THÜNEN

Setting Up a Bioeconomy Monitoring: Sustainability – Resources – Products

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List of Abbreviations

AGEB	Energy Balances Group (Arbeitsgruppe Energiebilanzen)
AGEE	Stat Working Group on Renewable Energy Statistics (Arbeitsgruppe Erneuerbare Energien)
AMI	Agricultural Market Information Company (Agrarmarkt Informations-Gesellschaft)
BLE	Federal Agengy for Agriculture and Food (Bundesanstalt für Landwirtschaft und Ernährung)
BMEL	Federal Ministry of Food and Agriculture (Bundesministerium für Ernährung und Landwirtschaft)
CEFS	Committee of European Sugar Producers (Comité Européen des Fabricants de Sucre)
CF	Conversion factor
CfW 2.0	Charter for Wood 2.0
CN	Combined (traffic and statistical) Nomenclature
CPA	Statistical Classification of Products by Activity
CRF	Common Reporting Format
DBFZ	German Biomass Research Centre (Deutsches Biomasse Forschungszentrum)
DEPV	German Pellet Association
DESTATIS	Official statistics published by the Federal Statistical Office of Germany
DTI	German Frozen Food Institute (Deutsches Tiefkühlinstitut e.V.)
EP	Eutrophication Potential
EPAL	European Pallet Association
ES	Earning Survey
EUROSTAT	European Statistical Agency
FAO	Food and Agriculture Organization of the United Nations
FNR	Agency for Renewable Resources (Fachagentur Nachwachsende Rohstoffe e.V.)
GP	National version of PRODCOM list (Güterverzeichnis für Produktionsstatistiken)
GVA	Gross Value Added
GWP	Global Warming Potential
HS	Harmonized Commodity Description and Coding System
ISIC	International Standard Industrial Classification of All Economic Activities
LCA	Life Cycle Assessment
LfL	Bavarian State Institute for Agriculture (Bayerische Landesanstalt für Landwirtschaft)
LFS	Labour Force Study
LOFASA	Logical Framework for a Sustainability Assessment
LULUCF	Land use, land use change and forestry
LWE	Live weight equivalent
m3(f)	Cubic meters of wood fibre equivalent
m3(r)	Cubic meters of roundwood equivalent
MFA	Material flow analysis
MGrE	Material and Goods received Enquiry
mil.	Million
MVO	Reporting Regulation for Goods with Market Regulations (Marktordnungswaren-Meldeverordnung)
NACE	Statistical Classification of European Activities
NIR	National Inventory Report for the German Greenhouse Gas Inventory
OVID	Association of the Oilseed Processing Industry in Germany (Verband der ölsaatenverarbeitenden Industrie in Deutschland e.V.)
PRODCOM	Products of the European Community
RRM	Rest raw materials, residues resulting from domestic processing of aquatic biomass
SBS	Structural Business Statistics
SDG	Sustainable Development Goals

SES	Structure of Earnings Survey
SME	Small and Medium Enterprises
t	Metric ton, metric tonnes
TFZ	Technology and Promotion Centre in the Competence Centre for Renewable Resources (Technologie- und Förderzentrum am Kompetenzzentrum für Nachwachsende Rohstoffe Technologie- und Forschungszentrum)
TI-WF	Thünen Institute of Forestry
UFOP	Union for the Promotion of Oil and Protein Plants (Union zur Förderung von Oel- und Proteinpflanzen e.V.)
VDGS	Association of German Grain Processors and Starch Manufacturers (Verband der deutschen Getreideverarbeiter und Stärkehersteller e.V.)
VDP	German Paper Association
VLOG	Association Food Without Genetic Engineering (Verband Lebensmittel ohne Gentechnik e.V.)
WA	National version of Combined Nomenclature (Warenverzeichnis der Außenhandelsstatistik)
WVZ	Wirtschaftliche Vereinigung Zucker (German Sugar Industry Association, Economic Association for Sugar) e.V.
WZ	German NACE version of 2008 (Klassifikation der Wirtschaftszweige)

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Preface

This Thünen Working Paper presents results of the research project „Setting up a systematic bioeconomy monitoring – Consolidation Phase (acronym MoBi II). The project follows on from the MoBi I project, the results of which were presented in the Thünen Working Paper 149. While the MoBi I project focussed strongly on fundamental methodological aspects of bioeconomy monitoring, MoBi II addresses additional methodological aspects, but also presents updated monitoring results. The project was funded by the Federal Ministry of Food and Agriculture based on a resolution of the German Bundestag (Funding Code 2221NR062A and 2221NR062B). We would like to thank the ministry for its support and open discussions.

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The MoBi II project was part of the second stage of the German Federal Government's initiative to further develop and consolidate a comprehensive monitoring of the German bioeconomy. The second stage of the initiative comprised two further projects: the second phase of the project Systemic Monitoring and Modelling of the Bioeconomy (SYMOBIO 2), funded by the Federal Ministry of Education and Research, and the project Further Development of the "Bioeconomy Monitoring System" with Special Consideration of Precautionary Environmental Protection (MonBio), funded by the German Environment Agency. We would like to thank the two other research consortia for fruitful discussions and good cooperation.

Special thanks go to Johanna Schliemann for her tireless support in elaborating e!sankey charts.

Vorwort

Das vorliegende Thünen-Arbeitspapier stellt Ergebnisse des Forschungsprojekts „Aufbau eines systematischen Monitorings der Bioökonomie - Konsolidierungsphase (Akronym MoBi II)“ vor. Das Projekt schließt an das Projekt MoBi I an, dessen Ergebnisse im Thünen-Arbeitspapier 149 vorgestellt wurden. Während das Projekt MoBi I stark auf grundlegende methodische Aspekte des Bioökonomie-Monitorings fokussierte, werden in MoBi II zusätzliche methodische Aspekte aufgegriffen, aber auch aktualisierte Monitoring-Ergebnisse präsentiert. Das Projekt wurde gefördert durch das Bundesministerium für Ernährung und Landwirtschaft aufgrund eines Beschlusses des Deutschen Bundestages (Förderkennzeichen 2221NR062A und 2221NR062B). Wir danken dem Ministerium für seine Unterstützung und die offenen Diskussionen.

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Das Projekt MoBi II war Teil der zweiten Phase der Initiative der Bundesregierung zur Weiterentwicklung und Konsolidierung eines umfassenden Monitorings der deutschen Bioökonomie. Die zweite Phase der Initiative umfasste zwei weitere Projekte: die Fortsetzung des vom Bundesministerium für Bildung und Forschung geförderten Projekts Systemisches Monitoring und Modellierung der Bioökonomie (SYMOBIO 2) und das vom Umweltbundesamt geförderte Projekt Weiterentwicklung des „Monitoringsystems Bioökonomie“ mit besonderer Rücksicht auf einen präventiven Umweltschutz (MonBio). Den beiden anderen Forschungskonsortien danken wir für fruchtbare Diskussionen und gute Zusammenarbeit.

Besonderer Dank gilt Johanna Schliemann für ihre unermüdliche Unterstützung bei der Erstellung der Abbildungen mit e!sankey.

Abstract

This Thünen Working Paper presents the results of the research project "Joint Project: Expansion of a systematic monitoring of the bioeconomy - consolidation phase." The project aimed to further develop the monitoring concept for the German bioeconomy and to update initial monitoring results. This Working Paper refers to the Thünen Working Paper 149 and presents updated monitoring results on the one hand, and approaches to the monitoring of substitution and the recording and tracking of import commodities and their sustainability effects on the other.

The report is divided into four main chapters. The first chapter explains the data bases, such as different statistical classification systems (NACE, WZ, GP, WA/CN), production, foreign trade and structural data, units, conversion factors and changes compared to the first monitoring.

Chapter 2 is dedicated to the resource base, material flows and bio-based sectors. The aggregated biomass flows as well as the biomass flows from agriculture, forestry and fisheries are updated and more differentiated for the year 2020. The amount of secondary biomass from waste and residues occurring in Germany is also newly estimated. Time series data of the potential of biogenic waste and residues in Germany are available via the ResDB Biomass Monitor of the DBFZ.

Chapter 3 deals with the analysis of substitution effects of biomass as a replacement for fossil raw materials. Within the framework of a systematic literature review, various definitions and methodological approaches to quantify substitution effects have been identified. Life cycle analysis (LCA) is most frequently used to quantify the substitution of fossil raw materials and products by bio-based ones, with substitution factors serving as a metric to quantify substitution effects.

Chapter 4 deals with the monitoring of imported agricultural and wood-based raw materials. An integrated approach combines Material Flow Analysis (MFA), Life Cycle Sustainability Assessment (LCSA) and the Logical Framework for Sustainability Assessment (LOFASA) to trace the value chain of imported raw materials and to record sustainability effects associated with cultivation, processing and transport. The examples of beef from Argentina and soy from Brazil show that sustainability effects can vary greatly regionally and, in order to avoid misinterpretations, should therefore also be recorded and evaluated at the regional level. The magnitude of the sustainability effects associated with the import of raw materials to Germany is determined by quantity, regional origin and the production chain.

In this and in Thünen Working Paper 149, both the methodological bases for a systematic monitoring, encompassing all areas of the bioeconomy, are presented and the applicability of the monitoring concept is proven using concrete examples. The monitoring concept is so far developed that it can be implemented step by step to provide important information for the development of a sustainable and resource efficient bioeconomy.

Keywords: bioeconomy, material flow, sustainability, monitoring, bio-based, assessment

Zusammenfassung

Dieses Thünen Working Paper stellt die Ergebnisse des Forschungsprojektes Verbundvorhaben: Ausbau eines systematischen Monitorings der Bioökonomie – Konsolidierungsphase vor. Das Projekt hatte zum Ziel, das Monitoringkonzept für die deutsche Bioökonomie weiterzuentwickeln und erste Monitoringergebnisse zu aktualisieren. Diese Working Paper nimmt Bezug auf das Thünen Working Paper 149 und stellt zu einen aktualisierte Monitoringergebnisse und zum anderen Ansätze zum Monitoring von Substitution und der Erfassung und Rückverfolgung Import-Commodities und deren Nachhaltigkeitseffekte vor.

Der Bericht gliedert sich in vier Hauptkapitel. Im ersten Kapitel werden die **Datengrundlagen** wie verschiedene **statistische Klassifikationssysteme** (NACE, WZ, GP, WA/CN), **Produktions-, Außenhandels- und Strukturdaten, Einheiten, Umrechnungsfaktoren** und Veränderungen gegenüber dem ersten Monitoring erläutert.

Kapitel 2 widmet sich der **Ressourcenbasis, den Materialflüssen und biobasierten Sektoren**. Die **aggregierten Biomasseflüsse** sowie die Biomasseflüsse aus Landwirtschaft, Forstwirtschaft und Fischerei werden für das Jahr 2020 aktualisiert und stärker differenziert. Die Menge der in Deutschland anfallenden **Sekundären Biomasse** aus Abfällen und Reststoffen wird ebenfalls neu abgeschätzt. **Zeitreihendaten des Potenzials biogener Abfälle und Reststoffe** in Deutschland sind über den ResDB Biomasse Monitor des DBFZ verfügbar.

Kapitel 3 befasst sich mit der **Analyse von Substitutionswirkungen** von Biomasse als Ersatz für fossile Rohstoffe. Im Rahmen einer systematischen Literaturrecherche sind verschiedene **Definitionen und methodische Ansätze** zur Quantifizierung von Substitutionseffekten zu identifiziert worden. Am häufigsten wird die **Lebenszyklusanalyse (LCA)** verwendet, um die Substitution von fossilen Rohstoffen und Produkten durch biobasierte zu quantifizieren, wobei **Substitutionsfaktoren** als Metrik zur Quantifizierung von Substitutionseffekten dienen.

Kapitel 4 befasst sich mit dem Monitoring importierter land- und forstwirtschaftlicher Rohstoffe. Ein **integrierter Ansatz** kombiniert Materialflussanalyse (MFA), Life Cycle Sustainability Assessment (LCSA) und den Logical Framework for Sustainability Assessment (LOFASA), um die Produktionskette **importierter Rohstoffe nachvollziehen zu können und mit Anbau, Weiterverarbeitung und Transport verbunden Nachhaltigkeitseffekte zu erfassen**. Die Beispiele Rindfleisch aus Argentinien und Soja aus Brasilien zeigen, dass **Nachhaltigkeitseffekte regional sehr unterschiedlich** sein können und um Fehlinterpretationen zu vermeiden, diese daher auch auf regionaler Ebene erfasst und bewertet werden sollten. Wie groß die mit dem Import der Rohstoffe verbundenen Nachhaltigkeitseffekte sind, wir durch Menge, regionale Herkunft und die Produktionskette bestimmt.

In diesem und im Thünen Working Paper 149 werden sowohl die methodischen Grundlagen für ein **systematisches und alle Bereiche der Bioökonomie umfassendes Monitoring** vorgestellt als auch anhand von konkreten Beispielen die Anwendbarkeit des Monitoringkonzeptes nachgewiesen. Das Monitoringkonzept ist so weit entwickelt, dass es schrittweise implementiert werden kann, um wichtige Informationen für die Entwicklung einer **nachhaltigen und ressourcenschonenden Bioökonomie zur Verfügung** bereitzustellen.

Schlüsselwörter: Bioökonomie, Stofffluss, Import-Commodities, Nachhaltigkeit, Monitoring, biobasiert, Bewertung

1 Setting the Scene

1.1 Introduction

The bioeconomy concept as a means of de-fossilising our economies is currently being implemented in many countries around the world. The specific goals for this transformation of our economies, however, vary greatly from country to country. As can be seen in the numerous bioeconomy strategies and action plans. Although bioeconomy is defined differently in different countries, many bioeconomy strategies consider bioeconomy monitoring to be essential for assessing the progress of strategy implementation and/or associated sustainability effects. The German National Bioeconomy Strategy defines six strategic goals (BMBF and BMEL 2020). First, it couples the National Strategy with the United Nations 2030 agenda for sustainable development. Second, it recognises the potential of bioeconomy within its ecological boundaries. Third, it wants to enhance and apply biological knowledge. Fourth, it wants to establish a sustainable raw material source for industry. Fifth, it wants to promote Germany as the leading location for innovation in bioeconomy. Finally, it wants to involve society and strengthen international collaboration.

One important aspect the German National Bioeconomy Strategy also addresses is the monitoring of bioeconomy. In order to get sound information on the status of bioeconomy, a frequent monitoring is essential. In continuation of the efforts to develop bioeconomy monitoring concepts that began 2016, the German government extended funding of two projects to consolidate the concepts for bioeconomy monitoring and initiated one additional project. Each research consortium had a different focus. The Federal Ministry of Education and Research extended the funding of the consortium called SYMOBIO that develops a scientific basis for a systemic monitoring and modelling of the German bioeconomy with respect to sustainability aspects on a national and international level. The Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection funded the project: Further Development of the "Bioeconomy Monitoring System" with Special Consideration of Precautionary Environmental Protection.

The Federal Ministry for Food and Agriculture extended the funding for the project: Establishment of a Systematic Monitoring of the Bioeconomy – Consolidation Phase (MoBi II) carried out by the Thünen Institutes of Market Analysis, Sea Fisheries and Forestry to continue to develop a monitoring approach that is able to assess the bio-based resources and sustainability effects associated with German bioeconomy. This working paper is a continuation of the earlier Thünen Working Paper 149 (Iost et al. 2020b) and presents methodological updates, updated monitoring results, new methodological approaches to monitor import commodities and associated sustainability effects, and options for the monitoring of substitution effects of bio-based products.

This Working Paper is structured into four chapters. Chapter 1 introduces data sources that are essential for the monitoring and highlights changes compared to the status of Working Paper 149 and introduces the objectives of the project. Chapter 2 presents the conceptual framework for material flow analysis of bio-based material flows as well as an adjusted approach for the quantification of bio-based shares in the economic sectors. The results of the material flow analysis of the most significant bio-based material flows originating from agriculture, forestry and fisheries, as well as the bio-based shares, are also presented. In chapter 3, options for the monitoring of substitution effects are presented and discussed. In the final chapter 4, an approach to identify and quantify sustainability effects associated with the import of major agricultural and forest commodities as well as results for selected countries and commodities are presented.

1.2 Available Data

In continued efforts to build and consolidate a bioeconomy monitoring, significant data sources are still been grouped in (i) official statistics published by the Federal Statistical Office of Germany (DESTATIS) and other Federal Agencies, (ii) specified statistics compiled by relevant associations, and (iii) empirical studies. Data provided by the first group remains the backbone of a continuous monitoring as the data is collected based on standardized and often internationally harmonized classification schemes and methods and in defined time intervals. Thus, official statistics allow for comparisons over time and between regions and even national states. Statistics revisions as a matter of routine, due to methodological adaptation or extraordinary reasons are transparently communicated and result in improved data quality (DESTATIS 2017a).

In the following subchapters, we give an overview on the harmonized statistics classification system (chapter 1.2.1) and on the statistics that are relevant for monitoring production and use of agricultural, forest and aquatic biomasses (chapters 1.2.2 to 1.2.4). The variety of bio-based products and uses is the result of a variety of production, processing and manufacturing processes that convert biomass in one way or another. Biomass contents change during these processes and vary considerably in the finished products. Details regarding conversion factors are given in chapter 1.2.5.

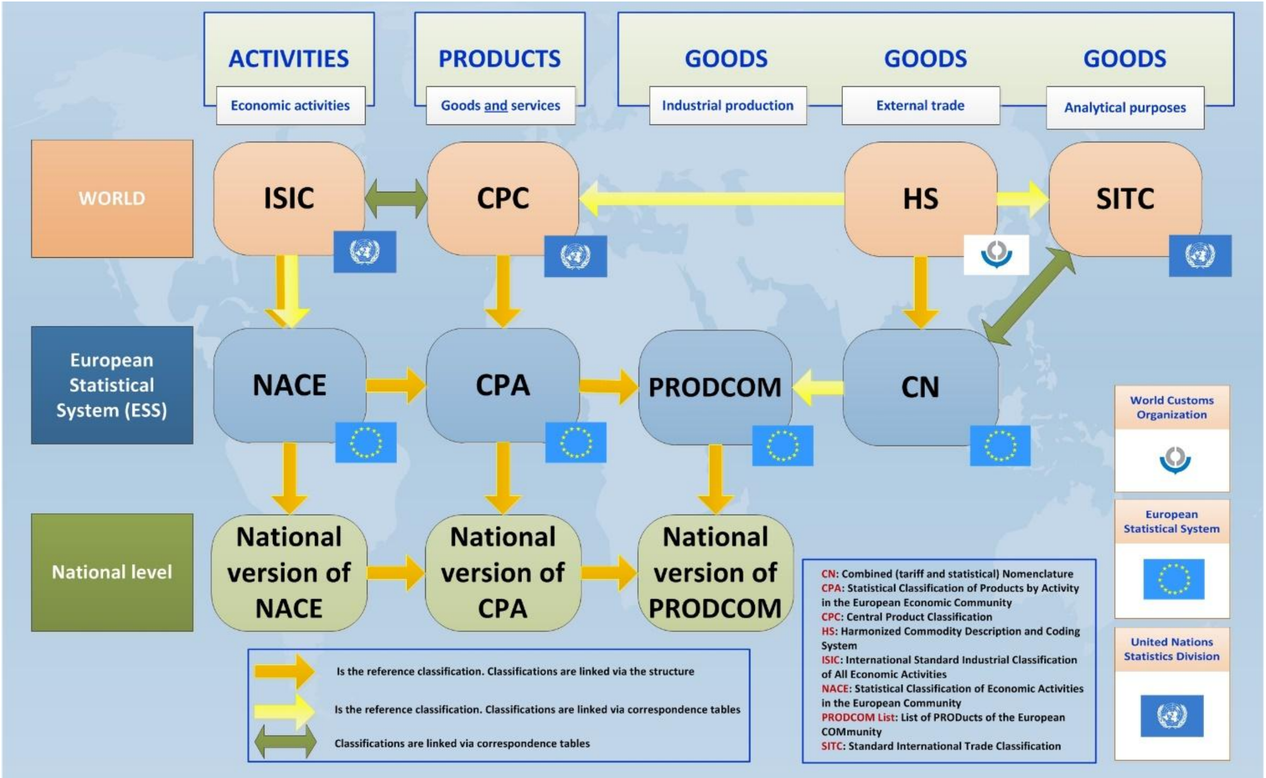
Data sources specific to agriculture, forestry and fisheries including aquaculture as well as sustainability effects of import commodities are described in detail in the corresponding parts of chapter 2.4 and chapter 4, respectively.

1.2.1 Economic Classifications

All data officially provided by international, EU- and national statistical agencies like the European Statistical Agency (EUROSTAT) and DESTATIS is based on a harmonized system of statistical classifications. This classification structures the data submitted by the contributing countries or member states and enables a comparison of the data submitted. Figure 1 outlines relevant classifications and illustrates connections between them. The classifications refer to economic activities, to products or services as outputs from economic activities or to traded goods. Classification systems correspond to each other because they have the same structure or are comparable via correspondence tables. However, single positions in the classifications are not always unambiguously comparable, which inevitably results in a certain level of inaccuracy.

In Germany, the national versions of the Statistical Classification of Economic Activities in the European Community, Rev. 2 (NACE Rev. 2 **N**omenclature européenne des **a**ctivités economiques dans la **C**ommunauté **e**uropéenne), i.e., Klassifikation der Wirtschaftszweige (WZ) and the more detailed PRODCOM (**Prod**uction **Com**munautaire), i.e. Güterverzeichnis für Produktionsstatistiken (GP) are the most relevant classification systems as official federal data on economic activities and production is structured accordingly. In order to represent economic developments and trends that result in new economic activities, products, goods and services, classifications are updated regularly. In the context of bioeconomy monitoring concept consolidation, German NACE version of 2008 (**WZ08**) and German PRODCOM of 2012 (**GP09**) as well as of 2019 (**GP19**) were used. Data on external trade is provided by the Combined Nomenclature (CN), the “Warenverzeichnis der Außenhandelsstatistik” (WA)., which is updated every year. From 2025 on, updates of NACE Rev. 2 and the corresponding German NACE version (WZ25) will come into force (EUROSTAT 2024c).

Figure 1: Integrated system of statistical activity and product classifications



Source: (EUROSTAT 2020b)

WZ08

WZ08 classifies economic activities. Structure and codes correspond to codes in NACE Rev. 2 down to the 4-digit level (i.e., classes). For some classes, WZ08 is more detailed and further disaggregated into subclasses (5-digits). Further description of economic activities classified into one (sub-)class can be derived from the "Klassifikationsserver" online (DESTATIS 2008). Companies are allocated to a statistical economic activity, depending on the share of generated gross value added attributed to different activities that companies may follow. If no data on gross value added is available, production value, turnover or number of employed persons are used for allocation. For example, manufacturer of wooden pallets often also run saw mills in order to produce their own sawn wood for production and repair of pallets. If the value-added share of pallet manufacture is larger than the share for saw milling, the company is allocated to WZ08 code 16.24, i.e., *Manufacture of wooden containers* and not in code 16.10 *Sawmilling and planing of wood*. This method for allocation leads to errors in estimating wood material flow-based on official classification of economic activities. In order to reduce errors, other statistics have to be included. Main and sideline activities of companies are registered in the official business register.

GP09

As described in Iost et al. (2020b) the German PRODCOM classifications GP09 and GP19 are directly related to PRODCOM codes. Produced goods are coded into a 9-digit numerical code, instead of 8 digits. According to the aim of harmonization between European and national classifications, the first four digits are identical to the equivalent classes of NACE Rev. 2 and WZ08, respectively. Together with the next two digits, the six digits are identical to those of the Statistical Classification of Products by Activity (CPA) code; therefore, fully consistent with the CPA. The GP09 codes correspond to one or more codes of the CN, which enables production data to be related to foreign trade data. The first eight digits are mainly identical to the PRODCOM list and the ninth digit allows a further subdivision on national level.

Table 1: Correspondence of GP09 and WA/CN

	GP09	WA/CN
I to XXI	Product section	section
2-digit code	Product division (Abteilungen)	chapters
3-digit code	Product group (Gruppen)	headings
4-digit code	Product class (Klassen)	
5-digit code	Product category (Kategorien)	
6-digit code	Product subcategory (Unterkategorien)	HS subheadings
8-digit code		CN subheadings
9-digit code	Product code (Güterarten)	

Source: own compilation

The PRODCOM list is updated annually and is always valid from the January 1st till December 31st of the same year. An updated GP (**GP19**) came into force January 1st 2019 and replaced GP09. It adapts the current version of PRODCOM on EU level and comprises minor changes as compared to GP09. In the bioeconomy monitoring consolidation phase both classifications were relevant. Changes in the structure with relevance to bio-based products were handled on basis of the respective correspondence tables. (DESTATIS 2018c)

WA, CN

As noted in Iost et al. (2020b) the WA is the national classification of the CN and used for categorizing traded goods. The classification is annually revised and implemented on January 1st. The list is annually updated and therefore allows a fast adaptation to innovations and changes in the market. An important characteristic is the trade volume. If this increases further, WA/CN are established. On the other side, WA/CN with reducing trade volume may be closed and aggregated. Consequently, the changes of CN reflect changes in markets and integrate market observations.

1.2.2 Production Statistics

The purpose of the product statistics is to report amount and value of production of all listed products at the respective aggregation levels and for the respective year. Consequently, the statistic is related to products and not to activities. The production statistics record the domestic production of all local units belonging to a legal unit, which is totally or primarily engaged in production and services of NACE sectors B and C Mining, Quarrying, and Manufacturing. That means the statistic contains also data of local units, which do not belong to the respective economic activity. The statistic covers the activities of enterprises with 20 or more employees; for sawmills, the cut-off is at less than 10 employees. The overall coverage error at EU27 level is less than 10% (Eurostat, 2024).(EUROSTAT 2018) In the case of sawn wood, the applied cut-off thresholds in Germany lead to a substantial underestimation. Collection quota of official production statistics for unplaned sawn softwood ranged from 76.7% to 87.3% and was 38.1% for unplanned sawn hardwood in average for the years 2002 – 2015 (Döring et al. 2017). For agriculture, the use of on-farm produced feed describes a problem to calculate the exact amount of produced cereals or oilseeds (Bundesanstalt für Landwirtschaft und Ernährung 2018).

Production statistics for Germany provide data at the level of a 9-digits numerical code, i.e., at the highest level of detail possible. The survey is conducted monthly for local units with 50 or more employees and quarterly for local units with 20 or more employees. Both data sets are combined for the quarterly published production statistics. The monthly and annual data are published with a delay of 4 months. The comparability of the results over time results may be limited, if methodological changes concerning cut-off threshold, sample size or other have occurred. The data is used by the national accounts, input-output accounts and the monthly production index (EUROSTAT 2018; Flores and Baumgärtner 2019; DESTATIS 2019b).

1.2.3 Foreign Trade Statistics

The foreign trade statistic records the value and quantity of goods that are exported from one country and imported into another country. Data is collected by customs authorities. Recording of trade between Germany and non-EU Member States (extra EU-trade) is done by custom declaration. In contrast, trade between EU Member States (intra EU-trade) is recorded by a system called Intrastat and the data are directly collected from traders. In addition, it is interlinked with the value added tax (VAT) system; therefore, it ensures the completeness and quality of the statistical data. To simplify data provision and to reduce the burden on traders, a threshold is established. Trading companies with an annual export value of less than 500,000 € or annual import value of 800,000 € are exempted. The value and quantity are estimated and listed in the statistics. Both results, extra EU-trade and intra EU-trade, are summarized in the foreign trade statistic (EUROSTAT 2020a).

Besides product value and quantity, the custom authorities collect data about the partner country, reference period (month), direction of the trade (import or export) and mode of transport. The traded products are allocated to the CN classification which is based on the globally applied HS (more information see chapter 1.2.1). The unit of quantity is mainly the net weight (without packaging), exceptions are for example pairs for shoes, liters for wine or square meters for carpets. Many wood-based products are registered in cubic meters. But also, a variety of other units are used, for example wooden window frames in absolute numbers, wooden flooring in m^2. The unit tons (net weight) must be reported. Data on monetary value and net weight allow the calculation of a price per unit which can be applied to production value of the respective GP09-code in order to estimate produced amounts, if in the production statistics only the production value is recorded. For this derivation of prices, the export value should be used. The export value of a traded good includes the value added by economic activity in Germany; therefore, it represents the true production value more likely.

1.2.4 Structural Business Statistics

Based on data provision from EU countries, EUROSTAT provides the structural business statistics (SBS) (EUROSTAT 2021). Main indicators are collected and presented as monetary values or as counts. SBS covers NACE Rev.2 sections B to N and Division 95, i.e., industry, construction, distributive trades and market services. Relevant statistics on the Federal level are manifold and structured according to NACE sections and the availability of data varies between sections. SBS are based on two different structural surveys: **cost structure survey** for entities with more than 20 employees and a **structure survey** for entities with less than 20 employees.

Traditionally, in manufacturing only companies with more than 20 employees are surveyed. However, on the EU level and for international comparisons, data from companies of all sizes is needed. Thus, both statistics are needed for secondary calculations like contributions of economic activities to gross domestic product as part of national accounting or in Input-Output-Table. At the same time, data requirements of the EU are fulfilled (DESTATIS 2018d). Survey results constitute an important data source for sectoral bioeconomy monitoring (chapter 2.5) and sustainability assessment (chapter 3).

Cost structure survey depicts economic performance and the respective expenditures of companies of selected economic sections (DESTATIS 2016b). These are sections C (manufacturing), D and E (energy supply, water supply, sewerage, waste management and remediation activities), F (construction), parts of section Q (Human health activities) and other service activities (DESTATIS 2017b). The sample consists of 5% of all companies of the respective economic section and selected companies are obliged to report based on Federal Laws (BMJV 7/21/2016, 10/20/2016). At the national level, the data collected is utilised for a variety of purposes, including the provision of policy advice, the calculation of national accounts, and the facilitation of scientific and educational endeavours. Additionally, business organisations employ the data for their own objectives. The data collated encompasses personnel and material expenditure, taxes, the number of employees, and the value of traded goods. The monetary value in Euros is the functional unit of most indicators. (DESTATIS 2016b). Cost structure statistics in manufacturing provide information on production output, exerted production factors as well as value added at different levels of aggregation (Ebnet 2014).

Structural statistics sample size is 6,000 companies with less than 20 employees. Thus, structural statistics results complement the cost structural survey for manufacturing, for example in National Accounts or Input-Output-Tables to estimate the material use of small enterprises. The underlying assumption is that small and bigger enterprises are structured equally. Compared to the cost structure survey, the structure survey has fewer indicators, lower accuracy of results and is not officially published by DESTATIS.

1.2.5 Units and Factors

Agricultural biomass

Compared to forest and aquatic biomass, the complexity is the highest for the agricultural sector, in which a wide range of biomass types are produced and processed into food, feed, and other final products. Unlike the forestry sector, where wood is commonly measured in cubic meters with well-established conversion factors, data on agricultural biomass is collected in diverse units—such as litres, kilograms, or hectares—without a universally applied denominator. This heterogeneity poses challenges for integrating data across different biomass streams and sec-tors.

For instance, the German Federal Agency on Agriculture and Food (BLE) publishes monthly statis-tics on milk production and deliveries to dairy companies, as well as data on the manufacture and consumption of dairy products. These reports include conversion factors that enable the translation of milk volumes from litres to kilograms, ensuring consistency in national and international reporting. Similarly, in arable farming, a frequently used reference measure is the “cereal unit,” which allows for a rough standardization of yield comparisons across different crops. How-ever, this approach remains limited to specific agricultural product groups and does not cover the entire spectrum of agricultural biomass.

A further challenge arises in the use of balance weighting factors, which are currently available only for selected agricultural balance groups and primarily in connection with the foreign trade statistics commodity codes (CN codes). This fragmentation means that deriving comparable quantities across the entire agricultural biomass spectrum requires extensive data harmonization efforts.

Unlike the forestry sector, where wood is often expressed in dry matter equivalents or energy content, there is no universally adopted conversion system for agricultural biomass that allows for consistent transformation of raw material quantities into dry matter. The absence of such a standardized methodology results in inconsistencies across data sources, making long-term monitoring of bioeconomic flows more difficult. In particular, efforts to compile biomass flows within the bioeconomy require researchers and policymakers to piece together conversion factors from multiple sources, leading to potential discrepancies and inefficiencies in data processing.

To establish a robust and long-term monitoring framework for the bioeconomy, it is essential to develop a harmonized set of conversion factors that enable the consistent translation of all agricultural raw materials into a common metric, such as dry matter or energy content. A coordinated effort among statistical agencies, research institutions, and industry stakeholders is required to define, standardize, and regularly update these coefficients. The implementation of such an initiative would result in substantial enhancements to the comparability and reliability of biomass flow analyses, thereby enabling informed decision-making in the transition to a sustainable bioeconomy.

Forest biomass

Processing of timber, manufacturing and production of wood products is highly diverse and the actual wood content of semi-finished and finished wooden products varies. In production and trade statistics, amounts of wood and wood products are listed in customary units like m^3, t or m^2 and m. Besides wood, these amounts may contain other materials like chemicals, glue or resins. Consequently, statistics do not give numbers on the sheer amount of wood contained in a product and conversion factors are needed to calculate respective wood contents. Furthermore, shrinking and swelling of wood and wood products have to be considered.

Against this background, Weimar (2011) developed a new reference unit, the wood fibre equivalent (m^3(f)). It defines the volume equivalent to all wood or wood-based fibres at fibre saturation point contained in a defined product. For every wood-based product, a specific conversion factor has to be calculated (Bösch et al. 2015). Furthermore, for WA 8-digit codes, information on carbon content (carbon factors) are available (Diestel and Weimar 2014).

The wood fibre equivalent is recommended for utilisation in the calculation of material flows of forest biomass, thereby ensuring the attainment of complete comparability between varying wood products. For the purpose of aggregating material flows, however, it is deemed appropriate to employ the unit "tonnes of dry matter" as the common unit for calculation.

Aquatic biomass

Aquatic biomass is traded at different levels of processing. Whole fish and seafood as well as semi-finished and finished products are consumed by the final consumer. Most data on aquatic biomass is available as net weight, which does not take into account the actual fish content or the amount fish and seafood caught for the products (live weight equivalent – LWE). Estimates of the raw materials used can only be determined by applying conversion factors (CF). The European Market Observatory for fisheries and aquaculture (EUMOFA) offers a list of factors based on the 8-digit code of CN to calculate the LWE (EUMOFA 2019). The list describes the processing procedure for Europe, justified by its purpose of application. Another list is used by the BLE to calculate the supply balance, per capita consumption, and level of self-sufficiency. This list is not published, but inspired by the list of AIPCE. A comparison between the CFs of EUMOFA and AIPCE has been conducted for the most relevant fish products and published in several finfish studies (AIPCE, 2018). Due to its structure, the EUMOFA CF is more practical, easier to apply, and has therefore been used for this study. However, it should be noted that the calculation of the LWE and its application is only an approximation of the actual use, as processing techniques and formulations are constantly changing.

The LWE is used to calculate the supply balance for Germany. LWE includes the entire catch, but the fish is also processed at sea. Consequently, the amount of fish landed includes both whole and processed fish. This means that the landed weight differs from the LWE. However, for the quantification of the material flows presented in this chapter, 2.4.5, the net product weight (i.e., the weight without sauce and other non-aquatic ingredients) and the landed weight were used. This allowed a more detailed description of domestic processing and, in particular, an accurate estimate of fish waste generated during processing.

As described above, the total biomass in dry matter is shown for the aggregated material flow of the German bio-economy (cf. 2.4.2). Fish and seafood have a high water content which varies from species to species. To calculate the dry mass, the conversion factor (CF) published by Gurria et al. (2017) is used, which assumes a dry mass content of 25%.

1.3 Objectives

The main objective of this working paper is to report the refinements and expansion of the bioeconomy monitoring concept described in Iost et al. (2020b).

This includes:

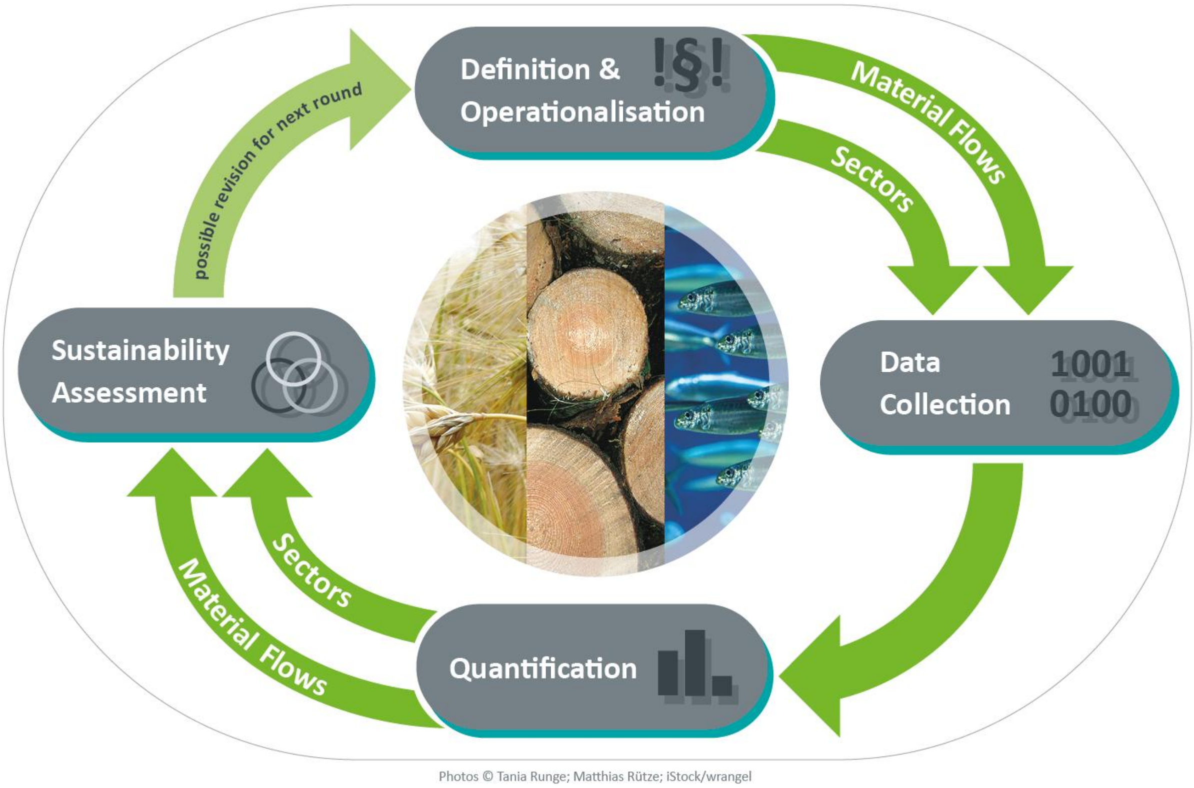
- Updating and deepening the material flow analyses
- Linking the bio-based material flows with residual materials
- Adjusting and updating the estimation of bio-based shares of economic activities
- Analysing the origin of import commodities
- Identifying suitable methods for the monitoring of substitution effects
- Best practice examples for the identification and quantification of sustainability effects of import commodities

2 Resource Base, Material Flows and Bio-Based Sectors

2.1 Conceptual Framework

Although the framework we developed for monitoring the German bioeconomy has not changed since the first publication in Iost et al., pp. 14–15 (2020b), it is presented again below for a better understanding of this report (cf. Figure 2). For more detailed information on the framework, please refer to Iost et al. (2020b).

Figure 2: Conceptional framework for a bioeconomy monitoring



Source: own illustration

2.2 Monitoring Scopes

In general, the requirements for monitoring depend on the topic to be monitored. In the case of monitoring the German bioeconomy, the requirements are derived from the goals formulated in the National Bioeconomy Strategy (BMBF and BMEL 2020). The central goals of the strategy are: First, to link the national strategy to the United Nations 2030 Agenda for Sustainable Development. Second, it recognizes the potential of the bioeconomy within its ecological limits. Third, it aims to increase and apply biological knowledge. Fourth, it aims to create a sustainable source of raw materials for industry. Fifth, it wants to promote Germany as a leading innovation location for the bioeconomy. And finally, it wants to involve society and strengthen international cooperation. Taken together, these central goals illustrate the comprehensive ambition of the bioeconomy. Against this background, the review of the available data has revealed two key monitoring areas, which we propose should also be taken into account in future monitoring activities.

First, the sectoral scope covers the broader context of economic sectors and underlying economic activities whose quantification makes it possible to capture the importance and development of the bioeconomy in the context of the national economy and to compare it internationally. The sectoral monitoring of the bioeconomy makes use of existing national and international statistics and classification schemes as well as official sectoral data from federal and EU statistical offices. It also provides insights into the sustainability impacts of the bioeconomy. This report updates gross value added and employment through 2020. However, due to the high level of aggregation, sectoral monitoring cannot determine whether the use of biomass in a particular value chain is efficient or more or less sustainable compared to another value chain.

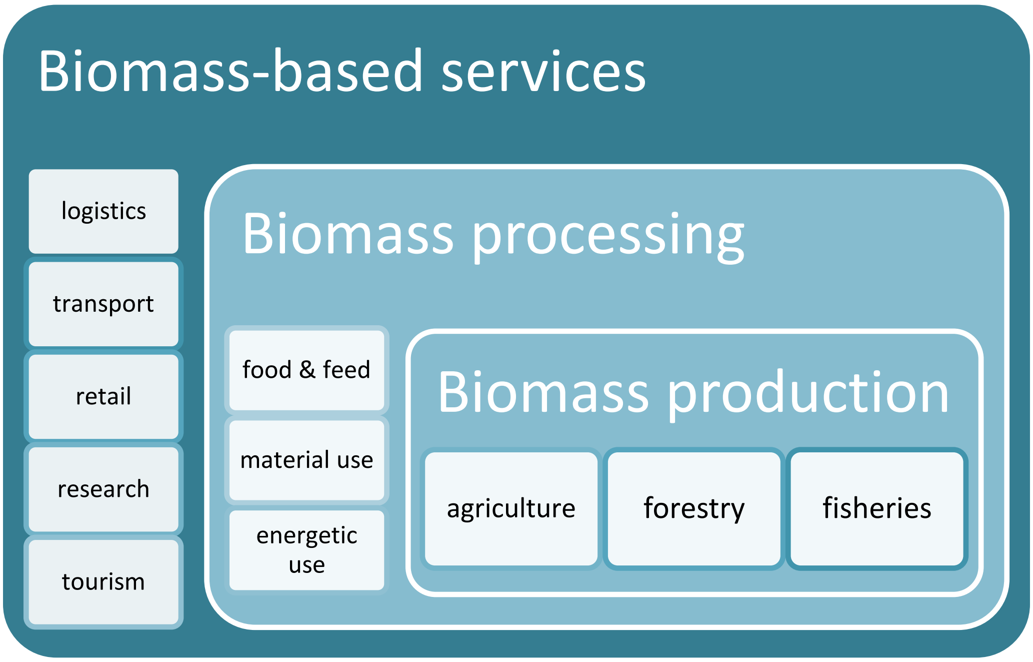
Therefore, the second monitoring scope covers material flow analysis (MFA) of relevant biomasses. In MFA, all possible modification steps of a certain biomass from production (harvest or catch) to final disposal are described and quantified. Every modification step is considered as a process and may constitute in industrial processing, manufacturing, final use, disposal or recycling (Schweinle et al. 2020). Thus, MFA provides data for evaluation of efficient use of resources and substitution of fossil resources in production, processing and manufacturing as well as use and post-use phases (Schweinle et al. 2020). Thinking along material flows helps to depict existing and possible uses and any processing of biomass, also residues and side-streams can be covered. As a starting point of a continuous monitoring and to reduce complexity, we chose to identify and quantify all material flows of biomass from agriculture, forestry and fisheries on a highly aggregated level (cf. chapter 2.4). In this report, the aggregated biomass flows, the agricultural, wood and aquatic biomass flows of the German bioeconomy were updated for the year 2020. The material flow data forms the basis for the assessment of sustainability effects of bio-based value chains and products and thus contributes to the assessment of the impact of resource substitution in a developing bioeconomy.

2.3 Definition and Operationalisation

Elaborating the conceptional framework and running the first cycle was based on the following definition (Iost et al. 2019): ‘Bioeconomy includes the production of biomass, bio-based manufacturing along the complete value chains as well as bio-based provision of services, like transport of retail of bio-based products. “Bio-based” refers to products that fully or partially consist of renewable material resources, i.e., biomass. […] The use of bio-based products and product-related services encompasses food and feed, material, and energetic use.’ This definition was operationalised by selecting economic activities as classified by NACE Rev. 2 that in some way process or convert biomass (see Iost et al. 2019). Selected economic activities are listed in Table 2. The underlying definition of bioeconomy includes transport and retail, but respective economic activities were not selected during operationalisation of the definition. Transport and retail are partly bio-based and existing methods for estimation their bio-based shares are only rough estimates (Efken et al. 2012). To our understanding, at this point no data is available to calculate reliable bio-based shares. Consequently, transport and retail were not included in this first monitoring cycle. This aspect underlines that the single steps of the monitoring cycle are closely connected and that iterations between them may be necessary. As exception from the rule of including only biomass-based economic activities, we also included certain divisions of NACE sector M due to the high importance of research in the fields of biotechnology, natural and engineering sciences for the bioeconomy (BMBF 2018).

Figure 3 assigns general economic activities to production and processing of biomass and biomass-based services and Table 2 gives more detail on the selected economic activities. Together, they illustrate the chosen definition of bioeconomy. Different national strategies basically include the same economic sectors into their respective bioeconomy definitions (Besi and McCormick 2015; Staffas et al. 2013). However, there are still different perceptions of bioeconomy which result in the attribution of varying sector and economic activities to bioeconomy. An example is the Spanish bioeconomy strategy. There, contrary to other national strategies, “uses and services linked to ecosystems, ranging from harvesting activities to tourism and leisure” are included in the definition bioeconomy, as especially tourism has a potential for generating jobs and value added (MINECO 2016, p. 12). Against this background and in order to be able to compare monitoring results in Germany to other countries, at the beginning of every monitoring cycle (Figure 2), the underlying definition of bioeconomy should be revised as societal, political and market conditions as well as objectives related to bioeconomy may have further developed and changed.

Figure 3: Proposed definition scheme of bioeconomy



Source: own illustration based on Iost et al. (2019)

Table 2: Selected economic activities for quantification and sustainability assessment of the bioeconomy

Section	Description	Bio-based share	Data source
A	Agriculture, Forestry, Fisheries	100%	
C	Manufacturing	Bio-based inputs into economic activities	Material and Goods Received Enquiry; Production Statistics
D	Electricity, gas, steam and air conditioning supply	Use of biomass related to all energy sources	Official data from environmental accounting (DESTATIS 2018e)
F	Construction		
41.20.1 & 41.20.2	Construction of residential and non-residential buildings (except prefabricated constructions) & Assembly and erection of prefabricated constructions	Wood construction share	Official data on construction permits (DESTATIS 2018a)
43.32.0 & 43.91.2	Joinery installation & Erection of frames and constructional timber works	100%	(COM 1999)
I	Accommodation and food service activities		
56.1 – 3	Food and beverage service activities	100%	Own assumption
M	Professional, scientific and technical activities		
72.11.0	Research and experimental development on biotechnology	100%	Own assumption
72.19.0	Other research and experimental development on natural sciences and engineering	Expenses for natural and agricultural sciences	Official data on public sector expenses (DESTATIS 2022b)

Source: based on Iost et al. (2019)

2.4 Material Flows

Understanding and quantifying material flows are the foundation for comprehending the processing of biomass along value chains and final biomass uses, which also provides the basis for sustainability assessment. In the following subchapters, we first present an aggregated material flow which differentiates only biomass according to its origin in agriculture, forestry and fisheries including aquaculture. In chapters 2.4.3 to 2.4.5, we show different material flows in more detail and discuss available data and existing data gaps.

2.4.1 Overview

In material flow Sankey diagrams, the following **terms** are used:

Domestic production: biomass that is produced in Germany; the data on agricultural biomass comprises not only information from official harvest and production statistics, but also unharvested plant parts, which are recorded as residues. Forest biomass includes roundwood (removed), bark, residues, waste wood and paper. Aquatic biomass includes catches from marine and freshwater fisheries and aquaculture production.

Supply is calculated as the sum of domestic production, imports and decrease in stocks, minus exports and decreases in stocks/ comprises domestic production, net imports.

Domestic consumption: use in Germany as food or feed, for material or energy purposes, or increase in stocks.

Raw materials refer to feedstock or unprocessed materials that are used to produce semi-finished and finished goods. Raw materials sourced from forests typically refer to felled logs. Aquatic biomass includes at most decapitated or gutted fish, at most cooked crustaceans without shells and mussels.

Processed materials encompass **semi-finished** and **finished products**, providing a simplified representation of aggregated material flows. In sector-specific material flow diagrams, either **processed material** or separate categories for **semi-finished** and **finished products** are used, depending on the complexity of the flow of goods.

Semi-finished products are defined as those that have not yet undergone complete assembly or manufacturing. These products serve as inputs in the production of other goods, including flour, which is utilised for consumption by private households or as an input in the baking industry. Examples of aquatic semi-finished products include fillets, rags, fish meat, and components of crustaceans. Sawn timber constitutes an instance of a wood-based semi-finished product.

Finished products, also known as final or consumer goods, are consumed to satisfy current wants or needs and are not used as inputs in the production of other goods. Examples of wood-based finished products include furniture, paper and viscose textiles. In addition, sawn timber sold in DIY stores is also a final product. Aquatic biomass includes smoked and/or dried products, prepared products such as fish fingers and marinades, breaded fillets, ready meals based on fish or crustaceans, fish meal and fish oil. In the case of food products, a strict separation between intermediate (semi-finished) and final (finished) products often seems impossible. For example, a product such as wheat flour is used both as an intermediate product in bakeries and as a product for private households. Other final food products are processed meat, sausages, cheese, butter, vegetable oil or jam and chocolate.

Residues are materials created during production and processing in households. Different types of residues are produced in different sectors. These residues may be labelled with different terms depending on their intended use or application. For example, residues from aquatic biomass are called Residual Raw Materials (RRMs) and are further subdivided into RRMs fit for human consumption, called co-products, and RRMs unfit for human consumption, called by-products.

Recovered materials are biomass that has been disposed of, collected and reused after domestic consumption. In some cases, recovered materials are also referred to as waste materials, recycled waste materials or secondary biomass.

2.4.2 Aggregated Biomass Flow

As demonstrated in Figure 4, the aggregated biomass flow for Germany in 2020 is delineated by the three sectors of agriculture (yellow and orange), forestry (green) and fisheries (blue). Furthermore, a distinction is made between primary biomass produced and residual materials and recycled waste materials (shown in a lighter colour). The sectoral biomass flows are examined in more detail in the individual sections 2.4.3 (agricultural biomass), 2.4.4 (forest biomass) and 2.4.5 (aquatic biomass).

The processing of biomass is mapped from top to bottom, starting from domestic production. Imports are located on the left, and exports are located on the right. In the supply process stage, raw materials, domestic production of primary biomass, imports of raw materials, and recovered materials for reuse are aggregated. After deducting exports of raw materials, these quantities are included in the first processing stage. The next level (one level lower) is the supply of processed materials. The supply of this stage is fed from above by the supply of the 1st processing stage and from the left by imports of processed materials. Between the supply of processed materials (I) and (II), the agricultural supply of livestock with biomass is shown. Exports of processed materials flow from the supply of processed materials (II) to the right. Depending on the sector, these goods then flow into the end use, which is divided into food, animal feed, material and energy utilisation. It is important to note that there are biomasses and residual materials whose use could not be clearly identified (unknown use). The material flows refer to pure biomass (dry matter, DM). Non-biomass components contained in products (which are added during processing) are not included in this diagram.

2.4.2.1 Domestic Production

The results for 2020 demonstrate that a total of 182 million tonnes of dry matter were produced in agriculture, forestry, fisheries and aquaculture. Agriculture constitutes the predominant source of domestic production, with a total of 140 million tonnes of dry matter. This encompasses the harvesting of arable crops and horticultural produce, which collectively amount to 117 million tonnes of dry matter, as documented in the official harvest statistics. Additionally, 23 million tonnes of dry matter residues, such as straw or grass cuttings from the maintenance of roadsides or railway embankments, are included in this category. The domestic production of raw materials from forestry, amounting to 42 million tonnes of dry matter, is derived from the extraction of roundwood from forests. The domestic provision of recovered paper (10 million tonnes) and waste wood (8 million tonnes) is also of significance. The domestic provision of dry matter from aquatic biomass (58 thousand tonnes) is derived from marine, aquaculture and freshwater fisheries, and includes fish, crustaceans, molluscs, aquatic snails, algae and other aquatic invertebrates.

2.4.2.2 Processing

When considering the import and export of raw materials, the total processed was approximately 220 million tonnes. The biomass input of forestry biomass consists of 39 million tonnes of wood including bark and 19 million tonnes of recovered paper and wood waste, while the input of agricultural biomass comprises 129 million tonnes of raw materials and 30 million tonnes of residues, including the above-mentioned 23 million tonnes of residues and 7 million tonnes of reused residues such as fermentation residues from biogas plants. The input of aquatic biomass comprises 60 thousand tonnes of raw materials and 4 thousand tonnes of residues, with additional residues resulting from processing.

2.4.2.3 Livestock

In total, 75 million tonnes of plant biomass, including 5 million tonnes of residues, were used in livestock farming. Livestock production amounted to 7 million tonnes of animal products and 19 million tonnes of manure, which is shown in olive green as a residue in the graph. 8 million tonnes of manure was used, mainly for energy production in biogas plants. The rest, shown here as 'losses', either remains in agriculture as fertiliser or is produced in the form of body heat or other emissions from livestock.

2.4.2.4 Imports and Exports

The total imports of raw and processed materials amounted to approximately 83 million tonnes, which was offset by total exports of around 82 million tonnes, resulting in net imports of just over 1 million tonnes. Agricultural biomass also played the largest role in total foreign trade volumes, with wood raw materials and processed wood-based materials being imported and exported to a slightly lesser extent. However, when considered as a proportion of the sectoral supply, the share of imports and exports in the wood sector was considerably higher than that of agricultural biomass. In contrast, biomass from fisheries and aquaculture contributed the least in terms of dry matter. Unlike other biomass sectors, significantly more aquatic biomass is imported than produced domestically, resulting in a negative foreign trade balance for this biomass.

2.4.2.5 Domestic Consumption

In terms of quantity, animal feed represents the most significant application of biomass. It is noteworthy that at approximately 80 million tonnes, almost fourfold the amount of agricultural biomass is utilised for animal feed as compared to food (21 million tonnes, inclusive of 7 million tonnes of biomass derived from animal products). Biomass from fisheries and aquaculture is predominantly employed for food production, whereas non-food utilisation (animal feed and material application) accounts for around 11% of total domestic consumption. It is estimated that approximately 11% of total domestic consumption remains unutilised, consisting of biomass discarded during fishing activities (production). Approximately 2 million tonnes of biomass were allocated to feeding pets and horses, with 0.4 million tonnes of this being residual.

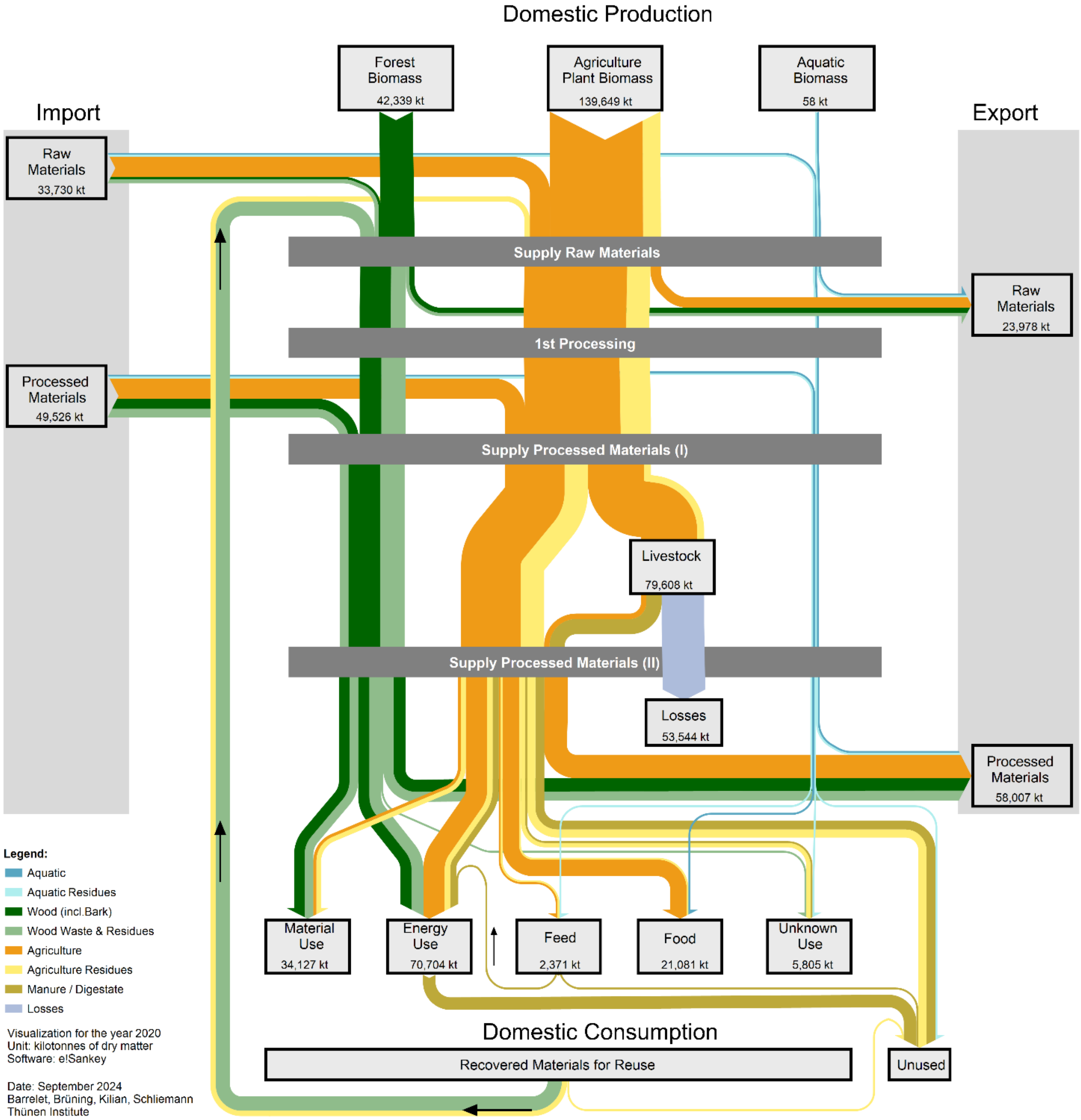
A total of 34 million tonnes were derived from agriculture, 7 million tonnes of which were agricultural residues, and 29 million tonnes from forestry, resulting in a total of 71 million tonnes. Biogas production led to the generation of 17 million tonnes of fermentation residues, which, akin to unused farm manure, were retained in agriculture for use as fertiliser. While the material use of agricultural biomass is comparatively low at 10 million tonnes, with 6 million tonnes consisting of residues, it is highest for forestry biomass at 24 million tonnes (a total of around 34 million tonnes of biomass used for material purposes in 2020).

2.4.2.6 Residues and Recovered Materials for Re-use

As demonstrated in Figure 4, the analysis encompasses both residues and recovered materials. For instance, the domestic utilisation of recycled waste paper amounts to 10 million tonnes, while recycled waste wood accounts for nearly 8 million tonnes. It is evident that waste paper and waste wood represent significant and extensively utilised sources of raw materials in Germany, accounting for approximately one-third of domestic production of wood raw materials.

Domestic agricultural production encompassed 23 million tonnes of crop residues, e.g., straw. During the processing of agricultural biomass, a further 9 million tonnes of residues were produced. Finally, after the (initial) utilisation of the biomass, 7 million tonnes of biobased waste and waste components could be used again and were circulated. It should be noted that the residual materials also include straw, which was used as bedding in animal husbandry. Agricultural residues were used for energy production (7 million tonnes), material use (6 million tonnes), pet and horse food (0.4 million tonnes), and re-entered food supply (0.1 million tonnes were residues, such as donations to food banks).

Figure 4: Aggregated material flow of agricultural, forest and aquatic biomass in 2020



Source: own illustration

2.4.3 Agricultural Biomass[1]

2.4.3.1 What is Agricultural Biomass?

Agricultural biomass represents the most significant form of biomass use in terms of quantity. Due to its diverse nature, it is utilized across all sectors, making it a crucial component of the bioeconomy. However, the great heterogeneity of agricultural biomass poses challenges when comparing individual material flows, as its characteristics vary widely. One key differentiating factor is **water content**, which ranges from very high levels — exceeding 90% in many vegetables such as tomatoes and cucumbers — to much lower levels, as seen in cereals and oilseeds, which contain approximately 14% and 9% water, respectively. Additionally, agricultural biomass differs based on whether it is produced on arable land or grassland, as well as in terms of its general usability, particularly regarding its metabolization by monogastric animals and humans.

Agricultural biomass can be further categorized into **three main types: plant-based** biomass, **animal-based** biomass, and **processed** biomass. Plant-based biomass originates from photosynthesis, utilizing solar energy to produce raw materials such as crops and forage. Animal-based biomass results from the metabolism of plant-based biomass and includes products such as meat, eggs, and milk. Processed biomass consists of modified and refined plant- or animal-derived materials, such as textiles and bio-based industrial products.

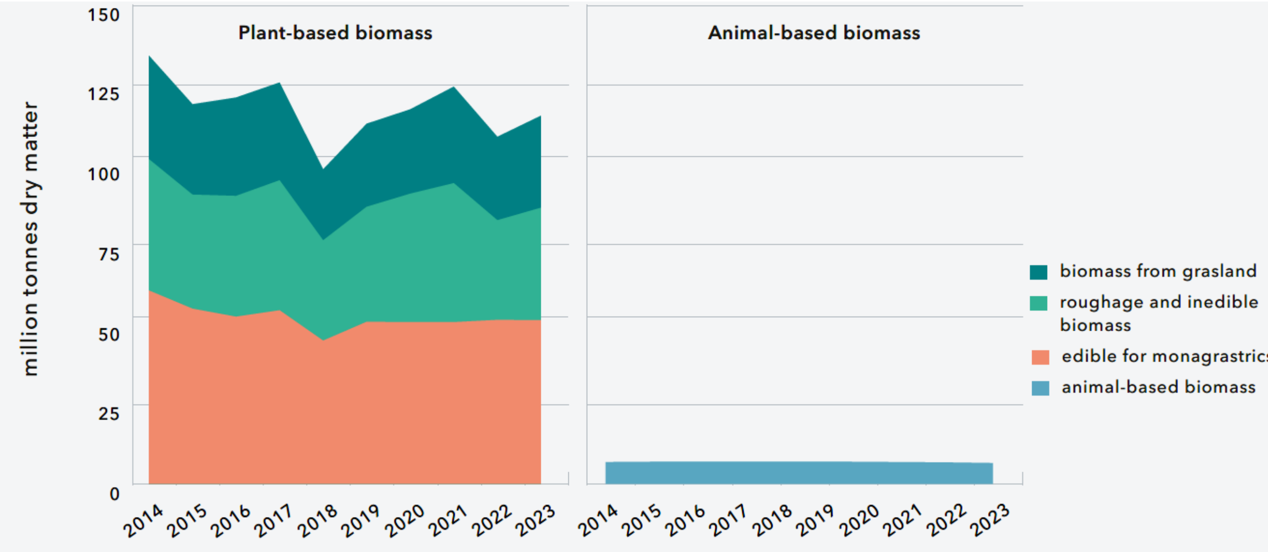
To systematically assess these various forms, all biomass flows are reported in dry matter and classified accordingly. Within plant-based biomass, a further distinction is made between bio-mass that can potentially be digested by monogastric animals and other types of biomasses. The latter category includes roughage, which is only digestible by ruminants or hindgut fermenters, as well as lignin-containing biomass, which is inedible. Additionally, roughage itself is subdivided based on its origin, differentiating between roughage from grassland and roughage from arable land. By structuring agricultural biomass in this way, its production, utilization, and conversion can be better understood and monitored within the framework of the bioeconomy.

2.4.3.2 Trends in Production and Trade

The amount of biomass produced over the last 10 years shows that the amount of plant-based biomass in particular is subject to fluctuations, e. g. due to weather conditions. In comparison, the amount of animal-based biomass produced has changed only slightly. The lowest plant-based biomass yield was recorded in 2018, with a total biomass yield of 98 million tonnes of dry matter. This is only 83% of the average dry matter yield for the years 2014 to 2023. In 2014, the total yield of 134 million tonnes of dry matter was the maximum for this period. The amount of animal-based biomass produced, i.e., animal products such as meat, eggs, milk or skins and hides, is almost constant at around 7 million tonnes (Figure 5).

[1] The text in chapter 2.4.3 is cited from Beck-O´Brien et al. 2024, pp. 114–117.

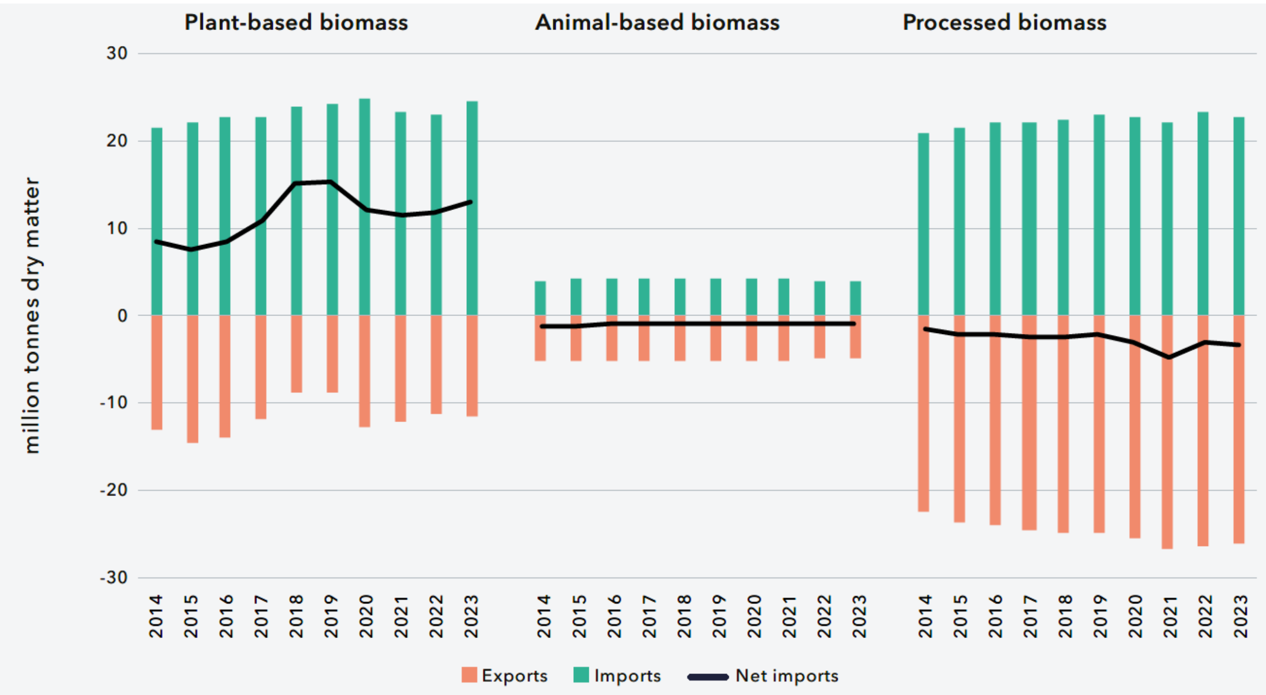
Figure 5: Agricultural biomass production in Germany



Source: based on (DESTATIS 2020b)

A look at the foreign trade volumes (Figure 6) shows that it is plant-based biomass that is imported. In years of low domestic production, less plant-based biomass is exported and more is imported, so that the lower domestic production is compensated by higher net imports. The highest net imports of plant-based biomass therefore occurred in 2018 and 2019, with a maximum of 15 million tonnes dry matter in 2019. In contrast, Germany is a net exporter of animal-based and processed biomass. Animal-based biomass exports decreased slightly, from 1.1 million tonnes in 2014 to 0.8 million tonnes in 2022. The trade volume for processed biomass increases steadily. Net exports of processed biomass from Germany are also increasing, with the highest net export volume of 5 million tonnes in 2021 and the lowest of 2 million tonnes in 2014. **Overall, Germany is a net importer of biomass. Net imports in the last 10 years ranged from 4 million tonnes in 2015 to 12 million tonnes in 2019**.

Figure 6: Foreign trade of biomass in Germany from 2014 to 2021



Source: own calculations based on (DESTATIS 2020b)

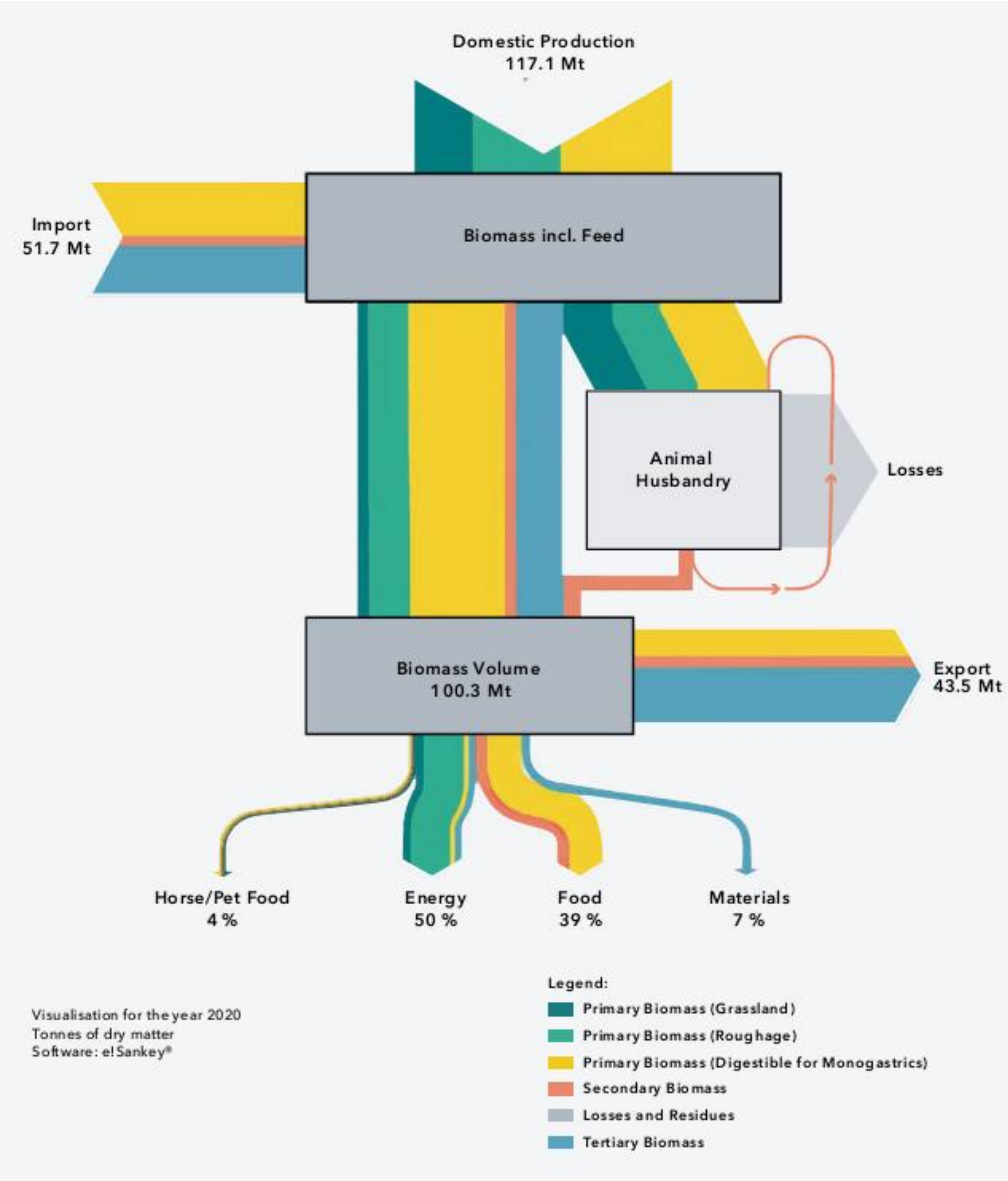
2.4.3.3 Agricultural Biomass Flow

The total material flow of agricultural biomass in Germany in 2020 provides a comprehensive overview of the production, import, processing, and utilization of biomass within the bioeconomy (Figure 7). The reported data include all biomass officially recorded as harvested; however, it is important to note that certain components of agricultural biomass, such as unharvested plant parts (e.g., cereal roots) and by-products like cereal straw, are categorized as residues. These residues are only partially included in the total biomass flow calculations for Germany (chapter 2.4.2).

In 2020, the production of plant-based biomass in Germany amounted to approximately 117 mil-lion tonnes. A significant share of this biomass—67 million tonnes, or 57%—was classified as roughage and biomass that is inedible for monogastric animals. Permanent grassland played a crucial role in domestic biomass production, contributing around 26 million tonnes, which accounted for 23% of total primary biomass production and 40% of roughage biomass production. This highlights the significance of grassland as a key source of biomass in Germany’s agricultural sector.

Apart from domestic production, biomass imports played an essential role in Germany’s agricultural material flow. In 2020, a total of 52 million tonnes of biomass was imported, with plant-based biomass accounting for nearly half (25 million tonnes). Additionally, Germany imported 4 million tonnes of animal-based biomass and 23 million tonnes of processed biomass. The higher economic value of pro-cessed biomass is due to its previous conversion from primary biomass into value-added products, making it a crucial component of the bioeconomy.

Figure 7: German agricultural biomass flow in 2020



Source: own calculations based on (Bundesanstalt für Landwirtschaft und Ernährung 2023a; Bundesministerium für Ernährung und Landwirtschaft 2023; Fachagentur Nachwachsende Rohstoffe 2023)

A major share of the agricultural biomass produced and imported in Germany was directed to-wards animal husbandry. In 2020, 79 million tonnes of biomass was used as animal feed, demonstrating the central role of agriculture in supporting livestock production. Within this total, 47 million tonnes consisted of roughage, which can only be digested by ruminants and hindgut fermenters, while 32 million tonnes comprised feed that could also be consumed by monogastric animals such as pigs and poultry. Although plant-based biomass dominated feed usage, a small proportion – 0.2 million tonnes – of animal-based biomass was also used as feed. This included products such as milk, which is often fed to calves in dairy farming operations.

The output of animal production in 2020 resulted in approximately 7 million tonnes of dry matter ani-mal-based biomass. This included meat (including offal), leather, milk, and eggs. Additional bio-mass flows, such as manure used for energy production or as fertilizer, as well as slaughterhouse waste, were classified as losses in the overall material flow framework. These outputs highlight the complexity of biomass utilization, where not all inputs are directly converted into consumable products, but some are repurposed for energy or agricultural applications.

Beyond its use as feed, agricultural biomass also plays a significant role in Germany's bioeconomy through processing and consumption. In 2020, the total volume of non-feed biomass pro-cessed in Germany amounted to 100 million tonnes. This included plant-based, animal-based, and pro-cessed biomass, originating from both domestic production and imports. Of this total, 43.5 million tonnes – equivalent to 43% – was exported, while the remaining portion was consumed domestically.

A considerable share of the non-feed biomass used domestically was directed toward energy production. In fact, approximately 50% of domestic non-feed biomass consumption was used for energy. However, the type and value of biomass used for energy production varied significantly. For instance, processed biomass flows already included 3 million tonnes of biofuel, which is classified as a secondary energy source. In contrast, plant-based biomass was primarily used as input material for biogas production. A key consideration in biogas production is that part of the biomass is converted into unused carbon dioxide (CO_2) or remains in agriculture as fermentation residue. If only the secondary energy source biomethane – the methane content of raw biogas – is taken into account, then the total biomass used for energy is reduced from 23 million tonnes of plant-based biomass to 6 million tonnes of processed biomass.

In addition to energy production, a significant portion of non-feed biomass was allocated for food consumption. In 2020, 39% of non-feed biomass was used for food, with a total volume of 21 mil-lion tonnes. Within this amount, 5 million tonnes – approximately one-quarter – was of animal origin. The substantial reliance on plant-based biomass for food production highlights the critical role of agricultural biomass in ensuring food security while balancing sustainability considerations.

Aside from food and energy use, the material utilization of non-feed biomass accounted for ap-proximately 7% of total non-feed biomass consumption. This category includes biomass used for the production of textiles, leather, and raw materials for the chemical industry. These applications demonstrate the diverse functions of agricultural biomass, extending beyond traditional food and feed uses to industrial and commercial sectors.

Another notable application of non-feed biomass is in pet food production. In 2020, pet food – including feed for companion animals such as dogs, cats, and horses – accounted for 4% of non-feed biomass utilization. Within this segment, 0.5 million tonnes of the total pet food volume consisted of animal-based biomass. This figure represents around 7% of Germany's domestic animal production, emphasizing the importance of animal-derived ingredients in the pet food industry.

In summary, the material flow of agricultural biomass in Germany in 2020 illustrates the complexity and interconnectivity of biomass production, trade, processing, and utilization. The agricultural sector plays a pivotal role in the bioeconomy, not only by supplying food and feed but also through its contributions to energy production and industrial applications. The integration of plant-based, animal-based, and processed biomass into different economic sectors underscores the need for efficient biomass management and sustainable resource utilization. Future strategies for optimizing biomass flows should focus on improving conversion efficiencies, minimizing losses, and enhancing the circularity of biomass use to support a resilient and sustainable bioeconomy.

Overall, Germany is a net importer of biomass, with a higher share of higher value, animal-based and processed biomass in exports. In terms of dry matter, energy use is the most important use pathway in terms of quantity after the use of animal feed for livestock production. This is due to the high share of low-value roughage (grassland and arable land) in the feed and energy uses (e.g., for biogas production). Nevertheless, these two uses are associated with high mass losses and therefore offer potential for optimisation to enable biomass to be used for new applications.

2.4.4 Forest Biomass

2.4.4.1 Introduction

According to the most recent forest inventory, forests in Germany covered 11.5 million hectares which equals a share of 32% of the total country's area (BMEL 2024). Based on the Federal Forest Act, forests in Germany are protected. This results in a not only constant but also slightly increasing forest area. When comparing forest inventory results from 2022 and 2012, an increase of 15,000 hectares can be observed. The major part of this area (11.0 million hectares) permanently serves wood production (BMEL 2024). In addition to forest areas, wood can also be provided from trees outside forests, e. g. from landscaping activities, parks or also private gardens.

Besides the above-mentioned primary wood resources such as roundwood from forests, wood from landscaping and wood from garden trees, also wood processing residues, bark and recovered wood and recovered paper play an important role in wood raw material procurement of the wood processing industries and for energy generation. For quantification of the wood flows in Germany, the wood resource monitoring (TI-WF 2024b; Mantau 2023) plays a crucial role as it gains information on production capacities and use of raw materials. This applies to both material use of wood resource in the wood processing industry in Germany (e. g. sawmills, manufacturer of wood-based panels, pulp mills) as well as the use of wood for energy in private households or in non-residential plants.

The structure of the wood flow is further developed compared to the wood flows presented in Iost et al. (2020b). Bark has been added as a further raw material. In the further processing and utilization, growing media industry has been added. As reference unit the wood fibre equivalent is used, expressed in cubic meters [m^3(f)]. It is defined as the equivalent volume of wood-based fibres at the fibre saturation point that are contained in a specific product (Weimar 2011).

2.4.4.2 Available Data

For removals and use of roundwood data from TI-WF (2024a) are used. Data on wood working industries is used, especially for stock changes of roundwood, wood processing residues and specific semi-finished wood products (DESTATIS 2024e). Further data have been used from official production statistics (DESTATIS 2024d).

Data from various federation were used. Especially to mention are data from German Paper Industry (DIE PAPIERINDUSTRIE e. V. 2024), from German Pellet Association (DEPI 2023) and from German Garden Industry Association(IVG 2024).

An important source of information for describing and monitoring wood flows are the empirical studies carried out within the framework of the wood resource monitoring (TI-WF 2024b). Most recent studies which have been carried out in the specific sectors of wood raw material use are on sawmills (Döring et al. 2020), wood-based panels (Döring et al. 2021a), wood pulp ((Gieseking et al. 2021), non-residential wood combustion plants (Döring et al. 2021b und Döring et al. 2021c) and private households (Jochem et al. 2023).

2.4.4.3 Wood Flow

Figure 8 provides an update wood flow model provided in Iost et al. (2020b). It breaks down the wood flow shown in the aggregated material flow (Figure 4) and shows supply and use of wood from raw materials via semi-finished products to finished products and to energetic use in Germany in more detail. External trade flows are differentiated into raw materials, residues and recycled raw materials, semi-finished and finished products. Additionally, flows of bark also have been added to the wood flow model.

In 2020, a total of 79 million m^3(f) of roundwood was removed from the forest in Germany. The increase compared to 2015 (69 million m^3(f)) is mainly caused by increased felling due to drought and bark beetle infestation. As a result of higher removals net trade changed significantly, from net imports of 5.5 million m^3(f) in 2015 to net exports of 7.0 million m^3(f) in 2020, mainly caused by changed in trade of coniferous roundwood.

After taking trade into account, domestic consumption of roundwood totalled 73 million m^3(f). Most domestic used roundwood (56%) is processed in sawmills, which mainly used coniferous wood (95%). Roundwood is also used for the production of wood-based materials (7%) and of wood pulp (7%), with coniferous wood also dominating here. Smaller quantities of the roundwood are used for production of veneer (< 0.5%) and pellets (1.4%). About 28% of domestic roundwood consumption is used for energy. Here, especially in private households (nearly two thirds of 28%), the use of non-coniferous roundwood dominates.

While Germany became a net exporter of roundwood in 2020 (compared to 2015), Germany remained a net exporter of sawnwood and wood-based panels, with an increase of net exports of sawnwood by about 3 million m^3(f) in 2020 compared to 2015. Within the production of sawnwood and wood-based panels, relevant quantities of wood processing residues (e. g. sawdust, wood chips) accrue as by-products; these are used both for material (e. g. wood-based panels, pulp, pellets, briquettes) and energy purposes (e. g. to cover the energy needs of sawmills). Wood processing residues and bark are also used as constituents for the production of growing media.

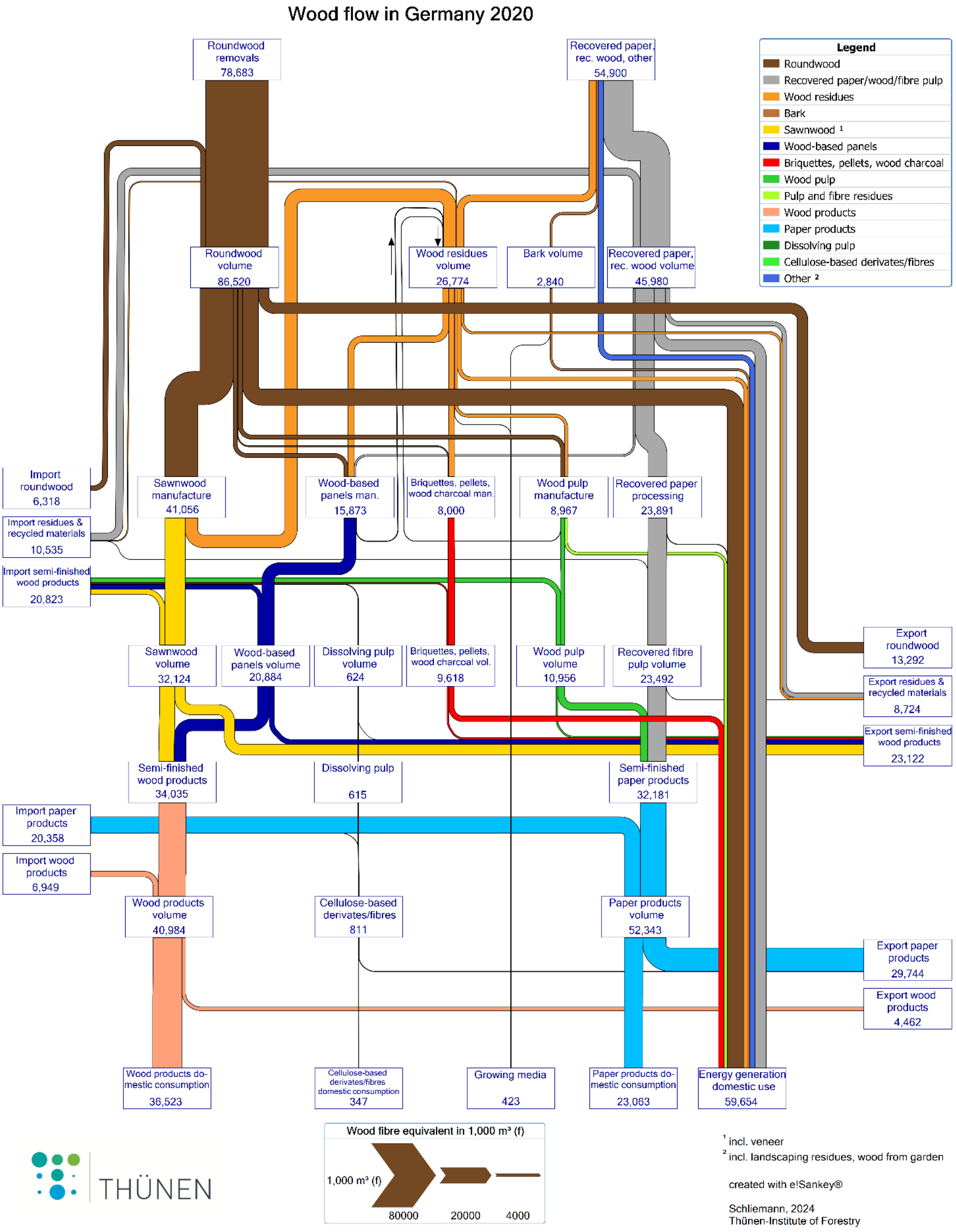
Dissolving pulp is not produced in Germany, but imported and further processed, e. g. in the form of regenerated cellulose. Biorefineries for production of various chemical compounds were not operating in Germany in 2020. However, the chemical sector is starting to shift toward biochemicals. Actually, a first industrial biorefinery is being constructed in Germany. According wood flows will be included in future analyses.

The wood flow in Germany is not only characterised by the use of roundwood and wood processing residues, recovered waste wood and waste paper also play a significant role with a total domestic supply of 37 million m^3(f). Trade shows net imports of these of raw materials of about 3.8 million m^3(f). Most of the recovered paper is processed and used for the manufacture of semi-finished paper. Recovered waste wood is mostly utilised for energy and, to a lesser extent, for material use in the wood-based panels industry. It can be noted that more recovered paper is used for the production of semi-finished paper than virgin fibres from wood pulp production.

The final consumption of wood products in the various consumption sectors amounted to 37 million m^3(f). For paper products, the consumption summed up to 23 million m^3(f). For energy generation in private households and in combustion plants, about 60 million m^3(f) of wood was used in 2020.

Germany remained a net exporter of finished paper products in 2020, but a net importer of finished wood products. In total for all wood raw materials, semi-finished and finished wood and paper products, net exports of wood fibres of Germany amounted to 14 million m^3(f) in 2020 while in 2015 net imports of 6 million m^3(f) could be observed.

Figure 8: Wood flow in Germany in the year 2020, in cubic metre wood fibre equivalents, m³(f)



Source: (own illustration)

2.4.5 Aquatic Biomass[2]

2.4.5.1 What is Aquatic Biomass?

The material flow analysis for aquatic biomass includes raw materials and products of fish, crustaceans, molluscs, snails, algae and other aquatic invertebrates in both limnic and marine waters. German fish production is made up of sea fisheries, aquaculture and freshwater fisheries. Annual production strongly depends on the fishing quota allocated to Germany. To meet the goal of sustainable fisheries, fishing quotas are modified in line with the development of stock in the respective fishing grounds and can therefore vary considerably from year to year (Patterson and Résimont 2007). In aquaculture, fish, crustaceans, molluscs and algae are farmed in controlled conditions. Freshwater fisheries include commercial fisheries in lakes and rivers, which may comprise natural and artificial water bodies, such as quarry lakes and river dams.

2.4.5.2 Overview and Challenges

With an increasing global consumption of fisheries and aquaculture products, ensuring the security of food supplies and sustainable production despite limited resources poses significant challenges. In Germany, a decline in catches and stagnation in aquaculture production can be observed, while consumption of fisheries and aquaculture products fluctuates around a consistent baseline. These developments have led to a significant drop in the self-sufficiency rate from over 40% in the 1980s to just 17 – 20% today. Despite extensive fish processing activities Germany is increasingly dependent on imports. In the past decade the main supplying countries were China, Denmark, Poland and Norway. Concurrently, a large proportion of the German fleet's catch is landed at international ports, and is counted as exports. In addition, Germany exports fish and seafood at different stages along the value chain. What remains of imports and own production goes into domestic processing plants, to manufacture fish fillets or otherwise processed products (i.e., smoked, marinaded, battered etc.). Fish and seafood are mainly used to produce food. However, the production of fish and seafood products generates rest raw material (residues) such as fish heads, bones and offal, which is referred to as fish co- and by-products. Co-products describe food-grade quality rest raw material, while by-products are not suitable for human consumption, due to treatment along the value chain (Aspevik et al. 2017). Depending on the type of fish, the percentage of rest raw material ranges between 30 and 85% (Rustad et al. 2011). This rest raw material is utilized for food and non-food purposes.

2.4.5.3 Available Data

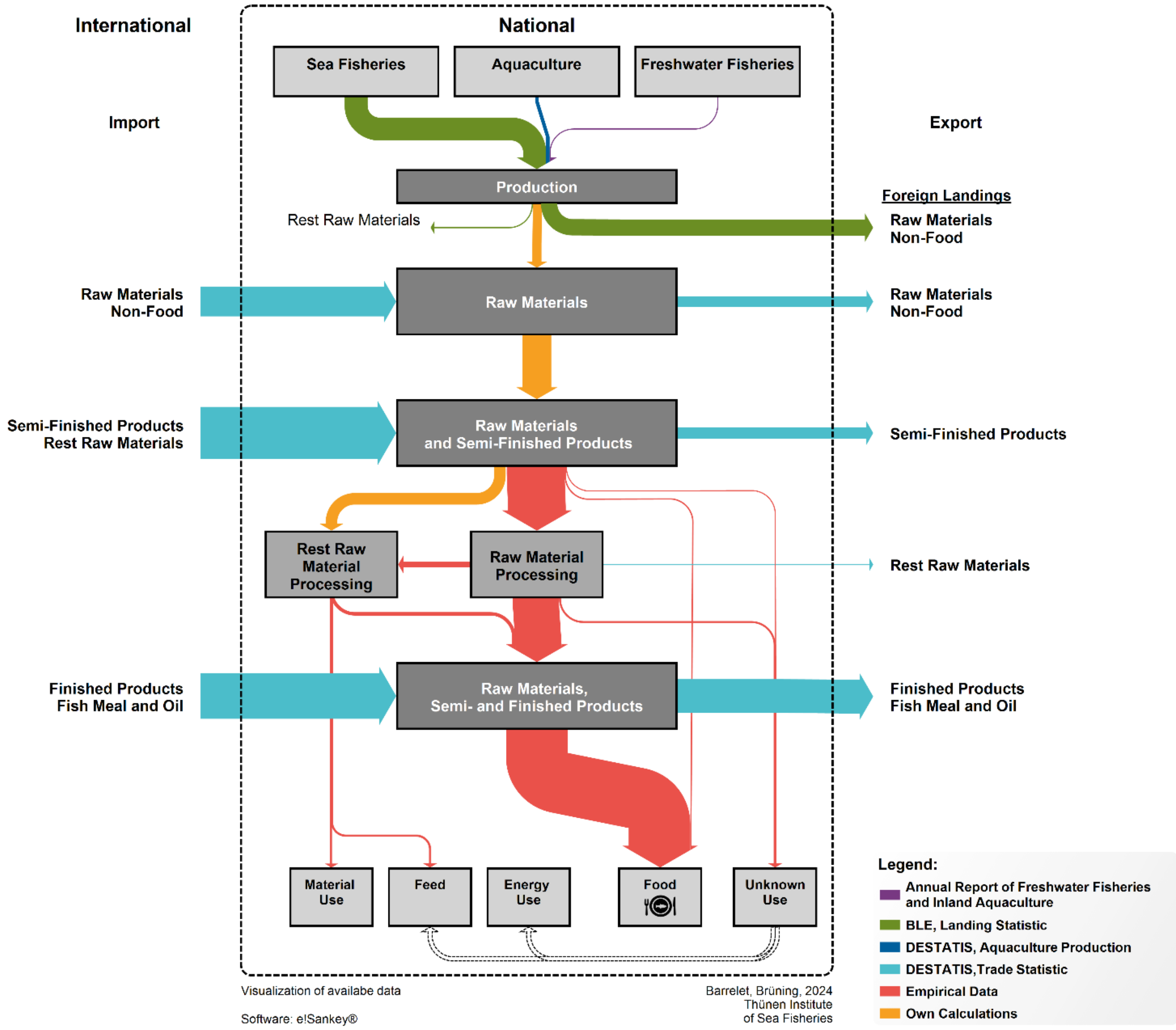
A strong and comprehensive dataset was built by integrating official statistics with direct industry insights. Secondary data included official trade and production statistics from the Federal Statistics Office (DESTATIS 2024d, 2024a) and national fisheries landings data from the Federal Institute for Food and Agriculture (Bundesanstalt für Landwirtschaft und Ernährung 2023b). In addition, the annual report of freshwater fishery and inland aquaculture (Brämick 2021), provided by the Institute of Inland Fisheries in Potsdam-Sacrow, contains information on commercial freshwater fishery in amounts of live weight.

Primary data were collected through both quantitative and qualitative methods. Structured questionnaires were distributed to all major processing companies in Germany involved in the production of salmon main products, co-products, by-products, oil and meal supplemented by semi-structured expert interviews, with a total of seven interviewees, each lasting between forty minutes and two and a half hours. Interview participants were selected using purposive sampling to ensure a broad representation of the salmon industry. Additional data were

[2] The text in subsections 2.4.5.1, 2.4.5.2, 2.4.5.4, 2.4.5.6, 2.4.5.8 is cited from Beck-O´Brien et al. 2024, pp. 120–124.

obtained from industry reports, which provided context and supplementary information (European Commission. Joint Research Centre. and European Commission. Scientific, Technical and Economic Committee for Fisheries. 2020; JRC 2021, 2022; Fisch Informationszentrum e.V. 2021).

Figure 9: Data Sources for Aquatic Biomass Monitoring



Source: own illustration

2.4.5.4 Aquatic Biomass Flow

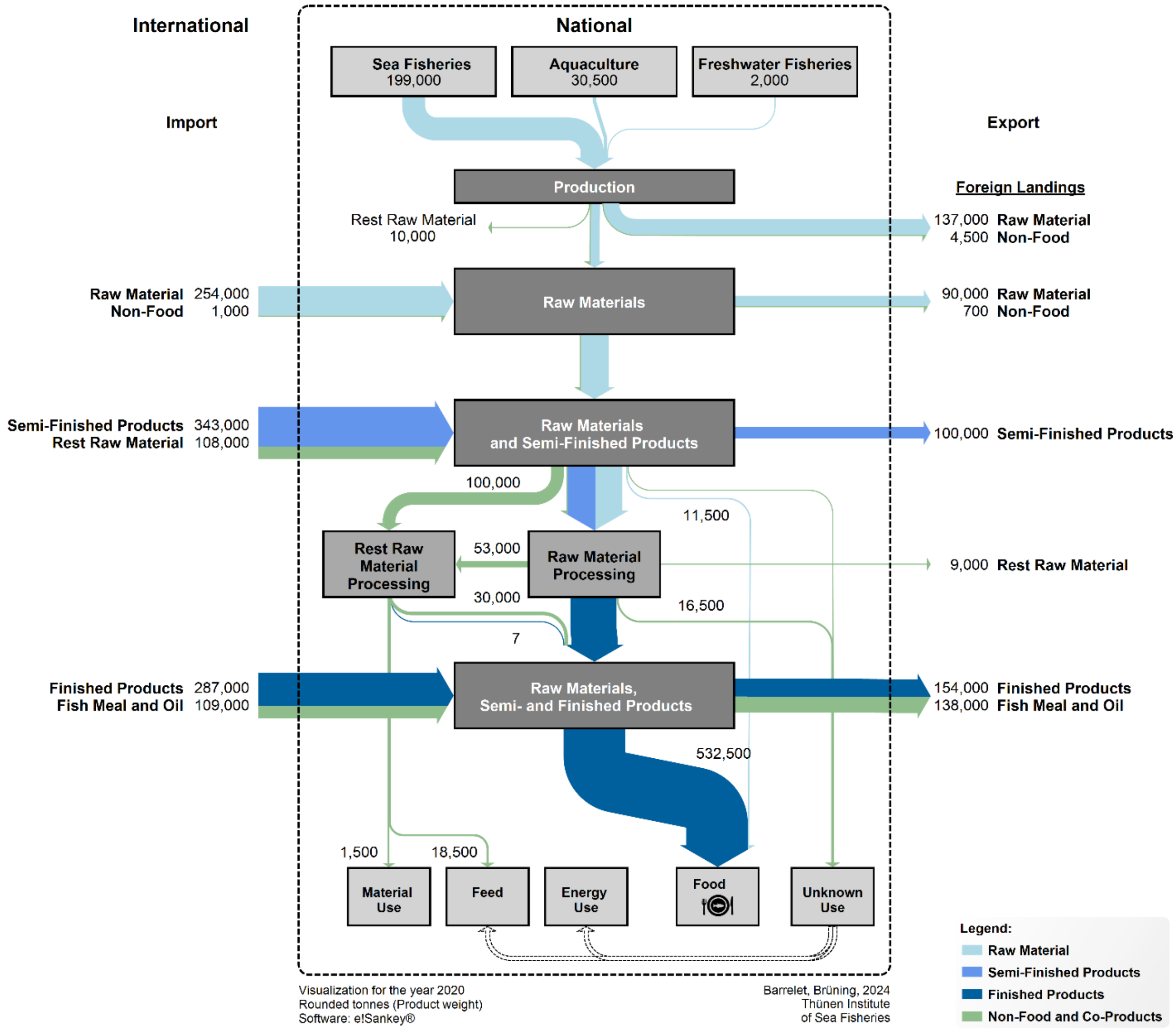
In 2020, production amounted to around 230,000 tonnes of aquatic biomass in Germany (Figure 9). Around 86% comes from sea fisheries, 12% from aquaculture production and 2% from freshwater fisheries.

However, the material flow shows that production only covered a fraction of what was consumed in Germany, which results in a self-sufficiency level of 18.6% (BLE 2021).

Goods were imported and exported at all processing stages. The largest share of imported goods was semi-finished products (mainly fillets) at around 340,000 tonnes, followed by around 290,000 tonnes of finished products (i.e., smoked, marinated, battered fish and seafood and a range of convenience products) and 260,000 tonnes of raw materials (whole or gutted fish, whole seafood). Raw materials account for the largest share of exports. It should be noted that of the approx. 230,000 tonnes raw material exports, almost 140,000 tonnes were landings of the German fleet in foreign ports. Exported finished products were mainly made up of fish fingers produced in Germany, prepared fillets of Alaska pollack and herring marinades. Of the raw material (whole fish) remaining in Germany, the largest part went into processing, a small part, an estimated 5% was sold whole, as a final product. This resulted in food consumption of about 530,000 tonnes (product weight) produced from domestic and internationally traded aquatic biomass.

During fish production and processing rest raw material occurs. Calculations show that over 10,000 tonnes of aquatic biomass were left unused and discarded at sea during fishing activities. Rest raw material from fish and seafood processing amounted to around 70,000 tonnes in 2020. Of this, over 50,000 tonnes went into rest raw material processing to produce fish oil and meal while another ~17,000 tonnes went into unknown use, most likely energy use and animal feed production. In addition to the rest raw material produced in Germany, another 100,000 tonnes were imported and merely 9,000 tonnes exported. After the processing of co- and by-products, almost 30,000 tonnes of domestically produced fish oil and meal were exported and nearly 20,000 tonnes used in Germany, with the largest share of over 18,000 tonnes going into animal feed production (petfood, aquaculture and livestock feed), and only around 1,000 tonnes going into material use in the form of oleochemical applications. In 2020, less than 1% of fish oil and meal produced in Germany went into human consumption, while nearly 2,000 tonnes would have been suitable for human consumption.

Figure 10: Material flow of aquatic biomass in Germany rounded for the year 2020



Source: own calculations based on data (Brämick 2021; DESTATIS 2024a; Bundesanstalt für Landwirtschaft und Ernährung 2023b)

2.4.5.5 Aquatic Biomass Trends

While aquaculture production stagnates and high-seas fisheries remain stable, coastal fisheries face major challenges, as catches are declining for several reasons; key Baltic Sea stocks, such as Western Baltic herring and cod, are severely depleted, while North Sea fisheries are under increasing economic pressure. Catches in the economically vital brown shrimp fishery fluctuate, and target stocks like North Sea plaice remain underfished, with quotas not fully used due to economic restraints.

These coastal fisheries struggle to remain economically viable and could benefit from increased value addition to their products, such as regionalizing value chains and promoting underutilized species in the market.

In contrast, German high-seas fisheries maintain stable catches and have improved resource efficiency. They have begun producing fish oil and fish meal from by-products directly at sea while simultaneously increasing fishing efficiency—reducing fleet capacities while maintaining catch volumes.

When comparing the aquatic biomass monitoring results for 2020 with data from the previous monitoring reports (Iost, et al. 2020; Bringezu et al. 2021), the following trends could be identified:

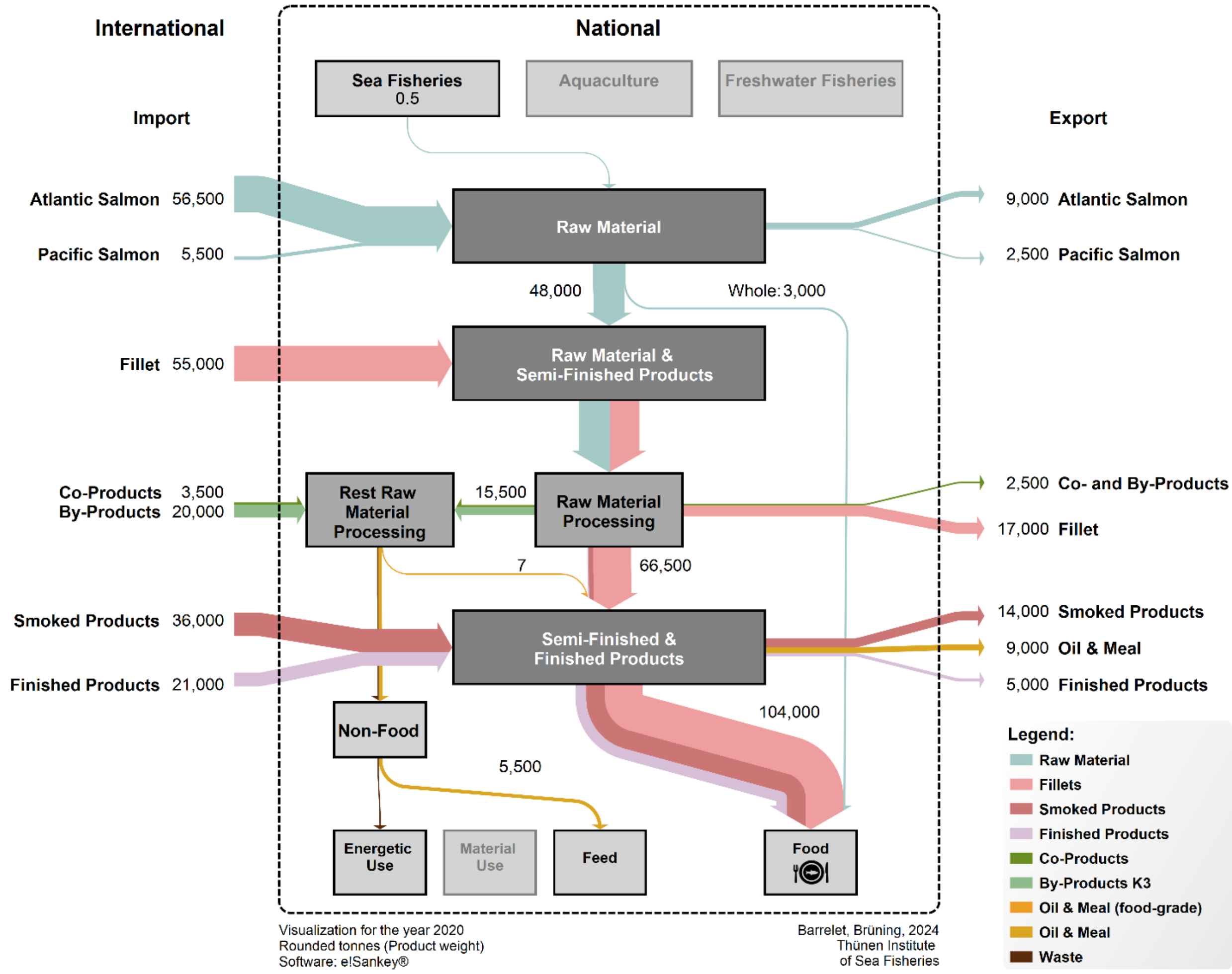
- Between 2015 and 2020 German production saw a decline of 11%, primarily due to reduced harvest from sea fisheries.
- The import volume remained stable compared to 2015, but the composition changed. Imports of raw materials and semi-finished goods decreased by 5% and 10% respectively, while the volume of imported finished products increased by 15%.
- This is also reflected in the production statistics. The production volumes of the most relevant products, such as smoked salmon and herring marinades, have dropped by 67% and 22% respectively. The production volume of fish fingers increased by 35%.
- Lower catches and lower production volumes led to a 16% decrease in exports, caused mainly by the 19% drop in exports of raw materials.
- Despite this, an 11% increase in domestic consumption was recorded and an increase in per capita consumption of 9% (BLE, 2021).

2.4.5.6 Case study – Salmon

Salmon was the most popular fish among consumers in Germany with a market share of 19% in 2020 (FIZ 2022). This product was almost exclusively imported, only 0.5 tonnes resulted from wild catches, and this occurred as by-catch from the German fishing fleet. The vast majority of salmon imported to Germany was farmed in Norway and arrived either gutted with heads on, as fillets or as finished products.

In 2020, around 60,000 tonnes of salmon raw material were imported around 10,000 tonnes exported (Figure 11). Nearly 3,000 tonnes of whole salmon were sold directly, without further processing, the rest went into German processing plants, where over 65,000 tonnes of finished products were produced. This resulted in almost 16,000 tonnes of rest raw material, which went into further processing, along with over 20,000 tonnes of imported rest raw material. After raw material and rest raw material processing over 100,000 tonnes of final products (whole, semi-finished and finished salmon products) were sold for human consumption, 5,500 tonnes (salmon meal and oil) were used for animal feed and a very small fraction was disposed of and used for energy production.

Figure 11: Material flow for salmon production in Germany rounded for the year 2020



Source: own calculations based on (Bundesanstalt für Landwirtschaft und Ernährung 2023b; DESTATIS 2024a)

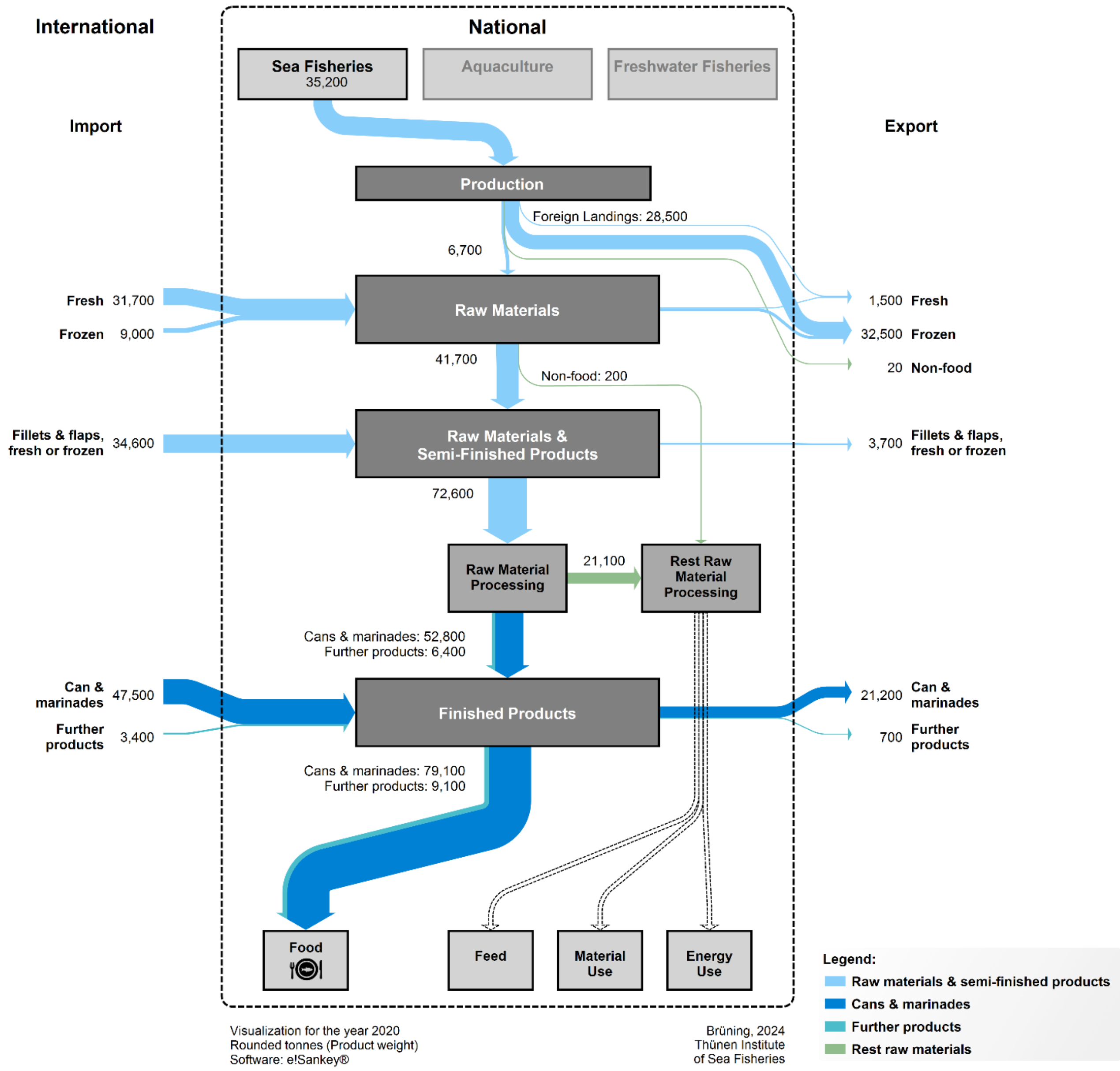
2.4.5.7 Case Study – Herring

Another very popular fish species in Germany is herring. The product range is wide and the most popular products are matjes, kipper, fried herring and Bismarck herring. In contrast to other popular fish species, such as salmon, herring is caught in large quantities by the German fishing fleet, particularly in the North Sea.

In 2020, German fishing vessels caught more than 35,000 tonnes of herring (Figure 12). However, the majority (28,500 t) was landed in foreign ports, consisting almost exclusively of frozen fish. The catches typically include a small proportion of non-marketable fish, which is landed as non-food goods for fish meal production. The herring caught by the German fleet was not enough to meet the demand of the domestic processing industry. Therefore, nearly 32,000 tonnes fresh herring were imported, mainly landed in German ports by foreign fishing vessels. Fresh herring accounts for 25% of the imported goods. In addition, ~9,000 tonnes of frozen herring were imported. Besides the mentioned whole fish, around 35,000 tonnes of semi-finished products in the form of frozen or fresh herring flaps and fillets were imported. Thus, the available quantity of raw materials and semi-finished products for fish processing resulted in around 72,600 tonnes. According to production statistics, canned herring and herring marinades amounted to approximately 53,000 tonnes. Based on our estimates, an additional 6,000 tonnes of herring products (e.g., smoked herring, herring salad) were produced domestically. The processing of herring resulted in an estimated 21,000 tonnes of rest raw materials such as heads, viscera, skins and frames. Depending on the type and quality, these were further processed into by-products, e.g., fish oil and fish meal, used as ingredients for aquafeed and pet food. In addition to the domestically produced herring products, around 47,500 tonnes of finished products, such as canned herring and marinades and 3,500 tonnes of other herring products were imported. In return, more than 21,000 tonnes of canned herring and marinades and 700 tonnes of other herring products were exported. This resulted in a calculated consumption of 79,000 tonnes of canned food and marinades and 7,000 tonnes of other herring products. Despite substantial catch volumes, the German market's self-sufficiency rate for herring products remained just 22%.

The flow of goods is subject to constant change, triggered, among other things, by adjustments in catch quotas or political events, such as Brexit. This has an impact on national self-sufficiency and the supply from trading partners, and consequently on the fish processing industry based in Germany. One example of this is the announced discontinuation of herring processing at the fish processing centre in Neu Mukran, which is likely to have a major impact on the industry.

Figure 12: Material flow for herring production in Germany rounded for the year 2020



Source: own calculations based on (Bundesanstalt für Landwirtschaft und Ernährung 2023b; DESTATIS 2024a)

2.4.5.8 Status of Aquatic Biomass Monitoring

During the analysis, it became clear that the official data available was not sufficient to fully describe fish processing and consumption. Not all goods are assigned to species-specific commodity codes in the statistics, which results in assumptions having to be made about proportions. In addition, the quantities of fishery and aquaculture products coming from processing and the quantities of final products going to consumption had to be estimated by weighing up a number of assumptions. Examining salmon and herring as one particular main commercial species in detail provided more precise information and helped identify gaps in the publicly available data (Figure 11). Simultaneously, this offered a manageable framework for filling these gaps with data from own surveys and calculations. The use of raw material and semi-finished goods in the catering trade or private households and the waste resulting from this consumption could not be taken into account due to unavailability of data. Still, most data gaps could be filled satisfactorily, thanks to the cooperation of experts within the sector and the models for calculating missing data developed during the MoBi I and II project periods.

2.4.5.9 Take-Home Messages

- Overall, German catch quotas are continuously falling, which impacts self-sufficiency and, in turn, influences the entire German value chain.
- Rest raw material from fish processing is utilized and further processed in Germany. Quantities can be calculated for the total aquatic biomass and for the most important commercial species separately.
- Data on aquatic biomass flows is available, but presents considerable gaps and imprecisions that can only be compensated by empirical data from surveys and/or assumptions.

2.4.6 Secondary Biomass

2.4.6.1 What is Secondary Biomass?

Re-use of waste and residues is the key functional component at the core of circular economy. Waste and residues form the reservoir of secondary resources (Körner 2015)[3]. 'Secondary biomass' comprises biogenic waste, residues, and by-products derived as residue or by-product from primary production, processing and the use and consumption of biomass and bio-based products. As per the 'Biomass Monitor' of the DBFZ resource data base (ResDB)[4], the whole of biogenic waste, residues, and by-products is captured by 77 aggregated biomasses from five sectors, which basically cover all sources areas and sources from within Germany. The five sectors and their set {n} of biomasses are Agricultural by-products {22}, Residues from forestry and wood industry {7}, Municipal waste and sewage sludge {14}, Industrial residues {23}, and Residues from other areas {11} (Brosowski et al.). Aggregation[5] reduces the lot of different biomasses to a tangible number. Some waste biomass is already aggregated such as household waste and urban green waste.

The ResDB Biomass Monitor provides a comprehensive compilation of the secondary biomass potential in Germany, including known downstream uses. With the choice to select individual biomasses and sectors, the open access platform informs not only about the size of different potentials. It implicitly visualizes the degree of circularity achieved so far. Readers can compare and follow which biomasses are actually used and to what degree, and whether they enter another material use or are directed to energetic use. Furthermore, the Biomass Monitor supports identification of possibly new options that may lead towards attaining greatest possible sustainability in resource use.

2.4.6.2 Calculation of Secondary Biomass Potentials

Secondary biomass is usually assessed as potential because few wastes and residues pass a balance or are recorded otherwise providing exact volume or mass values. Prominent exceptions include waste paper and to a certain extend biowaste from household (HH) collections. Source data accessed to calculate biogenic waste, residues and by-products are from official statistics, reports of producer associations, or individual studies presenting production or supply. The annually accruing secondary biomass is basically deducted by means of

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[3] Primary and secondary resource represent the basic concept; actual hierarchy may include up to tertiary bioresource, e.g., Körner I. 2015.

[4] ResDB Biomass Monitor at https://datalab.dbfz.de/resdb/potentials?lang=en

[5] Aggregations summarize over, e.g., many different vegetables, cereals, or by-products such as manure. The latter includes sub-categories, e.g., depending on how old cattle are and how they are kept, which evidently leads to different amounts of manure.

residue factors describing how much waste, residues or by-products arise during, e.g., harvest, certain types of processing and the subsequent primary use. In order to provide a serious assessment with respect to the deductions involved, the entire derivation procedure of potentials sets out from calculating minimum and maximum values. The minimum and maximum values serve the understanding of the uncertainties involved, thus cautioning decision and policy makers to not overemphasize means when weighing options. The wide spans between minimum and maximum do not serve descriptions of time series dynamics. Hence, much of the following descriptions refer to the mean value. Based on the 11 years from 2010 to 2020, a sample of means is available. The first approach to inform about the degree of dynamic in this sample is its variation expressed as standard deviation (SD).

The calculation of minimum and maximum continues through 10 levels of potentials (Px1-10). These levels include also potentials which capture vagueness of data descriptions at the source or inform about the degree of uncertainty in resource uses. The 10 potentials and their calculation are presented in Brosowski et al. (2019, Table 2 (Brosowski et al. 2019)). Details are also available online at the ResDB Biomass Monitor (Naegeli de Torres et al. 2023). The different potentials frequently used hereafter is the theoretical potential (P1), the technical {technically usable} biomass potential (P2), the split into the technical biomass potential used (P9) and the mobilizable technical biomass potential (P10). Also, the subdivisions of the technical potential used, i.e., material use (P5) and energetic use (P6), are discussed.

2.4.6.3 Challenges in Compiling Secondary Biomass Potentials

Two main challenges require continuous research for the derivation of secondary biomass potentials. One challenge lies with inconsistent continuation of data within sources. Changes in the form of re-grouping of categories occur in both the official statistical compilations and the reports issued by producer associations such as dairy, beverage and fodder industries. These relatively frequent alterations complicate the accounting for parts of or even entire aggregates. These changes prevent exhaustive use of Application Programming Interfaces (API) to collect data automatically from digital sources. Changes in the URL (uniform resource locator) or coding of the source are other causes for API failures. The second challenge lies with the tracking of physical changes on the ground. These are for instance, changes that affect the individual “residue factors” attached to biomasses. For example, the growth height of cereal crop may change with widespread use of new varieties, as a result of which the amount of the by-product straw changes and need to be reflected by a modified residue factor. Other changes might have evolved with advanced processing technology achieving higher product to residue ratios, etc. Thus, while the principle method remains the same as described by Brosowski et al. (2016), its structural components and processing details require renewed checks and eventually updates.

2.4.6.4 Status and Development of Secondary Biomass Potentials

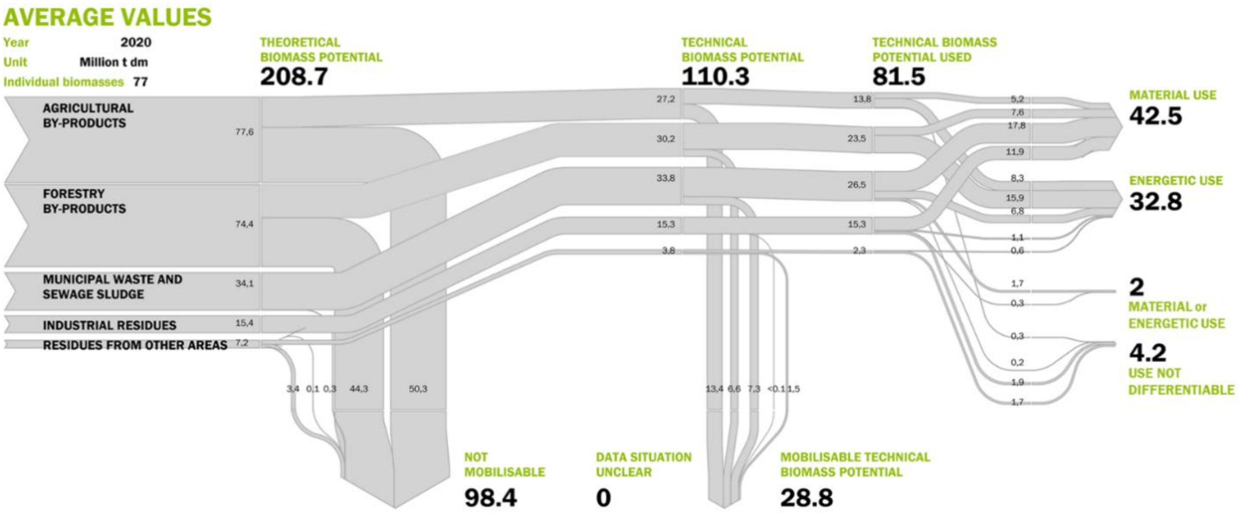
The base dataset of secondary biomass for the reference year 2015 was compiled in project ‘Monitoring the Bioeconomy – Phase I Resource base and sustainability” (MoBi I) of the Thünen Institute (TI). The data was expanded to encompass time series 2010-2020 of the 77 biomasses within the project ‘Monitoring the Bioeconomy – Phase II Consolidation of the monitoring” (MoBi II) in cooperation with the TIs Forestry, Market Analysis and Sea Fisheries. The time series data of potentials of biogenic waste, residues and by-products in Germany is available from the ResDB Biomass Monitor.

The time series 2010-2020 of the theoretical biomass potential of national secondary resources results in a mean and standard deviation across the years of 207.6 ± 5.3 million tonnes dry matter. Decreases and increases alternated. The mean value of the theoretical biomass potential peaked in 2014 at 216.1 million tonnes dry matter and was at a lowest level of 198.8 million tonnes dry matter in 2011. The preliminary last record tags the minimum theoretical biomass potential of the year 2020 at 185.2 million tonnes dry matter, the corresponding maximum at 232.2 million tonnes dry matter, and the mean at 208.7 million tonnes dry matter (Figure 13).

On average almost 47% of the theoretical biomass potential of the years 2010-2020 is to be attributed to a "potential not mobilizable", which takes account of the technical and regulatory limits of exploitation. The potential not mobilizable leaves on average 53% of the theoretical biomass potential as "technical biomass potential" available for use. Mean and standard deviation of the technical biomass potential across the years 2010-2020 are 110.9 ± 1.2 million tonnes dry matter. The minimum-maximum range of the technical biomass potential in 2020 spans from 91.7 million tonnes dry matter to 128.9 million tonnes dry matter resulting in a mean of 110.3 million tonnes dry matter (Figure 13).

The technical biomass potential divides into the "technical potential used" and the yet unused "mobilizable potential" (Figure 13). The time series average use is 81.0 ± 0.9 million tonnes dry matter or 73% of the technical biomass potential. The "technical potential used" peaked in 2018 at 82.1 million tonnes dry matter, which makes up almost 75% of the technical potential. In 2020, 81.5 million tonnes dry matter (ca. 74%) were used. This tags the 2020 mobilizable potential at 28.8 million tonnes dry matter (26%), which is just 1% less than the time series average of 27% mobilizable potential.

Figure 13: Material flow of biogenic waste, residues, and by-products from five sectors to material use and energy generation in 2020 (mean values)



Source: DBFZ 2025

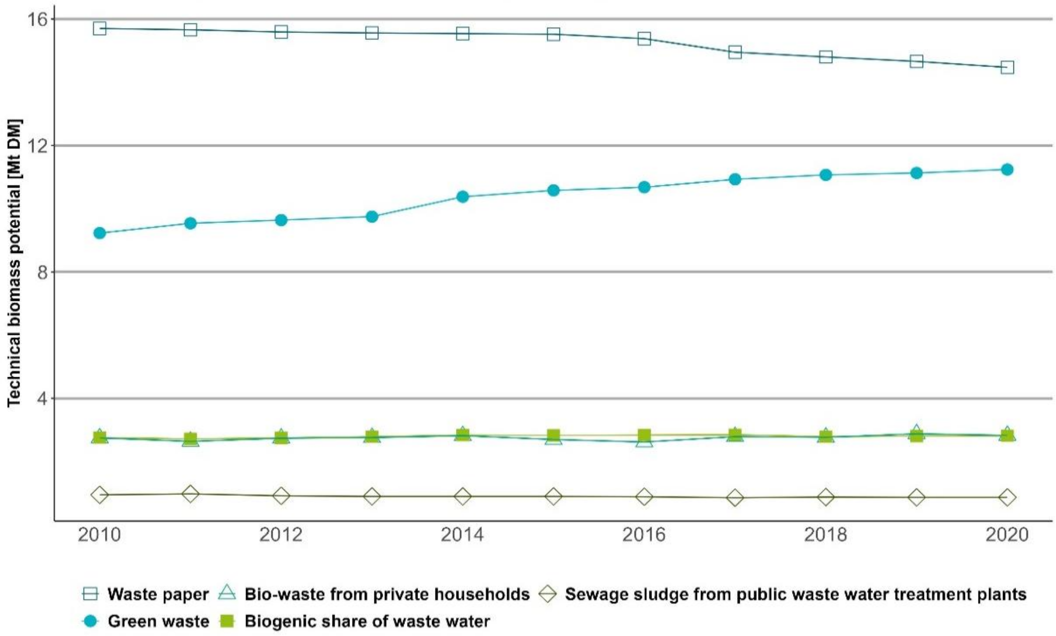
Between 52.2% (2020) and 55.5% (2014) of the technical potential used was allocated to "material use", which appears synonymous with EU publications terms "biobased products" or "biomaterials (European Commission. Joint Research Centre. 2022). In 2020, material use encompassed 42.5 million tonnes dry matter. There is no long-term trend in material use. Contrastingly, the energetic use increased - with few glitches - almost steadily by about 0.4 million tonnes dry matter per year between 2010 and 2020 attaining 32.8 million tonnes dry matter in 2020.

Concluding from the above, fluctuations may be projected into the future rather than growth in a biomass that can contribute proportionally to growing demands. Secondary bioresources are directly related to primary production, processing and consumption; and while the available land surface sets tight limits to biomass production, the processing technology tends to reduce residue-to-product ratio. This raises the question whether recovery and use of biogenic waste and residues from the sector municipal and sewage sludge are already completely optimized?

Municipal waste and sewage sludge (Mwss) contributed 33.8 million tonnes dry matter, and with 31% the largest share, to the overall technical biomass potential in 2020. Sectors following in decreasing order were the residues from wood industry and forestry (FoRes: 30.2 million tonnes dry matter), the agricultural by-products (AgriB: 27.2 million tonnes dry matter), the industrial residues (InRes: 15.3 million tonnes dry matter), and at last the residues from other areas (ORes: 3.8 million tonnes dry matter). The time series 2010-2020 of the technical potential shows some dynamics in the potentials of the different sectors except for ORes. Throughout the period 2010-2020, the sequence in magnitude of contributions to the total remained generally the same with Mwss > AgriB/FoRes >> InRes >> ORes. Only AgriB and FoRes changed their positions at least twice.

Municipal waste and sewage sludge increased from 32.9 million tonnes dry matter in 2010 to 33.8 million tonnes dry matter in 2020. Most of the increase occurred from 2013 to 2014. Before the rise, there were only slight annual increases. After the rise, the technical biomass potential of Mwss remained on a kind of plateau showing only a small decline from 2019 to 2020. The overall dynamic in the course of Mwss was driven by the counteracting developments in its two main contributors of biomass, i.e., waste paper and green waste (Figure 14).

Figure 14: Time series 2010–2020 of the technical potential of the Top 5 biomasses of the sector municipal waste and sewage sludge (Mwss, mean values)

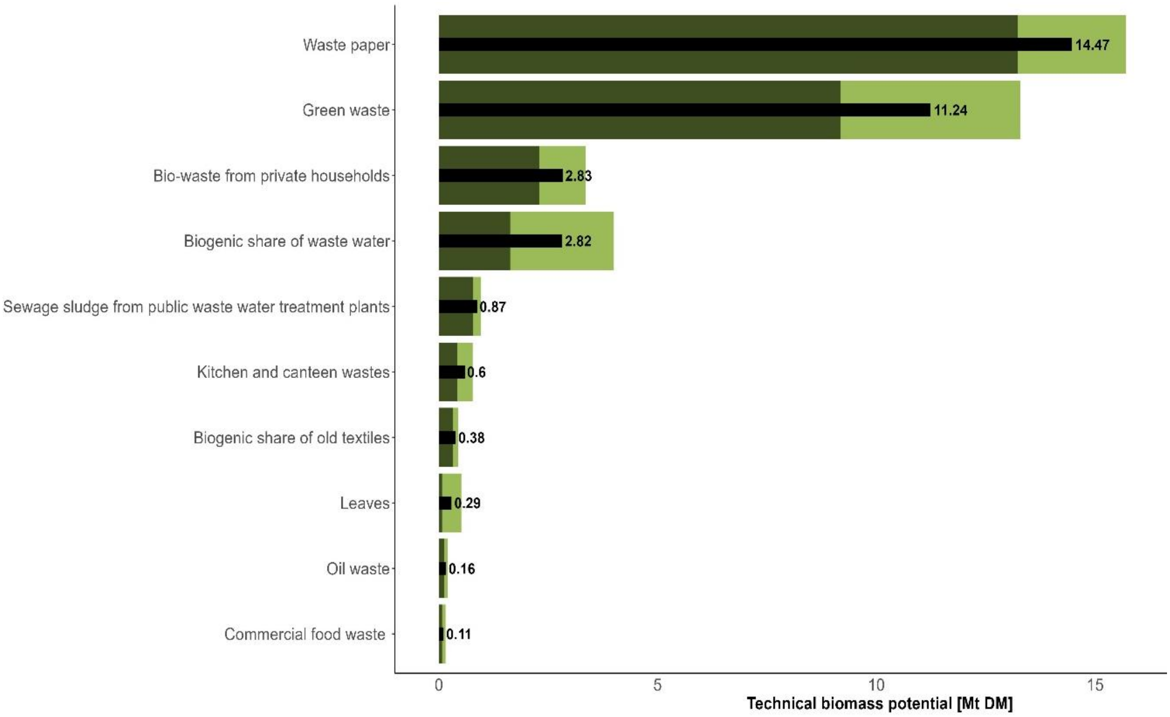


Source: DBFZ 2025

Waste paper and green waste rank top 1 and 2 on both the top 15 list of technical potential of the Mwss sector (Figure 14), as well as on the top 15 list of the national technical biomass potential consisting of five sectors. The technical potential of waste paper is in decline since 2010 and the decline increased at around 2016. Since digital communication and storage of information has become societal standard there is less need for paper to be used, and hence, the technical potential of waste paper will likely continue on its latest trajectory. Conversely, green waste increased since 2010 with the biggest uptick from 2013 to 2014. Over the recorded period, green waste increased by more than two million tonnes dry matter attaining 11.4 million tonnes dry matter in 2020. Regarding the call for greener cities in order to adapt urban habitats to extreme climate events and secure liveable conditions for its inhabitants, there is much reason to expect more green and green care producing more green waste in the future (Bundesinstitut für Bau-, Stadt- und Raumforschung BBSR 2022). While there is a space limit for conventional urban greens such as parks and lawns, there are public environments on the rise embedding blue-green infrastructure in multi-purpose spaces, various technical solutions are on offer for green roofs with or without combination of solar panels, green facades conquer the vertical space, and functional instead of decorative indoor greenings equip work spaces. With respect to the multitude of conversion technologies already available, it appears legitimate wondering whether all that biomass of green care is good for composting only, because this is the main pathways of usage. Separation of lignin-rich residues from the green cut is possible but seems being economically unviable in most cases. Although one might envision that ensilage of leafy green waste enables its use for anaerobic fermentation, and a clean lignin fraction finds other uses such as for wood pellets, substrate for wood borne mushrooms, or even wood liquefaction.

Regarding other secondary waste biomasses derived from human habitation and municipalities, the main question remaining is simply "when it will be more expensive to rely on imported carbon than to recover and exploit secondary resources in the neighbourhood?" Germany may be well advanced with regard to collecting biowaste from private households, but there is still potential to be mobilised. The recent regulation aimed at the increased reuse of old textile materials including their biogenic share represents another advancement (cf. Figure 15)(Circular Economy Act, §20 revision effective as of January 1st, 2025 (Federal Ministry of Justice 2024)). Collection of spent fats and oils from private households appears being difficult to implement, although their conversion to advanced biofuel for, e.g., air traffic is understood to represent a major opportunity to mitigate one of the most reduction-resistant carbon footprints. Waste separation at source is the key. At today's scale and sophistication, it was once unimaginable but has evolved.

Figure 15: Technical potential of the Top 10 biomasses of the sector municipal waste and sewage sludge in 2020 (numbers attached to bar represent mean value, dark bar represents minimum potential, light green bar the maximum potential).



Source: DBFZ 2025

How much effort in waste separation can be expected from citizens? While this is appears being a main motive in regional decision processes, from the scientific point of view the circular use of carbon is not a human invention but it is how the biosphere works sustainably. It may be due time to overhauling the concepts for dissemination and to foster a more participatory approach.

Regarding the perspectives in primary production and processing mentioned earlier, municipal waste and sewage sludge is the one sector among five with the largest growth potential. It could become a sector of even greater importance to bolster circular economy, if regulations promote more pathways to certification than to composting and incineration.

2.4.6.5 Key Findings

- With (a) demand for secondary resources settled well within utilisation but (b) a limited perspective to increase their technical biomass potential, accessing the remaining mobilizable potential ought to be first priority.
- The Circular Economy Act (KrWG), with its “construction site” character taken as symbol for continuing progress, is key to promote further development of new value-added products from secondary biomass as it can support redirecting or repurposing existing uses.
- Imports of biomass/bio-based products from residues and wastes ought to be considered case wise as the permission to increase certain import purposes, such as for biofuel production, may not be necessarily contradictory to overall sustainability.

2.4.6.6 Future Research Requirements

Beyond the research necessary for maintenance of the secondary resources data base, there are items of high priority that can be tackled only with new research projects receiving funds. For one, the publication of an array of important residue factors, although still commonly used in calculations of secondary biomasses, dates back to a past implicitly suggesting it being time to check their present-day validity.

Secondly, it is obvious in various cases that the data basis could be much improved with new research addressing stakeholders directly in form of interview and/or questionnaire-based studies. For the same, it appears being of great importance that policy issues a regulation, which ascertains obligatory periodical responsiveness of major actors to comprehensive surveys in order to support the versed promotion of bioeconomy.

Thirdly, new sources as well as uses of secondary biomasses evolve with the newly intensified research and development for solutions reducing the shortage of national biomass availability and bio-based products, respectively. Some of these can be already named though not be quantified appropriately for a national scale analysis. Resources and uses worth paying attention to their development include (i) third clearance stage of wastewater processing and its use to grow specific microalgae, (ii) secondary biomasses used as substrate to grow fungal mycelium for bio-based products other than food, (iii) residues used to grow insects/insect larvae for, e.g., energy or protein-rich additive to animal feed, and (iv) the recovery of nutrients from and/or use of human faeces, e.g. collected from dry toilets, for fertilizer production.

2.4.7 Case Study: Consumption of Waste Based and Advanced Biofuels

Biogenic wastes and residues are partly directly imported to Germany. However, they are also imported indirectly through intermediate or other final bio-based products. In the case of the transport sector, biogenic wastes and residues are imported via intermediate energy carriers and waste based and advanced biofuels. For the usage of wastes and residues, the transport sector currently represents the highest growth market due to strong policy incentives. With regard to the implementation of the EU Renewable Energy directive (RED II) in Germany, the policy instrument of the greenhouse gas quota (GHG-Quota) was implemented through §37 a-d of the Federal Emission Control Act – BImSchG (Deutscher Bundestag 5/17/2013). Distributors of fuels have the obligation to use certain kinds of fuels and to reduce average GHG emissions of fuels by blending fossil fuels with renewable fuels. The 38th Federal Emission Protection Order (§13a & §14, 38. BImSchVBundesregierung (11/25/2024) entails minimum sub quotas for advanced biofuels (0.1% in 2021 to 2.6% in 2030) and maximum quotas for waste based biofuels (1.9% 2021-2030). Especially due to the growing quota for advanced biofuels, a strong demand for biogenic residues and wastes can be expected for the transport sector.

Table 3 depicts the usage development (in TJ) of biofuels from wastes and residues in Germany from 2020 until 2022 according to the specific resources of the Annex IX of the EU Renewable Energy directive (REDII) (European Commission 12/11/2018). The highest shares of advanced biofuels (part A) come from only three wastes and residues, mainly wastewater from palm oil mills and empty palm fruit bunches (POME), industrial wastes and tall oil. Waste based biofuels (part B) mainly originate from used cooking oils (UCO) and to a smaller share from animal fats. The majority (80% in 2022) of the used biofuels from waste and residues comes from abroad while only 20% of the resources originate from Germany. This also means that the value-added of this growth sector is taking place mainly abroad and not within the German bioeconomy. Policy incentives within the German GHG quota have therefore not led to a ramp-up of the production infrastructure in Germany so far but to an increase of imports. While the usage of advanced biofuels already grew from 6 PJ in 2020 to 28 PJ in 2022, the demand could grow to at least 100 PJ (sub quota + over fulfilment) until 2030 (Schröder and Naumann 2023). Hence, policy updates within the GHG quota should pay special attention to the context of resource mobilisation within the German bioeconomy.

Table 3: Usage of biofuels from wastes and residues in Germany from 2020 until 2022 – in TJ

Usage of biofuels from waste and residues in Germany – in TJ	2020	2021	2022
Advanced biofuels from waste and residues (Part A) - in TJ	6,288	9,119	28,235
3 (biowaste from private households)	94	59	645
4 (Biomass share of industrial waste)	1,112	3,463	7,310
5 (straw))	129	302	371
6 (manure and sewage sludge)	184	228	1,886
7 (Wastewater from palm oil mills and empty palm fruit bunches)	3,290	2.835	12.,78
9 (crude glycerine)	47	697	1,277
15 (biomass shares of waste and residues from forestry) - mainly hydrogenated tall oil	1,433	1,495	3,431
Other (sum of digits 2, 8, 10, 11 and 16)	1	41	435
Share of top 3 waste/residual materials (items 4, 7 and 15)	93%	85%	84%
Biofuels from waste and residues (Part B) - in TJ	39,473	30,982	36,281
Used cooking oils	29,286	24,249	30,010
Other (e.g. animal fats)	10,188	6,733	6,271
Total waste and residues (Annex IX Part A and B)	45,761	40,102	64,516
Waste and residual materials from Germany	9,920	10,531	13,017
Waste and residual materials from Germany (%)	22%	26%	20%

Source: (BLE 11/18/2024; Cyffka 5/28/2024; European Commission 12/11/2018)

2.5 Bio-Based Shares of Economic Activities

2.5.1 Introduction

In addition to description and quantification of material flows, the analysis of bioeconomy sectors provides information on the development of bioeconomy in the context of the whole economy, over time and for comparisons between regions and countries (Ronzon and M'Barek 2018). Ronzon et al. (2024) review the main approaches to measure the size of the European bioeconomy. On EU level, the authors identify four families of methodologies that differ on the set of included sectors and the level of the contribution of these sectors to the bioeconomy. Ronzon et al. (2024) differentiate the output-based, input-based, weighted input-output based upstream and downstream approaches.

According to Ronzon et al. (2024) the selected method should match monitoring requirements, i.e. use data from statistical databases that build on data collection methods and statistical classifications, that are internationally harmonized. For the first estimate of the size of the German bioeconomy covering the years 2010 to 2017, Iost et al. (2020a) used an input-based approach and extended it with information on biomass content in products, i.e. outputs of biomass processing. Due to changed data availability, estimates of bio-based economic activities presented in this report (2018 – 2020) were calculated using output data only.

In the German bioeconomy monitoring, economic activities fully included in the bioeconomy are agriculture, forestry, and fisheries, specialized activities within wood construction, food and beverage service activities and research and experimental development on biotechnology (cf. Table 4). Certain activities within NACE section C "Manufacturing" like Manufacture of food products (10), of beverage products (11), and of tobacco products (12) were fully included. Furthermore, also the early timber processing steps, i.e., manufacture of wood and of products of wood and cork […] (16) and of paper and paper products (17) were fully included. For calculating the bio-based share of section D (Electricity, Gas, Steam and Air Conditioning supply) we followed Ronzon et al. (2021). Partly included are economic activities within NACE sections Manufacturing, Construction and research on natural sciences (cf. Table 4).

Table 4: Selected economic activities for quantification and sustainability assessment of the bioeconomy

Section	Description	Bio-based share	Data source bio-based share
A	Agriculture, Forestry, Fisheries	100%	
C	Manufacturing	Bio-based outputs of economic activities	Production Statistics
D	Electricity, gas, steam and air conditioning supply	Energy supply based on biomass	EUROSTAT official data (Complete energy balances Code nrg_bal_c) (EUROSTAT, 2024)
F	Construction		
41.20.1 & 41.20.2	Construction of residential and non-residential buildings (except prefabricated constructions) & Assembly and erection of prefabricated constructions	Wood construction share of residential and non-residential buildings	Official data on construction permits (Destatis, 2022)
43.32.0 & 43.91.2	Joinery installation & Erection of frames and constructional timber works	100%	
I	Accommodation and food service activities		
56.1 – 3	Food and beverage service activities	100%	
M	Professional, scientific and technical activities		
72.11.0	Research and experimental development on biotechnology	100%	
72.19.0	Other research and experimental development on natural sciences and engineering	Expenses for natural and agricultural sciences	Official data on public sector expenses (Fachserie 14 Reihe 3.6 Tab. 2.2 (Destatis 2017 – 2022))

Source: own compilation based on Iost et al. (2019)

2.5.2 Data and Methods

2.5.2.1 Manufacturing

For estimating bio-based shares of economic activities for the years 2010 to 2017, the main data source was the Material and Goods received Enquiry (MGrE) (Iost et al. 2020a, chapt. 1.2.5). Every four years, it surveys type and acquisition costs (in €) of inputs that are processed or consumed in companies classified in NACE sections B and C. However, up to now only data for 2010 and 2014 is available; data for 2018 or 2022 is not available yet (DESTATIS 2024c).

As a consequence of the changed availability of data, bio-based shares were calculated using only data on outputs of bio-based sectors (output-based approach). As Ronzon et al. (2024) state, “The output method aligns with the definition of the bioeconomy in the EU bioeconomy strategy and is therefore useful for monitoring progress from a policy perspective, both at the country and sectorial level.” Furthermore, the output-based approach relies on production statistics, which provide detailed data in regular time intervals (Flores and Baumgärtner 2019).

For estimating bio-based shares of the German bioeconomy for the years 2018 – 2020, the same economic activities (4-digit-level) were included as for the year 2015 (cf. 2.3, Table 4).

The first step in estimating bio-based shares of economic activities in manufacturing was to evaluate production outputs (cf. 1.2, production codes at 9-digit level, i.e., GP codes) of the respective economic activities. All outputs were categorized as fully, partly or not bio-based depending on their biomass content. Biomass content of GP09 and GP19 codes was deduced from the detailed description of the GP and after consulting experts of the Thünen Institutes of Market Analysis and Wood Research in order to capture possible developments in the substitution of fossil with bio-based resources. In a second step, production values of outputs were summed for the respective economic activity (i.e., 4-digit-level).

As neither the statistical classification nor the production statistics provide information on the actual biomass content and the categorization of GP might be biased. Thus, we calculate minimum and maximum bio-based shares in order to open a range rather than to give a less reliable fixed result. Minimum bio-based shares are defined as the accumulated production value of all fully bio-based outputs of the respective economic activity in proportion to the total production value. Maximum bio-based shares are defined as the accumulated production value of all fully and partly bio-based outputs of each economic activity in proportion to its total production value (Equation 1).

$$\boldsymbol{bbNACE_{min}} = \frac{\sum_j \boldsymbol{pv9_j^{min}}}{\boldsymbol{pv4}}; \ \boldsymbol{bbNACE_{max}} = \frac{\sum_k \boldsymbol{pv9_k^{max}}}{\boldsymbol{pv4}} \quad \textbf{Equation 1}$$

where

$bbNACE_{min}$	minimum bio-based share of an economic activity (at 4-digit-level)
j	products (at 9-digit level) with full bio-based products value
$bbNACE_{max}$	maximum bio-based share of an economic activity (at 4-digit-level)
k	products (at 9-digit level) with full or partial bio-based products value
$pv9$	production value (at 9-digit level) of fully and/or partly bio-based products
$pv4$	total production value (at 4-digit level)

2.5.2.2 Electricity, Gas, Steam and Air Conditioning Supply

Bio-based share of NACE code 35 (energy production) were calculated according to Ronzon et al. (2021) .Bio-based energy production is the proportion of bioenergy in total energy supply expressed in Terajoule as reported in the Complete Energy Balances (code nrg_bal_c) by EUROSTAT (2024a). Bioenergy supply includes solid biofuels, biogasoline, biodiesels, biogases and renewable municipal wastes.

2.5.2.3 Construction

In construction (NACE section F), four economic activities are relevant within the bioeconomy (cf. Table 4). While joinery installation (43.32.0) and roofing activities (43.91.2) are fully included in our bioeconomy definition, for construction of residential and non-residential buildings (41.20) bio-based shares are calculated based on official data on construction permits (DESTATIS 2021a), which provide information on cubic content of buildings differentiated into mainly used building material. Based on this, timber construction rate is calculated as the relation of cubic content of buildings mainly made of wood to the cubic content of all buildings (Iost et al., 2020).

2.5.2.4 Professional, Scientific and Technical Activities

NACE section M summarizes different professional, scientific and technical activities. As noted in our definition, bio-based services are a relevant part of bioeconomy. Due to its high relevance for developing the bioeconomy (BMBF 2023) we fully included NACE code 72.11.0, i.e. research and experimental development on biotechnology (NACE section M). NACE code 72.19.0 (Other research and experimental development on natural sciences and engineering) was partially included (Aarne and Hautakangas 2018).

We estimated the bio-based share of NACE code 72.19.0 using official statistics on public sector expenses (DESTATIS 2016a, 2017c, 2018b, 2019a, 2020a, 2021b, 2022a). From the variety of data and disaggregation this survey provides, we used internal expenses for research and development of public sector scientific institutions, differentiated into science fields and types of expense (Tab. 2.2 in the survey). We used only expenses for personnel; expenses related to administration, infrastructure, and investments are excluded. We used expenses for personnel as public sector institutions usually pay similar wages according to the public wage agreement which allows for comparison of the institutions.

Disaggregation into science fields of the used data does not directly reflect NACE categories. According to EUROSTAT, NACE Rev. 2 code 72.19.0 includes research and engineering on natural sciences, engineering and technology, medical sciences, agricultural sciences and interdisciplinary research with focus on fields listed above (Iost et al. 2020a). Thus, we assign the following categories of Table 2.2 to NACE code 72.19.0: mathematics and natural sciences; medical sciences and humanities; veterinary medicine, agricultural, forest and nutritional sciences; engineering sciences. From those, we selected all subcategories with high relevance for bioeconomy, i.e., chemistry, pharmaceutics, biology, geoscience, agricultural, forest and nutritional sciences and also engineering sciences (cf. Iost et al. 2020a).

In engineering sciences, research in architecture and construction engineering is relevant for bioeconomy when it comes to wood construction. Here, especially in multi-storey wood construction, advances are currently made. Thus, we calculated the contribution of this science field in relation to wood construction share.

We calculated the bio-based share for the years 2018 – 2020 as the sum of personnel costs of all selected subcategories in relation to the sum of personnel costs for all categories assigned to NACE code 72.19.0. As we fully attributed NACE code 72.11.0 to bioeconomy, we calculated a weighted mean of 72.11.0 and 72.19.0, using turnover data from structural statistics in the service sector (DESTATIS 2020b, 47415-0009). Data on value added is not available for this NACE section.

2.5.3 Results

The implications of the altered calculation method for bio-based shares of economic activities are presented using the example of the sectoral sustainability effects gross value added of the Germany bioeconomy and employment in the German bioeconomy. Both examples are also published in Beck-O´Brien et al. (2024).

2.5.3.1 Gross Value Added of the German Bioeconomy

A country's economic performance is measured in terms of gross value added. The share of the bioeconomy in gross value added and its development shows the overall economic importance of the bioeconomy.

Developments in the bio-based sectors and the German bioeconomy

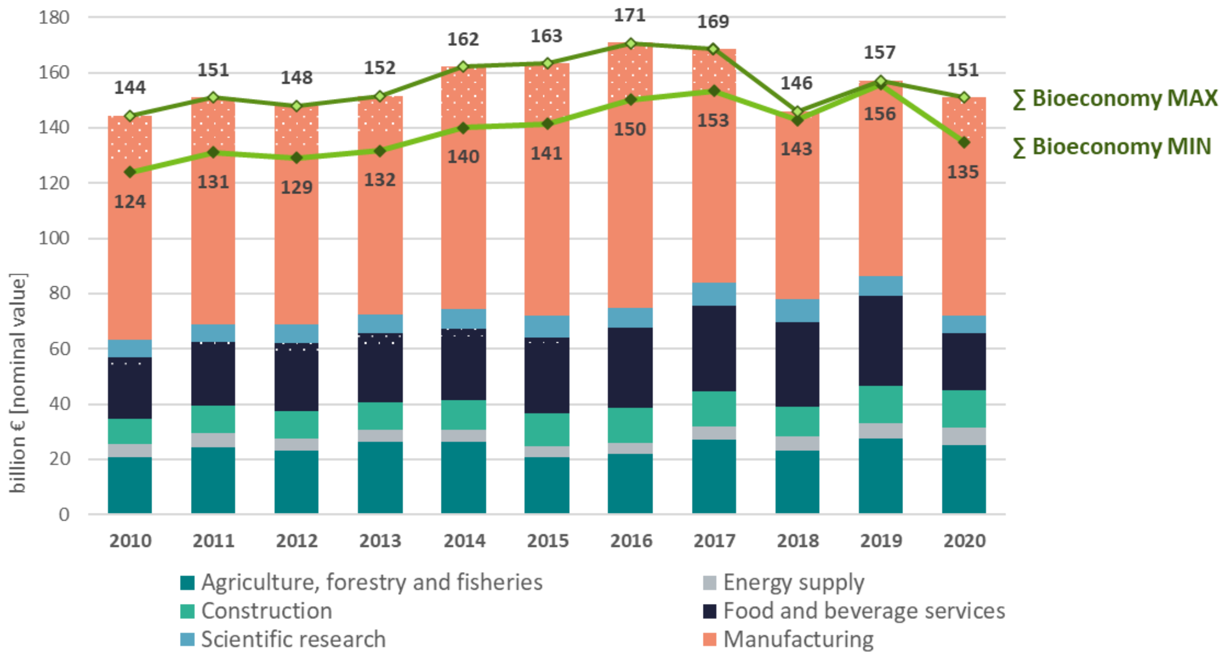
Figure 16 shows the development of the gross value added of the German bioeconomy until 2020. The apparent decline in gross value added in 2018 is immediately striking. However, this is solely due to the fact that the calculation of the bio-based shares had to be changed (cf. chapter 2.5.2). This change restricts the calculation of the minimum and maximum shares of manufacturing and food and beverages services in particular (depicted by the dotted range in Figure 16). Nevertheless, results show that:

- The minimum contribution of manufacturing to gross value added varies between € 63 billion and € 75 billion.
- The minimum contribution of food and beverage services to gross value added increased from € 19 billion to € 33 billion in 2019, before falling to € 21 billion in 2020 due to the coronavirus pandemic.
- Bio-based energy supply contributes around from € 4 billion to € 6 billion. Unfortunately, data for 2018 and 2019 are not available.

- Value added of bio-based construction and scientific research also remained pretty stable over time (€ 9 billion to € 14 billion and € 6 billion to € 8 billion respectively).
- Since agriculture, forestry and fisheries are considered to be fully part of the bioeconomy, value added of this sector is not affected by the missing material and incoming goods statistics. Their contribution fluctuates between € 22 billion and € 27 billion between 2010 and 2020.

This example clearly shows the effects of the altered calculation method for the bio-based shares and emphasises how important the continuous provision of official statistics is for consistent bioeconomy monitoring.

Figure 16: Gross value added of the German bioeconomy in the years 2010 – 2020 (nominal values)

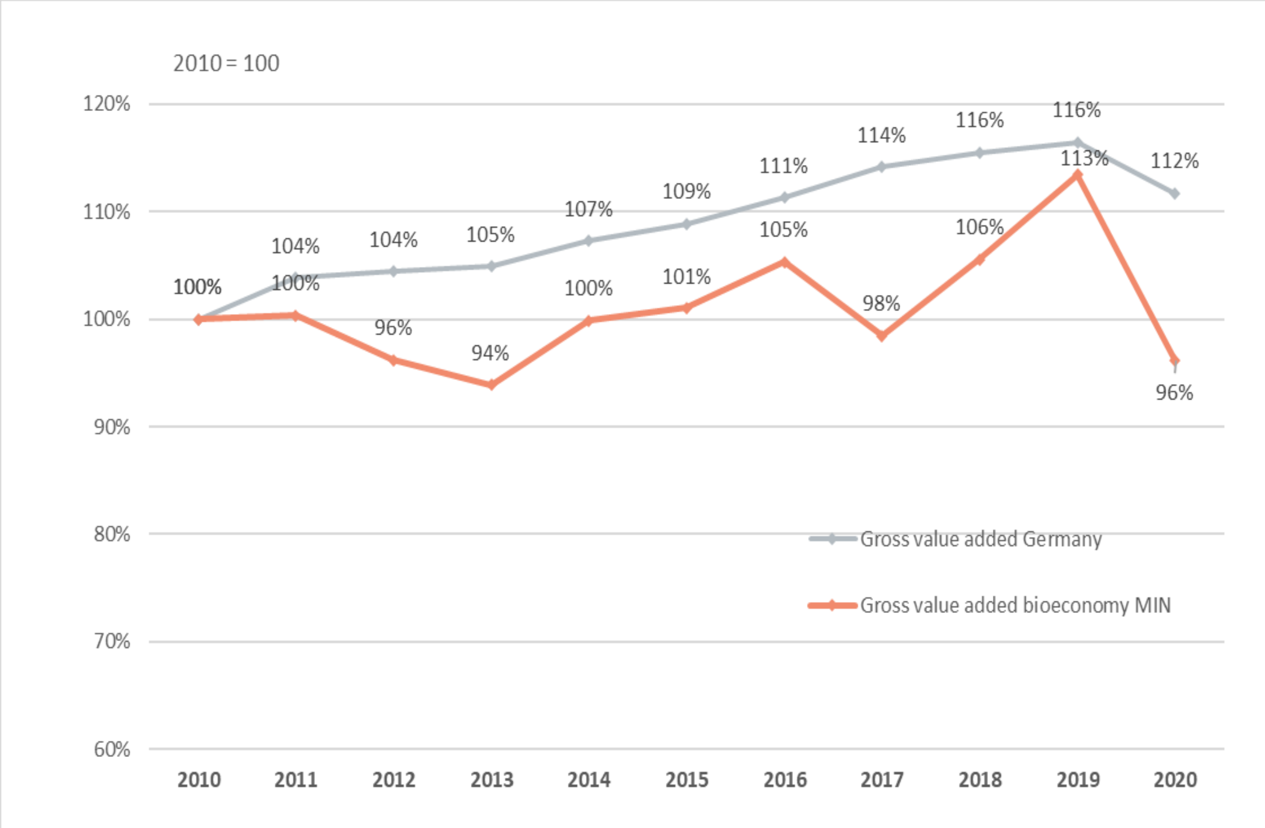


Source: own calculations based on DESTATIS (2018f, 2024f, 2024b) and EUROSTAT (2019b, 2024d)

Developments compared to Germany as a whole

Figure 17 shows the development of the price adjusted gross value added for Germany and the German bioeconomy relative to the year 2010. Between 2010 and 2019 price-adjusted gross value added increased by almost 16.5% in Germany, before falling back to 12% in 2020 due to the coronavirus pandemic. Compared to the development of the price-adjusted gross value added for Germany, the development of the minimum price-adjusted gross value added of the German bioeconomy fluctuates. It Increased by 5% in 2017, peaked in 2019 and in 2020 was back the same level as in 2010. As already mentioned, however, the development of the minimum gross value added of the bioeconomy from 2018 to 2020 must be interpreted with caution, as its calculation is no longer based on material and income goods statistics.

Figure 17: **Development of price-adjusted gross value added of the German bioeconomy compared to the German economy in the years 2010 – 2020**



Source: own calculations based on DESTATIS (2018f, 2024f, 2024b) and EUROSTAT (2019b, 2024d)

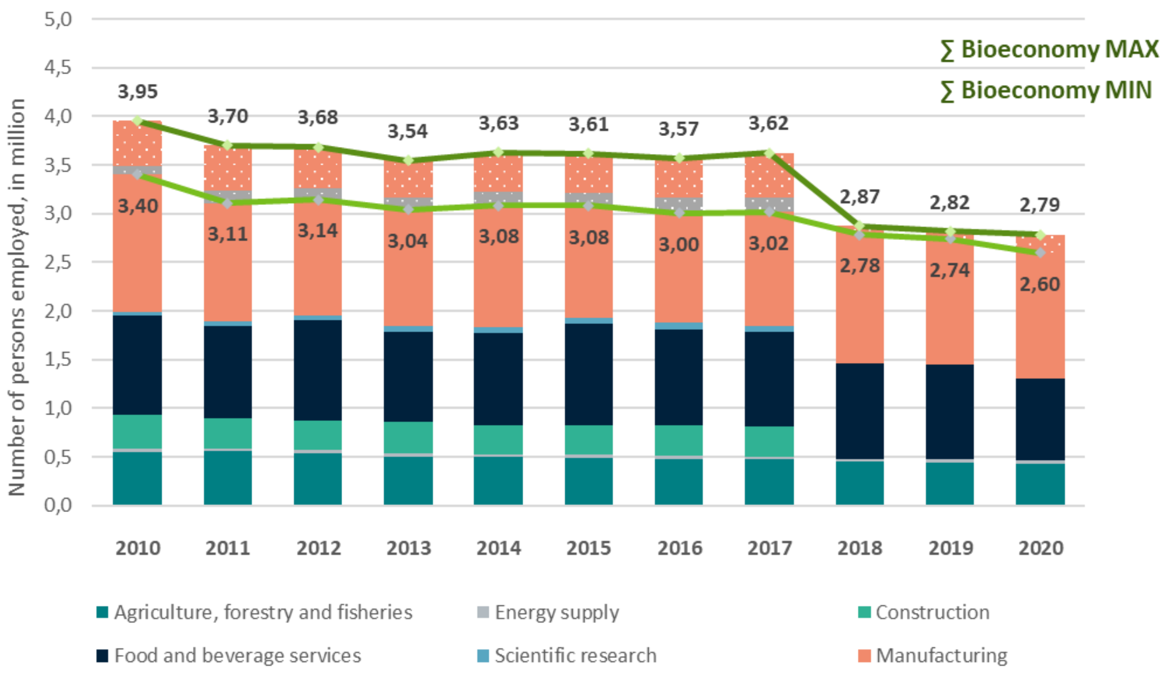
2.5.3.2 Employment

Not only the altered calculation method for the bio-based shares of economic activities but also the provision of less disaggregated employment data by EUROSTAT (2024b), the time series for employment is disturbed after 2017. On the one hand, this has an impact on the calculation of the minimum and maximum values and, on the other hand, employment in the construction sector can only be determined as a lump sum for all construction activities. Despite the disturbed time series, it can be said with a fair degree of certainty that employment in the German bioeconomy fell from at least 3.40 million in 2010 to at least 3.02 million in 2017 (Figure 18). The further decline between 2018 and 2020 should be interpreted with caution due to the mentioned changes in the base data. However, a decline in 2020 due to the coronavirus pandemic is plausible.

Employment breakdown in bio-based sectors

The majority of employees in the German bioeconomy, around 45%, work in manufacturing. The proportion has been largely stable over the years and shows no major fluctuations. Food and beverages services employ about 1 million people. Due to the coronavirus pandemic and the associated lockdowns, the figure fell to 0.8 million in 2020. The number of employees in agriculture, forestry and fisheries is slowly but steadily declining from 0.55 million in 2010 down to 0.43 million in 2020. As agriculture, forestry and fisheries are fully part of the bioeconomy, the time series is not affected by the change in the basic data. While in construction until 2017 a stable number of around 0.30 million employees could be identified as working in the bioeconomy, the number fell down to 0.14 million until 2019. This is due to the fact that disaggregated employment data for construction is no longer available. Research and bio-based energy supply are of more minor importance as regards employment shares in the Germany bioeconomy.

Figure 18: Persons employed in the German bioeconomy in the age group 20 – 64 years from 2010 – 2020

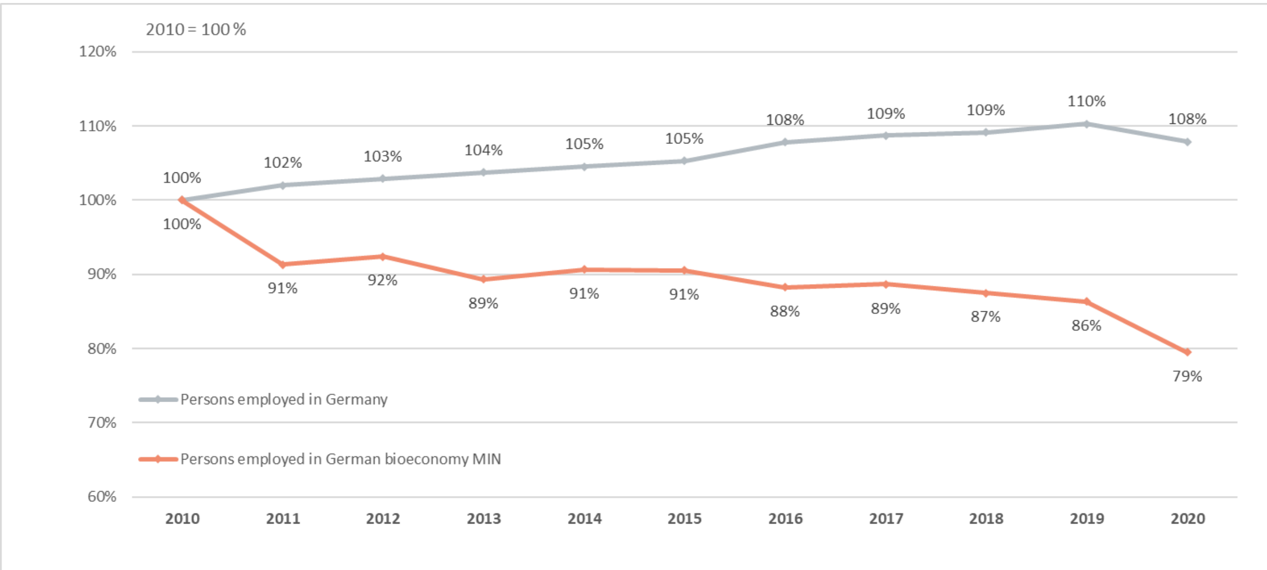


Source: own calculations based on EUROSTAT (2019, 2024b)

Developments compared to Germany as a whole

Looking at employment in Germany as a whole, it continuously increased by 8% between 2010 and 2020 (Figure 19). In contrast, the minimum number of people employed In the German bioeconomy decreased until 2017 by 11%. The trend appears to have accelerated until 2020. However, as mentioned above, it is difficult to estimate the impact of the changed base data from 2018 onwards.

Figure 19: Development of employment in the German bioeconomy compared to Germany in the age group 20 – 64 years from 2010 – 2020



Source: own calculations based on EUROSTAT (2024b)

3 Substitution Effects – Methodological Approaches for Monitoring the Bioeconomy

For the case of Germany, bioeconomy monitoring is framed by the “National Bioeconomy Strategy” (BMBF and BMEL 2020). A comprehensive objective of the strategy provides a monitoring framework for the assessment of biomass utilisation, focusing on the production and disposal of biomass along industrial and productive processes. This presupposes that the potential substitution of fossil with biomass-based resources in the various production phases and the associated effects of such substitution are assessed. Against this background, understanding various methodologies for analysing substitution effects becomes crucial for effectively implementing these monitoring requirements. The following sections explain what substitution effects are and provide an overview of the methods used to assess them.

3.1 Substitution Effects and Biomass Usage

A plausible pathway to further develop the bioeconomy relates to factor substitution as a mechanism through which scarcity and technology interact (Stark et al. 2022). This implies that a product or service containing biomass could serve as an alternative to replace fossil fuels (i.e. energetic use) or could be used in productive sectors as an alternative for resources such as steel or concrete in, e.g., the construction sector (i.e. material use). The scientific interest in resource substitution is reflected by the formulation of policies and development of monitoring frameworks aiming at evaluating the methods and preferences used for tracking the sustainability impacts arising from the sustainable use of renewable biological resources (Bracco et al. 2018; Robert et al. 2020; Jander and Grundmann 2019; Proestou et al. 2024). Moreover, the ongoing discussion regarding the transformation of biomass in a sustainable bioeconomy (Robert et al. 2020) prompted the need to analyse the impact that substituting one input for another into a production process has on long-term sustainability goals (El-Chichakli et al. 2016).

There are a large number scientific publications on the definition of substitution effects and the methodological approaches used to quantify them. Scientific research focused, for example, on the impact of substituting wood with non-wood materials, the role of forest products in the bioeconomy, highlighting the potential forest products to reduce GHG by substituting fossil-based materials and the challenges of quantifying GHG emissions from wood use using Life Cycle Assessments (LCA) (Hurmekoski et al. 2021; Rüter 2024; Verkerk et al. 2022). Before including substitution effects in the bioeconomy monitoring, it is important to review the available methods and assess their applicability. This chapter identifies the definitions of substitution effects as presented by different authors and the methodological approaches used for analysing substitution effects. This chapter concludes by presenting a brief discussion along with a methodological recommendation for application into a bioeconomy monitoring framework.

3.2 Delimited Structured Search in Databases

The search for literature was guided by the Preferred Reporting Item for Systematic Reviews and Meta-Analysis (PRISMA) extension for scoping reviews, PRISMA-ScR (Tricco et al. 2018) along with guidance provided in Page et al. (2021). PRISMA is a bibliographic tool used for the identification of available evidence and clarification of definitions in existing literature. However, it is not an evaluation tool for assessing the quality of the research presented (Arksey and O'Malley 2005). A key aspect of this review is the focus on substitution effects within the context of bioeconomy. The term “bioeconomy” was introduced in the late 1990s (Enriquez Juan 1998; Birner 2018) and therefore only publications between 1999 and 2022 are included in the review. The search is limited to scientific research published in English in peer-reviewed journals, and excludes grey literature, e.g., Rüter (2011), Leskinen et al. (2018). The eligibility criteria, along with each discussed criterion, is presented in Table 5.

Table 5: Eligibility criteria applied for the delimited structured search of literature

INCLUDE	Peer-reviewed article
	In English
	Published after 1999 until May 2022
	Unrestricted spatial scope
	Articles on types/forms of biomass for sectoral and material flow analysis
	Articles including forest management and/or HWP (harvested wood products)
	Articles with residues of biomass processing (e.g., wood processing residues)
EXCLUDE	Articles examining only inputs into biomass production
	Articles only on land management effects of GHG/GHG mitigation
	Disposal or management for conventional (mixed, household) waste
	Chemical substitution reactions (atoms or molecules)
	Reviews

Source: own compilation

The final sample of articles was gathered in two phases. For the first phase, the literature search and data collection relied on Web of Science and Elsevier´s Scopus as the search engines (Pranckutė 2021). To convey a scientific focus on substitution effects, variations of the terms: substitution, biomass, energetic use and material use were included in order to develop the final search strings. Additionally, the inclusion of the relevant major biomass groups (wood, agricultural, aquatic) and “waste” were included in the strings. The final selection of search strings is detailed in Table 6.

Table 6: Search strings applied to Web of Science and Elsevier´s Scopus databases

Scopus	**(TITLE-ABS-KEY ("substitution effect*" OR "substitution impact*" OR "biomass substitution") AND TITLE-ABS-KEY (bioecon* OR bio-based OR biobased OR biomass* OR *wood* OR timber* OR agri* OR aqua* OR fisher* OR waste* OR "material use*" OR "energetic use*")) AND PUBYEAR > 1999**
Web of Science	(TS=("substitution effect*" OR "substitution impact*" OR "biomass substitution") AND TS=(bioecon* OR bio-based OR biobased OR biomass* OR *wood* OR timber* OR agri* OR aqua* OR fisher* OR waste* OR "material use*" OR "energetic use*")) AND (PY==("2022" OR "2021" OR "2020" OR "2019" OR "2018" OR "2017" OR "2016" OR "2015" OR "2014" OR "2013" OR "2012" OR "2011" OR "2010" OR "2009" OR "2008" OR "2007" OR "2006" OR "2005" OR "2004" OR "2003" OR "2002" OR "2001" OR "2000"))
Asterisk (*) in the search strings represents any number of letters or variations of spellings in the searched terms.	

Source: own compilation

To address uncertainties associated with article selection (Levac et al. 2010; Peters et al. 2020), it was decided to exclude literature reviews, as these could increase the possibility of double counting of articles and potentially include articles that do not have an original methodological approach to quantifying substitution effects. Therefore, as in the second phase, literature reviews in our sample were identified and the articles contained therein were extracted for further processing. Subsequently, these articles were cross-referenced and screened against the initial list of articles. The combined search from databases and reviews returned an aggregate amount of 639 publications. The raw output of the searched databases was first exported from each respective database, organized in Microsoft Excel, imported into the reference manager CITAVI (Version 6.14.0.0 by Swiss Academic Software GmbH), and managed for title, abstract, text screening, and ultimately for data extraction.

Processing the articles obtained from the databases resulted in the selection of those which provided a mention of the term “substitution effect”, formulated and/or cited definitions, type of biomass (agricultural, woody, fish), and type of substitution (for material or energetic use). A total of 57 articles were finally selected for data extraction, which contained both an explicit definition and a corresponding explicit methodological approach for the quantification of substitution effects. These were primarily grouped according to the definition and quantification method for substitution effects, but were also summarized according to the various characteristics of their quantification method, e.g., the biomass substituted, the type of substitution, the metric and the sectors in which substitution effects were analysed.

3.3 Overview of Definitions and Methods Used to Quantify Substitution Effects

Current bioeconomy policies reflect the scientific interest and political importance of quantifying substitution effects (Allain et al. 2022; Hetemäki et al. 2024). This is reflected in current scientific research, e.g. on the specific intersection of bioeconomy, forest-based sector and substitution effects (Giurca and Befort 2023). In this context, researchers have focused on methodological approaches to analysing and quantifying substitution effects (Jasinevičius et al. 2015; Andersen et al. 2022) with less attention paid to generalising a definition of substitution effects within the bioeconomy.

3.3.1 Definition of Substitution Effects

In the articles analysed, some definitions of substitution effects within bioeconomy were explicit, i.e., 'fully revealed or expressed without vagueness, implication, or ambiguity: leaving no question as to meaning or intent' and others were implicit, i.e., 'capable of being understood from something else though unexpressed' (Merrian-Webster Online Dictionary - retrieved 17.08.23). For example, an explicit definition is as follows: '(iii) their substitution effect in markets (i.e. the avoidance of GHG emissions resulting from the displacement of GHG-intensive products with wood products' (Landry et al. 2021, p. 2). An implicit definition is expressed as follows: '… a range of substitution benefits of using bioenergy in place of contemporary and future fossil fuel energy, and solid wood products in place of alternates such as plastic, steel, and concrete' (Smyth et al. 2020, p. 2), or it could be defined without mentioning the term 'substitution effect', for example as follows: 'On the one hand, wood can be burnt directly for fuel (energy substitution). On the other hand, the production and disposal of wood products usually require less energy than competing products made of materials such as plastic, metal or concrete (material substitution).' (Bösch et al. 2019, p. 127). For the purposes of this review, 'substitution' refers to the extent to which a resource has an equivalent in a pool of resources, while 'substitution effect' refers to the quantifiable metric resulting from the specific change in an end-use resource.

In the majority of the articles analysed (n = 35), the term 'substitution effect' or its synonyms are only implicitly defined, while explicit definitions appear in 17 articles; for example the definition in (Landry et al. 2021, p. 2) cited above. Some authors explicitly distinguish the substitution effects into material and energy substitution effect (Kayo et al. 2015) or address the fossil fuel substitution effect (Tsunetsugu and Tonosaki 2010; Eriksson et al. 2007). In the articles analysed, the term 'substitution effect' is used to define effects that occur as a consequence of the replacement of fossil resources and products by bio-based resources and products. Most of the articles discuss environmental substitution effects, especially the avoidance or reduction of greenhouse gas emissions or the increase of carbon storage in biomass. The economic and socioeconomic substitution effects were estimated and discussed in fewer articles. An example of economic effects are substitution costs and cost advantages, as outlined in Sathre and Gustavsson (2009). Forest jobs as in Smyth et al. (2020) or land occupation aggregated in a single score indicator as in Höglmeier et al. (2015) are examples of socioeconomic effects. Other terms were also used when referring to 'substitution effect' such as: 'substitution impact' (Asada et al. 2020; Gustavsson et al. 2006a), 'substitution benefit' (Chen et al., 2018; Eriksson et al., 2007), 'climate benefit' (Gustavsson et al. 2017; Kunttu et al. 2021; Pingoud et al. 2010), 'carbon benefit' (Raymer et al. 2011; Raymer et al. 2009), 'climate change mitigation impact' (Mylyviita et al., 2022), 'carbon mitigation impact/benefit' (Nepal et al., 2016, D'Amico et al., 2021), or a very general 'external performance' (Yongmei et al., 2016). The analysis of the extracted definitions of substitution effects shows that these are often related to material and energetic substitution of forest biomass. However, the extracted definitions of substitution effects appear either too narrow or too broad to be generalised. In addition, a definition is often linked to a specific objective, e.g., forest biomass and climate change, ignoring the importance of other issues, e.g. biomass in agriculture, employment, human health, etc. Therefore, the aim of defining substitution effects in the bioeconomy should be to operationalise, standardise and use them consistently so that stakeholders do not over-interpret them and are not misguided by ambiguities. A definition should be precise, distinctive, robust, and simple and should explicitly describe its scientific concept (Strunz 2012; Wunder 2015).

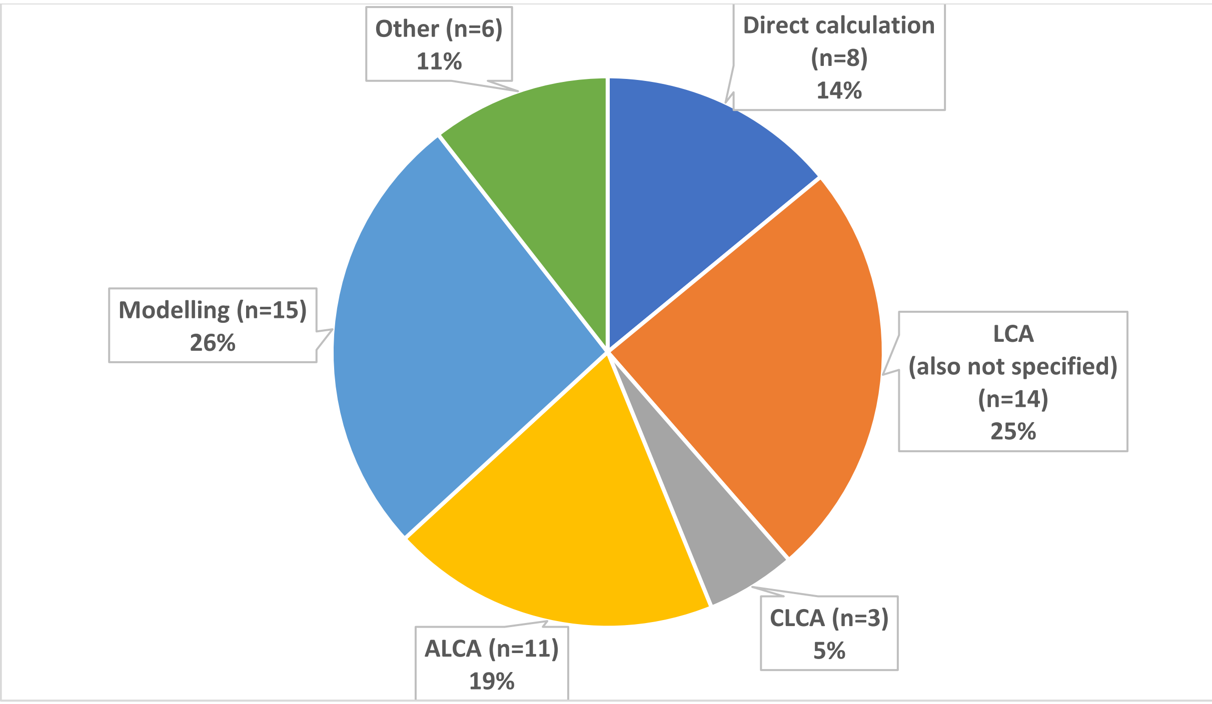
3.3.2 Methodological Approaches

A general stratification of the articles analysed shows that most focus on forest biomass as a substitute for fossil resources in either material or energy use, using Life Cycle Assessment (LCA) as a methodological approach and Displacement Factors (DF) as a metric for quantifying substitution effects. The use of forest biomass as a renewable resource for substitution purposes also predominates in the construction industry and the energy sector.

When quantifying substitution effects, life cycle assessment (LCA) methods are the most frequently used methodological approaches (cf. Figure 20), as they were adopted by around 49% (n = 28) of the articles analysed. Of these, 14 articles presented relevant aspects of an LCA, such as the definition of a functional unit and system boundaries. Other articles indicated that they followed an LCA approach, but did not explicitly state whether they followed an attributional or consequential approach. When explicitly indicated, the articles on attributional LCAs refer to the ISO standards. In our final sample, 19% (n = 11) of the articles explicitly mentioned ISO standards (ISO; ISO), e.g., as described in Herrmann et al. (2013). In 5% (n = 3) of the articles a consequential LCA was specified as the method used, i.e., it was taken into account that substitution itself changes the life cycle of a product and therefore the effects change with changing substitution (Ekvall and Weidema 2004), as described, for example, in Chen et al. (2018), Karlsson et al. (2015) and Nepal et al. (2016). In eight articles (14%) substitution was calculated directly, i.e., a displacement factor was estimated directly, while in fifteen (26%) articles modelling was used, indicating a variety of models.

Although the majority of articles are based on LCA, six (11%) articles, labelled here as 'Other', presented a different method of quantifying substitution effects. For example, Suh (2016) used a fuel allocation model that differentiates a firm´s cost-minimising conditions while using price elasticities to analyse their impact on CO_2 emissions, or as in Tsunetsugu and Tonosaki (2010), where three accounting approaches (stock-change, production, and atmospheric-flow) were used to estimate carbon storage effect, energy saving effect, and the fossil fuel substitution effect due to the use of harvested wood products.

Figure 20: Methodological approaches used to quantify substitution effects as reported in all articles (n = 57). LCA = Life Cycle Analysis; CLCA = Consequential Life Cycle Analysis; ALCA = Attributional Life Cycle Analysis



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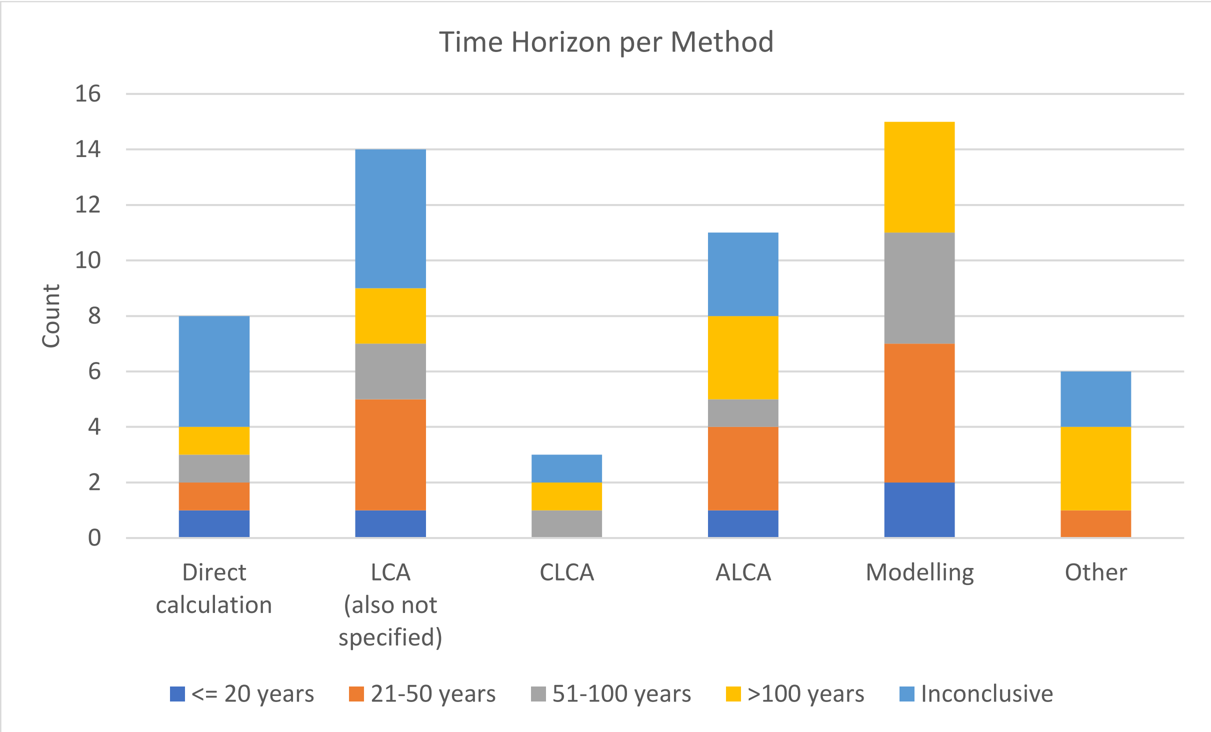
When assessing substitution effects, the time horizons, i.e., the length in years of the scenarios used to analyse the substitution effects, varied considerably in all articles. Figure 21 groups the time horizons by method category. Two articles analysed a single year (Chang et al. 2018; Ngunzi 2015); coincidentally, the year was 2014. Only one article (Schulte et al. 2021) used two different time horizons (100 and 50 years) for two different functional units. In the sample of articles analysed, most tended to assess substitution effects for time periods of 21-50 years (n = 14) and >100 years (n = 14), while the time horizons were inconclusive in about 26% (n = 15) of the articles analysed. Another aspect in connection with the time horizons in the assessment of substitution effects is the assumption that these vary and/or decrease over time. The time horizon of substitution effects is an important aspect in the decarbonization of the economy and the associated compliance with internationally agreed commitments (e.g., Paris Agreement). The variety of time horizons shows the complexity of estimating substitution effects and the difficulty in dealing with uncertainties when time horizons increase.

Figure 21: Time horizons grouped by methods across all analysed articles (n = 57)



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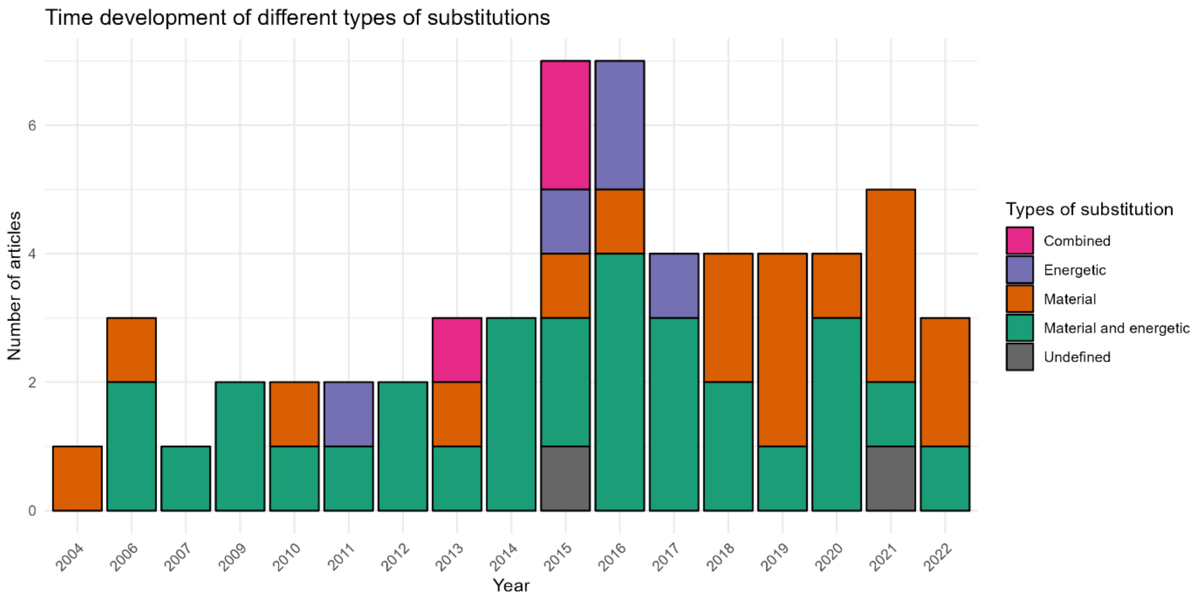
3.3.3 Types of Substitution

It was found that around 54% of the articles analysed carried out an analysis of material and energy substitution (fossil by biomass), around 30% only analysed material substitution (fossil by biomass), 9% only analysed energy substitution (fossil by biomass) and around 5% carried out a combined analysis of energy substitution (fossil by biomass) and material and energy substitution (biomass by biomass). Approximately 89% (n = 51) of the articles refer to forest biomass, presenting wood as a versatile biological material compared to fossil material, followed by 9% (n = 5) referring to agricultural biomass. One article (Asada et al., 2020) deals with mixed biomass (agricultural, forestry and aquatic biomass) and one article (Petersen and Solberg, 2004) with combined agricultural and forestry biomass. Furthermore, if we look at the development over time of the different types of substitution (cf. Figure 22), we see that in our sample of analysed articles there is a strong focus on the substitution of fossil fuels with biomass, with the exception of a few specific combined articles. An increasing interest in material and energy substitution is also observed, until 2016, when an increased research interest in material substitution can be observed. The year 2015 is of particular interest as it shows a diverse research interest that reflects the different types of substitution.

Figure 22: Development over time of the different types of substitution across all analysed articles (n = 57)



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3.3.4 Sectors, System Boundaries and Indicators

The review shows that substitution effects have only been analysed in a few economic sectors. Around 82% of the articles analysed focus on construction, the energy sector and the forestry sector. It can be seen that construction account for around 35% of the articles analysed, around 25% of the articles analysed relate to the energy sector, followed by the forest-based sector with around 23% of the articles analysed. Other sectors, e.g., agriculture, transport, chemicals, textiles, and automotive were represented in around 18% of the articles analysed. The focus of the sectors specifically addressed is also reflected in the products analysed. In this review, the description of the products in all articles was thoroughly broken down into specific components in order to fulfil the objective of the analysis. For example, Asada et al. (2020, p. 3) propose twenty-six sub-sectoral activities for substitution in the construction sector. Furthermore, the system boundaries stated in the reviewed analyses clearly indicate the levels at which substitution effects were measured. For example, in Smyth et al. (2014, p. 444) the system boundary is described to as 'forest management (FM), HWPs and bioenergy, and emissions displaced in the energy and product sectors' or as in Werner et al. (2006, p. 321), where the boundaries are depicted from roundwood as input until a hypothetically complete energetic use. In thirty-one articles (54%) the definitions of system boundaries were inconclusive, while in twenty-six articles (46%) the system boundaries were specified from cradle-to-grave, from cradle-to-gate and from cradle-to-cradle.

Although the articles analysed reflect the multi-sectoral and complex nature of substitution effects within bioeconomy, they consistently prioritise examining substitution through a primary focus on analysing the associated greenhouse gas emissions and climate impacts. Around 79% of articles (n = 45) used indicators related to climate change (e.g., CO_2, CH_4, N_2O, kt CO_2-eq, Cumulative Radiative Forcing, Global Warming Potential, Absolute Global Temperature Potential, and others) to analyse substitution effects, while the remaining articles combined climate change and economics (n = 7), focused only on economic (n = 1) and used other (n = 4). The latter group refers to aggregated single score indicators (Höglmeier et al. 2015), integrated indicator in monetary unit (Kayo et al. 2019), monetarised environmental score (Morris 2017), and social, economic, and environmental indicators (Mair-Bauernfeind et al. 2020).

3.3.5 Displacement Factors

The economics of using one resource over another was addressed in an early work in terms of opportunity costs (Boulding 1932); such opportunity costs can be measured in terms of, for example, in terms of the avoided carbon emissions that result from using one resource over another. A prevalent metric for quantifying climate impacts resulting from substitution is the estimation of a Displacement Factor (DF) (Schlamadinger and Marland 1996; Sathre and O'Connor 2010a; Sathre and O'Connor 2010b). A displacement factor – also called substitution factor, carbon substitution factor, substitution rate, substitution coefficient, marginal displacement factor, or displacement rate – expresses the efficiency with which the use of biomass reduces net GHG emissions compared to the use of fossil resources and thus quantifies the emission reductions (Leskinen et al. 2018; Sathre and O'Connor 2010b) and is estimated as follows:

$$DF = \frac{GHG_{non-wood} - GHG_{Wood}}{WU_{Wood} - WU_{non-wood}} \quad \textbf{Equation 2}$$

'where $GHG_{non\text{-}wood}$ and GHG_{wood} are the GHG emissions resulting from the use of the non-wood and the wood alternatives, respectively, expressed in mass units of carbon (C) corresponding to the CO2 equivalent of the emissions, and WU_{wood} and $WU_{non\text{-}wood}$ are the amounts of wood used in the wood and non-wood alternatives, respectively, expressed in mass units of C contained in the wood' (Sathre and O'Connor 2010b, p. 107). About 53% (n = 30) of the analysed articles analysed substitution effects by using a DF; half of them (n = 15) used DFs from the literature, while the authors of the remaining articles (n = 15) empirically estimated DFs themselves.

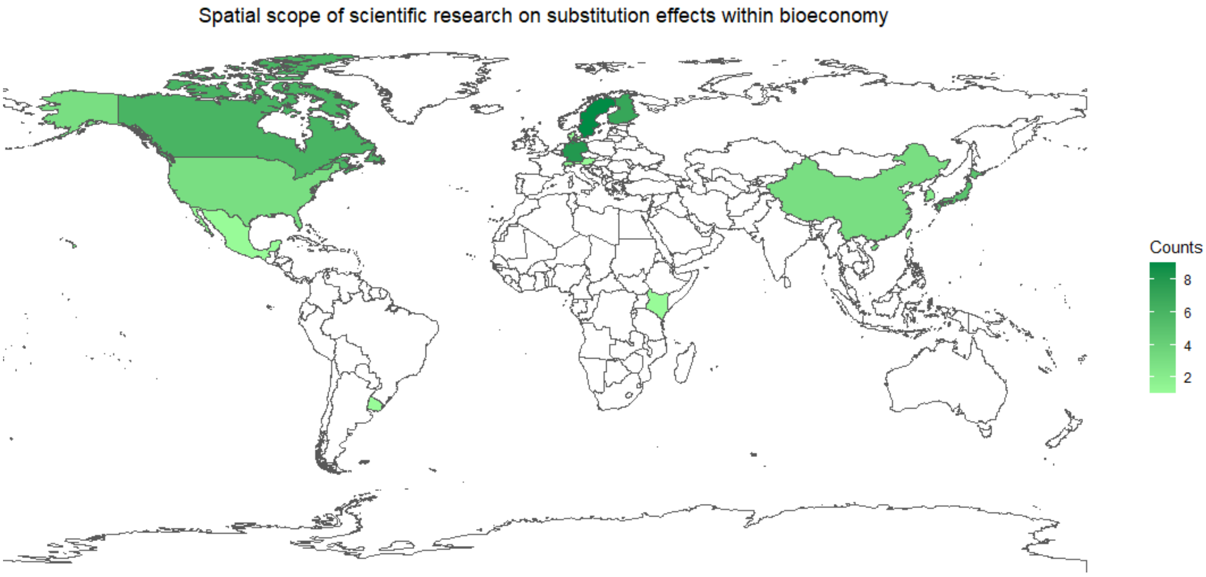
One factor that affects the estimation of DFs is the fact that production technologies evolve over time and therefore DF values may also change. The following development of the methods for estimating the DF was identified. The estimation of displacement factors for material substitution is usually carried out according to the generally used methodology of Sathre and O'Connor (2010b). Another example is given by Pingoud et al. (2010), who present a marginal displacement factor, a modification of Schlamadinger and Marland (1996), which describes the reduction in emissions in relation to additional biomass utilisation. For wood utilisation in Germany, Knauf et al. (2015) estimated DFs by sixteen displacement factors developed on the basis of a material flow analysis. Nepal et al. (2016) adjusted the average displacement factor of Sathre and O'Connor (2010b) and reduced it from -2.1 tCO_2eq/tCO_2eq to -1.68 tCO_2eq/tCO_2eq by including wood energy emissions for the manufacturing of wood products. In Smyth et al. (2017), displacement factors for HWP in Canada are estimated by compiling a basket of products and their avoided emissions weighted by consumption statistics. A different view is presented in Poljatschenko and Valsta (2021), in which displacement factors for logs by dominant tree species were estimated in Finland, or for different house types and business-as-usual or forecasting scenarios, as shown in Myllyviita et al. (2022). However, the estimates of displacement factors vary between the articles analysed (cf. Annex 1 for a complete listing of DFs per article).

In short, a DF is a multiplier and is used to show the mitigation impact of, for example, the use of forest biomass. However, the review show that the estimation of the DFs and the resulting substitution effects is generally inconsistent.

3.3.6 Spatial Scope

In terms of the spatial scope (cf. Figure 23), scientific research on substitution effects was mainly conducted at national level, i.e., 94% of the final sample of articles analysed substitution effects in relation to a specific country. Sweden, Germany, Norway and Finland are the countries in Europe (50% in total in the final sample of articles) where substitution was analysed most frequently. In addition, the articles that included a national analysis were unevenly distributed in terms of their regional coverage. Most of the articles (58%) related to Europe, followed by the Americas (18%) and Asia (18%), one country in Africa (2%) and the rest at regional or global level.

Figure 23: Number of countries (n = 58) represented in articles in this review. The number of countries does not correspond to the final number of articles since three articles used more than one country for their analysis



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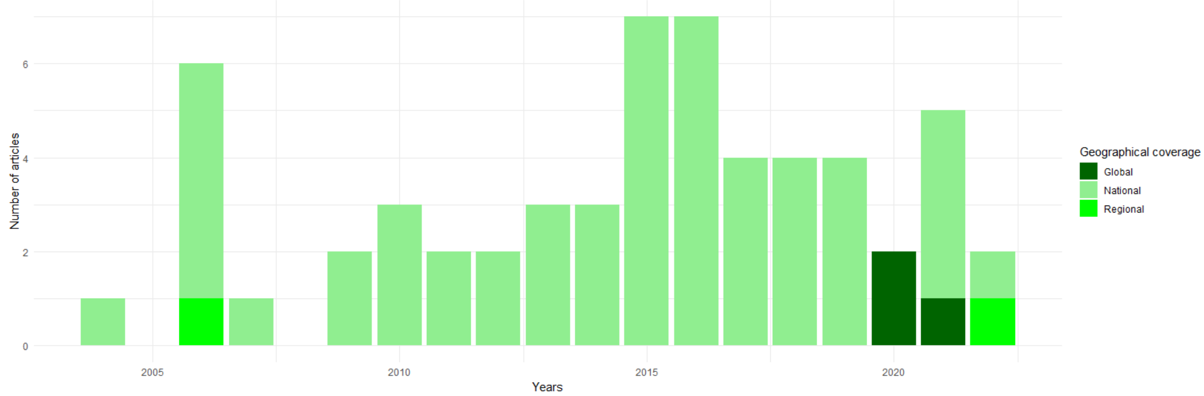
The rest represent 6% of the final sample of articles (cf. Figure 24).

Figure 24: Distribution of all articles (n = 57) via databases and reviews per date of publication and geographical coverage



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3.3.7 Application in a Bioeconomy Monitoring Framework

In this chapter, various definitions for substitution effects as they can be found in the scientific literature were examined, whereby the terminological differences between the individual authors were also analysed. In addition, common methodologies used by researchers to analyse substitution effects were identified. There is a consensus in the articles analysed that the use of forest biomass as an alternative to fossil-based resources contributes to a climate neutral bioeconomy. However, there is no generally accepted approach for analysing this or any other substitution effect. Furthermore, the results obtained by using different methodologies vary considerably due to the different contexts in which they were estimated, leading to a wide variety of possible substitution pathways. Against the background of these findings, this chapter discusses the methodological approaches previously presented above and presents a general recommendation for their application into a bioeconomy monitoring framework.

Recent scientific research (Myllyviita et al. 2021; Hurmekoski et al. 2021) suggests that wood as a substitute for fossil resources has a positive effect on reducing GHG emissions, based on the results of displacement factors quantifying avoided emissions. However, the use of estimated average displacement factors for wood utilisation is problematic, as different assumptions were made when estimating the factors. In addition, the DFs for different products are also estimated in a specific context, which makes a cross-country or cross-sector comparison difficult.

Although the use of a DF serves as a general indication of the benefits that replacing fossil resources with forest biomass could have, no policy conclusions should be drawn solely on this basis, as a DF is only one of many components in the assessment of substitution effects. The use of DFs to assess substitution effects has been critically scrutinised in light of the fact that markets, carbon flows and technologies change over time (Harmon 2019). DFs could also decrease over time as economic sectors reduce their use of fossil resources to meet climate change commitments. (Keith et al. 2015; Hurmekoski et al. 2022). In order to meet changing analytical requirements, the methods for estimating DFs have been improved over time. More recently, Brunet-Navarro et al. (2021) estimated dynamic substitution factors that adjust proportionally to emissions reduction in line with the Paris Agreement, and Seppälä et al. (2019) developed a methodology for estimating the required displacement factors (RDF) to achieve zero CO_2 emissions. If DFs are to be used to analyse avoided GHG emissions, their estimates should also include changes in carbon stock in trees and soils, relevant GHG flows, and the use of forest biomass products (Myllyviita et al. 2021; Leskinen et al. 2018).

It is important to note that the ‘analysis of wood substitution is a very complex issue, since the underlying system is complex. The influencing factors can be found along the entire wood chain; they include several industries, socio-economic and cultural aspects, traditions, cost dynamics, technical and structural change etc.’ (Gustavsson et al. 2006a, p. 1122). With this in mind, should LCA methods be the generally accepted methodology, along with the use of a DF as a commonly used metric, or should other potentially applicable methods and metrics be used? While LCAs are widely used to identify alternative products with lower environmental impacts and a DF provides an easy-to-understand metric to assess the impact of substitution effects, there are other effects of substitution such as leakage that are difficult to assess with attributive LCAs or DFs.

Leakage describes the effect that, for example, the consumption of a substituted fossil product could simply be shifted from country A to country B (Murray et al. 2004; Kallio and Solberg 2018; van Kooten and Johnston 2016; Gan and McCarl 2007; Schier et al. 2022; Dieter et al. 2020), thereby offsetting or even overcompensating for the potential substitution gains in country A. Another impact of substitution is rebound effects, i.e. although substitution means that fewer resources are used to manufacture products and less environmental impact results, this effect is cancelled out by the increasing consumption of these products (Stark et al. 2022; García et al. 2020). Finally, an important factor for the extent of substitution is the displacement ratio, i.e. the change in the amount of alternative and target products that serve as substitutes (Yang et al. 2024). The challenge is to determine the extent to which an alternative product can completely displace an existing product, which influences the estimation of the resulting environmental impact.

Based on these results, it is clear that there is no ready-made approach to quantifying and assessing substitution and all its different effects. At product level, attributive LCAs are a comparatively simple method for estimating the environmental effects of substitution, despite all the limitations regarding the consideration of leakage and rebound effects. In order to capture leakage, rebound effects and displacement ratios, a combination of economic equilibrium models with consequential LCA seems to be a possible approach. However, the complexity of this approach requires extensive development work before it can be integrated into bioeconomy monitoring.

4 Sustainability Effects of Import Commodities

In recent decades, the location of agricultural production has shifted due to various factors. Since 2000, agricultural trade has grown faster than food production, driven by reduced trade barriers and economic growth in developing countries (FAO 2020). This has shifted agricultural production globally, with Eastern Europe, Latin America, and the Caribbean increasing exports, while Asia and Africa have become net importers, raising concerns about long-term environmental impacts (Baylis et al. 2021).

Agricultural commodity production consumes substantial resources and generates significant pollution. According to the (OECD/FAO 2023) agriculture has a significant global impact by utilizing 40% of the world's land and consuming 70% of its freshwater resources and it is one of the primary drivers of deforestation and biodiversity loss and GHG emissions (Busch and Ferretti-Gallon 2017). Agriculture is the leading cause of global deforestation, responsible for about 80% of forest loss, with commercial agriculture driving deforestation in Latin America and subsistence farming playing a major role in Africa and (sub)tropical Asia. Timber extraction and logging account for over 70% of forest degradation in Latin America and Asia, while in Africa, fuelwood collection, charcoal production, and livestock grazing are the main causes of forest degradation (Kissinger 2012). Agricultural trade expansion can have detrimental social impacts as well. One significant issue is the displacement of local communities, which often leads to loss of livelihoods and cultural disintegration. For instance, in Southeast Asia, smallholder farmers have experienced negative socioeconomic outcomes due to agricultural land use changes, affecting their income, food security, and overall well-being (Appelt et al. 2022). Moreover, agricultural expansion frequently leads to conflicts over land ownership and usage rights. In regions like South America and Southeast Asia, the development of large-scale agricultural projects has often resulted in disputes between local populations and external stakeholders, exacerbating social tensions and inequities (Sales 2023).

Germany imports more biomass and biomass-based products than it produces. Approximately half of Germany's biomass is sourced domestically, with the other half originating from international imports. Notably, the largest share of these imports comes from Asia and the Pacific (accounting for 20%), followed by the rest of the EU, Central, and South America (Symobio 2023), meaning that a major share of the environmental effects associated with intensive land use occur in the producing countries (Buller et al. 2023) This not only raises environmental concerns but also underscores social and economic challenges in those exporting nations. Given this distribution, assessing sustainability effects of imported biomass at its country of origin is of critical importance for a holistic bioeconomy monitoring. This section presents the methodological framework for assessing sustainability effects of imported commodities.

The primary goal of this chapter is to introduce a method for evaluating sustainability effects of imported commodities as part of a bioeconomy monitoring framework. To demonstrate its applicability, the focus will be on tracing the origin of three key commodities, beef, soy, and pulp to identify the main exporters to Germany and the volume of exports, and quantify Germany's contribution to sustainability effects of these commodities in their countries of origin. While beef and soy are dealt with in the following sections, the results of the analysis for pulp are already published in Pozo et al. (2024). Each case study will conclude with a set of relevant indicators and a quantification of selected sustainability effects.

4.1 Methodological Concept and Indicator Selection

4.1.1 Concept

A comprehensive assessment of sustainability involves analysing its three core pillars: environmental, economic, and social aspects. The accuracy of such assessments is significantly influenced by the availability and quality of disaggregated data, which impacts both the depth and reliability of the analysis and the appropriateness of the selected indicators.

Various tools have been developed for the assessment of sustainability effects, including Life Cycle Assessment (LCA), which focuses on environmental impacts, and its counterparts for economic (LCC) and social (S-LCA) aspects. The primary assessment approaches—Life Cycle Assessment (LCA) , Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA)—are all based on the ISO 14040 framework (ISO 2006; Klüppel 2005). (Kloepffer 2008) introduced the Life Cycle Sustainability Assessment (LCSA) methodology, providing a systematic approach for achieving balanced and comprehensive sustainability evaluations of products or commodities. While the Life Cycle Sustainability Assessment (LCSA) compared to LCA, LCC and S-LCA offers comprehensive analytical capabilities for evaluating various sustainability aspects, it also faces significant criticisms. Firstly, to perform a comprehensive LCSA, it is crucial to select appropriate indicators. While, one of the main challenges of LCSA is the lack of a defined set of suitable indicators. (Guinée 2015) argued that several major topics still need further attention within the LCSA context. These include developing quantitative and qualitative indicators for S-LCA and creating more standardized methods to account for uncertainties and rebound effects. The other major criticism of the LCSA methodology is its lack of an integrating process, thus it revolves around the need to generate and balance separate findings, along with addressing relevant trade-offs between different sustainability dimensions and how integrate them (GIBSON 2006). To address the complexity of Sustainability assessment and making sustainable decisions an integrative approach is required.

Effective monitoring of sustainability effects of supply chains necessitates a holistic and integrated approach. Addressing only isolated segments of the value chain is insufficient. The monitoring should be specifically tailored to the commodities and production locations in question and should incorporate the perspectives of all relevant stakeholders, including producers, governments, companies, and consumers. In fact, involving diverse stakeholders is crucial for ensuring comprehensive and context-sensitive evaluations. Each group brings unique perspectives and expertise, with distinct interests in the sector's environmental, social, and economic impacts. Stakeholder participation enhances the legitimacy and acceptance of outcomes, improves interdisciplinary collaboration, and helps identify relevant indicators and context-specific solutions. It also facilitates conflict resolution by considering diverse interests (Reed 2009; Luyet 2012). Generally, a comprehensive sustainability assessment implementation involves participants from a wide range of public, corporate, and civil society organizations and institutions, as well as individuals with diverse capacities and inclinations (GIBSON 2006). (Meier 2014b) also offered Logical framework of sustainability analysis (LOFASA) which involves stakeholders in sustainability assessment process. (Schweinle et al. 2020) and (Pozo et al. 2023) utilized this participatory approach for sustainability assessment in two different contexts: softwood lumber and its core product, the EPAL 1 pallet, in Germany, and agricultural commodities in Uruguay, respectively (cf. Figure 25).

To conduct a comprehensive assessment of sustainability effects of imported commodities in their countries of production, we also apply the integrated approach combining Material Flow Analysis (MFA), Life Cycle Sustainability Assessment (LCSA), and the Logical Framework for Sustainability Assessment (LOFASA

As a prerequisite for the assessment, the material flows of the commodities to be analysed need to be identified and quantified conducting a Material Flow Analysis (MFA). Next, the life cycle and system boundaries of the commodities to be analysed should be defined, followed by identification of relevant stakeholders for the selection of sustainability effects to be quantified.

For each commodity and country, a stakeholder engagement approach should be implemented to identify relevant sustainability aspects and select appropriate indicators to quantify them as described by (Meier 2014a; Schweinle et al. 2020). The Logical Framework for Sustainability Assessment (LOFASA) LOFASA employs a participatory method that uses qualitative content analysis to determine relevant sustainability aspects. This involves examining societal discourse across public forums, stakeholder groups, media, and political discussions. A valuation analysis then filters out irrelevant aspects, producing a refined list that guides stakeholders and specialists in selecting indicators for quantifying the sustainability effects of selected products or commodities (Schweinle et al. 2020). This comprehensive approach ensures that the key indicators for each sustainability aspect of specific agricultural commodities within defined geographical boundaries are accurately identified.

However, given the time constraints of this study, it was not possible to involve stakeholders in the producing countries in the identification of relevant sustainability effects and the selection of indicators. Instead, findings from existing studies, frameworks and laws or standards were used to identify relevant sustainability effects and indicators.

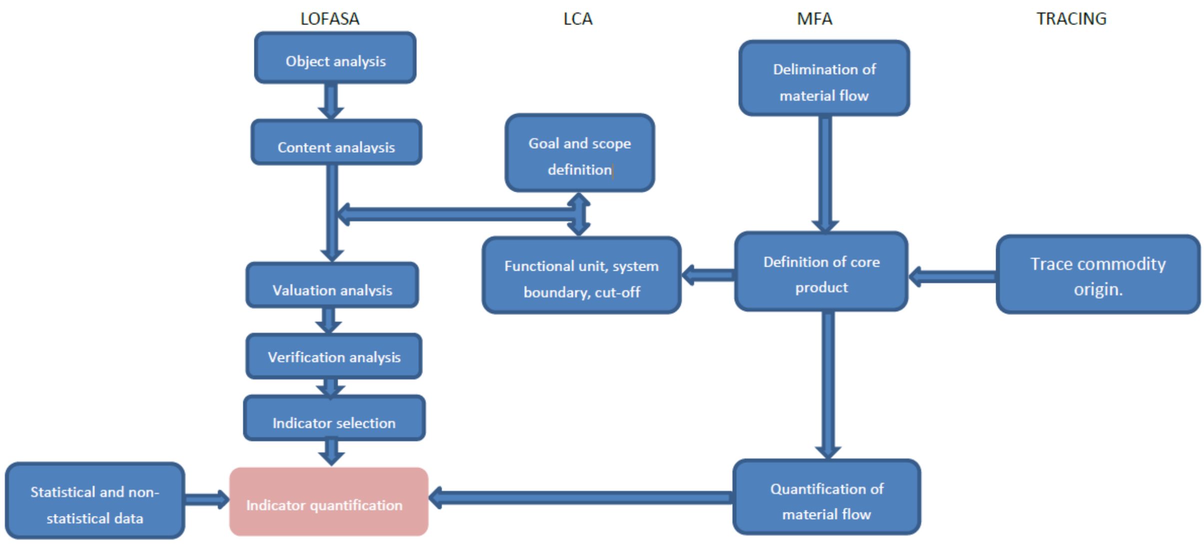
Below is a brief summary of the steps taken:

- The analysis began with an examination of bilateral trade data to determine the main exporting countries of important commodities—soybean, beef, palm oil, and pulp—to Germany. The study included an analysis of changes in trade volume of these commodities between Germany and the major exporting countries over the years.
- Following this, an analysis was conducted on the material flow of the commodities within their countries of origin. The focus was on identifying the predominant trade flows for each commodity - for example, whether soy is mainly traded in the form of grains, meal or oil. In addition, trade data between Germany and the main exporters was analysed to determine which specific forms of these commodities were predominantly exported to Germany. The material flow analysis serves two main purposes: firstly, to identify the main flows of the raw material or its derived products and secondly, to define the scope, functional unit, system boundaries for the assessment of sustainability effects.
- Due to the mentioned time constraints, it was not possible to conduct the LOFASA in the producing countries. Instead, the selected indicators were primarily taken from existing studies, directives, and standards specific to the commodities studied. If specific studies were unavailable, we relied on indicators introduced by the Reporting Advisory Group (EFRAG) for socio-economic and environmental indicators. For economic indicators, we also refer to the table introduced by (Arulnathan et al. 2023), while always considering data availability for each case.

The following step involves conducting a sustainability assessment across all three pillars.

- Environmental sustainability assessment: In assessing environmental sustainability, the main impact categories and environmental effects used in LCA were applied. Simultaneously, we cross-referenced our findings with official data wherever disaggregated data was available. This dual methodology enabled us to achieve a comprehensive understanding and facilitate comparisons of environmental impacts resulting from the two approaches. For the LCA approach, the focus will place on the production phase of the main products of each commodity, considering those with the highest export quantities to Germany. Transportation factors from the country of origin to Germany were also incorporated. Additionally, from various literature and legislative sources, the most critical environmental indicators associated with each commodity will be identified. Changes in these identified indicators over the years will then be examined using official and real data sources. This combined approach aims to better understand the environmental impacts associated with the production and transportation of agricultural commodities, as well as to track changes in key environmental indicators over time. Lastly, based on changes in the quantity of imports to Germany, the contribution of Germany to these environmental impacts will be quantified over the years, and changes will be tracked.
- Economic sustainability assessment: For the analysis of economic sustainability effects, a life cycle costing (LCC) approach was utilized to assess the production of commodities while maintaining a life cycle perspective. Whenever feasible and data was available, relevant microeconomic indicators were also quantified. Examining these different aspects and economic indicators will provide a more comprehensive and detailed understanding of the economic sustainability of agricultural commodity production in their respective countries.
- Social sustainability assessment: For the social sustainability assessment, a life cycle thinking approach was applied, utilizing legislative frameworks, previous studies, and available data for each agricultural commodity. At least two indicators were identified for each commodity, followed by an analysis of the different stages of the life cycle, if data was available, with changes tracked over time.

Figure 25: Schematic representation of the material flow-based sustainability assessment workflow



Source: own illustration based on (Schweinle et al. 2020)

4.1.2 Indicator Selection

Indicators to assess the progress and sustainability effects of the bioeconomy have been identified by multiple authors. Liobikiene et al. (2019) summarized the most common indicators in social, economic and environmental dimension as shown in Table 7. For economic development, shared GDP, employment levels, and trade volumes are often suggested as measures. To assess environmental effects, changes in land use, land use intensity, soil quality, biodiversity, water consumption, pollution levels, and greenhouse gas emissions are recommended. On the social front, the importance of monitoring food security, job creation, and household income is highlighted (O'Brien 2014)

Table 7: Collection of indicators used for assessments of bioeconomy

Dimension	Indicators	References
Social dimension	○ Share of employees in the bioeconomy sector ○ Labour productivity ○ Public acceptance	Efken et al. (2016); Schütte (2018); Arujanan and Singaram (2018); Scarlat et al. (2015); Bracco, Calicioglu, Juan, and Flammini (2018); Munizued et al. (2016); Lynch et al. (2017); Mustalahti (2018); Sleenhoff et al. (2015); Golembiewski et al. (2015
Economic dimension	○ Value added and revenue ○ Factor productivity R&D subsidies and investments ○ Patents of biotechnology	Heijman (2016); Vandermeulen et al. (2011); Schütte (2018); Efken et al. (2016); Arujanan and Singaram (2018); Bracco et al. (2018); Scarlat et al. (2015); Philip (2018); Arujanan and Singaram (2018); Lainez et al. (2018); M'Bareck et al. (2014); Scarlat et al. (2015); Woźniak and Twardowski (2018)
Environmental dimension	○ The contribution of bioeconomy to the reduction of environmental impact Consumption and potential of biomass ○ Land footprint	Cristóbal et al. (2016); Budzinski et al. (2017); Woźniak and Twardowski (2018); Scarlat et al. (2015); Kalt et al. (2016); Bentsen & Felby, 2012; Searle & Malins, 2015; Stecher, Brosowski, & Thrän, 2013; Batidzirai, Smeets, & Faaij, 2012; Steinberger et al., 2008; Schueler, Fuss, Stecch, Weidne, & Beringer, 2016; Bliber-Freudenberger et al., 2018; Hubacek & Feng, 2016; Schaffartzik et al., 2015; Brückner, Fischer, Trambrend, & Giljum, 2015; O'Brien, Schütz, & Bringezu, 2015; Kastner et al., 2014; Witing & Viringer, 2009; Arto, Genty, Rueda-Cantuche, Villanueva, & Andreoni, 2012; Yu, Feng, & Hubacek, 2013; Weinzettel, Steen-Olsen, Hertwich, Borucke, & Galli, 2014; Tukker et al., 2014

Source: own compilation

A viable approach for defining a set of indicators is to align them with political decision-making processes, as suggested by (Wulf et al. 2018). According to the LOFASA framework (Meier 2014b) the selection of indicators should be based on a screening of relevant sustainability topics including regulatory and legislative frameworks. This involves selecting indicators based on the sustainability criteria set forth by regulations in the country of origin or the importing regions, such as Germany or the European Union (EU). These legislative frameworks stipulate the standards agricultural commodities must meet to be eligible for entry into European or German markets. By following this approach, the selected indicators ensure compliance with the required sustainability standards. Below are examples of recent relevant legislation.

(1) Regulation on Deforestation-Free Products (Regulation (EU) 2023/1115)

This regulation aims to prevent products linked to deforestation and forest degradation from entering the EU market. It is mandatory and requires that commodities such as cattle, wood, cocoa, soy, palm oil, coffee, rubber, and their derived products be proven to be deforestation-free. Operators and traders must ensure that these products do not originate from recently deforested land or contribute to forest degradation. The regulation became effective on June 29, 2023, and allows 18 months for implementation (European Parliament and European Council 5/31/2023).

(2) EU Taxonomy Regulation

This regulation provides a classification system to define which economic activities are environmentally sustainable. Companies must disclose the extent to which their activities align with sustainability criteria such as climate change mitigation, climate change adaptation, and protection of biodiversity. The EU Taxonomy is integrated into the CSRD, ensuring that reported activities meet specific environmental sustainability standards. (Regulation (EU) 2020/852).

(3) Corporate Sustainability Reporting Directive (CSRD)

The CSRD mandates extensive sustainability reporting requirements for large companies and some SMES operating in the EU. It requires companies to disclose information on their environmental, social, and governance (ESG) impacts. This includes tracking and reporting on sustainability performance, climate risks, and impacts on society and the environment. The directive took effect in 2023, with reporting requirements starting for the fiscal year 2024 (DIRECTIVE (EU) 2022/2464). Companies subject to the CSRD will have to report according to the European Sustainability Reporting Standards (ESRS) framework. The ESRS, developed by the European Financial Reporting Advisory Group (EFRAG), provide detailed guidelines and standards to ensure that companies' sustainability disclosures are comprehensive, comparable, and aligned with EU sustainability goals (EFRAG 2022).Based on the standards and guidelines developed by EFRAG (EFRAG 2022), some of the impact categories that are already a matter of concern regarding the sustainability of exported agricultural commodities to the EU can be extracted. This guideline includes social, environmental, and governance aspects. However, for the purpose of this study, we will mainly focus on the social and environmental parts. These aspects are listed in Table 8.

Table 8: Indicators for Social and Environmental Sustainability Assessment of Agricultural Commodity Exports to the EU

Sustainability dimension	Impact category	Source	Potential indicator	Source
Environment	Deforestation and Land Use	(Regulation (EU) 2023/1115).	Percentage of raw materials sourced from land deforested within the past five years.	(own calculations based on (Bundesanstalt für Landwirtschaft und Ernährung 2023b; DESTATIS 2024a)
	Climate change/Greenhouse Gas Emissions	ESRS by EFRAG	Total greenhouse gas emissions (CO_2eq) per unit of product	Author
	Pollution /Pollution to air, water and soil	ESRS by EFRAG		
	Protection of water and marine resources	ESRS by EFRAG	• Total water consumption in m^3 • Total water consumption in m^3 in areas at material water risk, including areas of high water stress; • Total water stored and changes in storage in m^3 • Total water recycled and reused in m^3 • Total water consumption in m^3 per net revenue	ESRS by EFRAG
	Resource use and circular economy	(own calculations based on (Bundesanstalt für		

		Landwirtschaft und Ernährung 2023b; DESTATIS 2024a)		
	Biodiversity and Ecosystems	ESRS by EFRAG	• The number and area (in hectares) of sites owned, leased or managed in or near these protected areas or key biodiversity areas. • Their land-use via a Life Cycle Assessment, based on a Life Cycle Assessment. • How it manages pathways of introduction and spread of invasive alien species and the risks posed by invasive alien species	ESRS by EFRAG
	Resource Efficiency			
Social	**Equal treatment and opportunities for all** • gender equality and equal pay for work of equal value • training and skills development • employment and inclusion of people with disabilities • measures against violence and harassment in the workplace • diversity	ESRS by EFRAG	• Inequality • Non-Discrimination/Diversity, incl.* Gender * Race * Age * Disability * Migrants • Precarious work • Gender equality and equal pay for work of equal value, • Training and skills development • Employment and inclusion of persons with disabilities • Measures against violence and harassment in the workplace • Diversity	ESRS by EFRAG
	Working conditions • secure employment • working time • adequate wages • social dialogue • freedom of association • existence of work councils • collective bargaining including the rate of workers covered by collective agreements • the information, consultation and participation rights of workers • work-life balance • health and safety	ESRS by EFRAG	• Remuneration • Social security •Working hours • Work-life balance •Health & Safety • Water & Sanitation • Training & Development • Secure employment • Social dialogue • Freedom of association and collective bargaining	ESRS by EFRAG
	Respect for the human rights, fundamental	ESRS by EFRAG	• Freedom of Association & Collective Bargaining	

	freedoms, democratic principles and standards: •the International Bill of Human Rights and other core UN human rights conventions, including the UN Convention on Persons with Disabilities • the UN Declaration on the Rights of Indigenous Peoples • the International Labour Organisation's Declaration on Fundamental Principles and Rights at Work • the ILO fundamental conventions • the European Convention of Human Rights • the revised European Social Charter • the Charter of Fundamental Rights of the European Union		• Social Dialogue • Child labour • Forced labour • Privacy • Adequate housing • Forced labour • Adequate housing • Water and sanitation and Privacy • Free, prior and informed consent • Self-determination • Cultural rights • Adequate food • Water &sanitation • Land-related impacts • Security • Freedom of Expression • Freedom of Assembly • Human rights Defenders	

Source: own compilation

A holistic assessment of economic effects should cover a variety of categories. Based on a literature review in Arulnathan et al. (2023) identified and categorized six economic impact categories proposed in the literature: profitability, stability, autonomy, customers, and innovation, each with specific indicators

Table 9: List of identified indicators for the assessment of economic effects

Indicator/Criteria	Data (L1)	Functional Unit (L2)	Application (L3)	Specificity (L4)	Impact Category (L5)
Cost efficiency	+	Yes	Yes	No	Profitability
Indicators of profit	=	Yes	Yes	No	Profitability
Net Present Value (NPV)	=	Yes	Yes	No	Profitability
Internal Rate of Return (IRR)	=	No	No	No	Profitability
Payback Period (PP)	=	No	No	No	Profitability
Return on Investment (ROI)	=	Yes	Yes	No	Profitability
Return on assets, costs and sales	=	No	Yes	No	Profitability
Gross operating surplus	+	Yes	Yes	No	Profitability
Risk aspects	–	No	Yes	Yes	Stability
Contribution to GDP/GNP	=	No	No	No	Stability
Diversification	=	No	Yes	No	Stability
Employee satisfaction	=	No	No	No	Stability
Reliance on imports and contribution to exports	=	No	No	Yes	Autonomy
Subsidies	=	Yes	Yes	No	Autonomy
External finance	=	Yes	Yes	No	Autonomy
Invested Capital Generated in the Activity (ICGA)	=	Yes	Yes	No	Autonomy
Capital productivity	=	No	Yes	No	Productivity
Labor productivity	+	No	Yes	Yes	Productivity
Market share	+	No	No	No	Customers
Customer satisfaction	=	No	No	No	Customers
Innovation	=	No	Yes	Yes	Innovation

Source: (Arulnathan et al. 2023)

As already explained, these categories and their specific indicators, along with other sources of information, can serve as a starting point for a participatory approach to select the most relevant indicators for each specific commodity.

4.1.3 General Data Availability

This study employed the BACI database (Gaulier and Zignago 2010) to analyse bilateral trade data, aiming to identify the primary products associated with each commodity, their respective proportions exported to Germany, and to trace the main exporting countries. BACI (Gaulier and Zignago 2010) enhances the accuracy of information on trade flows by reconciling discrepancies in data reported to the United Nations Comtrade dataset, adjusting differences in CIF (cost, insurance, and freight) and FOB (free on board) values, and assessing the reliability of reporting countries, as there may be overlaps in the Comtrade dataset due to different reporting standards and occasional discrepancies.

To obtain data on the material flow of agricultural commodities for the year 2021, data and reports from the USDA (Degreenia 2023; Joseph 2023) were used to quantify production volumes at different stages of the value chain, including volumes for domestic use and export.

Disaggregated data for different life cycle stages of import commodities, particularly at the primary production level, are difficult to obtain, especially for social and economic assessments. While the Life Cycle Assessment (LCA) databases provide data for the assessment of environmental effects, it is difficult to obtain detailed official statistical data for social and economic effects on a value chain level. Hence, a full capture of sustainability effects of all stages of a value chain is challenging. For the case studies, data were collected from a variety of sources, including relevant literature, national and international databases, case studies, agricultural reports, and local government publications, all of which will be discussed in detail in the corresponding sections.

4.2 Beef

Beef is a crucial agricultural commodity, accounting for approximately 19% to global livestock production value and generating over US$ 245 billion worldwide in 2020 (FAO 2021). Although the global demand for beef as a protein source is increasing, it represents less than half of total meat consumption in most countries. In developed nations, and increasingly in developing regions, beef is prized for its superior culinary quality (Smith et al. 2018).

Cattle farming offers specific benefits, including contributing to food security by providing people with protein, energy, and essential micronutrients, as well as fostering economic growth in producing countries. Furthermore, rumination allows cattle and other ruminants to digest fibrous feed that is indigestible to humans, which has a positive impact on the food balances, particularly in marginal areas with limited agricultural alternatives. Cattle also convert crop residues into edible products and improve soil fertility by providing nutrients and organic matter (Gerber et al. 2015). However, the production and consumption of beef pose significant environmental challenges. Cattle farming is a major contributor to greenhouse gas (GHG) emissions, primarily methane (CH4) from enteric fermentation. Rising global methane levels have significantly contributed to anthropogenic climate change in recent years (Chen et al. 2022). Combined with land-use changes, these factors account for approximately 40% of all livestock-related emissions (Smith et al. 2018). According to the Global Livestock Environmental Assessment Model (GLEAM 2015), livestock production is responsible for a total of 6.2 gigatonnes of global emissions, representing 12% of total global emissions. Of this 6.2 gigatonnest, 3.6 gigatonnest of CO_2-equivalent (CO_2-eq) emissions are directly attributable to the farming of cattle.

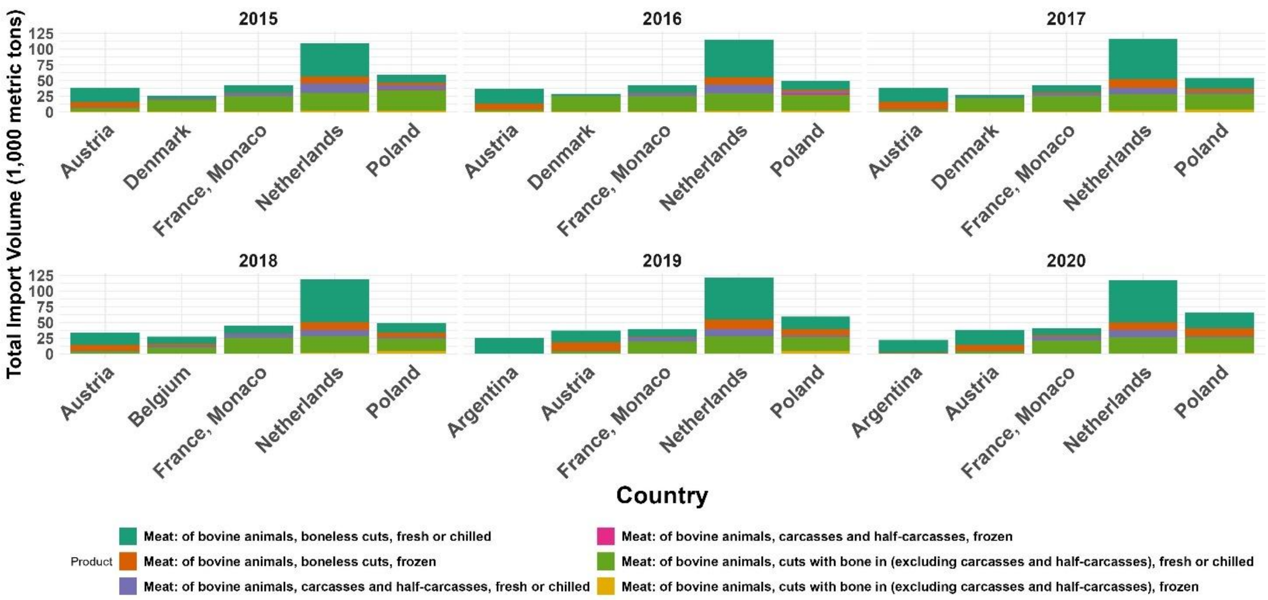
The sustainability of beef production is perceived differently in different geographical and socio-economic contexts. Key determinants influencing these perceptions include the availability of natural resources such as land and water, accessibility of animal feed and economic stability (Smith et al. 2018).

4.2.1 Germany’s Beef Imports

Based on Comtrade data modified by BACI (Gaulier and Zignago 2010), the most important countries exporting beef to Germany between 2012 and 2020 are the Netherlands, France, Poland, Denmark, Austria, and Argentina

(Figure 26). The main exported products are "Meat: of bovine animals, boneless cuts, fresh or chilled" and "Meat: of bovine animals, cuts with bone in (excluding carcasses and half-carcasses), fresh or chilled.

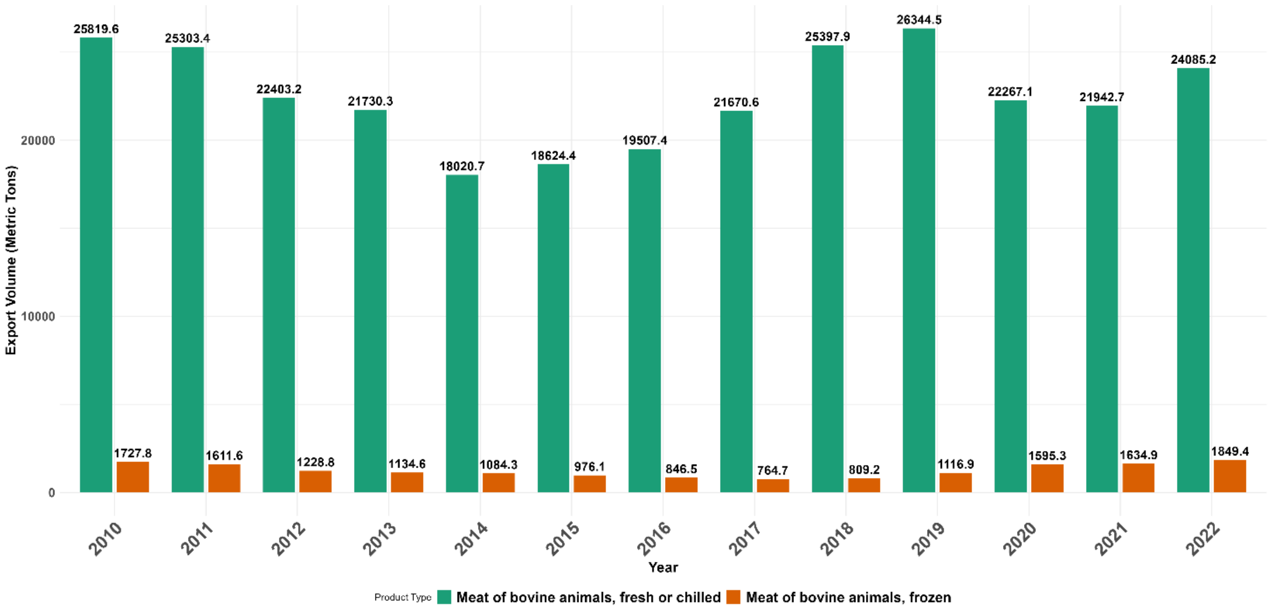
Figure 26: Top 5 Exporters of Beef to Germany by Year



Source: based on Comtrade data modified by BACI (Gaulier and Zignago 2010)

Germany's imports of frozen beef are relatively minor compared to the significant volumes of fresh or chilled bovine meat imported. As illustrated in Figure 27, the export volumes of both frozen and chilled beef from Argentina to Germany between 2016 and 2022 are presented, based on data from BACI (Gaulier and Zignago 2010).

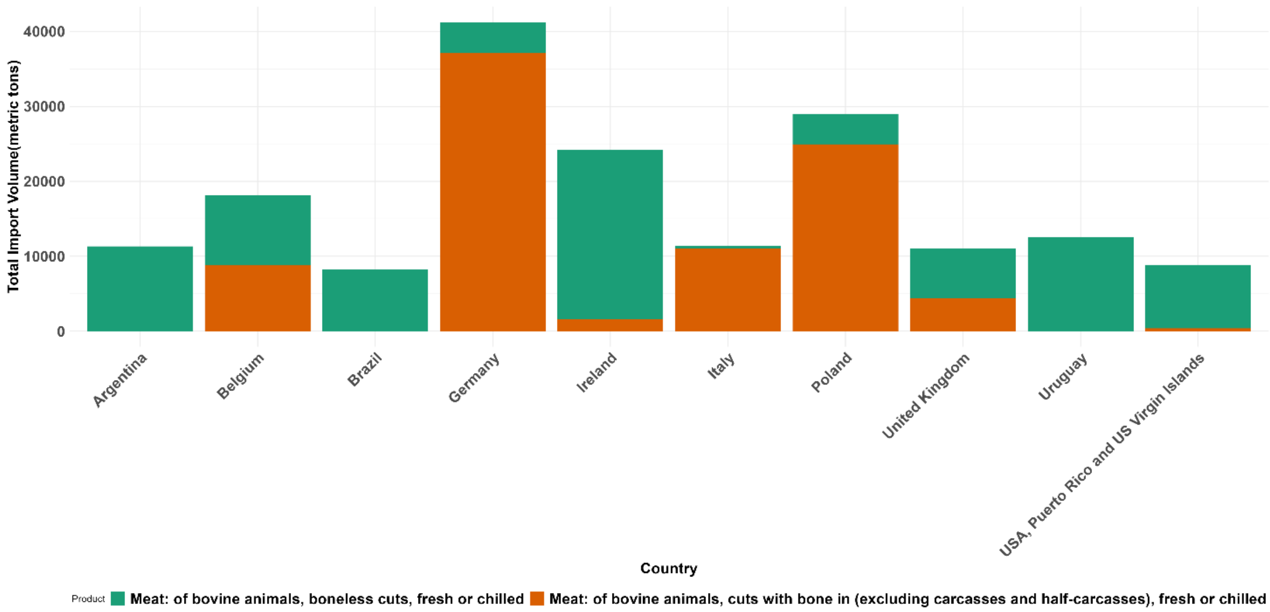
Figure 27: Export Volume (in Metric Tons) to Germany from Argentina



Source: based on Comtrade data modified by BACI (Gaulier and Zignago 2010)

Since many commodities enter the EU in Rotterdam and from there are transported to the final destination, it is important to also trace imports to and exports from the Netherlands. In 2022, the Netherlands imported beef worth $2.18 billion, with the main suppliers being Germany, Ireland, Belgium, the United States, and Argentina. A substantial portion of this imported beef is processed and re-exported to countries such as Germany, France, Italy, Spain, and Denmark. That same year, the Netherlands exported beef worth $2.86 billion of, with Germany as the largest importer.

Figure 28: Top 5 Exporters of Beef to the Netherlands in 2020



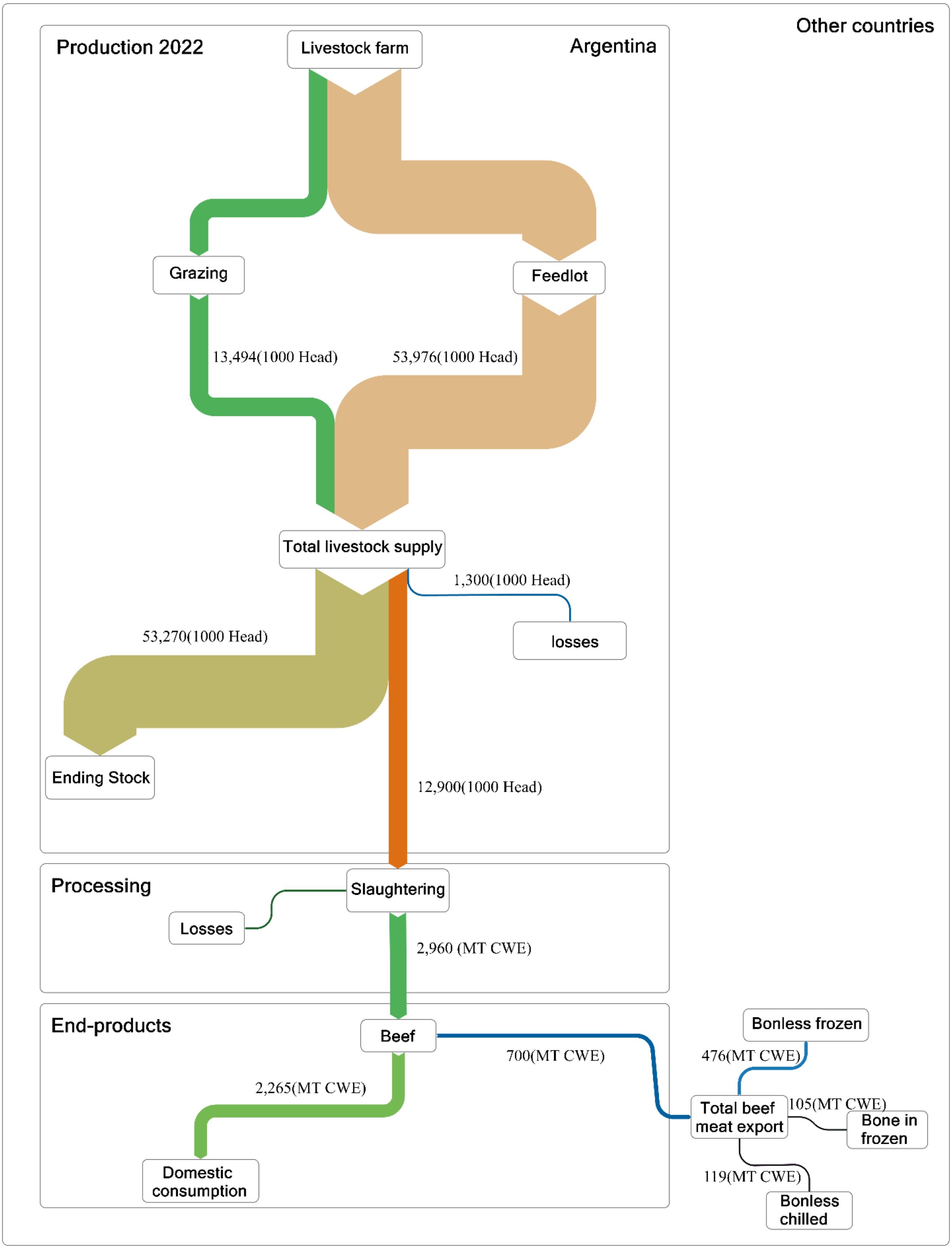
Source: based on comtrade data (Gaulier and Zignago 2010)

To gain a deeper understanding of the primary exporters of beef to the Netherlands, it is evident that Argentina, Brazil and Uruguay are the leading suppliers outside of Europe. Among them, Argentina plays a particularly important role, both in direct exports to Germany and in contributing to re-exports from the Netherlands, making it a key player in Germany's meat import market, as shown in Figure 28.

4.2.2 Material Flow Analysis

Conducting a material flow analysis of beef is essential to identify the predominant flow and establish the system boundaries, cut off criteria and functional unit required to assess sustainability effects. The material flow for 2022 as created on the basis of Joseph (2022). According to Figure 29, the total supply of cattle in 2022 was 67.47 million head, with 80% coming from feed lots and the remaining 20% from grazing systems (Leather Working Group 2023). The ending inventory for 2022 was recorded at 53.27 million head, with a total slaughter of 12.90 million head, from which 2.96 million tonnes of carcass weight equivalent (CWE) was produced. Of this, 2.265 million tonnes of (CWE) were consumed domestically and 0.70 million tonnes of (CWE) were exported.

Figure 29: Material flow of beef production in Argentina in 2022



Source: own illustration based on Joseph (2022)

Based on the material flow and bilateral trade data, which show that the main export product to Germany is "Meat: of bovine animals, cuts with bone in (excluding carcasses and half-carcasses), fresh or chilled", the functional unit for is defined as 1 ton of carcass weight equivalent.

Deblitz and Ostrowksi (2004) indicate that the conversion rate from live weight to carcass weight is between 56% and 59%. The reported live weight per head at slaughter in Argentina ranges from 460 to 480 kg (FAO and New Zealand Agricultural Greenhouse Gas Research Centre. 2017). Take 460 kg or 0.46 metric tons as the live weight of cattle in the slaughterhouse. Depending on the conversion rate applied, the resulting carcass weight would range from approximately 0.2576 to 0.2714 metric tons. To maintain consistency and adopt a conservative estimate, we use the lower conversion rate of 56%, which yields a carcass weight equivalent (CWE) of roughly 0.09075 metric tons per head of cattle. Additionally, following the 1:1 conversion rate from bone-in product to carcass weight (Joseph 2020), this 56% rate will be used in subsequent analyses to ensure more precise calculations of CWE in relation to per-cattle metrics.

4.2.3 Beef Production in Argentina

Before finalizing the goal, scope, system boundaries, and functional units, it is necessary to gather more detailed information on soybean production in Brazil. This additional information will provide a clearer understanding of the production dynamics, which is essential for accurately defining the system's parameters for the sustainability assessment.

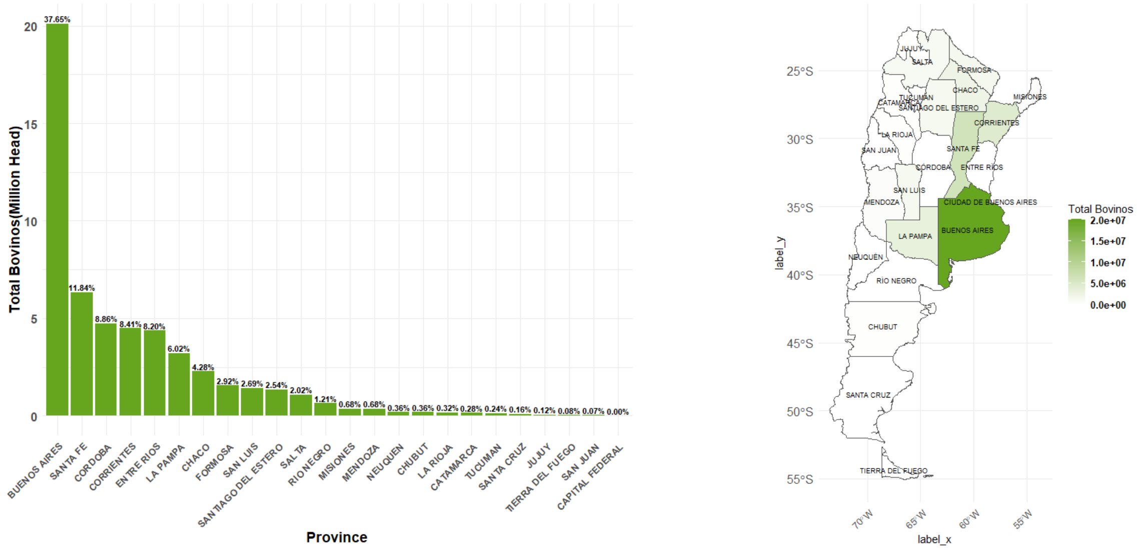
Argentina is a leading producer and consumer of beef. In 2022, the country slaughtered 12.90 million bovines, resulting in the production of 2.96 million tons of meat in carcass weight (CW). During the same period, Argentina exported around 0.70 million tons of beef, valued at 1.9 billion dollars. The primary importers were China (75%), Israel (5%), Germany (4%) , Chile (3%), the USA (3%), and the Netherlands (3%)(Joseph 2023).

Many Argentinian cattle are raised using a multi stepped farming process. Generally, beef production in Argentina can be divided into two main systems (cow-calf and growing and fattening systems) with three main phases: breeding, rearing and fattening on pasture and rearing and fattening mainly on grain (FAO and New Zealand Agricultural Greenhouse Gas Research Centre. 2017). As previously noted, over the last 30 years, Argentina has moved from a largely pasture-based production system to a more intensive system approximately 80% of cattle production now occurs in feedlots, while the remaining 20% involves grazing systems (Leather Working Group 2023).

Cow-calf systems in Argentina begin with the onset of pregnancy in January (summer) and end with the sale of older cows and calves after weaning. Rearing and fattening generally take place on pasture, supplemented with feed such as corn or sorghum silage. Fattening can be either pasture-based or grain-based, though finishing cattle entirely on pasture has become less common in recent years. When pasture-finished, cattle graze on high-quality pastures, often enriched with legumes like alfalfa, lotus, and red/white clovers to enhance nutritional value. According to the FAO, cattle production has increasingly shifted from 100% pasture to a combination of pasture supplemented with cereal grains and conserved forages, with greater reliance on confinement for grain feeding during the fattening period. This transition reflects broader changes in land use, including the displacement of cattle production from traditional pasture areas to new regions, further emphasizing the role of feedlots in the fattening phase (Arrieta et al. 2022) and (FAO and New Zealand Agricultural Greenhouse Gas Research Centre. 2017).

Argentina is a diverse territory and climates result in significant regional variations in beef production. Argentina is segmented into three primary climatic zones: arid/semi-arid, temperate, and subtropical. Within these zones, five key agro-ecological regions are identified: the Argentinean Northwest (NOA), the Argentinean Northeast (NEA), the Semi-arid region, the Pampas, and Patagonia (Deblitz and Ostrowksi 2004; FAO and New Zealand Agricultural Greenhouse Gas Research Centre. 2017).

Figure 30: Distribution of cattle in Argentina by provinces in 2021



Source: based on data from the National Food Safety and Quality Service (SENASA 2023)

Figure 30 illustrates the distribution of the total number of bovines across various provinces in Argentina, based on data from the National Food Safety and Quality Service (SENASA 2023), an independent agency of the Argentine government. Buenos Aires accounts for 37% of the total bovine population, followed by Santa Fe, Córdoba, Corrientes, and Entre Ríos, contributing 12%, 8.86%, 8.41%, and 8.20%, respectively. Therefore, approximately 80% of the beef cattle are established in the Pampas region (Buenos Aires, Santa Fe, Córdoba, Entre Ríos). This region supports lush pastures due to moderate rainfall and temperatures, leading to substantial bovine populations, with Buenos Aires alone accounting for 37% of Argentina's total bovine population.

In contrast, the Argentinean Northeast (NEA), encompassing provinces like Corrientes and Chaco, experiences a harsher and more variable subtropical climate. Despite challenges such as high humidity, heavy rainfall, and hot temperatures, these provinces still maintain significant bovine populations, with Corrientes contributing 8.41% and Chaco 4.28%, according to Joseph (2023). The NEA's weaning ratios, however, are lower, between 50 and 55%, illustrating the impact of less favourable environmental conditions on beef production.

According to (SENASA 2023) data, in 2021, 85% of farms in Argentina housed fewer than 500 animals. Notably, the remaining 15% of farms accounted for 63.15% of the total bovine population, highlighting a significant concentration of livestock within a smaller proportion of larger farms.

4.2.4 Goal, Scope, and System Boundaries of the Assessment of Sustainability Effects

Goal and scope are to assess Germany’s contribution to selected sustainability effects of fresh or chilled Argentinian beef exported from Argentina to Germany.

As already discussed, the different regions in Argentina have different production conditions and face distinct sustainability challenges. However, due to the lack of access to disaggregated data on the specific regions in Argentina from which Germany imports beef, as well as the absence of region-specific sustainability indicators, unfortunately the spatial system boundary is beef production in Argentina as a whole. The temporal system boundary varies between the year 2000 and 2023, depending on the assessed sustainability effect. The functional unit used is 1 metric tonne of carcass weight of beef.

4.2.5 Indicator selection

To effectively define and address the most critical sustainability effects in Argentinean beef production, it is important to base our approach on sound science while ensuring that sustainability indicators are socially accepted by stakeholders throughout the value chain. This approach is crucial for mitigating negative impacts, policy-making and guiding international negotiations.

According to Greenpeace (2019), Argentina is in a state of forest emergency. In 2014, the Intergovernmental Panel on Climate Change (IPCC) warned that 4.3% of global deforestation occurs here, and in the last decade this has been the main source of carbon emissions in northern Argentina. Between 1998 and 2018, Argentina lost 6.5 million hectares of native forests, of which 2.8 million occurred between 2008 and 2018 (Mónaco et al. 2020). 87% of deforestation took place in four regions: Santiago del Estero (28%), Salta (21%), Chaco (14%), and Formosa (13%) (Mendoza-Ponce 2021). The primary driver of deforestation in Argentina is the expansion of industrial-scale agriculture, particularly soy production and cattle farming. While the area under soy cultivation increased by 153% between 1991 and 2013, deforestation for cattle farming also increased significantly, exacerbating the loss of native forests and contributing to further environmental damage (Cáceres and Gras 2020; world bank 2016). Deforestation has therefore become an important indicator for assessing environmental sustainability effects. Consequently, deforestation linked to beef production is recognized as a significant environmental concern by EU regulations (Regulation (EU) 2020/852; REGULATION (EU) 2021/2115; European Parliament and European Council 5/31/2023),.

The EU Directive on Corporate Sustainability Reporting (CSRD) (DIRECTIVE (EU) 2022/2464) requires the assessment of key environmental indicators, with a focus on climate change. In addition to the CSRD, various standards and directives specifically address the environmental impacts of beef production, some of which are still under finalization. Notably, the draft EU-Mercosur Trade Agreement (European Commission 2024) includes relevant provisions concerning this sector. The EU-Mercosur Trade Agreement enforces strict environmental standards for imports, including Argentine beef, focusing on preventing deforestation and reducing GHG emissions in agriculture.

In Argentina, efforts to enhance sustainability within the beef industry have also gained momentum. The establishment of the Roundtable for Sustainable Beef (MACS) in 2017 marked a significant step towards integrating sustainability practices across the entire beef value chain. This initiative, in which more than 50 organizations are involved, is a response to national and international demands for more sustainable production. With a long history of livestock production, Argentina has implemented various regulatory frameworks, including National Law 26.331 for forest management and the National Plan of Forest Management with Integrated Livestock (MBGI) launched in 2015.

MACS emphasizes five key pillars of sustainability. The Natural Resources category addresses issues like deforestation, land conversion, vegetation cover management, GHG emissions, soil conservation, and water use. People & the Community focuses on labour law compliance, health and safety, prevention of child and forced labour, community engagement, and respect for traditional landowners. Animal Health & Welfare emphasizes the responsible use of pharmaceuticals, and efforts to minimize pain, stress, and diseases in livestock. Food covers food safety, beef quality, and transparency along the production chain. Lastly, Efficiency & Innovation involves improving resource efficiency, waste management, and incorporating sustainable technologies and training into production processes.

Table 10: List of selected indicators applied for the assessment of sustainability effects of Beef production in Argentina

Indicators	Data sources	Source of indicator
Environmental		
Deforestation	(Secretaría de Ambiente y Desarrollo Sustentable 2015)	Literature review and Regulation (EU) 2023/1115
GHG emission	(Ministerio de Ambiente y Desarrollo Sostenible 2019) and (SENASA 2023)	Literature review and Regulation (EU) 2023/1115
Synthetic Fertilizer Use	(Arrieta et al. 2020)	Literature review and (DIRECTIVE (EU) 2022/2464)
Land occupation	(Arrieta et al. 2020)	Literature review and (DIRECTIVE (EU) 2022/2464)
Pesticides use	(Arrieta et al. 2020)	Literature review and (DIRECTIVE (EU) 2022/2464)
Fossil energy use	(Arrieta et al. 2020)	Literature review and (DIRECTIVE (EU) 2022/2464)
Biomass consumption	(Arrieta et al. 2020)	Literature review and (DIRECTIVE (EU) 2022/2464)
Economic		
GDP	(world bank 2024), (Regunaga et al. 2006)and (Rossini et al. 2017)	Literature review
Social		
Employment rate/Number of Job position	Ministerio de Desarrollo Productivo. Unidad Gabinete de Asesores. Dirección Nacional de Estudios para la Producción,(AFIP et al. 2023)	Literature review and (DIRECTIVE (EU) 2022/2464)
Average monthly wage	Federal Administration of Public Revenue(AFIP et al. 2023)	Literature review and (DIRECTIVE (EU) 2022/2464)

Source: own compilation

4.2.6 Data Gaps

Argentina has made considerable progress in improving the accessibility of environmental information. The country hosts various online platforms that provide data on greenhouse gas emissions, native forests, biodiversity, protected areas, and climate change risks. However, there are plenty of areas that require further improvement.

As far as deforestation is concerned, there is no data available on deforestation rates per head of livestock, especially not on a regional level. Having this information would allow a more accurate assessment of the effect of cattle farming on deforestation. Similarly, data on recent land-use changes, such as the conversion of forests or other ecosystems into grasslands or cropland for livestock feed, are also lacking.

In terms of economic effects, no data is available on the share of cattle production in agricultural GDP or its contribution to Argentina's total GDP. Furthermore, there is no information on the value added for the entire beef value chain.

There is no gender-disaggregated data on employment, age and education level of workers in beef production that would allow an assessment of social effects, e.g., the extent of child labour.

Finally, there is a lack of data that makes is possible to trace the origin of beef exports, particularly to Germany and other countries.

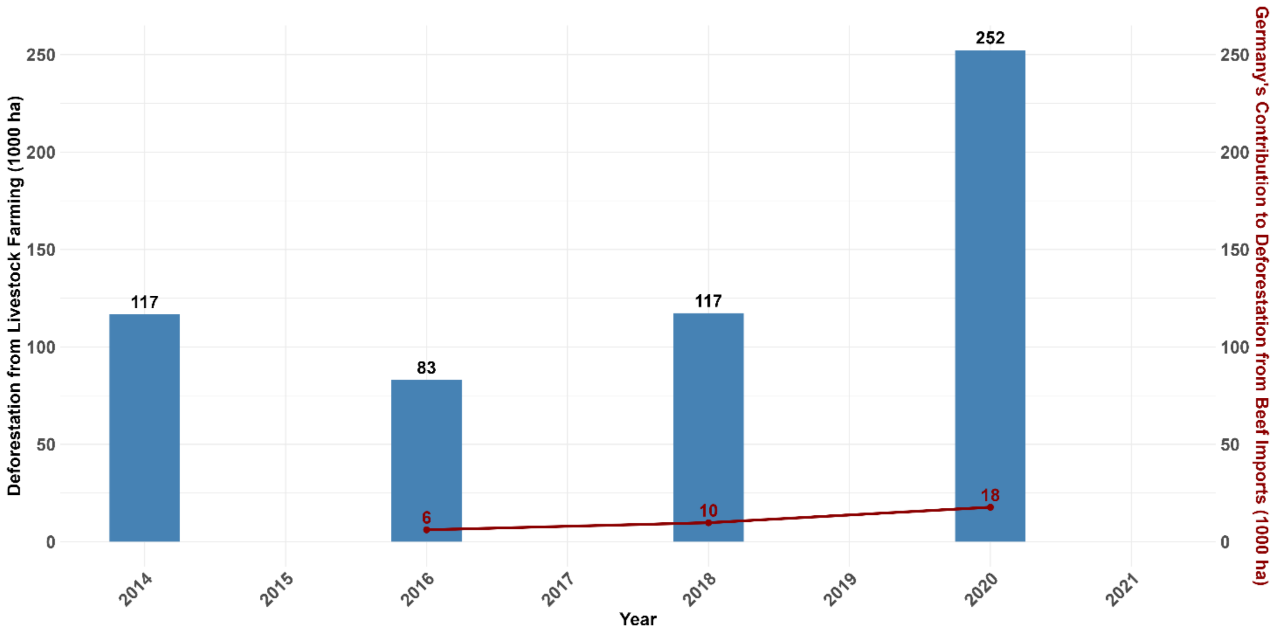
4.2.7 Assessment of Environmental Effects

The following sections, selected environmental sustainability effects of beef production and Germany's contribution through beef imports are presented and quantified. The effects covered are direct deforestation, GHG emissions, biomass consumption, land occupation, fossil energy use, synthetic fertilizer and pesticide use. As mentioned before, it was not possible to engage stakeholders in the selection. Instead, existing studies or officially published data were analysed, and Germany's contribution to the effects was calculated using trade statistics.

4.2.7.1 Direct Deforestation

The data presented in Figure 31, taken from the Secretaría de Ambiente y Desarrollo Sustentable (2015), show that the conversion of forest to livestock farming was significant. Although forest conversion declined slightly between 2014 and 2016, this decline was reversed in 2018. The conversion rate returned to the 2014 level. By 2021, the area of converted forest land more than doubled compared to 2018, with 250,000 hectares of forest being converted to agricultural use in 2020 alone. Germany's contribution to direct deforestation due to beef imports from Argentina amounted to 6,000 ha, 10,000 ha and 18,000 ha in 2016, 2018, and 2020 respectively.

Figure 31: Deforestation from livestock farming in Argentina and Germany's share via beef imports between 2014 and 2021

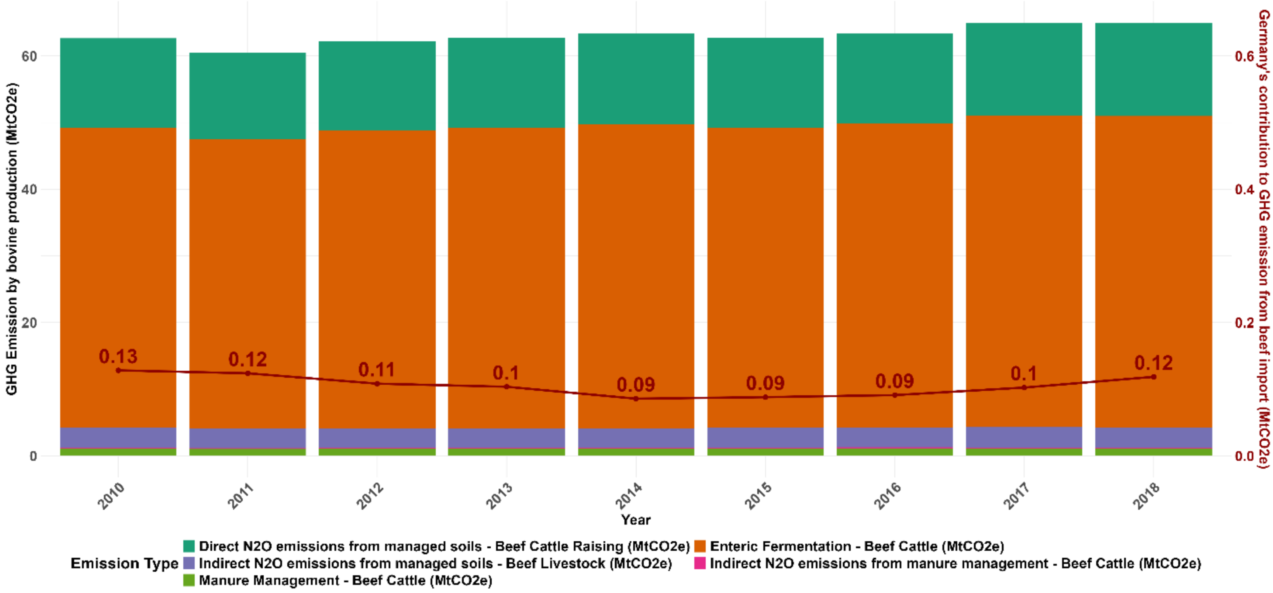


Source: based on data from Secretaría de Ambiente y Desarrollo Sustentable (2015)

4.2.7.2 GHG emission

Based on data from the (Ministerio de Ambiente y Desarrollo Sostenible 2019) and (SENASA 2023), the following Figure 32 shows the greenhouse gas (GHG) emission categories associated with beef production, expressed in million tons of CO_2 equivalent. The results show that enteric fermentation makes the largest contribution to GHG emissions in the various areas of beef production, with emission levels remaining relatively stable from 2010 to 2018. Direct emissions from cultivated soils are the second-largest source, which also remained stable during this period, but showed a decline compared to the longer-term trend from 2002 to 2018. The slaughter phase is deliberately excluded from these calculations, as its contribution to total GHG emissions is negligible and does not significantly influence the results. The red line in the figure illustrates Germany's contribution to total GHG emissions from beef cattle production, calculated based on the volume of imports from Argentina in the respective years. For clarity, the red line has been scaled to ensure visibility, although the actual values are displayed next to each data point. Germany's contribution to the GHG emissions remains fairly constant over time and is between 90,000 and 130,000 tonnes of CO_2 equivalents.

Figure 32: Greenhouse Gas Emissions from Cattle in Argentina and Germany's Contribution between 2010 and 2018 in million tons of CO_2 equivalent



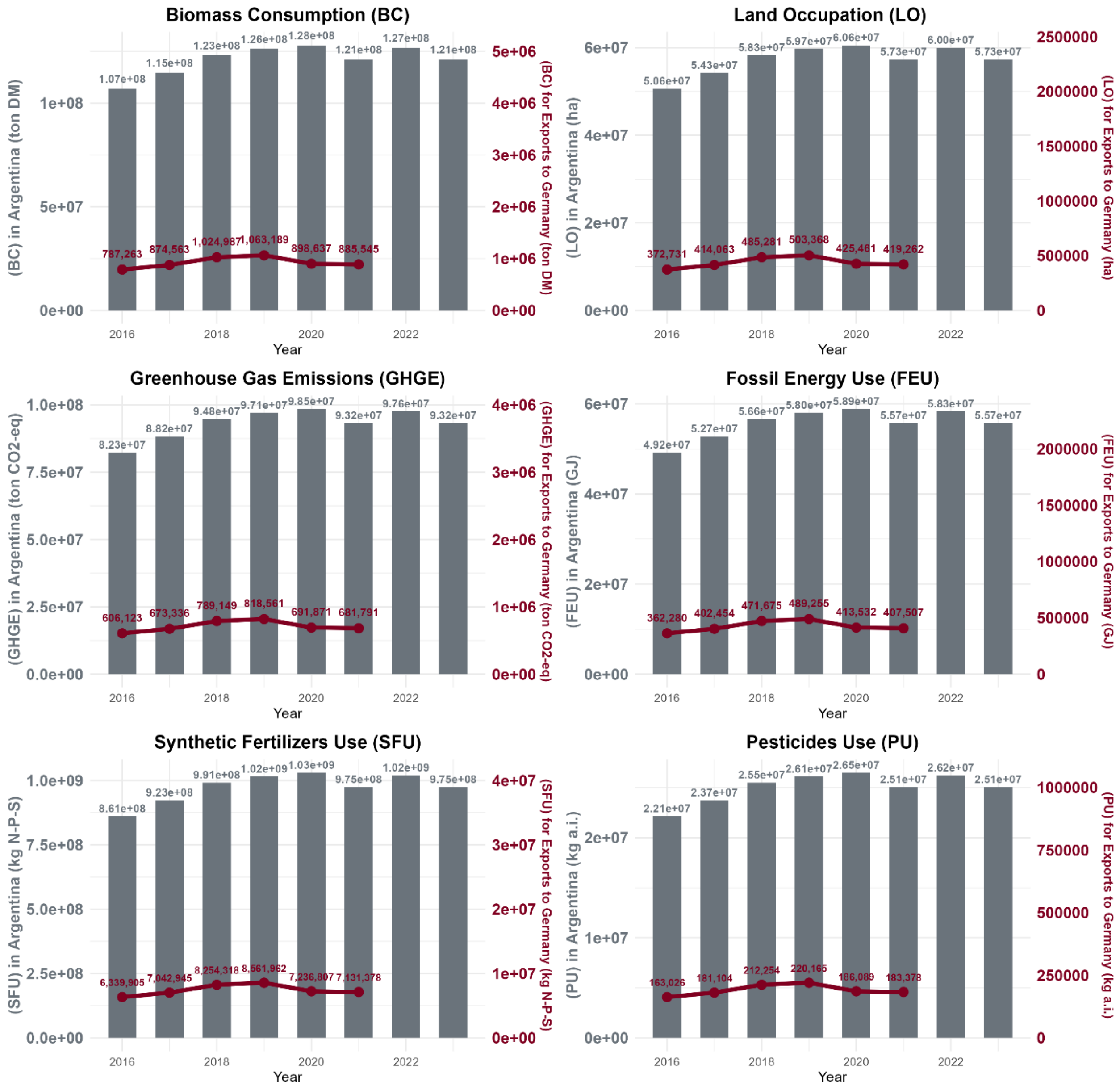
Source: based on data from the (Ministerio de Ambiente y Desarrollo Sostenible 2019) and (SENASA 2023)

4.2.7.3 Biomass Consumption, Land Occupation, Greenhouse Gas Emissions, Fossil Energy Use, Synthetic Fertilizer and Pesticide Use

The quantification of the listed environmental effects is based on the Life Cycle Assessment (LCA) for beef production titled "Biomass consumption and environmental footprints of beef cattle production in Argentina" by Arrieta et al. (2022). The study is a comprehensive assessment of environmental effects of beef production in Argentina, taking into account the country's different regional characteristics and production systems.

To assess the environmental effects beef production was divided into two main systems: cow-calf and finishing. The cow-calf system, responsible for reproduction and calf production, was modelled for 24 distinct sub-systems based on performance levels in the regions. The finishing system in which animals reach their slaughter weight was categorized into five types based on feeding practices: pure grazing, grazing with supplementation, mixed systems based on pastures, mixed systems based on grains, and confinement systems. These types reflect a balance between traditional extensive grazing and more intensive grain-fed methods, adapted to the regional conditions. The study assessed the environmental effects of each system. This study employs a functional unit of one ton of live weight (LW) of beef, which needs to be converted in our functional unit carcass weight equivalent (CWE).

Figure 33: Biomass Consumption, Land Occupation, Greenhouse Gas Emissions, Fossil Energy Use, Synthetic Fertilizer and Pesticide Use from Beef Cattle Production in Argentina and Germany's Contribution (2016-2023)



*For clarity, the red line has been scaled to ensure visibility, although the actual values are displayed next to each data point.

Source: based on Arrieta et al. (2022) and export volume data from Comtrade (Gaulier and Zignago 2010)

Arrieta et al. (2022) calculated the environmental impact of cattle production in Argentina based on the national cattle stock data from 2016, paying particular attention to the distribution of different types of cattle stock across regions, including cows, heifers, steers, light steers, male calves, female calves, and bulls. As the overall numbers for cattle production remained relatively stable between 2016 and 2022, we assume for our calculations that the distribution of cattle stock types across regions corresponds to the 2016 data. This assumption allowed us to use the results of the 2016 assessment of environmental effects per ton of live weight (LW) to estimate the environmental effects of beef production for subsequent years. Additionally, we calculated Germany's contribution by analysing direct imports of beef from Argentina. It is important to note that while our analysis focused on direct imports, some beef may also reach Germany through re-exports from other EU countries, which was not accounted for in this study. The live weight (LW) of cattle was converted to carcass weight equivalent (CWE), following the methodology outlined in the material flow section.

The discrepancy between the official greenhouse gas emissions data from the Argentinian Ministry of Agriculture (Figure 32) and the results of the study by Arrieta et al. (2022) is attributable to several methodological differences. The official data are based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, which provide a standardised approach for characterising livestock and estimating emissions. The IPCC asserts that the characterisation of livestock necessitates the identification of the relevant animal species and emission source categories, such as enteric fermentation and manure management, for each species. Countries are recommended to employ the most detailed methods for estimating emissions depending on the emission source, e.g., tier 2 or 3 methods. However, official data rely on tier 1 estimation methods, which are less detailed and focus on national averages. In contrast, the present study employs a cradle-to-farm life cycle analysis that incorporates more specific regional data, encompasses 75 cow-calf and finishing systems, and excludes post-farm activities such as slaughter and transport. This methodology captures regional variations and processes in greater detail, which likely accounts for the higher reported environmental impacts compared to the more generalised IPCC approach. Additionally, Arrieta et al. (2022) in their study include a more comprehensive assessment, covering emissions from feed production (including synthetic fertilizers and land-use changes), energy use in farm operations, and indirect emissions related to biomass consumption. This broader scope provides a more nuanced understanding of the environmental footprint of beef production in Argentina.

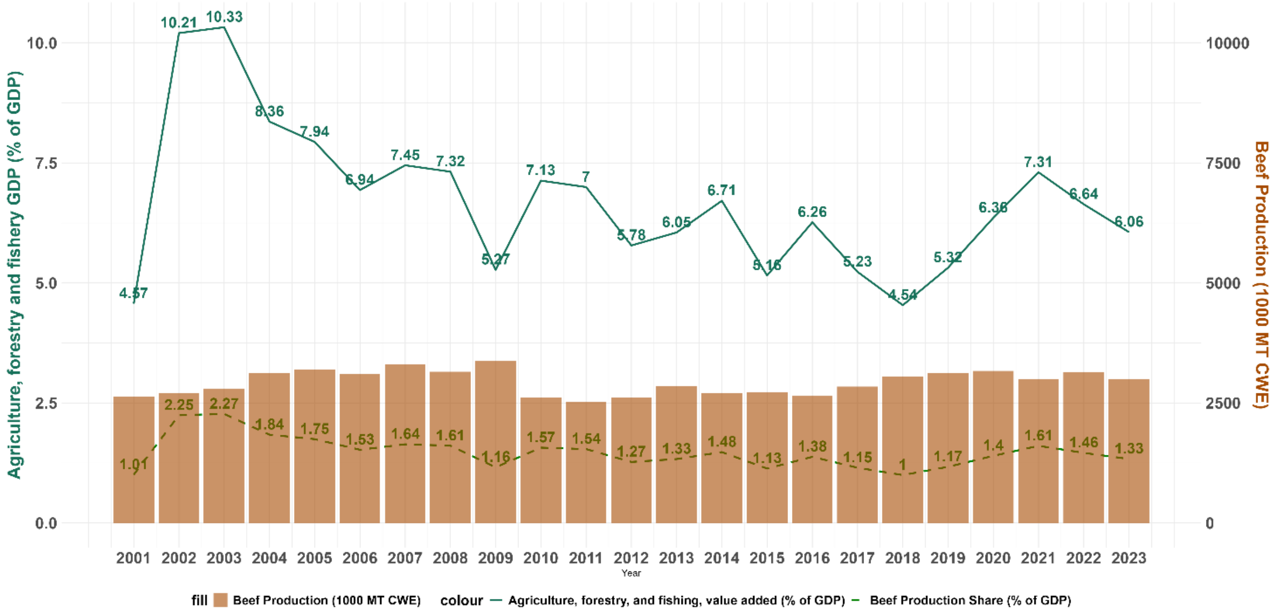
4.2.8 Assessment of Economic Effects

4.2.8.1 Share of Beef Production in Total GDP

Due to the lack of disaggregated data for Argentinian livestock farming, historical data on Agriculture, Forestry, and Fishing, Value Added (% of GDP) were extracted from the World Bank's World Development Indicators to observe the trend in the combined contribution of agriculture, forestry, and fisheries to Argentina's overall GDP over the years. Total GDP is measured at purchaser prices. For more information regarding the methodology, please refer to world bank (2024)

It has been stated by Regunaga et al. (2006) and Rossini et al. (2017) that the livestock sector has historically contributed approximately 20% to Argentina's agricultural GDP, with beef being a significant component of this. While Regunaga et al. (2006) provide an estimate for the entire livestock sector, Rossini et al. (2017) found that the beef sector alone accounts for around 22% of Argentina’s agricultural GDP. In the absence of more specific data for the beef production, the figure of 22% from Rossini et al. (2017) was selected as it more up-to-date and reflects the direct contribution of beef production. This choice ensures a more focused estimate for the share of beef production to agricultural value added (% of GDP).

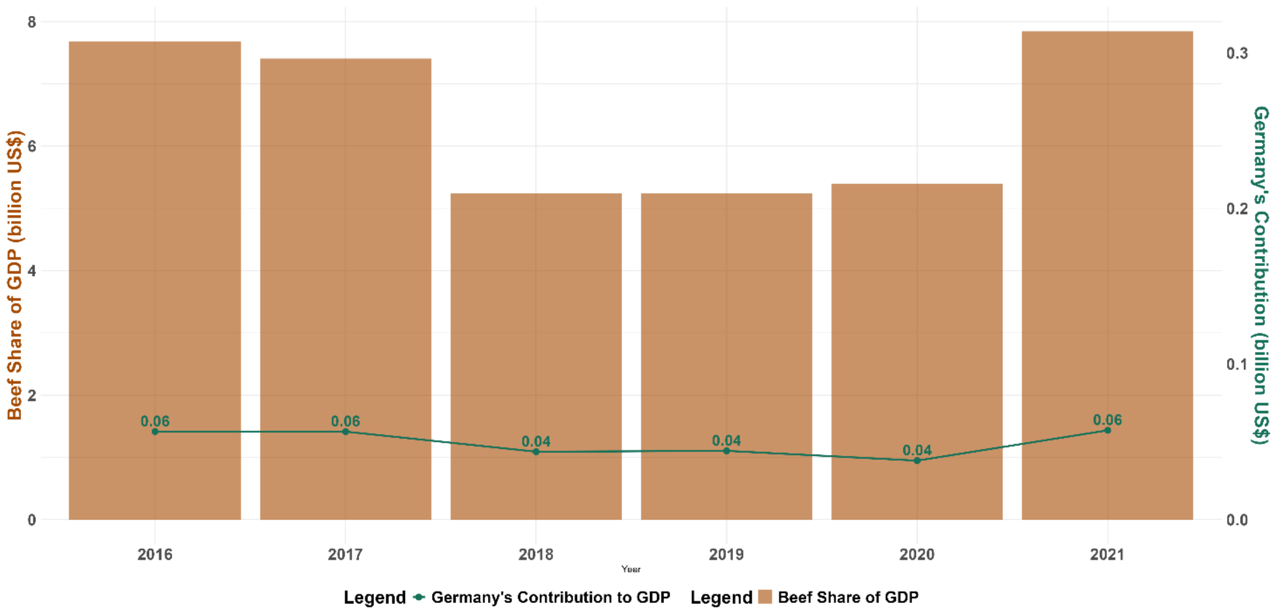
Figure 34: Development of Agricultural Share of GDP, Beef Sector Contribution (22% of Agriculture's Share in GDP), and Beef Production between 2001 and 2023



Source: based on (world bank 2024; Regunaga et al. 2006; Rossini et al. 2017)

Figure 34 illustrates significant fluctuations in the agricultural sector's contribution to GDP between 2001 and 2023, with notable peaks in the early 2000s and a resurgence around 2019, despite an overall declining trend. In contrast, both beef production and its share in GDP have remained relatively stable throughout this period. This stability suggests that the dramatic changes in overall GDP contribution are likely influenced by other agricultural activities or external economic factors and not by beef production.

Figure 35: Contribution of beef production to Argentina's GDP and Germany's contribution through imports between 2016 and 2021



Source: based on (world bank 2024; Regunaga et al. 2006; Rossini et al. 2017)

Figure 35 illustrates the contribution of the beef sector to GDP from 2016 to 2021, showing a decline in 2018, 2019 and 2020, followed by a rebound in 2021. The green line represents Germany's contribution to GDP, reflecting the share of beef imports from Argentina. This contribution has remained relatively stable, fluctuating between 0.06 and 0.04 billion USD throughout the period.

4.2.9 Assessment of Social Effects

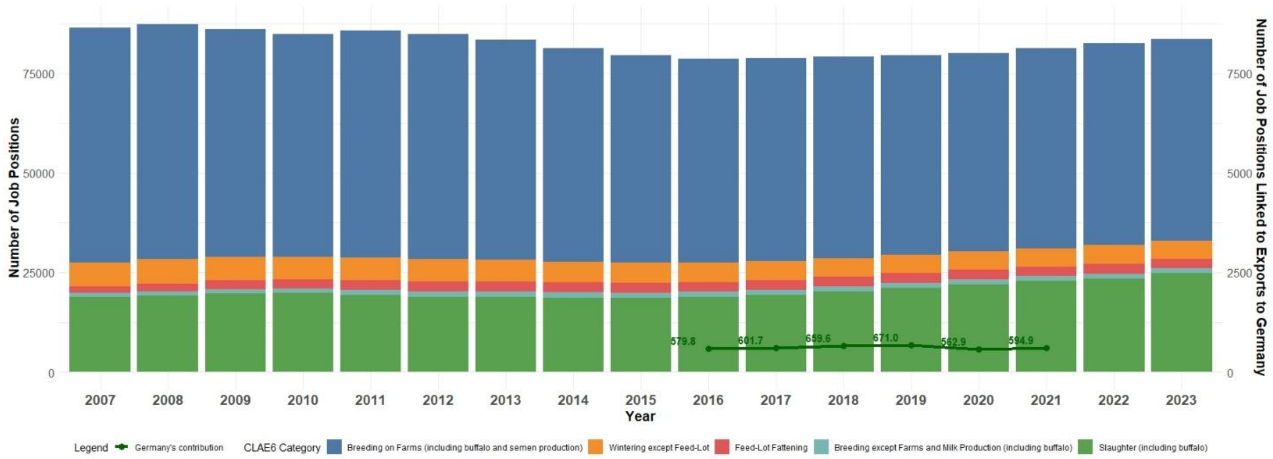
4.2.9.1 Employment

Data from the Ministerio de Desarrollo Productivo. Unidad Gabinete de Asesores. Dirección Nacional de Estudios para la Producción, (AFIP et al. 2023) were analysed to determine the number of jobs by in beef production. It is important to note that an individual may hold multiple jobs, meaning the total job count may exceed the number of workers. The geographic coverage of the data is national, and numbers cover breeding, wintering, and fattening of cattle, as well as slaughtering.

Figure 36 illustrates the annual mean number of jobs in the different steps of beef production in Argentina from 2007 to 2023. "Breeding on Farms (including buffalo and semen production)" consistently accounts for the largest share of jobs, indicating its significant role in the industry. The remaining activities – such as "Wintering except Feed-Lot," "Feed-Lot Fattening," "Breeding except Farms and Milk Production," and "Slaughter" – contribute smaller, yet stable, portions to the overall number of jobs in beef production.

Overall, the Figure 36 shows a consistent distribution of jobs over the years, with no significant changes. This stability suggests a resilient industry where employment levels have remained relatively constant over time. The green line shows the number jobs that depend on export of beef to Germany.

Figure 36: Jobs in Argentinian beef production depending on exports to Germany between 2007 and 2023



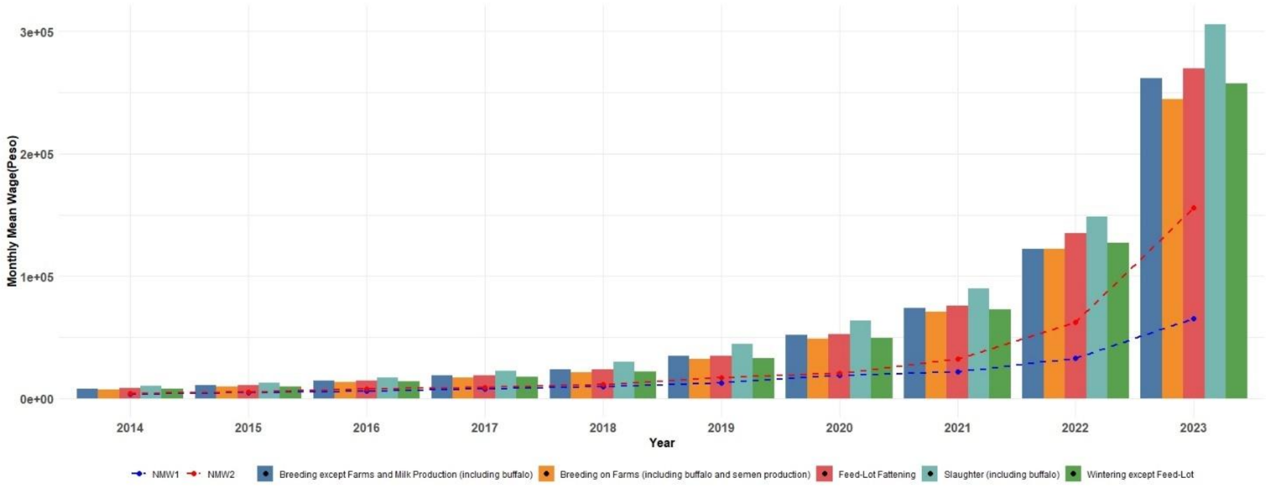
Source: based on Ministerio de Desarrollo Productivo. Unidad Gabinete de Asesores. Dirección Nacional de Estudios para la Producción (AFIP et al. 2023)

4.2.9.2 Mean Wage

Figure 37 shows the monthly mean wages for activities within the beef production value chain from 2013 to 2023, based on data from the 'Administración Federal de Ingresos Públicos' (AFIP et al. 2023). It highlights a consistent increase of wages in all activities, with a particularly sharp increase after 2020. While the average wages for most activities in 2023 are at a similar level, slaughtering stands out as the activity with the highest wage. In recent years, the wage gap between activities is increasing.

The two dashed lines represent the National Minimum Wage, where NMW1 and NMW2 are used to capture the minimum and maximum values of the national minimum wage within each year, given that Argentina has had multiple wage adjustments during different months of the same year. Although the wages in the beef production sector generally outpace the national minimum wage, the gap becomes more noticeable after 2021.

Figure 37: Monthly mean wages in Argentinian beef production and national minimum wage (2014 – 2023)



Source: based on data from Federal Administration of Public Revenue (AFIP et al. 2023)

4.3 Soy

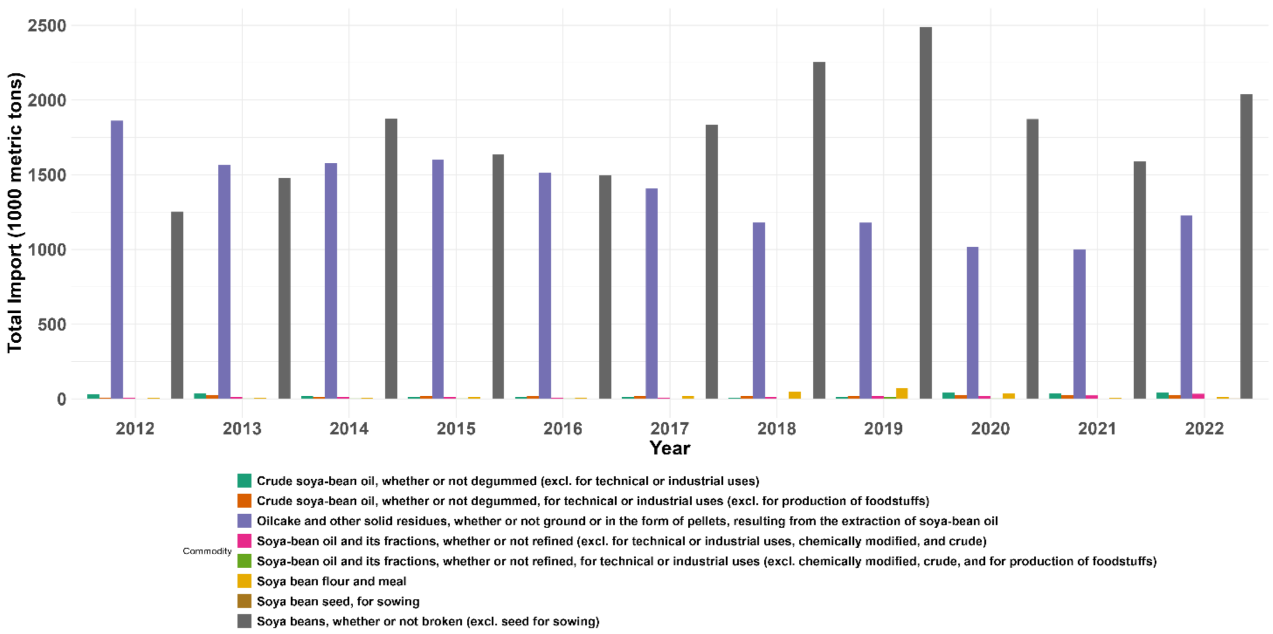
Soy is among the top 10 cultivated crop species worldwide (Hahn and Miedaner 2013). Due to its quantitatively and qualitatively superior protein composition, soy is an important source of commercial animal feed and one of the sources of biofuels. It is not only one of the main source of food, feed and bioenergy, but in addition there are also lots of co-products that can be obtained from soybean for example glycerine, lecithin, carboxylic acids and its derivatives, lubricants and biofuel (Sellare and Börner 2022b; Maciel et al. 2015).

The three main producers of soybeans are Brazil, the USA and Argentina, while China is the world's largest consumer. Following China, the European Union, comprising 27 countries, is the second-largest importer of soybeans. Additionally, when it comes to importing soybean meal, the EU27 ranks first globally.

4.3.1 Germany's Soy Imports

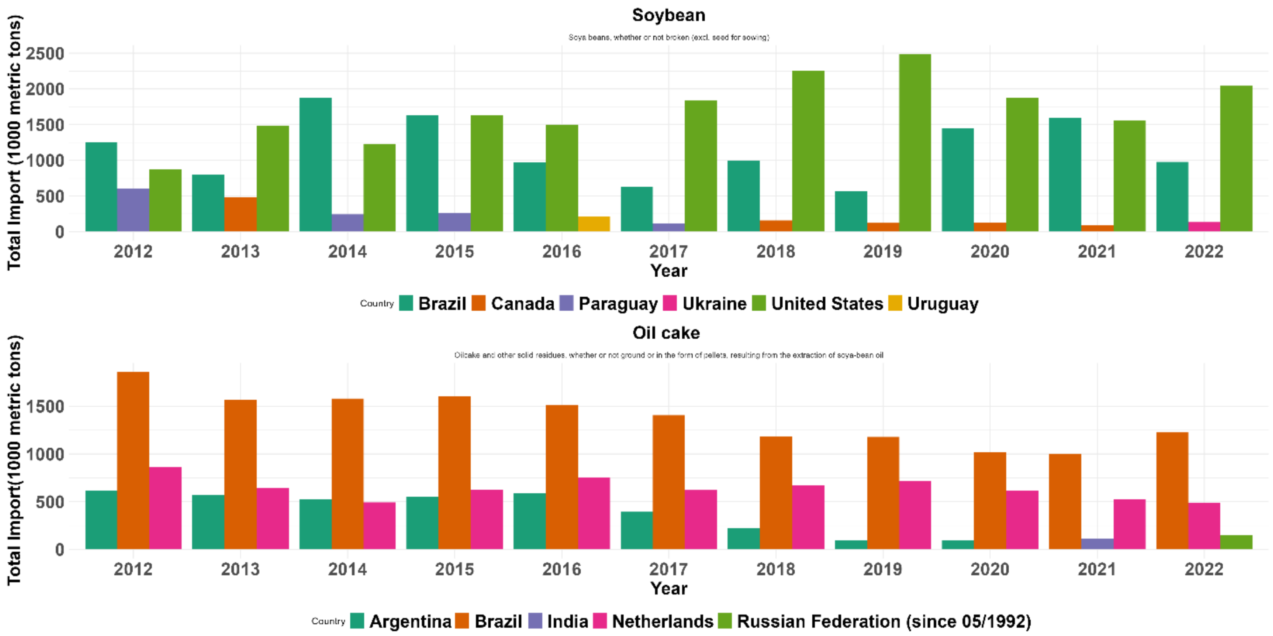
An analysis of soy trade based on the BACI database (Gaulier and Zignago 2010) indicates that raw soybeans and soy oilcake are the two primary soy products imported into Germany (cf. Figure 38). Figure 39, also based on (Gaulier and Zignago 2010), illustrates that the United States is the leading exporter of soybeans to Germany, followed by Brazil. In contrast, Brazil is the dominant exporter of soy oilcake to Germany followed by the Netherlands. The soy oilcake exported from the Netherlands to Germany predominantly also comes mainly from Brazil. Given that Brazil serves as the most significant non-EU exporter of soybeans and oil cake to Germany, alongside the US, and considering the potential sustainability concerns associated with its production, the focus is placed on assessing the sustainability effects of soybean production in Brazil.

Figure 38: Total import of soybean products to Germany between 2012 and 2022



Source: based on Comtrade data (Gaulier and Zignago 2010)

Figure 39: Top three soybean and oil cake exporting countries to Germany from 2012 and 2022



Source: based on Comtrade data (Gaulier and Zignago 2010)

Looking at data from TRASE (Lathuillière et al. 2022), it's clear that Germany imports soy from different areas of Brazil, particularly the Central West (CW), Northeast (NE), and Southern (S) regions (cf. Figure 40). As the Netherlands is one of the main ports in Europe, a portion of soy exports to the Netherlands are re-exported to other EU countries, including Germany. Therefore, the exports to the Netherlands have also been examined. We can see a noticeable trend where CW, followed by the S region, plays a significant role in exporting to the Netherlands between 2005 and 2020. When analysing data on European Union (EU) imports from the TRASE dataset (Lathuillière et al. 2022), CW and S are the most important export regions to the EU. This matches findings from a study by (Da Silva et al. 2010), highlighting the important role these regions play in meeting the EU's soy demand.

Figure 40: Total volume of soy exported to the European Union, Netherlands and Germany by region from 2004 – 2020

Source: based on (Lathuillière et al. 2022)

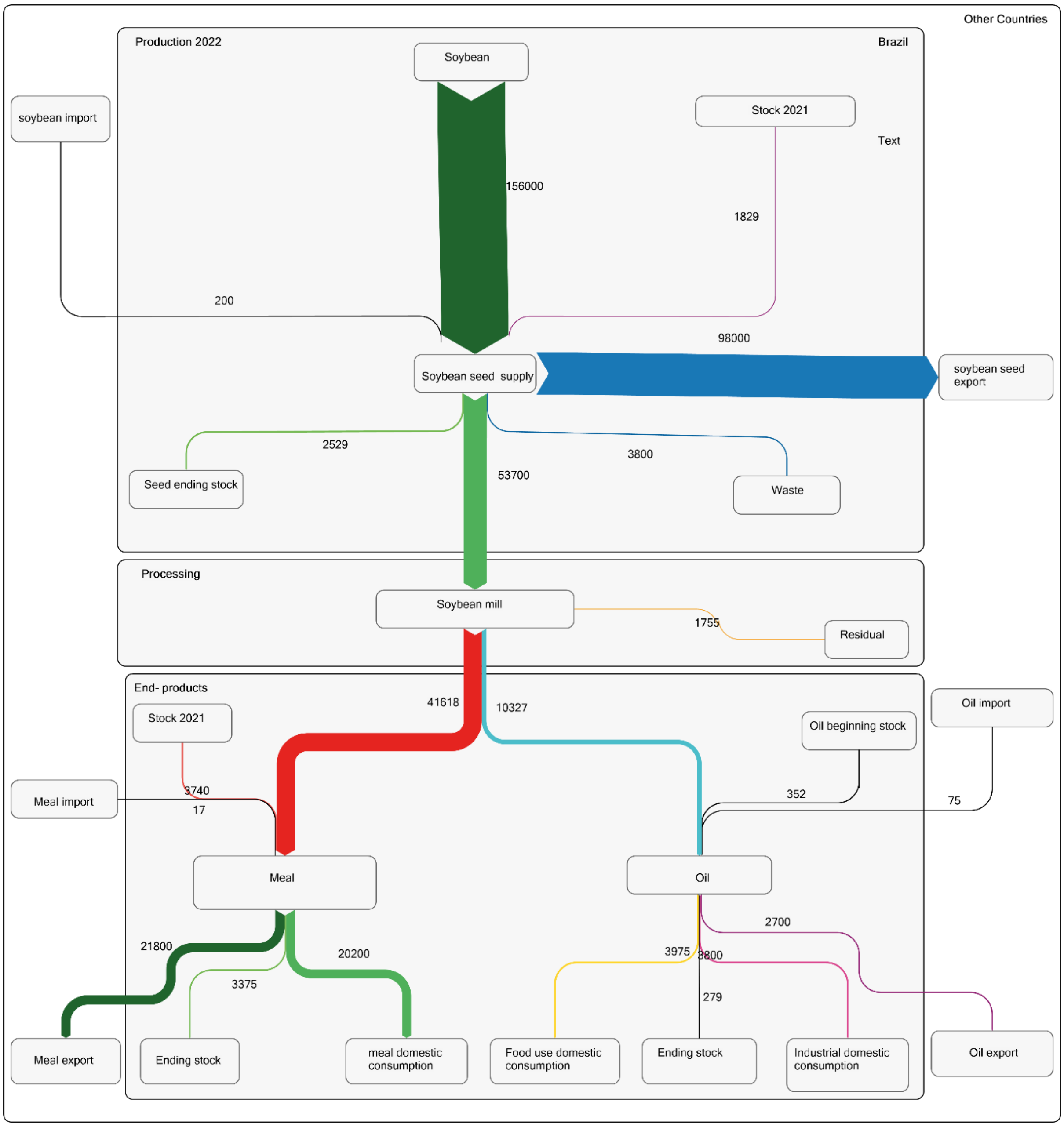
According to Sellare and Börner (2022a) and Escobar et al. (2020), Germany represents only 1.5% of Brazil's soybean trade, with China being the primary importer, accounting for approximately 70% from 2006 to 2016.

Iost et al. (2020b) found that 70.3% of soy imported to Germany is used as low-cost, high-quality protein for animal feed in meat and dairy production. About 18.9% is consumed as edible oils and human food products, such as tofu, soy milk, and tempeh. 9.2% is used for industrial purposes, primarily as biodiesel.

4.3.2 Material Flow Analysis of Soy Production in Brazil

Based on data from Degreenia (2023), Figure 41 illustrates the flow of soy from production through harvest, processing and export for the year 2022. The material flow begins with soy production and the initial stock in 2021. Roughly two thirds of soy production was exported as raw soybeans. Soybean meal (including oilcake) has the second largest share of exports. Additionally, as highlighted in the preceding section and Figure 39, the two principal soy commodities exported to Germany are predominantly raw soybeans, followed by oilcake and residues.

Figure 41: Material flow of soy production in Brazil in 2022 in 1,000 metric tonnes



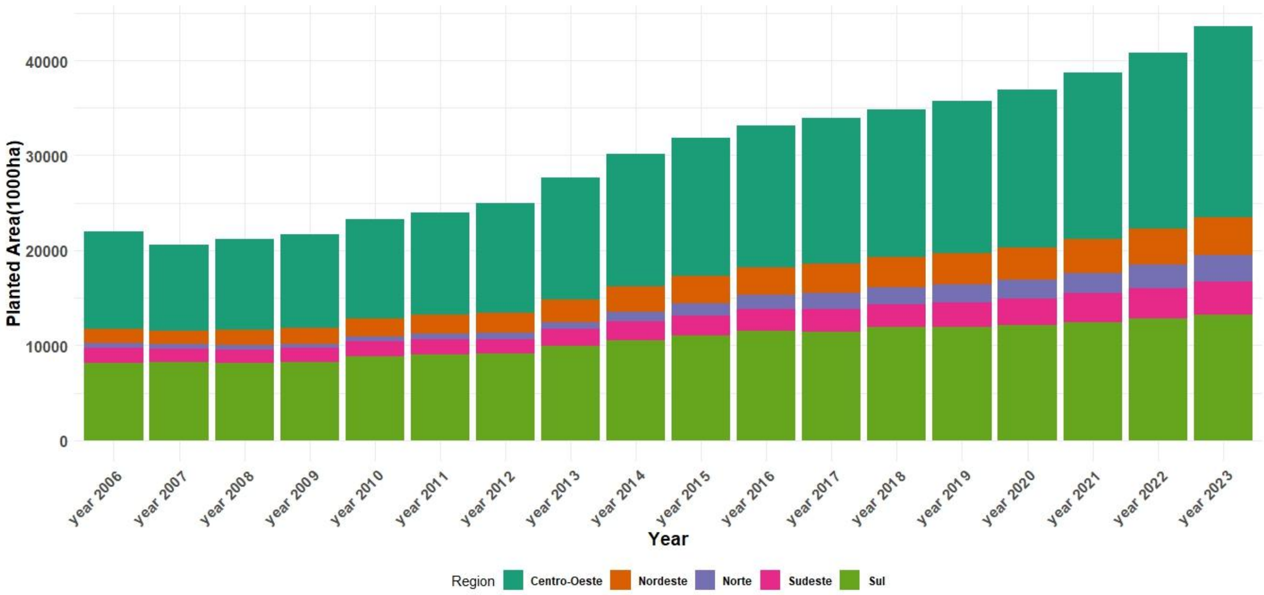
Source: own illustration based on (Degreenia 2023)

4.3.3 Soy Production in Brazil

Soybean production heavily relies on inputs like fertilizer, fuel, machinery, pesticides, and electricity (Da Silva et al. 2010), which can vary significantly in the different regions in Brazil. It is crucial to recognize that different geographic regions where soybeans are grown have very different characteristics, including soil types, land cover, transportation methods, and distances from production areas to the main export ports. Understanding these regional differences is crucial, as the challenges and sustainability effects may differ between regions.

Brazil supplies more than 50 percent of the soy traded worldwide (USDA 9/27/2022). Soy is the most produced crop in Brazil with around 162 million metric tonnes during the 2022/23 harvest (Degreenia 2024). The soy production in Brazil has experienced a remarkable surge in recent years, leading to a proportional increase in soy exports. According to Instituto Brasileiro de Geografia e Estatística (IBGE 2024) Automatic Retrieval System data (SIDRA 2024) and (Degreenia 2024), production increased from 52.2 million metric tonnes in 2006 to 162 million metric tonnes by 2023. Correspondingly, between 2006 and 2023, exports surged from 26.5 million metric tonnes to an impressive 103 million metric tonnes (Mello 2007; Degreenia 2024). As Figure 42 shows, the total production area for soy more than doubled between 2006 and 2023 (IBGE 2024).

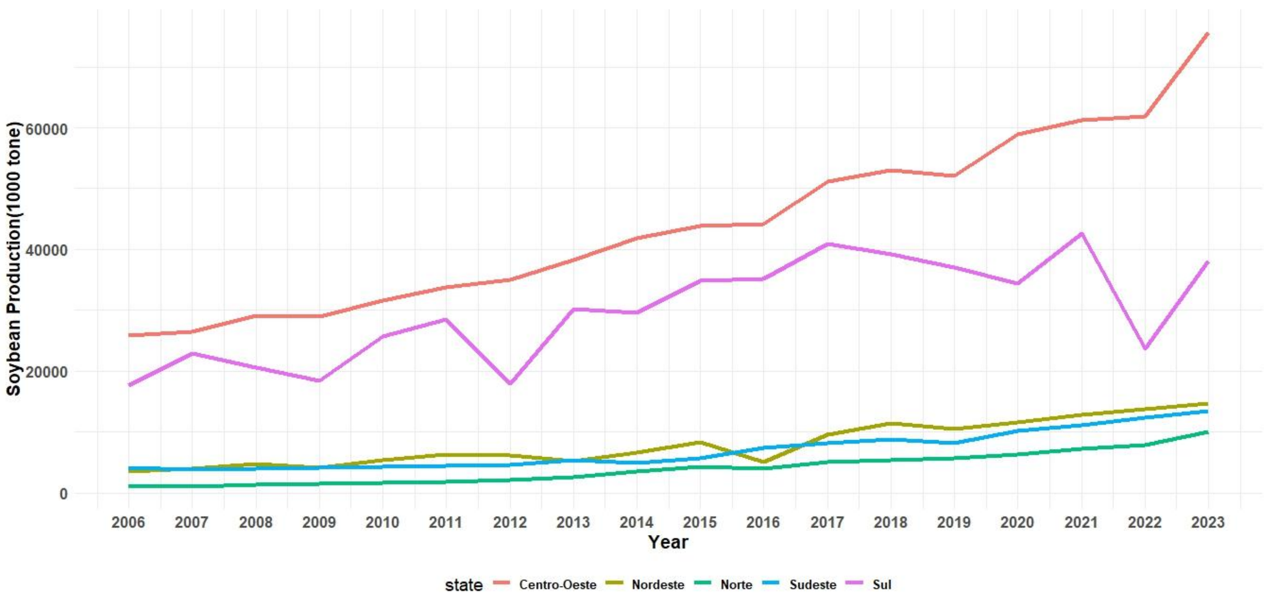
Figure 42: Area of soy production in Brazil from 2006 – 2023



Source: based on IBGE (2024)

The synergy of natural resource availability, technological progress, and supportive economic policies facilitated the substantial growth of agriculture in Brazil (Souza Ferreira Filho and Freitas Vian 2016).

Figure 43: Development of soy production in five main production areas in Brazil from 2006 – 2023



Source: based on SIDRA (2024)

Over the past 15 years, there has been a notable shift in soybean production to the Cerrado biome, where 16.6% of total deforestation has been transformed into cropland for soy cultivation (Song et al. 2021).

An analysis of data from SIDRA (2024), shows that soy production in the Central West and Southern regions is steadily increasing and clearly exceeds that of other regions (Figure 43). In contrast, the Northeast, Southeast, and Northern regions have experienced a gradual and continuous rise in production, particularly since 2013.

Since 1996, when the cultivation of genetically modified crops was legalized in the US, there has been a substantial and expansive transformation in the industry. Notably, soy has emerged as a frontrunner, constituting 50% of the global genetically modified crop landscape. Following the United States, Brazil, which obtained permission for cultivation in 2003, is the second-largest grower of genetically modified soy with an area of 31 million hectares (Bonciu 2023). That is 97% of the 34.7 million hectares of soybean area in Brazil in 2017. The 33.7 million hectares of genetically modified soy are made up of: 13.6 million hectares herbicide tolerant and 20.1 million hectares stacked Insect Resistant/Herbicide Tolerant (IR/HT) soy (ISAAA 2017). Therefore, soy from Brazil is in general genetically modified.

4.3.4 Goal, Scope, and System Boundaries of the Assessment of Sustainability Effects

The objective of the present assessment is to quantify the contribution of Germany to the sustainability effects of soy production in different regions of Brazil, as well as the transport of soy to Hamburg. As was demonstrated in a previous study, there are different production conditions in the various regions of Brazil, and therefore also different challenges in terms of sustainability. Furthermore, different export volumes from these regions to Germany were also found. This means that Germany may bear more responsibility for sustainability challenges in one region rather than another. Hence, the spatial system boundary covers the South, Southeast, North, Northeast, and Central-West of Brazil. However, to quantify environmental sustainability effects, three separate life cycle assessments are conducted for soy production in the Northeast, Central-West, and South (cf. 4.3.6). Detailed information about the technical system boundary and the data used for the LCAs are available in Annex 2. The temporal system boundary varies between the years 2010 and 2023, depending on the assessed sustainability effect. The functional unit is a metric tonne of raw soybean.

4.3.5 Indicator Selection

As mentioned in the methodology section, for a participatory process of indicator selection, stakeholders should be involved. (Sellare and Börner 2022a) conducted a semi-structured interview with German stakeholders from an industry association, a stakeholder dialogue platform, the retail sector, development agencies, and civil society to gather perspectives on the main sustainability challenges in soy supply chains and alternative policy mechanisms for soy production and export from Brazil to Germany. The results indicated that deforestation, GHG emissions, and biodiversity loss are the main environmental challenges from their perspective, and the primary social sustainability challenges include land use rights, conflicts with indigenous communities, and forced displacement.

In addition, Zortea et al. (2018) used a participatory approach among workers, value chain actors, and the local community/society in South Brazil to identify the most important sustainability challenges as follows: for workers, social benefits/social security, freedom of association and collective bargaining, working hours, and education and training. Education and training were crucial for both workers and value chain actors. For value chain actors, the key challenges also included fair competition and supplier relationships. For the local community and society, the primary concerns were local employment and community engagement.

From an ecological standpoint, the practice of deforestation for the purpose of soy production, in conjunction with the role of soy trade in this context, constitutes a significant environmental concern (Carreira et al. 2024).

The process of deforestation has been demonstrated to result in substantial biodiversity loss, augmented greenhouse gas emissions, and disruption to water systems (Jaureguiberry et al. 2022). Moreover, the cultivation phase of soy production has been shown to engender considerable environmental repercussions, including acidification, eutrophication, and greenhouse gas emissions.

According to IDH (2021), Germany sources over 80% of its soy consumption from FEFAC SSG (European Feed Manufacturer's Federation) compliant standards, including SSAP, ADM Responsible Soy, BungePro-S, CSR, Donau Soja, Europe Soya, ProTerra, and RTRS, with more than 50% meeting criteria that ensure the soy is deforestation and land conversion-free. Therefore, the European Feed Manufacturers' Federation Soy Sourcing Guidelines (FEFAC SSG) compliant standards are an important source for the selection of indicators for the assessment of sustainability effects. Profundo (2023) benchmarks the FEFAC SSG and 20 Voluntary Standard Systems (VSS)(cf. Annex 3) against key sustainability criteria. The focus is on preventing deforestation, conserving biodiversity, upholding human rights, ensuring supply chain transparency, and implementing good governance practices. These indicators align with the EU Deforestation Regulation (EUDR), Core Principles of the Accountability Framework Initiative (2020), the upcoming EU Corporate Sustainability Due Diligence Directive (CSDDD), and FEFAC SSG guidelines (FEFAC 2021). A list of these indicators for environmental and social aspects is provided in the following table for information purposes:

Table 11: List of indicators for environmental and social sustainability effects

Pillars	Themes	Indicators
Environment	Avoiding Deforestation and Conversion of Natural Ecosystems	**Deforested Land:** Producers cannot produce soy on deforested land or deforest land for expansion. **Converted Natural Ecosystems:** Producers cannot produce soy on land where natural ecosystems have been converted or convert natural ecosystems for expansion.
	Avoiding Degradation of Natural Ecosystems and Biodiversity Loss	**Protected Areas:** No operations in or impacting IUCN I-VI protected areas. **UNESCO Sites:** No operations in or impacting UNESCO World Heritage sites. **Ramsar Wetlands:** No operations in or impacting Ramsar Wetlands. **Restoration:** Restore altered protected areas or take legally approved compensating actions. **Additional**: Detail quantity, quality, and permanence of compensation. **Biodiversity Identification:** Identify natural vegetation and biodiversity values on land and surrounding areas. **Additional:** Regularly monitor impacts and adapt management. **Minimize Impact:** Minimize and mitigate negative impacts on on-farm biodiversity. **Additional:** Measures for off-farm impacts, timebound biodiversity management plan. **High Conservation Value Areas:** Provide details of identified high conservation value areas upon request. **Additional:** Map showing HCV areas. **Species Protection:** Protect rare, threatened, and endangered species and their habitats. **Hazardous Chemicals:** No use of WHO Class Ia, Ib, and II hazardous chemicals.

		Additional: Record agrochemical use. **Biological Control**: Use biological control agents per international standards. **Integrated Pest Management:** Implement practices to minimize or avoid agrochemical use. **Additional:** Promote native predators. **Wetland and Water Quality:** Minimize impact on wetlands and groundwater from chemicals and erosion. **Additional:** Evidence of proper agrochemical waste management. **No Degradation of Restoration Areas:** Activities must not degrade areas where forest restoration or wildlife reintroduction is happening. **Invasive Species:** No introduction or use of invasive alien species. **Additional:** Effective action to limit damage from present invasive species. **Soil Quality:** Maintain soil quality and prevent erosion. **Irrigation Systems:** No irrigation systems causing degradation of wetlands and other ecosystems.
Social	Social Issues and Human Rights	**Decent Wage**: Economic actors must pay a decent wage. **Living Wage:** Economic actors must pay a living wage. **Working Conditions:** Ensure decent living, safe and healthy working conditions, and reasonable working hours for all workers. **Anti-Discrimination**: Implement a gender-sensitive zero tolerance policy towards all forms of discrimination and violence. **Freedom of Association:** Uphold rights to freedom of association and collective bargaining. **Forced Labor:** Ensure no forced labor, slavery, or similar practices in the entire supply chain. **Child Labor:** Do not employ children under the compulsory schooling age, which is at least 15 years. **Indigenous Rights:** Respect Indigenous peoples’ rights to give or withhold Free, Prior and Informed Consent (FPIC) for operations affecting them. **Community Land Rights**: Respect communities’ customary land rights to give or withhold FPIC for operations affecting them. **Evictions:** No unlawful evictions or taking of land, forests, and waters. **Compensation:** Provide compensation for negative impacts of operations on local communities and individuals.

Source: based on Profundo (2023)

Based on the above-mentioned studies, guidelines and legislation for assessing the bioeconomy and sustainability effects of agricultural commodities, a list of sustainability indicators for the assessment of soy production in Brazil was selected and listed in Table 12.

Table 12: List of selected indicators applied for the assessment of sustainability effects of soy production in Brazil

Indicators	Data sources
Environmental	
Deforestation	Trase (Lathuillière et al. 2022)
GHG emission	Trase (Lathuillière et al. 2022) and (ecoinvent 2024)
GWP	(ecoinvent 2024)
Land use change	(ecoinvent 2024) and Trase (Lathuillière et al. 2022)
Acidification	(ecoinvent 2024)
Eutrophication	(ecoinvent 2024)
Economic	
Gross Production Value	CONAB[1] (CONAB 2024)
Value added at factor cost	SIDRA[2] (SIDRA 2024)
GDP	CEPEA[3] and ABIOVE[4] based on data from the IBGE[5] (CEPEA and ABIOVE 2024; IBGE 2024)
Trade volume	Trase (Lathuillière et al. 2022), CEPEA and ABIOVE (CEPEA and ABIOVE 2024)
Social	
Employment rate	CEPEA, ABIOVE(CEPEA and ABIOVE 2024) and IBGE(IBGE 2024)
Average annual earning	CEPEA, ABIOVE(CEPEA and ABIOVE 2024) and IBGE(IBGE 2024)
Gender imbalance	CEPEA, ABIOVE (CEPEA and ABIOVE 2024)and IBGE(IBGE 2024)
Education	CEPEA, ABIOVE(CEPEA and ABIOVE 2024) and IBGE(IBGE 2024)

Source: own compilation

1, 2 ,3: Center for Advanced Studies on Applied Economics, 4: the Brazilian Association of Vegetable Oil Industries, 5: Brazilian Institute of Geography and Statistics

4.3.6 Assessment of Environmental Effects

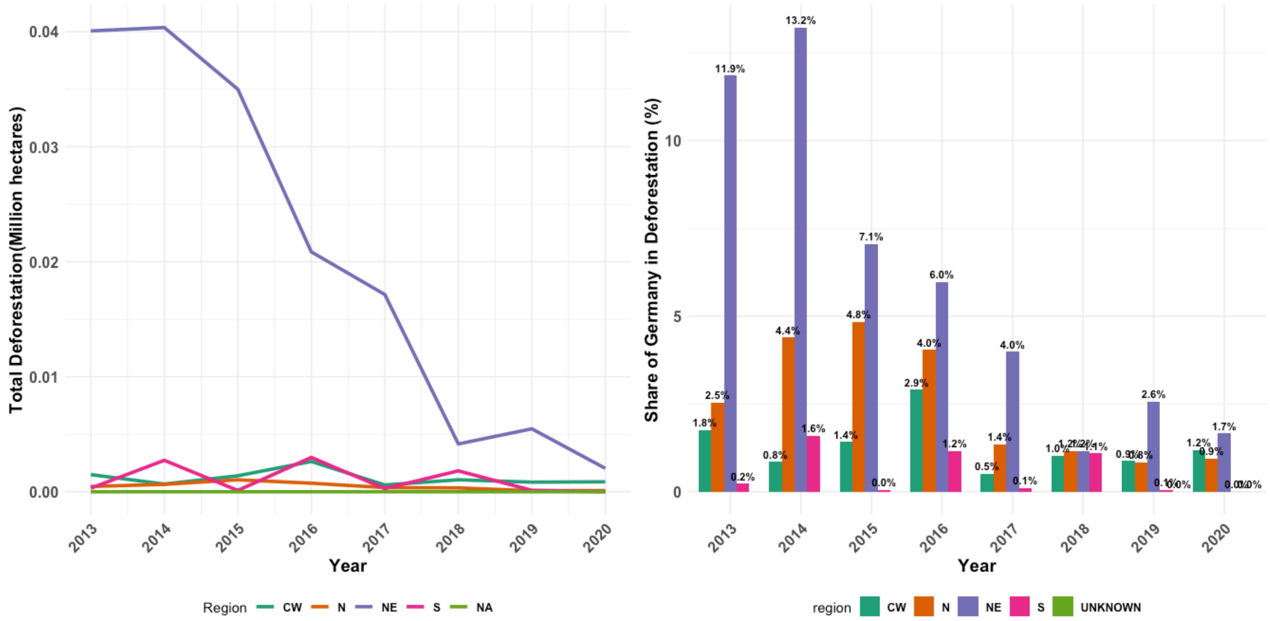
Regional differences are taken into account when assessing the impact on environmental sustainability. Two different data sources are used: The first is official data (Trase 2025), which provides region-specific information on GHG emissions and deforestation related to soy production in the north, north-east, south, south-east and central-west of Brazil. The second is the Ecoinvent database (ecoinvent 2024), which provides LCA-data based on models and empirical data for global warming potential, land use, eutrophication, acidification and water consumption of soy production in the regions as well as transport.

4.3.6.1 Deforestation

Deforestation is a significant environmental challenge linked to the expansion of soy production and exportation in Brazil. To quantify the deforestation caused by soy production, we relied on data from Trase (2025) relating to the export of soy, including raw soybeans, oilcake and soybean oil, to Germany. To understand the deforestation impact, Trase (2025)also assesses both the net and gross CO_2 emissions resulting from the conversion of forests into agricultural land in different Brazilian states. More detailed information is available in Trase (2025).

Trase provides detailed information about deforestation for soy production over a five-year period, known as the "5-year total soy deforestation exposure". Most of the deforestation related to soy export to Germany occurred in the north-eastern (NE) region, followed by the central-western (CW) and southern (S) regions, and finally the northern (N) region (cf. Figure 44).

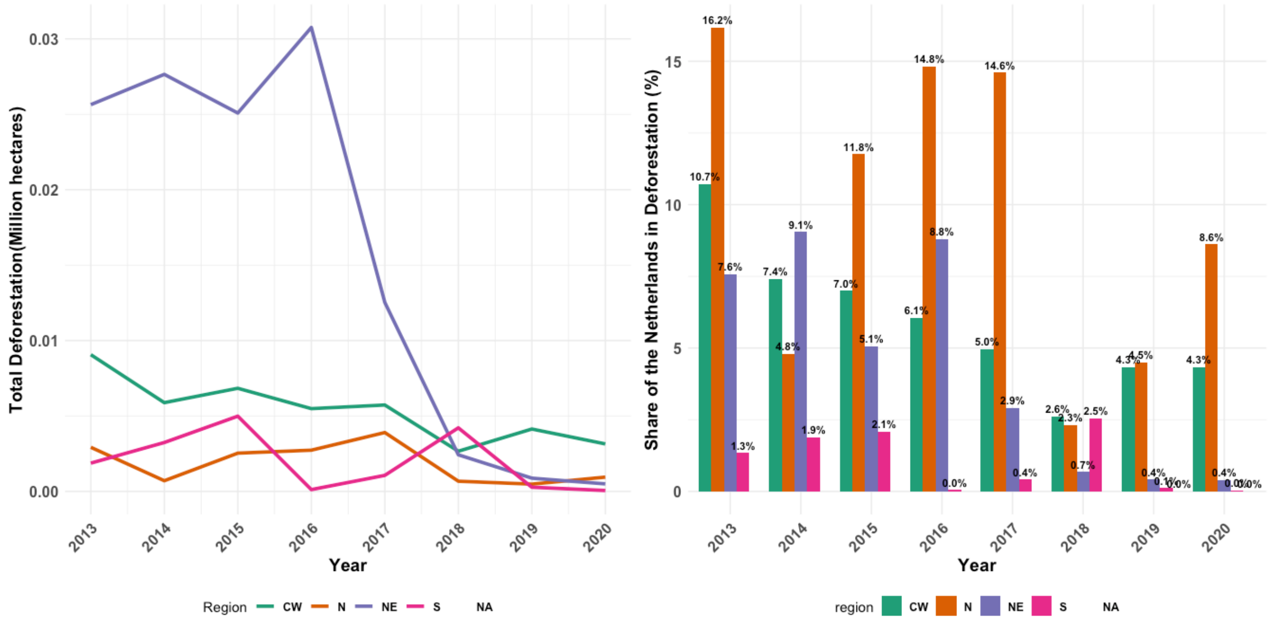
Figure 44: Deforestation related to soy exports to Germany and Germany's contribution to total soy-related deforestation in Brazil from 2013 – 2020



Source: own calculations based on (Trase 2025)

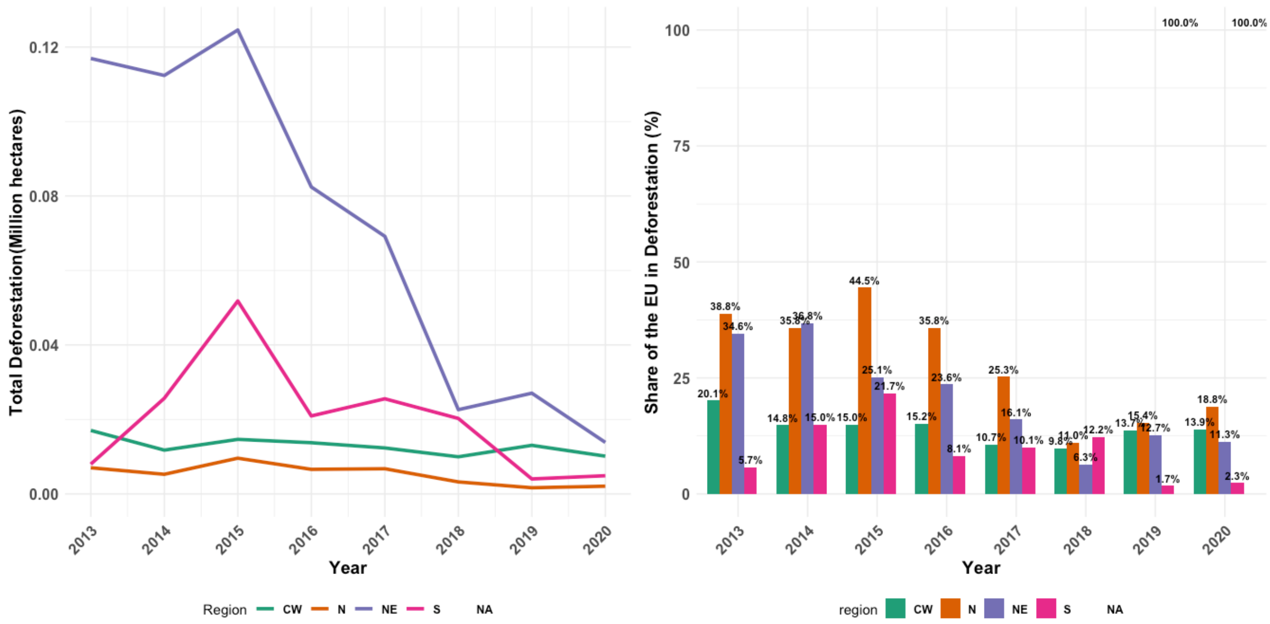
Figure 45 shows that deforestation, which peaked in 2014, has been declining since 2015. This trend is particularly pronounced in the north-eastern region, where soy production has been accompanied by extensive deforestation. In other regions, the impact on deforestation was comparatively lower. The most likely explanation for this pattern is that soy production has only recently started in the north-eastern region. Hence, the primary deforestation activities occurred until 2018. Additionally, it can be observed that the five-year deforestation exposure associated with soy exports to Germany is decreasing despite an increasing exports volume. In particular, the share of total deforestation in the north eastern region decreased from 13.9% in 2014 to 1.7% in 2020. The same pattern can be observed for exports to the Netherlands (cf. Figure 45 and the EU (cf. Figure 46).

Figure 45: Deforestation related to soy exports to the Netherlands and the Netherland's contribution to total soy-related deforestation in Brazil from 2013 – 2020



Source: own calculations based on (Trase 2025)

Figure 46: Deforestation from soybean exports to the EU and the EU's share in total soy-related deforestation in Brazil over the years



Source: own calculations based on (Trase 2025)

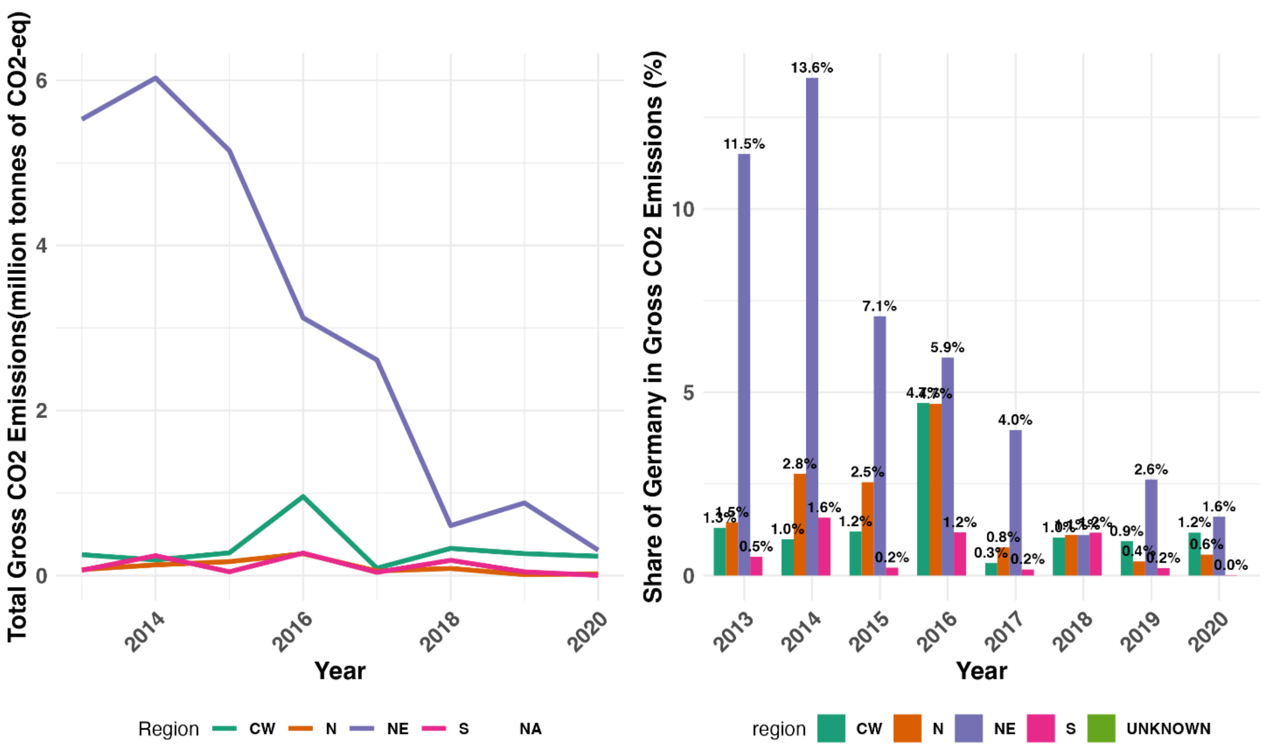
4.3.6.2 GHG Emissions

Gross CO_2 emissions

To quantify the gross emissions from deforestation caused by soy production, data from (Trase 2025)was used.Gross emissions from deforestation refer to the total potential CO_2-equivalent emissions resulting from the complete removal of native vegetation in a given year and municipality. This measurement includes carbon stored in both above and below-ground biomass and necromass (dead organic material in an ecosystem, such as fallen trees, leaves, and animal remains, that contributes to nutrient cycling and habitat for decomposers). The gross emissions are calculated without taking into account subsequent land-use changes and represent the maximum possible emissions if the entire biomass were converted into CO_2.

According to Figure 47, the main source of gross CO_2 emissions related to direct soy export from Brazil to Germany is found primarily in the north-eastern region of Brazil. For the other three regions, the contribution remains relatively constant. It is also evident that emissions from the north-eastern region have decreased dramatically since 2018, although they remain higher than in other regions. As far as the share of total gross CO_2 emissions related to direct exports to Germany is concerned, this has decreased significantly after peaking in the north-eastern region, from 13.8% of total gross CO_2 emissions to 1.8% in 2020. However, after a sharp decline in CO_2 emissions in the central-west region, this amount gradually increased from 2018 to 2020.

Figure 47: **Gross CO_2 emission from soy exports to Germany and Germany's contribution to total soy-related gross CO_2 emission in Brazil from 2013 – 2020**

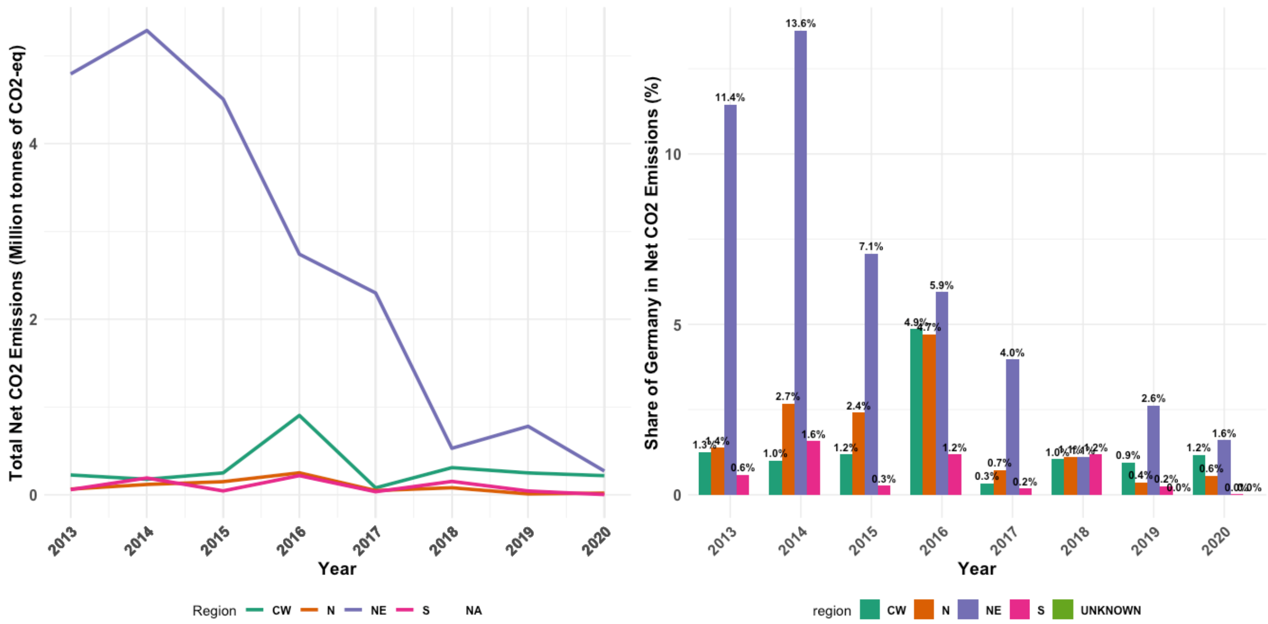


Source: own calculations based on (Trase 2025)

Net CO_2 emission:

The analysis of net CO_2 emissions was conducted using data from Trase (2025), with the understanding that net CO_2 emissions encompass the carbon sequestration in land-use types that replace forested areas. After calculating the gross emissions, the carbon stored in the subsequent vegetation is subtracted in order to calculate the actual increase in atmospheric CO_2. This provides a more accurate balance between the carbon lost through deforestation and the carbon gained through new land use, thus giving a realistic picture of the net impact on greenhouse gas levels.

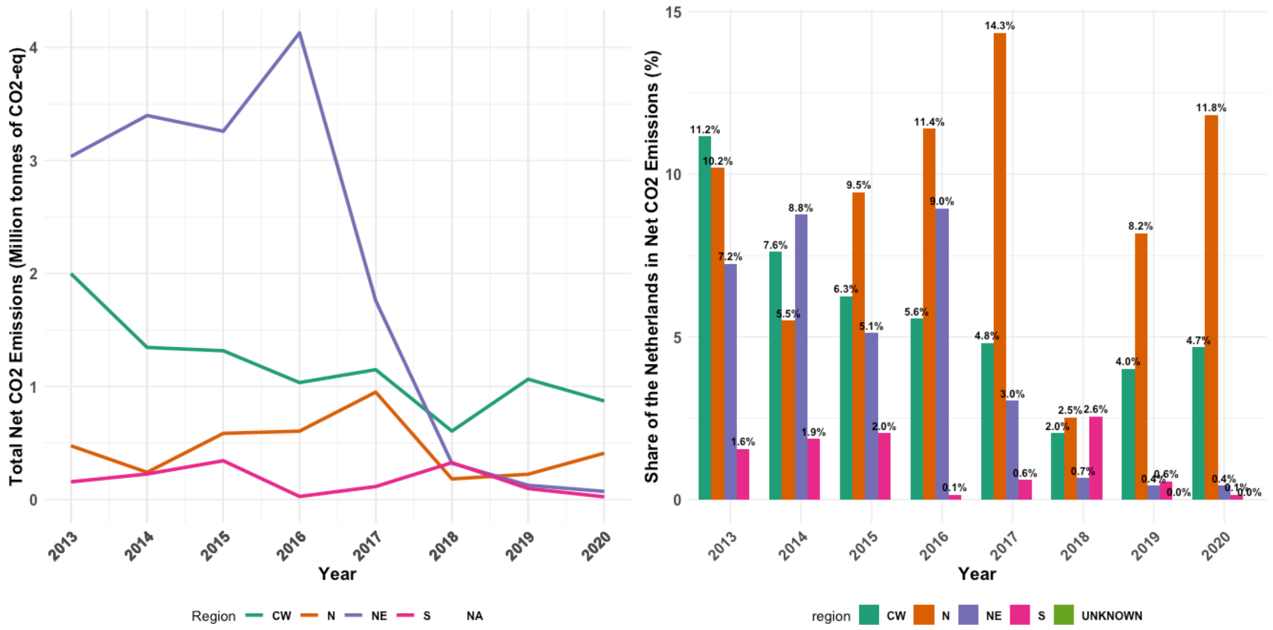
Figure 48: Net CO_2 emission from soy exports to Germany and Germany's contribution to total soy-related net CO_2 emission in Brazil from 2013 – 2020



Source: own calculations based on (Trase 2025)

Figure 48 shows that net CO_2 emissions in Brazil have decreased significantly since 2014, with the contribution related to exports to Germany dropping from 13.6% to 1.6% in 2020. While the impact of exports to Germany is smaller in other regions, a general decreasing trend in emissions is observed, particularly after 2016. However, the second graph indicates that the production of soy re-exported from the Netherlands to Germany, is more responsible for net CO_2 emissions in the northern and central-western regions of Brazil.

Figure 49: Net CO_2 emission from soybean exports to the Netherlands and the Netherlands' contribution to total soy-related net CO_2 emission in Brazil from 2013 – 2020



Source: own calculations based on (Trase 2025)

4.3.6.3 Global Warming Potential, Land Use, Terrestrial Acidification, Freshwater Eutrophication, Water Consumption

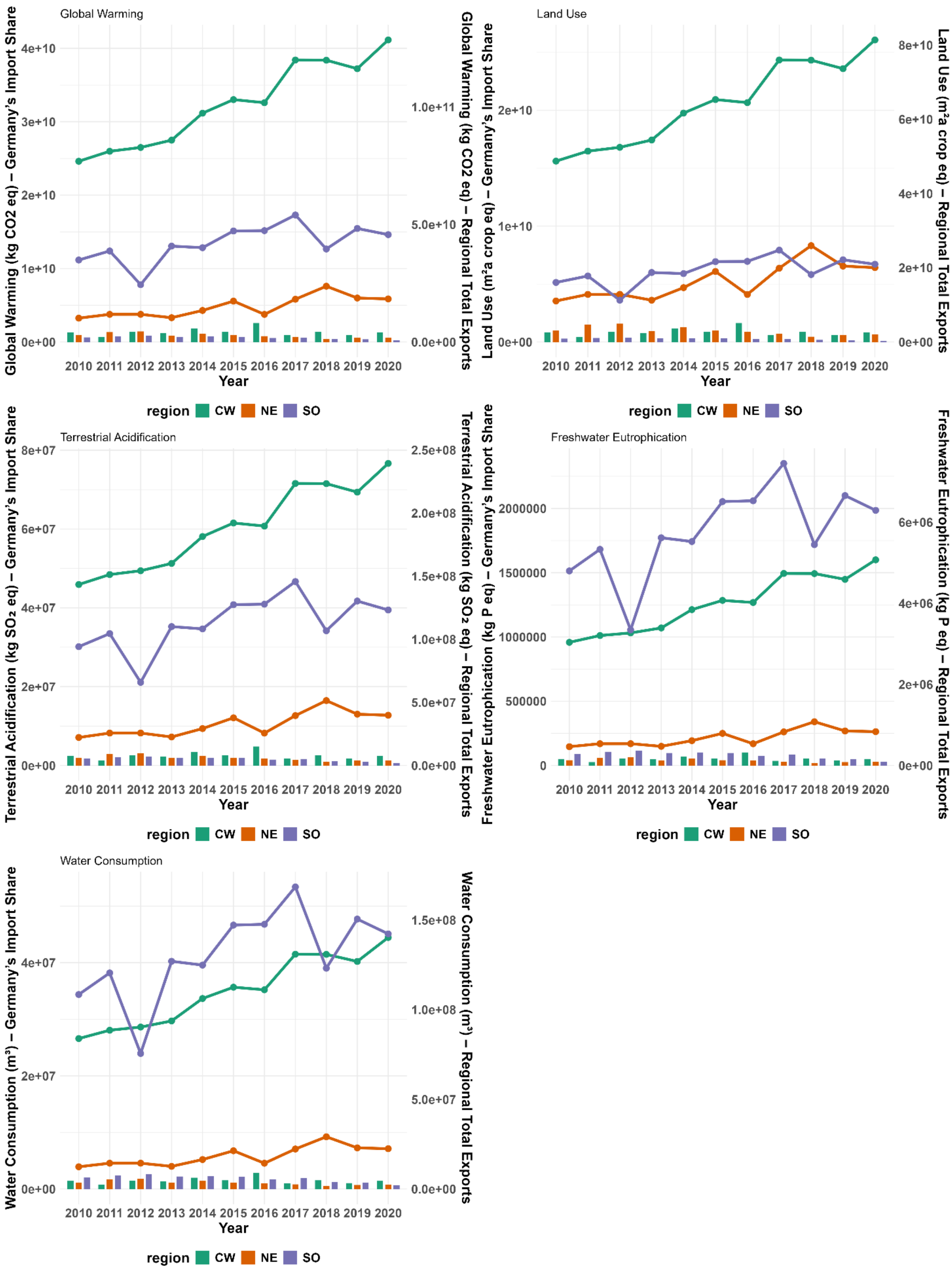
Table 13 shows life cycle assessment results for the production of one tonne of soybeans across different regions based on ecoinvent (2024). The environmental effects vary from region to region. For instance, the global warming potential of soy production is highest in the Central-West (CW) region. In terms of land use, the North-eastern region shows the highest effect, while in the Southern region water consumption is highest. In general, environmental effects are highest in the Central-West region.

Table 13: LCA for the production and transport of one tonne of soybeans in the Central-West, Northeast, and South regions of Brazil

Impact Categories	Unit	Central West	North East	South
Fine particulate matter formation	kg PM2.5 eq/t	4.25	2.73	1.98
Fossil Resource scarcity	kg oil eq/t	138.13	73.03	95.97
Freshwater ecotoxicity	kg 1,4-DCB/t	30.45	58.46	43.09
Freshwater eutrophication	kg P eq/t	0.10	0.07	0.19
Global Warming	kg CO_2 eq/t	2619.86	1650.47	1364.50
Human carcinogenic toxicity	kg 1,4-DCB/t	124.56	55.62	66.33
Human non-carcinogenic toxicity	kg 1,4-DCB/t	2962.66	2620.76	2464.10
Ionizing radiation	kBq Co-60 eq/t	10.09	5.53	7.67
Land use	m^2a crop eq/t	1657.75	1813.19	620.87
Marine ecotoxicity	kg 1,4-DCB/t	56.84	39.51	81.72
Marine Eutrophication	kg N eq/t	3.10	2.14	2.92
Mineral resource scarcity	kg Cu eq/t	2.40	1.26	2.26
Ozone formation, Human health	kg NO_x eq/t	4.26	2.66	2.83
Ozone formation, Terrestrial ecosystems	kg NO_x eq/t	4.62	2.87	2.95
Stratospheric ozone depletion	kg CFC11 eq/t	0.01	0.01	0.01
Terrestrial acidification	kg SO_2 eq/t	4.87	3.56	3.68
Terrestrial ecotoxicity	kg 1,4-DCB/t	9853.67	12792.00	10198.90
Water consumption	m^3/t	2.86	2.04	4.28

Source: own calculations based on ecoinvent (2024)

Figure 50: Germany's contribution to various environmental impact categories, including Global Warming Potential, Land Use, Terrestrial Acidification, Freshwater Eutrophication, and Water Consumption, associated with production and transport of soy from Brazil's Central-West, North-East, and South regions



Source: own calculations based on Trase (2025)[6] and ecoinvent (2024)

[6] The right y-axis corresponds to the line graphs, which show the total values of each impact category based on the total export volume from each region to the world. The left y-axis is for the bar charts, which represent Germany's contribution to these impact categories, calculated based on the export volume of soy from Brazil to Germany.

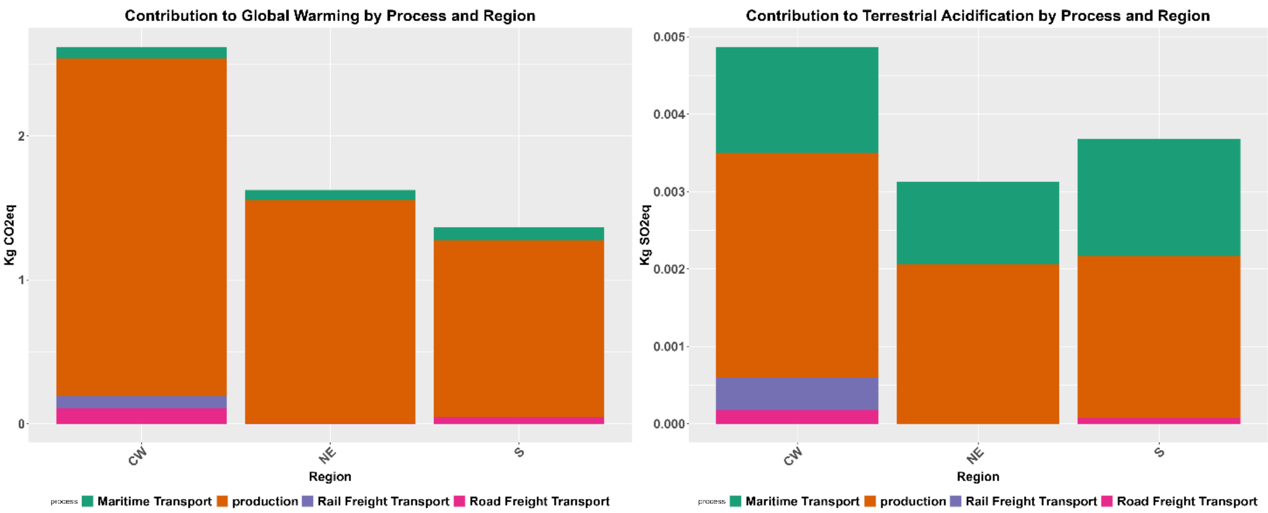
Germany's contribution to various environmental effects, related to soy exports from different regions in Brazil is quantified for the years 2010 to 2020 (cf. Figure 50). In order to quantify Germany's contribution to environmental effects of soy production in three regions in Brazil the amount of soy exported to Germany from the three regions is obtained from Trase (2025).

Figure 50 shows clear regional differences in the contribution to various environmental effects associated with soy exported to Germany. In the domain of land use, Germany's contribution is the highest in the North-East region. Compared to the other regions, Germany's contribution to freshwater eutrophication and water consumption, is highest in the Southern region. In contrast, Germany's contribution in both terrestrial acidification and global warming is the highest in the Central-West region.

Across all these impact environmental effects and regions, there is a clear decreasing trend associated with soy exports to Germany over the period analysed.

Looking at the value chain, the production of soy contributes the most to global warming and terrestrial acidification (cf. Figure 51). Additionally, long maritime transport from Brazil to Germany significantly contributes to terrestrial acidification.

Figure 51: Germany's contribution to Global Warming and Terrestrial Acidification per tonne of production by process and region



Source: own calculations based on ecoinvent (2024)

4.3.7 Assessment of Economic Effects

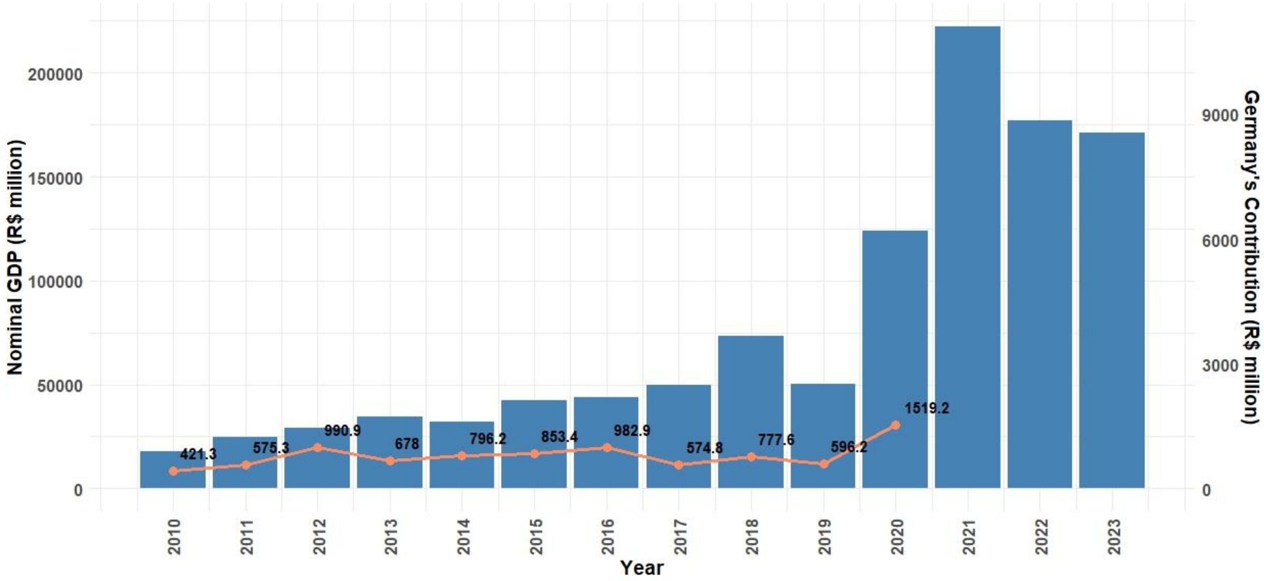
The economic sustainability of soy production in Brazil is assessed in terms of its share to total GDP. The assessment is based on data available in the "First Report - Soy and Biodiesel Chain - Complete," accessible at CEPEA and ABIOVE (2024). Germany's contribution through imports is calculated based on data from Trase (2022).

4.3.7.1 Share of Soy Production in Total GDP

As demonstrated in Figure 52, the temporal progression of the share of soy production in Brazil's nominal GDP from 2010 to 2023 is illustrated, alongside the contribution of Germany through its imports. The overlaid line chart illustrates Germany's contribution, with a scaling factor having been applied to facilitate enhanced visual comparison.

The data show a notable upward trend in the contribution of soy production to nominal GDP, reflecting the robust performance of Brazil's soybean production over the years. At the same time, however, the line chart showing the contribution Brazilian GDP through exports to Germany remains relatively stable from 2010 and 2019. It fluctuates between 421 and 983 million R$ or 1 – 2% of the contribution of soy production to Brazilian GDP. In 2020 the contribution increased significantly to 1,519 million R$.

Figure 52: Contribution of soy production to Brazil's GDP and Germany's contribution to GDP through exports between 2010 – 2023



Source: own calculations based on CEPEA and ABIOVE (2024) and Trase (2022)

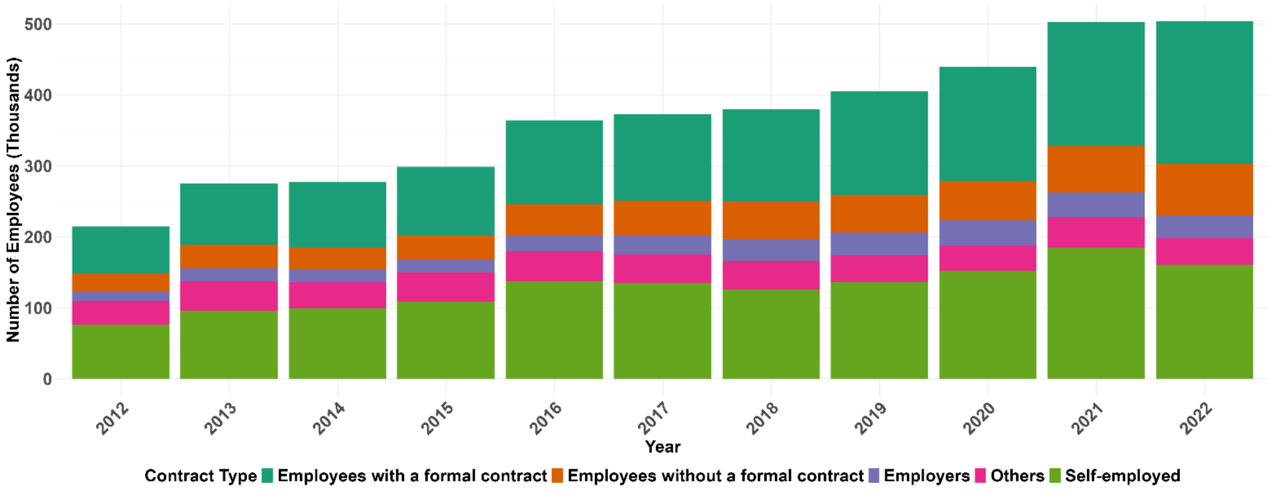
4.3.8 Assessment of Social Effects

In order to capture social sustainability effects of Brazilian soy production, fair labour practices, impact on community health, and the fair distribution of economic benefits are addressed. The assessment is based on data from CEPEA and ABIOVE (2024) and the Brazilian Institute of Geography and Statistics (IBGE 2024) with an emphasis on the primary stage of soy production. "Primary stage" refers to the initial cultivation and harvesting of soy production.

4.3.8.1 Employment

As the soy production has expanded, employment in the primary stage of soy production increased from 214,816 in 2012 to 504,217 in 2022 (Figure 53). However, the ratio of formal and informal contracts has not improved. Throughout the years between 2012 and 2022, formal contracts have consistently been about three times the number of informal contracts.

Figure 53: Distribution of types of employment in the primary stage of soy production between 2012 and 2022



*** Definitions:**
Employees: individuals who worked for an employer (either a person or a legal entity).
Self-employed: individuals who operated their own business, either alone or with a partner, without having employees and possibly with the help of an unpaid family worker.
Employers: individuals who operated their own business with at least one employee.
Unpaid family workers: individuals who worked without remuneration for at least one hour during the reference week, assisting in the economic activity of a household member or a relative living in another household.
Others: mainly include unpaid family workers.
Formal employees: Employees with a signed contract (private, public, domestic workers)
Informal employees: Employees without a signed contract (private, public, domestic workers)

Source: based on CEPEA and ABIOVE (2024) and IBGE (2024)

Table 14: Proportion of employment types in the primary stage of soy production (2012-2022)

Year	Formal Contract Share (%)	Informal contract Share (%)	Employers Share (%)	Self employment Share (%)	Other Share (%)
2012	30.64	11.76	6.24	35.57	15.79
2013	31.44	11.93	6.68	34.90	15.04
2014	33.13	10.97	6.88	35.86	13.15
2015	32.52	11.21	6.20	36.37	13.70
2016	32.48	12.12	6.06	37.69	11.65
2017	32.54	12.28	6.06	37.68	11.92
2018	32.48	12.19	6.08	37.44	11.82
2019	32.47	12.26	6.06	37.31	11.79
2020	32.61	12.37	6.08	37.70	11.75
2021	32.37	12.39	6.10	37.85	11.68
2022	32.27	12.37	6.10	37.95	11.61

Source: based on CEPEA and ABIOVE (2024) and IBGE (2024)

4.3.8.2 Monthly Income

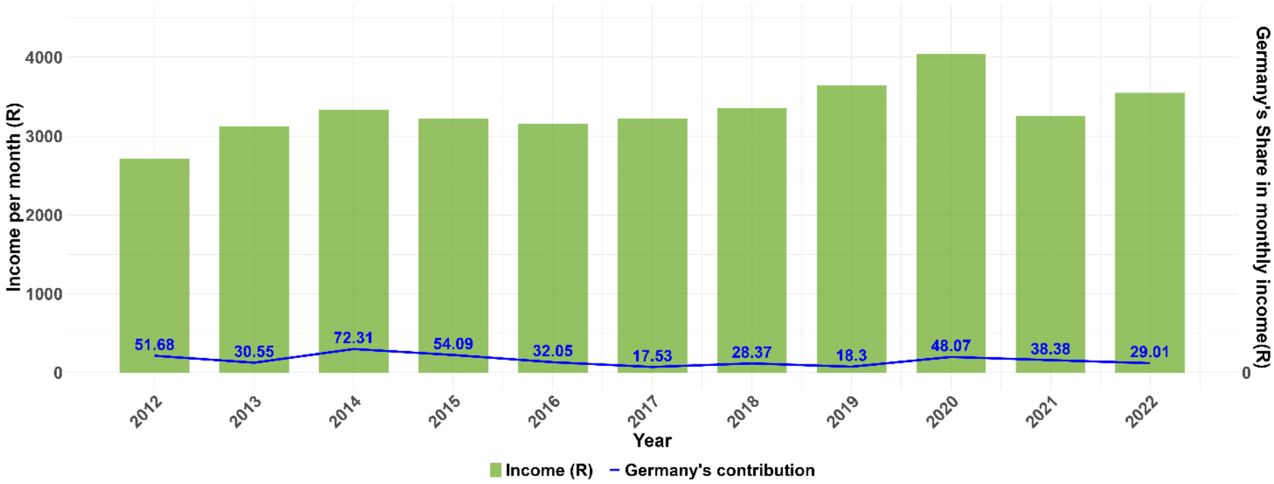
The monthly income in the soy production significantly exceeds the national minimum wage. However, there are considerable differences depending on the type of employment. Employers earn more than three times the average income. In contrast, informal employees earn less than their formal counterparts and self-employed individuals in this sector earn more than those formally employed. To summarise, it can be said that despite the higher average income in the primary soy production, income equity remains an issue.

Figure 54: Monthly income in primary soy production by type of employment between 2012 and 2022

Source: own calculations based on CEPEA and ABIOVE (2024) and IBGE (2024)

The average monthly income in soy production slightly increased from 2750 R in 2012 to around 4000 R in 2020. In 2021 in dropped to 3250 R but increased again in 2022 (cf. Figure 55). The share of monthly income that arithmetically results from soy exports to Germany fluctuates between a minimum of 17.53 R and a maximum of 72.31 R. Depending on the year, this is less than 1% to a maximum of 2.5%.

Figure 55: Average monthly income and Germany's contribution through soy exports between 2012 and 2022

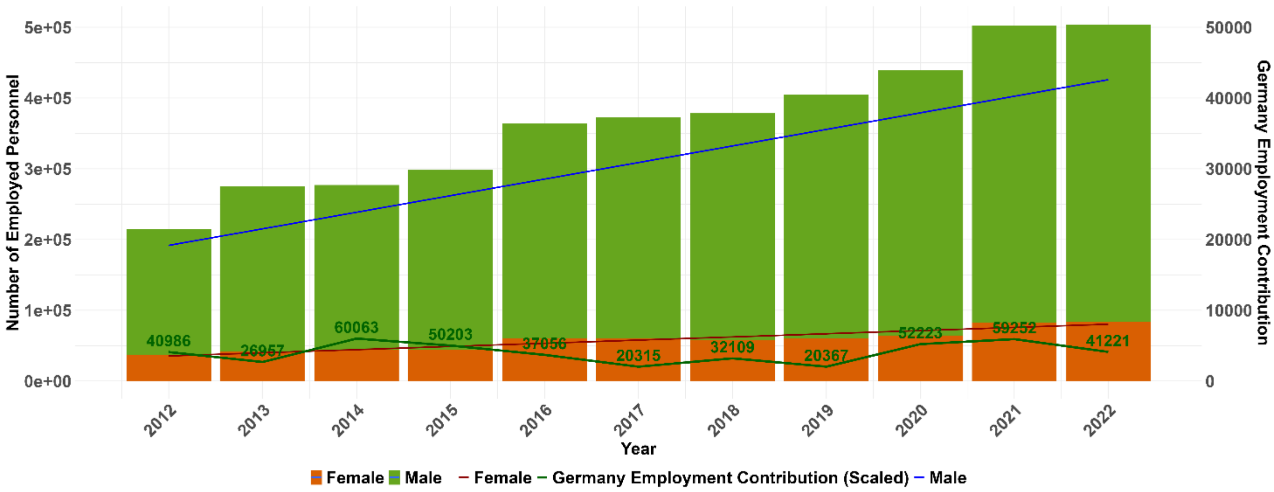


Source: own calculations based on CEPEA and ABIOVE (2024) and IBGE (2024)

4.3.8.3 Gender Balance

Figure 55 shows that the number of men employed in the soy production is still significantly higher than that of women. Between 2012 and 2022, the share of female employment in soy production fluctuated only between 15% and 17%. In contrast, male employment consistently accounted for 82% to 85%. Notably, this gender gap has even widened between 2012 and 2022, despite the growth and the overall increase in employment in soy production. Total employment in soy production increased from around 220,000 in 2012 to round about 500,000 in 2022. The green line represents the number of individuals employed in Brazil's soy production corresponding to the share of soybeans exported to Germany each year. While there was a slight decline in these numbers from 2016 to 2019, the last three years have shown a modest increase. The percentage of persons employed in soy production for export to Germany, however, declined from 1.8% in 2012 to 0.9% in 2022.

Figure 56: Gender balance in employment in soy production and Germany's contribution to total employment through exports between 2012 and 2022



Source: own calculations based on CEPEA and ABIOVE (2024) and IBGE (2024)

4.4 Conclusions

In order to carry out a comprehensive assessment of the sustainability effects of imported raw materials in their countries of production, we have applied an integrated approach consisting of material flow analysis (MFA), life cycle sustainability assessment (LCSA) and logical framework for sustainability assessment (LOFASA). Using the examples of beef from Argentina, soya from Brazil and pulp from Uruguay, we can show that the chosen approach enables a differentiated analysis of the sustainability effects of important import commodities for all steps of the value chain. If the information from the producing countries is combined with information on further processing, utilisation and disposal, a complete picture of the sustainability effects of products made from imported biomass is obtained.

Due to the size of individual producing countries (e.g., Brazil, Argentina), environmental sustainability effects in particular should be recorded as regionally as possible in order to take account of regional geographical, climatic and natural differences. National averages do not do this and can lead to considerable underestimation or overestimation of effects. While regional data is available for Brazil, it is not yet available in comparable quality for Argentina. Another critical aspect is the need for stakeholder engagement in sustainability assessments. A participatory approach to indicator selection can enhance the relevance and applicability of the framework for different commodity sectors and in different regions. Overall, however, the data situation is satisfactory. Data can be found in official statistics, association statistics and scientific studies. When using these, it is important to ensure that they have been collected for the same accounting period. If this is not the case and they cannot be scaled to the same accounting area, they should not be used.

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Annex

Annex 1

Author(s)	Definition		Method	Type of biomass	Type of substitution	Sector	Country	Time horizon (years)
Asada et al. (2020)			Modelling	Various	Material and Energetic Use	Other	Global	14
Bösch et al. (2019)		Implicit	Modelling	Forest	Material and Energetic Use	Other	Germany	34
Braun et al. (2016)		Implicit	LCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Forest-based	Austria	91
Chang et al. (2018)		Implicit	Direct calculation	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Forest-based	Korea	Inconclusive
Chen et al. (2018)		Implicit	CLCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Forest-based	Canada	100
D'Amico et al. (2021)		Implicit	LCA	Forest	Fossil by biomass (Material use)	Construction	Global	31
Eriksson et al. (2007)	Explicit		Direct calculation	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Energy	Norway	Inconclusive
Geng et al. (2019a)		Implicit	LCA	Forest	Fossil by biomass (Material use)	Forest-based	China	Inconclusive

Geng et al. (2019b)		Implicit	Direct calculation	Forest	Fossil by biomass (Material use)	Construction	China	11
Gustavsson et al. **(2006a)**	Explicit		LCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Construction	Sweden Finland Norway	Inconclusive
Gustavsson et al. (2006b)		Implicit	LCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Energy	Sweden Finland	100
Gustavsson et al. (2017)		Implicit	Other	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Construction	Sweden	100
Han et al. (2016)	Explicit		Modelling	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Forest-based	Korea	280
Haus et al. (2014)		Implicit	LCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Energy	Norway	240
Herrmann et al. (2013)			ALCA	Agricultural	Fossil by biomass (Energetic use) Biomass by biomass (Energetic use)	Energy	Denmark	2
Höglmeier et al. (2015)			ALCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Construction	Germany	Inconclusive
Hurmekoski et al. (2020)		Implicit	Modelling	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Energy	Finland	40

Karlsson et al. (2015)		Implicit	CLCA	Agricultural	Biomass by biomass (Material use) Biomass by biomass (Energetic use)	Energy	Sweden	Inconclusive
Kayo and Noda (2018)			Modelling	Forest	Fossil by biomass (Material use)	Forest-based	Japan	36
Kayo et al. (2015)		Implicit	LCA	Forest	Biomass by biomass (Material use) Fossil by biomass (Energetic use)	Construction	Japan	36
Kayo et al. (2019)		Implicit	ALCA	Forest	Fossil by biomass (Material use)	Construction	Japan	37
Klein et al. (2013)	Explicit		Modelling	Forest	Material and Energetic Use	Other	Germany	180
Knauf (2015)		Implicit	LCA	Forest	Fossil by biomass (Material use)	Other	Germany	6
Knauf et al. (2015)	Explicit		Modelling	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Forest-based	Germany	89
Knauf et al. (2016)	Explicit		Modelling	Forest	Material and Energetic Use	Other	Germany	90
Kunttu et al. (2021)		Implicit	LCA	Forest	Inconclusive	Construction	Finland	35
Landry et al. (2021)	Explicit		Direct calculation	Forest	Fossil by biomass (Material use)	Other	Canada	100

Li (2012)		Implicit	ALCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Construction	Taiwan	Inconclusive
Lun et al. (2016)		Implicit	ALCA	Forest	Material and Energetic Use	Construction	China	41
Lundmark et al. (2014)	Explicit		ALCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Energy	Sweden	205
Mair-Bauernfeind et al. **(2020)**		Implicit	ALCA	Forest	Fossil by biomass (Material use)	Forest-based	Global	Inconclusive
Martes and Köhl (2022)		Implicit	Modelling	Forest	Fossil by biomass (Material use)	Forest-based	Germany	88
Moreau et al. (2022)		Implicit	Direct calculation	Forest	Fossil by biomass (Material use)	Other	Canada	80
Morken and Sapci (2013)		Implicit	LCA	Agricultural	Fossil by biomass (Material use)	Energy	Norway	Inconclusive
Morris (2017)	Explicit		ALCA	Forest	Fossil by biomass (Energetic use)	Energy	United States	100
Myllyviita et al. (2022)		Implicit	Direct calculation	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Construction	Nordic countries	30

Nepal et al. (2016)		Implicit	CLCA	Forest	Fossil by biomass (Material use)	Construction	United States	51
Ngunzi (2015)	Explicit		Direct calculation	Agricultural	Fossil by biomass (Energetic use)	Construction	Nairobi	1
Olguin et al. (2018)		Implicit	Modelling	Forest	Fossil by biomass (Material use)	Forest-based	Mexico	51
Petersen and Solberg (2004)		Implicit	LCA	Forest	Fossil by biomass (Material use)	Construction	Norway	45
Pingoud et al. (2010)		Implicit	Modelling	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Construction	Sweden Finland	40
Poljatschenko and Valsta **(2021)**		Implicit	LCA	Forest	Fossil by biomass (Material use)	Construction	Finland	4
Poudel et al. (2012)		Implicit	Modelling	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Energy	Sweden	100
Pukkala (2011)	Explicit		Modelling	Forest	Fossil by biomass (Energetic use)	Other	Finland	240
Raymer et al. **(2009)**	Explicit		Other	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Other	Norway	120
Raymer et al. (2011)	Explicit		Other	Forest	Fossil by biomass (Material use)	Other	Norway	150

					Fossil by biomass (Energetic use)			
Sathre and Gustavsson (2009)		Implicit	Other	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Construction	Sweden	Inconclusive
Schulte et al. (2021)	Explicit		ALCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Forest-based	Sweden Uruguay	100 50
Smyth et al. (2014)		Implicit	Modelling	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Forest-based	Canada	36
Smyth et al. (2017)		Implicit	Modelling	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Energy	Canada	Inconclusive
Smyth et al. (2020)		Implicit	Direct calculation	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Energy	Canada	56
Suh (2016)		Implicit	Other	Forest	Fossil by biomass (Energetic use)	Energy	United States	Inconclusive
Suter et al. (2017)	Explicit		LCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Construction	Switzerland	Inconclusive
Tsunetsugu and Tonosaki (2010)	Explicit		Other	Forest	Fossil by biomass (Material use)	Construction	Japan	44

Werner et al. (2006)	Explicit		ALCA	Forest	Fossil by biomass (Material use)	Construction	Switzerland	131
Wilnhammer et al. (2015)			ALCA	Forest	Fossil by biomass (Material use) Fossil by biomass (Energetic use)	Forest-based	Germany	26
Yongmei et al. (2016)		Implicit	LCA	Agricultural	Fossil by biomass (Energetic use)	Energy	Japan	Inconclusive

Annex 2

System boundary of soy production in Brazil

This stage encompasses soil preparation, seed treatment and sowing, the growing period, and, finally, harvest and drying. Data regarding soybean production across various states in Brazil have been obtained from ecoinvent (2024). For the purpose of this study, the states of: Mato Grosso (MT), Bahia (BA), and Rio Grande do Sul (RS) are selected. The following sections will provide detailed explanations of agricultural practices within each region.

In Annex Figure 1 the system boundary for soybean production stage is defined to include the inputs (lime, fertilizer, fuel, seeds, and pesticides), the key stages of soybean production (soil preparation, seed treatment and sowing, growing period, and harvest), and the associated emissions (soil, land use change, and transport emissions). The ecoinvent dataset offers a comprehensive overview of agricultural inputs and operations, structured as follows:

Included Inputs and Operations:

The dataset includes key agricultural inputs, specifically seeds, mineral fertilizers, and pesticides, under the assumption that no organic fertilizers are utilized. It outlines various machine operations, and the necessary infrastructure required for several activities, such as the application of limestone and gypsum, the use of plant protection products, planting with starter fertilizers, fertilization processes, combine harvesting, and drying of grains.

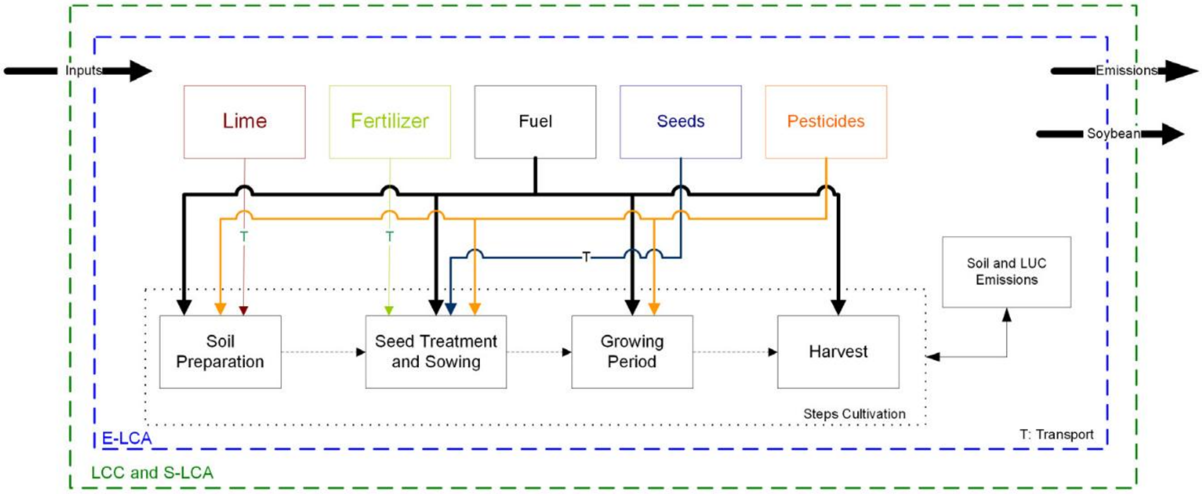
Estimations and Emissions:

For agricultural operations not explicitly detailed, the dataset estimates fuel consumption and associated emissions. It also includes the transportation of essential products within the farm, which comprises the movement of water, soil correctives, and fertilizers from storage facilities to fields, as well as the transportation of harvested grains from the field to trucks.

Emissions Accounting:

The dataset accounts for direct emissions generated from the fields and emissions related to land-use changes, incorporating significant regional distinctions to enhance accuracy.

Annex Figure 1: Technical system of soy production in Brazil

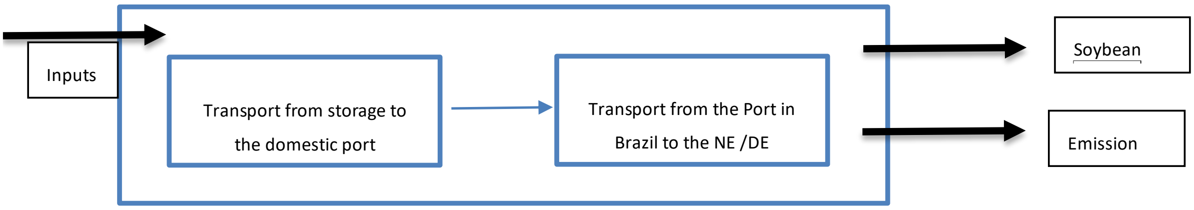


Source: own illustration based on (Zortea et al. 2018)

Transportation

The final stage involves the transportation of soy from the distribution centre to the domestic port in Brazil, followed by shipping to Hamburg. The transportation process varies from region to region and requires customised and optimised logistics. Further elaboration on these specifics will be provided subsequently.

Annex Figure 2: Technical system of soy transport from production sites in Brazil to Germany



Source: own illustration based on ecoinvent (2024)

Data and tools

For the environmental assessment of soy production in Brazil and its transportation to Hamburg, Germany, the openLCA version 2.1.0 in conjunction with the ecoinvent database version v3_10 is utilized. To ensure comprehensive coverage and detailed insights, the unit process database with a cut-off approach is selected. The cut-off approach, known for its simplicity and ease of application, assumes that any recyclates used in the system come without any environmental burdens from their previous life. Specifically, the dataset **ecoinvent_v3_10_Cutoff_Unit_Processes_Superseded_Regionalisation_2024_01_22** is employed. This approach provides more granular and localized data, essential for capturing the specific environmental impacts associated with soy production and transportation from different regions in Brazil to Hamburg. Furthermore, the ReCiPe 2016 Midpoint (H) method for calculating environmental impacts is selected. By integrating region-specific information on elementary flows within the processes, the accuracy and specificity of our assessment is enhanced, thereby contributing valuable insights to the understanding of the environmental footprint of soy trade between Brazil and Germany.

Transport routes for each region

The Ecoinvent database includes detailed flows and processes for soy production in different regions in Brazil. For the purpose of this study, the states of: Mato Grosso (MT), Bahia (BA), and Rio Grande do Sul (RS) are selected. These states respectively represent the Central-West, Northeast, and South regions of Brazil. For each of these regions, we the typical transport chain from a nearby port in Brazil to Hamburg is identified utilizing the Route Scanner website., The means of transport are identified and the corresponding distances for each leg of the journey from the distribution centre in Brazil to the port of Hamburg are calculated. Then the means of transport are sorted based on CO_2 emissions and the journey with the lowest emissions is selected. This approach is adopted because numerous factors can influence the emissions associated with transportation routes, including the mode of transport, fuel type, loading conditions, and specific transportation routes. Given the complexity of accounting for all these variables to achieve a realistic assessment, we opted to focus on minimizing emissions. This strategy allows us to gain a clearer understanding of transportation emissions in relation to production. The transport chains are detailed as follows.

Annex Table 1: Transport routes from distribution centre in Brazil to Hamburg

		Place of departure	Place of arrival	Place of departure	Place of arrival	Place of departure	Place of arrival	Place of departure	Place of arrival
Production region	C W	Avenida Matto Grosso, Juína	Rondonopolis - Brado Logistica	Rondonopolis - Brado Logistica	Brasil Terminal Portuario (BTP)	Brasil Terminal Portuario (BTP)	APM Terminal Tangier Med (TC1)	APM Terminal Tangier Med (TC1)	Eurogate Container Terminal Hamburg
Means of transport		Lory		Train		Ship		Ship	
distance		1012 km		1579 km		8221 km		3217 km	
Production region	NE	Rua São Desidério, Salvador	Tecon Salvador Container Terminal (TECSV)			Tecon Salvador Container Terminal (TECSV)	Container Terminal Altenwerder Hamburg (CTA)		
Means of transport		Lorry				Ship			
distance		10 km							
Production region	S	Tupanciretã	Rio Grande Port Spermar(SUPMA)			Rio Grande Port Supermar (SUPMA)	Eurogate Container Terminal Hamburg (EGH)		
Means of transport		Lorry				Ship			
distance		458 km				12588 km			

Source: own compilation

In Brazil, transport service providers commonly use double trailer trucks with either seven or nine axles for shipping agricultural bulk goods. The seven-axle model, Bitrem, has a net weight cargo of 37 tons and a maximum gross weight of 57 tons, while the nine-axle model, Rodotrem, has a net weight cargo of 50 tons and a maximum gross weight of 74 tons (Fliehr 2013).

In addition, Brazil's P-8 emission standards for heavy-duty vehicles (HDVs), which are equivalent to the Euro VI standards in the European Union, were established by the National Council for the Environment (CONAMA) and became effective for new type approvals on January 1, 2022, and for all new sales and registrations on January 1, 2023. (P-8 Emission standard). Therefore, for the land transport from distribution centre to the port in Brazil for the data set 'transport, freight, lorry >32 metric ton, EURO6' was used.

Cut-off criteria

To assess the sustainability effects associated with soy, the steps of use, recycling, and disposal are excluded. Also, sustainability effects associated with cleaning of soy after harvest and storage are in general cut-off from the assessment. It is essential to recognize the limitations of the dataset, particularly regarding certain excluded elements. Specifically, the dataset does not include seed treatment processes or the application of bacterial seed inoculants, such as Rhizobium sp., which play a significant role in nitrogen fixation. Furthermore, the dataset omits the cleaning and storage of harvested grains. The dataset delineates the conclusion of agricultural activities at the point when the products reach the farm gate.

Annex 3

Annex Table 2: Overview of VSS included in the benchmark

Voluntary Standard System	Organisation	Scope
FEFAC Soy Sourcing Guidelines 2021	Industry	Soy only
ADM Responsible Soybean Standard	Producer/Trader	Soy only
Agricultura Sustentable Certificada + Module on Non-conversion	Industry	Soy only
Amaggi Origins Field	Producer/Trader	Various
Bunge Pro-S Assuring Sustainable Sourcing	Producer/Trader	Various
CSQA Sustainable Cereal and Oilseed Standard (DTP 112)	Company	Various
Cargill Triple S Soya Products	Producer/Trader	Soy only
Cefetra Certified Responsible Soya Standard (CRS)	Producer/Trader	Soy only
Donau Soja	Multi-Stakeholder	Soy only
Europe Soya	Multi-Stakeholder	Soy only
FEMAS Responsible Sourcing Module 2021	Industry	Various
ISCC EU	Multi-Stakeholder	Various
ISCC Plus	Multi-Stakeholder	Various
Louis Dreyfus Company (LDC) Program for Sustainable Agriculture	Producer/Trader	Soy only
PROFARM Production Standard	Company	Various
ProTerra Europe	Multi-Stakeholder	Various
ProTerra Foundation	Multi-Stakeholder	Various
Round Table on Responsible Soy Association (RTRS)	Multi-Stakeholder	Soy only
SODRU Sustainable Soy	Producer/Trader	Soy only
Sustainable Farming Assurance Programme – Non-Conversion (SFAP)	NGO	Soy only
U.S. Soy Sustainability Assurance Protocol (SSAP)	Industry/Government	Soy only

Source: (Profundo 2023)

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