%	64%	156%	76%	6%	96%	-22%
RoW_America	-18%	87%	82%	-58%	12%	107%	143%	206%	24%
RoW_Europe	-67%	-39%	-57%	-67%	-21%	-85%	-8%	-41%	-55%
RoW_Africa	-15%	160%	-4%	-39%	-23%	-65%	-64%	113%	202%
RoW_Middle_East	34%	13%	42%	60%	76%	18%	288%	16%	55%

5. SI.5 – National production-based accounts of biodiversity impacts

a. Production based accounts – Total country level impacts

Table S16. Absolute national production-based biodiversity impacts of global agriculture and food demand in [PDF.yr] for the year 2010. The land occupation and wetland impact pathway results are mutually exclusive and are not to be compared against one another.

Region	Land occupation impacts	Wetland impacts	Region	Land occupation impacts	Wetland impacts	Region	Land occupation impacts	Wetland impacts
AT	4.87E-06	8.42E-07	NL	2.41E-06	5.18E-07	**TW**	0.000166043	0
BE	2.33E-06	2.77E-09	PL	4.54E-05	7.12E-07	**NO**	6.13E-07	6.34E-09
BG	1.88E-05	5.65E-07	PT	4.41E-05	6.86E-06	**ID**	0.002750056	0.000172895
CY	4.94E-06	1.02E-05	RO	4.32E-05	5.55E-06	**ZA**	0.00059079	5.18E-05
CZ	9.74E-06	6.80E-08	**SE**	5.49E-06	6.45E-09	**WA**	0.004778489	0.004227756
DE	3.38E-05	4.89E-07	**SI**	1.03E-06	3.78E-08	**WL**	0.003749031	0.001301895
DK	6.56E-06	3.53E-08	**SK**	6.53E-06	1.35E-06	**WE**	0.000167524	4.39E-06
EE	1.27E-06	7.72E-12	**GB**	1.30E-05	4.58E-08	**WF**	0.00337615	0.001006848
ES	0.00068056	0.000161785	**US**	0.000746314	0.096570149	**WM**	0.000326691	0.00154856
FI	6.94E-07	4.01E-09	**JP**	0.000126402	2.63E-05			
FR	0.000120531	1.72E-06	**CN**	0.001171624	0.000255598			
GR	0.000143837	1.36E-05	**CA**	0.000152811	0.000104887			
HR	8.31E-06	2.67E-08	**KR**	1.44E-05	2.43E-05			
HU	1.61E-05	1.43E-06	**BR**	0.001759109	1.82E-05			
IE	1.87E-06	2.12E-10	**IN**	0.003291267	0.003501754			
IT	0.000285728	1.67E-05	**MX**	0.002177891	0.000256046			
LT	5.46E-06	6.37E-10	**RU**	0.000454423	8.35E-05			
LU	1.04E-07	2.30E-14	**AU**	0.001384168	0.008823313			
LV	2.33E-06	9.70E-11	**CH**	9.07E-07	5.48E-09			
MT	4.12E-07	2.82E-08	**TR**	0.000807831	0.000266676			

b. Production based accounts – Individual stressor impacts by country

Table S17. Absolute national production-based biodiversity impacts of global agriculture and food demand for individual crop categories in [PDF.yr] for the year 2010.

STRESSOR CATEGORY	IMPACT PATHWAY	AT	BE	BG	CY	CZ	DE	DK	EE	ES	FI	FR	GR
CEREAL GRAINS NEC	**Land Occupation**	2.37E-06	4.57E-07	3.68E-06	2.04E-06	2.86E-06	1.21E-05	2.53E-06	5.24E-07	0.000173	3.85E-07	2.46E-05	2.19E-05
CROPS NEC	**Land Occupation**	1.57E-08	1.17E-09	4.87E-07	2.02E-09	3.40E-08	7.73E-08	3.14E-10	0	1.13E-06	0	1.17E-07	9.31E-07
OIL SEEDS	**Land Occupation**	6.73E-07	6.65E-08	6.66E-06	8.50E-07	2.10E-06	6.15E-06	6.26E-07	3.05E-07	0.000199	1.08E-07	1.58E-05	6.44E-05
PADDY RICE	**Land Occupation**	0	0	1.01E-07	0	0	0	0	0	1.05E-05	0	1.36E-06	1.72E-06
PLANT-BASED FIBERS	**Land Occupation**	6.23E-10	2.69E-08	8.22E-10	0	4.60E-11	0	0	5.19E-11	3.10E-07	0	5.49E-07	0
SUGAR	**Land Occupation**	1.36E-07	2.89E-07	0	0	3.08E-07	1.49E-06	1.61E-07	0	2.72E-06	9.60E-09	7.78E-06	7.49E-07
VEGETABLES, FRUIT, NUTS	**Land Occupation**	4.88E-07	5.70E-07	1.13E-06	1.57E-06	4.22E-07	1.92E-06	1.77E-07	5.26E-08	0.000167	7.45E-08	3.52E-05	2.27E-05
WHEAT	**Land Occupation**	1.19E-06	9.18E-07	6.77E-06	4.75E-07	4.02E-06	1.20E-05	3.07E-06	3.90E-07	0.000127	1.17E-07	3.51E-05	3.15E-05
AGRICULTURE - WHEAT	**Blue Water Consumption**	2.48E-11	0	3.02E-10	1.04E-07	0	1.04E-13	1.74E-08	0	3.19E-06	0	2.51E-08	1.54E-07
AGRICULTURE - RICE	**Blue Water Consumption**	0	0	1.26E-07	0	0	0	0	0	1.61E-05	0	0	4.07E-07
AGRICULTURE - OTHER CEREALS	**Blue Water Consumption**	5.81E-08	2.67E-10	1.59E-07	1.10E-07	0	3.13E-08	3.49E-10	0	2.37E-05	9.36E-11	9.86E-07	1.86E-06
AGRICULTURE - OIL CROPS	**Blue Water Consumption**	1.43E-08	5.07E-11	8.82E-08	0	0	1.50E-10	0	0	9.13E-06	0	7.52E-08	1.95E-07
AGRICULTURE - SUGAR CROPS	**Blue Water Consumption**	1.18E-07	1.87E-11	0	0	9.02E-12	1.40E-07	0	0	1.44E-06	2.08E-10	2.26E-08	1.34E-07
AGRICULTURE - FIBRES	**Blue Water Consumption**	0	1.32E-10	2.52E-11	0	0	0	0	0	0	0	1.47E-08	0
AGRICULTURE - OTHER CROPS	**Blue Water Consumption**	3.25E-10	3.17E-12	4.30E-08	0	6.19E-09	1.25E-09	0	0	1.87E-06	0	1.90E-10	2.32E-06
AGRICULTURE - FODDER CROPS	**Blue Water Consumption**	3.50E-10	0	5.67E-09	1.35E-06	0	1.47E-08	6.20E-09	7.72E-12	2.97E-06	4.19E-11	1.20E-07	0
AGRICULTURE - VEGETABLES	**Blue Water Consumption**	2.96E-07	1.74E-09	1.07E-07	1.46E-06	3.21E-08	1.26E-07	1.19E-09	0	5.80E-05	1.56E-09	1.89E-07	4.04E-06
AGRICULTURE - FRUITS	**Blue Water Consumption**	2.01E-07	2.14E-10	2.23E-08	5.74E-06	1.68E-08	2.26E-08	3.68E-10	0	3.88E-05	6.80E-10	1.33E-07	3.39E-06
AGRICULTURE - NUTS	**Blue Water Consumption**	1.06E-08	9.29E-13	9.21E-10	9.87E-07	7.15E-09	2.61E-10	2.47E-14	0	3.87E-06	0	2.90E-08	4.86E-07
AGRICULTURE - PULSES	**Blue Water Consumption**	4.41E-10	9.96E-11	5.99E-10	1.58E-07	5.09E-12	9.15E-11	2.16E-14	0	8.03E-07	5.50E-14	4.15E-08	1.30E-07
AGRICULTURE - ROOTS AND TUBERS	**Blue Water Consumption**	1.44E-07	2.44E-10	1.25E-08	2.94E-07	5.77E-09	1.53E-07	9.79E-09	0	1.84E-06	1.42E-09	8.31E-08	4.46E-07

STRESSOR CATEGORY	IMPACT PATHWAY	HR	HU	IE	IT	LT	LU	LV	MT	NL	PL	PT	RO
CEREAL GRAINS NEC	**Land Occupation**	4.44E-06	6.89E-06	1.19E-06	3.89E-05	1.94E-06	3.94E-08	7.24E-07	1.92E-08	1.48E-07	2.35E-05	7.63E-06	1.82E-05
CROPS NEC	**Land Occupation**	6.22E-08	5.14E-08	2.63E-10	1.17E-06	0	0	0	0	8.98E-10	9.11E-08	1.37E-08	5.26E-07
OIL SEEDS	**Land Occupation**	1.94E-06	3.56E-06	4.90E-08	7.35E-05	1.06E-06	1.34E-08	4.56E-07	3.25E-10	1.21E-08	4.63E-06	1.59E-05	7.41E-06
PADDY RICE	**Land Occupation**	0	1.09E-08	0	5.06E-06	0	0	0	0	0	0	1.66E-06	9.71E-08
PLANT-BASED FIBERS	**Land Occupation**	0	9.77E-10	0	8.85E-09	3.46E-11	0	1.97E-11	0	1.77E-08	8.94E-10	0	9.71E-09
SUGAR	**Land Occupation**	6.14E-09	5.32E-08	0	2.91E-06	7.10E-08	0	0	0	4.46E-07	6.79E-07	1.58E-08	2.14E-07
VEGETABLES, FRUIT, NUTS	**Land Occupation**	1.03E-06	9.13E-07	1.13E-07	8.01E-05	3.33E-07	6.34E-09	1.08E-07	2.89E-07	1.14E-06	4.67E-06	1.64E-05	4.49E-06
WHEAT	**Land Occupation**	8.26E-07	4.62E-06	5.20E-07	8.41E-05	2.05E-06	4.48E-08	1.04E-06	1.03E-07	6.41E-07	1.18E-05	2.40E-06	1.22E-05
AGRICULTURE - WHEAT	**Blue Water Consumption**	0	0	0	3.54E-07	7.79E-15	0	1.13E-14	0	0	0	5.07E-08	0
AGRICULTURE - RICE	**Blue Water Consumption**	0	0	0	2.60E-06	0	0	0	0	0	0	9.68E-07	0
AGRICULTURE - OTHER CEREALS	**Blue Water Consumption**	2.52E-09	2.36E-07	0	2.86E-06	3.45E-10	0	1.58E-11	0	9.21E-10	5.05E-09	1.95E-06	1.89E-06
AGRICULTURE - OIL CROPS	**Blue Water Consumption**	0	2.49E-07	0	0	3.00E-13	0	5.56E-13	0	0	6.90E-10	9.57E-08	2.12E-06
AGRICULTURE - SUGAR CROPS	**Blue Water Consumption**	0	3.86E-09	0	2.33E-07	1.80E-13	0	0	0	9.80E-10	1.42E-09	3.60E-09	2.95E-08
AGRICULTURE - FIBRES	**Blue Water Consumption**	0	0	0	6.23E-10	1.15E-14	0	0	0	0	3.85E-14	0	4.54E-11
AGRICULTURE - OTHER CROPS	**Blue Water Consumption**	0	4.70E-08	0	0	0	0	0	0	0	1.23E-12	5.68E-10	7.68E-08
AGRICULTURE - FODDER CROPS	**Blue Water Consumption**	0	1.01E-07	0	1.52E-06	1.46E-13	2.30E-14	8.73E-15	0	4.88E-07	6.87E-07	1.44E-06	1.24E-07
AGRICULTURE - VEGETABLES	**Blue Water Consumption**	7.93E-09	5.98E-07	6.77E-11	4.49E-06	1.61E-10	0	2.78E-11	1.16E-08	1.26E-08	3.48E-09	5.00E-07	8.56E-07
AGRICULTURE - FRUITS	**Blue Water Consumption**	1.09E-08	1.22E-07	1.05E-11	3.55E-06	1.30E-10	0	1.60E-11	9.57E-09	2.17E-09	1.14E-08	1.51E-06	2.23E-07
AGRICULTURE - NUTS	**Blue Water Consumption**	1.13E-09	8.40E-09	0	8.43E-07	0	0	0	0	0	6.97E-12	1.07E-07	1.28E-09
AGRICULTURE - PULSES	**Blue Water Consumption**	1.70E-10	3.17E-08	2.83E-13	3.02E-08	4.93E-13	0	0	0	2.59E-10	6.03E-12	3.42E-09	1.11E-08
AGRICULTURE - ROOTS AND TUBERS	**Blue Water Consumption**	4.03E-09	3.47E-08	1.33E-10	2.39E-07	1.91E-13	0	3.69E-11	7.09E-09	1.30E-08	3.20E-09	2.35E-07	2.15E-07

STRESSOR CATEGORY	IMPACT PATHWAY	SE	SI	SK	GB	US	JP	CN	CA	KR	BR	IN	MX
CEREAL GRAINS NEC	**Land Occupation**	2.10E-06	4.82E-07	1.99E-06	3.01E-06	0.000276	4.55E-06	0.00027	3.36E-05	7.34E-07	0.000403	0.000479	0.001414
CROPS NEC	**Land Occupation**	0	3.33E-08	4.84E-09	3.92E-09	4.73E-06	3.88E-06	2.47E-05	2.43E-07	1.77E-07	0.000341	0.000126	0.00017
OIL SEEDS	**Land Occupation**	7.53E-07	4.73E-08	1.82E-06	2.49E-06	0.000187	4.87E-06	8.58E-05	4.82E-05	1.03E-06	0.000311	0.000421	7.09E-05
PADDY RICE	**Land Occupation**	0	0	0	0	3.09E-05	6.76E-05	0.000277	0	8.20E-06	9.01E-05	0.001033	6.47E-06
PLANT-BASED FIBERS	**Land Occupation**	0	0	0	6.85E-09	9.00E-07	0	7.90E-07	6.82E-09	3.32E-11	3.95E-06	4.86E-06	3.28E-06
SUGAR	**Land Occupation**	2.28E-07	0	9.73E-08	3.65E-07	2.12E-05	1.05E-05	3.36E-05	6.64E-08	0	0.000283	7.36E-05	0.000127
VEGETABLES, FRUIT, NUTS	**Land Occupation**	2.93E-07	2.49E-07	4.42E-07	1.10E-06	0.000102	2.66E-05	0.000359	1.72E-05	4.14E-06	0.000276	0.000725	0.000343
WHEAT	**Land Occupation**	2.11E-06	2.21E-07	2.17E-06	5.98E-06	0.000123	8.35E-06	0.000121	5.35E-05	1.31E-07	5.13E-05	0.000429	4.42E-05
AGRICULTURE - WHEAT	**Blue Water Consumption**	0	1.00E-09	4.16E-08	0	0.003203	2.07E-08	8.72E-05	2.85E-05	0	1.32E-08	0.00154	1.86E-05
AGRICULTURE - RICE	**Blue Water Consumption**	0	0	0	0	0.003044	2.60E-05	6.63E-05	0	2.14E-05	6.14E-06	0.000695	6.53E-07
AGRICULTURE - OTHER CEREALS	**Blue Water Consumption**	2.42E-10	3.33E-09	5.70E-07	0	0.030535	2.44E-09	3.58E-05	4.10E-05	1.48E-09	1.18E-07	5.75E-05	9.58E-05
AGRICULTURE - OIL CROPS	**Blue Water Consumption**	0	0	1.48E-07	0	0.00742	0	5.50E-06	2.14E-05	0	2.68E-07	0.000127	2.55E-06
AGRICULTURE - SUGAR CROPS	**Blue Water Consumption**	1.94E-09	0	1.20E-07	2.18E-09	0.003812	1.05E-07	1.02E-06	0	0	5.62E-06	0.000344	1.52E-05
AGRICULTURE - FIBRES	**Blue Water Consumption**	0	0	0	0	0	0	6.98E-09	8.11E-09	0	1.39E-07	3.43E-08	1.52E-07
AGRICULTURE - OTHER CROPS	**Blue Water Consumption**	0	1.70E-09	9.36E-09	0	0.030217	0	3.95E-05	1.17E-07	7.91E-08	1.42E-06	0.000365	1.08E-05
AGRICULTURE - FODDER CROPS	**Blue Water Consumption**	0	1.73E-08	1.07E-07	4.11E-10	0.017136	2.32E-09	1.62E-12	6.10E-06	0	0	0	4.16E-05
AGRICULTURE - VEGETABLES	**Blue Water Consumption**	1.10E-09	4.25E-09	3.07E-07	8.76E-09	0.000285	2.53E-08	7.07E-06	8.52E-07	2.01E-06	7.61E-07	7.38E-05	1.38E-05
AGRICULTURE - FRUITS	**Blue Water Consumption**	5.19E-10	8.54E-09	2.80E-08	1.85E-09	0.000391	1.96E-08	1.07E-05	6.83E-06	3.93E-07	1.51E-06	0.00024	4.74E-05
AGRICULTURE - NUTS	**Blue Water Consumption**	0	2.40E-10	2.67E-09	0	0.000418	3.51E-09	9.43E-07	0	2.03E-07	1.32E-06	1.85E-05	5.04E-06
AGRICULTURE - PULSES	**Blue Water Consumption**	0	0	1.36E-09	3.76E-11	3.38E-05	2.70E-08	1.57E-07	1.52E-08	0	5.68E-07	2.60E-05	2.54E-06
AGRICULTURE - ROOTS AND TUBERS	**Blue Water Consumption**	2.65E-09	1.49E-09	1.74E-08	3.26E-08	7.54E-05	6.45E-08	1.30E-06	0	2.89E-07	2.91E-07	1.49E-05	1.99E-06

STRESSOR CATEGORY	IMPACT PATHWAY	RU	AU	CH	TR	TW	NO	ID	ZA	WA	WL	WE	WF
CEREAL GRAINS NEC	**Land Occupation**	0.000118	0.000337	1.02E-07	0.000197	5.74E-06	3.79E-07	0.000502	0.000199	0.000641	0.000704	5.04E-05	0.000879
CROPS NEC	**Land Occupation**	2.24E-07	1.43E-07	3.48E-09	9.63E-06	3.63E-06	0	0.000571	3.28E-06	0.000436	0.000614	6.55E-07	0.000363
OIL SEEDS	**Land Occupation**	0.000102	0.000115	3.26E-08	8.32E-05	4.53E-06	7.49E-09	0.000533	5.55E-05	0.000496	0.000247	4.55E-05	0.000304
PADDY RICE	**Land Occupation**	3.82E-06	3.29E-07	0	3.06E-06	7.45E-05	0	0.000801	3.06E-08	0.001636	0.000385	2.39E-07	0.000344
PLANT-BASED FIBERS	**Land Occupation**	2.43E-07	0	0	1.71E-06	1.10E-07	0	1.31E-06	2.72E-07	4.81E-05	1.96E-05	2.45E-08	1.26E-05
SUGAR	**Land Occupation**	1.15E-05	4.94E-05	5.72E-08	3.21E-06	0	0	5.87E-05	2.75E-05	5.06E-05	0.000266	1.97E-06	1.99E-05
VEGETABLES, FRUIT, NUTS	**Land Occupation**	3.89E-05	7.11E-05	4.27E-07	0.000128	7.75E-05	5.19E-08	0.000283	0.000103	0.001291	0.001398	3.11E-05	0.001259
WHEAT	**Land Occupation**	0.00018	0.000812	2.84E-07	0.000382	2.57E-08	1.75E-07	0	0.000202	0.00018	0.000115	3.77E-05	0.000195
AGRICULTURE - WHEAT	**Blue Water Consumption**	1.58E-05	0.000297	0	5.01E-05	0	0	0	8.99E-06	0.001042	1.13E-05	2.58E-07	2.37E-05
AGRICULTURE - RICE	**Blue Water Consumption**	5.47E-05	7.93E-05	0	1.09E-06	0	0	0.000133	0	0.001781	0.000306	2.04E-07	0.00026
AGRICULTURE - OTHER CEREALS	**Blue Water Consumption**	4.45E-06	0.000501	1.30E-10	2.37E-05	0	0	6.07E-06	1.20E-05	0.000233	0.000116	1.53E-06	3.22E-05
AGRICULTURE - OIL CROPS	**Blue Water Consumption**	2.06E-07	5.32E-05	0	8.25E-07	0	0	2.22E-06	9.10E-07	2.41E-05	2.72E-06	1.51E-07	8.53E-06
AGRICULTURE - SUGAR CROPS	**Blue Water Consumption**	2.04E-06	0.003186	1.60E-10	9.24E-06	0	0	2.30E-05	2.14E-06	0.000161	8.87E-05	8.07E-08	1.37E-05
AGRICULTURE - FIBRES	**Blue Water Consumption**	5.35E-09	0	0	0	0	0	0	4.36E-09	2.78E-07	1.30E-06	1.83E-11	3.31E-08
AGRICULTURE - OTHER CROPS	**Blue Water Consumption**	5.63E-10	0	6.93E-13	8.38E-05	0	0	1.14E-06	5.62E-07	0.000337	3.61E-05	1.52E-08	6.10E-06
AGRICULTURE - FODDER CROPS	**Blue Water Consumption**	1.29E-06	0.002801	2.01E-10	0	0	2.40E-10	0	7.18E-06	3.03E-05	1.57E-05	6.46E-07	8.08E-05
AGRICULTURE - VEGETABLES	**Blue Water Consumption**	3.38E-06	0.000397	3.93E-09	4.03E-05	0	4.87E-10	5.19E-06	4.46E-06	0.000194	0.000157	9.16E-07	0.000245
AGRICULTURE - FRUITS	**Blue Water Consumption**	4.42E-07	0.001245	3.19E-10	2.86E-05	0	5.32E-10	0	1.29E-05	0.000341	0.000443	2.40E-07	0.000271
AGRICULTURE - NUTS	**Blue Water Consumption**	2.60E-16	0.000131	3.23E-11	1.55E-05	0	0	0	2.74E-07	2.00E-05	1.51E-05	5.00E-08	2.68E-05
AGRICULTURE - PULSES	**Blue Water Consumption**	7.38E-07	1.95E-06	7.52E-11	6.94E-06	0	3.20E-12	1.51E-06	5.61E-07	1.93E-05	2.22E-05	1.53E-08	9.67E-06
AGRICULTURE - ROOTS AND TUBERS	**Blue Water Consumption**	4.70E-07	0.00013	6.32E-10	6.65E-06	0	5.08E-09	1.18E-06	1.74E-06	4.52E-05	8.68E-05	2.77E-07	2.84E-05

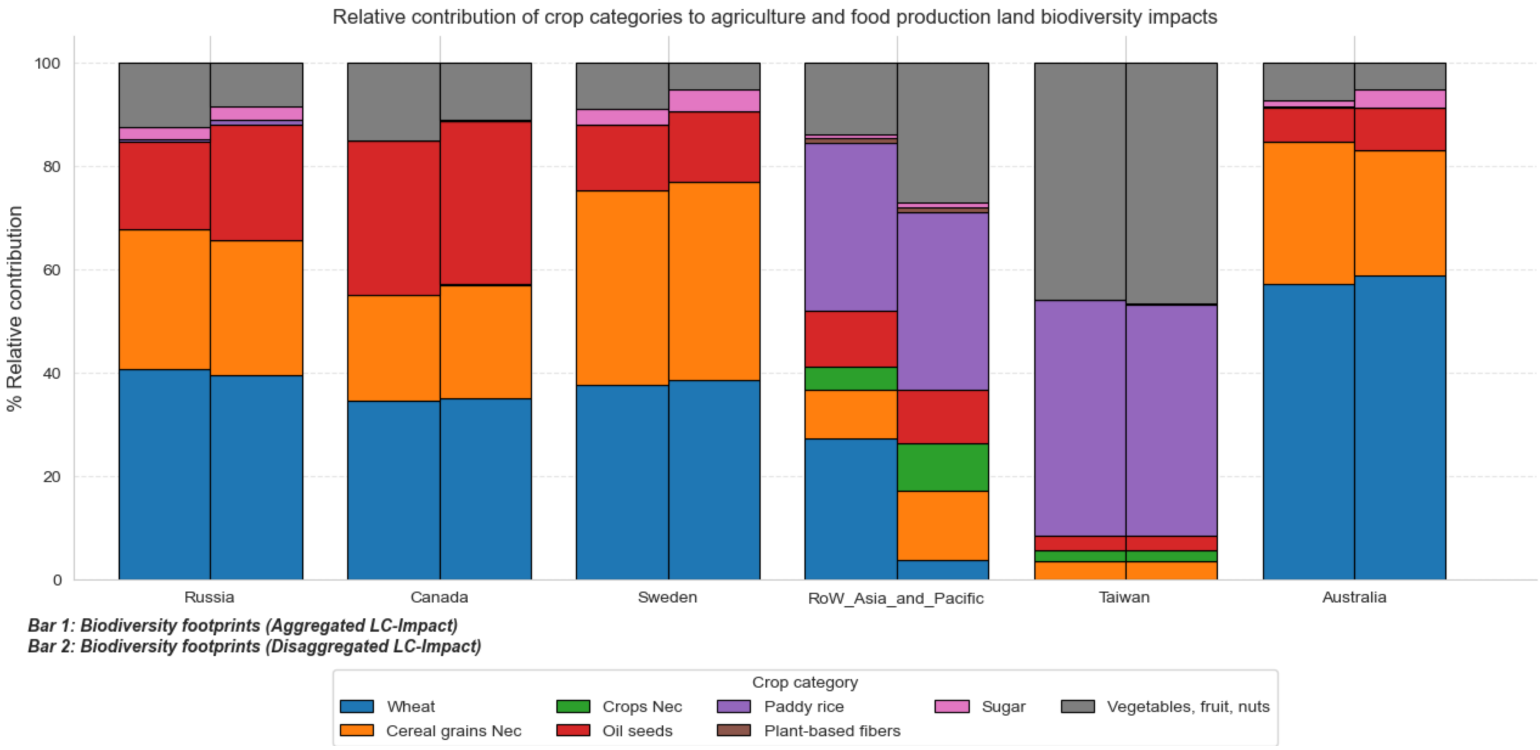

*Figure S6. Relative contribution of crop categories to absolute production-based biodiversity land impacts for six countries with the **largest increase** in their respective production-based impacts post disaggregation. Each country is represented by two bars. Bar 1 is the relative crop contributions to impacts when the current LC-IMPACT cropland CFs are applied. Bar 2 is the relative contributions of crop categories when the crop-specific, spatially dissolved CFs in this study are applied with the EXIOBASE MRIO model.*

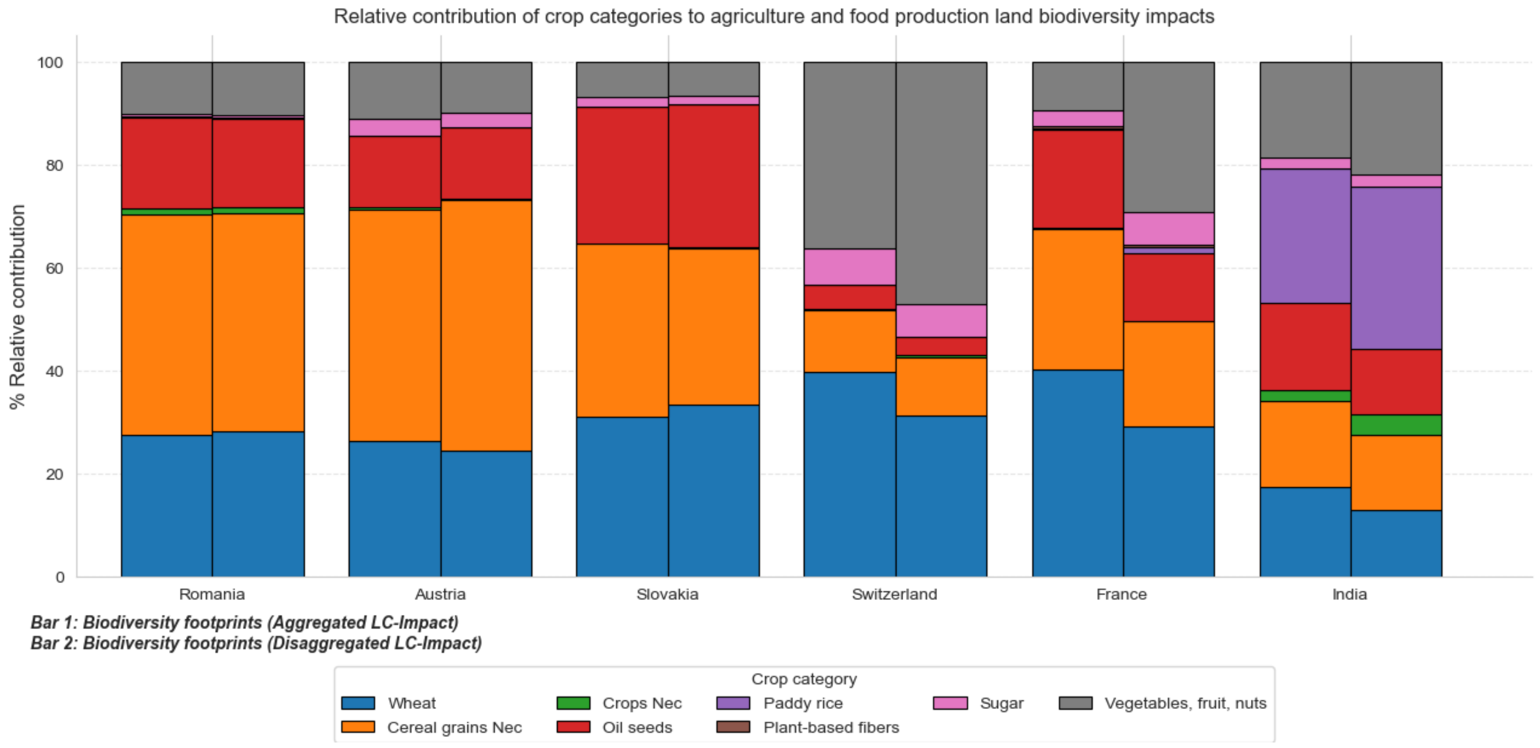

*Figure S7. Relative contribution of crop categories to absolute production-based biodiversity land impacts for six countries with the **largest decrease** in their respective production-based impacts post disaggregation. Bar 1 is the relative crop contributions to impacts when the current LC-IMPACT cropland CFs are applied. Bar 2 is the relative contributions of crop categories when the crop-specific, spatially dissolved CFs in this study are applied with the EXIOBASE MRIO model.*

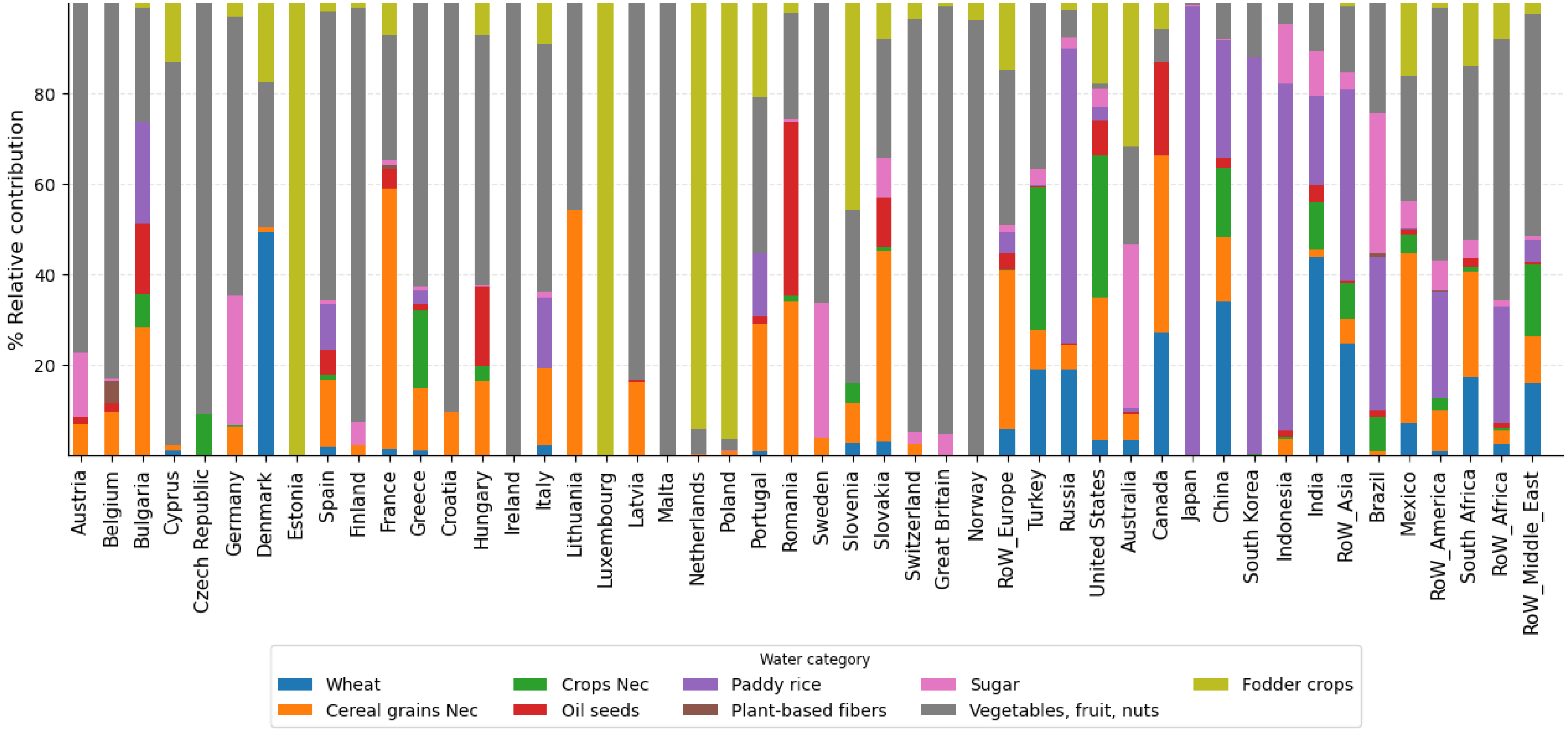

Figure S8. Relative contributions of the eight EXIOBASE crop categories to the total production-based wetland impacts of agricultural crop systems in the year 2010 and for the 49 EXIOBASE regions. Note the variation of crop importance for describing land impacts between geographical regions of the world.

6. SI.6 - National consumption-based footprints

a. Consumption-based biodiversity footprints – Total country level impacts

Table S18. Absolute national consumption-based biodiversity footprints of global agriculture and food demand in [PDF.yr] for the year 2010. The land occupation and wetland impact pathway results are mutually exclusive and are not to be compared against one another.

Region	Land occupation impacts	Wetland impacts	Region	Land occupation impacts	Wetland impacts	Region	Land occupation impacts	Wetland impacts
AT	2.75E-05	3.15E-05	PL	9.65E-05	0.000131	ID	0.002750056	0.000172895
BE	0.000119	0.000237	PT	8.47E-05	6.41E-05	ZA	0.00059079	5.18E-05
BG	1.68E-05	1.97E-05	RO	4.32E-05	5.55E-06	WA	0.004778489	0.004227756
CY	5.14E-06	1.02E-05	SE	5.49E-06	6.45E-09	WL	0.003749031	0.001301895
CZ	2.68E-05	2.87E-05	SI	1.03E-06	3.78E-08	WE	0.000167524	4.39E-06
DE	0.000396	0.000773	SK	6.53E-06	1.35E-06	WF	0.00337615	0.001006848
DK	1.92E-05	3.36E-05	GB	1.30E-05	4.58E-08	WM	0.000326691	0.00154856
EE	9.49E-06	6.39E-06	US	0.000746314	0.096570149			
ES	0.000624	0.000387	JP	0.000126402	2.63E-05			
FI	2.17E-05	2.24E-05	CN	0.001171624	0.000255598			
FR	0.000328	0.00033	CA	0.000152811	0.000104887			
GR	0.000131	9.55E-05	KR	1.44E-05	2.43E-05			
HR	1.33E-05	9.90E-06	BR	0.001759109	1.82E-05			
HU	1.50E-05	1.59E-05	IN	0.003291267	0.003501754			
IE	1.53E-05	4.85E-05	MX	0.002177891	0.000256046			
IT	0.000473	0.000333	RU	0.000454423	8.35E-05			
LT	1.09E-05	3.29E-05	AU	0.001384168	0.008823313			
LU	1.69E-05	1.98E-05	CH	9.07E-07	5.48E-09			
LV	6.70E-06	6.21E-06	TR	0.000807831	0.000266676			
MT	1.04E-06	1.09E-06	TW	0.000166043	0			
NL	0.000143	0.000235	NO	6.13E-07	6.34E-09			

b. Consumption-based biodiversity footprints – Individual stressor impacts by country

Table S19. Absolute national consumption-based biodiversity footprints of global agriculture and food demand for individual crop categories in [PDF.yr] for the year 2010.

STRESSOR CATEGORY	IMPACT PATHWAY	AT	BE	BG	CY	CZ	DE	DK	EE	ES	FI	FR	GR
CEREAL GRAINS NEC	**Land Occupation**	4.17E-06	8.97E-06	2.77E-06	1.62E-06	4.18E-06	4.56E-05	4.23E-06	1.85E-06	0.000148	1.89E-06	4.45E-05	2.37E-05
CROPS NEC	**Land Occupation**	3.36E-06	3.41E-05	2.77E-06	9.78E-08	2.93E-06	0.000119	1.34E-06	4.11E-06	3.75E-05	7.56E-06	4.07E-05	3.67E-06
OIL SEEDS	**Land Occupation**	5.44E-06	2.17E-05	4.86E-06	1.24E-06	4.68E-06	7.68E-05	4.53E-06	8.92E-07	0.000158	4.37E-06	6.08E-05	5.65E-05
PADDY RICE	**Land Occupation**	9.29E-07	6.89E-06	6.36E-07	2.22E-07	1.29E-06	2.14E-05	1.10E-06	6.39E-07	1.86E-05	1.18E-06	1.55E-05	2.64E-06
PLANT-BASED FIBERS	**Land Occupation**	1.88E-07	6.71E-07	2.72E-08	4.50E-09	1.68E-07	6.74E-07	7.04E-08	1.87E-08	6.19E-07	2.89E-08	2.23E-06	1.15E-07
SUGAR	**Land Occupation**	3.52E-07	1.61E-06	5.04E-07	5.01E-08	4.68E-07	5.62E-06	6.62E-07	7.73E-08	6.16E-06	3.75E-07	8.26E-06	1.28E-06
VEGETABLES, FRUIT, NUTS	**Land Occupation**	1.08E-05	3.87E-05	3.54E-06	1.19E-06	9.01E-06	9.52E-05	3.85E-06	9.92E-07	0.000132	5.28E-06	0.00012	2.03E-05
WHEAT	**Land Occupation**	2.29E-06	6.06E-06	1.66E-06	7.26E-07	4.05E-06	3.10E-05	3.47E-06	9.12E-07	0.000123	9.74E-07	3.55E-05	2.32E-05
AGRICULTURE - WHEAT	**Blue Water Consumption**	1.44E-06	9.54E-06	6.97E-07	1.69E-06	1.39E-06	3.08E-05	2.01E-06	8.67E-07	2.76E-05	1.52E-06	1.74E-05	1.02E-05
AGRICULTURE - RICE	**Blue Water Consumption**	1.11E-06	7.57E-06	7.41E-07	2.90E-07	1.48E-06	2.43E-05	1.31E-06	5.69E-07	2.45E-05	1.30E-06	1.54E-05	1.75E-06
AGRICULTURE - OTHER CEREALS	**Blue Water Consumption**	4.65E-06	1.69E-05	1.42E-06	5.61E-07	3.74E-06	7.02E-05	6.79E-06	7.89E-07	7.48E-05	2.89E-06	4.06E-05	7.72E-06
AGRICULTURE - OIL CROPS	**Blue Water Consumption**	4.90E-06	1.63E-05	1.37E-06	3.46E-07	4.00E-06	0.000135	4.92E-06	6.10E-07	7.54E-05	2.83E-06	5.65E-05	5.17E-06
AGRICULTURE - SUGAR CROPS	**Blue Water Consumption**	7.03E-07	4.34E-06	2.56E-07	8.88E-08	6.12E-07	1.19E-05	2.09E-06	1.73E-07	8.21E-06	7.99E-07	7.36E-06	9.23E-07
AGRICULTURE - FIBRES	**Blue Water Consumption**	4.76E-09	1.14E-08	3.68E-10	1.22E-10	3.27E-09	1.44E-08	2.20E-09	2.28E-10	1.23E-08	5.83E-10	3.21E-08	1.82E-09
AGRICULTURE - OTHER CROPS	**Blue Water Consumption**	7.01E-06	9.61E-05	7.95E-06	8.40E-07	7.68E-06	0.000247	8.29E-06	9.75E-07	5.70E-05	4.94E-06	7.94E-05	3.64E-05
AGRICULTURE - FODDER CROPS	**Blue Water Consumption**	4.70E-06	5.60E-05	4.71E-06	1.67E-06	4.04E-06	0.000152	5.22E-06	1.35E-06	3.36E-05	2.85E-06	5.13E-05	2.05E-05
AGRICULTURE - VEGETABLES	**Blue Water Consumption**	2.18E-06	7.74E-06	7.74E-07	8.53E-07	1.93E-06	2.84E-05	9.72E-07	2.10E-07	3.88E-05	1.35E-06	2.29E-05	4.54E-06
AGRICULTURE - FRUITS	**Blue Water Consumption**	3.66E-06	1.43E-05	9.80E-07	2.79E-06	2.84E-06	4.57E-05	1.43E-06	3.32E-07	3.47E-05	2.32E-06	2.85E-05	5.93E-06
AGRICULTURE - NUTS	**Blue Water Consumption**	5.95E-07	2.49E-06	2.71E-07	5.54E-07	5.46E-07	1.15E-05	3.11E-07	7.28E-08	5.46E-06	5.91E-07	5.37E-06	1.43E-06
AGRICULTURE - PULSES	**Blue Water Consumption**	1.43E-07	1.93E-06	1.88E-07	1.80E-07	1.39E-07	4.56E-06	8.92E-08	1.15E-07	2.35E-06	2.40E-07	1.66E-06	2.88E-07
AGRICULTURE - ROOTS AND TUBERS	**Blue Water Consumption**	4.12E-07	4.23E-06	3.38E-07	3.06E-07	3.08E-07	1.20E-05	2.06E-07	3.30E-07	4.91E-06	7.38E-07	4.04E-06	6.72E-07

STRESSOR CATEGORY	IMPACT PATHWAY	HR	HU	IE	IT	LT	LU	LV	MT	NL	PL	PT	RO
CEREAL GRAINS NEC	**Land Occupation**	4.71E-06	3.43E-06	2.70E-06	5.57E-05	2.43E-06	8.42E-07	9.00E-07	1.79E-07	1.64E-05	2.46E-05	1.86E-05	2.16E-05
CROPS NEC	**Land Occupation**	9.81E-07	1.56E-06	2.46E-06	3.60E-05	1.31E-06	4.05E-06	2.34E-07	3.95E-08	3.65E-05	1.81E-05	2.98E-06	6.06E-06
OIL SEEDS	**Land Occupation**	3.10E-06	3.59E-06	2.07E-06	0.000132	2.71E-06	3.90E-06	3.70E-06	1.99E-07	2.36E-05	1.70E-05	2.42E-05	7.12E-06
PADDY RICE	**Land Occupation**	4.31E-07	6.22E-07	1.55E-06	1.34E-05	4.89E-07	8.83E-07	1.32E-07	4.69E-08	9.32E-06	3.87E-06	3.73E-06	1.00E-06
PLANT-BASED FIBERS	**Land Occupation**	1.88E-08	7.31E-08	5.51E-08	3.82E-07	3.31E-08	1.00E-08	4.00E-07	1.72E-09	4.23E-07	1.64E-07	1.06E-07	5.36E-08
SUGAR	**Land Occupation**	5.36E-07	2.79E-07	3.70E-07	6.20E-06	2.49E-07	1.08E-07	8.74E-08	3.65E-08	1.77E-06	1.41E-06	4.07E-06	1.25E-06
VEGETABLES, FRUIT, NUTS	**Land Occupation**	2.43E-06	2.36E-06	4.73E-06	0.000124	1.85E-06	6.62E-06	6.62E-07	3.83E-07	4.69E-05	1.76E-05	2.48E-05	7.14E-06
WHEAT	**Land Occupation**	1.13E-06	3.11E-06	1.42E-06	0.000105	1.82E-06	5.32E-07	5.78E-07	1.53E-07	8.41E-06	1.38E-05	6.28E-06	7.38E-06
AGRICULTURE - WHEAT	**Blue Water Consumption**	6.98E-07	8.11E-07	1.81E-06	6.05E-05	5.21E-07	9.51E-07	2.94E-07	1.15E-07	1.36E-05	6.06E-06	3.11E-06	1.32E-06
AGRICULTURE - RICE	**Blue Water Consumption**	5.07E-07	7.75E-07	1.97E-06	1.23E-05	1.86E-06	9.56E-07	6.40E-07	5.32E-08	9.79E-06	4.33E-06	3.45E-06	1.11E-06
AGRICULTURE - OTHER CEREALS	**Blue Water Consumption**	1.87E-06	2.39E-06	1.26E-05	3.62E-05	2.00E-06	1.23E-06	1.01E-06	1.72E-07	2.25E-05	1.12E-05	9.71E-06	5.15E-06
AGRICULTURE - OIL CROPS	**Blue Water Consumption**	1.38E-06	2.69E-06	6.33E-06	4.38E-05	1.27E-06	1.45E-06	1.08E-06	1.27E-07	1.86E-05	2.22E-05	1.44E-05	8.50E-06
AGRICULTURE - SUGAR CROPS	**Blue Water Consumption**	5.95E-07	4.70E-07	2.46E-06	6.92E-06	2.84E-07	2.77E-07	1.75E-07	5.95E-08	4.47E-06	1.46E-06	1.62E-06	7.34E-07
AGRICULTURE - FIBRES	**Blue Water Consumption**	4.53E-10	1.03E-09	8.43E-10	1.07E-08	5.39E-10	2.41E-10	2.49E-09	2.95E-11	5.75E-09	4.06E-09	1.84E-09	1.22E-09
AGRICULTURE - OTHER CROPS	**Blue Water Consumption**	2.19E-06	4.28E-06	1.25E-05	6.64E-05	1.63E-05	6.19E-06	1.53E-06	2.04E-07	7.05E-05	4.77E-05	1.45E-05	1.44E-05
AGRICULTURE - FODDER CROPS	**Blue Water Consumption**	1.25E-06	2.32E-06	7.48E-06	4.34E-05	9.27E-06	3.54E-06	8.89E-07	1.41E-07	5.41E-05	2.70E-05	9.57E-06	8.02E-06
AGRICULTURE - VEGETABLES	**Blue Water Consumption**	3.97E-07	9.36E-07	9.16E-07	1.92E-05	4.53E-07	1.40E-06	1.90E-07	6.45E-08	1.11E-05	3.24E-06	2.46E-06	1.83E-06
AGRICULTURE - FRUITS	**Blue Water Consumption**	6.96E-07	7.52E-07	1.65E-06	3.08E-05	6.67E-07	2.59E-06	2.83E-07	1.12E-07	2.02E-05	4.81E-06	4.13E-06	1.72E-06
AGRICULTURE - NUTS	**Blue Water Consumption**	1.80E-07	1.96E-07	3.41E-07	7.51E-06	1.66E-07	4.33E-07	8.63E-08	2.51E-08	4.30E-06	8.67E-07	3.50E-07	5.00E-07
AGRICULTURE - PULSES	**Blue Water Consumption**	4.40E-08	1.11E-07	1.27E-07	1.61E-06	5.57E-08	2.69E-07	1.23E-08	5.20E-09	1.73E-06	6.29E-07	1.72E-07	1.88E-07
AGRICULTURE - ROOTS AND TUBERS	**Blue Water Consumption**	9.85E-08	2.02E-07	2.81E-07	3.94E-06	1.20E-07	5.58E-07	2.66E-08	1.47E-08	4.43E-06	1.35E-06	5.55E-07	5.70E-07

STRESSOR CATEGORY	IMPACT PATHWAY	SE	SI	SK	GB	US	JP	CN	CA	KR	BR	IN	MX
CEREAL GRAINS NEC	**Land Occupation**	4.43E-06	1.10E-06	2.39E-06	3.60E-05	0.000371	0.000123	0.000335	3.47E-05	3.10E-05	0.000357	0.000481	0.001284
CROPS NEC	**Land Occupation**	8.18E-06	4.49E-06	5.30E-06	5.12E-05	0.000225	0.000127	0.000141	3.96E-05	3.70E-05	0.00035	0.000168	0.000161
OIL SEEDS	**Land Occupation**	7.67E-06	2.01E-06	1.24E-06	4.95E-05	0.000147	0.000132	0.000377	2.57E-05	3.01E-05	5.88E-05	0.000589	9.75E-05
PADDY RICE	**Land Occupation**	2.23E-06	4.82E-07	1.41E-06	2.14E-05	9.55E-05	0.000118	0.000319	9.43E-06	2.38E-05	0.000107	0.001033	1.23E-05
PLANT-BASED FIBERS	**Land Occupation**	5.75E-08	6.67E-08	2.52E-08	2.49E-06	2.06E-06	9.68E-07	4.51E-06	1.60E-07	3.53E-07	3.81E-06	2.68E-06	3.07E-06
SUGAR	**Land Occupation**	4.87E-07	7.78E-08	1.28E-07	1.21E-05	0.000119	2.48E-05	5.22E-05	1.10E-05	1.36E-05	0.000125	9.14E-05	0.000106
VEGETABLES, FRUIT, NUTS	**Land Occupation**	9.36E-06	2.22E-06	3.95E-06	0.000113	0.000526	0.000113	0.000494	4.92E-05	2.83E-05	0.000209	0.000805	0.000176
WHEAT	**Land Occupation**	5.61E-06	5.55E-07	1.12E-06	2.30E-05	0.000102	7.87E-05	0.000171	2.64E-05	3.98E-05	5.72E-05	0.000452	4.84E-05
AGRICULTURE - WHEAT	**Blue Water Consumption**	1.12E-05	4.05E-07	7.01E-07	3.53E-05	0.001468	0.000287	0.000164	5.47E-05	0.000101	5.54E-05	0.001551	0.000218
AGRICULTURE - RICE	**Blue Water Consumption**	2.65E-06	5.29E-07	1.58E-06	2.38E-05	0.002307	8.21E-05	0.000126	3.47E-05	3.71E-05	3.04E-05	0.000702	0.000228
AGRICULTURE - OTHER CEREALS	**Blue Water Consumption**	8.06E-06	9.17E-07	1.51E-06	7.13E-05	0.020706	0.00287	0.000493	0.00066	0.001084	4.91E-05	9.17E-05	0.002182
AGRICULTURE - OIL CROPS	**Blue Water Consumption**	5.28E-06	7.36E-06	1.42E-06	4.97E-05	0.002435	0.000462	0.001506	0.000195	0.000129	1.91E-05	0.000198	0.000666
AGRICULTURE - SUGAR CROPS	**Blue Water Consumption**	2.18E-06	2.04E-07	2.61E-07	3.20E-05	0.003652	0.000394	9.63E-05	7.75E-05	0.000544	8.62E-06	0.000336	9.46E-05
AGRICULTURE - FIBRES	**Blue Water Consumption**	1.21E-09	1.03E-09	4.15E-10	1.56E-08	5.17E-08	1.94E-08	5.92E-08	9.49E-09	8.44E-09	1.37E-07	3.78E-08	1.36E-07
AGRICULTURE - OTHER CROPS	**Blue Water Consumption**	1.35E-05	2.07E-06	4.08E-06	0.000103	0.023501	0.000923	0.000498	0.001028	0.000335	7.03E-05	0.00039	0.000898
AGRICULTURE - FODDER CROPS	**Blue Water Consumption**	8.02E-06	9.72E-07	1.61E-06	7.45E-05	0.013384	0.001015	0.000301	0.000596	0.000451	4.29E-05	4.91E-05	0.00054
AGRICULTURE - VEGETABLES	**Blue Water Consumption**	2.25E-06	7.84E-07	9.47E-07	2.65E-05	0.00028	1.99E-05	3.43E-05	2.14E-05	6.97E-06	1.20E-06	0.000103	1.14E-05
AGRICULTURE - FRUITS	**Blue Water Consumption**	3.69E-06	1.37E-06	1.19E-06	4.62E-05	0.000441	4.16E-05	6.33E-05	3.66E-05	9.86E-06	2.60E-06	0.000293	3.06E-05
AGRICULTURE - NUTS	**Blue Water Consumption**	7.86E-07	4.30E-07	2.62E-07	9.67E-06	0.000356	7.70E-06	7.31E-06	2.44E-05	2.67E-06	1.16E-06	2.79E-05	7.99E-06
AGRICULTURE - PULSES	**Blue Water Consumption**	3.22E-07	1.23E-07	1.73E-07	2.26E-06	3.19E-05	4.39E-06	3.54E-06	2.17E-06	1.57E-06	1.61E-06	2.50E-05	3.80E-06
AGRICULTURE - ROOTS AND TUBERS	**Blue Water Consumption**	9.25E-07	2.29E-07	4.34E-07	5.60E-06	7.67E-05	3.34E-05	1.13E-05	5.79E-06	1.59E-05	3.01E-06	1.73E-05	5.75E-06

STRESSOR CATEGORY	IMPACT PATHWAY	RU	AU	CH	TR	TW	NO	ID	ZA	WA	WL	WE	WF	WM
CEREAL GRAINS NEC	**Land Occupation**	0.000138	0.000245	2.88E-06	0.000188	2.61E-05	2.98E-06	0.000523	0.000166	0.000567	0.000547	2.66E-05	0.000859	0.00015
CROPS NEC	**Land Occupation**	4.01E-05	1.00E-05	5.96E-06	3.26E-05	6.45E-05	5.32E-06	1.99E-05	9.70E-06	0.000235	0.000369	8.88E-06	0.000131	6.34E-05
OIL SEEDS	**Land Occupation**	0.000137	4.00E-05	3.35E-06	0.000108	0.000147	3.73E-06	5.62E-05	4.85E-05	0.000423	6.33E-05	2.40E-05	0.000233	0.000119
PADDY RICE	**Land Occupation**	2.06E-05	1.48E-05	1.65E-06	1.07E-05	9.03E-05	1.55E-06	0.000781	1.02E-05	0.001011	0.000373	4.57E-06	0.000475	0.000149
PLANT-BASED FIBERS	**Land Occupation**	1.96E-06	3.40E-07	1.11E-06	1.83E-06	5.43E-07	7.89E-08	1.73E-06	2.87E-07	4.13E-05	1.77E-05	1.21E-07	4.21E-06	7.91E-07
SUGAR	**Land Occupation**	3.77E-05	2.40E-05	2.96E-07	3.50E-06	5.19E-06	5.86E-07	6.50E-05	2.26E-05	7.07E-05	0.000111	7.67E-06	5.49E-05	5.57E-05
VEGETABLES, FRUIT, NUTS	**Land Occupation**	0.000165	7.83E-05	1.09E-05	0.000118	9.42E-05	1.06E-05	0.000252	8.65E-05	0.000826	0.000923	4.02E-05	0.001042	0.000106
WHEAT	**Land Occupation**	0.000139	0.000311	2.24E-06	0.000374	1.36E-05	2.02E-06	0.000122	0.000179	0.000289	0.000109	1.94E-05	0.000312	0.000159
AGRICULTURE - WHEAT	**Blue Water Consumption**	3.43E-05	0.000132	3.09E-06	0.000142	2.20E-05	2.82E-06	8.88E-05	1.70E-05	0.000904	0.000442	4.12E-06	0.000359	0.000284
AGRICULTURE - RICE	**Blue Water Consumption**	7.11E-05	8.80E-05	1.82E-06	0.000102	2.40E-05	2.00E-06	0.000157	1.11E-05	0.001123	0.000647	6.81E-06	0.00042	0.000223
AGRICULTURE - OTHER CEREALS	**Blue Water Consumption**	6.16E-05	0.000387	4.83E-06	4.66E-05	0.000125	1.17E-05	7.93E-05	1.64E-05	0.000552	0.001357	7.82E-06	0.000197	0.000488
AGRICULTURE - OIL CROPS	**Blue Water Consumption**	4.60E-05	4.50E-05	4.02E-06	7.20E-05	0.000605	5.35E-06	3.68E-05	4.61E-06	0.000299	0.000188	8.05E-06	0.000158	0.000118
AGRICULTURE - SUGAR CROPS	**Blue Water Consumption**	2.01E-05	0.001432	1.19E-06	1.11E-05	2.86E-05	2.56E-06	7.60E-05	3.50E-06	0.000638	7.03E-05	3.20E-06	4.38E-05	5.73E-05
AGRICULTURE - FIBRES	**Blue Water Consumption**	2.23E-08	4.32E-09	4.10E-09	4.24E-09	8.03E-09	1.96E-09	8.20E-09	2.92E-09	2.51E-07	1.11E-06	2.22E-09	2.75E-08	7.84E-08
AGRICULTURE - OTHER CROPS	**Blue Water Consumption**	0.000119	8.71E-05	4.79E-05	0.000146	0.000229	1.16E-05	7.40E-05	8.48E-06	0.000615	0.000569	1.68E-05	0.000121	0.000724
AGRICULTURE - FODDER CROPS	**Blue Water Consumption**	8.25E-05	0.001371	2.79E-05	4.68E-05	0.000147	7.09E-06	9.82E-05	1.66E-05	0.000468	0.000353	1.00E-05	0.000113	0.00046
AGRICULTURE - VEGETABLES	**Blue Water Consumption**	3.74E-05	0.000327	2.51E-06	3.75E-05	7.50E-06	2.59E-06	9.51E-06	4.39E-06	0.000167	0.000106	5.10E-06	0.000206	0.000126
AGRICULTURE - FRUITS	**Blue Water Consumption**	6.13E-05	0.001018	3.85E-06	3.15E-05	1.45E-05	4.75E-06	1.24E-05	1.18E-05	0.000336	0.000293	7.96E-06	0.000234	0.000229
AGRICULTURE - NUTS	**Blue Water Consumption**	1.50E-05	0.000109	8.47E-07	1.52E-05	1.77E-06	1.01E-06	1.90E-06	4.77E-07	4.07E-05	1.40E-05	2.18E-06	2.59E-05	8.73E-05
AGRICULTURE - PULSES	**Blue Water Consumption**	2.48E-06	1.43E-06	2.99E-07	6.87E-06	1.73E-06	2.07E-07	4.68E-07	7.81E-07	8.09E-06	1.38E-05	3.91E-07	4.81E-06	2.73E-05
AGRICULTURE - ROOTS AND TUBERS	**Blue Water Consumption**	5.40E-06	6.23E-05	7.46E-07	7.81E-06	5.12E-06	5.80E-07	3.52E-06	2.44E-06	2.43E-05	5.25E-05	1.03E-06	1.27E-05	3.35E-05

c. Changes in absolute biodiversity footprints for the EU-27 post disaggregation of characterization factors

Table S20. Absolute change in national biodiversity footprints in [PDF.yr] post disaggregation of LC-IMPACT CFs for the EU-27 in the year 2010. Fields labelled green indicate decreases from baseline impacts, whereas brown ones highlight increases.

		AT	BE	BG	CY	CZ	DE	DK	EE	ES	FI	FR	GR
Cereal grains Nec	**Land Occupation**	-2.49E-06	4.93E-07	-5.49E-07	3.14E-08	-1.01E-07	3.21E-06	6.71E-07	-4.94E-08	1.34E-05	4.21E-07	-8.41E-06	-6.01E-07
Crops Nec	**Land Occupation**	1.89E-06	2.21E-05	9.84E-07	5.47E-08	1.75E-06	6.87E-05	8.09E-07	2.50E-06	2.08E-05	4.77E-06	2.11E-05	1.84E-06
Oil seeds	**Land Occupation**	-2.26E-07	5.97E-06	-1.21E-06	-1.09E-08	-4.10E-07	-1.04E-05	-3.88E-07	1.53E-10	8.87E-06	1.10E-06	-1.24E-05	-8.77E-07
Paddy rice	**Land Occupation**	5.81E-07	4.55E-06	3.94E-07	1.44E-07	8.60E-07	1.43E-05	7.00E-07	4.18E-07	6.98E-06	7.91E-07	1.02E-05	2.55E-07
Plant-based fibers	**Land Occupation**	9.79E-08	3.83E-07	-1.62E-08	2.37E-10	1.02E-07	3.11E-07	4.12E-08	1.09E-08	7.65E-08	1.31E-08	7.37E-07	-1.73E-06
Sugar	**Land Occupation**	5.98E-11	8.19E-07	9.42E-08	2.59E-08	1.07E-08	2.37E-06	3.93E-07	4.42E-08	2.43E-06	1.63E-07	3.61E-06	2.22E-08
Vegetables, fruit, nuts	**Land Occupation**	4.86E-06	2.39E-05	7.73E-07	2.49E-07	4.08E-06	4.40E-05	1.61E-06	4.71E-07	3.76E-05	2.57E-06	5.20E-05	4.02E-06
Wheat	**Land Occupation**	-5.44E-07	2.49E-08	-2.61E-07	-1.66E-07	-2.21E-07	1.47E-07	2.45E-07	1.95E-07	1.01E-05	5.54E-08	-1.48E-05	-1.97E-06

		HR	HU	IE	IT	LT	LU	LV	MT	NL	PL	PT	RO
Cereal grains Nec	**Land Occupation**	-2.32E-06	-3.02E-07	8.78E-08	-1.58E-05	6.46E-08	1.21E-07	9.52E-08	1.24E-08	2.26E-06	-3.01E-06	-4.40E-07	-1.02E-05
Crops Nec	**Land Occupation**	5.58E-07	8.91E-07	1.43E-06	2.03E-05	4.77E-07	2.82E-06	1.28E-07	2.24E-08	2.31E-05	7.87E-06	2.05E-06	1.60E-06
Oil seeds	**Land Occupation**	-8.51E-07	-5.66E-07	-1.45E-07	3.91E-07	-5.73E-09	1.69E-06	1.48E-06	8.99E-09	-6.99E-07	-3.01E-06	5.67E-07	-2.08E-06
Paddy rice	**Land Occupation**	2.69E-07	4.07E-07	1.08E-06	-5.64E-07	3.32E-07	6.15E-07	8.81E-08	2.80E-08	6.27E-06	2.59E-06	1.57E-06	5.66E-07
Plant-based fibers	**Land Occupation**	4.35E-09	3.66E-08	3.03E-08	1.67E-07	1.72E-08	5.52E-09	2.92E-07	6.23E-10	2.26E-07	8.19E-08	3.96E-08	8.37E-09
Sugar	**Land Occupation**	1.37E-07	-8.27E-08	2.28E-07	1.84E-06	8.34E-08	6.64E-08	3.81E-08	1.76E-08	1.00E-06	2.77E-07	2.34E-06	3.49E-07
Vegetables, fruit, nuts	**Land Occupation**	4.20E-07	4.41E-07	2.47E-06	3.87E-05	7.69E-07	4.29E-06	2.70E-07	1.21E-07	2.79E-05	6.63E-06	5.72E-06	-1.70E-06
Wheat	**Land Occupation**	-1.14E-06	-2.55E-07	1.16E-07	1.05E-05	6.85E-08	2.42E-08	5.90E-08	2.00E-08	9.76E-07	-7.76E-07	4.46E-07	-2.88E-06

		SE	SI	SK
Cereal grains Nec	**Land Occupation**	1.46E-06	-3.72E-07	-9.51E-07
Crops Nec	**Land Occupation**	5.46E-06	1.49E-06	3.04E-06
Oil seeds	**Land Occupation**	4.89E-07	-1.33E-06	-2.26E-07
Paddy rice	**Land Occupation**	1.54E-06	3.24E-07	1.01E-06
Plant-based fibers	**Land Occupation**	2.59E-08	4.07E-08	1.31E-08
Sugar	**Land Occupation**	2.80E-07	2.74E-08	-1.59E-09
Vegetables, fruit, nuts	**Land Occupation**	4.71E-06	7.99E-07	1.38E-06
Wheat	**Land Occupation**	2.05E-07	-1.36E-07	-4.07E-07

7. SI.7 - Published project code - GitHub

The code written for the execution of this project is published on the online software code repository service Github. The code can be retrieved from the address posted below.

https://github.com/KillianDavin/Master-Thesis-code

The python code was used for several mathematical operations involved in the calculation of the disaggregated, crop-specific, LC-IMPACT CFs and for the resulting production and consumption-based impact modelling with the MRIO database, EXIOBASE, using the Leontief analytical calculus (Leontief, 1936, 1970).

We first provide 6 python scripts for the calculation of the disaggregated land use and wetland characterisation factors respectively (2 for land-use and 4 for wetland CF construction). In these scripts we use the following python programming libraries:

Table S21. Python libraries used for national and continental CF construction

Python library	Function
Pandas.py	Applied for the construction of data tables and structures
Numpy.py	Applied for matrix multiplication and other matrix operations
Rasterio.py	Used for the conversion of raster files into mappable cartesian co-ordinates for shapefile overlaying
Geopands.py	A GIS package available in python and applied for intersecting different shapefile layers and the formation of resulting polygons
Rasterstats.py	Applied for the calculation of raster statistics in resulting polygons after shapefile intersections

The python scripts are listed as the following and need to be executed in sequence for each impact pathway:

Table S22: Python files for characterisation factor construction

Impact pathway	Python script	Description
Land occupation CF construction	Land_Use_Step01.py	Overlaying of shapefiles and raster files and calc of national CFs
Land occupation CF construction	Land_Use_Step02.py	Calculation of continental CFs
Wetland stress CF construction	Watershed_Step01.py	Overlaying of the water CF shapefile from LC-IMPACT with the Pfister & Bayer watershed shapefile
Wetland stress CF construction	Watershed_Step02.py	Calculation of total production of irrigated crops in Tonnes from the MapSPAM model per Watershed layer
Wetland stress CF construction	Watershed_Step03.py	Calculation of total blue water consumption per crop per watershed
Wetland stress CF construction	Watershed_Step04.py	CF construction

We then publish a python script for the calculation of production and consumption-based biodiversity footprints using the Leontief analytical calculus and EXIOBASE tables for the year 2010. Within Python, the purposely built python library for EE-MRIO database analysis, PYMRIO, was harnessed for the calculation of the different impact accounts (Stadler, 2014). Documentation and insights into the PYMRIO library, its mathematical background and its functionality can be retrieved from the PYMRIO website (Stadler, 2014). The following PYMRIO functions were used in the calculations:

1. *Pymrio.load all()*
2. *Pymrio.calc_system*
3. *Pymrio.Calc_accounts*
4. *Pymrio.calc_x()*
5. *Pymrio.calc_F()*
6. *Pymrio.calc_M()*
7. *Pymrio.calc_Z()*
8. *Pymrio.calc_F_Y()*
9. *Pymrio.calc_S_Y()*

The python scripts for biodiversity impact calculations are listed as the following and need to be executed in sequence.

Table S23. Python files for biodiversity footprint calculations

Impact pathway	**Python script**	**Description**
All impact pathways	Footprints_Step01	Construction of desired stressor table S and pressure footprint calculation
All impact pathways	Footprints_Step02	Calculation of biodiversity footprints

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