Monitoring Bioeconomy

3 DECEMBER 2024

Monitoring the German Bioeconomy

STATUS, PERFORMANCE, TRENDS AND IMPLICATIONS FOR SUSTAINABLE DEVELOPMENT

Bioeconomy Monitoring Report 2024

Monitoring the German Bioeconomy: Status, performance, trends and implications for sustainable development

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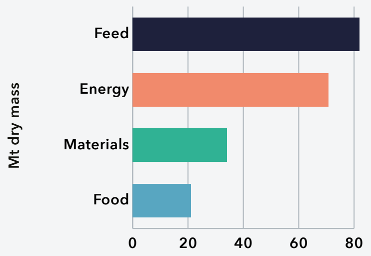
BIOMASS USE

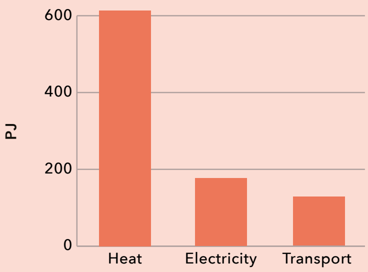
Overview



Total biomass end uses in 2020, including residues

Over 200 million tonnes (t) dry mass of biomass from agriculture, forestry and fisheries were used by the German bioeconomy in 2020. 4 times as much biomass is used for feed than for food.

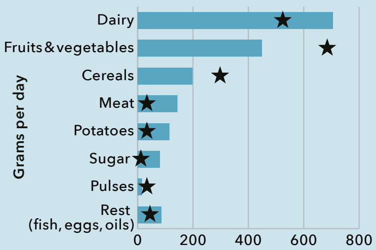
Energy



Bioenergy use in 2023, in petajoules

Biomass contributed 919 petajoules to German energy supply in 2023, or 12 % of total energy and 49 % of renewable energy provision. While agricultural crops were the largest source of biomass input material for bioenergy in Germany in 2020 (44 % in terms of tonnes dry mass), a significant shift towards the use of residues and wastes occurred from 2020 until 2022.

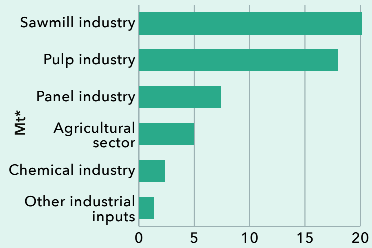
Food



Average German diet (2022) compared to dietary recommendations (★)

Meat consumption in Germany is at least 3 times higher than recommended.

Materials



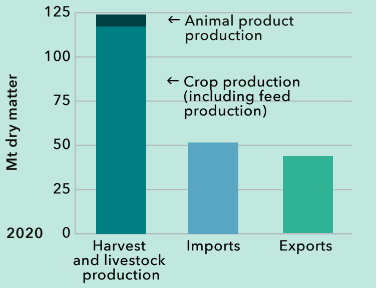
Biomass use in material sectors in Germany, 2020

Biomass use by German 'material' processing industries is dominated by forest-based biomass streams, especially as inputs to the sawmill and pulp industries (38 million t combined). Around 2 million t of agricultural biomass were used as inputs in the chemical sector in 2020.

* Data depicts input mass used for processing biomass in German industries (some of which is later exported for material end use abroad). It is based on multiple sectoral reports and does not include conversion losses, causing deviations to the overview (which shows final end use amounts). For the agr. & chem. sectors, ingredient materials are included, whereas for forestry, dry mass is depicted.

BIOMASS FLOWS

Agricultural biomass

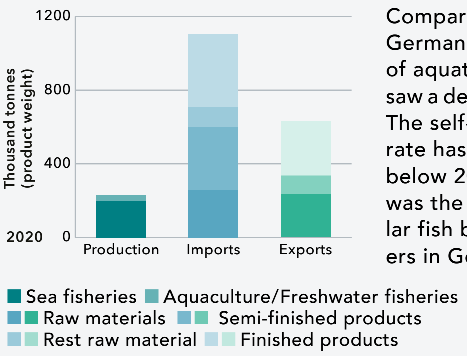


Nearly 80 million t dry matter of agricultural biomass were used for feed for animal husbandry in 2020. 100 million t were used for non-feed purposes (energy (50 %), food (39 %), material use (7 %) and pet food (4 %)).

Forestry biomass

Removals of roundwood increased significantly, due to salvage fellings caused by forest disturbances, also causing Germany to become a net exporter of roundwood in 2020. Most roundwood is processed in sawmills and around 28 % is used for energy.

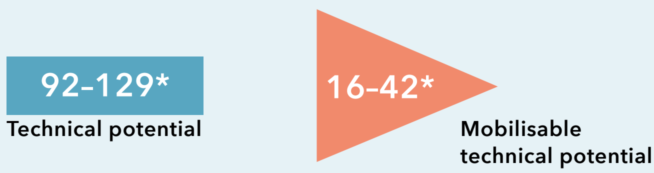
Aquatic biomass



Compared to 2015, German production of aquatic biomass saw a decline of 11 %. The self-sufficiency rate has dropped to below 20 %. Salmon was the most popular fish by consumers in Germany.

* Note: Finished products includes fish meal and oil

Secondary biomass



The potential of secondary biomass (waste, by-products and residues) has slightly decreased rather than increased from 2015 to 2020.
The largest share of technical potential stems from municipal waste and sewage sludge.

* Million tonnes dry mass in 2020

SOCIO-ECONOMIC TRENDS AND IMPACTS

Employment **2.7–2.9** million jobs in Germany

Decreasing trend

The bioeconomy comprised at least **7 % of total employment** in Germany. Nearly half of all bioeconomy employment in 2020 was in manufacturing. Unlike the rest of the economy, employment is in decline, in particular in primary sectors.

Gross value added **€ 134–150 billion**

Fluctuating and rather steady since 2010

The bioeconomy comprised around **5 % of total gross value added** in Germany. In contrast to the price-adjusted gross value added for Germany as a whole, the development of the German bioeconomy fluctuated (with 5 % growth between 2010 and 2017 and back to the same level in 2020 as in 2010).

Innovation

Comparatively high*

Innovative wood products (44)
Agriculture 4.0 (55)
Bio-based surfactants (66)

Increasing since 2009

Comparatively low*

Biotechnology (–47)
Biopharmaceuticals (–55)
Plant breeding (–59)
Microbiomes (–71)

Decreasing since 2009

Technology trends in Germany are characterised by a wide range of innovations. Patent analysis shows that Germany has a relatively high degree — and increasing level — of specialisation in some areas, whereas in all technology-related areas specialisation is below the global average.

* Relative patent advantage index (2019–2022)

ENVIRONMENTAL IMPACTS, FOOTPRINTS AND SUSTAINABILITY

Agricultural biomass footprint

4.1 tonnes per capita in 2021

30 % of the footprint in 2021 was sourced from Germany (with another 21 % stemming from the EU). In comparison to the global average, German total consumption is around one-third higher. It is over double the suggested reference value (of 2 t of both agriculture and forestry biomass) for keeping global consumption levels within planetary boundaries.

Timber footprint

0.8 cubic meters roundwood equivalents for industrial use per capita in 2021

Looking only at industrial use of timber (excluding fuel wood), it was found that a little more than 80 % of the estimated footprint stems from Europe.

Climate footprint

1.9 tonnes CO_2 equivalents per capita in 2021

The bioeconomy climate footprint comprised around **15 % of the total German economy footprint** in 2021. Domestic-related emissions accounted for 1.05 t of CO_2 equivalents per capita in 2021. Adjusting meat consumption and energy use are key reduction potentials.

Agricultural land footprint

5.6 Square meters per capita in 2021

The agricultural land footprint was around 2.8 times larger than the land used for agricultural production within Germany in 2021. Grassland for grazing comprised more than 60 % of the footprint, with particularly high land demands in Argentina, Germany, the USA and China. Around two-thirds of the total footprint was on land associated with medium risk of soil erosion.

Water footprint

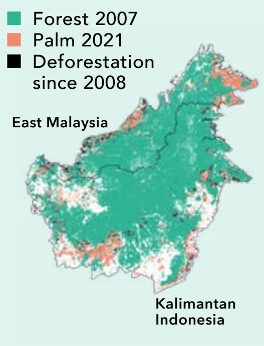
451 Cubic meters per capita in 2020

The total water requirement of the German bioeconomy was 37 km³ in 2020, of which around 8 % was irrigation water withdrawals. 16 % of agricultural goods for the German bioeconomy were produced in regions with high or medium water stress.

Biodiversity footprint

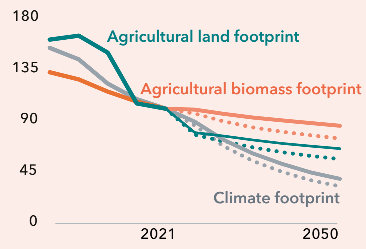
Preliminary results on the biodiversity footprint, calculated as a case study, show that the biodiversity impacts of German consumption of Brazilian soybean increased by 134 % from the period 1997–2007 to the period 2008–2018, despite decreasing levels of imports. This was mainly a result of the expansion of soy-production areas into biodiverse landscapes.

Crop-driven deforestation abroad



Using remote sensing technology to monitor crop-driven deforestation hotspots is useful to facilitate an understanding of the implications of the German bioeconomy on global resources. The consolidated map shows the deforestation attributed to oil palm cultivation between 2015 and 2021 in specific regions of Indonesia and Malaysia.

Future scenarios



Solid line: Past trend and reference scenario
Dotted line: Dietary change scenario

The biggest lever for reducing environmental footprints depicted in this report is shifting diets toward less meat. If meat intake levels in Germany were reduced to the level recommended by national dietary guidelines (300 g per week), it would reduce the agricultural biomass footprint by 13 %, the agricultural land use footprint by 14 % and the climate footprint by 17 % in 2050 compared to the reference scenario.

1. Introduction

Aims of the report

This report aims to further develop a regular reporting of bioeconomy monitoring in Germany. It builds on the pilot bioeconomy monitoring report published in 2021 (Bringezu et al. 2021a). Specifically, it is intended to:

- Provide an overview of the current status and performance of the German bioeconomy from a systemic sustainability perspective
- Build the evidence base for policies to steer the bioeconomy transition in Germany based on relevant and robust data, indicators, trends and scenarios
- Showcase key findings of two research projects, including reflections on monitoring methods, capacities, and needs: SYMOBIO (funded by BMBF; symobio.de) and MoBi II (funded by BMEL; Thuenen.de)

Policy context

The German ***National Bioeconomy Strategy*** (BMBF and BMEL 2020) outlines policy guidelines and strategic goals for promoting innovation and collaboration to harness biogenic raw materials. It aims to establish a sustainable and circular bioeconomy which operates within ecological boundaries. It also sets out the objectives of and needs for developing a comprehensive monitoring system. Monitoring should both measure and analyse biomass flows as well as evaluate sustainability in order to develop the evidence base needed for guiding policies. The Strategy states:

> "To achieve these [multifaceted] goals, it is important that we **take the right path.** Observing, measuring and evaluating the process of transformation … are an important prerequisite in ensuring that we do not achieve individual goals at the expense of others …[and] to make certain that we **set priorities correctly."** (BMBF and BMEL 2020).

The ***National Biomass Strategy*** (BMWK, BMEL and BMUV 2022) should contribute to the medium and long-term sustainable production and use of biomass, taking climate change mitigation, biodiversity conservation and resource efficiency into account. According to the press release announcing the strategic direction for the planned

policy, it should be aimed at creating the necessary political framework in Germany by establishing a mix of instruments with practical steering effects, including the adoption of measures incentivising or disincentivising biomass production and use as well as compulsory requirements.

Target audience and how to read the report

This report is intended for a wide public audience (policymakers, researchers, NGOs, industry and civil society) and is designed to reach readers with different levels of pre-existing knowledge about the bioeconomy. **Newcomers** to the topic will find an introduction to the wide array of issues relevant to the bioeconomy and the kinds of considerations needed for a successful transition. **Experts** will gain a quick overview of updated data and new results, and find links to the in-depth research describing those results.

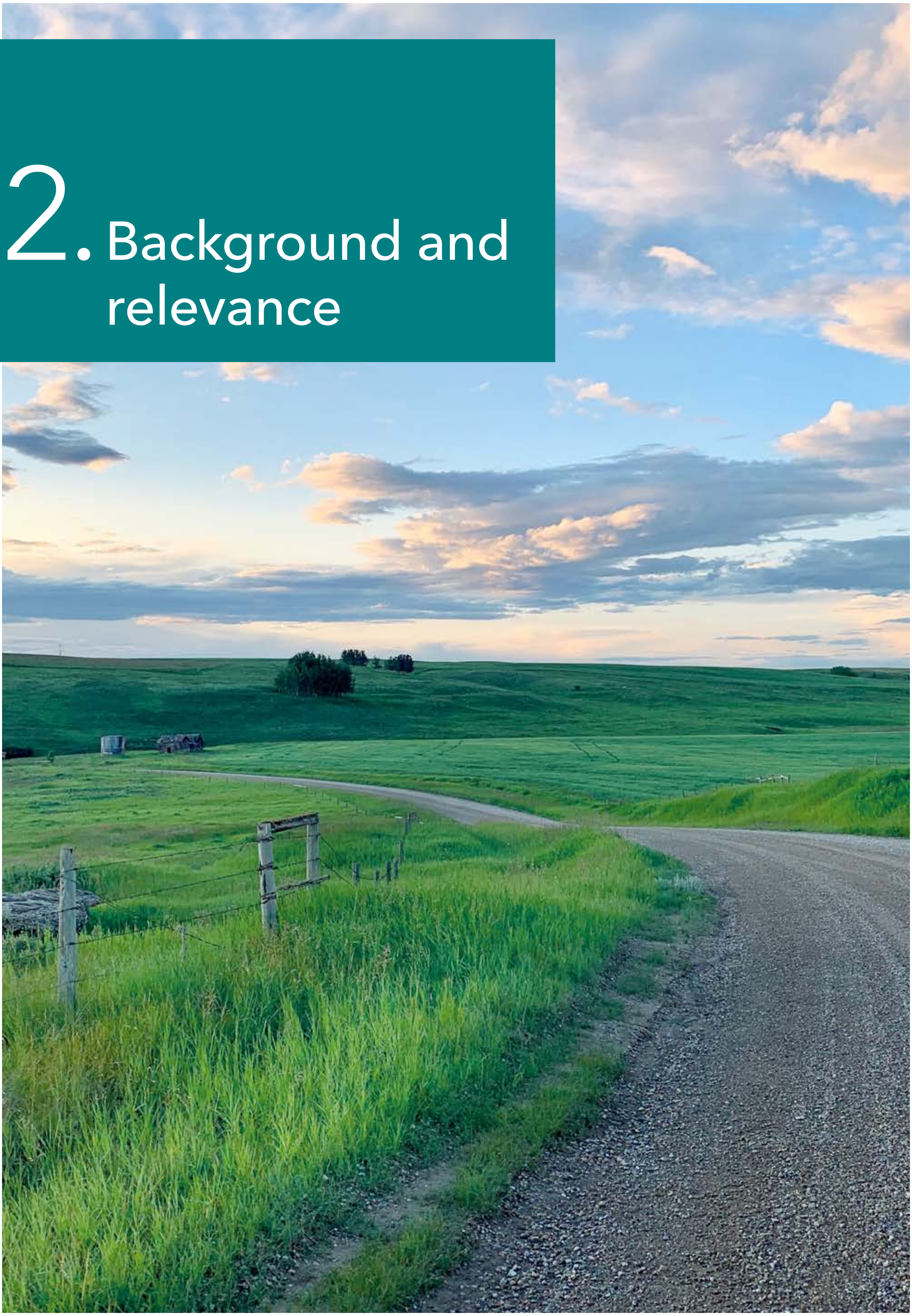
Chapters are organised around the dimensions of a sustainable transition and key indicators, trends and drivers are included throughout the report. Chapter 2 provides background information on definitions, context, narratives, and monitoring challenges, while Chapter 8 summarises key messages and overarching conclusions. Finally, **"Monitoring Check"** information boxes throughout reflect on the state-of-the-art of monitoring tools. They provide assistance on how to interpret data, highlight strengths and limits of different methods, consider needs for filling gaps, and together emphasise that multiple tools — and likewise indicators — are needed to cover the varied aspects of the bioeconomy.

Further information, supplementary data and descriptions of methods

- Supporting data and tables as well as methodological descriptions are found in supplementary information annexes, published simultaneously to this report and available on our website under publications: bioeconomy monitoring report

- Visit our Bioeconomy Monitoring Website to get up-to-date news about the bioeconomy as well as an overview of data, indicators, and monitoring tools: www.monitoring-biooekonomie.de/en/

2. Background and relevance



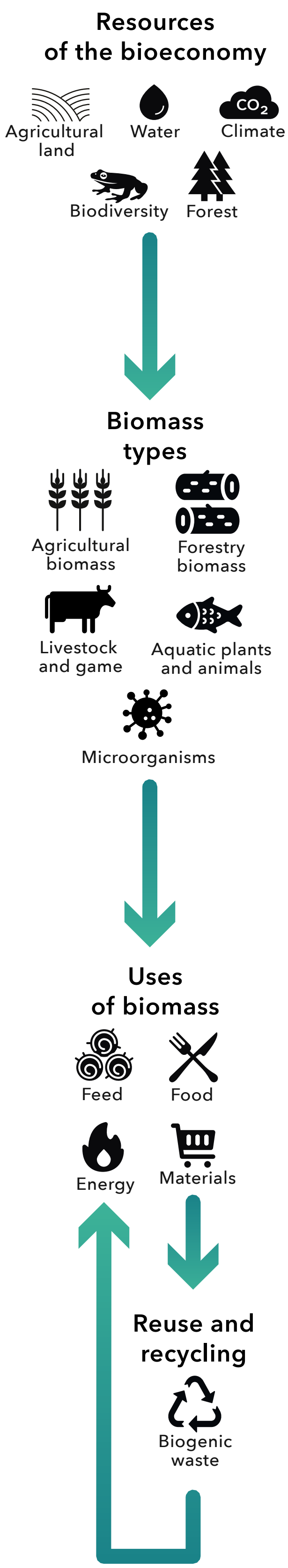
Authors: Section 2.1: Meghan Beck-O'Brien[1] I Section 2.2: Walther Zeug[2] I Section 2.3: Christina Zinke[2], Daniela Thrän[2], Alberto Bezama[2]

Key findings

- The bioeconomy is needed to replace fossil resources, but how it is implemented matters significantly to whether climate, environmental and socio-economic aims are met or missed.
- As a cross-cutting topic, the bioeconomy spans all production and consumption activities where biomass is used. Innovation is at the heart of the transition.
- A systemic monitoring is needed to understand, manage and overcome challenges, in particular as regards identifying trade-offs between sustainability dimensions.
- Sustainability in this report is linked to aims for a holistic bioeconomy transition. Core elements include climate-neutrality, circularity, and balance between production and consumption systems. Sustainable biomass use is efficient, sufficient, just and safe. The capacity for monitoring these aspects, however, still varies widely.
- Stakeholder participation helps to build a monitoring that is credible, transparent, and covers multiple perspectives.
- The perception of stakeholders as regards narratives versus implementation of the EU and German bioeconomy strategies differs widely, with an express desire towards a socio-ecological transformation, but a perception of the bioeconomy's current performance as closer to green capitalism.
- Stakeholders have identified monitoring gaps in the coverage and robustness of social indicators as compared to environmental and economic dimensions. This gap was also identified in a review of the monitoring landscape (assessing more than 60 reporting systems with relevance for bioeconomy monitoring).
- Dedicated reporting initiatives, programs and activities monitor specific and varied aspects of the bioeconomy (from natural resource management to innovation activities and social change). While individually they do not provide a systemic overview of the bioeconomy transition, they can provide deep insights into detailed aspects, as well as potential overlaps, synergies and connection points for bioeconomy monitoring as a whole.
- The six environmental footprints presented in Chapter 7 have thematic links to more than 60 reviewed monitoring initiatives with bioeconomy relevance, revealing the potential for the monitoring presented in this report to complement on-going activities.

1 Center for Environmental Systems Research (CESR), University of Kassel
2 Helmholtz Centre for Environmental Research (UFZ)

Figure 2.1 The bioeconomy spans production and consumption systems



2.1 Scope, challenges and sustainability

What is the bioeconomy?

The bioeconomy is seen as a way to reduce the consumption of non-renewable resources, ensure global food security, and promote local primary sectors (agriculture, forestry, fishing) as well as high-value manufacturing. It is defined in the German National Bioeconomy Strategy as:

> **"The production, exploitation and use of biological resources, processes and systems to provide products, processes and services across all economic sectors within the framework of a future-oriented economy" (BMBF and BMEL 2020).**

The overarching **aim is to combine economy and ecology to ensure a more sustainable use of resources.** It should contribute to reaching the Sustainable Development Goals (SDGs) as set out in United Nations' 2030 Agenda**.** The bioeconomy is thus a **cross-cutting topic** that includes all sectors where biomass is grown, harvested, produced, manufactured, consumed and re-used (Figure 2.1). It crosses global supply chains and spans a wide range of industrial uses: Examples include food, chemicals, construction, paper, textiles, energy and wood-product markets. Although currently small in size, expectations for new markets and applications based on microbes and biotechnology[1] are high, relating especially to e.g. pharmaceuticals and plastics. That said, the largest end-use of biomass in the German bioeconomy is, by far, feed for livestock. Germany uses around 4 times as much biomass for feed than for food (see Chapter 6).

Innovation is at the heart of the bioeconomy transition. It is explicitly formulated as the 5th strategic goal (see Figure 2.2), with recognition that innovation includes both high-tech solutions as well as new business models and forms of social organisation. Along these lines, also the German Bioeconomy Council calls for the coordinated promotion of **technological, organisational and social innovations** — as well as the transformation of markets and institutions — to strengthen social cohesion toward a sustainable and **circular** bioeconomy (Bioeconomy Council 2022).

Challenges: Navigating trade-offs to steer the bioeconomy

The bioeconomy is needed to move away from fossil fuels, but how it is implemented makes a large difference to whether overarching sustainability goals can be achieved. While the three dimensions of sustainability (environmental, economic and social) are core to the strategic goals, they do not always overlap in ideal 'win-win' outcomes. **Compromise, recognition of limits** and **risk mitigation** are necessary.

1 Biotechnology is defined as an application-oriented science that uses organisms, cells or bio-molecules in technical applications to manufacture products for different industries or to develop new technologies (BMBF and BMEL 2020).

Table 2.1 Opportunities and risks of the bioeconomy transition at the extremes

Opportunities	Risks
Lower fossil fuel use and dependence on fossil imports to reduce GHG emissions	Drive (massive) increased demands for crops and timber that trigger deforestation, degradation and unsustainable intensification worldwide, thereby increasing GHG emissions
Increase local supply loops that strengthen job and revenue opportunities within German communities	Increase import dependencies and incentives for land grabbing, illegal logging and environmental crime across the globe
'Made in Germany' is indicative of innovative and competitive marketplaces for green biotech — and as a pioneer and hub, Germany has created the jobs of tomorrow	High demands for primary biomass with the continued mass extinction of species and irreversible damage to Earth systems
Thriving circular bioeconomy business models and engaged citizens (repairing, sharing, collaborating and participating—in e.g. adapted social norms like on healthy levels of meat consumption) drive a socio-economic transformation (and help push forward the structural and institutional changes needed for up-scaling)	Unethical distribution of resources, including hunger, disease and loss of power in global markets
Agro-ecological farming, multi-purpose forestry and sustainable fishing embedded in healthy and robust ecosystems	Toxic and pollutive natural capital production causing disease in the workforce and poisoning soils and water

For monitoring, this means that an understanding of the trade-offs and conflicts between forms of biomass use, interests and corresponding societal goals is needed. Trends can point to potentially problematic developments. Many of the complex issues, however, require both social discourse (see Section 2.2 on stakeholder participation) and decisions based on broad societal consensus, especially as regards the prioritisation of sustainability objectives and ethical questions (related to e.g. concepts like food first, the quantification of environmental limits and the fair global distribution of limited resources). **The aim of our monitoring is to provide comprehensive, significant and reliable information for the public and political discussion.**

The opportunities and risks at the extremes of the spectrum are depicted in Table 2.1. Opportunities are mostly linked to the vision of a sustainable bioeconomy embedded in political strategies and the narratives for sustainable development. Risks particularly are linked to the resource base and its limits. This is compounded by two factors: **long supply chains** and the **scale of consumption**. As regards the former, efforts to ensure sustainable production and responsible supply chains range from voluntary (e.g. certification, round tables, reporting, voluntary standards, etc.) to regulatory, including e.g. the German Supply Chain Act (BJ 2021) and the EU Regulation on Deforestation-Free Products (EU 2023b). Tools and data presented in this report can underpin these efforts (in particular life cycle assessment in Chapter 4 and remote sensing in Chapter 5). However, even *if* 100 % of the bio-based materials and products imported to Germany were produced according to sustainability criteria, German consumption could still contribute to overburdening the planet. It comes down to scale. Resources like land and water are limited. The question is, **how much biomass** is available for German consumption in a sustainable way, and how does this amount (safe and fair biocapacity) relate to current and expected levels of German consumption? This report looks to and further develops consumption footprints and sustainability scenarios to start to answer this question (Chapter 7).

Developments on both the demand and supply sides of the bioeconomy need to be assessed in context of one another, and their **systemic** impacts. The National Bioeconomy Strategy emphasises the need for systemic monitoring and defines systemic as: "**looking at systems in their entirety and their interactions with one another, from the fundamental molecular principles to the complex interplay in ecosystems**" (BMBF and BMEL 2020). The following examples depict the types of fundamental questions about **trade-offs which must be navigated by society and policy**, and for which strong monitoring data is needed:

Figure 2.2 Strategic goals of the German National Bioeconomy

STRATEGIC GOALS OF THE GERMAN NATIONAL BIOECONOMY STRATEGY

1.	2.	3.	4.	5.	6.
Develop bioeconomy solutions for the 2030 Agenda for Sustainable Development	**Recognise and harness the potential of the bioeconomy within ecological boundaries**	**Enhance and apply biological knowledge**	**Establish a sustainable raw material base for industry**	**Promote Germany as the leading location for innovation in the bioeconomy**	**Involve society in the bioeconomy and strengthen national and international collaboration**
(e.g. guarantee global food security)	(e.g. establish comprehensive monitoring)	(e.g. promote innovation, research, collaboration and technology transfer)	(e.g. maintain soil fertility, conserve agricultural land and develop recycling)	(e.g. support start-ups, clusters and model regions)	(e.g. promote dialogue and social sciences)

Note: the examples present a selection of implementation objectives to depict the vast scope of the bioeconomy but are not comprehensive.

Source: BMBF and BMEL (2020)

- **Organic farming** in Germany has reached more than **10 % coverage of total utilised agricultural land area**, which is one-third of the 30 % target (BMEL 2022). While the target aims to promote agro-ecological farming — core to the attainment of e.g. biodiversity targets, there may also be a trade-off for the bioeconomy as regards lower **yields** for some crops. This could impact production levels and shift cultivation abroad, if not combined with adjusted consumption levels. The questions are, to what extent, and how can and should such potential impacts be mitigated?
- Drought, storm and insect damage has led to **unprecedented levels of stress on German forests** in recent years: only **1 in 5 trees are healthy** according to German national forest monitoring (BMEL 2024b). This raises questions such as: What impact does salvage logging, time needed for forest recovery, and programmes to re-structure forests have on the potentials for increasing the use of wood in the bioeconomy — e.g. for **building with wood** in the construction sector as well as in new applications such as biochemicals) — over the short-, mid- and long-term?
- All global **targets for biodiversity were unmet** in 2020 (CBD 2020). More ambitious goals have been set in regulatory (EU Biodiversity Strategy[2]) as well as voluntary frameworks (like The Bonn Challenge[3] for global forest restoration). How do these goals, if implemented rigorously, impact **biomass production potentials** nationally and internationally. In other words, is there a *nature conservation* versus *bioeconomy supply* dilemma, and if yes, where and at what scale?
- Drastically **reduced fish stocks** in the Baltic see have led to **job loss** (both for fishing and fish processing sectors). Are there lessons for other extractive and productive industries related to environmental impacts and harvesting quotas? What social measures are needed to accompany closures related to a transition (like new training programmes)?

Our report will not provide definitive answers to these questions. Instead, these questions are meant to show the kinds of questions core to the rationale, context, and importance of the monitoring.

2 See the dashboard online to check progress toward specific targets in the EU, including aspects like 30 % legal protection, 10 % strict protection and implementation of the new Nature Restoration Law; https://dopa.jrc.ec.europa.eu/kcbd/EUBDS2030-dashboard/?version=1#Target%203

3 The Bonn Challenge aims to bring 350 Mha of degraded and deforested landscapes into restoration by 2030. More information online at; https://www.bonnchallenge.org

What does a 'sustainable bioeconomy' mean?

A sustainable bioeconomy contributes to the **attainment of the SDGs**. It is **climate neutral**, supports **circular use** (with considerations of re-use already integrated into the product design), keeps levels of consumption **within ecological limits** (fair distribution of global planetary boundaries), and promotes the use of bio-based products in **prosperous** and **competitive** German markets (characterised by social acceptance and economic viability). The sustainable bioeconomy drives Germany towards becoming a **hub** for high- and low-tech **innovation**, creating jobs and new opportunities. Getting there will require compromise, as ultimately **balance** (Figure 2.3) is at the heart of a **coherent** and **holistic** transition.

This vision of the bioeconomy is rooted in the principles expressed by the European and German political strategies. It forms the basis for our understanding of monitoring needs and depicts the type of bioeconomy we understand to be 'sustainable'. That said, **the monitoring capacities connected to these concepts differ widely,** with some aspects much more advanced than others. In this report, we use e.g. simple scenario "wedges" to model and assess specific consumption and production levers connected to a sustainable bioeconomy transition. The needs for being able to better evaluate sustainability and improve monitoring tools, data and indicators are included throughout this report.

SUSTAINABLE BIOMASS PRODUCTION AND CONSUMPTION IS …

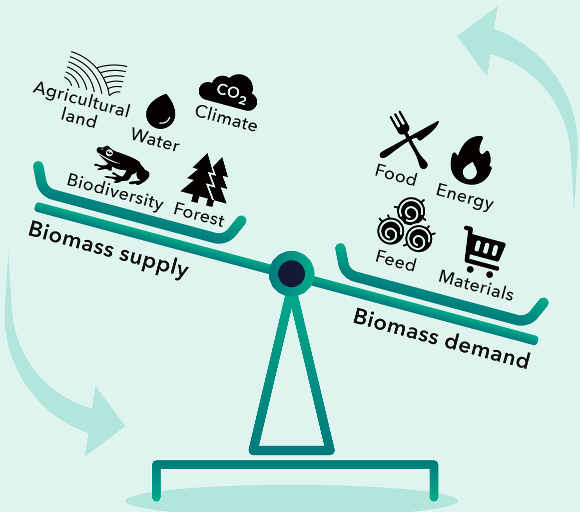
→ **Efficient:** Based on the principles of optimisation (of e.g. processes) as well as prioritisation (e.g. long-term and durable applications as well as material use before energy use) when appropriate (see e.g. Section 6.5.2 on cascades, circular economy and co-production)

→ **Sufficient:** Using as little energy and raw materials as possible (BMBF and BMEL 2020), and in particular minimising wasteful and excessive consumption practices—e.g. unnecessary throw-away products are eliminated; social norms align with goals of sustainable consumption; and structural change and business model innovation enable better consumer choices for engaging in sustainable consumption practices

→ **Just:** A level of consumption that does not prohibit others from reaching a minimally adequate level of resource use (to meet needs connected to basic human rights). That also means it follows the principle of e.g. food first at a global scale and allows for a fair distribution of total biomass use and resource appropriation (e.g. no land grabbing) now and over time

→ **Safe:** A level of consumption that does not disproportionally overburden the planet for future generations (within planetary boundaries) and is produced in a way that meets sustainability criteria (on farms, in forests and across supply and value chains)

Figure 2.3 A balanced bioeconomy



A **balanced bioeconomy** uses biomass and land in a way that is **safe, just** and compatible with long-term sustainable development.

It provides for people in a humane way while also leaving space for the flora and fauna of our world to thrive.

2.2 Stakeholder perceptions

Why is stakeholder participation key for bioeconomy monitoring?

Besides technical and economic factors, societal factors, interests, perceptions, mentalities, narratives and ideologies — beyond solely 'acceptance' – will mainly determine the further development of the bioeconomy (Eversberg 2021, Eversberg et al. 2021, Zeug et al. 2021, Zeug et al. 2023). These factors are evaluated in the SYMOBIO project using tools of stakeholder participation. Systematic stakeholder participation as an integral part of scientific endeavours can play an important role in analysing persistent societal problems and challenges, such as developing the bioeconomy in a **credible, transparent, and multi-perspective way** (Bezama 2018), as well as enable innovations (Kircher et al. 2018). Public decision making on sustainability is characterised by uncertainty, different values and interests, communities in dispute, as well as urgency (Funtowicz and Ravetz 1990, Martinez-Alier et al. 1998, Munda 2008). For that reason, systemic assessments, like the holistic and comprehensive monitoring strived for in the SYMOBIO project, have to include multiple fields of knowledge and perspectives of different stakeholders (Garmendia and Gamboa 2012).

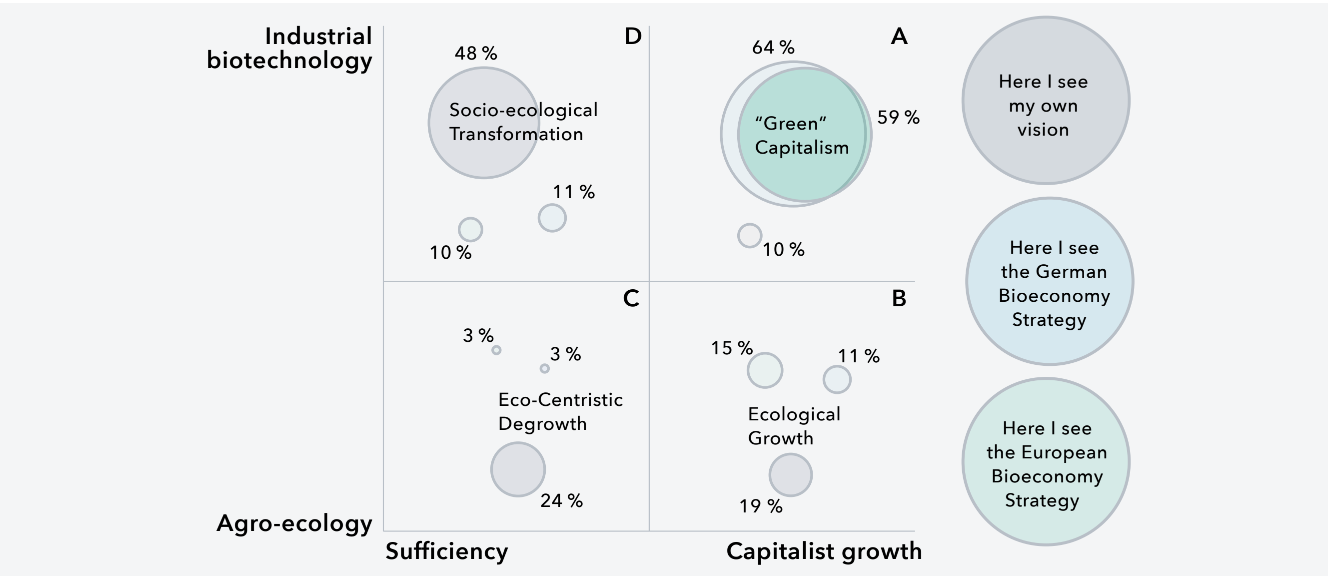
Stakeholder workshops 2017: The bioeconomy and the Sustainable Development Goals (SDGs)

Stakeholder expectations of a bioeconomy monitoring in Germany were first assessed in stakeholder workshops in 2017. The stakeholders from science and society showed more universal interests than business stakeholders, which follow particular interests when it comes to the relevance of different SDGs for bioeconomy monitoring. A strong influence of **changing discourses** and narratives affecting policy processes and public opinions could be observed, as well as a growing awareness of global shifts and **big societal challenges**, e.g. hunger, poverty, and inequality. After the elimination of hunger, which is seen as particularly relevant at a global scale, stakeholders put particular emphasis on the links between the German bioeconomy transition and SDGs 12 (responsible consumption and production), 15 (life on land), 14 (life below water), 6 (clean water and sanitation) and 13 (climate action).

Stakeholder workshops 2020: Toward a socio-ecological transformation

In January 2020, a further stakeholder workshop served to develop and underline the conceptual framework of the bioeconomy monitoring and its indicators, as well as to question it (Zeug et al. 2021). According to the participant stakeholders, the bioeconomy monitoring should be **continuous** and contribute to developing possible **future visions** of the bioeconomy. Developing future visions and narratives of a sustainable bioeconomy, knowledge transfer and discourse towards societal change were identified as major challenges in the future. Stakeholders

Figure 2.4 Shares of responses to the questions „Where do you see your own bioeconomy vision?", "Where do you see the German Bioeconomy Strategy?", "Where do you see the European Bioeconomy Strategy?"



Source: Zeug et al. (2021)

also evaluated the pilot bioeconomy monitoring report (Bringezu et al. 2021a) through a survey. Stakeholders considered the results in general as acceptable (with an overarching score of 3.2 / 5.0). However, social impacts were perceived as underrepresented (2.4 / 5.0) and the socio-economic coverage as too narrow, e.g. as regards working conditions, inequalities, and sustainable consumption and production. The stakeholders also saw the need for the bioeconomy to be part of a socio-ecological transformation, beyond business-as usual (Eversberg and Holz 2020), claiming global responsibility and providing a good life for all within planetary boundaries.

Table 2.2 Research framework and timeframe of SYMOBIO 2.0 workshops and surveys

	Stakeholder workshops	Stakeholder surveys
Stakeholders	Experts from science, business, politics and NGOs	Public, but not representative
2023	Workshop on specific ecological aspects of bioeconomy, monitoring and transformation (November 23rd)	Survey on specific ecological aspects of bioeconomy, monitoring and transformation (July — October)
2024	Workshop on specific social aspects of the bioeconomy, monitoring and transformation (March 13th)	Survey on specific social aspects of the bioeconomy, monitoring and transformation (February — March)
2024	Workshop on specific economic aspects of the bioeconomy, monitoring and transformation (July 17th)	Survey on specific economic aspects of the bioeconomy, monitoring and transformation (May — June)

Stakeholder participation in 2023 and 2024: Framing and selected results

In order to continue, build on and deepen stakeholder participation in the SYMOBIO 2.0 project, the bioeconomy is understood as an **emerging transformation**. We use a conceptual understanding of transformation characterised by three differentiated but mutually intertwined aspects.

- Mentalities and discourses in transformations and their bioeconomy specific aspects
- Physical infrastructures and technologies
- Political economy for transformation; perception of synergies and trade-offs; and expected solutions for societal and political aspects.

These aspects can unfold in partly very different as well as partly overlapping ways in narratives, which are reflected in the changing relevance of specific aspects and indicators for bioeconomy monitoring. Based on our experiences with the different stakeholder workshops and surveys developed and conducted in SYMOBIO 1.0, the methods and procedures for stakeholder participation in SYMOBIO 2.0 were further developed and employed to gain **comparable, traceable and comprehensive results** throughout the years.

The stakeholder workshops and surveys were split up into **ecological, social and economic aspects** in 2023 and 2024 (Table 2.2). The differentiation between ecological, social and economic aspects was communicated to stakeholders as an approach to look at the same object from different perspectives in order to identify and understand their links from an overarching **holistic and integrated sustainability framework** oriented on the SDGs.

That said and to a certain extent, what stakeholders and participants understand under such narratives cannot be generally characterised as homogenous. For that reason we gave instructions and introduced the two leading narratives as a result of previous stakeholder participation (Zeug et al. 2021) at the beginning of each survey. These narratives offer polarised boundaries of a corridor of possible scenarios.

As an impression of preliminary results, the results of the **survey on ecological aspects** are presented in this report. All results will be available in 2025, first on the bioeconomy monitoring website, later as a journal publication (Zeug et al. in prep). A total of 55 stakeholders, mainly from an unspecified stakeholder

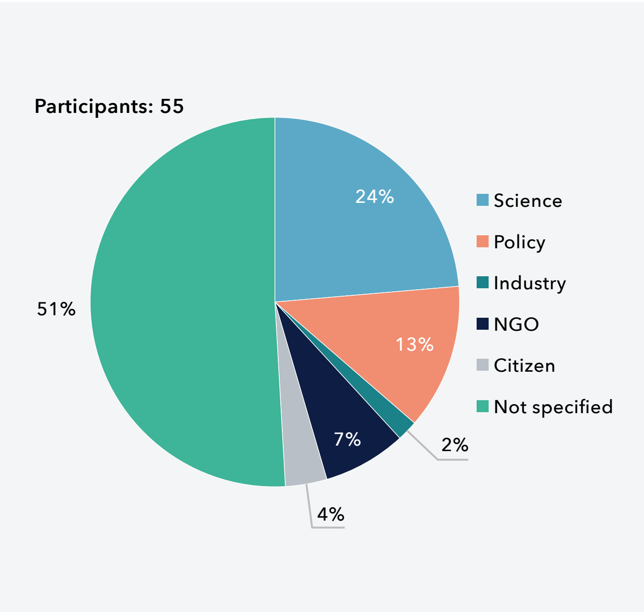
Table 2.3 Lead narratives of stakeholder participation

Green Capitalism	Societal-Ecological Transformation
• Technology-supported transition to a global bioeconomy and the continuation of the capitalist economic model and growth	• Combining a high (bio)tech vision with a sufficiency narrative
• Technology plays a key role by unlocking further potential for new economic growth & expansion and accumulation of capital through, for example, genetic and biomolecular applications & industrial innovations	• Requires a reduction in material production and consumption (at least in industrialised countries) and global sustainable resource use patterns
• Planetary boundaries are not boundaries for economic activities	• Advanced large-scale industrial technologies can include biorefineries, ecological-functional intensification of the agricultural sector, global trade and, if necessary, biotechnologies and plant genetics
• No profound changes in the political-economic structures of society and no reduction in production and consumption	• Technologies are not used as a source of further growth and capital accumulation, but as part of a politically coordinated strategy for a good life for all within planetary boundaries
• Global challenges are merely an efficiency problem that is addressed by intensifying production and increasing production	• Political and social structures and patterns are profoundly changed
• Companies are important economic and social actors, and profit-oriented markets coordinate the distribution of production and consumption	• NGOs, states and community-run companies are key bodies for the design, planning and organization of economic activities that are geared towards sufficiency, efficiency and justice

Source: Derived from Hausknost et al. (2017), Zeug et al. (2021)

group as well as science and industry, participated in the survey (Figure 2.5). Most of them indicated a **change of their perception of bioeconomy** towards a narrative of "socio-ecological transformation" and that our system should be transformed accordingly. However, the German and European Bioeconomy Strategies are still seen as promoting a "Green Capitalism" narrative (Figure 2.6). The general ecological impacts of each of the narratives are perceived as very different (Figure 2.7) as well as the specific impacts of biomass imports, forestry and agriculture (Figure 2.8).

Figure 2.5 Participation in the stakeholder survey on ecological aspects



Besides the perceptions of different narratives and their impacts, the stakeholders were asked about their perception of different methodologies applied in SYMOBIO 2.0 to monitor the bioeconomy, with a particular focus on how well-understood footprint approaches are among stakeholders. In general, most of the footprint methodologies are widely accepted. In some cases, stakeholders indicated that the footprint approach alone was not sufficient to monitor the global impacts of the German bioeconomy, on e.g. climate, water, forests and agricultural land. This is well aligned with the overarching rationale for a systemic bioeconomy monitoring approach, which relies on a multifaceted toolbox of methods to monitor different activities, impacts, outcomes and outlooks covering multiple dimensions, levels and perspectives of a bioeconomy transformation.

Figure 2.6 Perception of bioeconomy and strategies

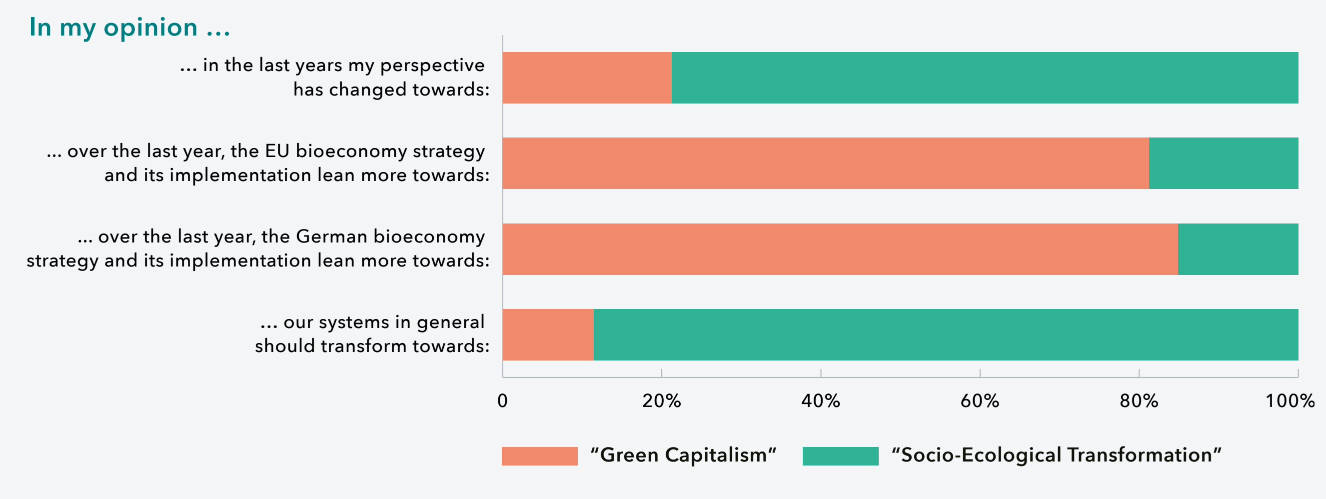


Figure 2.7 Perception of ecological impacts in a green capitalism or societal-ecological transformation narrative

Survey Question:
In my opinion, the successful development of the German bio-economy according to the Green Capitalism or Social-Ecological Transformation narrative would have an overall impact on the following ecological aspects, on which …

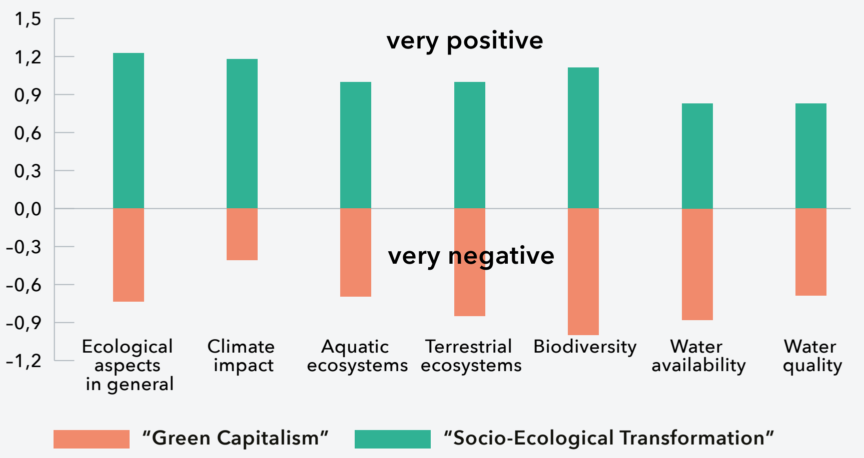
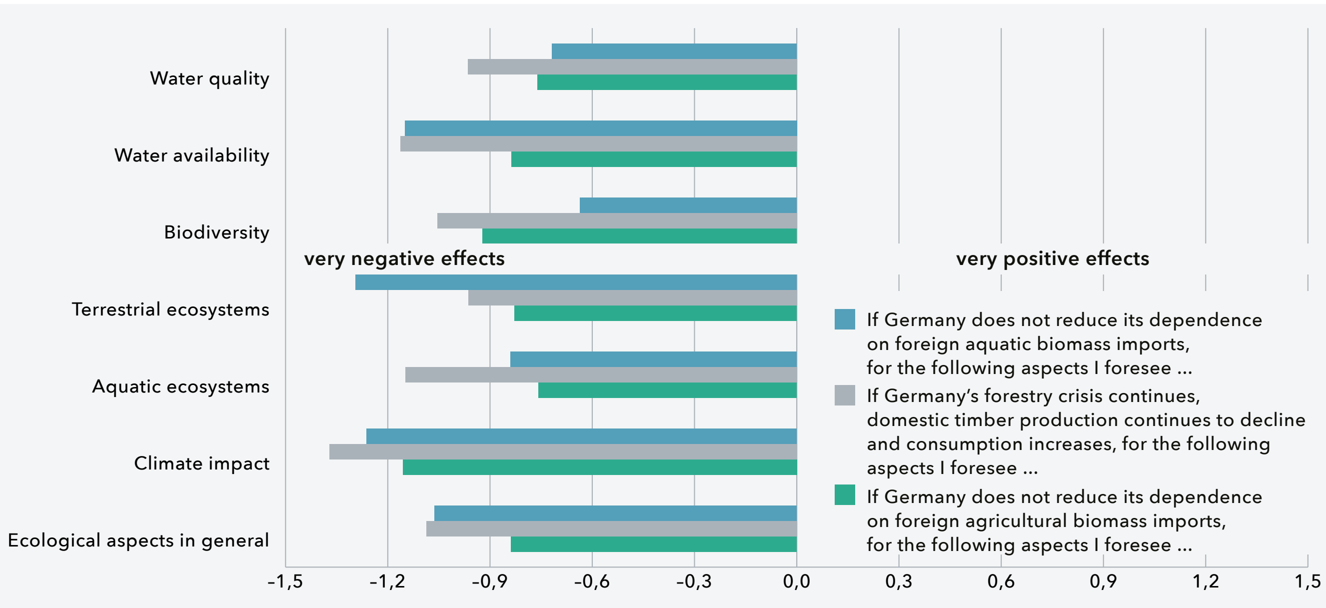


Figure 2.8 Expectations on ecological impacts of biomass trends



2.3 The monitoring landscape[4]

The bioeconomy monitoring landscape is **complex.** It involves a number of different actors, and, due to its cross-sectoral character, is regulated by the various ministries and governance frameworks related to the sectors involved. This includes forestry, agriculture, energy, industry, climate, environmental and even waste policy. At the same time, these fields are also **interdependent,** which can make it difficult to keep track of overarching developments, their synergies and trade-offs. For that reason, monitoring the bioeconomy as a whole can help to map and identify the influence of changes within the system, both on those interdependent fields and on overarching developments. This enables more informed policy steering measures, and in particular, the avoidance of unintended impacts (like indirect land use change). Bioeconomy monitoring is therefore being pursued or has already been implemented at national levels, such as in Germany, Finland or the Netherlands, as well as at the EU level (Giuntoli et al. 2020). It should be noted that within Germany, specific states (the Länder) and even communities may have their own dedicated bioeconomy strategies, but the focus here is the **national and international level**.

Bioeconomy monitoring allows us to track progress towards goals like the SDGs. However, it also makes it more challenging as it requires considering environmental, economic and social aspects.

Bioeconomy monitoring makes it possible to **track the achievement of defined goals** such as the SDGs, for which the transformation to a sustainable bioeconomy could be a key driver. It also makes it more challenging, as in order to capture the whole meaning of the bioeconomy transition, a bioeconomy monitoring system must consider environmental, economic and social aspects. While environmental and economic indicators are more established**, social indicators are more challenging to define and measure**. Nonetheless, considering the significant disruptive potential of the bioeconomy in social aspects, it is essential to delve into the long-term effects of the bioeconomy on human and social dimensions.

Monitoring landscape related to bioeconomy

Besides the tools developed and assembled for a bioeconomy monitoring system of the German bioeconomy, there are already **multiple reporting initiatives, programs and activities** that have been started in the past for documentation and assessment in particular areas. Although these initiatives do not aim to provide a specific overview of the bioeconomy as a whole, they can provide **deep insights into detailed aspects of their specific working fields**. They bundle a wide diversity of information ranging from statistical data to the development of indicators or the provision of geodata. These initiatives go beyond the scope of an overarching bioeconomy monitoring system, which would lose clarity of purpose and interpretability if it covered all sub-themes in such breadth and depth. Altogether, specific monitoring efforts thus provide the opportunity to deepen the knowledge that has already been generated and provide connection points, which can also become the **basis for developing a learning monitoring system**.

Considering the definition of the bioeconomy in the EU Bioeconomy Strategy (EC 2018), a bioeconomy monitoring could be deepened and enriched by any monitoring initiative that addresses any sector or system that relies on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste) and/or that covers aspects about ecosystems, natural resources, innovation and social aspects at the locations where the biomass is produced and used, and which are

4 This section is based on the report Zinke et al. (2023). Detailed methods and results are available in that report.

influenced by the bioeconomy or vice versa. **Examples of connected monitoring initiatives include:**

- FAOSTAT (FAO 2024b), 'Wood resource monitoring' (Mantau et al. 2018b) or 'State of Europe's forests' (Forest Europe 2020) providing insights into specific primary biomass production sectors
- The 'Statistics report on cultivation and use of renewable raw materials in Germany' (FNR 2024b), which provides information about economic and industrial sectors that use and process biological resources
- Monitoring according to the 'Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora' (BfN 2019) or 'FAO fisheries and aquaculture' (FAO 2024a) covering land and marine ecosystems
- The 'Federal Initiative Core Indicators' (König et al. 2022), 'Monitoring of agricultural areas with high natural value' or indicators and maps on spatial and urban development (BBSR 2024) that provide indicators on environmental, economic and social sustainability in the regions of biomass production, processing and use
- The 'Drought monitor Germany' (UFZ-Drought Monitor Germany 2024) or the 'Global material flow database' (UNEP 2024) with information about natural resources
- The surveys of the 'Poverty and wealth report of the Federal Government' (BMAS 2021) tracking the social transformation

This list is only a small sample of available monitoring systems, and it shows that the **current monitoring landscape is characterised by a broad thematic range with a variety of output formats**. These can be reports, interactive maps, databases, platforms for knowledge provision, dashboards, and/or survey results, among others. They provide information on regional, national, European and/or global levels. A challenge for identifying these reporting instances is that they do not always define themselves as part of „monitoring systems". Moreover, the **frequency** in which reports and statistics are updated differs widely. It is necessary to differentiate between regularly updated systems and one-time studies. The later may be more limited in terms of coverage over time (needed e.g. to discern trends), but potentially deeper as regards specific activities, impacts or outcomes (e.g. as in the case with a one-time survey providing detailed information, but only for one glimpse in time).

Key findings: Coverage and gaps of the monitoring landscape

We reviewed almost **100 specific monitoring systems across Germany, the EU and at a global level**, from which over **60 provide information on the indicator level**. While there is potential to continuously expand this collection, our analysis of the coverage of these systems already provides some key insights and connection points for bioeconomy monitoring as a whole. A list of collected monitoring initiatives can be found in the Supplementary Material. Most of the evaluated monitoring activities contain indicators focusing on primary biomass resources like wood and agricultural crops. Also, the conservation of ecosystems and status of habitats including their biodiversity are often addressed. Climate change is also a significant topic in the monitoring systems.

While the produced biomass is thoroughly monitored, **the actual use, demand and circularity of biomass materials is not documented in such detail.** This applies, for example, to indicators on changes in demand for food and feed, waste recycling, replacement of conventional materials with bio-based products, as well as self-sufficiency associated with such a transition. While some monitoring initiatives provide information on aspects like recycling rates or the market shares of bio-based products, the variety of indicators used is still limited. It can also be seen, that while socio-economic factors are typically reported alongside other economic and environmental indicators in various databases, they are not as deeply focussed compared to economic and environmental issues.

When the covered topics are compared to the five EU Bioeconomy Strategy goals (EC 2018), it can be seen that "Manage natural resources sustainably" and "Mitigating and adapting to climate change" show **a high level of overlap** among the monitoring initiatives assessed. A smaller number of indicators in the current monitoring landscape address the objectives "Food and nutrition security", "Reducing dependence on non-renewable, unsustainable resources" and "Strengthening European competitiveness and creating jobs". These aspects as well as social indicators offer a high potential for mutual complementarities of indicator sets.

Integration potential of environmental footprints

The monitoring indicators for the bioeconomy proposed in the following chapters of this report have strong connections to the described monitoring landscape. For example, we explored in detail the links between the six proposed environmental footprints presented in Chapter 7 (representing one aspect of the systemic monitoring) and the corresponding monitoring initiatives. Figure 2.9 depicts the results. It shows that **connections to over 60 monitoring initiatives have been identified.**

For the further analysis of linkages between the monitoring systems, a set of 27 indicators were selected, addressing the five goals of the EU Bioeconomy Strategy and sustainability aspects. From these, 18 indicators could be associated with one or more of the environmental footprints. For instance, the indicator "domestic food supply of food commodities" is thematically linked to the agricultural biomass footprint, while „land use change" is thematically associated with both the agricultural biomass footprint and the biodiversity footprint. For each of the monitoring systems, it was analysed which of the selected indicators it covers, and thus, to which footprints there are overlaps in terms of content. The more indicators are addressed in a monitoring system, the stronger and broader the links between it and the footprints were.

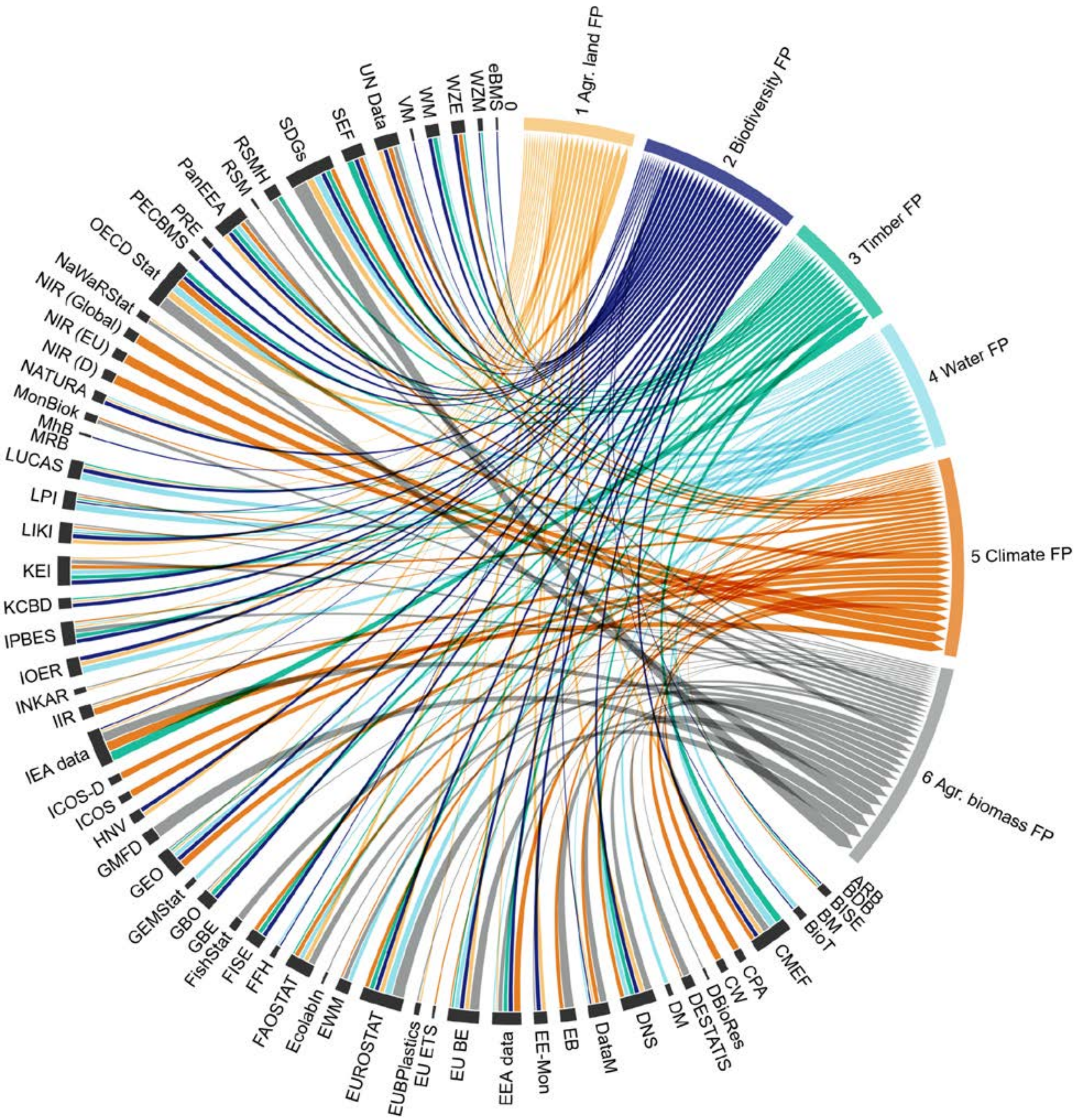
For example, in Figure 2.9 it is possible to observe that **biodiversity** is addressed in many of the initiatives, as shown by the number of connections between the biodiversity footprint and the individual reports and initiatives that comprise the monitoring landscape. The biodiversity footprint could thus complement the indicators depicted in those monitoring systems, or vice versa, even be taken up by some of the corresponding monitoring initiatives themselves. It should be noted, however, that just because an area like biodiversity is covered by indicators in the monitoring landscape, it does not mean that the quality, comprehensiveness and robustness of those specific indicators are equally comparable. For an area like biodiversity, this is especially relevant, as the capacities for monitoring are continuously improving (CBD 2020, IPBES 2019). Finally, the environmental footprints developed for this monitoring report could provide insights into the consumption levels in Germany and potential pressures and impacts abroad, which is a perspective that is missing in most of the corresponding monitoring activities.

Need for a systemic perspective of a flexible monitoring system

The example of the connections between environmental footprints and the identified monitoring landscape showcases the multiple connections between monitoring activities. As a very diverse group of actors is involved in the bioeconomy, many stakeholders from politics as well as from business, science and society need a comprehensive but still manageable tool with a set of key indicators to help guide decision-making. The potential connections between the monitoring system for the bioeconomy proposed in this report and other monitoring initiatives could help to **close gaps in the monitoring landscape**, but also to **keep the future reporting flexible** without building up new indicators from scratch.

Altogether, this monitoring report intends to learn from both the potential gaps in representation from a systems perspective identified in the analysis of the monitoring landscape and the input of stakeholders (Section 2.2) to develop a regular monitoring geared toward providing the information needed to steer the German bioeconomy towards a sustainable, circular and balanced transition (Section 2.1). To that end, this report highlights some of the above-mentioned underrepresented issues (e.g. on consumption dynamics, like diets) and some of the monitoring challenges (e.g. as regards biomass substitution potentials) in order to meet its main priority of providing a comprehensive overview of the bioeconomy.

Figure 2.9 Connection of the environmental footprints (FP) in this monitoring report (right) to the bioeconomy monitoring landscape assessed (left)



Note: The wider the connection arrow, the more indicators address the same thematic area as the respective footprint and the more potential for links (including streamlining and knowledge sharing). For a list of abbreviations for the shown monitoring systems please refer to the Supplementary information available on our website (under downloads): https://www.monitoring-biooekonomie.de/en/

3. Socio-economic performance and innovation

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Key findings

- The gross value added of the German bioeconomy ranged from € 134 billion to € 150 billion in 2020. This corresponds to 5 % of total gross value added. Roughly half of this was generated by the manufacturing sector.
- In comparison to the price-adjusted gross value added for Germany as a whole (which grew rather steadily by almost 16.5 % between 2010 and 2019 before falling due to the Covid-19 pandemic), the development of the German bioeconomy fluctuated (with 5 % growth between 2010 and 2017). A gap in data availability since 2018 has disrupted the time series, making it difficult to monitor and draw conclusions on trends over the whole time period.
- 2.7 – 2.9 million people were employed by the German bioeconomy in 2020 (a minimum of 7 % of total German employment), with nearly half working in manufacturing. Employment in the German bioeconomy decreased by around 11 % between 2010 and 2017. Trends beyond 2018 are difficult to estimate due to data gaps. The number of employees in agriculture, forestry and fisheries is slowly but steadily declining.
- Bio-based shares currently represent small shares of the markets presented (ca. 1 % of the global plastic market is bio-based; 6–15 % of the German chemical industry; 4–10 % of the share of construction in new buildings in Germany is wood-based; and around one-third of global textiles (22 % of which is cotton and 6 % wood-based fibres). Main drivers are the need to substitute fossils and to improve environmental performance. Cost-competitiveness in many cases is the largest barrier.
- Technology trends in Germany are characterised by a wide range of innovations with potential for both incremental (e.g. substitution with bio-based feedstocks) and disruptive (e.g. carbon capture and use, cultured meat, biotechnology in healthcare, microbiomes in agriculture) change. Maturity, up-scaling and performance reliability despite fluctuating feedstock quality are key challenges.
- Patent analysis shows that Germany has a relatively high degree — and increasing level — of specialisation in the areas of innovative wood products, agriculture 4.0 and surfactants. Nevertheless, the US leads patenting in all technology-related areas, and China is strongly catching up and has surpassed the EU in some cases.
- Meat alternatives are attracting wide interest and show significant growth (nearly tripling turnover in Germany between 2019 and 2023 to reach € 580 million), and make up around 1 % of total meat product markets in terms of economic value.
- Most of 2028's top 10 drugs are expected to be biotechnology-based, and the sector is a significant and growing opportunity for employment in the processing sectors of German bioeconomy (with around 50,000 employees in 2022).
- Bio-based surfactants represent a flagship product group and a success story in terms of market relevance for bio-based chemicals. Investments in 2nd generation biosurfactant technologies have intensified and a number of SMEs are dedicated to expanding the use of inputs like food-waste to develop bio-based surfactants.

1 Thünen Institute of Forestry
2 Fraunhofer Institute for Systems and Innovation Research (ISI)

3.1 Gross value added

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. The gross value added at producer prices of the German bioeconomy is calculated based on the bio-based shares of economic activities, data from the national accounts, cost structure surveys of companies, structural surveys and sales tax statistics of the German Federal Statistical Office.

Developments in the bio-based sectors and the German bioeconomy

Figure 3.1 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 can no longer be based on the material and incoming goods statistics, as these are currently not available. As a result, the bio-based shares are calculated in a less differentiated manner, which limits the calculation of the minimum and maximum shares of manufacturing and food and beverages services in particular (depicted by the dotted range in Figure 3.1). Nevertheless, results show that:

5%

of total gross value added in Germany corresponds to the bioeconomy

- The total gross value added varies between **€ 144 billion** in maximum in 2010 and **€ 150 billion** in maximum in 2020. This corresponds to **5 %** of total gross value added.
- 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 Covid-19 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 both **bio-based construction** and **scientific research** 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 fluctuated between **€ 22 billion** and **€ 27 billion** between 2010 and 2020.

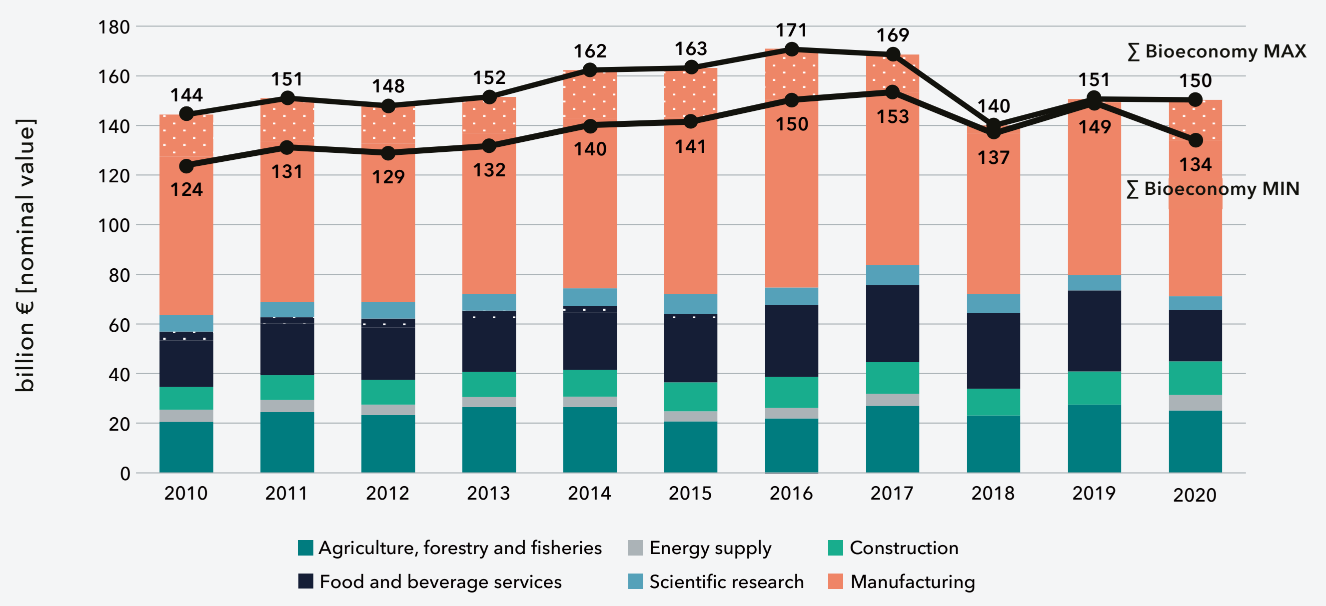
This example clearly shows the **effects of a disturbed time series** and emphasises how important the continuous provision of official statistics is for consistent bioeconomy monitoring.

Developments compared to Germany as a whole

Gross value added of the German bioeconomy increased by 5 % between 2010 and 2017, peaked in 2019 and returned to 2010 levels in 2020.

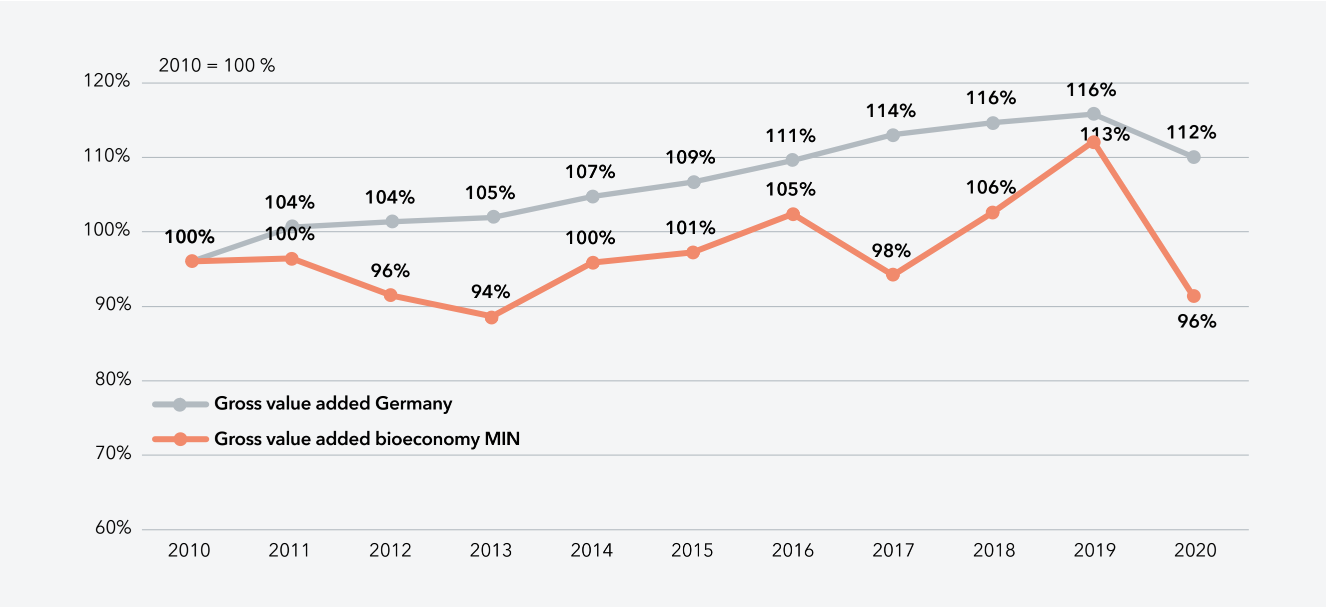
Figure 3.2 shows the development of the price adjusted gross value added for Germany and the German bioeconomy relative to the year 2010. Between 2010 and 2019 price-adjusted gross value added increased by almost 16.5 % in Germany, before falling back to 12 % in 2020 due to the Covid-19 pandemic. Compared 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

Figure 3.1 Gross value added of the German bioeconomy in the years 2010–2020 (nominal values)



Source: Thünen Institute of Forestry based on Destatis (2024a), Destatis (2024b) and EUROSTAT (2024a)

Figure 3.2 Development of price-adjusted gross value added of the German bioeconomy compared to the German economy in the years 2010–2020



Note: The increasing trend between 2017 and 2019 for the bioeconomy appears to the opposite of what would be expected looking at Figure 3.1. The reason is the break in the database in 2018 and the impact of the price adjustment. Only the minimum values of the estimated range are depicted for the bioeconomy.

Source: Thünen-Institute of Forestry based on Destatis (2024a), Destatis (2024b) and EUROSTAT (2024a)

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.

3.2 Employment

7 %

of total employment in Germany was in the bioeconomy

Due to the missing materials and incoming goods statistics (see Section 3.1) as well as provision of less disaggregated employment data by Eurostat (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. **Between 2010 and 2020 at minimum 7 % of total employment in Germany was in the bioeconomy**. 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 3.3). The further decline between 2018 and 2020 should be interpreted with caution due to the mentioned changes in the base data. Nevertheless, a decline in 2020 due to the Covid-19 pandemic is plausible.

Employment breakdown in bio-based sectors

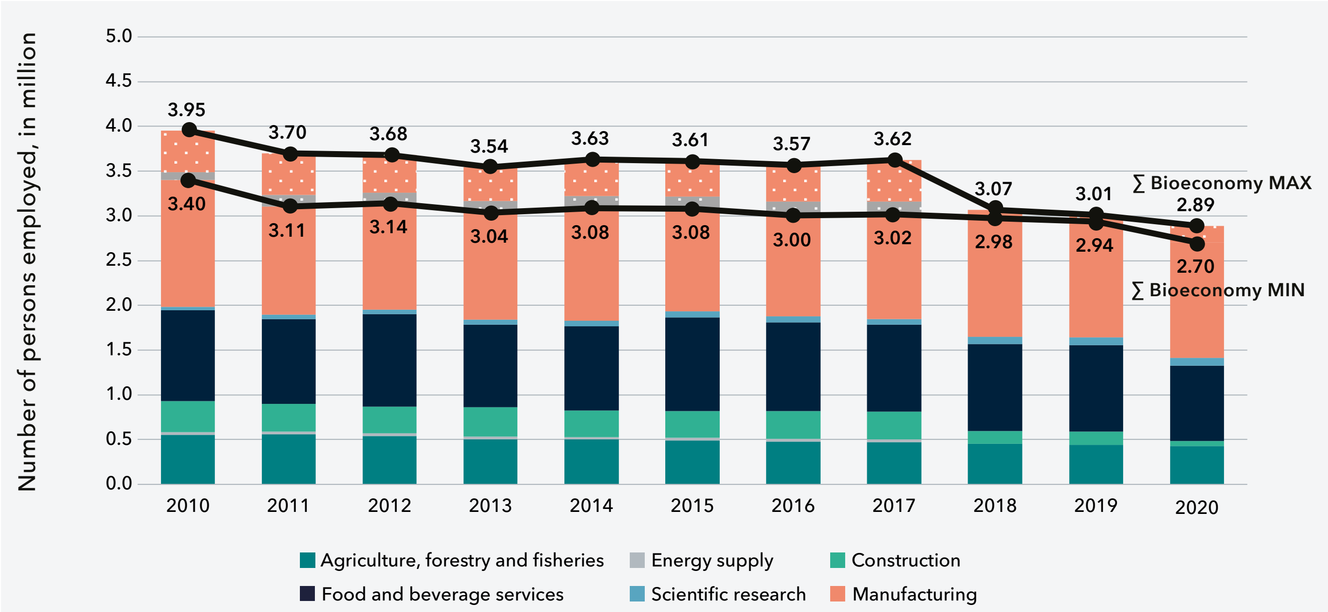
The majority of employees in the German bioeconomy, **around 45 %, work in manufacturing**. The proportion has been largely stable over the years and shows no major fluctuations. Food and beverages services employ about 1 million people. Due to the Covid-19 pandemic and the associated lockdowns, the 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 persons could be identified as working in the bioeconomy, the number apparently fell down to 0.14 million in 2019. However, the low number is a result of the fact that from 2018 onwards only aggregated **data for employment in construction is available**. Research and bio-based energy supply are of more minor importance as regards employment shares in the Germany bioeconomy.

In contrast to the overarching trend for Germany, employment in the bioeconomy has decreased over the last two decades.

Developments compared to Germany as a whole

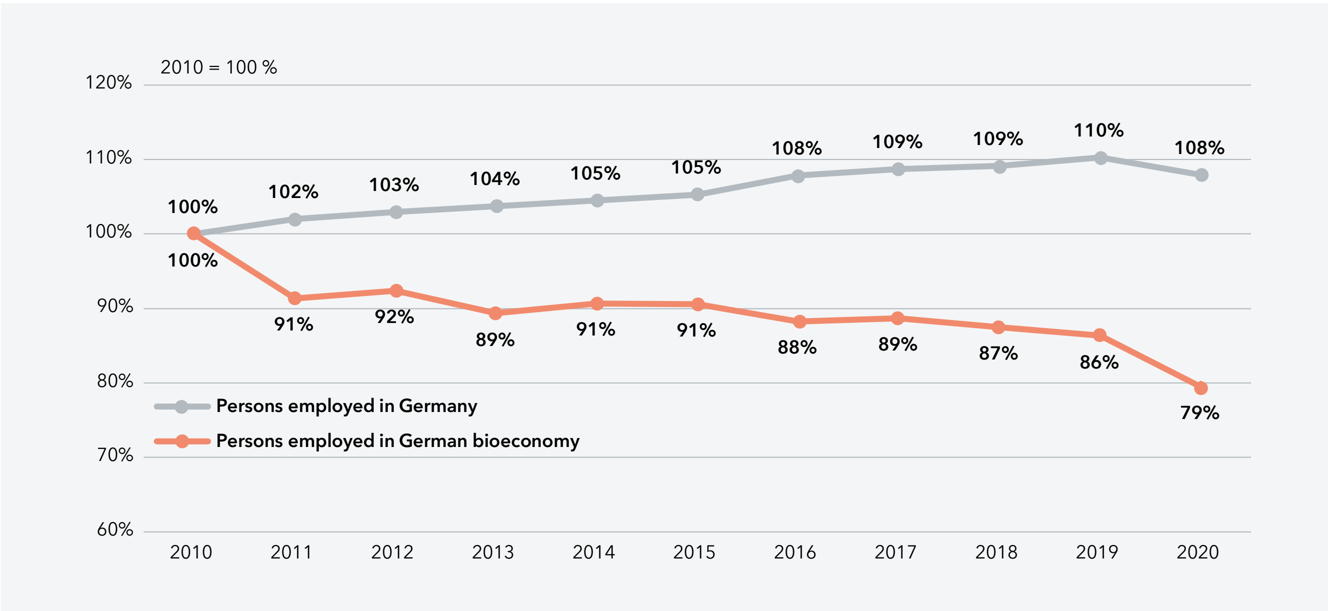
Looking at employment in Germany as a whole, compared to 2010 it continuously increased by 8 % until 2020 (Figure 3.4). In contrast, compared to 2010 the minimum number of people employed In the German bioeconomy **decreased until 2020 by 21 %.** However, as mentioned above the trend since 2018 is a result of the changed base data from 2018 onwards and in 2020 the impact of the Covid-19 pandemic on employment is visible.

Figure 3.3 Persons employed in the German bioeconomy in the age group 20–64 years from 2010–2020



Source: Thünen Institute of Forestry based on EUROSTAT (2024b)

Figure 3.4 Development of employment in the German bioeconomy compared to Germany in the age group 20–64 years from 2010–2020



Note: The minimum values of the estimated range are depicted for the bioeconomy.

Source: Thünen Institute of Forestry based on EUROSTAT (2024b)

MONITORING CHECK BOX 1

How are bio-based shares measured?

General approach

Monitoring the size of the bioeconomy starts with selecting sectors and industries that are fully or partly based on the processing and use of biomass. This selection might change over time, if increasing amounts of fossil resources are substituted with bio-based ones.

Quantification criteria of the contribution of sectors to the bioeconomy, i.e. sectoral bio-based shares, can be: biomass content of products and energy produced (outputs); biomass content of inputs in biomass processing sectors/industries; bioeconomy relevance of the services delivered; the actual (final) use of biomass (Ronzon et al. 2024). As data on actual amounts of biomass of in- or outputs often is missing, in quantifications of sectoral bio-based shares usually the monetary value of the used bio-based inputs or of produced bio-based goods is used to calculate bio-based percentages of the selected sectors. Sectoral bio-based shares are applied to sectoral data of value added or employment. The size of the bioeconomy then is estimated by aggregating all fully and partly bio-based sectors.

Benefits and challenges

The described approach relies on monetary data and is based on statistical databases that are harmonised at an EU level and are updated in regular intervals (Ronzon et al. 2024). This allows for comparisons between EU countries and over time. However, data in general is often available at only highly aggregated levels and smaller bio-based sectors cannot be accounted for. Also, monetary data does not provide consistent information on the related material flows. Information on actual biomass amounts processed and used in bio-based sectors is crucial for a comprehensive sustainability assessment, as extraction and processing of biomass has other effects than generation of value added and employment.

Needs for future monitoring

For monitoring the size of the bioeconomy, the public availability of official statistical data is crucial. Especially detailed data on specific material and energetic inputs into economic activities, as surveyed by the 'Material and Goods received Enquiry', should be made available. Furthermore, exact knowledge on supply and use of biomass amounts can be gained only by monitoring biomass material flows as well. Statistical classifications should be further developed and updated in regular intervals to differentiate bio-based and fossil-based sectors and products.

3.3 Sectoral perspective: Toward innovative material use applications and markets

3.3.1 Bio-based plastics and rubber

General scope

The rubber and plastics industries in Germany encompass around 2,000 companies and employ around 341,000 people in total (Destatis). The share based on biomass is growing. However, bio-based plastics comprise a very small portion of total plastic production; globally they represent a share of around **1 percent** (appr. 4.6 million tonnes (t) of the 320 million t of plastic produced annually). For Germany, related bio-based value-added is estimated to be around **€ 1.1 billion** and employment to be around **15,000 employees** in 2021 (JRC DataM). While there is currently no large production plant for bio-based plastics in Germany, there is a significant presence of **R&D institutes and SMEs** active in this field (e.g. FKuR, Traceless, Tecnaro). However, most production takes place in Asia and capacities there may exceed the 70 percent share of global production by 2026 (European bioplastics).

State of innovation

Regarding innovation, there are intensive efforts to develop further new bioplastic products (e.g. PEF), to use various waste and residues as feedstocks (e.g. chitin, lignin, food waste) and to increase the efficiency of production processes to reduce costs and decrease environmental impacts. Still in the R&D phase are **3rd generation bio-based plastics,** which are produced from sugars or oils produced by micro-organisms (microalgae, bacteria, mushrooms, yeasts and others) or from municipal waste material. A prominent example for rubber is the R&D lab of Continental in Anklam (Mecklenburg-Vorpommern) to produce tires made of dandelion rubber. Commercial production is expected to start in around 5 years.

Future markets and challenges

According to global market outlooks, the share of bioplastics may rise to around 2 to 5 % until 2030 (IfBB 2022), with the highest growth rates expected for biodegradable bioplastics. A key market driver is the high need of industry to substitute fossil-based plastics, and especially some large brand owners show considerable interest in bio-based plastic. On the supply side, **technological advances** have increased the diversity of types of bio-based plastics available on the market, partly with additional functionalities that the fossil-based substitutes cannot provide. However,

What are bio-based plastics?

Bio-based plastics are at least in part produced from biomass as a feedstock. They may be biodegradable or durable. Bioplastics have already a long history and have been used in niche applications for a long time. The majority are currently used for packaging (around half), followed by applications in the textiles, consumer goods, agriculture, automotive and transport, electronics and building market segments (ifBB 2024). There are many different types of bio-plastics and different feedstocks used (e.g. oil, lignin, starch, protein, rubber, etc.).

Toy set partly made from bio-based PE © Hape

Bottles made from 100 % bio-based PE and 30 % bio-based PET. © Spectra Bioploymer

Spectra BiopolymerIPhone Case © Bioserie

Photos depict the wide array of applications for bio-based plastic. Further examples and source: © European bioplastics; www.european-bioplastics.org limited price competitiveness, missing policy incentives for bio-based plastics and missing infrastructure for bio-plastics recycling may limit growth in the future. Moreover, **critical questions about the sustainability** of bio-based plastics have been raised, especially considering that around two-thirds of plastic waste streams are dominated by short-lived applications and global plastic production is expected to triple by 2060 if no changes are made (OECD 2022). While shifting to bioplastics could potentially relieve some of the environmental burden in specific cases, at the heart of transformation in the plastics sector is reduction (UNEP 2023b).

What are bio-based chemicals?

Bio-based chemicals refer to a category of chemicals produced using biomass through physical, chemical, biological and other methods. Bio-based chemicals are highly important for the segment of specialty chemicals, such as detergents, cleaning agents, cosmetics, plastics and lubricants. They are less relevant for chemical building blocks produced in large quantities and used as platforms for many products. Most biomass-based raw materials used in the chemical industry today are vegetable oils obtained from palm fruits, rapeseed and soya, as well as animal fats.

Biorefinery plant being built in Leuna, Germany by UPM. The biorefinery will use wood, in particular beechwood, to produce various industrial products and consumer goods, such as PET bottles, cleaning agents, and rubber. More information: https://www.upmbiochemicals.com/about-upm-biochemicals/biorefinery-leuna/

Source: UPM Biochemicals GmbH

3.3.2 Bio-based chemicals

General scope

As industrial biotechnology progresses, the chemical industry is expected to develop many new bioeconomy applications. Today, however, the use of fossil resources in the German chemical industry is still immense, and biomass comprises only a small proportion of total feedstocks.

The estimations of **bio-based shares for the German chemical industry vary from around 6 to 15 %[5].** Using the lower figure, value-added is estimated to be around **€ 3 billion** with employment of around **25,000 employees** in 2021 (all excluding biofuels, biopharmaceuticals and bioplastics) (JRC DataM).

State of innovation

The build-up and presence of larger bio-based chemical **pilot plants in Germany are still limited**, mostly because of the higher costs of bio-based chemicals compared to fossil-based ones. That said, there are some examples of **current investments worth noting**:

- UPM is building a large biorefinery in Leuna with a capacity up to 220 thousand t per year that uses wood to provide ethylene glycol, which in turn is used to produce polyester and PET
- CropEnergies started construction of its 50 thousand t per year energy-efficient green ethyl acetate facility based on ethanol located at the Zeitz Chemical and Industrial Park in Germany
- Covestro has put a first-of-its kind pilot plant into operation in Leverkusen for producing the chemical aniline entirely based on plant biomass instead of petroleum

5 The estimation of bio-based shares is highly challenging for the chemical industry (see above Monitoring Check Box 1), in particular due to issues of statistical accounting of feedstock inputs in the further processing steps within the chemical industry. The JRC reports values around 6 to 9 % for 2021 for Germany (JRC DataM) whereas FNR reports shares close to 15 % for 2022 (FNR 2024a; see Section 4.3).

- Verbio is starting construction of the world's first ethenolysis production plant based on rapeseed methyl ester on an industrial scale at the Bitterfeld site and aims to start regular production in 2026. The goal is to produce a total of 60 thousand t per year of biomass-based products per year for the chemical industry.

In addition, some larger chemical companies are adopting **mass balancing approaches** in production. In the mass balance process, biomass-based feedstock is introduced to the production process and further processed together with fossil raw materials. The result is a physically mixed product. From a bookkeeping perspective, the biomass share can be allocated to selected products.

Future markets and challenges

In the future, bio-based chemicals are expected to gain a significant role in the **de-fossilisation pathway** of the chemical industry, next to the use of CO_2 as well as recycling of fossil or bio-based chemicals. Explorative scenarios by the Nova Institute for a global net-zero chemical industry in 2050 show an expected increase of the bio-based share (without recycled biomass) of all inputs for global chemical production from around **8 %[6] in 2020 to around 20 % in 2050** (Kähler et al. 2023). However, as the global chemical industry is assumed to double its volume in carbon demand between 2020 and 2050, demand in biomass would increase under these assumptions to fivefold of the volume of 2020 (from 44 million t of carbon to 230 million t). Such a strong level of growth may not be compatible with sustainable biomass cultivation potentials, depending on how demands and supply develop in other sectors.

Altogether, the main driver for bio-based chemicals is the pressure on industry to reduce CO_2 emissions, which not least increasingly becomes an economic issue due to increasing prices of CO_2 certificates. The currently **limited cost-competitiveness of bio-based chemicals** forms a main barrier. Accordingly, substantial increases of bio-based chemicals will depend largely on regulation and policy incentives to use biomass as a feedstock, but these must also consider how much biomass is available for material use in light of global food security and ecological limits.

3.3.3 Bio-based textiles

General scope

The textile industry has a long tradition of using plant fibres, such as **linen** or **cotton**, and animal products, such as **wool, silk** or **leather**. However, nearly two-thirds of the global fibre market in 2021 was comprised of synthetics, like polyester, made of fossil fuel derived resources (Textile Exchange 2022). Recently, alternative feedstocks have gained importance. Manmade cellulosic fibres, such as **viscose**, are overwhelmingly made of wood fibres (in the form of pulp). Next to higher varieties of used plant fibres (e.g. cork, coconut, vegetable oil, natural rubber, fungi, cellulosic, etc.), biotech silk, vegan leather, products from algae and vegetable tanning and dyeing agents are also used. Moreover, enzymes are used to biodegrade PET polyester in textiles for recycling. To this end, the first plant on an industrial scale is currently being built in France (Carbios 2022).

Textiles from cotton and leather from animals are still the most important bio-based textiles currently, with

What are bio-based textiles?

For textiles, the term "bio-based" refers to the origin of the carbon backbone of the fibre polymer. For example, the carbon content of conventional synthetic fibres such as polyester, is derived from non-renewable fossil fuels — petroleum, gas, coal — while fibres derived from natural polymers such as cellulose are made from 100 % biomass-based carbon content.

6 Please note that this is measured in carbon input and not in tonnes of dry matter input, which is partly used in other estimations for biomass in the chemical industry.

Synthetic fibres dominated global fibre production in 2021. Bio-based textile production included cotton (22 %), other plant-based fibres (jute, flax and hemp; 6 %), man-made cellulosic fibers (6 %), and wool (1 %, followed by down and silk). Global leather production required more than 1.4 billion animals in 2021.

Source: Textile Exchange 2022

around one-third of textile production value attributed to the bioeconomy. For Germany, such share estimations relate to a value-added of around **€ 3 billion** and employment of around **45,000 employees** in 2021 (JRC DataM).

State of innovation

Current innovation activities in Germany include, e.g. the BIOTEXFUTURE, which is an innovation space on bio-based textile research funded by the BMBF. The innovation space comprises 75 partners (two-thirds companies, one-third academia) and aims to develop bio-based materials, coatings and processes by improving existing production routes and researching new fibres and manufacturing processes. **Germany is strong in applied research on textiles,** e.g. the German Institute of Textile and Fibre Research (DITF) forms the largest textile research centre in Europe and some established firms (e.g. Adidas, Vaude) increasingly focus on biomass-based feedstocks and more sustainable textiles.

Future markets and challenges

While quantified future scenarios for the sector are severely limited, the textile industry has gained increasing attention in the bioeconomy transition. The bio-based fibre textile market is expected to grow substantially in the upcoming years. Germany, as well as Europe, largely import textiles. However, the remaining industry is specialised on high-performance materials, which is a potential entry point for new bio-based materials. Potential drivers are **consumers' demand for animal-free, high-performance textiles with lower environmental impacts**. Moreover, the EU has launched its strategy for sustainable and circular textiles, which includes various measures, e.g. setting design requirements and incentives for circular business models. Such activities may support bio-based fibres.

On the other hand, technological hurdles (e.g. low yields for feedstock) have to be overcome, and the fast fashion culture, higher costs as well as product performance (fibre strength; heat resistance) form additional challenges. Moreover, the transition to **circular value chains** will be challenging, as difficulties associated with the collection process of used textiles, achieving suitable quality, or the processability (e.g., recyclability, reusability) arise.

3.3.4 Modular timber construction

In the whole construction sector, wood use provides opportunities to store carbon in supporting structures and envelopes of buildings (BMWSB and BMEL 2023). The construction sector includes the construction of buildings, civil engineering and specialised construction activities, like joinery installation and floor and wall covering also associated with refurbishment (Destatis 2019).

General scope

Of all the wood used in construction, about **one-third is used for new buildings** and about **two-thirds are used in modernisation and refurbishment** of existing buildings (Weimar and Jochem 2013, Mantau et al. 2018a). Comparative analysis has shown that the substitution potential of wood construction contributes to GHG emission reductions, as compared to construction based on non-renewable resources (See also the LCA case study in Section 4.5.1 as well as e.g. Hafner et al. 2017, Rüter and Hafner 2021). The share of wood construction for **new** buildings, when calculated based on permits issued for the construction of new residential and non-residential buildings and their enclosed space in cubic meters (m^3) by predominantly used building material, has **increased from 4 % to almost 10 % between 1993 and 2021**[7]**.** Recently, modular timber construction is gaining importance, for example in the construction of new buildings (single or double family houses) and in the context of the densification of urban space, like the addition of storeys on or the extension of existing buildings (BMWSB and BMEL 2023).

State of innovation

Glued laminated timber (Glulam), cross-laminated timber (CLT) or laminated veneer lumber (LVL) as relatively young wood products are gaining market shares in the construction sector. In parallel, modular timber construction systems have been further developed. While mainly **small and medium-sized enterprises** (SMEs) have been active in the production of 2D and 3D wooden modules so far, also larger enterprises have entered the market in recent years (Wassermann 2024).

Future markets and challenges

In Germany, 46 % of apartment buildings urgently need energetic refurbishment in order to meet Federal and municipal climate goals (Eck 2024). Mainly, these are buildings constructed before 1977, when the first thermal insulation ordinance came into force, and up to now are not equipped with any thermal insulation. The use of 2D timber construction modules provides **strong opportunities for the serial energetic refurbishment of such apartment buildings**. The main criteria for a cost-effective serial energetic refurbishment include a minimum size of 1000 square meters and a height of at least two storeys, a simple shape, and enough operational space around the buildings (e.g. to allow cranes to "lift in" modules). Serial energetic refurbishment also is relevant for non-residential public buildings like schools, gymnasiums or libraries, especially when they are of similar designs (FNR 2024).

Drivers for serial energetic refurbishment are increasing prices for heating, GHG emission reduction goals of municipalities and the availability of subsidies (**up to 45 % can currently be subsidised**) (Eck 2024). One of the main barriers is the future availability of, especially, softwood. Even though wooden construction products entirely or partly made of hardwood are established in the market, softwood still plays a major role in the construction sector (UBA 2020, Mantau 2023). Due to climate change and its effects on German forests, a **decline in softwood availability can be expected from the 2030ies on** (see Section 5.2.2 as well as Bolte and Rock 2023).

What is modular timber construction?

Modular timber construction builds on prefabricated wooden structures, that are either two-dimensional (2D) wall or ceiling elements or three-dimensional (3D) modules. The modules are prefabricated off-site, which guarantees faster production, as it is largely independent of weather conditions at the construction site. Also, production is highly automated, which leaves module production less affected by skilled worker shortages as compared to the total construction sector. Especially for the production of 3D modules, off-site automated production enables more efficient and reliable planning and coordination of assembly steps (Zeman 2023).

The use of 2D timber construction modules provides strong opportunities for the serial energetic refurbishment of e.g. apartment buildings in Germany

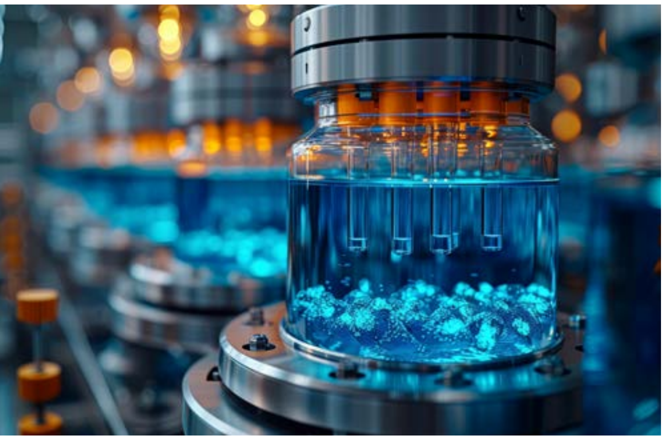
© Photo from B&A Seriell GmbH

7 Update based on the same calculation method as presented in Iost et al. (2020)

3.4 State of technological innovation[8]

Technological innovation is integral to meeting the vision of a multifaceted, sustainable and circular German bioeconomy. That said, other forms of innovation (frugal, social, business model, etc.) also play essential roles. The focus in this report is developing an **overview of diverse bioeconomy fields**. Typically, a prospective outlook for technological innovation would provide information about likely pathways and potential impacts. However, the technology portfolio relevant to the bioeconomy is characterised by high levels of diversity. It lacks a broadly accepted common technology concept and knowledge about potentials is fragmented. For that reason, the following section provides a screening and assessment selected to cover a broad range of technology fields as regards their **innovativeness, prospective development** and **impacts**.

This monitoring differentiates between innovation fields that address the supply of biomass, process technologies and application fields (distinguished by green, blue and orange respectively in Table 3.1). The technology fields were selected based on relevance, innovativeness and novelty, e.g. in terms of significant technological advances and/or significant potential for change in certain applications. The aim was to assess a **broad range of potential innovations**, noting that this list is neither comprehensive nor completely representative. We considered technology fields at different levels of aggregation and different types of innovations. Table 3.1 summarises the selected innovations with a qualitative assessment of degree of disruption, key types of impacts (substitution, new processes, new products) and impact paths (e.g. increases in primary sector productivity).



Technology trends

A wide variety of innovations has emerged in the bioeconomy with different levels of **maturity and disruptiveness**. Those innovations with a high potential of disruptiveness could also lead to significantly lower demands for fossil or bio-based feedstocks, but still have to overcome the upscaling challenge. Examples include 'carbon capture and use' (CCU) or cultured meat. In healthcare, biotechnology could redefine approaches to diagnosis, treatment, prevention and production. Microbiomes[9] can contribute to maintaining agricultural productivity, by complementing or replacing chemical fertilizers and pesticides and by building resistance or tolerance to diseases and harmful environmental conditions (e.g. drought, extreme temperatures).

Other innovations are **incremental,** leading to new processes or substitution of existing fossil-based products with bio-based ones. Significant efforts are being made to avoid tropical oils and/or find alternative food feedstocks (e.g. alga-based products).

8 This section is based on a larger report (Wydra et al. 2023) with more detailed information about status, technological and market outlook, and impact of the technology fields available at symobio.de.

9 A microbiome is a microbial community — comprising e.g. bacteria, archaea, viruses, unicellular eukaryotes and fungi — and its functions that are characteristic of a specific habitat, e.g. soil, water, humans, plants or animals as hosts, being inhabited by microbiomes.

Table 3.1 Characterisation of the technology fields

Technology Field	Sector	Disruption	Innovation type	Impact path
Agriculture 4.0	Primary Production	Medium, key enabling technologies for the bioeconomy	New processes	Increases in primary sector productivity
Indoor Vertical Farming	Primary Production	Low to medium, potential to establish new plant production practices and value chains	New processes	New/additional feedstock sources
Algae	Primary Production	Low to medium, biomass production potentially requiring less arable land, biomass as carbon and energy source	Substitute Products/ new Products	New/additional feedstock sources
Plant breeding	Primary Production	Low to medium, technological potential, but /legal hurdles high	New processes	Increases in primary sector productivity
Carbon Capture and Use (CCU)	Many manufacturing sectors	Rather high, may provide large-scale substitution of fossil resources or biomass as carbon feedstock	Substitute products/ new processes	New/additional feedstock sources
Biotechnology	Primary Production, industry and services	High, key enabling technologies for the bioeconomy for many sectors	Substitute Products/ new Products and processes	All paths
Microbiome	Primary Production, Food, health and environmental services	Medium to high, ability to engineer microbiomes is an emerging key enabling technology within biotechnology	New products	Bio-based value added in low-volume/ high-value industries
Alternative proteins	Food and Feed	High; substitution of meat production and industrial livestock "farming" possible with less need of biomass; Germany: meat production challenged	Substitute products	Increases in biomass use efficiency and new biomass uses
Biopharmaceuticals	Pharmaceuticals	Medium to high; completely new kind of therapeutics, potentially better health effects	New products	Bio-based value added in low-volume/ high-value industries
Innovative wood products	Many manufacturing sectors	Low to medium, mainly substitution	Substitute products	Increases in biomass use efficiency and new biomass uses:
Bio-based plastics	Plastics	Low to medium, partly substitution, partly innovative non drop-ins	Substitute products	Substitution of fossil- by bio-based resources:
Bio-based surfactants	Chemicals	Low to medium, second-generation bio-based surfactants may enhance product performance and broaden range of applications	Substitute products/ new products	Bio-based value added in low-volume/ high-value industries

Note: The innovation type is mostly based on characteristics of the innovation taxonomy for the bioeconomy by Bröring et al. (2020) and the impact path is mostly derived from the taxonomy for the bioeconomy by Stark et al. (2022).
Legend: Green — Biomass; Orange — Process, Blue — Applications

Source: Wydra et al. (2023)

Table 3.2 Patent applications in Germany and world-wide for selected technology fields in the bioeconomy

	Germany 2009-2012	Germany 2019-2022	World 2009-2012	World 2019-2022	RPA index 2009-2012	RPA index 2019-2022
Agriculture 4.0	132	542	1030	4107	-13	55
Indoor Vertical Farming	23	42	100	351	43	25
Algae	262	186	2598	2454	-35	-37
Plant breeding	283	107	2338	1996	-18	-59
Carbon Capture and Use (CCU)	218	213	1655	1991.6	-10	8
Biotechnology	5340	4848	53304	81063	-36	-47
Microbiome	17	21	158	521	-30	-71
Alternative proteins	37	90	293	976	-14	-13
Biopharmaceuticals	2303	2372	24979	40853	-43	-55
Innovative wood products	1120	869	5080	5557	39	44
Bio-based plastics	422	398	3302	4207	-13	-1
Bio-based surfactants	305	315	1359	1622	41	66

Source: Fraunhofer ISI based on STN.
RPA: Revealed patent advantage. Legend: Green — Biomass; Orange — Process, Blue — Applications

However, technological development is often still not mature, needing further improvements in upscaling, reliable performance despite fluctuating feedstock quality, or expansion of application ranges (e.g. for bio-based plastics, biosurfactants, wood-based products).

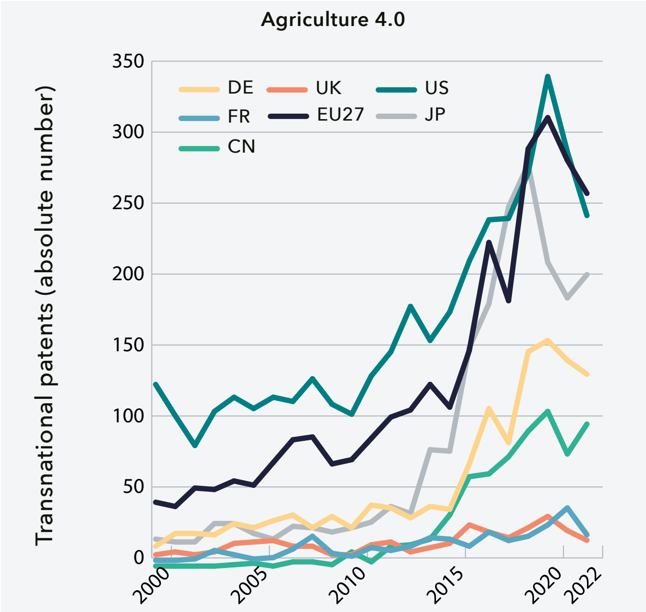
One tool for monitoring technology dynamics and the competitiveness of countries is **patent analysis**. However, patent dynamics of the different technologies of the bioeconomy are diverse. Some emerging fields present significantly increasing patent counts, such as alternative proteins and vertical farming. Other more mature technologies have already reached high patent intensity in the past, and they are stagnating. To illustrate the position of Germany, the **revealed patent advantage (RPA) index** provides an indication of the **relative specialisation of a given country in selected technological domains**. It is based on patent applications filed and is defined as a country's share of patents in a particular technology field divided by the country's share in all patent fields. With the taken normalisation by using a logarithmic function, the index is zero when the country's share in the sector equals its share in all fields (no specialisation); and above zero when a positive specialisation is observed (and vice versa).

The results for Germany are mixed (Table 3.2). This is not surprising, as Germany is rather specialised in areas like machinery related technology. Interestingly, the specialisation profile becomes more pronounced over time as regards the areas of innovative wood products, agriculture 4.0 and surfactants. In contrast, the degree of specialisation in biopharmaceuticals, biotechnology, microbiomes or especially plant breeding become progressively weaker over time.

As regards global patent coverage, the US leads in all technology-related fields, while the EU-27 leads for the areas algae, detergents and wood-based products. China, coming from a rather low level, is strongly catching-up in recent years, and already surpassed the EU-27 in biotechnology, biopharmaceuticals and plant breeding. As an example, Figures 3.5 and 3.6 show the patent dynamics for the two broadest technology fields of the bioeconomy considered in this analysis: agriculture 4.0 and biotechnology.

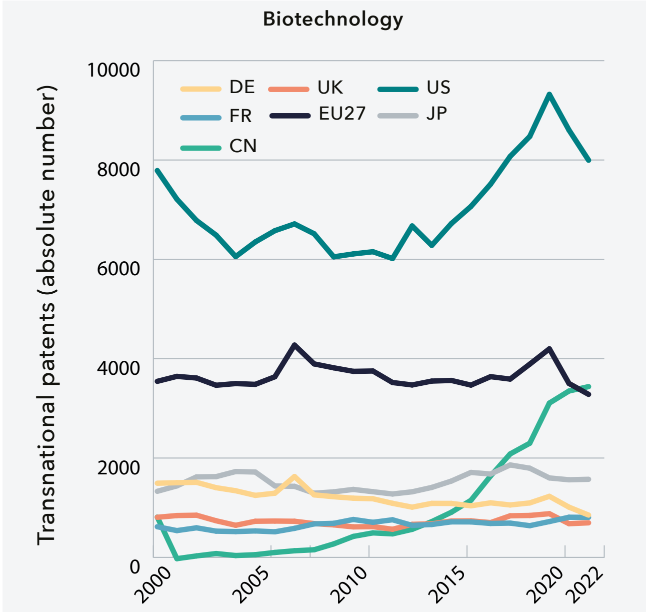
In both cases, the US shows rather strong growth patterns in the second half of the last decade. China presents high dynamics as well, and it surpasses the EU-27 in biotechnology. **German performance in biotechnology rather stagnated,** and it falls behind China and Japan to the level of the UK and France. However, **Germany shows strong development in the past 6 to 7 years for agriculture 4.0** and participates in more than half of the EU-27 patents. Altogether, the stagnation or sight decline of patent applications in 2021 and 2022 are most likely due to the Covid-19 crisis.

Figure 3.5 Transnational patents agriculture 4.0 between 2000–2022



Source: Fraunhofer ISI based on STN

Figure 3.6 Transnational patents for biotechnology between 2000–2022



Source: Fraunhofer ISI based on STN

Market evolution and location Germany for bio-based innovations

Considerable growth is expected for all of these technology fields. However, it should also be noted that high expectations have often not been achieved in the past. The market drivers and barriers show rather high similarities across the technology fields. In many fields, technological progress is directed towards the provision of more sustainable products and processes compared to existing ones. On the demand side, a growing preference for eco-friendly products and processes in general is seen.

However, persistent **barriers** continue to block upscaling. Generally, costs for bio-based products are usually higher than for existing fossil-based products. While some improvement has been achieved, for many of the assessed innovations **full price competitiveness is unlikely for the upcoming years**. As it is unlikely that placing the burden for change on consumers alone—paying more ("green premium") for bio-based products—will achieve the desired political goal of a bioeconomy transition, market regulation gains increased importance. Today, market incentives, for example for material use of bio-based products, bio-based plastics, CCU or biosurfactants, are largely absent. Regulations and consumer acceptance pose additional challenges. There is an intensive debate about the **EU regulatory framework**, which mandates extensive approval process in the case of **novel foods**. The regulation of waste hinders the development of potential circular value chains, as the use of waste in some cases is not allowed. For some technology fields, **consumers are also reluctant**, such as for certain applications for biotechnology (e.g. food), bio-based plastics or plant engineering.

As regards Germany, potentials differ between these technology fields. **Germany has a rather strong position for e.g. biopharmaceuticals, biosurfactants and CCU,** due to its rather strong pharmaceutical chemical industry, which has to align to a green transition pathway in the upcoming decades. A limited role for Germany can be expected for algae or plant breeding. In these cases, significant domestic production in Germany is unlikely due to economic or regulatory issues. For other emerging fields, such as alternative proteins, bio-based plastics, vertical indoor farming or agriculture 4.0, some German firms and activities can be identified. Whether they succeed on the world market and dynamic developments emerge still has to be seen.

Impacts of bio-based innovations

Many technology fields demonstrate high impact potential. The bioeconomy's potential development aligns well with the SDGs. Various technology fields could contribute to achieving specific SDGs, such as zero hunger (through agriculture 4.0, alternative proteins), climate action (via CCU), algae, and bio-based plastics),

and sustainable industry and innovation (via biopharmaceuticals and biotechnology). **Many technology fields (e.g. alternative proteins and CCU) show potential for market disruption, challenging conventional practices and fostering a shift towards bio-based alternatives**. However, the realisation and uptake of such innovations is also highly uncertain as well as ambiguous. Exclusively positive effects in all dimensions cannot be expected. Unavoidable negative impacts must be mitigated (e.g. as regards jobs and necessary retraining; higher land use for algae production or timber) and unintended negative effects cannot be ruled out. The diffusion of some of the innovations would probably lead to higher feedstock demand, partly for waste or by-products, but also these might be limited in sustainable supply.

Policy options

Policy plays a critical role in **creating and enabling a flourishing environment for bio-based innovations**. To promote investment in research and development, governments may establish supportive regulatory frameworks that incentivise private sector involvement. This includes e.g. providing **funding opportunities** or **tax incentives** to further support technological progress and innovation activities as well as **streamlining approval processes and regulations** for bio-based products. At the same time, the regulatory landscape has to consider issues of **social acceptance** for some technologies, as well as to ensure sustainability and circularity, encouraging the adoption of bio-based alternatives over fossil-based counterparts.

Biomass is a critical resource in the bioeconomy, and its sustainable management is paramount to the impact of bio-based innovations. Hence, **strategies for sustainable biomass production**, considering land use, biodiversity conservation, and carbon sequestration should be developed. Encouraging the use of non-food feedstocks and implementing circular approaches to biomass utilisation may mitigate potential negative ecological impacts, although here bottlenecks in supply cannot be ruled out.

As novel technologies and approaches arise in the bioeconomy, there is a need for a skilled workforce to drive its implementation. **Investment in education and skills development programs** to equip the current and future workforce with the necessary expertise in biotechnology, digitalisation, and other bio-based technologies is needed.

3.5 Innovation potentials

The following case studies consider three innovation fields in the area of applications in a more in-depth way. Each depicts considerations of potential market developments, drivers and barriers, economic and ecological impacts, as well as relevant broader insights for the overarching bioeconomy transition.

3.5.1 Meat alternatives

The market for plant-based meat alternatives has shown continuous growth in Germany since reporting in official statistics began in 2019.Meat alternatives are attracting wide interest as possible solutions to meet the growing global demand for proteins in a sustainable, ethical, and healthy way. The most relevant alternatives for the coming decade are **plant-based meat alternatives (PBMA)**, which are innovative food products that **mimic meat products in appearance, taste, texture, and cooking practices**. The basis for PBMA are plant proteins, isolated from agriculturally grown crop plants such as wheat, soybeans, peas, and beans. **Cultivated meat** may also enter commercial markets in the upcoming years. It is produced by cultivating animal cell lines in bioreactors under controlled conditions.

In Germany, as one of very few innovative products in the bioeconomy, plant-based meat alternatives are explicitly included as an own product group in official statistics since 2019. The numbers show a **continuous growth of turnover and produced weight of meat alternatives** over the last four years (Destatis 2024). In 2023, turnover exceeded **€ 580 million** per year compared to € 200 million in 2019. In addition, the number of companies in the field rose from 33 in 2019 to 67 in 2023. However, in 2023 the value of meat and meat products produced in Germany was € 44.8 billion, which is nearly 80-times higher than the turnover in meat alternatives. In other words, meat alternatives make up around **1 % of total meat products** as regards economic value.

The market for plant-based meat alternatives has shown continuous growth in Germany since reporting in official statistics began in 2019.

Future **global outlooks for alternative meat differ widely**. Well-known estimates from BCG/Blue Horizon (2021) expect the plant-based meat alternatives market to surpass $ 10 billion in 2027, and the cultivated meat market to reach $ 1 billion by 2035. Still, conventional meat will continue to dominate the market in the next one or two decades. Optimistic scenario outlooks for alternative meat are in the range of about 25 % market share in 2040. However, this would require the establishment and/or scale-up of production facilities and the development of new product generations which meet consumer's expectations regarding price and taste. In addition, price competitiveness is not reached yet. Regulation is another key market factor as cultivated meat producers will require product authorisation at the EU level for potential marketing in the EU (Regulation (EC) No 1829/2003 and Directive 2001/18/EC). This would require thorough testing activities and may present a challenge as regards global competition, as e.g. the US and Singapore installed faster procedures and already authorised the first products.

Currently, in Germany there are some **start-ups** and also some **leading players from the meat industry** in both plant-based meat alternatives and cultivated meat. Germany's position in the global competition is difficult to determine due to lacking comparative data. As alternative meat has mainly a substituting effect with potentially limited changes in cost and prices, the effects are related largely to structural changes from e.g. the feed industry and meat producers as well as to the new value chains and potential changes of trade balances.

Regarding sustainability impacts, many studies emphasise the **potential for saving land** by substituting with meat alternatives (in particular related to feed; for example, 62% of farmland is used to produce feed in Germany (BMEL 2020). Some estimations go up to more than 90% land saving potential. This would also lead to lower GHG emissions, less air pollution, less acidification of soils, and less marine eutrophication. While many studies claim an overall sustainability advantage compared to conventional meat products, the impacts highly depend on the type of meat replaced (chicken, beef, pork). Moreover, for cultivated meat the environmental effects largely depend on whether the firms would have to continue to use expensive and energy-intensive pharmaceutical grade ingredients and highly refined or purified growth media, or **whether more efficient food processes** can be applied. Next to environmental effects, there may be significant positive impacts on public health via nutrition and animal welfare. However, for a reliable assessment more research is needed.

At the bottom line, in the light of the manifold sustainability weaknesses of our food system, and the significant resistance of politics to "meddle" with peoples' diets, **alternative proteins constitute one lever for sustainability.** They show the potential to reduce GHG emissions and save land and water, although the assessment is rather complex and potential impacts depend on future technological advances.

3.5.2 Biopharmaceuticals

There is a clear shift toward biopharmaceuticals in medicine. The industry is continuously growing, and it has become one of the most significant employment opportunities in bioeconomy processing industries in Germany. Biopharmaceuticals are complex molecules derived from a biological source, with the purpose to diagnose, prevent, treat, or cure diseases or conditions of human beings. They can be divided into three groups according to their biological structure: pharmaceuticals based on **amino acids**, pharmaceuticals based on **nucleic acids**, and **vaccines**. The production host systems most often used are mammalian cell cultures, but also (genetically modified) bacteria, yeast, fungi, plants, and cell-free expression systems are used.

Biopharmaceuticals represent a **disruptive innovation** when compared to well-established, small-molecule medicines. That is because they make tailor-made, personalised treatments — adapted to specific characteristics e.g. of a particular type of cancer and the genetic information of an individual patient — possible. Biopharmaceuticals already **dominate the market in terms of turnover** for e.g. immunology or sense organ diseases, and they comprise almost half of the turnover for oncology and metabolism disorders. During the Covid-19 pandemic the biopharmaceuticals sector demonstrated how rapidly it could respond to an urgent need. The growth and increasing importance of biopharmaceuticals compared to the still growing overall pharmaceutical market is likely to continue and extend to larger unmet needs like Alzheimer's disease and obesity. As climate warming supports the spread of formerly tropical infectious diseases globally, the need for vaccines and other biopharmaceuticals is also likely to grow. **Most of 2028's top 10 drugs are expected to be biotechnology-based**.

The number of employees attributed to biopharmaceuticals in Germany is growing continuously and reached around **50,000 employees in 2022** (BCG and VFA 2023), making it one of the **more significant employment opportunities in the processing industries of the**

There is a clear shift toward biopharmaceuticals in medicine. The industry is continuously growing, and it has become one of the most significant employment opportunities in bioeconomy processing industries in Germany.

German bioeconomy. Moreover, biopharmaceuticals contribute to better health, and therefore an increase in a relative healthy workforce is seen. In biopharma, the search for new targets and respective active pharmaceutical ingredients is particularly knowledge and resource intensive. Artificial intelligence technologies could thus improve the efficiency of research, reduce the high failure rate of drug candidates, and open new opportunities for growth.

Biopharmaceuticals consisting of naturally occurring substances (amino acids, peptides, proteins, particles of RNA or DNA) are considered **less hazardous** than small-molecule drugs because of their supposed rapid degradation. Biologically generated raw materials for biopharmaceuticals have the potential to reduce the industry's GHG emissions and use of hazardous substances. For example, cell culture media ingredients are partly made of bovine serum. However, rearing farm animals results in large GHG emissions. Substituting animal-sourced materials in the production media can significantly reduce the environmental impacts of biopharmaceuticals production. **Plant biosystems are also inexpensive and easy to scale-up**, and do not require refrigeration or a sophisticated medical infrastructure. First successes have been reached with a **plant-derived therapeutic protein** granted marketing authorisation and vaccine candidates, which completed phase III clinical trials (Stander et al. 2022).

High water use is a challenge. Water usage in biopharmaceutical production may be more than 100-fold higher than that used in small molecule manufacturing (Ho et al. 2010, Kokai-Kun 2022). In batch production, bioreactors can either be disposed of after each batch or need costly cleaning before reuse. Specific solutions for improving the cell's growth characteristics and combinations of batch and continuous methods have the potential to substantially reduce energy consumption, water use and waste production.

Altogether, the **functional diversification and increased effectiveness of medical treatments** represent an obvious direct contribution of biopharmaceuticals to social sustainability. Biological processing offers **wider accessibility** of pharmaceuticals through a decentralised and flexible workforce, research and development, and biomanufacturing supply chains. Because of their high sales price, biopharmaceuticals are less easily available in low-income countries than small-molecule medicines. Biosimilars, i.e. biopharmaceuticals highly similar to an original biopharmaceutical, can substantially reduce sales prices and thus improve access to biopharmaceutical treatments.

Germany leads production of bio-based surfactants in the EU and is in second place in global patent applications. Surfactants are used e.g. for household detergents.

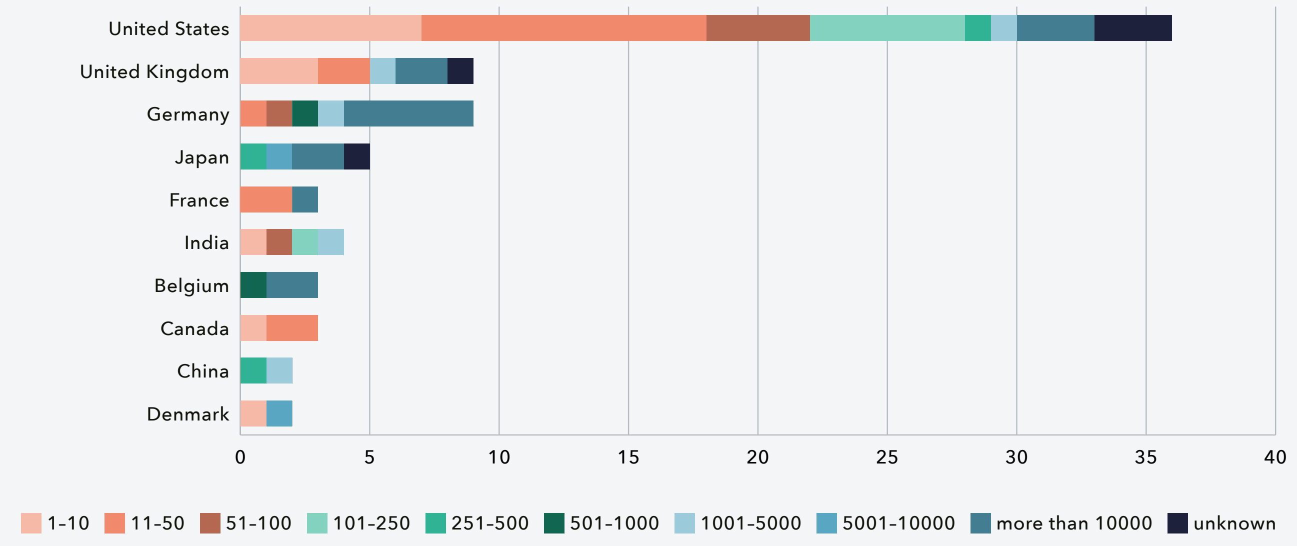
3.5.3 Second generation bio-based surfactants

According to European CEN standards a bio-based surfactant is a surface-active compound that is wholly or partly derived from biomass produced either by chemical or biotechnological processing (CEN/TR 17557:2020). They are used in various industries, such as **household detergents**, **agriculture, food,** and the **pharmaceutical industry.** Bio-based surfactants represent a flagship product group and a **success story in terms of market relevance for bio-based chemicals**. On the one hand, there is already a certain traditional market based on bio-based feedstocks, and on the other hand, there are significant innovation activities to advance bio-technological products with innovative product performance and the use of more sustainable feedstocks, that will likely be commercialised in the coming years. A key recent development is the high focus of R&D&I activities on the so-called 2nd generation of bio-based surfactants, namely **microbial bio-based surfactants** (e.g. rhamnolipids, sophorolipids, surfactin). They are fermentation-based and produced by microbes — such as fungi, yeasts, and bacteria — through metabolic processes. For that reason, they are also termed "microbial surfactants". Usually these surfactants do not use tropical oils, such as the case for many 1^{rst} generation biosurfactants, but are made from sugar or potentially in the future from waste.

The most significant driver in the development of 2nd generation biosurfactant technologies and markets is the need for sustainable solutions. The need to move away from fossil-based feedstocks, coupled with the fact that 2nd generation biosurfactant technology does not require the use of refined substrates and significant energy inputs (Albrecht et al. 2022, ACI 2022), have prompted manufacturers to intensify research and development efforts in this area. Moreover 2nd generation biosurfactants pose less environmental risks and safety concerns. Consequently, developing and employing sustainable processes and feedstocks for surfactant production is a vital issue.

Currently 2nd generation bio-based surfactants represent a small niche. Market studies estimate the current market size to be around $ 15–30 million (**1–2 % of the current biosurfactant market**), and expect an annual growth rate of around 4–5 % until 2030. Such projections may be too moderate, considering very recent key developments such as the opening of Evonik's 2nd generation facility in Slovakia. This three-digit million-euro sum investment may present the beginning of a strong dynamic development in this segment. As has been observed earlier for other first-of-its kind investments in bio-based chemicals in Europe (e.g. for biosuccinid), existing facilities owned by the operator are used and modified. A main challenge in this business-to-business market for Evonik and potential others is to **support and persuade the downstream industry** to develop new applications that use the potential superior

Figure 3.7 Company size distribution in 2nd generation biosurfactant-active countries



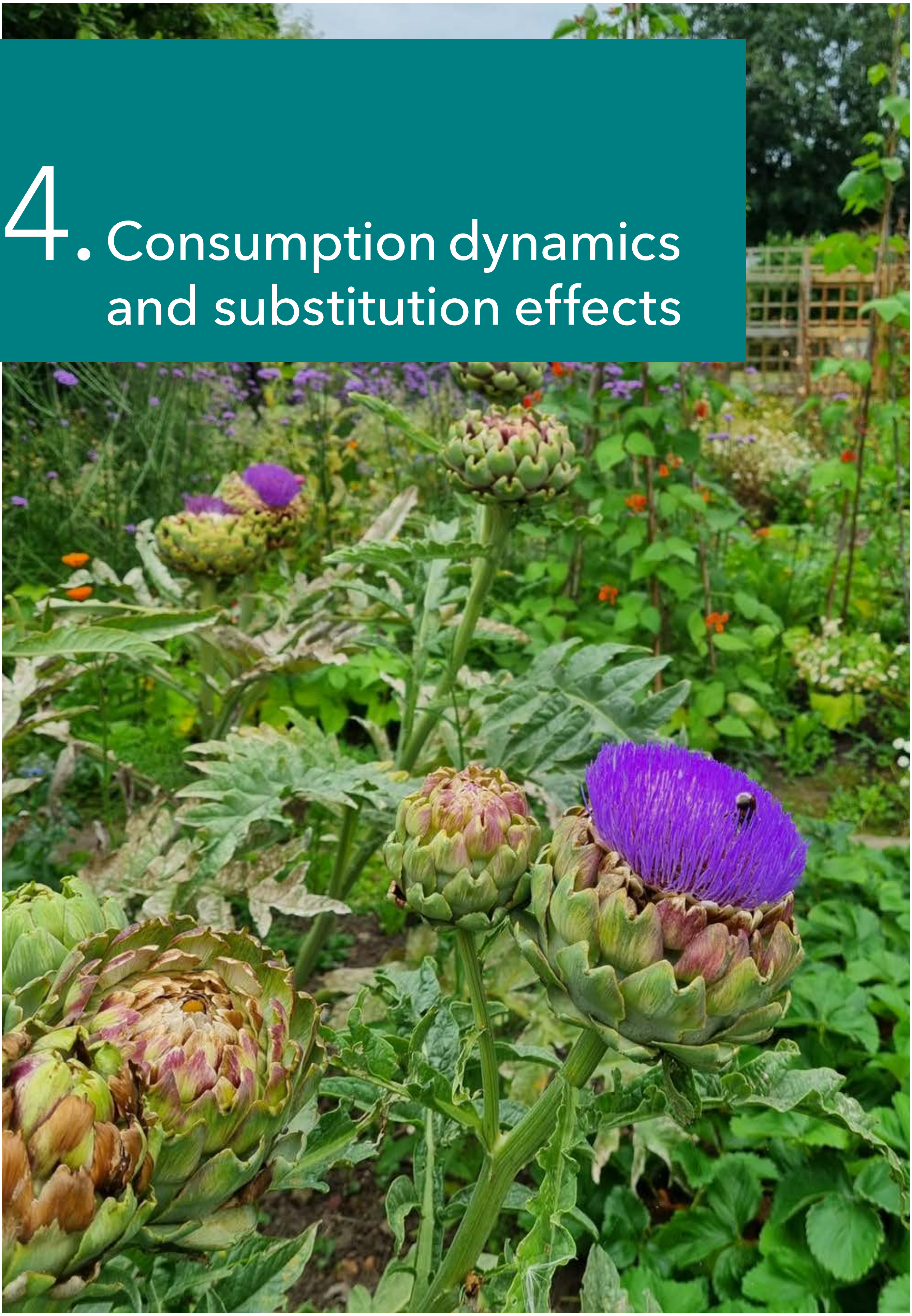
Source: Fraunhofer ISI based on Crunchbase

characteristics of these new bio-based surfactants. This challenge is reinforced by other hurdles such as the cost disadvantages compared to traditional (fossil or bio-based) surfactants.

Economically, **bio-based surfactants present one of several rather high value added markets.** The use of innovative technology and prospectively alternative feedstock resources together with strong application sectors (detergents, chemical processing) presents favourable conditions to secure Germany's strong competitiveness. **Germany is in second place for applying for patents,** behind the US, and has strong players in the market of bio-based surfactants, leading production in the EU. There are close strategic links between the bio-based surfactant providers (next to Evonik, BASF, Beiersdorf and Bayer) and the users (Unilever, Henkel). Hence, **Germany has a strong position to generate positive economic impacts**. In other countries, such as the US, SMEs dominate in the development and production of 2nd generation biosurfactants. Figure 3.7 summarises relevant firms identified.

General potential ecological advantages of second-generation bio-based surfactants include the use of novel biomass streams with potentially lower trade-offs to other sectors (like food), their low eco-toxicity, full biodegradability, and lower CO_2 emissions from the mild conditions of fermentation, which are carried out at ambient temperatures and pressure. However, assessments on the environmental impacts of 2nd generation biosurfactants are rather scarce, product specific and with different foci. In general, the existing studies indicate that certain processes, products, or applications may lead to a potentially beneficial sustainability performance, but it depends largely on the specific products and processes compared. Moreover, while 2nd generation biosurfactants require relatively less energy inputs (see e.g. Balina et al. 2023), further optimisation and use of renewable energy is key to reducing environmental impacts. A current hurdle is that the 2nd generation bio-surfactants available on the market now are still based on sugar, with direct competition to food and feed use and potential land-use conflicts. A range of current projects and SMEs are dedicated to expanding the use of inputs like food-waste to develop **bio-based surfactants** with a stronger environmental performance.

4. Consumption dynamics and substitution effects



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Key findings

- Meat consumption in Germany is, at a minimum, more than triple the amount recommended by German dietary guidelines. Although meat consumption has been in steady decline since 2010 (falling around 0.8 kilograms per year), the rate of change is insufficient to reach recommended dietary guidelines in coming decades. 11 million tonnes (t) of food were reported as lost and wasted in 2020 in Germany.
- Biomass contributed a total of 919 petajoules (PJ) to German energy supply in 2023, or 12 % of total energy and 49 % of renewable energy provision. It was mostly used for heat (614 PJ), followed by electricity production (177 PJ) and biofuels (127 PJ). The latter two sectors show decreasing absolute trends since 2021, and the relative contributions of biomass to overall renewable energy supply has been in decline since 2010 as alternatives (like wind and solar) grow in importance.
- Import dependencies for both conventional and advanced (based on wastes and residues) biofuels remained high in 2022 (with more than 80 % originating outside Germany).
- Modelling comparative scenarios for future biofuel use shows that the GHG quota requirements defined by RED II do not yet promote the use of biofuels in areas or sub-sectors of the transport sector in which they should be cost optimally allocated according to a long-term energy optimisation scenario.
- 54 million t dry mass (DM) were estimated as inputs to German processing industries for material use in 2020. Forest-based biomass comprises the largest share, in particular for sawmill and pulp processing, noting that some of these products were exported for final material consumption abroad. Around 3.3 million t DM of agricultural-based biomass were used for material processing in 2020, with the vast majority (73 %) used in the chemical sector. This sector is in particular expected to increase its use of biomass in the future.
- Life cycle analysis shows potentially positive environmental benefits of substituting wood for concrete and steel as a load bearing element in the construction sector, as well as CO_2-based ethylene for mineral naphtha in the chemical sector. However, robust analysis of substitution may require a blend of methodological approaches to take system wide impacts into account. How biogenic carbon is treated in GHG balances can significantly impact LCA results.

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4.1 Diets and food waste

The global food system faces multiple challenges:

- **Eradicating hunger, decreasing malnutrition and meeting the future food needs of a growing global population:** More than 700 million people faced hunger and almost 30 % of the world's population — 2.33 billion people — were moderately or severely food insecure in 2023 (FAO et al. 2024). Malnutrition challenges additionally include micronutrient deficiencies, overweight and obesity. In Germany, as in many other rich countries, overweight and obesity is a growing health problem (Schienkiewitz et al. 2022). Decreasing malnutrition is fundamental to achieving several SDGs, particularly SDG 2 (zero hunger), SDG 3 (good health and well-being) and SDG 10 (reducing inequalities) (FAO et al. 2024).
- **Reducing pressures on global ecosystems:** Food, in particular animal-based food, is a major driver of environmental degradation and planetary boundary overshoot (Gerten et al. 2020, Rockström et al. 2020).
- **Navigating land use competition for other biomass end uses:** The ultimate aim is to meet food demands within ecological limits while preserving ecological space for other bioeconomy purposes.

Feed is the largest end-use of biomass, both globally and nationally (see Chapter 6). Thus, **addressing the German food and feed systems has great potential to influence the development of the bioeconomy,** both in terms of potential (how much biomass is available) and environmental and social impacts at home and abroad. Synthesised research shows that a shift toward more healthy and sustainable dietary patterns is likely to reduce multiple environmental footprints of food consumption by 20–30 %, and some diets have the potential to reduce GHG emissions and land use by up to 70–80 % (Jarmul et al. 2020, Aleksandrowicz et al. 2016). Changing dietary patterns is the single most promising lever in this context (see also Chapter 7).

Dietary patterns compared to nutrition guidelines

The German population eats significantly more meat than recommended by both national guidelines and the 'planetary health diet'. The benefits of promoting dietary changes in line with available guidelines are accentuated by the high levels of people overweight in Germany: five out of ten women and six out of ten men living in Germany are overweight (Schienkiewitz et al. 2022).

The German Nutrition Society (DGE) provides dietary guidelines for the German population. The guidelines were updated in early 2024, mainly to better consider environmental aspects and to make methodological considerations more consistent and transparent (Schäfer et al. 2024)[10]. The recommendation for meat intake is **26-43 grams per day (or 300 grams per week)**. This is equivalent to 18–30 % of the per capita meat intake of 2022 (**143 grams per day**; BMEL 2023a). In addition to eating less meat, it is recommended to eat more pulses, beans and nuts and to avoid added sugars (Figure 4.1).

At the global level, the so-called 'planetary health diet' of the EAT Lancet Commission provides a reference diet to help feed a growing population in a healthy way and within planetary boundaries (Willet et al 2019). The planetary health diet proposes a similar meat intake as the German guidelines. It suggests 43 grams per day, with a possible range between 0 and 86 grams reflecting a wide range of food cultures and local production conditions.

Compared to the national recommendations, EAT Lancet suggests half the amount of milk (250 grams per day), but with a possible range from zero to the German guideline levels (500 grams per day). As with many animal-based products, milk products also have a high conversion rate from biomass (Shepon et al. 2018). This makes milk reductions an additional potential lever to decrease German land demands. Next to health benefits, the objective of reducing animal-based food is to better align consumption levels with sustainable livestock farming and production levels. The Eat Lancet diet also highlights the role of pulses, beans, and nuts as a significant protein source, as well as the importance of vegetable oils. These products are energy dense, which explains why the total amount of food in grams per day is smaller than for the German Society of Nutrition recommendations.[11]

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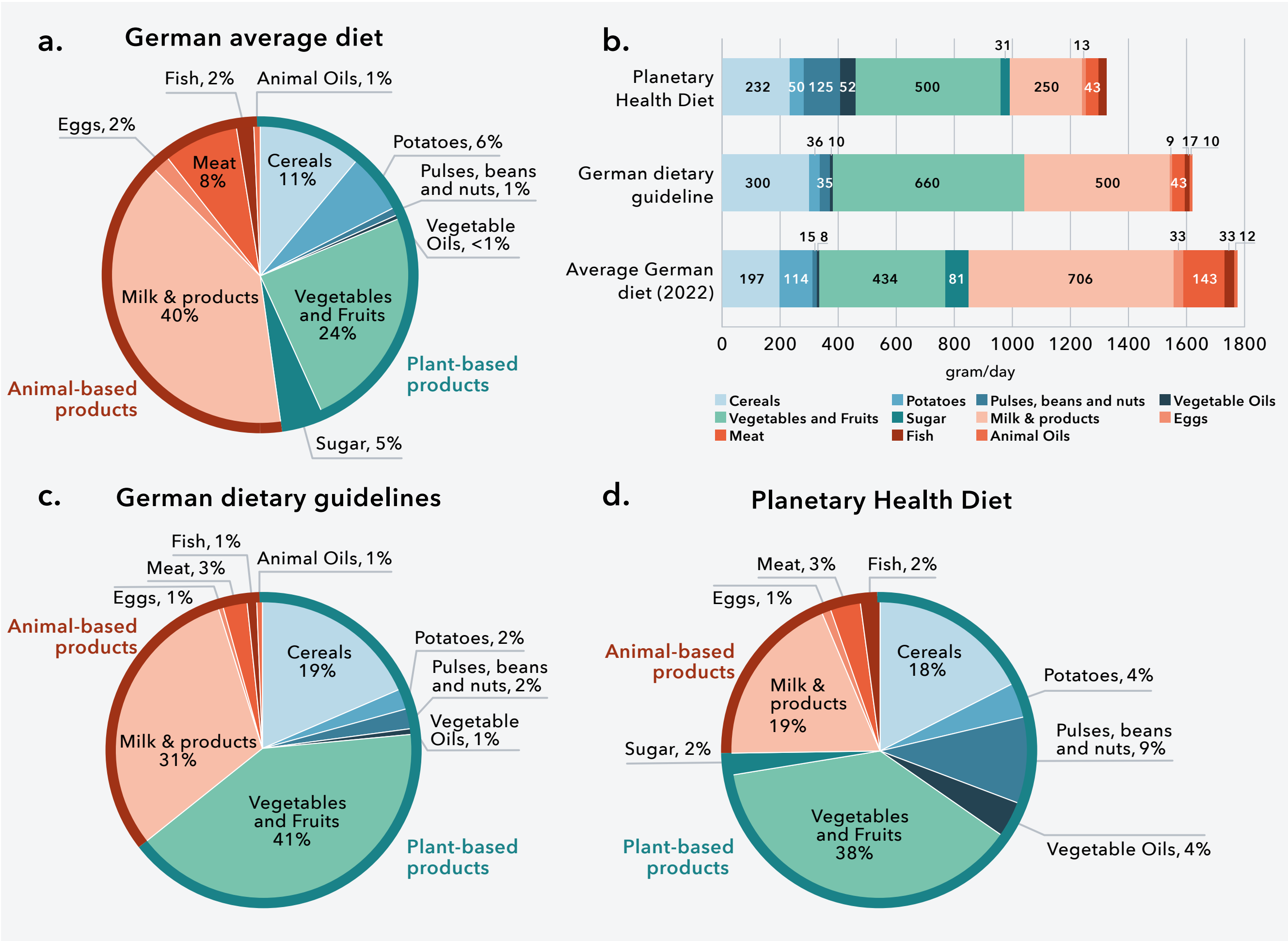
10 Updated dietary recommendations lowered meat consumption suggestions from less than 86 grams (Oberritter et al. 2013) to less than 43 grams per day (Schäfer et al 2024).

11 Energy content depends on the product properties (harvest specific and water content). Therefore, conversion rates between grams and calories slightly differ between sources. Using German data on energy content [Bundeslebensmittelschlüssel], the German Environmental Agency (UBA 2024) estimated the calorie intake of the DGE recommendations to be 2076 kilocalories and the calorie intake of the planetary health diet to be 2382 kilocalorie. The EAT Lancet designed the diet for 2500 kilocalories (Willet et al. 2019).

Figure 4.1 German dietary patterns 2022 and nutrition guidelines–comparison of diet compositions in percentual shares (a, c, d) and in gram/capita/day (b)



Note: German dietary guidelines refer to dietary recommendations of the German Nutrition Society, DGE. The planetary health diet refers to a reference diet supporting human and planetary health proposed by the EAT Lancet commission.

Sources: Estimated average German diet is based on food consumption data for year 2022 from BMEL (2023a) and adjusted for food waste shares as compiled by Helander et al (2021) (see 'final consumption' in Figure 4.2.3 below). Meat is provided as intake data by BMEL and hence not adjusted for food waste. Pulses, beans and nuts was last reported in 2016/17. We use the average of the last three years for which consumption of pulses was reported. c) Schäfer et al. (2024) d) Willet et al. (2019).

Dietary trends in Germany

According to data from the German Ministry of Food and Agriculture (BMEL 2023a, BMEL 2024a), food habits in Germany have remained largely consistent over the past decade. Besides rice intake, which slightly rose from very low levels, meat intake shows the most significant change. **Between 2010 and 2023 the trend shows a decrease of 2.2 grams per day** (0.8 kilograms per year) (Figure 4.2). However, this decrease[12] in meat consumption is **insufficient** to meet sustainable and healthy consumption levels in the coming decades. If the trend would continue, Germany would first meet recommended levels in 2070.

Food waste

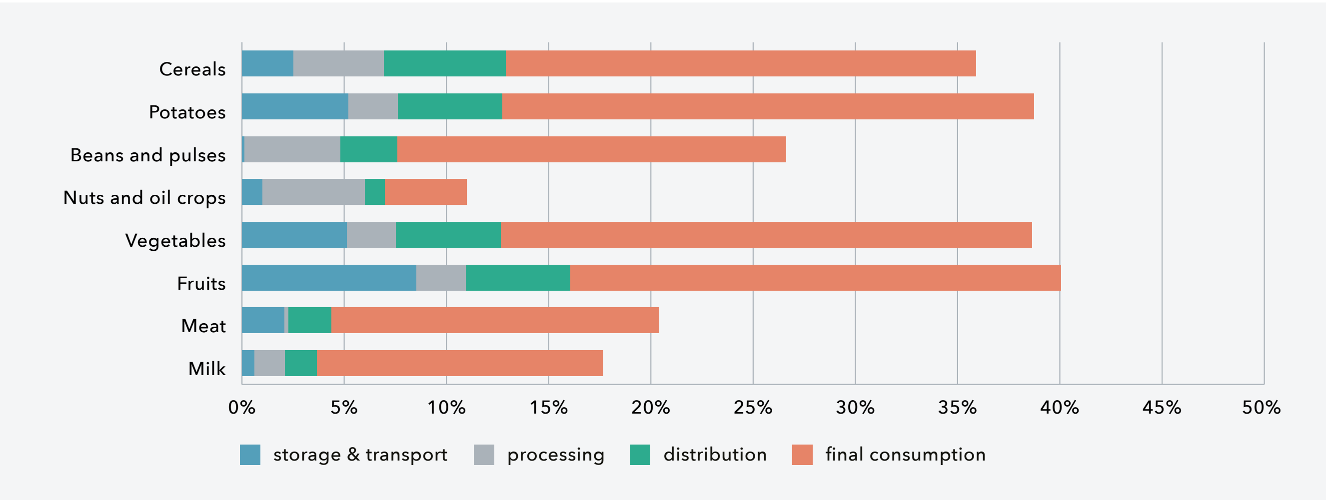
About one-third of the globally produced food (post-harvest, including non-edible parts) are lost or wasted (UNEP 2021). In Germany, **food loss and waste were estimated to be 11 million t in 2020** (Destatis 2022). More than half arises at the final consumption stage. Fruit, vegetables, potatoes, and cereals have the

12 A recent survey of 1,000 German citizens on their eating habits confirms a decline in meat consumption among some groups. According to the report, the proportion of people who eat meat every day has fallen from 34 % to 23 % since 2015 and more people are regularly turning to vegetarian and vegan alternatives (BMEL 2024c).

Figure 4.2 German meat consumption development between 2010 and 2023 compared to the upper limit of recommended meat intake

Sources: BMEL (2023a, 2024a), where data for 2023 is preliminary. Reference level from Schäfer et al. (2024).

Figure 4.3 Food loss and waste shares along the food supply chain in Germany (% of food in the supply chain step)



Source: Helander et al. 2021

highest food waste shares due their short durability. For fruits and vegetables, it is estimated that about 45 % of the household waste is avoidable. For eggs, milk, cereals, potatoes, sugar, oils, and fats it is more than half (Schmidt et al. 2019).

The German strategy for food waste reduction (BMEL 2019) and SDG 12.3 **aim to cut food waste quantities in distribution and consumption steps in half**. Such a food waste reduction implies significant behavioral changes in how consumers plan, buy, store and manage food in their households (Hebrok and Boks 2017). Reaching food waste targets has the potential to decrease biomass and land use footprints by 11–15 % (Helander et al. 2021). A revised EU directive from 2018 set standards for consistent monitoring and ensures a regular monitoring (EU 2018a).

Key policy messages

- Meat consumption in Germany is 3.3 to 5.5 times higher than recommended by dietary guidelines (143 grams per day compared to the recommended 26–43 grams per day). Although meat consumption is declining, it is not at a rate fast enough to meet nutritional guidelines.
- Ongoing efforts to reduce food waste are fundamental to achieving SDG 12.3. Systemic upgrading of food systems to support public health (reducing overweight and obesity) within planetary boundaries will require increased efforts to change dietary patterns.
- An integration of dietary indicators, such as meat intake, in the bioeconomy monitoring system may support the development of targeted and efficient policy interventions.

MONITORING CHECK BOX 2

Monitoring dietary patterns and food waste

Monitoring dietary patterns — or the consumption and intake of different food products — is highly relevant for the social and the environmental aspects of the bioeconomy. Dietary patterns significantly influence both public health and the resource requirements and environmental pressures of food systems. A targeted monitoring of dietary patterns could help political priority-setting and the identification of policy measures. For the bioeconomy monitoring, future indicators may focus on meat and milk intake, highlighting key variables of social change or (undesired) stability, and complementing the ongoing food waste monitoring.

The state of the art and data availability

While food waste monitoring is regulated by an EU Directive (EU 2018a)–which ensures reporting based on disposal quantities at least every 4 years — continuous monitoring of dietary patterns is lacking behind. The most robust data can be provided by longitudinal survey-based intake studies. Yet, the latest survey on food intake was done between 2005 and 2007 ("The German National Nutrition Survey II" (NVS II); MRI 2008). Due to the lack of up-to-date survey data, intake data is estimated based on consumption data from the Federal Ministry of Food and Agriculture (BMEL) and assumptions on food waste shares. For meat, BMEL provide intake data based on a similar procedure (Thies et al. 2022). For the other product groups, this report uses food waste estimations compiled by Helander et al. (2021, supplementary data). The survey-based food intake studies (NVS II) and the adjusted consumption food intake data provided by BMEL diverge. As regards of meat and dietary intake, the NVS II reports lower values (milk intake 541 grams per day in contrast to 706 grams per day and meat 114 grams per day in contrast to 143 grams per day). The differences are not yet fully explained (Thies et al. 2022).

Needs and next steps

The availability of official and reliable data is decisive for monitoring dietary change. The Max Rubner Institute is currently establishing a German National Nutrition Monitoring, which aims to provide regular reporting of survey-based food intake and changes over time (MRI 2024). This initiative is central to increase the knowledge about dietary patterns in Germany and to mitigate uncertainty regarding both dietary composition and trends over time. It could also provide the basis for a future dietary indicator in the context of the bioeconomy.

BOX 1: ALTERNATIVE FEED

by Karl-Friedrich Cyffka, DBFZ

Alternative feed includes **residues (e.g. from tea production), algae, insect protein/fats (possibly fed with residues) and by-products from food processing** (Smith et al. 2024, UFZ et al. 2022, fodjan 2024, Hu et al. 2023, Vauterin et al. 2021). It has been argued that redesigning the European food system on the basis of circularity principles (partly utilising residues as feed) could reduce agricultural land use (e.g. Van Zanten et al. 2023). Research from China has pointed to connected GHG mitigation potentials (Nayak et al. 2015) and the FAO (2023b) highlights the possibility to reduce feed-food competition through innovative and alternative feed sources. However, it is **not a silver bullet** and there are risks, depending on the feed used. As the primary aim of waste management is reduction, the potentials for alternative feed may also be limited in the future. If pursued, the sustainability requirements for advanced biofuels from residues and wastes [§28 (6) RED II] could represent a starting point for possible sustainability requirements of alternative feed, such as the need to avoid creating an additional demand for land and to avoid negative impacts on the environment and biodiversity (EU 2018b).

4.2 Trends for non-food biomass for energy purposes

Biomass continues to play a major role in Germany's energy sector. The extent and further development of bioenergy use in the future will depend mainly on the regulatory framework, such as the Renewable Energy Sources Act (EEG), the German Buildings Energy Act (GEG), the federal funding for efficient buildings (BEG), the German Fuel Emissions Trading Act (BEHG) and biofuel regulations like the GHG Reduction Quota (GHG-Quote) and the 38th Federal Imission Control Ordinance (BT 2024a, BT 2024b, BRg 2023, Köppen et al. 2024). On the EU level, the revision of the Renewable Energy Directive (REDIII) is decisive (EU 2023a). This section thus looks at an overview of biomass use for energy supply in general, the trends specific to different biomass types (agricultural, forestry and waste and residues), as well as the relevant policy developments driving future use. A special feature showcases modelling capacities and two comparative scenarios.

Biomass supplied 919 PJ of energy in Germany in 2023.

Overview of biomass use for energy supply

From 2010 (800 petajoules (PJ)) the overall energy provision from biomass grew and peaked in 2021 (934 PJ) and has since then fallen slightly. In 2023, biomass contributed a total of **919 PJ** to overall energy supply in Germany, or **12 % of total energy provision** and **49 % of total renewable energy provision**[13]. The heating sector (with 614 PJ or 67 %) was supplied with the most bioenergy, followed by the electricity (177 PJ or 19 %) and transport sectors (with 127 PJ or 14 %) (UBA 2024). Figure 4.4 shows that for the year 2023:

- In the **heat sector** the majority of energy (83 %[14]) and GHG emission reductions (82 %[15]) among renewable energies comes from bioenergy. The share of bioenergy in the whole heating sector (including non-renewable energy sources) accounts for 16 %[16].
- In the **electricity sector,** the bioenergy supply (18 %) and GHG emission reductions (15 %) among renewable energies is smaller, as solar and wind energy are the dominant renewable energy sources. Within the whole electricity sector (including non-renewable energy sources) bioenergy has a share of 9 %.
- The **transport sector** is still dominated by biofuels since they supply most energy (82 %) and contribute the most GHG reductions (93 % in 2022, renewable energies used in GHG quota regulation) among renewable energies (UBA 2024, ZOLL 2024). The bioenergy supplied to the overall transport sector (including non-renewable energy sources) comprises 6 % (UBA 2024).

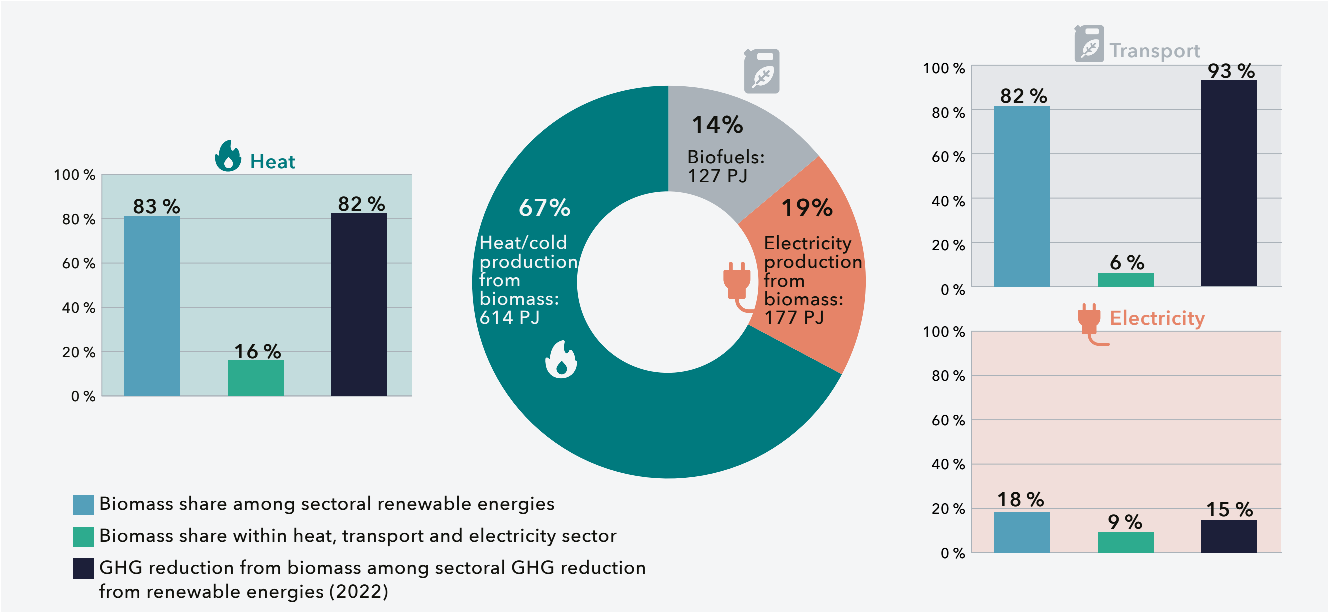
Since 2010 absolute energy provision from biomass grew in all sectors, but short-term perspectives (2020–2023) show a shifting trend with reductions in electricity and transport.

Trends

In the **long-term perspective**, the absolute energy provision from biomass grew in all energy sectors from 2010 until 2023 (see Figure 4.5). Within those 13 years, the strongest growth occurred in the electricity sector (41 %), followed by the heat (11 %) and the transport sector (5 %). In a **short-term perspective**, the energy provision from biomass fell between 2020 and 2023 in two sectors **(–7 % in electricity**, **–10 % in transport**) while increasing in the heat sector (10 %).

13 Other renewable energy sources include: hydro, wind, solar, geothermal, solar thermal, E-mobility
14 Energy from biomass of overall energy from renewable sources
15 GHG reduction from biomass among overall sectoral GHG reduction from renewable energies
16 Energy from biomass of overall energy in this sector (including non-renewable energy)

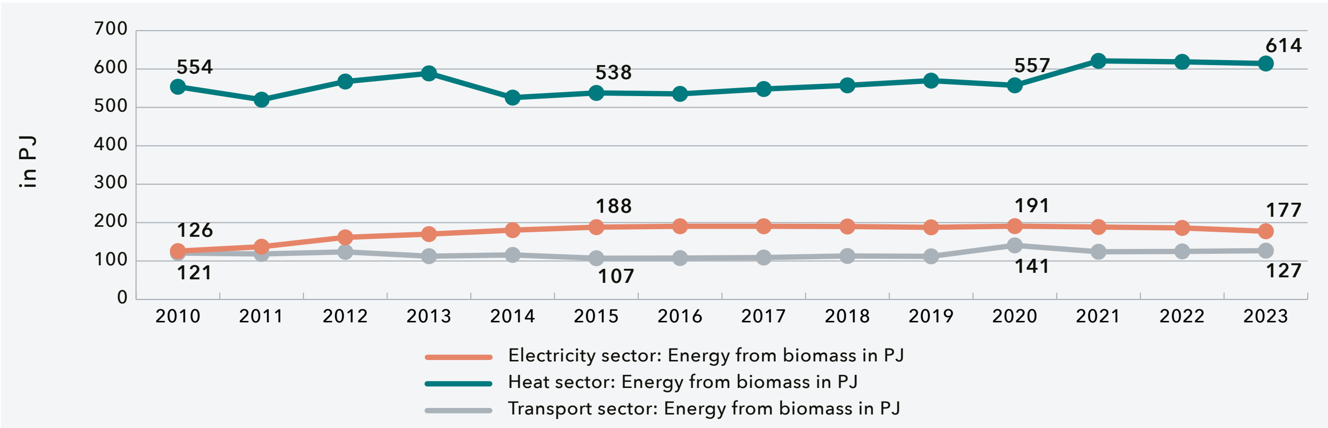
Figure 4.4 Bioenergy use, share of bioenergy and bioenergy GHG reductions in Germany in 2023 by sector



Note: Heat/cold and electricity production: with biogenic portion of the waste; GHG emissions transport based on GHG quota fulfilment (ZOLL) 2024

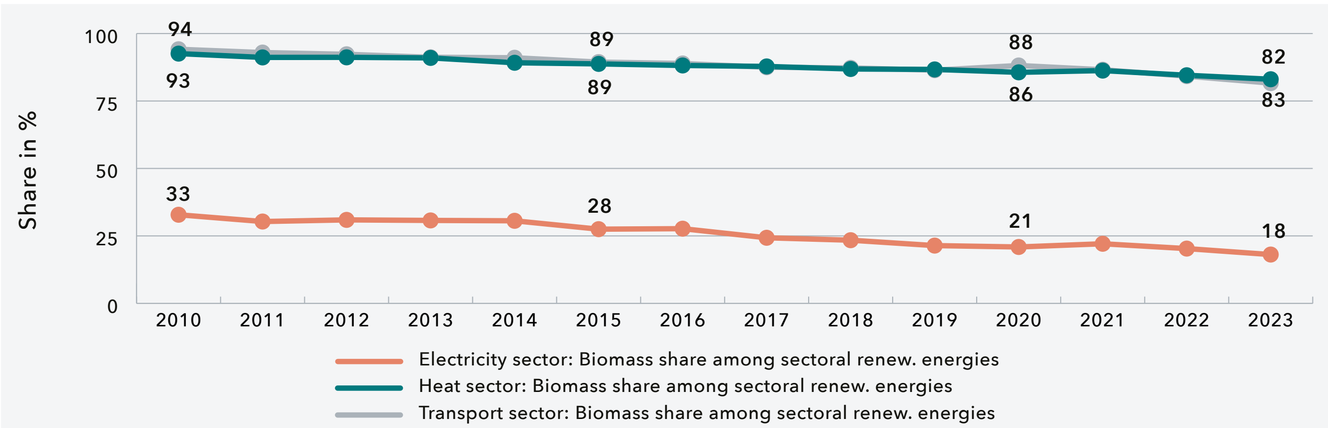
Sources: UBA (2024), ZOLL (2024)

Figure 4.5 Development of bioenergy by sector in Germany from 2015 to 2023



Source: UBA (2024)

Figure 4.6 Share of bioenergy of sectoral renewable energies in Germany from 2015 to 2023



Source: UBA (2024)

Across all energy sectors there is a clear trend of **declining bioenergy shares among all renewable energies** in the respective energy sectors from 2010 to 2023. This decline is much stronger in the electricity sector as other renewable options like wind, solar and hydro power are more readily available. With regard to the heating and transport sectors, alternatives like heat pumps, solar thermal energy, geothermal energy and electro mobility were historically not able to acquire similar market shares like the non-biogenic renewable energy alternatives in the electricity sector. Overall, the developments show that **non-biogenic renewable energy technologies are increasingly outperforming bioenergy in terms of growth across all sectors**.

Biomass flows for energy use

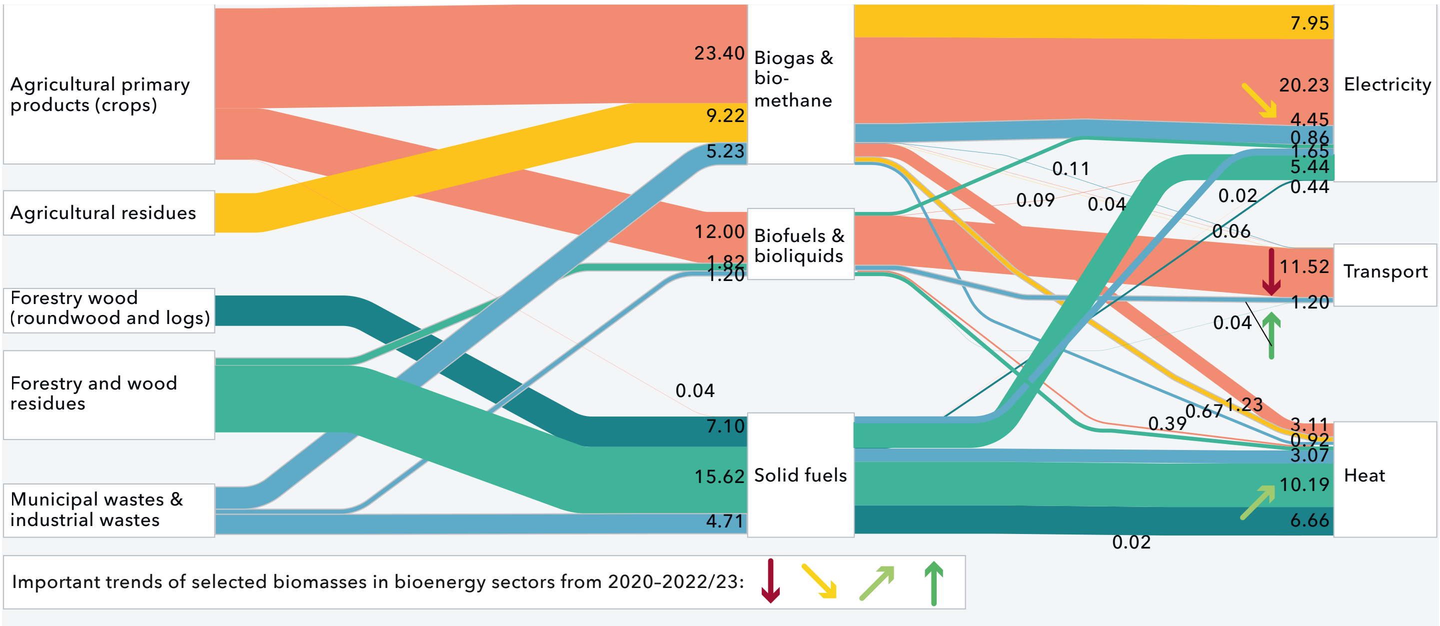
While Figure 4.4, Figure 4.5 and Figure 4.6 depict final bioenergy supply (output), Figure 4.7 displays the use of biomass in terms of biomass input in million tonnes dry mass (t DM) for energy purposes. It is important to note that the displayed data outlines the input mass (pure resource allocation) and does not include by-product streams. The publication of Thrän et al. (2023) describes the German energetic use of biomass and resource-to-bioenergy flows including by-products and conversion losses for the year 2019. In addition, Figure 4.7 displays the biomass use of the transport sector in terms of biofuels consumption at the fuel pump as reported by BLE (2024b) and not the amount of input material for biofuels production in Germany as reported by FNR (2024a). A comparison of those two sources can be found below.

Agricultural biomass

- The amount of food and feed crops for biogas, biomethane and biofuel production was much larger compared to the use of residues and wastes in 2020 (results would look different in terms of fresh mass as manure has higher water contents compared to crops). However, the use of food and feed crops dropped by 21 % from 2020 to 2022 mainly due to a decrease in usage for biofuels (−35 %) but also due to a decline in usage for biogas/biomethane (−13 %). The **overall use of crops for energy purposes** (bioenergy carriers from crops including biofuel imports) **was 17 % higher than the production of bioenergy carriers from energy crops in Germany in 2020**. This ratio dropped to 3 % higher use versus production of crops for energy purposes in 2022 (FNR 2024a, BLE 2024b).
- The share of used crops (without food and feed) as an input material for the production of bioenergy has remained rather stable (around 95 %) since 2012 until 2022, with approximately 5 % of crops (non-food/feed) used for material (mainly chemical sector) purposes (FNR 2024a).
- As regards **the importance of by-products** (not visualised in Figure 4.7): digestate as a by-product within the biogas/biomethane production process is **usable as fertiliser and peat substitute**; rapeseed meal, dried distillers grains with solubles (DDGS) and beet pulp as by-products of biodiesel and bioethanol production are **usable as feed**; glycerine from biodiesel production is **usable in the pharmaceutical industry.**
- **Agricultural residues and wastes are mainly used in the electricity sector**. However, **the transport sector,** with currently low usage levels, **represents a strong growth market** due to growing sub quotas for advanced biofuels[17] from

17 Share of advanced biofuels of energy used in road and rail (RED II)

Figure 4.7 Use of biomass by biomass category, energy carrier and sectoral use, in million tonnes dry mass in 2020, and trends until 2022 / 2023



Notes: Input mass without by-product streams; Directional trends until 2022/23 if data was available

Sources: BLE (2024b), Mantau (2023), UBA (2024), Krause et al. (2020), Rensberg et al. (2023), FNR (2024a), StMELF (2024), Bergophor (2024), Misron et al. (2017), Meisel und Braune (2015), Majer et al. (2015), Kamble and Kharate (2019), Braune et al. (2016), Göbel-becker (2022), Mantau (2023), Naegeli de Torres et al. (2023)

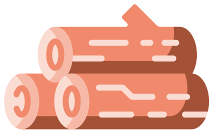
2022 (0.2 %) until 2030 (2.6 %). In just the past years (2020–2022), the usage of agricultural residues and waste **increased by approximately a factor 8** in terms of input material. From 2020 to 2022 there was a strong shift from food- and feed-based biofuels (73 % to 54 %) to waste and residue based biofuels (27 % to 46 %) due to the mandatory quota regulations for biofuels (§13–14 38. BImSchV) (BLE 2024b, BRg 2023).

- While the crops used in biogas and biomethane production are mainly sourced from Germany, **with regard to the used conventional biofuels only 11 % of the crops originated from Germany in 2022** (45 % from EU and 44 % non-EU) (BLE 2024b). However, especially biodiesel from rapeseed was largely produced domestically (3.3 million t), and Germany was a net exporter of biodiesel (imports: 1.3 million t, exports: 2 million t) in 2022. In contrast, bioethanol was produced in lower quantities in Germany (0.6 million t) and bioethanol imports (0.8 million t) were much higher than exports (0.14 million t) in 2022 (Destatis 2023, EUROSTAT 2022b, EUROSTAT 2022a).

From 2020 to 2022 there was a strong shift from food- and feed-based biofuels (73 % to 54 %) to waste and residue based biofuels (27 % to 46 %).

Forestry biomass

- **The use of roundwood for energy purposes was overall much smaller compared to the use of wood and forestry based residues and wastes** in 2020. Of all roundwood used for energy purposes (7 million t dry mass), larger bioenergy facilities use a lower share (3 %) compared to smaller bioenergy facilities (10 %). Households use the largest share (87 %) of roundwood (logs) for energy purposes (Jochem et al. 2023a, Mantau 2023). The share of primary forestry residues (residual forest wood less than 7 cm and bark) of overall solid forestry/wood residues and wastes used for energy amounts to 26 % (Mantau 2023).



- Most forestry and wooden biomass is used as solid fuel for the production of heat, while parts (around 25 %) also contribute to the production of electricity generation via combined heat and power generation (UBA 2024). Black liquor contributes as a bioliquid towards the production of process heat and electricity.
- In comparison, very small shares of hydrated tall oil are used as residues of the pulp and paper production process for the production of advanced biofuels for the transport sector (BLE 2024b).
- Between 2013 and 2022 the overall use share of roundwood for energy purposes dropped from 35 % to 30 % while the share for material use increased from 65 % to 70 % (Weimar and Jochem 2023; see also Section 6.3)
- With regard to the trade balance of wood pellets (mainly made from sawmill by-products), they currently feature an export surplus of around 0.25 million t in 2022 (Dena 2023b).

Municipal waste and industrial residues

- The majority of energy use of other residues and wastes, like municipal wastes and industrial residues, occurred via waste incineration as the biogenic shares of wastes were mostly used to produce heat but also electricity in 2020 (UBA 2024).
- Especially organic waste and other industrial wastes are utilised as input materials for biogas plants (Rensberg et al. 2023).
- The strongest growth sector for the use of especially industrial residues, but also municipal waste, is the transport sector as their **use as advanced biofuels increased by 43 % from 2020 to 2022** (BLE 2024b). Currently **high shares of used cooking oils and fats** (e.g. frying fat), animal fats of categories 1 and 2, oils from waste waters of the palm oil production (**palm oil mill effluent, POME**) and industrial wastes are utilised.

80 %
of residues and wastes used for biofuels were imported in 2022.

Overall there are clear indications that the German federal government policy goals of increasingly shifting the production of bioenergy towards residues and wastes is overall on its way (BRg 2019). However, currently problematic is that especially **in the strongest growth sector (transport), residues and wastes are mainly imported (78 % in 2020 and 80 % in 2022) while new production infrastructure for especially advanced biofuels is not yet being built in Germany.** This also means that the mobilisable potentials of residues and wastes for the increased production of advanced biofuels in Germany (See Section 6.5.1) are not yet being mobilised to the degree possible (Brosowski 2021, Brödner et al. 2024, Brosowski et al. 2020).

SPECIAL FEATURE: Modelling of future optimal biomass usage in the energy sector with BENOPT

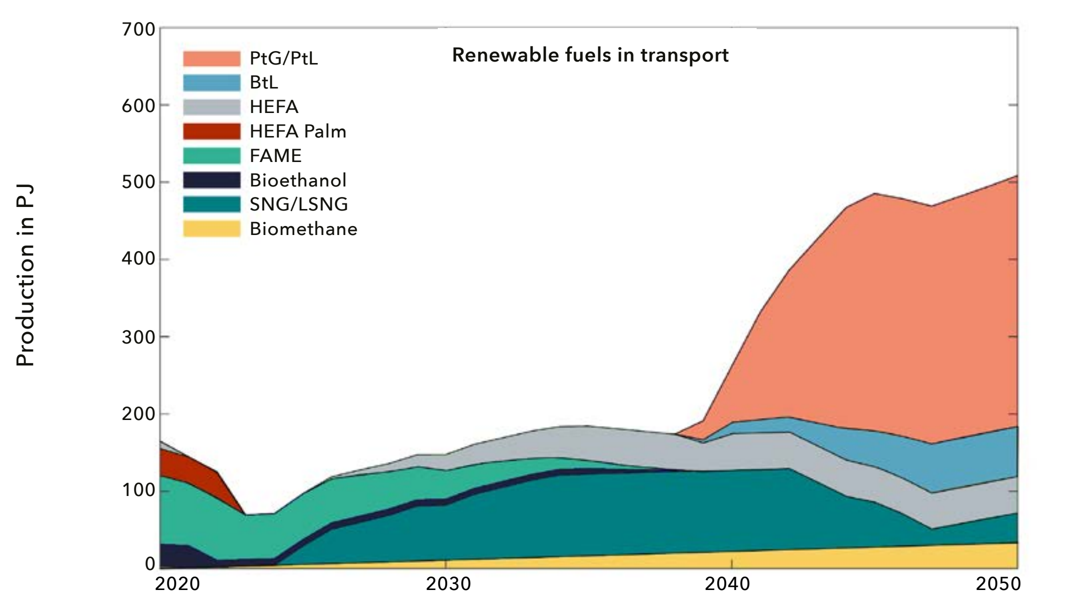
The intended transformation towards a net zero energy system comes along with many expectations for the bioenergy sector. In order to consider this appropriately, **two energy scenarios** were modelled in this project in accordance with the scenario framework for SYMOBIO 2.0 (Lutz and Többen 2023). First, a **short-term policy scenario** investigating the effect of political instruments on the role of biomass in the energy transition up to 2030 (Jordan et al. 2024). For the heat and power sector, minimum shares of renewable technologies are to be achieved (BT 2024a). For the transport sector, the GHG quota requirements defined by RED II were integrated into the BenOpt model for the German road transport sector (BT 2021b). Second, **a long-term cost-optimal transformation pathway** until 2050 was modelled, in which the German GHG emission target needs to be fulfilled as a restriction. The use of crops for energy purposes is phased-out until 2030 and they are not available until 2050, see *Biomass Scarcity Scenario* in Jordan et al. (2023b). Forest residues are kept constant and parts of the unused, mobilisable potential of residues are moderately exploited for energetic purposes in this scenario.

For modelling we used **BenOpt,** a classic bottom-up energy system optimisation model, as they are used in many cases to provide policy insights (Welfle et al. 2020). Within the model, the future optimal allocation of the limited biomass potential in Germany is determined in competition with fossil and other renewable options. BenOpt models the competition in 19 heat sub-sectors and, 8 transport sub-sectors as well as the provision of residual load in the power sector (Jordan et al. 2023b). The model considers feedstocks (over 30 types of biomasses), conversion technologies, vehicle types and detailed demand sectors for economic competition. Market prices for the different types of biomass as well as for fossil fuels and other materials, were compiled from various statistical databases (Jordan et al. 2023b). The model is fully deterministic and assumes perfect foresight. Total system costs are minimised, while fulfilling the demand and scenario constraints. The allocation of technologies, fuels and feedstocks is internally optimised.

Results of the short-term policy scenario:

Show an increase of especially heat pumps and the use of solid biomass in industrial applications in the heat sector up to 2030. In the transport sector, the GHG quota promotes the use of biofuels in the passenger road sector and leads to higher shares of biofuels than today (Jordan et al. 2024). The proportion of battery electric vehicles also increases. The shares of SNG (Synthetic Natural Gas (gasification of lignocellulosic biomass)) and HEFA (hydroprocessed esters and fatty acids) increase up to 2030. The shares of FAME (fatty acid methyl ester) and bioethanol slowly decrease and biomethane is only temporarily competitive. The switch from biomethane to SNG in this scenario can also be interpreted as a switch from the cultivation of maize to the cultivation of Miscanthus or as a switch from conventional biofuels to advanced biofuels. The results also show that biofuels are used in all sub-sectors of the transport sector except in aviation. The highest shares of biofuels are promoted in (passenger) road transport by the GHG-quota.

Figure 4.8 BENOPT model results in the transport sector for the long-term "Biomass Scarcity Scenario"



Note: PtG=Power to Gas; PtL=Power to Liquid; BtL=(lignocellulosic) Biomass to Liquid (gasification + Fischer-Tropsch synthesis); HEFA=Hydroprocessed Esters and Fatty Acids; FAME=fatty acid methyl ester; SNG/LSNG=(Liquified) Synthetic Natural Gas (gasification of lignocellulosic biomass).

Source: Meisel et al. (2024)

Results of the long-term scenario:

Show that the limited potential of biomass is optimally used in areas which are hard to electrify or as a way of providing energy as a flexibility option (Jordan et al. 2023b). Domestic solid biomass potentials are prioritised in medium- to high-temperature heat applications. However, as the biomass potentials are limited due to the phase-out of energy crops, high shares of green hydrogen are used additionally in the steel industry. Advanced biofuel imports and domestic oily biomass potentials (UCO and animal fats) are prioritised in the shipping and aviation sector (HEFA and SNG). Finally, the domestic potential of digestible residues provides flexibility in the power sector (biogas) in the mid-term. However, due to the strong limitations in energetic biomass use, this limited potential shifts completely to hard-to-electrify areas of the heat sector (biomethane) in the long-term.

Comparisons of the scenarios

A **comparison of the short-term and long-term scenarios** (up to 2030 vs. 2050) shows whether the current political measures promote the use of bioenergy in areas in which it should be cost-optimally used according to the long-term scenario results. In particular, a comparison of the results in the transport sector reveals some differences (Jordan et al. 2024). The GHG quota applied in the short-term scenario encourages the use of biofuels in passenger road transport, which, according to the long-term scenario results, should be cost-optimally electrified. The GHG quota therefore initially appears counterproductive, as the findings in the long-term scenario and also in further literature (Luderer et al. 2021, BMWK 2021) show that if biomass is to be used in transport, it should be used in areas that are difficult to electrify. These areas are aviation and shipping, not passenger road transport. It can be argued that the biofuels promoted by the GHG quota in road transport can easily be used in shipping or processed into aviation fuels via suitable product developments. However, the GHG-quota does not provide the necessary incentives for the rapid electrification of the passenger road transport sector, which is the long-term cost optimal solution under the assumptions used in our model.

Policy and trend developments for bioenergy

Transport biofuels – (policy) trends[18]:

- The adjusted National Energy and Climate Plan (NECP) outlines a growing bioenergy usage for transport (131 PJ, +3 % from 2023) (BMWK 2020, EU 2023a, BMWK 2024a). This growth, however, can only come from advanced biofuels (Annex IX part A, REDII) due to an increasing sub quota of 0.4 % in 2024 to 2.6 % in 2030 (BRg 2023). **Advanced biofuels could grow from 28 PJ in 2022 to 100–200 PJ in 2030,** depending on the over fulfilment of the sub quota for advanced biofuels, the future final energy demand in transport and the growth of non-biogenic quota options like E-mobility (BLE 2024b, BMUV 2023, DBFZ 2022). Waste-based biofuels (Annex IX part B, REDII) are capped at 1.9 % and will therefore decline with a reduced final energy demand in transport (BRg 2023). The fulfilment of these quotas is ensured by the GHG quota regulation (Naumann et al. 2021).
- Currently the GHG quota entails a maximum quota (4.4 % of energy used in road and rail[19]) for food- and feed-based biofuels, combined with a future declining final energy use in transport both factors will automatically result in a **declining crop consumption for biofuels** (DBFZ 2022).
- The BMUV proposed to **phase out food- and feed-based biofuels** by 2030 in order to further reduce land consumption (BMUV 2023). However, it has also been argued that food- and feed-based biofuels will likely be needed to some extent (probably lower levels than today) in machines that are difficult to electrify, such as in heavy forestry and agriculture machinery (KTBL 2023). Also, phasing out food- and feed-based biofuels much quicker than allowed by EU policy could further increase penalty payments of around € 16.2 billion towards the EU, due to lacking climate protection efforts in the transport sector (T&E 2024).
- Due to EU policy for aviation and marine shipping, a strong mobilisation of forestry (wood) and agricultural residues and wastes could be required following the assessments and modelling of the EU. Furthermore, perennial and annual crops from **marginal lands** could be required in large quantities (EC 2021b, EC 2021c), which could impact biodiversity (see the biodiversity footprint case study in Section 7.7, describing especially the impacts of intensification of land use).
- Among advanced biofuels in Germany in 2022, oils from waste waters of the palm oil production (palm oil mill effluent, POME) currently make up the largest share of 46 % (BLE 2024b). However, as recently outlined in an assessment report for potential new feedstocks for the production of advanced biofuels by the European Commission (EC et al. 2022), **POME residues entail high fraud risks**[20]**.** In order to tackle this problem, future policy could follow the suggestion (ECA 2023) to consider a **cap for certain advanced feedstocks** (Annex IX part A RED II) (EU 2018b).

46 % of advanced biofuels in 2022 stemmed from the waste waters of palm oil production, with high risks of fraud.

18 Discussion paper of GWS and DBFZ in preparation for more details
19 as of REDII; reference level needs to be adjusted to overall transport sector according to RED III
20 Fraud risk indicators relate to physical characteristics, feedstock definition characteristics, supply chain characteristics and assurance

Electricity, biogas/biomethane – (policy) trends:

- The **future use of biomass is very much dependent on the regulatory environment** in the EEG (BT 2024a). Looking ahead to 2030, the NECP (2020) outlines a declining bioenergy usage for electricity (151 PJ, −15 % compared to 2023) (BMWK 2020). Biogas for electricity production is not used as a base load in the future, but rather as a means to level the fluctuating supplies of other renewable energies. Hence, the flexibilisation of biogas plants, which can be described by the quotient of installed capacity and rated capacity[21], needs to further increase (Lauer 2019, Daniel-Gromke et al. 2019, Schindler et al. 2023b). Moreover, biogas will be increasingly upgraded to biomethane for storage and usage possibilities in other energy sectors.
- At the same time, the EEG 2023 put an emphasis on lowering crops as input materials (**maize cap**) and increasingly shifting towards using residues and wastes (especially manure) (BMEL 2023c). The mobilisation of manure for energy purposes is especially important in terms of GHG emission reduction as it is also addressed in the climate protection program 2030 as an individual task (BRg 2019). In the mid-term perspective, the usage input material for biogas plants could be shifted towards mainly residues and wastes until 2035 (Dotzauer et al. 2022).
- In the future, there will likely be no crop-based liquid biofuels for electricity (and heat) production needed, as the currently already low usage levels dropped further by 51 % from 2020 to 2022 (BLE 2024b).

Heat sector, solid fuels (and biomethane) – (policy) trends:

- The NECP outlines a growing bioenergy usage for heat (647 PJ, +5 % from 2023) (BMWK 2020). However, in terms of the possibility to use woody biomass for heat energy purposes, the NECP is somewhat outdated. New policy changes on the EU level, especially the Revision of the Renewable Energy Directive (REDIII) and its implications on the usability of woody biomass, were agreed upon years after the publication of the NECP (EU 2023a).

- The principle of the **cascading use of woody biomass** should be implemented following its highest economic and environmental added value while mostly prioritising material over energy usage (see also 6.5.2). Exceptions are possible as regards use possibilities of the local industry and concerning energy security. Moreover, negative effects due to the use of woody biomass on soil quality and on biodiversity shall be prevented. In order to achieve some of the goals, it is not allowed to grant "direct financial support for the production of energy from saw logs, veneer logs, industrial grade roundwood, stumps and roots" EU 2023a). However, those regulations only target bioenergy plants over a certain rated thermal input (more than 7.5 megawatt), which already use low shares of roundwood in Germany (Döring et al. 2021, Mantau 2023). **Overall, these policy changes might lead to a lowered energy use of sawable roundwood by the addressed bioenergy plants in the future.**
- In addition, policies and goals regarding **Land Use, Land Use-Change and Forestry** (LULUCF) and biodiversity requirements tend to decrease the overall availability of forest biomass in Germany (and Europe) for bioenergy purposes, possibly leading to increased imports (BT 2021a, EU 2023c, Schier et al. 2022).

21 average electricity generated over one calendar year

Since fossil CO_2-emission prices are increasing in the future while biogenic CO_2-emissions are counted with the emission factor zero, the incentive to use biomass as a fuel could increase (BT 2023, Schindler et al. 2023a).

- **Private households**, which still use the largest share of roundwood (logs) for energy purposes (in comparison to larger bioenergy production facilities) and whose overall solid fuel usage for heat production increased from 2020 to 2022 by 20 %, are not targeted by the REDIII requirements due to the rated thermal input limit (more than 7.5 megawatt) (Mantau 2023, UBA 2024, EU 2023a). Especially alternative heating technologies (e.g. heat pumps), when appropriate, are needed in order to reduce the quantities of wood being used in private households for energy purposes. If necessary, a combination of hybrid technologies, e.g. by using wood residues (like pellets) in addition to heat pumps, could be applied in certain cases. Some first necessary steps in this direction were taken on a policy level with the adoption of the GEG (German Buildings Energy Act; BRg 2024). However, the adoption of the GEG could also lead to a strong demand growth of biomethane in the heating sector until 2040 (Dena 2024).

Key policy messages

- Germany's policy goal of increasingly shifting the production of bioenergy towards residues and wastes (BRg 2019) is positively progressing in general. Future policy making with regards to sustainable wood use and increasing cascading of woody biomass could consider whether to apply regulatory law (e.g. REDIII) and/or price incentive mechanisms (Schindler et al. 2023a).

- Currently high import levels of advanced biofuels (80 % in 2022, origin of wastes and residues) need to be critically questioned in terms of energy independence and with regards to the progress on competitiveness of clean energy technologies outlined by the EU (EC 2023).

- Beyond the current trends, bioenergy cost optimisation modelling shows the need for a stronger transition of bioenergy towards optimal contribution to net zero energy systems.
  - The instrument of the GHG quota does not yet promote the use of biofuels in areas or sub-sectors of the transport sector in which they should be cost optimally allocated according to the long-term energy scenarios. Biofuels are currently mainly promoted in passenger road transport instead of in shipping and aviation (Jordan et al. 2024).

- Future bioenergy policy could try to integrate carbon capture, utilisation and storage where possible (e.g. as in the German carbon management strategy (BMWK 2024b) in order to work towards counterbalancing unavoidable emissions (Smith et al. 2022, Borchers et al. 2022).

4.3 Trends for non-food biomass for material purposes

This section focuses on trends in material non-food biomass use from both agriculture and forestry. It is based on multiple data sources and is organised around biomass flows entering the first stage of industrial processing as well as sectoral perspectives for construction, the chemical industry, the paper sector and peat substitutes.

54 million tonnes dry mass were used as inputs for material industries in 2020.

Overview of biomass supply for material use

The status quo of non-food biomass in the material sector is strongly characterised by the use of lignocellulosic biomass as well as residues. Following the German Bioeconomy Strategy (BMBF und BMEL 2020) and the German Climate Law (BRg 2021) the focus is on central sectors, key for both current and prospective bioeconomy markets. Biomass use for material value chains for the year 2020 is shown in Figure 4.9 in order to illustrate the status quo as a basis for elaborating on prospective developments and trends. Altogether, the material use of primary biomass is clearly dominated by wood. The analysed sectors use around **54.26** million tonnes dry mass (t DM) of biomass[22], differentiated between lignocellulosic materials from the forestry sector (**32.6** million t DM; Mantau 2023), agricultural renewable raw materials (**2.8** million t DM; FNR 2024b) and residues (**18.7** million t DM; Brödner et al. 2023, Naegeli de Torres et al. 2023)[23].

Biomass flows for material use

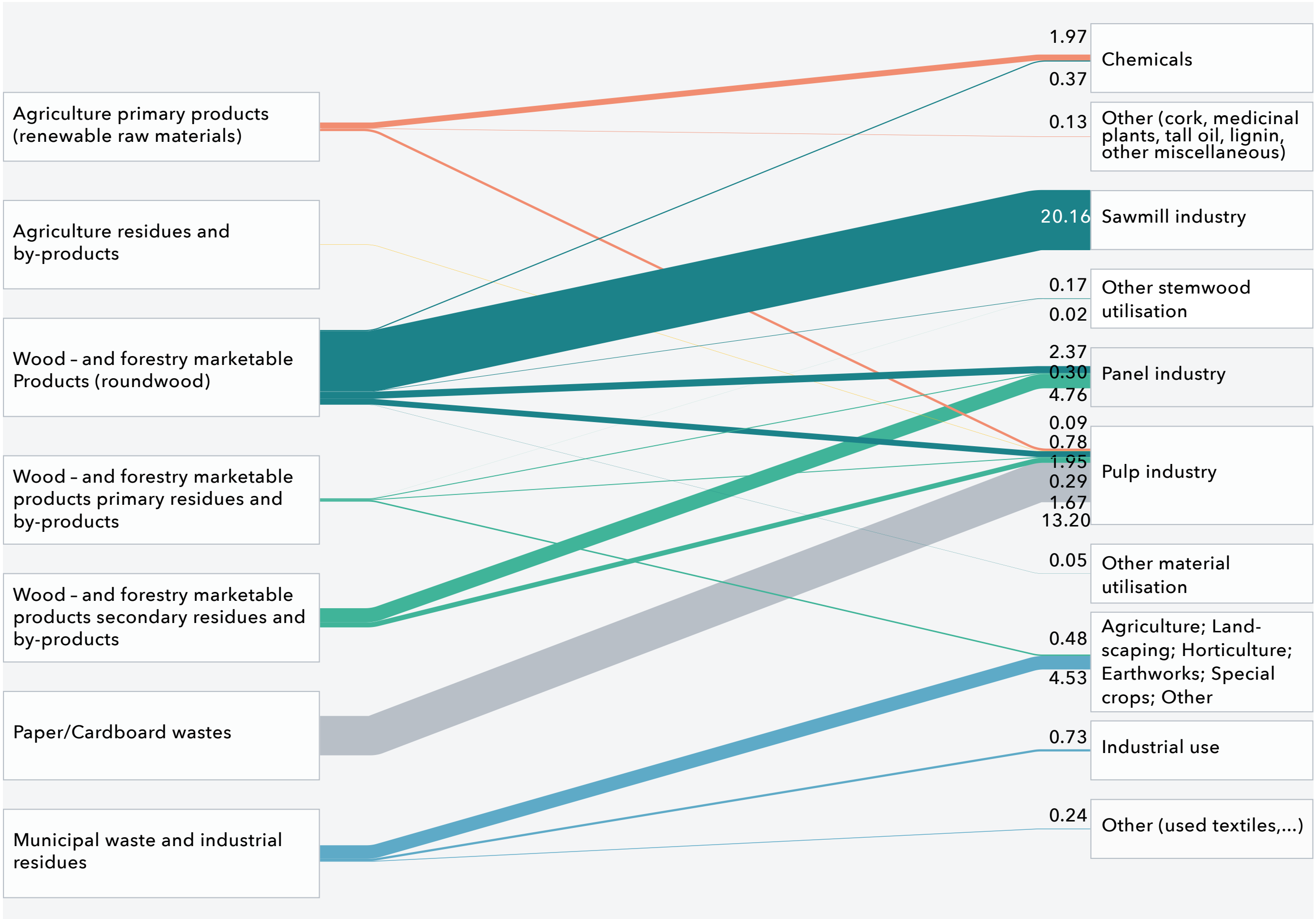
Data in this section focuses on German industries at the first level of processing.

While on the energy output side it is possible to depict the end use form, in the material sector this is not possible in a straightforward way. Therefore, the material output side is visualised from the raw material side to the **first conversion level (i.e. inputs to different material use industries)**. Figure 4.9 displays the use of biomass in terms of biomass input in million tonnes dry mass for material purposes. It should be noted that more detailed biomass flows — from extraction, through processing and to end use (including trade) — are presented in Chapter 6. Here, the overall biomass use is clustered into five biomass categories and 11 use sectors. The displayed data does not include conversion losses. In addition, Figure 4.9 displays the biomass use in the chemical sector in terms of broken down ingredients of sugar, starch or oils as reported by FNR (2024b) and does not give any information about biomass cultivation in Germany. Imports are included, but not exports, as this chapter focusses on biomass use by German material industries at the first level of processing.

22 This differs from the overarching amount of biomass (34 million tonnes dry mass) found to be used for material purposes in the analysis of biomass flows presented in Section 6.1. That is because this section focuses on inputs of biomass to German industries (data to the first level of processing) instead of end use. This section is also based on a compilation of multiple data sources. Chapter 6 traces the flows of biomass in a detailed way from extraction, through multiple processing stages and to final end use, including imports and exports at all those stages. Final end uses are then aggregated to derive the 34 million tonnes material use (See Section 6.1), making it the more reliable estimate of end use based on biomass throughput.

23 To illustrate a Status quo of biomass use as the basis for assessing trend developments in a more detailed way, data is used that compiles different data sources. For a more detailed overview about specific data please have a look at http://infro.eu/rohstoffmonitoring.php; https://www.thuenen.de/de/fachinstitute/waldwirtschaft/projekte-liste/holzmaerkte/rohstoffmonitoring-holz; https://statistik.fnr.de/

Figure 4.9 Use of biomass by biomass category and sectoral industrial inputs in 2020



Note: Given in million tonnes dry mass for five of the seven categories on the left hand side. Only the two categories 'Agriculture primary products (renewable raw materials)' and 'Agriculture residues and by-products' are given only in million tonnes

Sources: Mantau (2023), FNR (2024b), Naegeli de Torres et al. (2023)

Use of forest-based biomass in processing industries

- The main biogenic raw material used in the year 2020 in Germany is lignocellulosic based on primary resources such as forests (Mantau 2023). From these sources about 79.5 % are used in the sectors of the sawmill industry, other log stemwood uses, panel industry, pulp industry, and other material utilisation. The sawmill industry and the panel sector (particle boards, OSB boards, fibreboards (MDF, HDF) and lightweight boards (LDF, insulation board)) are the main upstream chain producer for the **construction sector**. The pulp industry is deeply connected to the **paper sector**.
- Other stemwood use encompasses further roundwood processing industries, which includes traditional usage forms such as plywood, but also innovative forms such as wood-polymer composites or wood as a raw material for the **chemical industry**.
- Regarding the production shares of primary and secondary raw materials there are major differences between the use sectors, and especially the paper and construction sector for example. The sawmill industry sector, mainly fed by primary raw materials, is a strong contrast to the other sectors that integrate a higher amount of **residue and by-products streams** (panel industry (about 68 %) and pulp industry (87 %) in the production processes (FNR 2024b).

73%

of biomass used in the chemical sector stems from agriculture.

Use of agricultural-based biomass

- Around **3.25** million t of Agricultural-based biomass was utilised by material industries in 2020. This amount is composed of pre-processed input materials of fats and oils, starch, sugar, chemical pulp, natural fibre, proteins and other fibres.
- The main demand sector for agricultural biomass as regards material use is the **chemical sector**, with about a **73 % share** of the overall renewable raw materials used. After this, the paper sector is the second main demand sector for starch, with about a 19.4 % share. Additional sectors that comprise a share of 7 % include natural fibres, cork, medicinal plants, tall oil, lignin or further more specific forms of application.
- While in other sectors it is possible to analyse the used materials from the production side perspective, the focus here is on the different pre-processed input materials and therefore only in tonnes instead of tonnes dry matter. Following this and the high dependencies of import materials in the chemical sector (about 55–60 %) it is not directly possible to calculate the direct land use impact of the biomass used on the basis of the data used (FNR 2024a; for more information about data see footnote 22).

Use of wastes, residues and by-products

- A major waste material stream is the utilisation of paper and cardboard wastes in the pulp industry for paper production. With about **13.2** million t DM[24] it is one of the major raw material suppliers for the industrial sector, leading into a utilisation of recycled fibres of about 83 % of overall production of the paper sector.
- The use of residue and by-products for material purposes is characterised by the utilisation of municipal waste, industrial residues and agricultural by-products especially for the sectors: agriculture, landscaping, horticulture, soil works, special crops as fertilizer and substrates (Bieker et al. 2021).
- In general, residues and by-products are more strongly integrated into energy supply, and therefore have only a limited share of biomass integration in sectors with large material flows, such as e.g. the chemical sector (Naegeli de Torres et al. 2023, FNR 2024b).

Trends in end-use sectors

Different trends within the bio-based material sectors in Germany influence prospective developments of biomass in the main demand sectors assessed here: construction, chemical, paper and peat substitutes. Trends from the sectors and market challenges that occur are reviewed, and important policy developments based on strategies and regulations are highlighted in this section. Different expectations and trends for the specific sectors are summarised, based on market reports, scenario analysis, grey literature and policy documents.

Overall the trends show that in the forestry sector, the use of roundwood has increased continuously, but the growth rate has slowed down in the last decades (growth

24 Data differentiation between the chapters based on usage of different databases. Here DBFZ Database is used, generated in cooperation with University of Kassel/Witzenhausen based on data sourced from Federal Statistical Office, Primary data, expert evaluation and industry statistics.

rates 1990–2000: 19 %; 2000–2010: 10 %; 2010–2020: 6 %) (Mantau 2023). Within the paper sector, the trend reveals a declining utilisation of primary biomass in the sector (2010–2020: −21.7 %) and increasing use of recycled materials (VDP 2024). For material biomass use in the chemical sector, the input material has been stable over the last decade, with only minor changes in the utilisation of starch (increasing trend) and plant-based oils and fats (decreasing trend since 2017) (FNR 2024b, FNR 2022).

Construction sector

The construction sector is characterised by a high dependency, of about 90 %, on mineral raw materials for building materials and construction products (Purkus et al. 2020). Increased application of bio-based materials is seen as a possibility to reduce these dependencies and contribute to reaching sectoral and overall climate goals (BMWSB und BMEL 2023, Backes et al. 2024, WBW 2021). In the year 2020, the share of permits granted for timber construction was 20.4 % for residential buildings and 21.0 % for non-residential buildings in Germany.

Building with wood has several advantages that address challenges in the construction sector, such as potential reductions in GHG emissions from substitution of raw materials (see the LCA case study in Section 4.4.1), shorter construction times, and long-term carbon storage with the opportunity to build-up cascade systems (DHWR 2020, Öko-Institut 2021). Some sectoral actors propose the goal to reach a 30 % wood-based building rate by 2030 and 50 % by 2050 (DHWR 2020). To meet these expectations and developed policy strategies (Charter of Wood 2.0, Wood-building Initiative) an increase in the share of permits for wood building of around 9 % would be needed, which would be a strong increase in comparison to the decade from 2010–2020. The availability of wood within Germany over especially the mid-term could be a challenge, if forest disturbance rates in Germany continue (see Section 5.1.2). Independent of the sectoral goals in general, an increase in demand for wood-based building construction materials is expected.

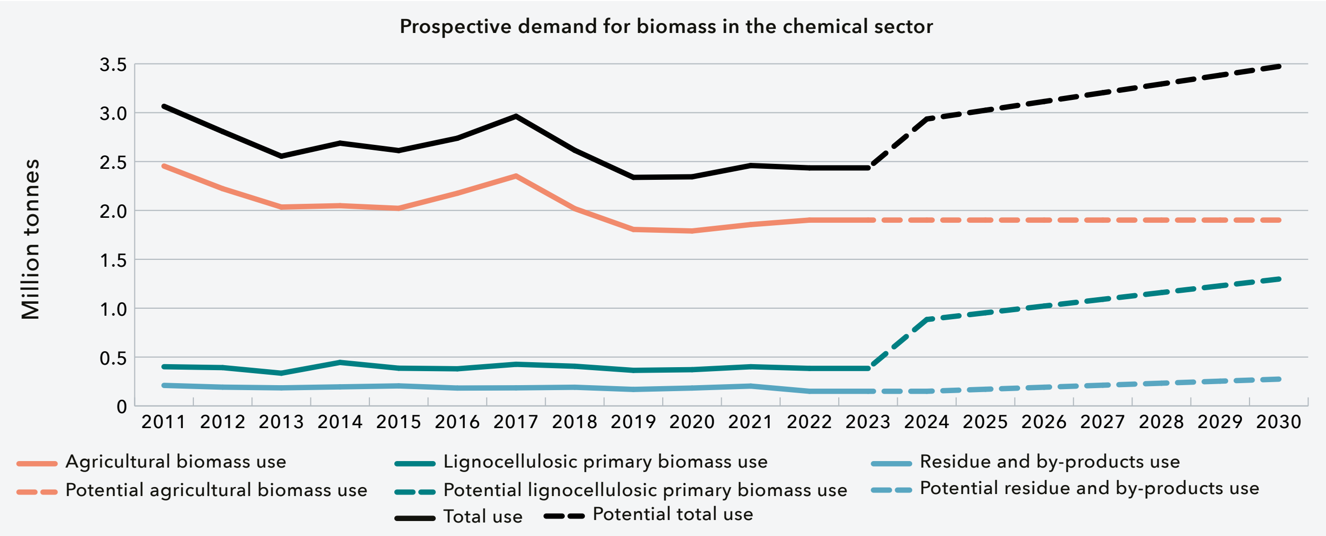
It should be noted that the timber construction share only refers to new buildings. However, it has been estimated that around 69 % (Weimer and Jochem 2013, Mantau et al. 2018a) of the wood used in the construction sector is used in **renovation and modernisation of existing buildings**. Thus, the wood construction share is only one indicator of wood use in this sector. Consequently, it is important to review beside the use of wood for new buildings, necessary amounts for reaching modernisation and renovation rates to support the climate neutrality of the building sector (Dena 2021). Nevertheless, the sector is characterised by a high degree of data inaccuracy and ambiguity depending on the individual system boundaries used.

Policy documents with major influence on the sector:
- Charter of Wood 2.0. (BMEL 2018)
- Handout — Timber construction initiative (BMWSB und BMEL 2023)

Chemical sector

The chemical sector is the third largest industrial sector in Germany and generates around 10 % of German industrial turnover (Borgnäs et al. 2021). Within Germany it is relevant for 20 % of the fossil-based resource demand (Scholz et al. 2023) and within the sector about 85 % (2022) of used raw materials stem from fossil-based sources (FNR 2024b). The chemical-pharmaceutical industry is characterised by a high degree of vertical integration, with a wide variety of products and a very broad product range.

Figure 4.10 Long term illustration of biomass utilisation in million tonnes in the chemical sector in Germany (solid line) and prospective possible utilisation of biomass based on plants under construction and policy trends (dotted line)



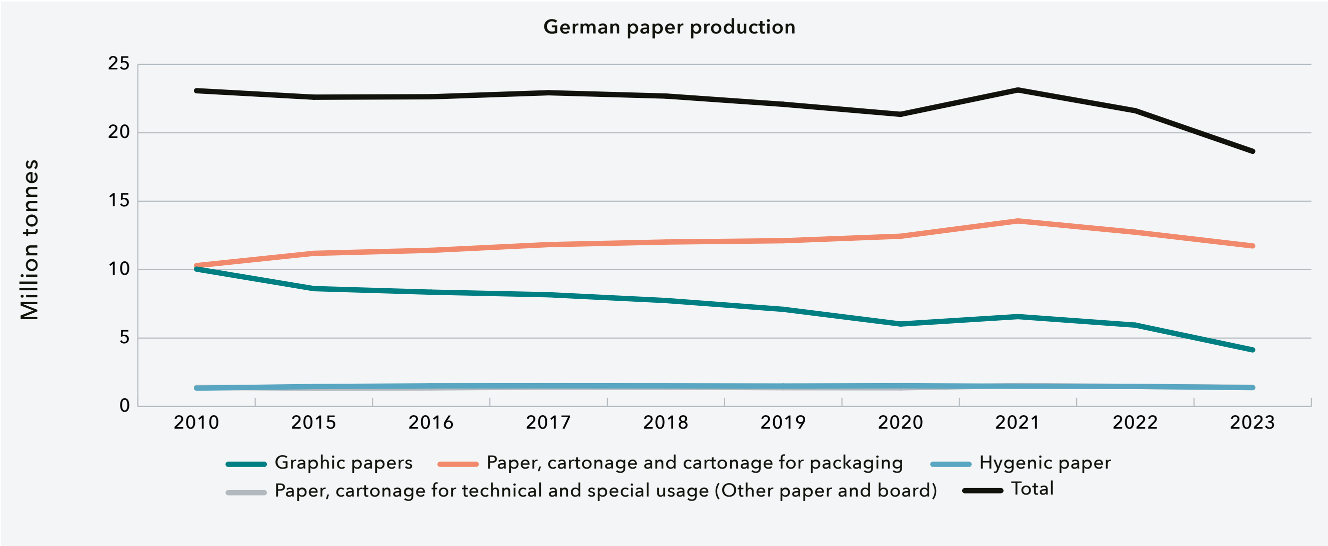
Sources: https://statistik.fnr.de/ (accessed; 06.2024), Mantau (2023), EC (2021a)
Notes: Agricultural biomass includes carbohydrates; lignocellulosic primary biomass includes chemical pulp; residue and by-products includes animal fats & oils

After 2017, a reduction of biomass input to the sector could be seen, down to 2.34 million t of biomass-based input, where it remained quite stable until latest data available in 2022 (2.44 million t). This level will change from the year 2024 on, when the first large-scale biorefinery plants are constructed and start production. For example, the new biorefinery of the company UPM in Leuna (UPM Biochemicals 2023), will produce basic chemicals, such as Bio-Mono-ethylengylcole, from lignocellulosic sources. The plant would need about 450,000 t of beech wood chippings, which would result in an increased demand of lignocellulosic materials by 1 million m^3 of deciduous beechwood annually (Mantau 2023).

Figure 4.10 illustrates this increase of biomass demand in the sector and the impact for overall biomass utilisation in the chemical sector in Germany. This current development is in-line with ambitions in the sector to reduce the dependency on fossil resources and to adjust the production processes for a more renewable energy and material-based system (VCI and VDI 2023). Another important influence on the sector is coming from policy trends that promote a feedstock change in the industry. At the European level a proposal for a quota is in the "Sustainable Carbon Cycle", which entails the aim of 20 % of renewable carbons based on non-fossil raw materials for 2030 (EC 2021a). Latest initiatives on the EU level are supporting this approach. **The proposed quota would increase the demand for biomass for chemical products from about 14.9 % (2022) (FNR 2024a) to 20 % in 2030.** The possible trend for biomass demand is illustrated as a dotted line in the Figure 4.10, and would lead to an **increase of about 1 million t in comparison to the status of 2022.** In Figure 4.10, the increase of biomass demands is based on new innovative technologies that use mainly lignocellulosic and residual biomass products for the increased demand.

Overall, it can be stated that the market for these products have a **high potential**, as they are platforms for various products (Mantau 2023). The analysed data of the status quo in connection to the policy proposal for a feedstock change in the industry illustrate that biomass-based innovations will probably play a more important role in future production schemes (see also Section 3.3.2). Nevertheless, as indicated in

Figure 4.11 Paper production in million tonnes of different categories: graphic paper, hygienic paper, paper cartonage and cartonage for packaging, paper, cartonage for technical and special usage (other paper and board) and total



Sources: VDP (2021); Die Papierindustrie (2024)

analysed scenario studies, other raw materials for production, such as hydrogen, CO_2 recycling or chemical recycling will have a more important role, due to the **limitation of biomass availability** for substituting the large quantities of used fossil resources in the present state (Geres et al. 2019, VCI and VDI 2023, Kloo et al. 2023).

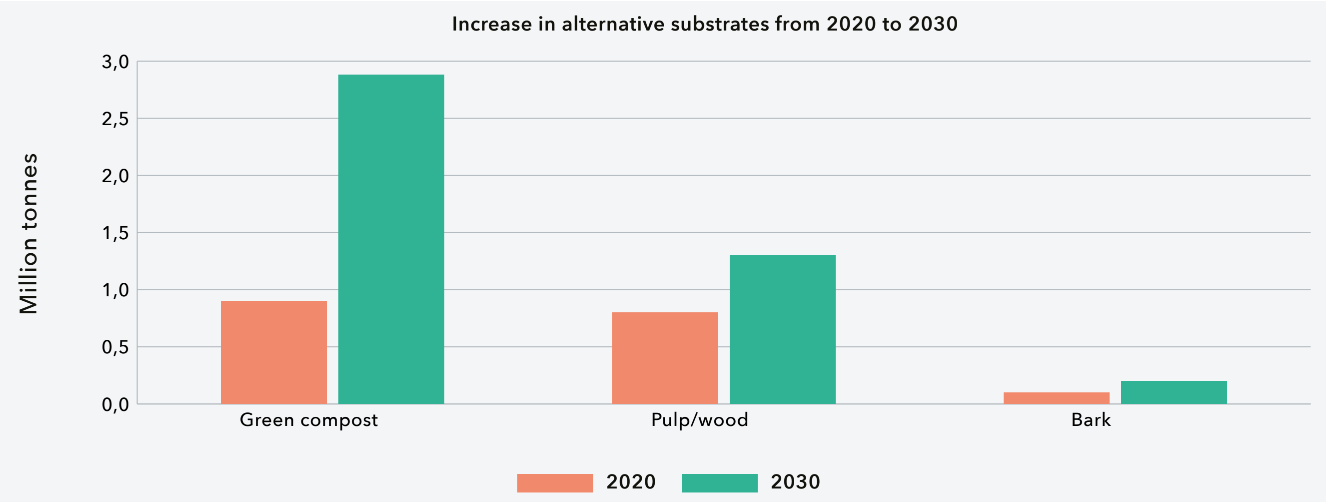
Policy documents with major influence on the sector:

- EU Sustainable Carbon Cycles Communication (EC 2021a)
- EU Member States Joint Statement on a European Sustainable Carbon Policy Package for the Chemical Industry (The Netherlands Ministry of Infrastructure and Water Management 2024)

The paper sector

Germany is the largest paper producer in the EU with a share of around 25 % of the market. It is the third most energy-intensive industry after metal production and the chemical industry, accounting for 9 % of energy consumption in the manufacturing sector (Borgnäs et al. 2021). As regards biomass use, the sector is highly important as it is one of the oldest production sectors utilising lignocellulosic and residual materials. Major trends in the sector are digitalisation, which have led to a reduction of especially graphical paper, and vice versa the increased use of cartonnage for packaging (see Figure 4.11). Overall, it could be stated that there is a declining trend of biomass utilisation in the sector, due to reduction of production as well as increased integration of pulp from recycled fibres (VDP 2021, Die Papierindustrie 2024) (see Figure 4.11). As the integration of residue and by-product use from recycled fibres is at a high level, of about 83 % (2023) (Die Papierindustrie 2024), the ability to increase this further is limited, in particular due to fibre qualities (Borgnäs et al. 2021). Following the trends on the production side and the reduction of primary biomass usage from about 10.56 million t in 2010 to about 8.27 million t in 2023 (Die Papierindustrie 2024), an increase of biomass usage for production in Germany is not assumed.

Figure 4.12 Comparison of potential uses of alternative peat substrates between the years 2020 and 2030 in million tonnes



Source: BMEL (2022b)

Digitalisation has led to a reduction of graphical paper, but to an increase of packaging paper and board.

Changing the perspective to the apparent consumption of paper products, there is another picture. From 2000 to 2021 apparent consumption increased for the categories of paper and board for packing: +44 %; sanitary and household papers: +42 % and for other paper and board +24 % while decreasing −40 % for graphical paper. This illustrates the above-mentioned trends. In the short term perspective, a turning point seems to have been reached in 2021, leading to a decrease in apparent consumption for all categories: paper and cardboard for packaging (−21 %) and graphical paper (−30 %) as well as to a limited extent for sanitary and household paper (−3 %) and other paper and cardboard (−13 %) (Die Papierindustrie 2024). Nevertheless, in 2021 Germany had one of the highest rates of per capita paper consumption in the world, consuming more than 228 kilograms per person. This was higher than the EU average (180 kilograms per person) and more than 4 times the global average (55 kilograms per person) (Die Papierindustrie 2022, NABU 2022). Germany is also one of the largest importers of paper products in the EU (see the case study in Section 5.2.3). As many parts of the world are increasing their paper consumption, as needed to raise their standard of living, the pressures on global forests for pulpwood plantations will grow, further calling into question the disproportionally high demands in high-income countries like Germany (EPN 2018).

Policy documents with major influence on the sector:
- EU ETS (DEHSt 2023)

Substrate and growing media for horticulture

In the **substrate and growing media sector around 4.7 million m^3 of peat were used in 2019, with around half extracted and processed in Germany. The major use of peat is horticulture substrates** (IVG 2024). Although the extraction in Germany has been declining since 2002, the overall utilisation is quite stable. As the extraction of peat and the reduction of peatlands are connected to high GHG emissions, the sector is crucial for reaching climate goals (Tanneberger et al. 2021). The main influencing trend in this sector is policy. Permits for extraction in Germany will expire by 2040, which will stop the extraction from domestic sources. However, to reduce also negative impacts of peat extraction on the international level, efforts have been made

to increase the use of peat alternative substrates (BMEL 2022b). As peat substitutes, especially wood fibres, bark humus, coconut fibres and green waste have been identified. While the demand for horticulture products and especially substrates will likely increase on the national market, within Germany the major driver until 2030 is the substitution of peat in horticulture substrates. This increase of alternative substrates would influence the availability of mobilisable residue and by-product streams, as well as lignocellulosic raw material streams for other sectors (Hirschler et al. 2022). Along the assumption of replacing the peat usage until 2030, in comparison to 2020 an additional about 1.98 million t DM of green compost, 0.5 million t DM wood and 0.1 million t DM bark (see Figure 4.12) biomass from domestic resources would be necessary (to substitute peat in the production of substrates in order to meet substrate use demands as in 2020). Including the prospective increase demand for horticulture substrates in the world (Hirschler et al. 2022), more biomass from alternative sources would be needed, and the increase of pressure to the named resources raised.

Policy documents with major influence on the sector:
- The peat reduction strategy of the BMEL (BMEL 2022b)

Key policy messages and implications

- Trends illustrate that especially sectors with high innovation potentials (like chemistry) are increasing their shares of biomass use.
- In comparison to the energetic sector, the material use of biomass is generally more influenced by long-term strategies and less by regulatory frameworks and measures (such as quotas, exclusion of biomasses, price incentives or sustainability requirements).
- The current use of biomass in the material sector seems to be undergoing a shift. An increased use in innovative material applications could increase the competition for non-food biomass. To this end, dedicated monitoring and modelling are necessary to evaluate the integration of biomass in the most beneficial way from a systems perspective.

MONITORING CHECK BOX 3:

Approaches for monitoring substitution effects

Why monitor substitution?

Effective monitoring of resource substitution is crucial for understanding the use of non-renewable resources and bio-based alternatives. It helps identifying sectoral decisions, resource allocation mechanisms, contextual factors, and the long-term impact of policies. Promoting the use of bio-based alternatives as a climate mitigation strategy spans various sectors like construction and energy. However, trade-offs exist as reflected in the food-fuel debate, use of biomass for energy vs. material applications, and increase or decrease in resource demand as a result of substitution. Within this context, existing methodological approaches for monitoring substitution effects concentrate mostly on environmental consequences, i.e., reducing GHG emissions and on tracking changes in resource use over time.

Life Cycle Assessments (LCAs) – a currently dominant approach

To monitor substitution effects, an approach should consider the use of different resources at various use stages. LCAs are generally selected for this purpose, particularly for assessing avoided emissions over different time intervals and life cycle phases, i.e., from raw material through production or use stages until finally to waste handling options. Briefly speaking, when resource use/allocation decisions are made, LCAs can assess the replacement of a resource with another resource with the possible substitutions being delimited by a functional unit. As a monitoring tool, LCAs assess not only the effects of a specific resource substitution but also facilitate analytical decisions, e.g., tracing a specific aspect of resource allocation or identifying expected environmental changes.

Displacement Factor (DF) – a metric to monitor substitution

A caveat in the LCA analysis is that the resources selected for comparison need to be defined beforehand; it does not identify an optimal resource to be used but rather states a comparison on the grounds of an indicator, e.g., GHG emissions. In order to better understand the impact of substitution, a specific metric is required. Typically based on a LCA approach, and with regards to a single functional unit, a Displacement Factor (DF) is a metric that indicates the efficiency of resource use and establishes the difference in emissions regarding the use of non-renewable resources versus bio-based alternatives. A DF is generally estimated for material and energetic substitution and is usually expressed as avoided carbon or CO_2 equivalents.

GHG emissions – a mostly used indicator

A selected indicator when monitoring substitution effects should be reliable and flexible, provide a better understanding of substitution effects on the climate in a long-and short-term perspective, and ensure a clear and concise measure of changes. GHG emissions, and a wide array of related indicators, are commonly used due to their straightforward interpretability in analysing the time development of environmental goals, thus serving as an early warning signal when monitoring substitution effects. At the same time, relying only on the observation of climate impacts remains risky, if other relevant indicators are not considered appropriately.

Monitoring possibilities

Despite the importance of environmental impacts when monitoring substitution effects, the LCA methodological rationale can also be applied to assess other aspects, such as economic or social factors, using different indicators like added value (the contribution of a sector or activity) and employment (the number of jobs created or sustained). Moreover, to monitor substitution effects, it is necessary to model the consequences of increased production and consumption of alternative products. For instance, conventional biofuels perform better than fossil fuels for key indicators when assessed by attributional LCA. When, however, much more of the relative better is being produced, large amount of additional cropland is needed, which leads to conversion of natural and biodiversity rich lands. This can only be discovered when applying also analysis at the macro scale (e.g. by multi-regional Input-Output analysis, MRIO). Also, the decarbonisation of the economy reveals that substitution effects vary over time due to the adjustments needed to comply with internationally agreed commitments (e.g., the Paris Agreement) thus making it essential to include the temporal aspect of substitution effects, despite the challenges in accounting for uncertainties.

Key messages

Monitoring substitution effects faces the challenge that it relies on assumptions that may not fully capture real-world complexities. A robust analysis of substitution effects requires a blend of methodological approaches to strengthen the reliability of its findings. LCA needs to be complemented by macro level analysis in order to minimise trade-offs and unintended consequences.

4.4 Biomass substitution potential in products

Life-Cycle Assessment (LCA) focuses on the material flows and related environmental pressures of products or services at the level of product systems. Most commonly, it is used to **compare the environmental performance of different but functionally identical systems.** In the case of biomass systems, for example, this is often a comparison with a fossil system. The reference flow in this comparison is the functional unit, which is defined as the quantified benefit of a product system. The case studies depicted in the section provide examples.

4.4.1 Wood as a building material[25]

Compared substitution options

Biomass-based options

Bio1: Glued laminated timber (Glulam) or glulam beams based on beech wood
Bio2: Sawn beam from spruce

Reference options

Ref1: Steel beam
Ref2: Reinforced concrete

This case study compares 4 options for a structural load-bearing element (girder construction for a hall ceiling) with a span of 10 meters. The functional unit is the support of an (equal) ceiling load and the spanning of a defined space.

System boundary

The system boundary is limited to the phase from the extraction of the raw materials (primarily wood, iron ore, limestone, gravel, sand) to the provision of the building supports. Installation is not considered here, nor is any difference in service life or the end-of-life options (like combustion or re-use). The effect on carbon storage is also not shown. However, the removal of wood from the forest can play just as much a role as the storage in the building, which lasts for several decades (see Monitoring Check Box 4). All these aspects could have an influence on the overall result.

Data and calculations are based partly on modelling and partly on data taken from the ecoinvent 3.10 database[26]. Six impact categories were compared, with descriptions available in the supplementary information. For example, the Life Cycle Impact Assessment (LCIA) indicator "distance to nature potential" (DNP) based on the hemeroby concept (Fehrenbach et al. 2022) is applied. It allows consideration of the ecological quality of different land-use types, such as semi-natural beech forests, spruce plantations and mining areas for limestone, gravel or iron ore. The assessment does not provide an outlook for the future, when steel or concrete is expected to be produced with significantly lower GHG emissions.

In order to illustrate the impact categories from all three case studies in a uniform way, the LCIA results are **normalised** using the average per capita burdens for Germany. Net results are presented where the two reference cases (Ref1 and Ref2) each are subtracted from the biomass-based cases (Bio1 + Bio2). Bars pointing to the left express a net saving of the biomass-based case against the respective reference base.

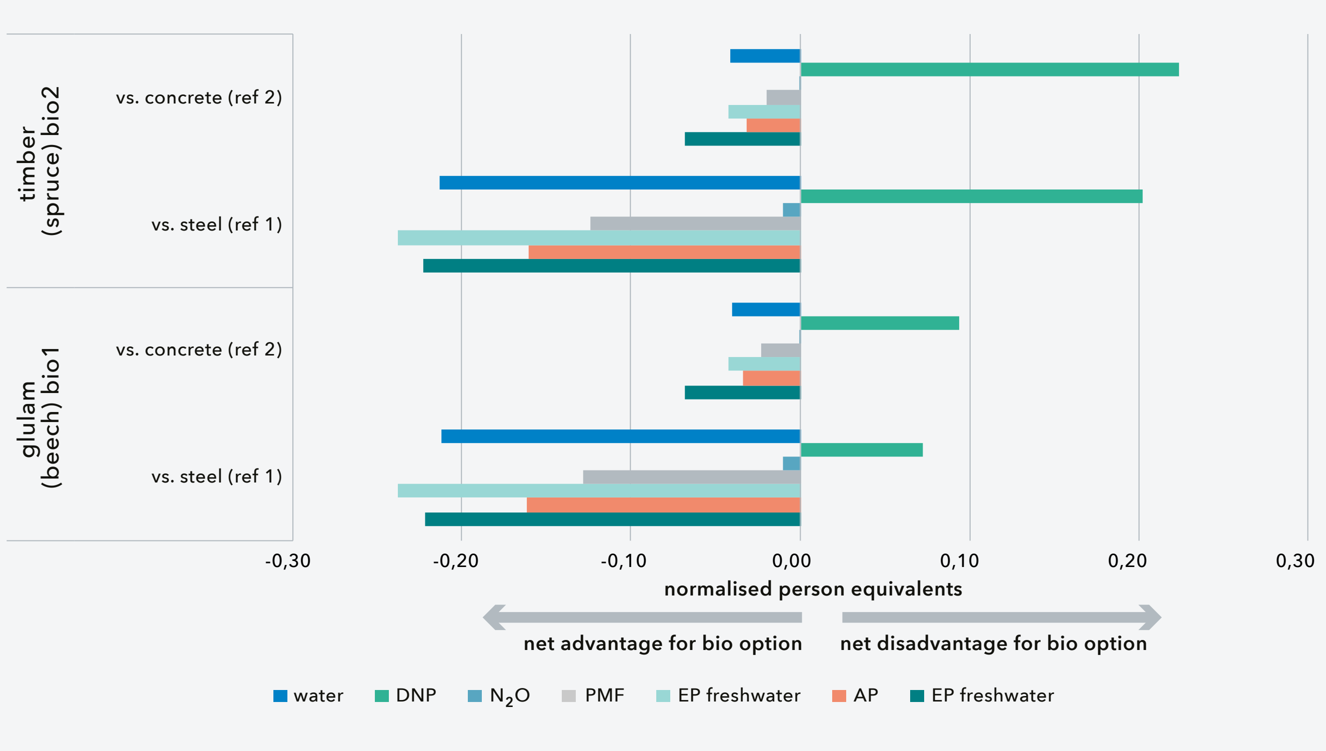
Results

- Apart from land use (DNP), all LCIA results are in favour of the biomass-based cases, while the net burden by the beach Glulam (Bio1) is significantly lower than the one for the spruce timber beam (Bio2).

25 This section depicts a short overview of the longer case study. See Fehrenbach, Köppen, Schlamp, and Wehrle (in prep): Product Life Cycle Assessment — case studies in the framework of SYMOBIO 2.0, for the full story and supplementary information for descriptions of the impact categories

26 https://ecoinvent.org/ecoinvent-v3-10/

Figure 4.13 Normalised LCIA results for two biomass-based options (Glulam beech and timber spruce) balanced against two non-biomass options (steel and reinforced concrete, references)



Note: Functional unit: beams for a hall roof spanning 10 meters; GWP: global warming potential; AP: acidification potential; EP Eutrophication potential; PMF: particulate matter formation; DNP: distance to nature potential. More information on the impact categories and definitions is in the supplementary information

- The advantages of the biomass-based options compared to steel (Ref1) are significantly higher than when compared against concrete (Ref2).
- The highest normalised net savings can be identified for fossil fuel depletion, climate change and water depletion, however acidification and particulate matter formation (PM2.5) give also clear advantages for the biomass-based cases.
- If the one drawback for biomass-based case (DNP) would be "weighted out" by the number of benefits by the other impact categories, we might conclude following environmental ranking:

  1. Glulam beams based on beech wood, (Bio1)
  2. sawn beam from spruce (Bio2)
  3. reinforced concrete (Ref2)
  4. steel beam (Ref1)

- The key message for policy makers is that there are potentially positive environmental benefits of substituting wood for concrete and steel in the construction sector (see also Section 3.3.4 for an example of modular renovation). However, the scale of construction and level of demand for timber also plays a role (see Section 5.1.2 on the outlook for the German forestry sector). As such, **substitution could and should be promoted, but only when system wide impacts are taken into account** with monitoring tools and regulatory boundaries in place.

4.4.2 Bioethylene for chemicals

Compared substitution options

Biomass-based options

Bio1: Crop-based ethanol converted to ethylene
Bio2: Straw-based ethanol converted to ethylene

Reference options

Ref1: CO_2-based ethylene, from CCU synthesised with green hydrogen
Ref2: Conventionally produced ethylene by steam cracking of mineral naphtha

Ethylene is a basic chemical substance widely used as a feedstock for the chemical industry. Pathways modelled here allow a direct comparison of this product. Bioethanol, as a direct output from the biomass fermentation pathway, can be converted to ethylene by the so-called E2E process[27].

System boundary

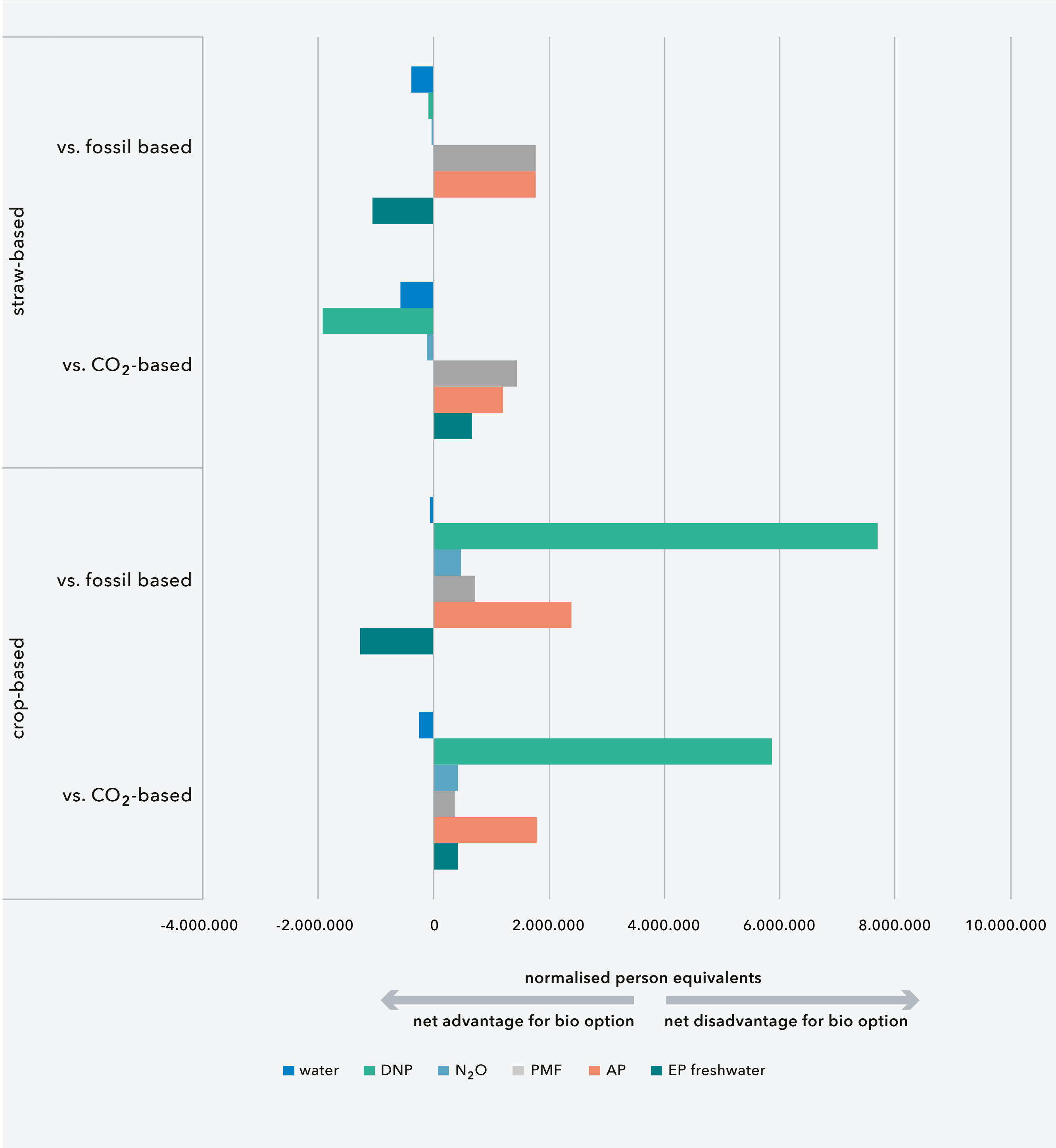
The system boundary follows the same principle as for the previous case study (value chain from extraction to production are considered, use phase and end-of-life are excluded, with the exception of the final CO_2 emissions at the end of the fossil-based product's life cycle). The same is true for data and calculations as well as the selection of impact categories, and further descriptions are available in the supplementary information.

Results:

- The results with regard to net savings and net burdens point in different directions in this case study. Clear results are difficult to identify.
- For the bio-based options, the categories acidification and particular matter formation are generally associated with net burdens.
- The GHG balance and fossil resources are favourable for both the bio-based options compared to the fossil reference, while the balance is unfavourable for both compared to the CO_2-based reference, albeit at a lower order of magnitude.
- The crop-based biomass option is clearly at a disadvantage in terms of land use and biodiversity (DNP), while the straw-based option has an advantage over the references.
- An overall environmental ranking is hard to determine, but these tendencies can be extracted:
  - CO_2 based ethylene achieves the bulk of advantages, taking into account drawbacks concerning water and land/biodiversity
  - Straw-based ethylene is clearly beneficial against cop-based and fossil options due to advantages in GHG and resource savings and no land requirements (supposing the "residue rule", i.e. no attribution of land-use).
  - Remaining crop-based and fossil based ethylene have contradictory results in GHG/resource saving and land use/biodiversity, providing no clear LCA preference for these options.
- The overarching message for policymakers is therefore to **prioritise residues such as straw as a raw material for the chemical industry**. In the future, however, the major share of this raw material should come from the utilisation of CO_2 (CCU) and green hydrogen. Crop-based ethylene, by contrast, offers no clear advantage over the fossil reference.

27 E2E: ethanol to Ethylene; see https://chemicals.basf.com/global/en/Catalysts/hydrogenation-specialty/products-we-offer/alumina/Ethanol-to-Ethylene-E2E.html

Figure 4.14 Normalised LCIA results for crop-based and straw-based ethylene balanced against two non-bio options (CO_2-based and fossil based) for the case study ethanol (or derived ethylene) as chemical building block



Note: Functional unit: 4 million tonnes ethylene as the German production capacity of ethylene;GWP: Global warming potential; AP: acidification potential; PMF: particulate matter formation; DNP: distance to nature potential.

4.4.3 Cotton and wood-based textiles[28]

Compared substitution options

Biomass-based options

Bio1: Conventional cotton-based textile fibre
Bio2: Wood-based textile fibre
Bio3: Bamboo-based textile fibre

Reference options

Ref1: CO_2-based fibre, from CCU synthesised with green hydrogen
Ref2: Conventionally produced polyester fibre. For this case study the functional unit of 1 tonne textile fibres were compared

System boundary

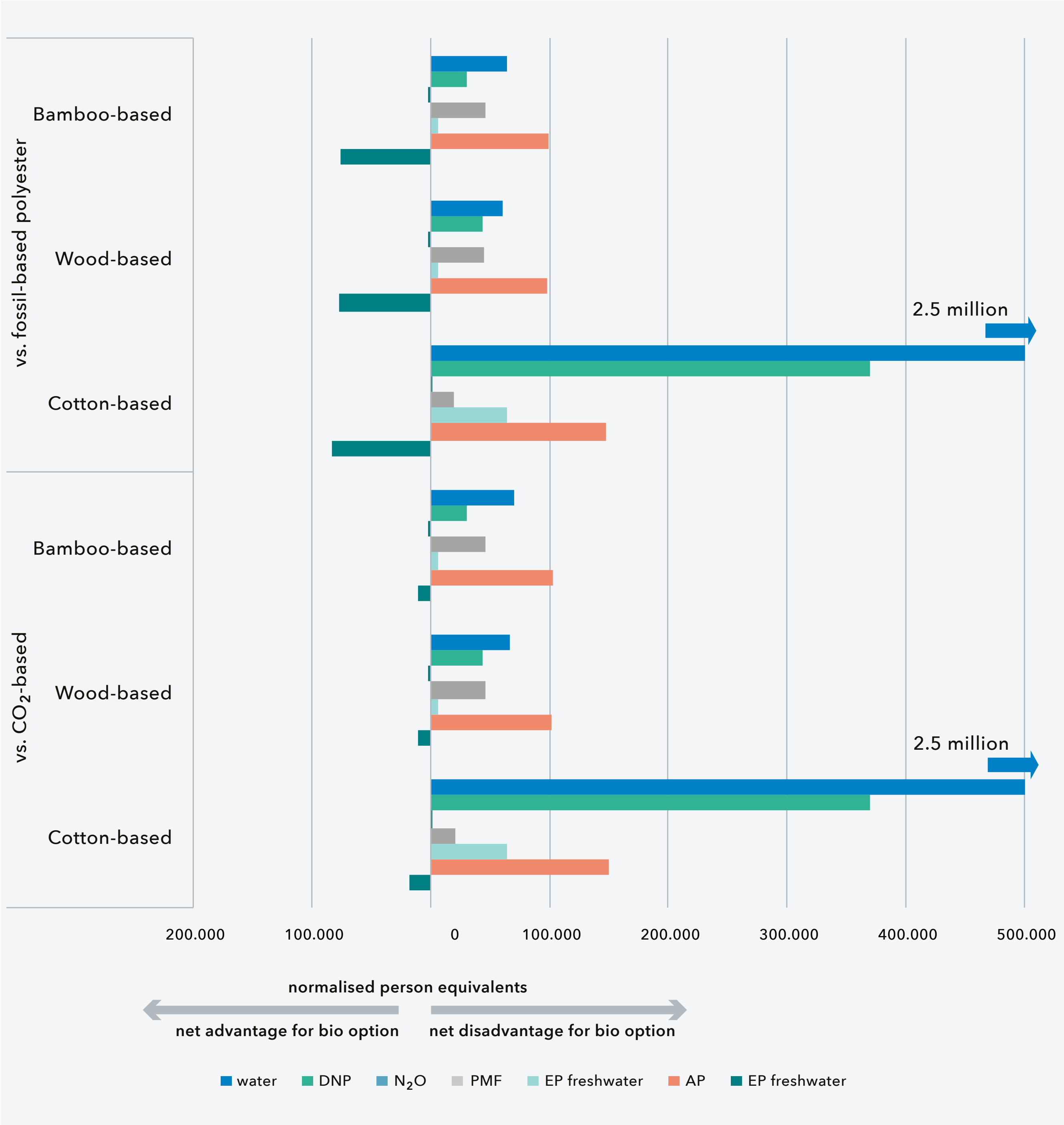
The system boundary follows the same principle as for the previous case studies. In other words, only harvest to production of the compared products are assessed without consideration of the product use phase and end-of-life impacts (such as microplastic pollution, just CO_2 emission from fossil-based fibres are accounted) or options for re-use (such as recycled PET — see also Section 3.3.3). The same is true for data and calculations and the selection of impact categories, with further descriptions available in the supplementary information.

Results

- Overall, the biomass-based options show disadvantages compared to the reference systems in the majority of the effect categories. The relevant exception is that all bio-based fibres have a clear advantage over conventional PES fibres (Ref 2) in terms of climate change. However, this advantage is very small when compared to CO_2-based fibres (Ref 1).
- The result for conventional cotton (Bio 1) is quite clear, apart from the climate advantage compared to fossil textiles. Compared to both reference systems, the disadvantages in land use (DNP) and water consumption are particularly striking, even in comparison with the two organic options. Moreover, in all other categories conventional cotton performs significantly worse than polyester and CO_2-based fibres.
- Water consumption in particular is extremely unfavourable, with a difference in consumption of around 2.5 million German citizens if the demand were to be met entirely with cotton instead of polyester.
- Wood-based fibres show a partly better picture: The advantages in the GWP and resource balance are evident in Figure 4.15, while for the other categories like acidification (AP) and eutrophication (EP) the normalised net results show drawbacks in a comparable order of magnitude to the case of conventional cotton. However, the data available here presumably does not represent the current state-of-the-art. A large proportion of the emissions here originate from a high demand for sulphuric acid. There may be great potential for optimisation here.
- **Conventional textile production has a highly negative environmental footprint**. It is therefore essential to promote alternative raw materials to conventional cotton. Further information and options (organic cotton, bamboo or CCU-based fibres) can be found in the final report on the case studies (Fehrenbach et al. in prep).

28 See the report Product Life Cycle Assessment — case studies in the framework of SYMOBIO 2.0 (Fehrenbach et al. in prep.) for more information and the full case study description

Figure 4.15 Normalised LCIA results for cotton (Bio 1), wood- (Bio 2) and bamboo-based textiles (Bio 3) balanced against two references (ref 1: CO_2-based and ref 2: fossil-based polyester)



Note: Functional unit: 216,000 tonnes textiles corresponding to the annual German consumption; PES: Polyester; GWP100: Global warming potential; AP: acidification potential; PMF: particulate matter formation; DNP: distance to nature potential.

MONITORING CHECK BOX 4:

Carbon balancing in product LCA

GHG balances, as part of LCAs, examine GHG emissions and savings along the process chain of products and compare them with alternatives such as fossil and mineral products. When considering biomass products, whether for material use or as an energy carrier, the question arises of how biogenic carbon is treated in GHG balances. This box presents three concepts on how to handle biogenic carbon in different contexts.

1. Assessment of existing land use

The first question is based on a retrospective approach, in the sense of the question ‚What could be instead?' Agriculture prevents succession to forest or reforestation (Searchinger et al. 2018). When biomass is cultivated on arable land for material or energy use, the potential storage effect of natural vegetation is forgone. This is described by the so-called carbon opportunity costs (COC). If these COC are taken into account, for example, in the GHG balance of biofuels, some research has shown that renaturation or reforestation of arable land (with continued use of fossil fuels) would lead to a higher GHG reduction (of about 40 %) compared to the use of specific first generation biofuels (with substitution of fossil fuels) (Fehrenbach and Bürck 2022).

2. Carbon emissions from indirect land-use changes

The second approach deals with changes in land use, specifically with emissions from indirect land use changes. These describe the effect that the cultivation of energy crops could cause on land that was previously used for the production of food or feed. Their calculation is complex and is usually done by combining land use models with economic or partial equilibrium models. Considering such model results in product LCAs is problematic due to the consistency of system boundaries. However, land use changes do occur in reality and can be demonstrated using various data sources. Therefore, general emission factors can be derived on an empirical basis. They attribute the emissions from actual land use changes in a defined agricultural area to all producers in that area proportionally to their land requirement. This is an attributive allocation, which is why this value is referred to as aLUC (attributive land use change) (see Fehrenbach et al. 2016, Fehrenbach et al. 2021).

3. Management of the carbon stock in forests

Traditionally, the energetic use of (woody) biomass is considered 'CO_2-neutral'. This is based on the assumption that the CO_2 released from combusting wood was previously absorbed during the growth of the tree. However, various projects and scientific articles have demonstrated a connection between wood harvesting and the forest carbon sink. The impact of wood harvesting on the CO_2 storage capacity of a forest as a whole can be described by the so-called **CO_2 storage balance**. This indicates how much the CO_2 storage capacity changes when one cubic meter of wood is harvested. The CO_2 storage balance can be quantified using forest models and by comparing different intensity scenarios of wood utilisation. In this process, the difference in the CO_2 storage capacity in the forest for alternative forest management scenarios is related to the difference made by wood harvesting. For example, Soimakallio et al. (2022) and Hennenberg et al. (2024a) calculated an average CO_2 storage balance for temperate and boreal forests based on a large number of studies, finding that, increased harvest intensity negatively affects carbon storage in such forests over short-, mid- and long-term time horizons. Including such CO_2 storage balances in the LCAs of woody biomass would help reflect the dynamics in the forest carbon sink related to harvests. However, modelling is labor-intensive and it is methodologically challenging to integrate the results of forest modelling into product GHG assessments. An alternative, conservative approach is to account for the release of carbon contained in the wood during the energetic use of wood. In that way, part of the CO_2 emissions associated with wood extraction in the forest can be included in the product's GHG balance by accounting for carbon emissions previously stored in the wood.

Implications

The concepts described above show that **the narrative of 'CO_2-neutral' biomass needs to be questioned.** The use of agricultural biomass for additional energetic and/or material use can be a driver of (indirect) land use changes, which annually leads to immense GHG emissions worldwide. For example, according to Friedlingstein et al. (2022) over the period from 2012 to 2021, 17 % of global GHG emissions were associated with land use changes, including deforestation.

The overuse of forests for wood supply can have significant impacts on the forest as a CO_2 sink, while long-lived "harvested wood products" can also be a strategy to "store" carbon. Against this backdrop, the consumption of ‚land' and ‚forest-based wood' should be weighed against the goals for a sustainable and balanced bioeconomy (see Section 2.1). This means not only focusing on the sustainable production of biomass, but also on the sustainable consumption of biomass-based products. For this, monitoring tools like LCA need to be adapted, augmented or complemented by approaches that reflect the system-wide impacts of that consumption, especially as regards GHG emissions.

5. Resource base and environmental impacts

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Key findings

- 243 specific indicators addressing environmental sustainability were identified and narrowed to a core set of nearly 20 suitable indicators for monitoring the agricultural-environmental impacts of the German bioeconomy.
- 84 studies were reviewed to identify 18 models capable of modelling the identified core indicators for agriculture. However, only a very limited number of scenario results are available for Germany, and of those, most focus almost exclusively on GHG emissions. To develop a regular bioeconomy monitoring, inclusion of relevant bioeconomy issues, including coverage with spatial variation, in existing agricultural modelling frameworks is needed.
- Out of more than 70 surveyed models, 10 were identified as suitable for monitoring Germany's forestry sector at a national level. Biodiversity, ecosystem services and water indicators are represented by forest growth models, but require further developments to improve the level of detail and coverage by all 10 models.
- Forest disturbance rates could significantly impact future harvest potentials and growing stock levels (particularly for conifers). Positive trends in forest biodiversity were found (based on indicators derived for broadleaf species). Soil carbon content may converge towards saturation, underscoring the importance of long-term modelling for climate change mitigation strategies.
- Weser-Ems is one of the most developed biogas production regions in Germany, with more than 800 agricultural biogas plants operating in the region. A case study using remote sensing techniques found that between 1999 and 2019 the area of maize cultivation increased by 94 %, while the areas of other summer crops and grasslands decreased by 66 % and 14 %. Major land cover changes occurred in areas that overlap with high and medium biogas capacity zones, indicating a direct relationship between biogas production and agricultural land cover change.
- Crop-driven deforestation related to oil palm in both Indonesia and Malaysia as well as soybean and sugarcane in Brazil peaked in 2012 and, as a result of dedicated policy measures, has since been in decline. Mapping showed substantial overlap between soybean- and sugarcane-driven deforestation and High Conservation Values 1 (species diversity), 2 (landscape-level ecosystems) and 3 (ecosystems and habitats) in Brazil. Further extending and operationalising the semi-automated remote sensing tool could support prioritising targeted conservation actions and promoting sustainable supply chains.
- Nearly 113 million m^3 fibre equivalents of wood contained in finished paper products were consumed in the EU-27 in 2018. Around 65 % originated domestically and 35 % originated from other countries (especially the US, Brazil and Uruguay). Germany was the largest consumer country in the EU (consuming 26 % of the total). To assess socio-economic and environmental impacts, a case study looked at employment, value added generation and global warming potential in Uruguay connected to the EU consumption of paper products, underlining that impacts of the bioeconomy are not confined to national borders.

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5.1 German resources and their development

5.1.1 The agricultural sector: Projection of future potentials and risks for the environment

An increase in demand for bio-based materials (e.g. for the innovative applications shown in Chapter 3) could lead to an increased demand for agricultural biomass. Conversely, a growing consumer preference for meat and milk alternatives (See Section 4.1) may result in a decreased demand for livestock farming, potentially reducing land requirements for feed production. These contrasting trends are likely to significantly impact agricultural production and have associated environmental implications. Therefore, an effective monitoring system of the bioeconomy should be capable of ex-ante assessment of the **future impacts of changes in demand for bio-based materials and agricultural products**. Such predictive information can inform policymakers in implementing appropriate measures to mitigate potential negative effects. Agricultural models serve as a **critical tool in forecasting these developments** and identifying potential adverse outcomes, such as those observed in the promotion of biogas production (see Section 5.1.3). To effectively comprehend, assess, and communicate the impacts of the bioeconomy, it is imperative to select an appropriate set of indicators that accurately quantify the environmental effects of agricultural production.

The focus of this section is thus shifted to the monitoring capacities and reflection on the state and relevance of indicators, models and scenarios for regular bioeconomy monitoring, alongside the presentation of data on the state, trends and performance of Germany's agricultural sector.

Indicators

In recent years, various indicator systems have been developed at different political levels (international, EU, national, and state-specific) to track the implementation of political goals. Notably, major bioeconomy monitoring systems — such as the EU Bioeconomy Monitoring System (Kilsedar et al. 2023), FAO's bioeconomy indicators (FAO 2019), and Germany's indicators aligned with the SDGs (Destatis) — collectively report over 400 indicators, including duplications. These indicators serve as a comprehensive "target catalogue", covering social, economic, and ecological dimensions, with **243 indicators specifically addressing environmental sustainability**.

Environmental indicators are defined by various factors, including the type and method of management (e.g., crop cultivation or animal husbandry), the scale of management (e.g., livestock size), management intensity (organic vs. conventional practices, proportion of fallow land), and the use of technical environmental protection measures (e.g., manure fermentation, covering manure stores, and employing inhibitors in fertilization or feeding). These indicators are always directly related to the agricultural production system.

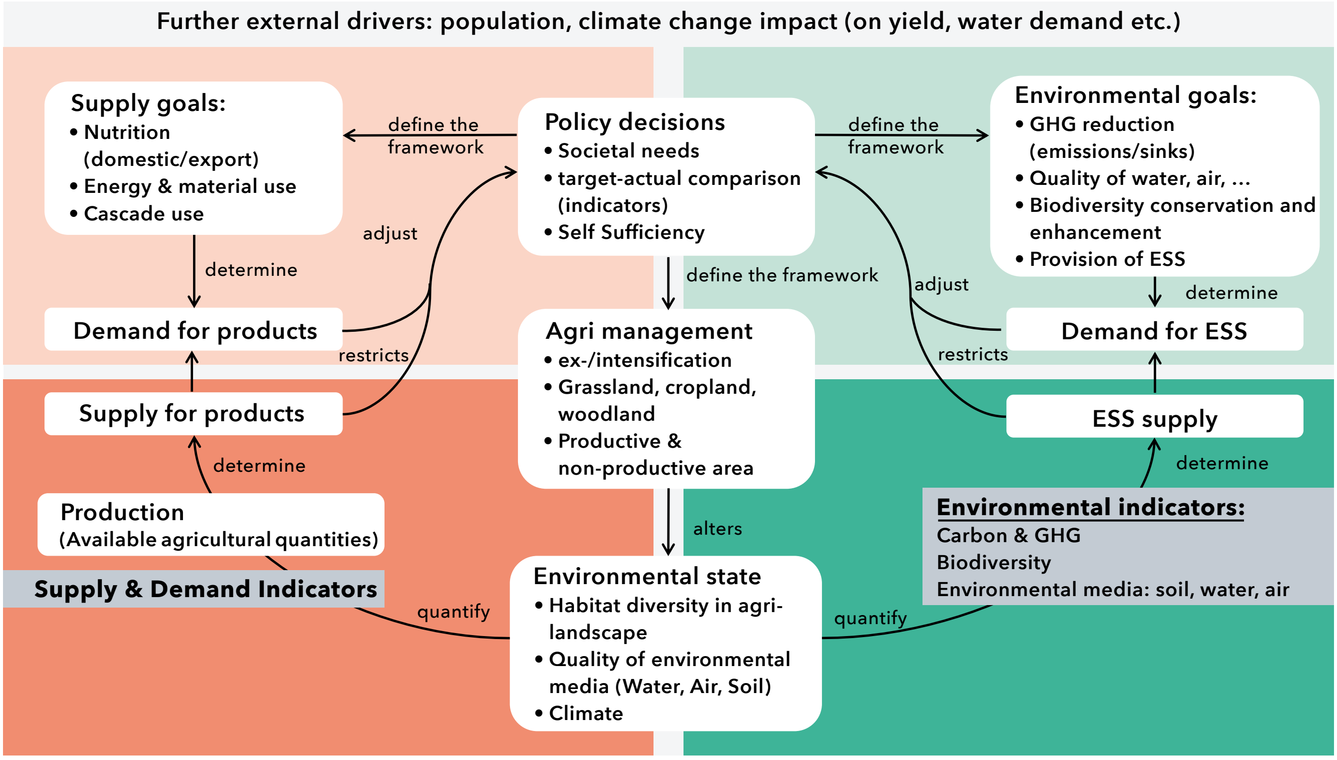
Additionally, **information that couples production and demand sides (e.g., self-sufficiency rates) is needed**. This is due to the limitations in the 'greening of production', as extensive agricultural methods are associated with yield losses. Consequently, extensive production systems require additional land to provide the same product portfolio (quality and quantity), which in turn can have a negative ecological impact, either domestically or through **leakage effects abroad**. This relationship is visualised in the diagram (Figure 5.1). It demonstrates that **system optimisation requires both process optimisation on the supply side and a simultaneous shift in demand towards less space-intensive products**, which could be reflected in a relevant indicator. Furthermore, leakage effects are included into the monitoring through the footprint concept (Chapter 7), and an additional level of indicators could also cover the demand side.

Identifying an indicator set for monitoring agricultural-environmental impacts at a national level

Suitable indicators were identified with the primary purpose of quantifying the environmental impacts of agricultural production. Building upon preliminary work from the SYMOBIO project (Egenolf and Bringezu 2019), the selected indicators adhere to the SMART concept, which stands for *specific, measurable, achievable, relevant and timebound*[29].

29 Specific, i.e., having a precise definition with a physical unit; Measurable, i.e., quantifiable, or computable; Achievable/Attainable, i.e., having a clear direction of development and sufficient data availability; Relevant, i.e., directly related to bioeconomy activities; Timebound, i.e., allowing accurate tracking through clear data sources and consistent data collection over time.

Figure 5.1 Framework for defining the role of indicators for monitoring agricultural-bioeconomy interactions



Note: ESS = Ecosystem Services

Source: Öko-Institut based on Pfeiffer et al. (in prep.)

Projections are crucial tools for describing the future effects of the bioeconomy on agriculture in Germany. They are usually realised using quantitative models. Consequently, the selection of indicators is influenced by the capabilities of agricultural models. We conducted a **comprehensive analysis to assess the extent to which existing models can represent the selected indicators,** and to identify ongoing model developments that may enable the production of additional indicators in the future. Based on this criteria, the indicators in Table 5.1 were identified in expert workshops, attended by specialists in environmental and agricultural sector modelling.

These indicators focus on the production side because the agricultural models only reflect internal use (e.g. feeding, biogas substrate use) whereas the demand side (market) serves as an input parameter. Indicators that provide information on the land use intensity per product unit can offer an alternative. The four indicators for sustainable agricultural production were selected accordingly. Supplemented by information on the land footprint for foreign trade, this selection is judged to provide a complete picture for currently evaluating the agriculture-associated aspects of the bioeconomy, if modelling capacities improve in the future.

The role of spatial representation for indicators

The climate impact of GHG emissions is largely independent of their emission location, rendering detailed spatial mapping for an impact assessment unnecessary. In contrast, other environmental impacts are closely linked to the place of production. This applies particularly to indicators for biodiversity, water and air quality, which significantly affect specific regions, making national-level mapping less informative in terms of spatially-explicit impacts. For example, spatial distribution plays a crucial role in developing biodiversity indicators. The nitrogen area balance indicator, essential for assessing water quality, gains significance at the regional level due to its impact on water catchment areas. High livestock densities have negative effect on the nitrogen balance, which is most evident at the farm level and becomes less apparent with larger areas and lower spatial resolution. In dedicated livestock farming regions, stocking density is high. When the balance area is enlarged, the number of remaining farms (with less or no livestock) increases, improving the nitrogen balance per hectare. Consequently, the effects of changes in the nitrogen balance (e.g., NUTS2 content) are therefore only marginally recognisable in a nationwide

Table 5.1 Suitable indicators for monitoring agricultural-environmental impacts at a national level

Indicator Group	Indicators	Unit
Climate change	GHG emissions from agriculture; Possible differentiation by gases: CH_4, N_2O, CO_2 and production: Animal, Plant-based, Bioenergy	kt CO_2e
	GHG emissions from land use change	kt CO_2e
	Carbon sinks from land use	kt CO_2e
Water quality	Nitrogen area balance *Improvements recommended: to couple with regional seepage water quantities*	kg N/ha
	Phosphor balance	kg P/ha
Water quantity	Share of irrigated area	% of total UAA
Air quality control	Ammonia (NH_3) emissions	kt NH_3
	Total nitrogen balance	kg N/ha
Soil fertility/soil carbon	Soil organic carbon content	%
	Soil erosion	t/ha
Biodiversity	High Nature Value Farmland (HNV)	% of UAA*
	Livestock density	LSU/ha
	New: share of agricultural land with structurally rich landscape elements *Under development to monitor nature restoration law*	% of UAA*
	New: Pesticide load/pesticide sale *Under development on EU level to monitor goals of green new deal; differentiated in risk categories*	kg/ha or €/ha
Land use	Area of cropland, grassland, agroforestry, rewetted organic soils/paludiculture, Agri-PV, fallow cropland/grassland	ha
Sustainable agricultural production	Share of organic farming	% in UAA*
	Development of plant and animal and biomass for energy or material use production	Cereal Units
	Share of human edible production rate	% of total production
	New: Area saving production on-farm — share of residual material used for fodder and biogas *Own proposal, drawn from different other indicators on use of residuals*	% (to be specified in detail)

Note: *UAA = Utilised agricultural area — includes all land that is used for agricultural purposes (grassland, cropland, permanent crops)

Source: Compilation by the Öko-Institut based on literature review and an expert workshop

representation. **This spatial heterogeneity underscores the importance of considering regional variations in environmental impact assessment and the development of appropriate indicators for comprehensive bioeconomy monitoring.** Maps illustrating regional variations are, for example, depicted in Figure 5.3 below.

Models

Agricultural models play a crucial role in predicting relevant developments and identifying potential adverse effects. In our comprehensive literature review of agricultural models, we **analysed 84 studies and identified a total of 18 models capable of producing results specific to German**y. These include **15 production models**, of which 6 are biophysical models, and 3 economic per

Table 5.2 List of identified models

Market model	Farm Level/Regional (NUTS2/NUTS3)	Biophysical models	Run by
AGMEMOD (EU)	***GAS-EM (für gasförmige Emissionen)***		Thünen Institute (TI)
	RAUMIS (DE)		
	FARMIS (DE)		
	CAPRI (EU)		TI/Uni Bonn
	FARMDYN (EU)		Uni Bonn
MAGNET (World)	MITERRA-EU, partly based on CAPRI, includes N-leaching module (EU)		WAGENINGEN
	FSSIM	WOFOST (growth and production of annual field crops)	
		APES (Interaction at field scale — weather, soil, technology)	
	MODAM	MONICA (Nitrogen and Carbon dynamics)	Leibniz Centre for Agricultural Landscape Research (ZALF)
		HERMES (Crop model)	
	FASSET		University of Arhus
		PESERA (Erosion risk)	ISRIC
		DAISY (Soil-Plant-Atmopshere)	University of Copenhagen
AGLINK-COSIMO			OECD/FAO

Note: The models marked in italics and bold are part of the Thünen Institute model networkSource: Compilation by the Öko-Institut

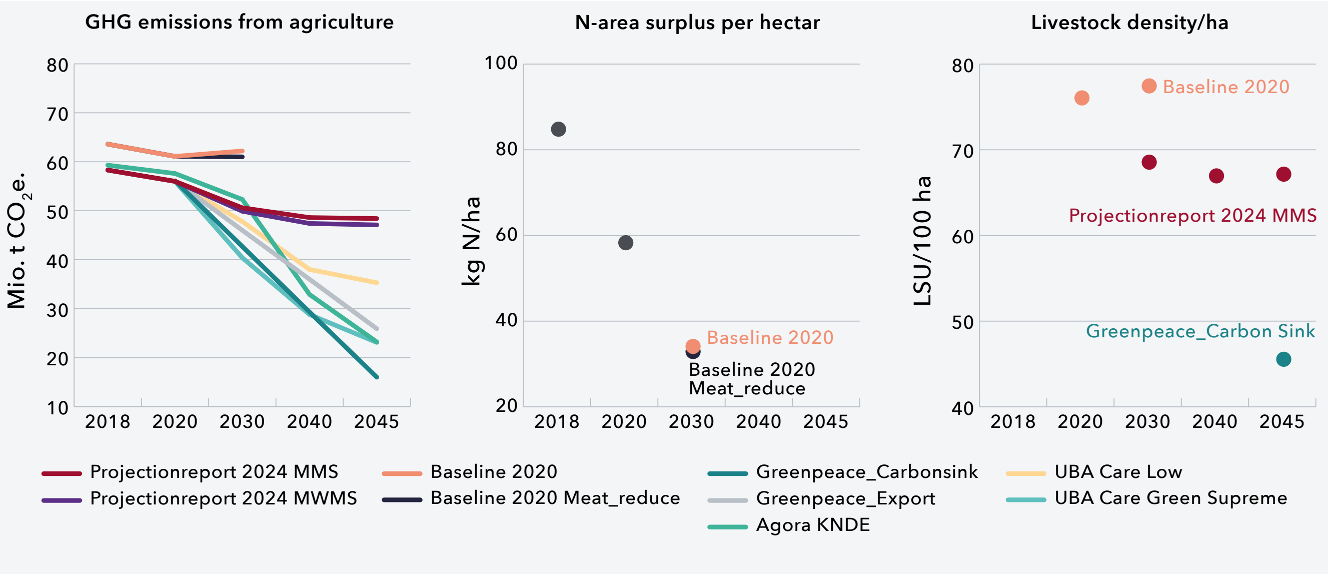
market models. Most of these models operate within coupled model families, where their results interact with each other. Market models play a crucial role in forecasting demand and establishing the framework conditions, while regional farm production models apply economic insights from market models to the production side.

Relevant institutions that have developed and maintain models are, aside from Thünen Institute and Bonn University, Leibniz Centre for Agricultural Landscape Research and Wageningen University. Further models with a focus on e.g. environmental indicators, representation of sector coupling and resource use are in use at the Institute for Energy and Environment (ALMOD), Öko-Institut (LISE), UBA (EMMa, developed by the University of Gießen) and RegNBil-Düv from the University of Gießen. Four of the regional/farm models are part of the Thünen Institute model network and **already serve as the foundation for reporting requirements and impact assessments under various environmental laws**, including GHG reporting, the NEC Directive, and evaluation of the CAP reform, monitoring in relation to fertilizer regulations. Furthermore, the models can simulate price effects related to energy and trade agreements, emission trading in the agricultural sector, biomass policies, and the impact of dietary changes.

Indicator dashboards and representation of spatial patterns

Although most of the production models at a regional or farm level listed in Table 5.2 **are capable** of modelling the indicators listed in Table 5.1, **only a limited number of the models have produced results for recent scenarios in Germany.** In accordance with the specifications for suitable indicators, models should provide scenario results for Germany as a whole, preferably at the NUTS 2 resolution. Models employed in current scenario studies for Germany include those from the

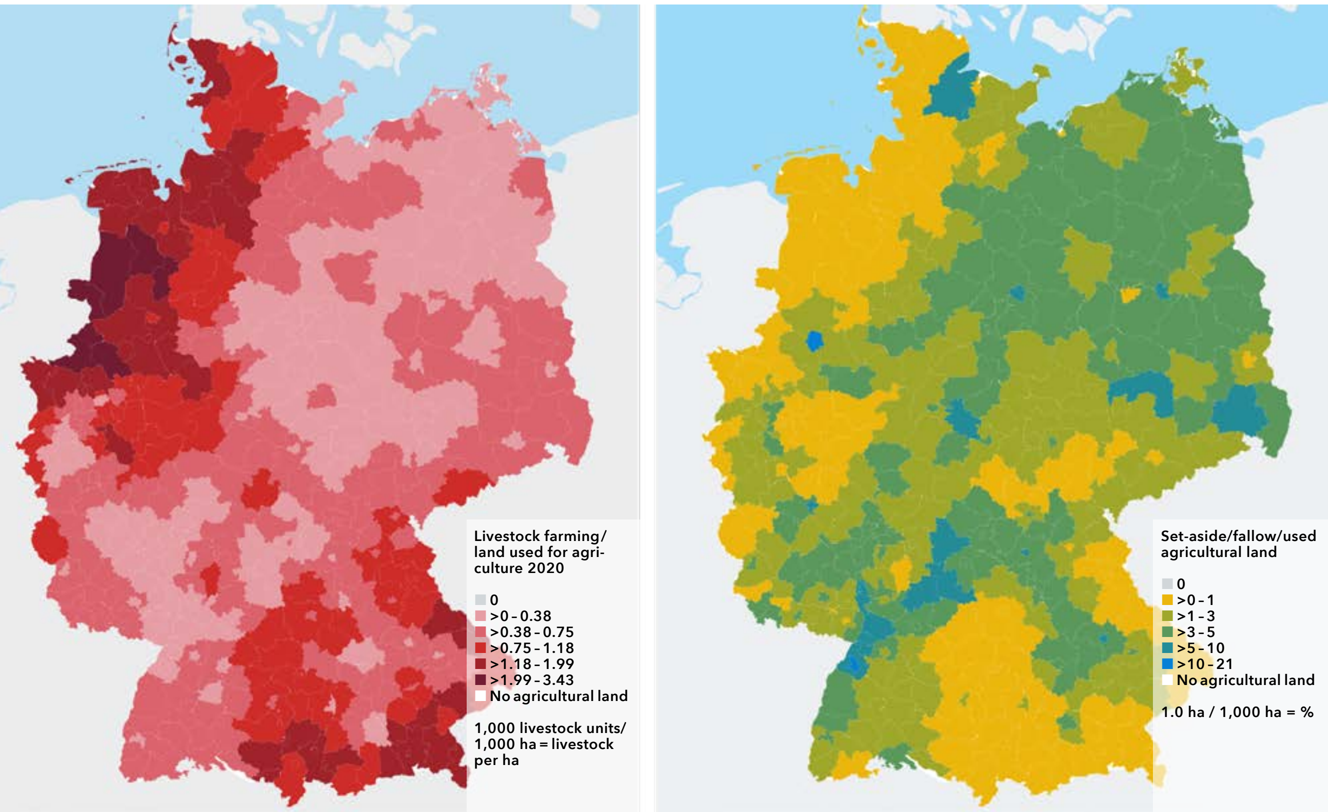
Figure 5.2 Development of different indicators in the scenarios for monitoring agricultural impacts of the bioeconomy



Note: *LSU = Livestock unit, one livestock unit corresponds to about 500 kilogram live weight. This is roughly equivalent to a dairy cow. For smaller animal species, there are more individuals behind the figure. The following values were used here: cows 1; cattle 2.3; pigs 9.1 and poultry 250.

Source: Compilation by Öko-Institut based on collection of different scenarios

Figure 5.3 Representation of livestock density (livestock units per area) and fallow land at the regional level for the year 2020



Source: Thünen Atlas[30]: Agricultural use (2020); Method: Gocht and Röder (2014)

30 https://atlas.thuenen.de/webspace/agraratlas/agraratlas/index.html?LP=1

TI- model network (NUTS 2 region) and the LISE model (Federal states) from the Öko-Institut.

Numerous scenarios and models primarily focus on GHG emissions. While these models can potentially provide insights into other indicators, these additional indicators are often not presented in the available scenario results, as they were not relevant for the specific research questions addressed by the scenarios. Some indicators can only be calculated by sub-models, necessitating separate computational runs. It is noteworthy that **no single scenario currently available encompasses the entire list of identified indicators**.

Figure 5.2 shows key findings. It only depicts scenarios and models for which results are available for Germany as a whole. The figure illustrates the progression of various indicators across selected scenarios, incorporating historical data as reference points. It should be noted that the initial values for GHG emissions vary among these scenarios based on the respective inventory base years used for calculation (values have not been standardised to a common base in our analysis). Altogether the limitations in comprehensive scenario modelling underscore the **need for more integrated approaches that fully capture the multifaceted interactions between agricultural systems, environment, and bioeconomy developments**.

The comparison of the **GHG emission indicator** (Figure 5.2) across different scenarios reveals a wide range of results, influenced by the specific storyline of each scenario. In the most ambitious scenario (Greenpeace_Carbon Sink), GHG emissions from the agricultural sector are reduced by −59 % compared to 2020. In contrast, the business-as-usual scenario from the national projection report shows only a −14 % reduction in emissions compared to 2020. A similar trend is observed in **the livestock density indicators** (Figure 5.2), which show the number of animals per hectare of land. This also reflects the overall development of animal numbers. In the Greenpeace scenario, livestock density drastically decreases until 2045, whereas the German projection report scenario shows only a moderate reduction in livestock density and animal numbers. N-surplus per hectare is not detailed in many scenarios and requires more comprehensive data for accurate calculation. Consequently, only a few figures are available. However, the available data indicates a **recent decrease in N-surplus** and a further reduction in the baseline scenarios, attributed to increased nitrogen efficiency resulting from stricter fertilizer legislation.

Spatially differentiated presentation of specific indicators often provides more informative insights than a mere listing of national average values. Maps can provide quick overviews on the range and spatial distribution of the data. Figure 5.3 illustrates the **benefits of spatial visualisation** for the two examples livestock density and distribution of fallow land (see also above). However, explicit spatial representation of indicators is challenging when attempting to visualise the temporal development of a given indicator. Alternatives are possible (e.g. through tables) and should be explored in the context of further developing a regular bioeconomy monitoring.

MONITORING CHECK BOX 5:

Modelling Germany's agriculture sector

Suitability of assessed models

Numerous available models are well-suited for bioeconomy monitoring and can effectively represent selected indicators. This specifically includes environmental indicators (GHG, NH_3) relevant for future projections and contributions to international monitoring processes. In addition to the CAPRI model, models suitable for bioeconomy monitoring in the agricultural sector include further models of the Thünen Model Network, which can also simulate other selected indicators. These models provide outputs at the NUTS 2 level for the entirety of Germany. Another advantage of these models is that they are **continuously updated with the latest data due to their regular use in policy advice and reporting** and are perpetually updated and improved through new developments. It is advisable to consistently use the same models for the bioeconomy monitoring to foster synergies with other reporting obligations.

Indicators: Existing gaps and challenges

The indicator list compiled during the workshops predominantly comprises established parameters. However, aspects related to **water, biodiversity, and biomass utilisation efficiency,** including cascade and residual material utilisation, **remain underrepresented**. Given the effects of observed climate change and the requirements of the Nature Restoration Act, there is an urgent need to enhance existing models to incorporate water and biodiversity indicators. Further challenges include:

- **Refining the indicators to create a concise set of core metrics** suitable for dashboards and reporting frameworks for regular bioeconomy monitoring. For comprehensive reporting, the complete set of indicators should be utilised.

- **Pursuing research focused on core issues related to the bioeconomy**: To date, many of the indicators identified as suitable and relevant for monitoring the interface of agricultural-bioeconomy-environment have not been systematically reported in scenario studies. This is because the primary focus of such studies — so far — has predominantly been on GHG emissions.

- **Effectively presenting regional differentiation within a time series**: Numerous agricultural models can display indicators at various spatial levels, including at least NUTS2 regions. However, spatial-temporal representation is crucial for a comprehensive understanding of bioeconomy trends and their environmental impacts.

Altogether, the models described analyse the situation and development within the EU and within Germany, respectively. **So far, they do not capture transboundary effects** of domestic production and consumption to other regions outside. For policy development, this implies that relying solely on domestic data carries the risk of shifting problems abroad while trying to optimise the situation at home.

5.1.2 The forestry sector: Future potentials and risks

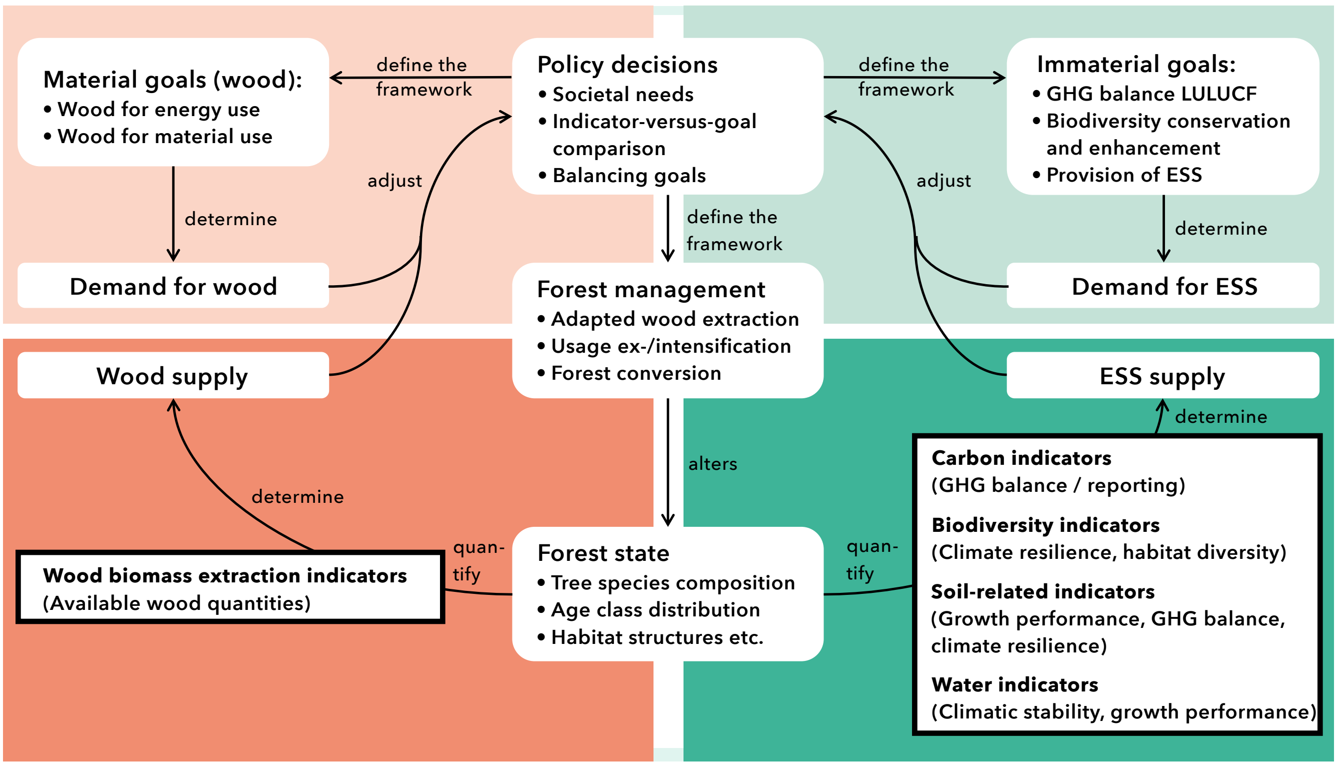
Forests are a vital component of the bioeconomy, contributing to carbon sequestration, timber and non-timber product supply, and various ecosystem services that enhance human well-being. The socio-economic, cultural, and ecological value of ecosystem services of German forests should inform decision-making processes. These services include water storage and purification, air filtration, soil stabilisation, and climate regulation (Brockerhoff et al. 2017). They support biodiversity by providing habitats for diverse flora and fauna.

Wood, traditionally used for energy and material applications, can also be used for innovative bioeconomy products such as chemicals, fibres, textiles, plastic substitutes, and insulation materials. However, wood supply is limited and requires sustainable management to reconcile various demands. Potential conflicts may arise between ecosystem services, such as enhanced carbon sequestration, and the need for intensified resource use (Lin and Ge 2020), exacerbated by the need for adaptation measures to increase forest resilience against climate change impacts (Gregor et al. 2022). On the other hand, appropriate management might increase forest biomass growth and timber production while decreasing the risk of climate change-related decline (Collalti et al. 2018).

Conceptual framework – The role of indicators

The conceptional framework illustrated in Figure 5.4 was derived based on a synthesis of several concepts that connect goods and services related to societal needs with sustainable use and environmental protection (Pfeiffer et al. in prep.). It integrates information from, e.g., the DPSIR framework (Driving forces, Pressures, State, Impacts and Responses; Kristensen 2004), footprint analysis (ISO 14067:2018, Bringezu et al. 2021b) and biomass certification systems (ISO 13065:2015, FSC, PEFC). For the forestry and wood sector, the framework in Figure 5.4 assumes **societal needs as drivers behind policy decision making** in the context of bioeconomy development. Policy decisions define the settings for material and immaterial goals as well as for forest management. Material goals are defined by the quantities and qualities of wood needed for, e.g., paper, construction, and energetic use, whereas immaterial goals focus on the provision of ecosystem functions and services that extend beyond the material and energetic use of wood extracted from forests. Such ecosystem services include the achievement of target GHG balances within the LULUCF (Land Use, Land Use Change, and Forestry) sector, the conservation and

Figure 5.4 Conceptual framework defining the role of indicators in forest and forestry monitoring for bioeconomy



Note: ESS = ecosystem services; LULUCF = land use, land use change, and forestry enhancement of biodiversity, and ensuring the continued provision of ecosystem services by protecting the ecosystem functions delivering these services.

In summary, the material goals determine the demand for wood from forests, whereas the immaterial goals determine the demand for other ecosystem services. Political decisions also influence the type and intensity of forest management, including forest conversion to climate-resilient forest stands. The **comparison of wood demand and supply as well as ecosystem-services demand and supply** are intended to support policymakers in deciding whether targets and objectives for material and immaterial goods and for forest management should be adapted. Here, information on the forest state is key. Indicators addressing wood supply should cover how much wood can be extracted, and indicators informing about the ecosystem-services supply should cover carbon fluxes, biodiversity, soil, and water.

Indicator and scenario selection

Empirical data from forest inventories, remote sensing and harvest statistics offer information on historical developments. In addition, forest growth models can project how forests will respond to different management practices, climate conditions, and disturbances (Gutsch et al. 2018, Pfeiffer et al. 2023). They simulate interactions between various ecological and environmental factors influencing forest growth, including tree growth, competition for resources, mortality, and regeneration. Due to this complexity, it is appropriate to include various scenario assumptions for projections in the monitoring system to **establish a corridor for an expected development**.

For each of the indicator groups in Figure 5.4, one to two indicators have been identified as relevant for forest and forestry bioeconomy monitoring during expert exchange and were selected for the forest dashboard (Figure 5.5). In the dashboard, all results are presented in the unit cubic meters. The results originate from modelling studies carried out with the forest model 'FABio-Forest' covering three scenarios of different intensities of forest management. To assess possible future climate-related influences on mortality and growth, three sensitivities for altered growth and mortality were simulated for each forest scenario (see details in Table 5.3). An exception is the change in soil carbon, which is shown in tonnes CO_2 equivalents modelled with the soil model 'Yasso'.

Altogether **three basic scenarios** were selected and modelled in different studies (BioSink, CARESupreme, and Projection report (ProRep)), **each with three different disturbance sensitivities** (e.g., low, medium and high disturbances as well as an alternative model for ProRep (ProRep-FABio and ProRep-Yasso).

Table 5.3 Specifications of covered forest and soil scenarios

Forest scenario	Model	Source	Harvest intensity	Natural disturbances
Reference scenario of the UBA BioSINK project **(BioSINK)**	**FABio**-Forest	Pfeiffer et al. (2023)	High wood demand modelled by wood use model TRAW (Total Resource Assessment of Wood)	**Low disturbances (lowD):** mortality and growth are equal to the average of the period 2013–2017 **Mean disturbances (meanD):** mortality and growth are equal to the average of the period 2002–2017 **High disturbances (highD):** mortality equals the average of the period 2002–2021, while growth increment is set as 0.9 times the average for 2002–2017
Scenario Supreme of the UBA-CARE-project **(CARESupreme)**	**FABio**-Forest	Harthan et al. (in press.)	Projection of the mean harvest rate from 2013–2017, followed by a reduction of harvest of broadleaves	
Recalculation of projection report 2024 "with measures scenario" **(ProRep)**	**FABio**-Forest	Hennenberg et al. (2024b)	Projection of the mean harvest rate from 2013–2017	
Projection report 2024 "with measures scenario" **(ProRep)**	**Yasso**	Harthan et al. (2024)	Projection of the mean harvest rate from 2013–2017	Low disturbances (lowD), see above

Source: Pfeiffer et al. (2023), Hennenberg et al. (2024b), Harthan et al. (in press.), Harthan et al. (2024).

Substantial natural disturbances in 2007 and 2018–2020 resulted in high volumes of damaged coniferous wood and consequently elevated extraction rates. A scenario of high natural disturbance in the future shows significantly impaired productivity of coniferous stands, leading to a harvest deficit in the mid-2030s.

Key findings

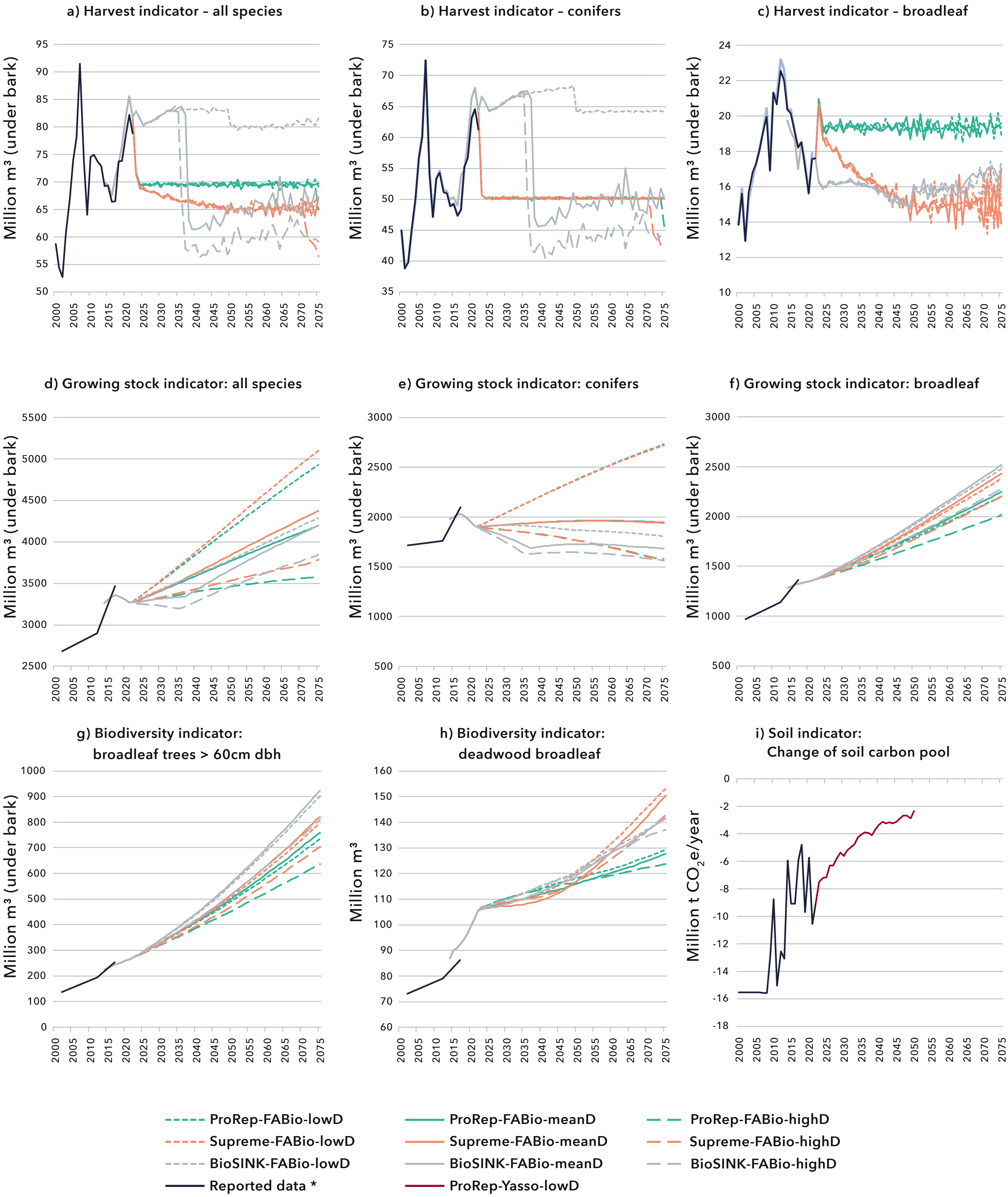
Harvest scenarios

The harvest indicator (Figure 5.5a-c) represents the indicator group wood biomass extraction. This indicator covers the amount of wood extracted from forests in Germany. On the one hand, information on the amount of harvested wood is needed to compare wood supply and wood demand to **inform policy makers about the scale of demand compared to supply.** On the other hand, the intensity of wood harvests directly influences forest structure, the growing stock and, consequentially, the carbon sink in German forests.

The scenarios presented demonstrate significant variations in the quantities of harvested wood. The Federal Government's projection report extrapolates wood extraction at 70 million cubic meters (m^3) per year (refer to scenarios 'ProRep-FABio', Figure 5.5a). For coniferous wood, the extraction rate of 50 million m^3 per year is relatively low compared to historical data. This is due to substantial natural disturbances in 2007 and 2018–2020, which resulted in high volumes of damaged coniferous wood and consequently elevated extraction rates (Figure 5.5b). The 'BioSINK scenarios' project a very high coniferous wood demand, exceeding 65 million m^3 per year. In the 'BioSINK scenario' with low natural disturbances ('BioSINK-FABio-lowD'), wood demand can be met until 2050. Subsequently, a slight harvest deficit occurs as older stands are harvested, and the annual growth becomes insufficient to fully satisfy the coniferous wood demand. **Higher natural disturbances** ('BioSINK-FABio-meanD', 'BioSINK-FABio-highD') **significantly impair the productivity of coniferous stands**, **resulting in a substantial harvest deficit emerging by the mid-2030s.** Consequently, coniferous wood extraction decreases to levels similar to those in the 'ProRep scenarios'. The 'CARESupreme scenarios' assumed the same coniferous wood extraction as in the projection report. These findings underscore the importance of considering various factors, including natural disturbances and stand age distribution, when projecting future wood availability and harvest potentials.

Hardwood extraction, i.e., wood extracted from broadleaf trees, is in Germany approximately 2.5 times lower than softwood extraction, i.e., wood extracted from conifers. The **projected hardwood demand can be met in all presented scenarios**. In the 'ProRep scenarios', hardwood extraction is around 20 million m^3 per year, which is consistent with historical values. The assumptions in the 'BioSINK' and 'CARESupreme scenarios' lead to a reduced hardwood extraction of 15–16 million m^3 per year (Figure 5.5c), assuming a decline in hardwood use for energy production.

Figure 5.5 Dashboard of forest indicators



Note: * Reported data: Einschlagsrückrechnung (ESRR, Jochem et al. 2023b) in panel a-c; forest inventory (www.bwi.info) in panel d-h, national GHG Inventory (UBA 2024) in panel i.

Growing stock scenarios

The growing stock indicator (Figure 5.5 d-f) illustrates the temporal changes in the wood stock of living trees. **For broadleaf trees, all scenarios demonstrate a continuous increase in the growing stock** (Figure 5.5 f). This increase is more pronounced when natural disturbances are low and/or hardwood removal is reduced. Furthermore, an early reduction in wood removal leads to a stronger growing-stock accumulation in later years. This development results in continuous CO_2 sequestration in broadleaf tree stands, contributing to an annual sink capacity of −17 to −25 million t of CO_2 by 2045.

The development of **the growing stock of conifers, however, only increases when wood extraction is low and minimal natural disturbances are assumed** ('ProRep-FABio-lowD' and 'CARESupreme-FABio-lowD'; Figure 5.5e). Only in these scenarios can coniferous stands in Germany contribute to the forests' carbon sink capacity. With low wood extraction and moderate natural disturbances, the growing stock of conifers remains approximately constant. In scenarios with high wood extraction and/or significant natural disturbances, the growing stock of conifers decreases (Figure 5.5e).

Biodiversity scenarios

Two biodiversity indicators have been selected for the dashboard: the wood volume of broadleaf trees larger than 60 cm diameter at breast height (dbh), and the wood volume of forest deadwood from broadleaf trees. Older broadleaf trees with larger stem diameters provide an increased number of microhabitats such as bark pockets or dead branches, which are essential for rare and endangered species. This also applies to the availability of broadleaf deadwood, which benefits species ranging from woodpeckers to fungi. In all considered scenarios, the number of broadleaf trees with a dbh over 60 cm increases significantly, although higher wood extraction rates and increased natural disturbances dampen this development (Figure 5.5 g). Similarly, the amount of broadleaf deadwood consistently increases across all scenarios. Notably, the 'CARESupreme-FABio' scenario, which has the lowest hardwood harvest, shows the most substantial increase in broadleaf deadwood (Figure 5.5h). **These findings highlight the positive trends in forest biodiversity indicators across various management scenarios.** The results suggest that current and projected forest management practices are generally conducive to improving habitat quality for species dependent on large trees and deadwood. However, the variations observed between scenarios underscore the importance of carefully balancing wood extraction and conservation efforts to optimise biodiversity outcomes in forest ecosystems.

Soil carbon scenarios

The soil indicator in Figure 5.5i illustrates the annual change in soil carbon. Soil carbon is crucial for both soil structure and forest soil fertility. Additionally, CO_2 sequestration is relevant for climate protection. Historically, German forest soils have sequestered significant amounts of CO_2, reaching nearly −16 million t of CO_2 per year. However, modelling using the Yasso soil carbon model indicates that **the soil carbon content in forest soils is approaching saturation**. As a result, the annual CO_2 sequestration is projected to decrease to approximately −2 million t of CO_2 by 2050. This implies that while the achieved carbon stock in forest soils will be maintained, it will only increase slightly (Figure 5.5i). These findings highlight several important points:

- The historical role of German forest soils as a substantial carbon sink;
- The gradual saturation of soil carbon content in forest soils over time;
- The projected decrease in annual CO_2 sequestration rates, despite maintaining overall carbon stocks; and
- the continued, albeit slower, increase in forest soil carbon stocks through 2050.

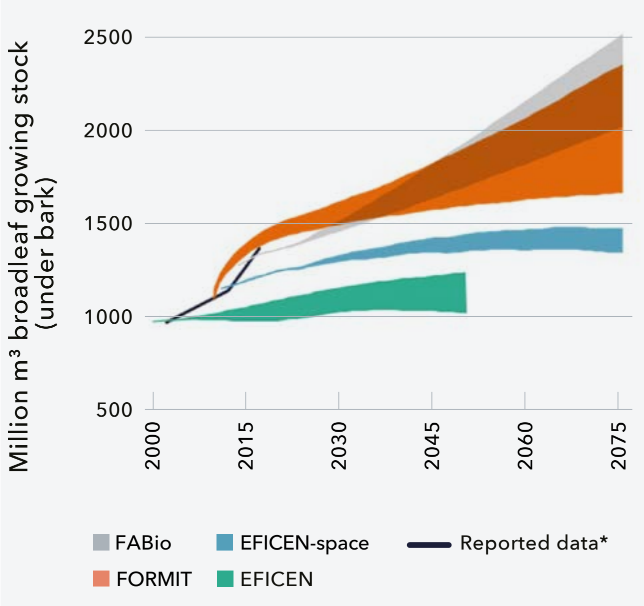
Altogether, results underscore the complex dynamics of soil carbon sequestration in forest ecosystems and the importance of long-term monitoring and modelling to understand these processes in the context of climate change mitigation strategies.

First results from model comparisons

Scenarios simulated for Germany's forests with 4 different forest growth models for different climate change and management assumptions reveal that projected pathways may differ considerably. Figure 5.6 shows results for stock development of broadleaf trees (volume under bark). **Volume increases are predicted by all four models.** However, the outcomes between models differ due to the following factors: 1) temporal starting point of simulation, 2) management assumptions regarding wood withdrawal, and 3) climate and disturbance regime.

Except for FABio Forest, all models prescribe wood harvest based on availability of harvestable wood according to management rules, implying that wood withdrawal from forests is decoupled from wood demand in these three models. This implies that the quantity of harvested wood is determined by the management rules prescribing the characteristics of trees that are suitable for harvest. Independent of market needs, all trees that fulfill the management requirements are always extracted. Therefore, broadleaf wood withdrawal is modelled as more intense in these models (EFICEN and FORMIT) than under a demand-driven withdrawal regime (FABio). Demand for broadleaf wood (unlike demand for conifers) is usually much lower than the harvest potential for broadleaf wood. That means that in a demand-driven model, like FABio, wood extraction is double-capped by management rules as well as market demands, implying that not all harvestable trees are cut if market demands require a quantity that is less than the harvest potential. A general conclusion from the simulations has been that the influence of the wood withdrawal and management regime on the development of broadleaf stocks can be as high or even higher than the influence of the prescribed climate/disturbance scenarios. Comparisons for further indicators and results from more models are currently being compiled and will be discussed in more detail in a planned separate scientific publication.

Figure 5.6 Projected broadleaf wood stock development in German forests from 4 different forest growth models



Note: *Reported data: forest inventory (www.bwi.info)

Many thanks for providing the model results go to Annikki Mäkelä (University of Helsinki, FORMIT), Sara Filipek (University of Wageningen, EFICEN-space) and Mart-Jan Schelhaas (University of Wageningen, EFICEN)

Interim discussion

Since model results are dependent on the underlying algorithms, parameterisations, and assumptions, it is prudent to consider results from various forest models. Ideally, an ensemble modelling approach using different forest models with prescribed common assumptions and scenario settings would be employed. Currently, such a systematic and comprehensive ensemble modelling for German forests is unavailable. However, specific scenarios exist that compare outcomes in the context of, e.g., GHG emission inventory reporting. For instance, the matrix model developed by the Thünen Institute (Rock et al. 2021) is utilised for forest projections as part of the national GHG emissions inventory. Hennenberg et al. (2024b) compare the results of GHG balance for forest areas in the 2024 Projection Report with results from the ProRep-FABio-lowD scenario. The outcomes from both models show only minor deviations, which are likely attributable to different assumptions about forest management rather than methodological differences.

Furthermore, although no formal model intercomparison exists for forest modelling in Germany, **10 forest growth models have been identified as suitable for modelling the development of forest stands in Germany** (see Monitoring Check Box 6). This diversity of models provides an opportunity for more comprehensive comparisons and potentially more robust projections of forest dynamics under various management and climate scenarios. Using multiple models and comparing their results for specific indicators can help to identify areas of consensus and uncertainty in forest projections and thus provide a more robust basis for policy decisions. It also highlights areas where further research or data collection may be necessary and helps to improve our understanding of the strengths and limitations of different modelling approaches. **As climate change continues to impact forest ecosystems, the use of multiple modelling approaches will become increasingly important for reliable projections and effective forest management strategies.**

First assemblies of data from the models that were identified as suitable for monitoring show that the basic development tendencies of the indicators in Figure 5.5 are consistent. For example, the scenario results clearly depict that climatic risks in coniferous stands are higher than in broadleaf stands, while simultaneously the demand for coniferous wood exceeds the demand for broadleaf wood. However, the variability and therefore range of uncertainty of results from different models can be high (Pfeiffer et al. in prep.), and indicator representation by models varies considerably. While indicators shown in Figure 5.5 are covered by the different models, the abundance of representation varies depending on indicator type. While **biomass and carbon indicators are covered well by all models, the representation of biodiversity indicators varies more strongly between models**. The **largest gaps were identified for soil indicators and water indicators**, regarding the number of models that can provide indicators for these two groups as well as indicator detail and quality. Some degree of variance in indicator representation can be attributed to the different modelling approaches and therefore requirements in process-based vs. empirical forest growth models. For example, process-based models are more likely to include (more detailed) soil dynamics representation routines, including carbon and in some cases nutrient turnover, as well as (soil) water dynamics.

Key messages

- Wood demand from forests for material and energetic use must be carefully balanced against negative effects on carbon sink capacity caused by wood withdrawal, in particular if withdrawn wood is combusted or used in **short-lived wood products**. In this context, different climate change mitigation strategies may compete against each other, as well as balancing of material demands vs. non-material ecosystem services.
- While model results from different scenarios and projected disturbance sensitivities indicate growing stocks of broadleaf trees that will continue to contribute to CO_2 sequestration, coniferous stand's growing stocks are predicted as more vulnerable to natural disturbances, while simultaneously the demand for coniferous wood considerably exceeds the demand for broadleaf wood.
- Natural disturbances significantly impact forest productivity, especially for coniferous stands, potentially leading to harvest deficits.
- Harvest scenarios reveal significant variations in wood extraction, emphasising the need for careful planning to balance supply, demand, and conservation efforts to maintain biodiversity and mitigate climate change impacts.
- Long-term monitoring and modelling are essential for understanding complex forest ecosystem dynamics in the context of climate change mitigation. A systematic, collaborative model-based monitoring framework with standardised conventions is urgently needed for German forests. Multiple modelling approaches and scenarios are crucial for reliable projections and deduction of effective forest management strategies.
- Current forest bioeconomy monitoring models represent biomass and carbon indicators well, but have some shortcomings regarding comprehensive coverage of biodiversity, soil, and water indicators. Biodiversity indicators show positive trends across scenarios, but careful management is needed to optimise outcomes. Tentative results for forest soil carbon sequestration indicate that soils may approach saturation, with projected significant decreases in annual CO_2 sequestration by 2050.

MONITORING CHECK BOX 6:

Modelling Germany's forestry sector

Suitability of assessed models

Out of **more than 70 surveyed models** in the literature review, the following models were identified as potentially suitable for monitoring of the forest and forestry sector in Germany: 4C, EFISCEN-space, EFISCEN 4.1, FABio Forest, FORMIND, FORMIT-M, LandscapeDNDC, LPJml-FIT, LPJ-GUESS, the Thünen Matrixmodell, and WEHAM (references for each model can be found in the supplementary information). These models fulfil the requirement that they can spatially cover all of Germany and at the same time provide all or at least a subset of the monitoring indicators depicted in Figure 5.5.

Indicators: Existing gaps and challenges

- **Five key indicator groups** were identified as crucial for monitoring the bioeconomy in the forest and forestry sector: wood extraction indicators, carbon sequestration, biodiversity metrics, soil quality, and water-related aspects. While the first indicator group quantifies wood supply potential and associated risks, the other four were selected to monitor the environmental impacts of the bioeconomy transition, aiming to balance material and immaterial ecosystem services.

- Although the models identified as suitable can provide quantitative information on these relevant indicator groups, a significant challenge remains: **the absence of a systematic, collaborative, model-based monitoring framework that adheres to standard conventions and coordinates contributing models**. Such a framework would necessitate the establishment of common standards, infrastructure, and documentation to facilitate the characterisation, comparison, and distribution of model outputs. This standardisation is essential to ensure consistency and comparability across diverse models and experiments.

- Implementing these **standards** is a crucial step towards making multi-model outputs publicly available in standardised formats, thereby fostering broader scientific analysis and enhancing their applicability in policy making. In this context, the framework format of established Climate Model Intercomparison Projects (CMIPs) can serve as a valuable guideline for developing a comparable framework for forest-model-based bioeconomy monitoring efforts.

- Forest growth models were primarily designed to predict growth and yield based on forest dynamics simulations under specific management rules. Consequently, their traditional focus has been more strongly oriented towards addressing economic questions and providing decision support. In contrast, the evaluation of ecosystem services is a more recently emerging field of research for these models. As a result, **biodiversity-related indicators are less well represented compared to biomass and carbon indicators**. This disparity is evident both in the number of models capable of representing specific biodiversity indicators and in the level of detail in their representation. It is important to note that biodiversity indicators derived from forest growth models tend to be more simplistic and less refined than those obtained from field studies. This limitation reflects the models' original design focus and the complexity of accurately representing biodiversity in simulated environments.

- **Water-related indicators cannot be predicted by forest growth models alone**. Empirical models usually lack explicit representations of water cycle-related aspects, whereas process-based models represent those to varying degrees of detail but require additional climatic and soil-related input parameters as water cycling extends across different spheres of the Earth system and therefore beyond forest stands. Therefore, while water-related aspects are crucial for forest growth and dynamics, water indicators cannot be produced by forest growth models as a stand-alone.

5.1.3 Regional case study: Land use change driven by biogas demand in Lower Saxony[31]

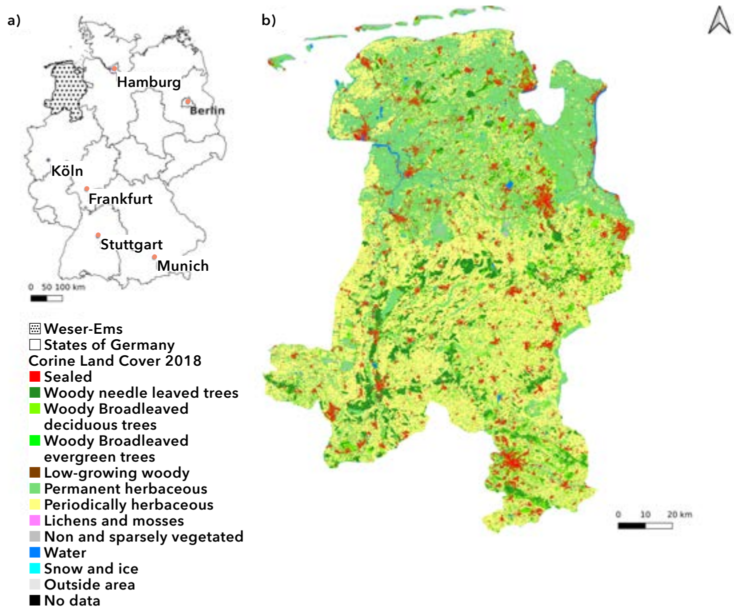
The Weser-Ems region

Weser-Ems is a former government district of Lower Saxony in the northwest part of Germany. It consists of 12 districts and five district-free towns and has a total area of ca. 14,965 square kilometers (km²). The region is characterised by **high agricultural activity**. The southern part is dominated by pig and poultry farms and the northern part hosts high shares of permanent grasslands for cattle farming. While high quality soils (Soil Quality Rating values of 70 to 85) are found e.g. in some of the coastal areas, the majority of agricultural soils in the Weser-Ems region are of low (50 to 60) and average (60 to 70) quality (Mueller et al. 2007). The area belongs mainly to the Northwest German lowlands climate region with a mean average annual temperature of 8.6°C and a mean average annual rainfall of 730 mm.

Due to its prominent agricultural sector, Weser-Ems is **one of the most developed biogas production regions in Germany**. Supported by the guaranteed feed-in tariff and bonus payment mechanisms established by the German Renewable Energy Act (EEG), by the end of 2020, there were around **825 agricultural biogas plants operating in the region** (Figure 5.8). Moreover, in comparison to the overall German biogas landscape, biogas plants in the Weser-Ems region are larger (the average installed electric capacity is over 600 kilowatts) and feature higher density in terms of the number of biogas plants per area.

The unique characteristics of the region, with high biogas development on the one hand, and a diversity of agricultural land use and intensification patterns on the other, were the main reasons to select this region for studying the long-term impacts of biogas development on land cover change.

Figure 5.7 Location of the Weser-Ems region in Germany (a) and land cover of the region in 2018 (b)



Source: Based on EEA data

Remote sensing assisted monitoring

The aim of the study was to assess the applicability of remote sensing techniques for monitoring the change in agricultural land cover driven by biogas development. In recent years, remote sensing based methods have demonstrated the potential to acquire efficient and accurate information about agricultural land cover. The availability of remote sensing satellite data and the development of machine learning algorithms has made **large-scale cropland mapping** possible.

In this study, Landsat satellite data was used to map agricultural land cover. Changes over the time span of 20 years (1999–2019) were assessed. The period of assessment was aligned with the progression of biogas sector development from early introduction until late consolidation in the region. Satellite-based remote sensing models were trained using machine learning algorithms and validated with actual agricultural land use data recorded in the Integrated Administration and Control System (IACS). The accuracy of the machine learning model with remote sensing data used to predict past years' crop types was 85 % (macro F1 = 0.7) (Wijesingha et al. 2024). The major benefit of using remote sensing data is the possibility of going back in the past (in this study, starting from the year 1999) to **capture historical land cover developments**. This is particularly important because, in most cases, high quality, spatially explicit data from the past are not available. This feature

31 More information on this case study can be found in the scientific publications Wijesingha et al. 2024 The impacts on biodiversity are also being assessed in relation to biogas induced land use change; results will be available in 2025 by Wijesingha and Dzene.

Figure 5.8 Biogas sector development in Weser-Ems (1999–2019)

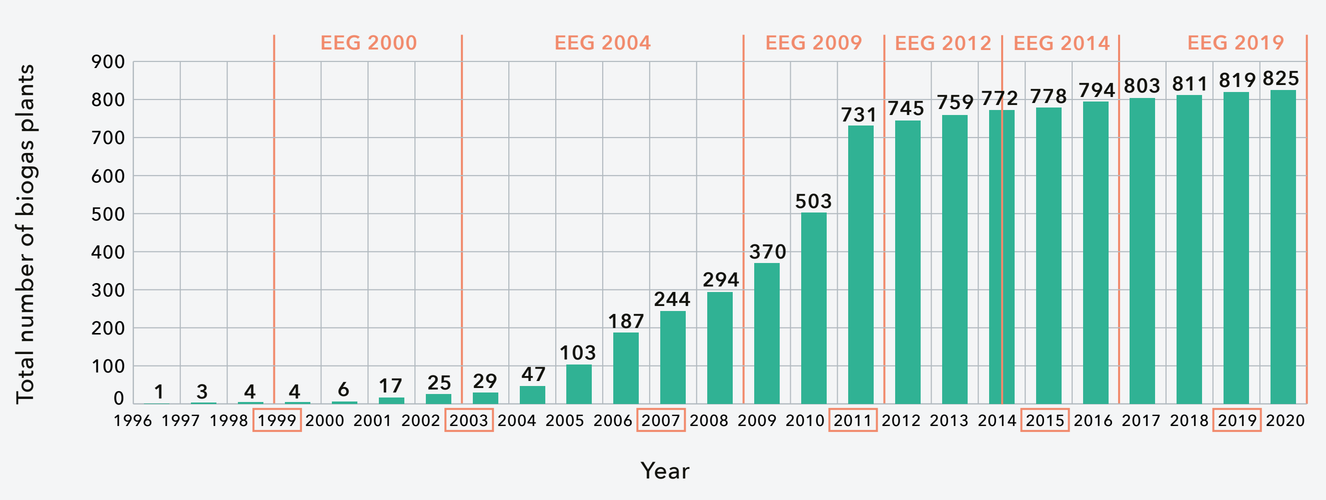
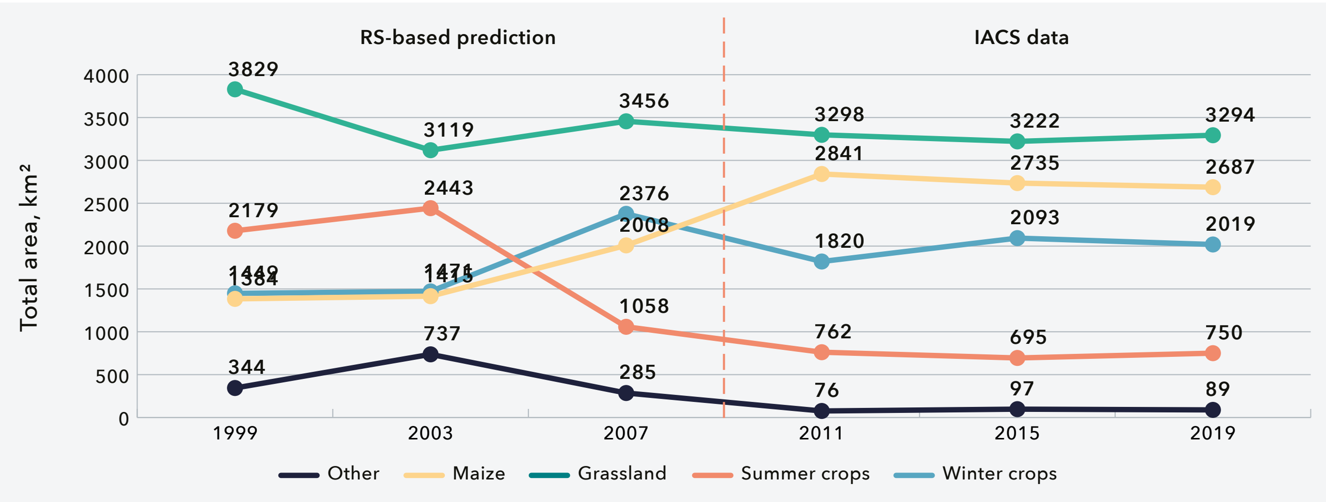


Figure 5.9 Agricultural land cover changes in Weser-Ems (1999–2019)



Note: Values for years 1999–2007 were predicted based on remote sensing, while the values for years 2011–2019 were obtained based on IACS (Integrated Administration and Control System) data.

can be used to **develop long-term bioeconomy related monitoring systems**.

To assess the potential impact of biogas, the land cover changes were further linked to the number and the installed capacities of biogas plants in the region. The assessment was done in six time points — in the years 1999, 2003, 2007, 2011, 2015 and 2019.

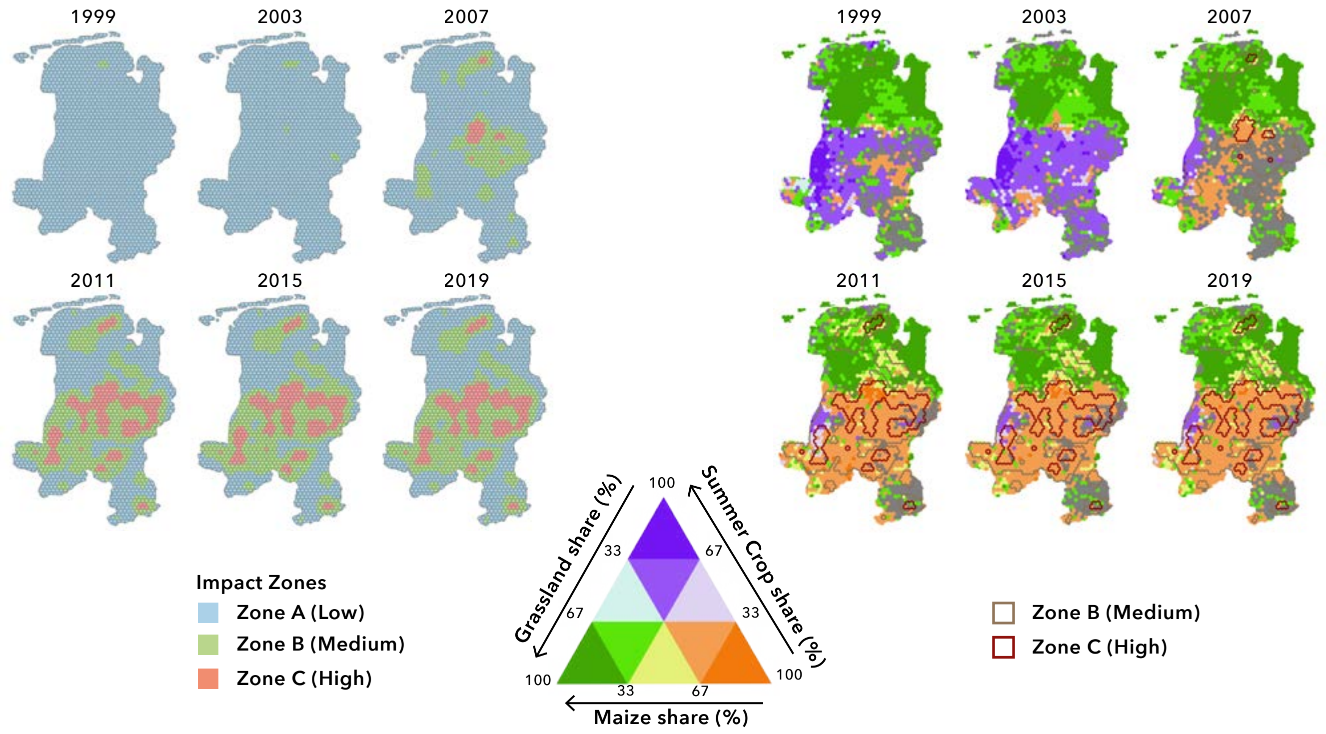
Agricultural land cover changes in Weser-Ems, 1999–2019

Spatial and temporal agricultural land cover changes in the Weser-Ems region indicated a **significant increase in maize cultivation areas after the year 2003** (Figure 5.9). This development is in line with the EEG 2004 and 2007 amendments increasingly supporting biogas generation from energy crops.

Expansion of maize cultivation areas reduced the area of other summer crops in the southern part and grassland areas in the northern part of the region. Between 1999 and 2019, the **area of maize cultivation increased by 94 %** (from 1384 km² to 2687 km²), while the areas of other summer crops and grasslands decreased by 66 % and 14 % respectively. The major land cover change occurred in the areas that overlap with the high and medium biogas capacity kernel density impact zones (Zones B and C in Figure 5.10). This is an indication of a **direct relationship between biogas production development and agricultural land cover change**.

The results of this study are generally in line with the trends reported in other studies concerning biogas development as a driver of agricultural land cover and landscape changes in different regions of Germany

Figure 5.10 Temporal and spatial biogas capacity kernel density distribution (a) and crop share distribution in Weser-Ems region (b)



Note: ESS = ecosystem services; LULUCF = land use, land use change, and forestry

(Csikos et al. 2019, Kyere et al. 2021, Lüker-Jans, et al. 2017, Vergara et al. 2019). The advantage of the remote sensing based analysis applied in this study is that, once the models are developed and validated and automated workflows are established, the model can be applied without the need for further extensive collection of data. This is an important prerequisite for the establishment of a **functional and cost-efficient monitoring system**. Although the level of detail is limited by the spatial and temporal resolution of the available satellite images, the approach still provides a first good indication for monitoring and quantifying landscape change induced by biogas production and can serve as information for future policy intervention planning.

Furthermore, previous studies emphasised the **importance of regional level assessments**. Due to the regional heterogeneity caused by spatial characteristics, e.g., topographic, soil, climatic, and other social-economic variations, the EEG's impact on different regions in Germany contained large discrepancies (Yang et al. 2021) and the extent of the agricultural land cover change on regional and local scales presented high variations. Therefore, the strategies of substituting maize silage for other crops or alternative feedstocks needs to be adapted for strategies which consider the crop mixtures fed into biogas plants and how they perform altogether under the specific regional and locational conditions (O'Keeffe and Thrän 2020), considering their GHG emission mitigation potentials (O'Keeffe et al. 2019).

Key messages:

- There is a scientific consensus that starting from the early 2000s, **the area of maize silage in Germany has increased, and this increase was strongly linked and correlated to biogas production** development.
- Remote sensing data can be successfully applied to overcome the lack of high quality, spatially explicit historical land use data and to quantify landscape level changes induced by, e.g., biogas production.
- Methods to account for and monitor **regional heterogeneity,** as presented in this case study, can help support targeted policy intervention options at the regional and local scales.

5.2 Global resources and their impacts

Why the global perspective matters

A semi-automatic approach was developed to quantify the extent of deforestation driven by crops in global hotspot regions, referring to regions around the world that are experiencing significant levels of deforestation due to the cultivation of a crop. Monitoring crop-driven deforestation hotspots is useful in facilitating an understanding of the implications of the German bioeconomy on global resources using remote sensing technology.

5.2.1 Crop-driven deforestation in Indonesia and Brazil

Oil palm-driven deforestation in Indonesia and Malaysia

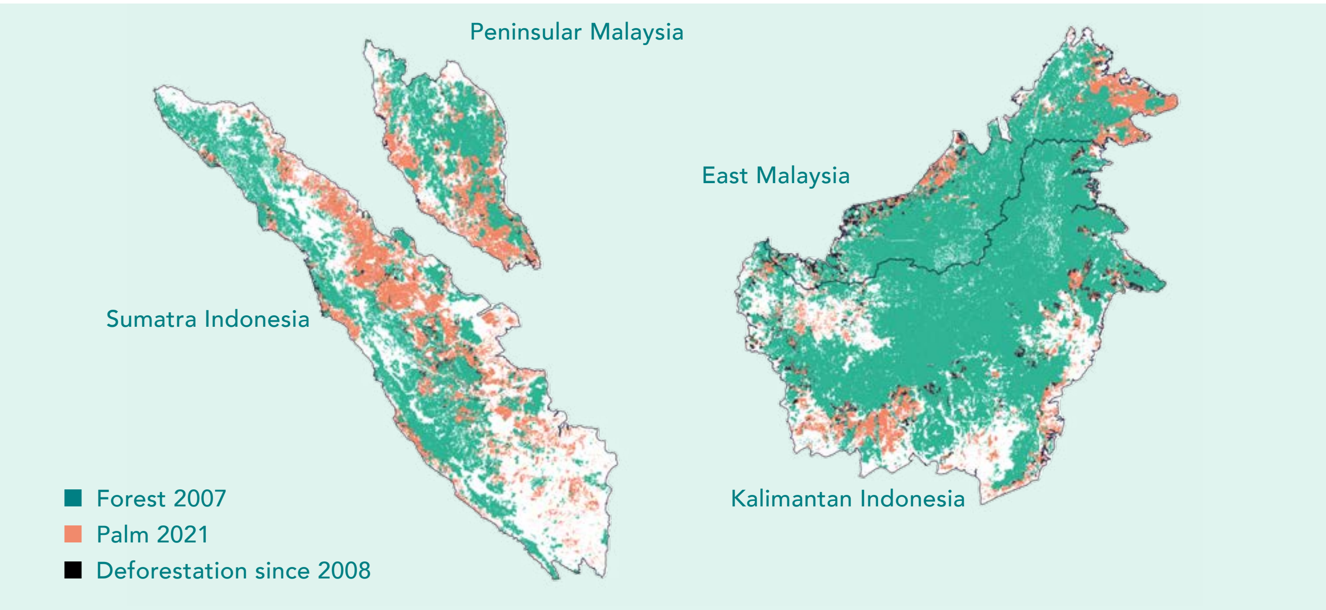
Indonesia (60 %) and Malaysia (24 %) produced over 83 % of the world's palm oil in 2022/2023 (USDA 2024). It has long been proven that part of the expansion of oil palm plantations in both countries has taken place within areas of high carbon stock[32]. We mapped the expansion of palm trees into forested high carbon stock areas during 2008–2021 in the main palm regions in Indonesia and Malaysia, namely: Borneo, Sumatra and Peninsular Malaysia.

Oil palm plantations were mapped following and adapting a methodology developed by Descals et al. (2021). A convolutional neural network[33] was trained on optical and radar satellite imagery (Sentinel-1 and Sentinel-2) and ground truth data was used to map the annual extent of oil palm plantations in Indonesia and Malaysia. The ground truth data are reference images showing the precise extent of oil palm plantations in certain regions.

The study area includes the sub-regions of Peninsular Malaysia, East Malaysia, and the Indonesian regions of Sumatra and Kalimantan. To determine the total extent of oil palm, oil palm areas were mapped on an annual basis from 2015 to 2021. The individual maps created by GRAS were integrated to create a consolidated oil palm map, forming the basis for a thorough assessment of deforestation attributable to oil palm cultivation (Figure 5.11).

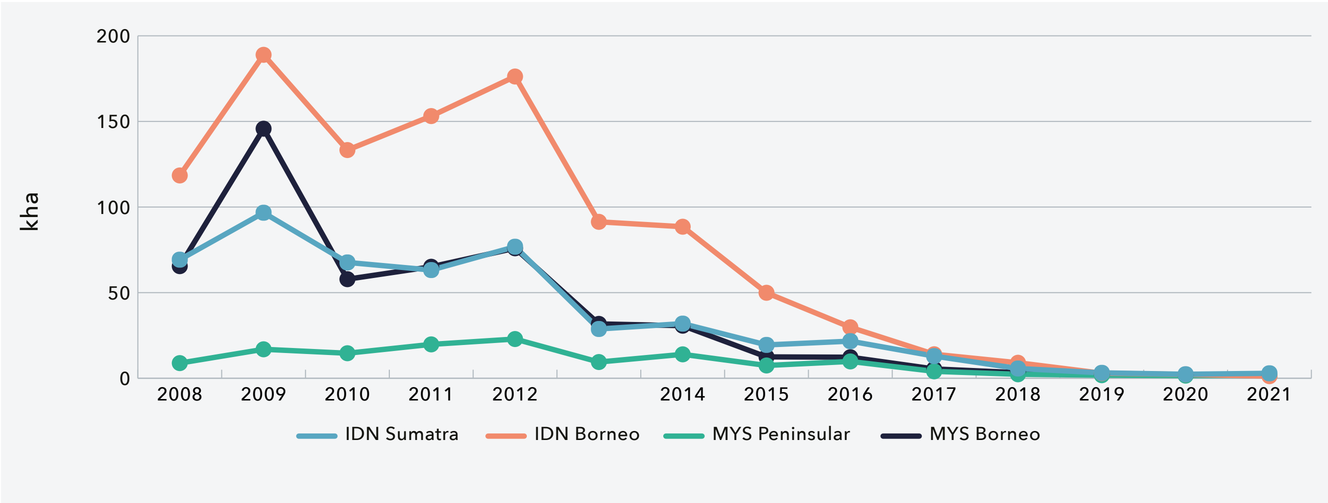
The impact of oil palm expansion into the forest of Indonesia and Malaysia reveals significant patterns (Figure 5.12). Within the observation period, Borneo experienced the strongest effects during the years 2008–2012. Notably, the **deforestation peaks (2009 and 2012) align with periods of high palm oil prices**, such as in 2008 and 2011 (World Bank 2024). This finding is also confirmed by the research of Gaveau et al. (2022) calculating a positive correlation between annual crude palm oil (CPO) prices and the expansion of oil palm plantations.

Figure 5.11 Overview map of forest, palm, and deforestation distribution in the regions of Indonesia and Malaysia



32 High carbon stock are areas with significant amounts of carbon stored in vegetation and soils
33 Artificial neural network used in machine learning tasks for image recognition

Figure 5.12 Annual palm-driven deforestation per region from 2008–2021 in Indonesia and Malaysia



Source: produced by GRAS

Post-2012 data indicates a declining deforestation trend, converging toward a minimum deforestation rate between 1,224 and 2,910 hectares per subregion in 2021. However, the correlation between palm oil prices and deforestation was only noticeable until 2016, when oil prices increased slightly without causing increasing deforestation rates. **Policy measures, such as the forest moratorium implemented in 2011, contributed to a reduction in deforestation activities**, similar to the palm oil moratorium that was in place from 2018 to 2021. After 2019, palm oil prices increased following the implementation of the permanent forest moratorium, peaking in 2022. A subsequent decline occurred in 2023. Continued monitoring is essential to assess these market dynamics and policies and their implications on deforestation.

In addition, this analysis also highlights the capabilities and limitations of mapping oil palm plantations using remote sensing techniques. Detecting small-holder plantations and young palm stands (less than 3 years old) remains challenging due to the sparse distribution of oil palms in Sentinel-2 image pixels with a spatial resolution of 10 meters (Descals et al. 2019). Due to this, and the growth stages of palm trees, continuous monitoring is required to make accurate statements about recent palm oil expansions.

Soybean and sugarcane-driven deforestation in Brazil

According to studies that focused on soybean and sugarcane-driven deforestation, the deforested areas follow a distinct timeline for crop cultivation. Zalles et al. (2019) found that 79 % of soy cropland expansion occurred on previously utilised pasture lands, while approximately 20 % was attributed to the conversion of natural vegetation. Many studies also suggest that deforested land remains fallow for a few years, transitions into pasture for another few years, and is eventually utilised for soy cultivation (Brown et al. 2005, Morton et al. 2006, Song et al. 2021, Zalles et al. 2019). Hence, defining an analysis period that establishes a specific cut-off date for crop-driven deforestation assessments was necessary. We conducted assessments on deforestation driven by soybean and sugarcane in Brazil for the period between 2008 and 2021. The extent of deforestation driven by soybean and sugarcane was evaluated by employing aggregated maps (2008–2021) produced by MapBiomas Brazil (Souza et al. 2020), in conjunction with tree loss data from Hansen et al. (2013) that were confined to the forest area in 2007.

Soybean

We quantified the deforestation driven by soybean from 2008 to 2021 measured in thousand hectares (ha) for Brazil. Overall, the trend shows a **peak in 2012**, followed by a general decline with minor fluctuations, leading to very low levels from 2018 onwards (Figure 5.13). Soybean-driven deforestation remains very low at 4 thousand ha per year in 2020 and 2021, but this **recent deforestation may not give a clear picture due to the complexity of delayed land use transition**, as cattle ranching may occur after immediate deforestation and then soybean cultivation follows after a certain duration (Morton et al. 2006, Song et al. 2021).

This trend aligns with the broader context of soybean-driven deforestation in Brazil. The significant peak in

Figure 5.13 Soybean-driven deforestation in thousand hectares (kha) in Brazil between 2008 to 2021

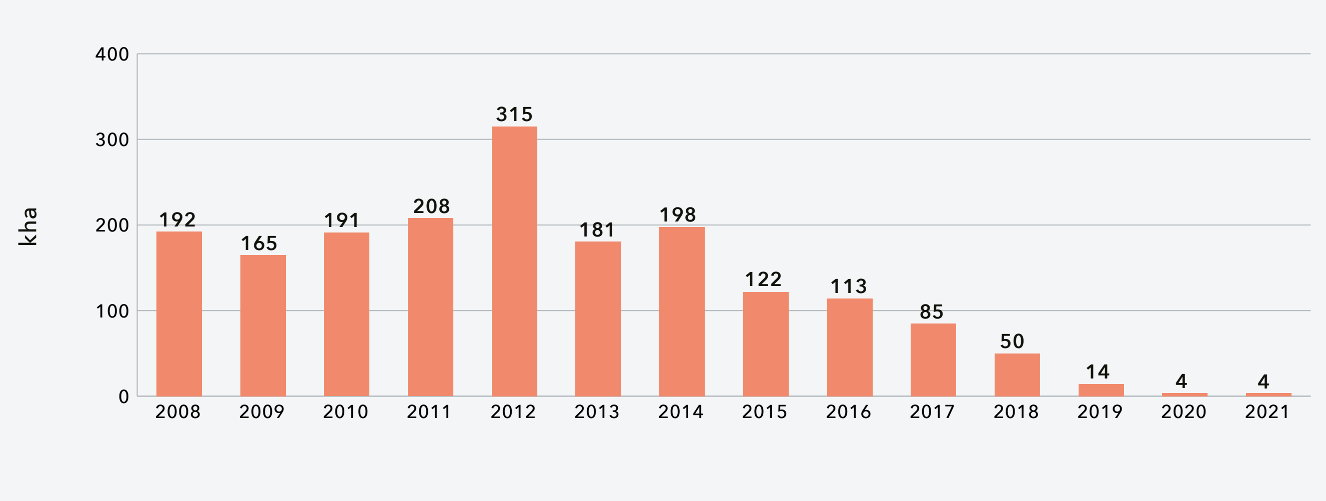


Figure 5.14 Spatial distribution of soybean extent (shown yellow in A and B) and soybean-driven deforestation over time (shown by blue to red colour range in C)

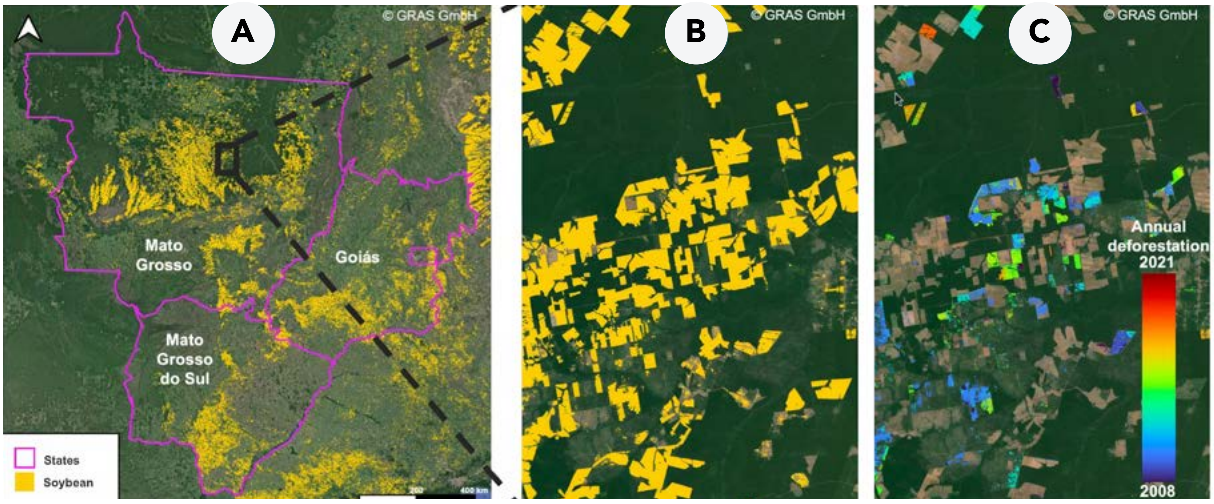


Figure 5.15 Sugarcane-driven deforestation in thousand hectares (kha) in Brazil between 2008 to 2021

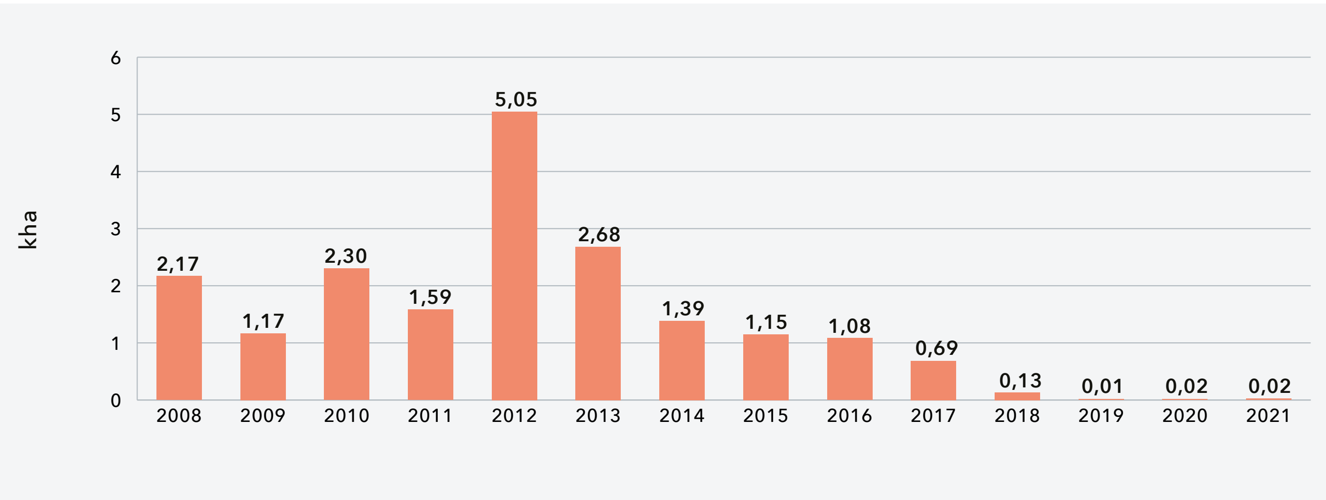
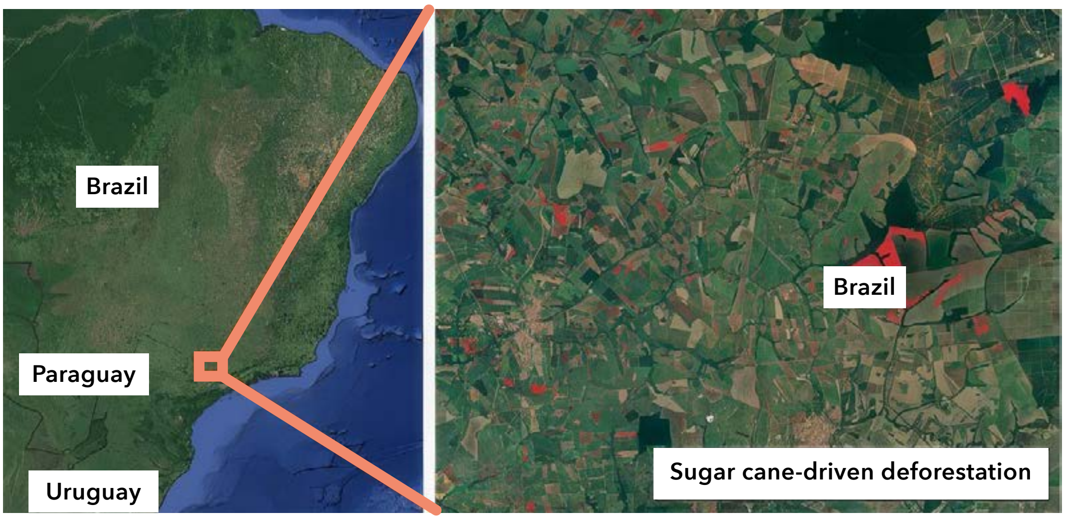


Figure 5.16 Spatial distribution of sugarcane-driven deforestation in Brazil



2012 can be linked to global market dynamics and rising demand for soybeans, as discussed by Nepstad et al. (2014), who highlight how global commodity prices and demand spikes can drive rapid land-use changes. The subsequent decline in deforestation rates aligns with the implementation of policies and agreements aimed at curbing deforestation. For instance, the **Soy Moratorium**, an agreement established in 2006, prohibited the sale of soybeans grown on land deforested in the Amazon after that year (Song et al. 2021, Rudorff et al. 2011). Implementing a soy deforestation monitoring system would facilitate quantifying the extent of deforestation and tracking the extent and spatial distribution of the likely impacts of soybean cultivation (Figure 5.14).

Sugarcane

In Brazil, sugarcane ethanol represents the primary biofuel, and the expansion of sugarcane production is considered another driver of deforestation (Hernandes et al. 2021). We quantified the deforestation driven by sugarcane from 2008 to 2021 using satellite-derived datasets. Overall, the trend shows a **significant decrease in sugarcane-driven deforestation in Brazil from 2008 to 2021**, with a notable peak in 2012 (Figure 5.15).

The pattern observed in the data is consistent with existing research on the impact of agricultural expansion on deforestation in Brazil. Studies such as Gibbs et al. (2015) highlight that the expansion of agricultural commodities, including sugarcane, has significantly contributed to deforestation in tropical regions. The peak in deforestation around 2012 could be attributed to the increased demand for ethanol, a biofuel derived from sugarcane, as noted by Macedo et al. (2008). The subsequent decline in deforestation rates is likely due to the implementation of stricter environmental regulations and improved land use practices as highlighted by Assunção et al. (2015). The spatial distribution of the sugarcane-driven deforestation in Brazil was mapped, which can help identify the highest hotspot states of Brazil (Figure 5.16).

Key messages

- Quantifying the extent to which crop production contributes to global deforestation provides valuable context for understanding the role of the German bioeconomy within broader global trends. This insight helps to assess the associated risks and reveals how consumption patterns influence deforestation rates based on the sourcing of specific crops.
- Remote sensing offers a significant advantage by delivering near real-time, up-to-date data on deforestation, surpassing conventional statistical methods in tracking changes in natural resources and environmental impacts.
- By monitoring deforestation hotspots with remote sensing technology, we can better understand the wider implications that changes in global demand have on specific locations. This provides insights into how shifts in consumption and trade patterns influence deforestation rates in particular regions, enabling more targeted and effective responses.

5.2.2 High value nature areas in Brazil

Presence of HCV in Brazil

This section looks at how crop-driven deforestation specifically threatens High Conservation Values (HCV), which denote richness in biodiversity, critical ecosystem services, or valuable cultural importance. A methodology based on the HCV screening approach by Watson et al. (2019) was adapted, implementing available georeferenced datasets, remote sensing technologies, and secondary sources to identify the probability of HCV presence for multiple landscapes in Brazil. This approach covers larger scales with diverse land cover, ecosystems, or culture types providing a framework for large-scale conservation efforts and guiding local site-level HCV assessments.

WHAT IS HCV?

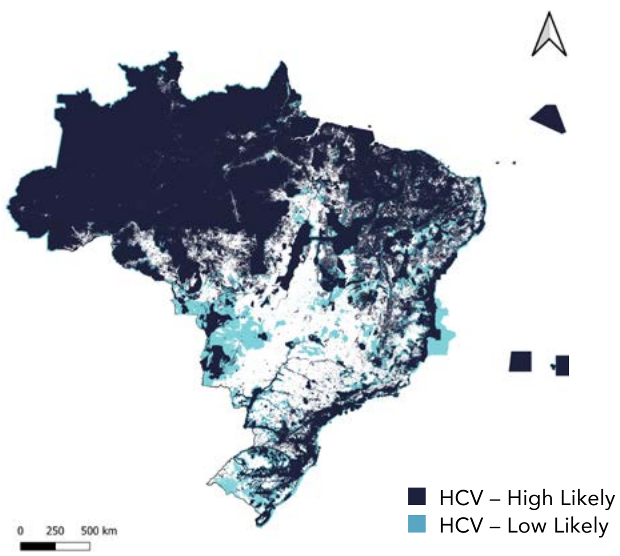
The Forest Stewardship Council (FSC) defines High Conservation Values (HCV) as environmental, social, and cultural values of outstanding significance or critical importance. This approach is widely recognised and commonly used in environmental conservation and sustainability land management. The HCV consists of 6 categories focusing on different aspects of conservation:

HCV 1 – Species Diversity
HCV 2 – Landscape-level Ecosystem
HCV 3 – Ecosystem and habitats
HCV 4 – Ecosystem Services
HCV 5 – Community Needs
HCV 6 – Cultural Values

The analysis utilised a comprehensive collection of national and international datasets, including land use and land cover (LULC), conservation units, protected areas, biodiversity, water bodies, elevation, slope, social variables, etc. **Over 90 datasets were gathered, screened, and analysed** to select the most suitable ones for assessing High Conservation Values (HCVs) across Brazil at a national scale. These datasets were categorised into the relevant HCV categories, reflected in twelve indicators for HCV1 and HCV2, eight for HCV3 and HCV4, five for HCV5, and seven for HCV6, with some indicators applicable to multiple categories.

Each indicator was further classified by its probability of presence, distinguishing between high likelihood (likely and very likely) and low likelihood (low likely). Some datasets were directly usable as indicators, while others required geoprocessing techniques to classify them into the probability of HCV presence. The resulting map (Figure 5.17) illustrates the compiled areas of high and low HCV presence across Brazil. Specific examples include HCV1 areas for species diversity (e.g., migratory bird concentrations, key biodiversity areas), HCV2 for landscape-level ecosystems (e.g., RAMSAR sites, intact forest landscapes), HCV3 for ecosystems and habitats (e.g., key biodiversity areas, important bird areas), HCV4 for ecosystem services (e.g., slopes, hydrography), HCV5 for community needs (e.g., indigenous lands, world heritage sites), and HCV6 for cultural values (e.g., archaeological sites, world heritage sites).

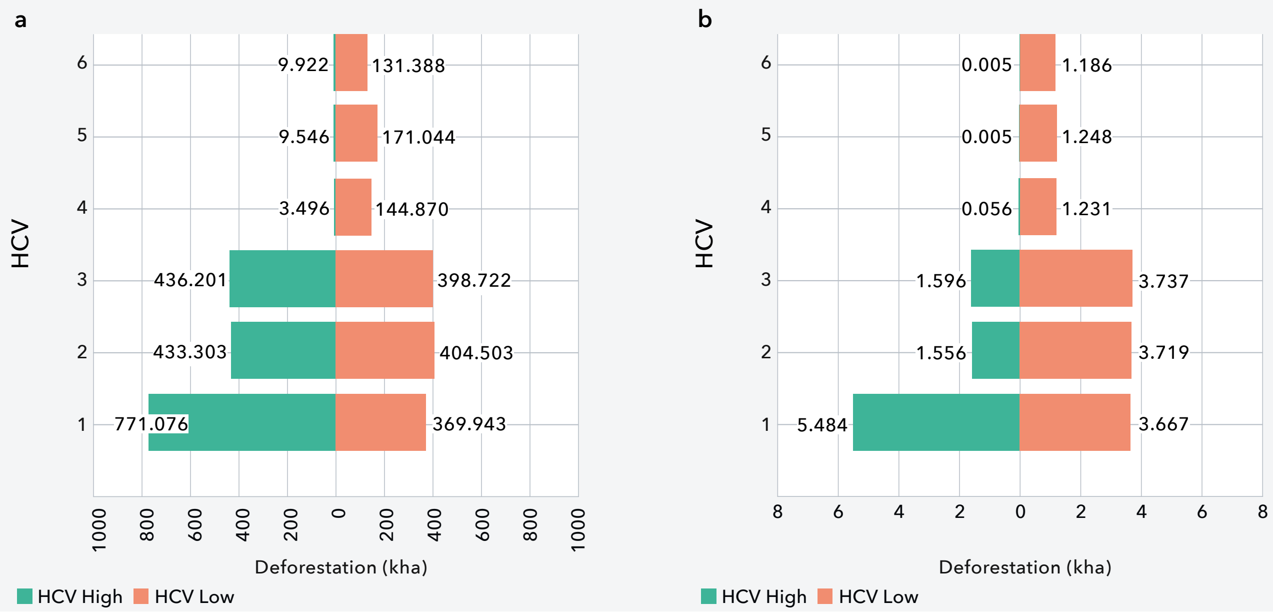
Figure 5.17 Compiled high and low likelihood presence of HCV 1-6



Potential impact of crop-driven deforestation on HCV areas in Brazil

The impact of crop-driven deforestation in HCV areas is identified by implementing the results obtained from remote sensing and geospatial data to map deforestation patterns since 2008 and overlap them with HCV presence. The spatial analysis and overlapping of the crop-driven deforestation with areas of high and low presence of HCV reveal the extent and distribution of this threat. Focusing specifically on soybean and sugarcane-driven deforestation provides direct links to specific agricultural practices, like soybean and sugarcane expansion, to the degradation of HCV areas. By this

Figure 5.18 Soybean and sugarcane-driven deforestation impact on high and low HCV



link, the insights into **how these crops are affecting biodiversity, ecosystems, and critical environmental services can be targeted.**

Since 2008, crop-driven deforestation in Brazil, particularly from soybean and sugarcane cultivation, has impacted High Conservation Value (HCV) areas. **For soybean and sugarcane-driven deforestation, substantial overlap has been identified mainly in HCV 1, 2, and 3,** whereas HCV 4, 5, and 6 show a lower impact from deforestation, although they are not exempt from the pressures of agricultural expansion (Figure 5.18).

HCV1 and HCV3 areas undergo habitat loss and fragmentation due to agricultural expansion, threatening species survival and disrupting ecological networks. For HCV2 areas **deforestation results in large landscape-level ecosystems being fragmented**. For example, the Cerrado biome has experienced a rapid conversion of its landscape to soybean plantations threatening endemic species, ecosystem functions, and resilience (Zu Ermgassen et al. 2020, Green et al. 2019). HCV4–6, results show a lower impact coming from crop-driven deforestation, which could partly be due to limited data availability, and which may not fully represent the extent of the impact. Despite this, deforestation still threatens vital ecosystem services such as water cycle regulation and erosion control, and it compromises the livelihoods and cultural practices of local communities and Indigenous peoples.

Figure 5.18 shows the impact of deforestation driven by soybeans and sugarcane on High Conservation Values (HCVs), with high-likelihood areas marked by green bars and low-likelihood areas marked by orange bars. The results indicate that **both soybean and sugarcane deforestation have the greatest impact on areas with a high likelihood of HCV 1–3**, while the impact on areas with a low likelihood of HCV 4–6 is less severe. Additionally, the findings reveal that soybean-driven deforestation exerts a higher pressure on environmental values compared to sugarcane.

Key messages

- Identifying and managing HCVs are key for maintaining ecological balance, protecting biodiversity, and supporting the well-being of local communities and Indigenous peoples.
- The results indicate which HCVs are most affected by the two types of crop-driven deforestation. Determining the extent of deforestation within these areas provides data-based information to prioritise targeted conservation actions to mitigate the impact on environmental and cultural values.
- Prioritisation of conservation efforts is urgent in areas where deforestation overlaps most intensely with high HCVs, requiring immediate action to mitigate these threats and preserve Brazil's critical conservation values amidst ongoing environmental pressures.

MONITORING CHECK BOX 7:

A semi-automated remote sensing tool to monitor crop-driven deforestation

The GRAS approach of monitoring crop-driven deforestation has been shown to be applicable to palm, soybean, and sugarcane production regions. In this way, the monitoring of the bioeconomy can be extended to the earliest stages of the supply chain, namely the production of biomass at the farm or plantation level. Subsequently, GRAS developed a semi-automated system (SAS) based on a case study of palm-driven deforestation in Indonesia and Malaysia from 2008 to 2021, and a separate assessment of soybean- and sugarcane-driven deforestation in Brazil over the same period. The SAS employs remote sensing mapping techniques and satellite-derived map datasets as inputs, to furnish a crop-specific historical account of deforestation in a given region or a country (Figure 5.19).

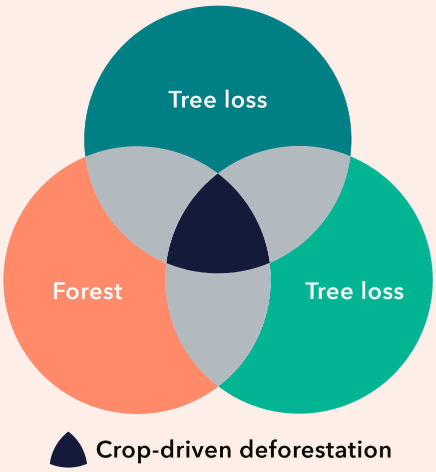


Figure 5.19 Blueprint of a semi-automated remote sensing system (SAS) for the assessment of crop-driven deforestation

The SAS developed by GRAS can be **replicated as a definitive tool** for detecting crop-driven deforestation. This system overlays a temporal aggregation of crop expansion and tree loss layers with a forest basemap, using semi-automatically derived inputs from satellite imagery. The system's key features enable the precise tracking of crop-driven deforestation for specific crops and regions, providing data-based facts and figures over time.

The main functionality provides data to policy makers and stakeholders, which helps them to **make informed decisions** and understand the impacts of certain crops on the quantity of deforestation. In the future, the results of the SAS could be employed as inputs to determine the contribution of the German bioeconomy to crop-driven deforestation. Operationalising the data as part of an interactive web application could also help to raise awareness and provide continuous and regularly updated data to help guide decisions about sustainable supply chains.

5.2.3 Tracing wood products[34]

Where does the wood come from and what are the associated sustainability effects?

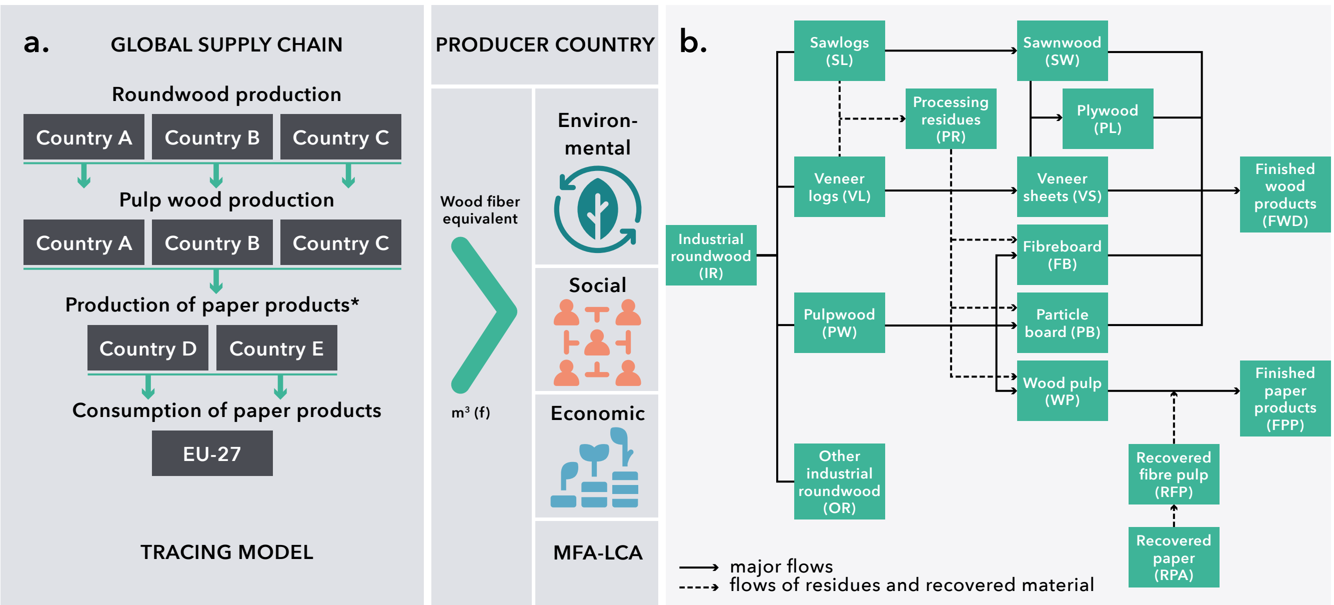
In a globalised bioeconomy, wood is traded along complex supply chains and over large distances. Thus, it is often imported via third countries. Especially for those products, production and consumption are spatially disconnected. To better monitor the foreign impacts of production associated with the German bioeconomy, a novel approach combining a physical accounting model with a material flow life-cycle assessment approach was developed and used to trace the locations of origin of specific wood flows and their associated sustainability effects.

Tracing model

The approach is depicted in Figure 5.20. The tracing model is used to trace the wood origin contained in finished paper products consumed in the EU in 2018, considering the current EU-27 Member States (i.e., without the UK). The material flow analysis and life cycle assessment approach were used to assess the sustainability impacts in the producer countries. Uruguay, as one of the main suppliers of wood consumed in finished paper products in the EU and in Germany, is used as a case study to assess associated sustainability effects.

The tracing model is based on a new mathematical model that links the consumption of finished wood and paper products in a country with the location of origin of the roundwood. All calculations were carried out for the year 2018. The data are mainly from publicly available international databases (FAOSTAT and UN Comtrade). For the modelling of the wood flow, a total of 16 different product categories (such as sawnwood, fibreboard, particleboard, wood pulp, processing residues, recovered paper, etc.) were considered (Figure 5.20 b). The different units given in the statistics (e.g. m^3, t) were converted into the common unit cubic metre fibre equivalent (m^3 (f)) using conversions values from Bösch et al. (2023). The data are used to establish an interconnected series of production-consumption links between countries at various processing levels, i.e. roundwood, semi-finished and finished wood-based products. The main results of the modelling approach are detailed

Figure 5.20 Methodological approach of the wood tracing model* (a) and (b) Industrial roundwood and derived products in the global forest-based sector as implemented in the tracing model

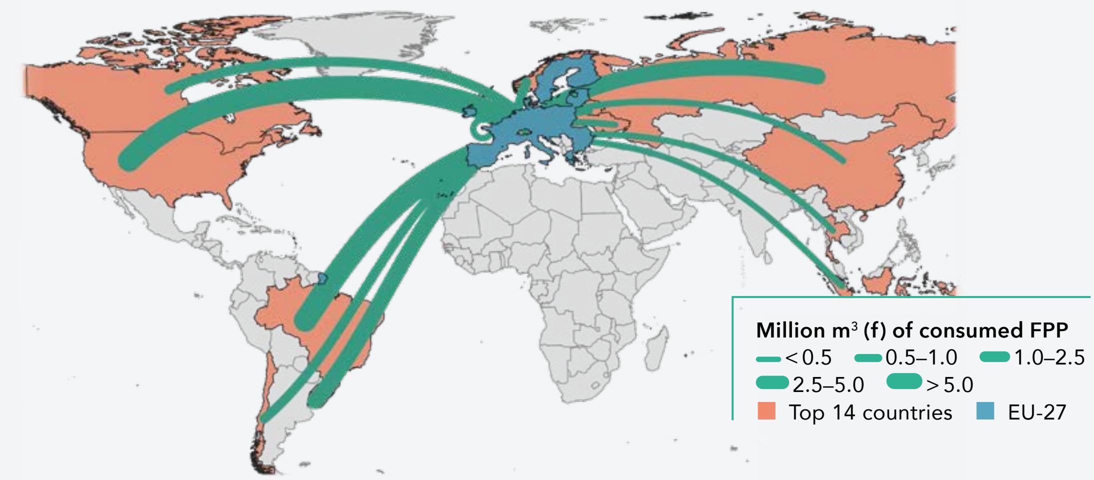


Note: a) *Production of paper products might take place also in one of countries A-C. The functional unit is cubic metre fibre equivalent m^3(f) (as in Section 6.3)

Source: Pozo et al. 2024 and Bösch et al. 2023.

34 More information on the physical accounting model can be found in Bösch et al. (2023) and the combined novel methodological approach in Pozo et al. (2024)

Figure 5.21 Global distribution of international wood origin contained in finished paper products in the EU



Note: Top 14 most important countries exporting to the EU. Arrowheads represent the countries of origin; the width of the lines are proportional to wood quantities. FFP refers to finished paper products.

Source: Pozo et al. (2024)

country-by-country matrices indicating the locations of origin of the products consumed in a given nation.

Material Flow–Life Cycle Assessment Approach

Sustainability impacts are quantified for wood production in Uruguay. The material flow analysis and life cycle assessment approach assess the total amount of biomass produced, used and recycled in any value chain or even a national economy, as well as the associated sustainability impacts. Hence, it enhances the resolution at the supply chain level and captures how much each step contributes to sustainability and where the opportunities are to improve it. The production data of *Eucalyptus* pulp were obtained from the Uruguayan production statistics. In order to calculate the sustainability impacts in relation to the results of the tracing model, the reporting units of production statistics were converted into cubic meters of wood fibre equivalent (m^3 (f)). Then, national statistics, empirical studies and experts' consultations were used to quantify the sustainability impacts within Uruguay in relation to the functional unit, i.e., value added per m^3 (f). GHG emissions and carbon sequestration were analysed according to LCA estimates of Schulte et al. (2021). Employment was quantified as the number of persons employed in the different steps of the supply chain (roundwood production, pulping and transport) in the full-time equivalent using official data from the General Directorate for Forestry in Uruguay, cross-checked and complemented with estimations of Exante 2020. Value added expressed in US dollars was calculated based on the estimations of Exante 2020 and national accounts of the Central Bank of Uruguay (BCU). The consumption impacts of finished paper products linked to the EU's demand were quantified by multiplying the physical values of the sustainability impacts in Uruguay, for instance, employment generated per m^3(f), with the quantity values of wood originated in Uruguay and exported to the EU Member States from the physical account.

Results

Wood origin in finished paper products

In 2018, 112.8 million m^3 (f) of wood contained in finished paper products (which includes e.g. books, newspapers, magazines) were consumed in the EU-27, 65 % of which originated domestically (i.e. from within the EU) and 35 % originated from other countries. Germany (26 %), Sweden (12 %) and France (12 %) are the main consumer countries in this respect. Moreover, Germany (27 %), Italy (15 %) and France (15 %) are the largest consumers of imported wood in finished paper products.

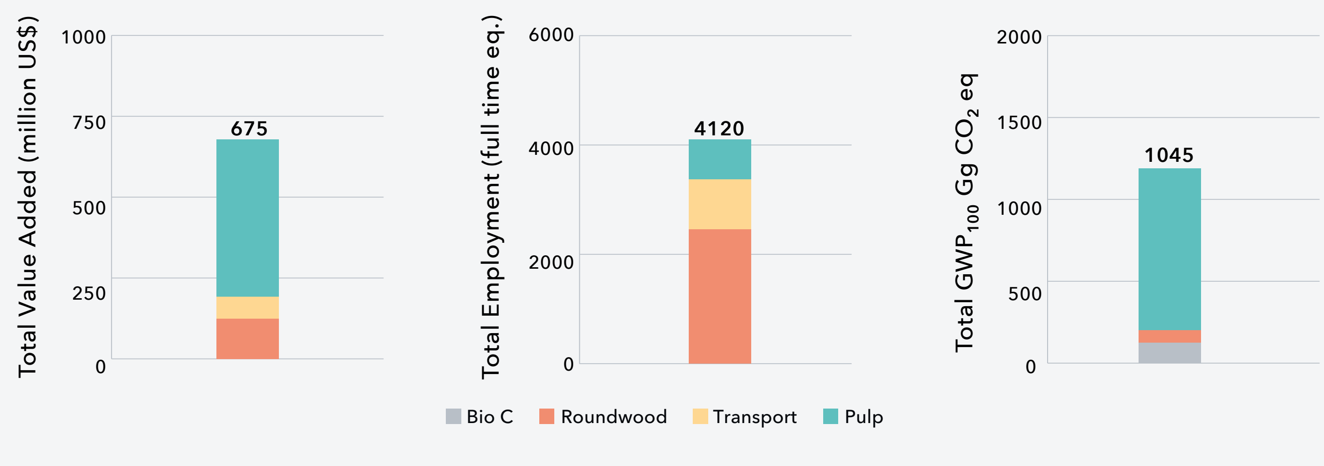
Top suppliers outside the EU

The most important countries of origin outside the EU were the USA (11 %), Brazil (10 %), Uruguay (4 %) and Russia (3.5 %). Figure 5.21 illustrates the global distribution of wood origin contained in the consumed finished paper products within the EU.

Associated sustainability effects

EU countries with the highest consumption of Uruguayan wood contained in finished paper products

Figure 5.22 Related socio-economic and environmental impacts in Uruguay linked to EU demand (value added, employment and global warming potential (GWP100))



Note: Bio C: Biogenic carbon (carbon stored in above-ground and below-ground biomass, soil organic carbon)

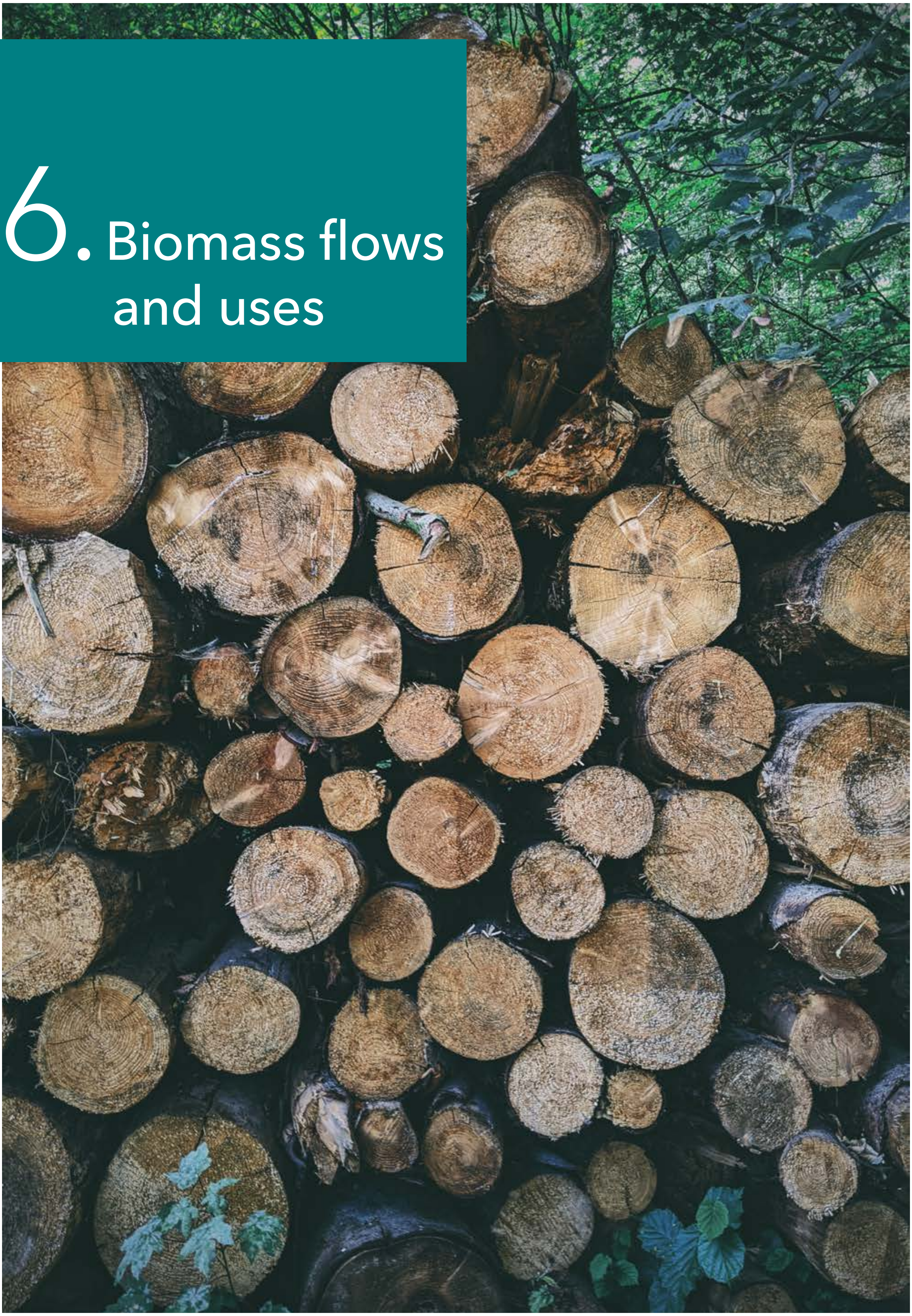
Source: Pozo et al. (2024)

include Germany (28 %), Italy (15 %) and the Netherlands (13 %). To illustrate the potential socio-economic and environmental impacts of EU consumption of finished paper products, this case study looked at connected employment and value-added generation in Uruguay, as well as the trade-offs with land use change and Global Warming Potential (GWP_{100}). Figure 5.22 shows that the total value-added generated in Uruguay related to the exports to the EU in 2018 accounted to around $ 175 billion. The pulping process accounted for 72 % of the total value added; it was three times the value of roundwood production and transport (which accounted for 28 % of the total). The total employment generated linked to the export to the EU accounted for around 4,120 people in full time equivalents. Contrary to the value added generated, the production of roundwood and transport contributed 82 % of the total employment effect, while processing into pulp accounted for 18 %. The total global warming potential (GWP_{100}) and carbon sequestration related to exports to the EU for 2018 were analysed. GHG emissions generated in the production of roundwood are minor (9 %) compared to the industrial phase, which represents 91 % of total emissions, dominated by the operations and energy requirements within the pulp mill.

Key messages

- The presented hybrid approach allows German bioeconomy monitoring to trace the wood used in imported bio-based products to the site of origin and to quantify sustainability impacts. As such, it can improve the level of detail as regards wood origin and sustainability effects.
- Data gaps, uncertainty and lack of harmonisation regarding trade data and conversion factors remain key challenges to further improve results. Despite recent advances, the lack of disaggregated data at the supply chain level, especially in environmental statistics, remains a main shortcoming. Future work should cover additional commodities and geographical contexts, additional stages along the global supply chain (e.g., post-use) and other sustainability indicators (e.g., biodiversity and water use).
- The results highlight that the German bioeconomy is a major consumer of finished paper products while relying heavily on imports of wood from other regions, particularly North and South American countries.
- Altogether, our case study shows that socio-economic and environmental impacts are not confined to national boundaries. Thus, the EU and German bioeconomy should be assessed not only territorially, but also from a global consumption perspective, with the potential impacts on distant ecosystems.

6. Biomass flows and uses



Authors: Section 6.1: Martin Banse[1], Simone Brüning[2], David Kilian[1] and Holger Weimar[3] | Section 6.2: David Kilian[1] | Section 6.3: Holger Weimar[3] | Section 6.4: Simone Brüning[2] and Johna Barrelet[2] | Section 6.5.1: Burkhard Wilske[4] and Karl-Friedrich Cyffka[4] | Section 6.5.2 and Monitoring Check 8: Johna Barrelet[2], Burkhard Wilske[4], David Kilian[1] and Karl-Friedrich Cyffka[4]

1 Thünen Institute of Market Analysis, 2 Thünen Institute of Sea Fisheries, 3 Thünen Institute of Forestry, 4 German Biomass Research Centre (DBFZ)

Key findings

- More than 182 million tonnes dry mass (t DM) of biomass were produced in Germany in 2020, with around 77 % stemming from agriculture. Around 83 million t DM were imported and 82 million t DM exported.
- Feed is the most important use of biomass (around 80 million t), followed by energy (nearly 71 million t), material use (around 35 million t) and food (21 million t, of which 7 million t is biomass from animal products).
- Recovered paper and recovered wood add an additional 40 % or 18 million t to the domestic production of forestry raw materials. Around 7 million t of agricultural residues were used for energy production and 6 million t for material use in 2020.
- In forestry, domestic removals increased significantly due to salvage fellings caused by drought and bark beetle infestations. 79 million cubic meters (m^3) wood fibre equivalent of roundwood were removed from German forests in 2020. Net trade also shifted as a result, with Germany becoming a net exporter (of 7 million m^3) in 2020, mainly due to changed trade of coniferous roundwood.
- Around 230,000 t of aquatic biomass were produced in Germany in 2020. Around 86 % stemmed from sea fisheries, 12 % was a result of aquaculture production and 2 % was from freshwater fisheries. Compared to 2015, German production saw a decline of 11 %. At the same time, domestic consumption increased by 11 %.
- Despite extensive fish processing activities, Germany is increasingly dependent on imports. Catch quotas are continuously falling and stagnation in aquaculture production can be observed. The self-sufficiency rate has dropped from over 40 % in the 1980s to 17–20 % today. The composition of imports also changed between 2020 and 2015, toward less imports of raw materials and increased volumes of finished products.
- Salmon was the most popular fish by consumers in Germany and it is almost exclusively imported. Detailed analysis of the material flows for salmon provided more precise information and helped identify gaps in the publicly available data to improve monitoring.
- The potential of secondary biomass (i.e. biogenic wastes, residues and by-products) for material and energetic use has slightly decreased rather than increased from 2015 to 2020.
- The 'technical potential' of total secondary biomass amounted to 91.7–128.9 million t of dry mass in 2020, of which 68–83 % were used. The largest share stems from municipal waste and sewage sludge (around 31 % of technical potential).
- There were 15.7–41.9 million t of mobilisable technical potential in 2020. Six biomasses — deciduous forest (7 %), cattle slurry (12 %), cereal straw (15 %), solid cattle manure (14 %), wood residues of coniferous forests (16 %) and of green waste (20 %) — contributed 84 % to the mean mobilisable potential.
- While circularity, cascading and efficiency concepts are at the core of political strategies for a sustainable bioeconomy, a broad variety of monitoring methods are still being tested and discussed in the scientific literature.

6.1 Total biomass use for food, feed, materials and energy [35]

Figure 6.1 shows the aggregated biomass flow for Germany in 2020. A distinction is made between the three sectors agriculture (yellow and orange), forestry (green) and fisheries (blue). Furthermore, a distinction is made between produced primary biomass and residues and recycled waste materials (shown in a lighter colour). The sectoral biomass flows are examined in more detail in the individual sections 6.2 (agricultural biomass), 6.3 (forestry biomass) and 6.4 (aquatic biomass).

Starting with domestic production, the processing of the biomass is mapped from top to bottom. Imports enter from the left; exports leave to the right. In the level '**supply raw materials'**, domestic production of primary biomass, imports of raw materials and recovered materials for reuse are aggregated. After subtraction of exports of raw materials, these quantities enter the first level of **processing**. The next level (one level down) is '**supply of processed materials (I)'**. This is fed from above by the supply from 1st processing and from the left by imports of processed materials. Between supply of processed materials (I) and (II), the agricultural supply of biomass to livestock is displayed. From '**supply of processed materials (II)'**, exports of processed materials flow to the right. Depending on the sector, these goods then flow into **final use,** which is divided into food, feed, material and energetic use. In addition, there are biomasses and residues of which the utilisation could not be clearly identified (unknown use). The material flows refer to pure biomass (dry mass, DM). Non-biomass shares contained in products (added during processing) are not taken into account in this diagram.

Domestic production

The results for 2020 show that **almost 182 million t DM were produced in agriculture, forestry, fisheries and aquaculture**. The largest source of domestic production is agriculture, with 140 million t DM. This includes the harvesting of arable crops and horticulture of 117 million t DM as derived from the official statistics of harvested produce and 23 million t DM of residues such as straw or grass cuttings from the maintenance of road verges or railway embankments. The domestic production of raw materials from forestry (42 million t DM) is made up of removals of roundwood from the forest. In addition, domestic supply of recovered paper (10 million t) and recovered wood (8 million t) play a significant role. 58 thousand t DM aquatic biomass result from sea fisheries, aquaculture and freshwater fisheries and include fish, crustaceans, molluscs, water snails, algae and other aquatic invertebrate.

Processing

Taking into account imports and exports of raw materials, around 220 million t went into processing. The biomass input of the forest biomass consists of 39 million t wood including bark and 19 million t recovered paper and wood waste, and the agricultural biomass consists of 129 million t raw materials and 30 million t residues including the above mentioned 23 million t residues and 7 million t of reused residues like digestate from biogas plants. This amount is increased by aquatic biomass of 60 thousand t raw materials and 4 thousand t residues. Further residues were produced during the processing.

Livestock

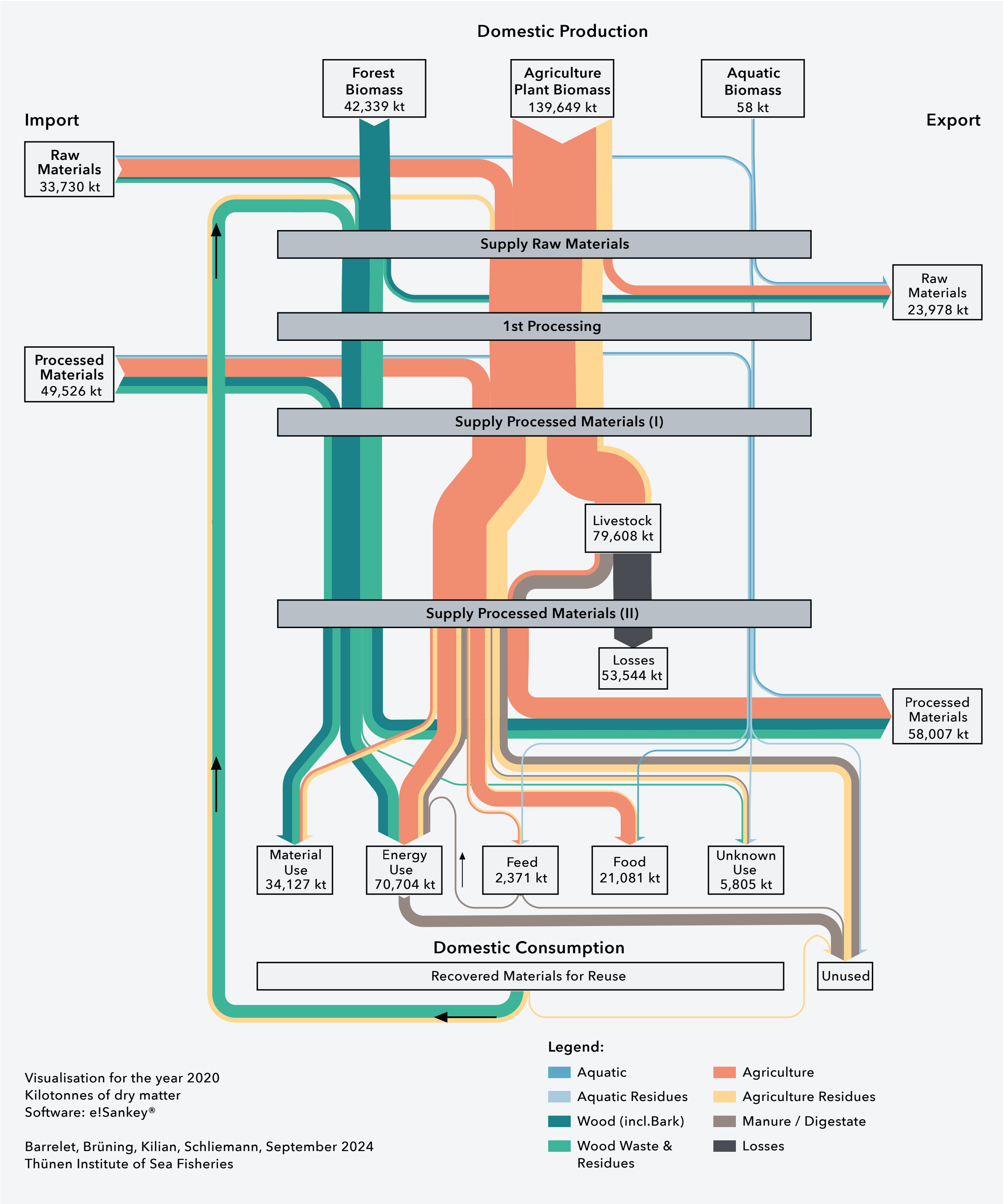
75 million t of plant biomass and 5 million t of residues were used in agricultural livestock farming. The output of agricultural livestock farming was **7 million t of animal products** and 19 million t of manure, which is shown in brown in the diagram as a residue. 8 million t of the manure were used, mainly to generate energy in biogas plants. The remainder, declared here as 'losses', includes biomass which remain in agriculture as fertiliser or occurs in the form of the body heat or other emissions of farm animals.

Imports and exports

Imports of raw and processed materials amounted to approximately 83 million t. This was set off by total exports of about 82 million t, resulting in **net imports of a little more than 1 million t**. In terms of total foreign trade quantities, agricultural biomasses also played the largest role. Wood raw materials and processed wood materials were imported and exported to a slightly lesser extent. However, in relative terms, the share of imports and exports in sectoral supply for the case of wood were considerably higher than for agricultural biomass. Biomass from fisheries and aquaculture is the least significant in terms of quantities of dry mass. In contrast to the other biomass sectors, considerably more aquatic biomass is imported than is produced

35 More information on the methods and results for calculating biomass flows can be found in the forthcoming Thünen Working paper summarising the results of the MoBi II project; See www.thuenen.de

Figure 6.1 Aggregated material flow of agricultural, forest and aquatic biomass in 2020 in thousand tonnes (kt)



Source: Thünen Institute

domestically. Further, looking at imports and exports of this biomass, the foreign trade balance is negative.

Domestic consumption

In terms of quantity, **feed is the most important use of biomass**. It should be pointed out that, at just under **80 million t**, almost four times as much agricultural biomass is used for feed as for **food** (**21 million t**, of which 7 million t is biomass from animal products). Biomass from fisheries and aquaculture is mainly used for food, while non-food utilisation (feed and material use) made up approximately 11 % of the overall domestic consumption. 1 % remains unutilised, which consists of biomass discarded at sea during fishing activity (production). To feed pets and horses around 2 million t of biomass were used, of which 0.4 million t were residues.

34 million t from agriculture, 7 million t of agricultural residues and 29 million t from forestry are used for **energy purposes (71 million t)**. Biogas production produced 17 million t of digestate, which, like the unused farm manure, remained in agriculture as fertiliser. While the **material use** of agricultural biomass is low compared to energy uses at 10 million t, with 6 million t comprising residues, it is most significant for forest biomass at 24 million t (totalling around **34 million t** of biomass used for material purposes in 2020).

Residues and recovered materials for re-use

Residues and recovered materials are included in Figure 6.1. For example, the domestic use of recovered waste paper accounts for 10 million t and recovered waste wood accounts for nearly 8 million t. Recovered paper and recovered waste wood are crucial sources of raw material in Germany and equate to nearly **one-third of the domestic production of wood raw materials.**

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

6.2 Agricultural biomass

What is agricultural biomass?

Agricultural biomass is the most important form of biomass use in terms of quantity. Agricultural biomass is very diverse and is used in all sectors. The great heterogeneity of agricultural biomass makes it challenging to compare individual material flows. **Agricultural biomass differs considerably** depending on

- the water content, ranging from very high (e.g. more than 90 % for many vegetables such as tomatoes, cucumbers, etc.) to low water content (such as for cereals and oilseeds with 14 % and 9 % respectively)
- whether it is produced on arable land or grassland
- the usability in general and whether it can be metabolised by monogastric animals and humans in particular.

In addition, agricultural biomass can be divided into different types of biomasses (Kaltschmitt et al. 2016):

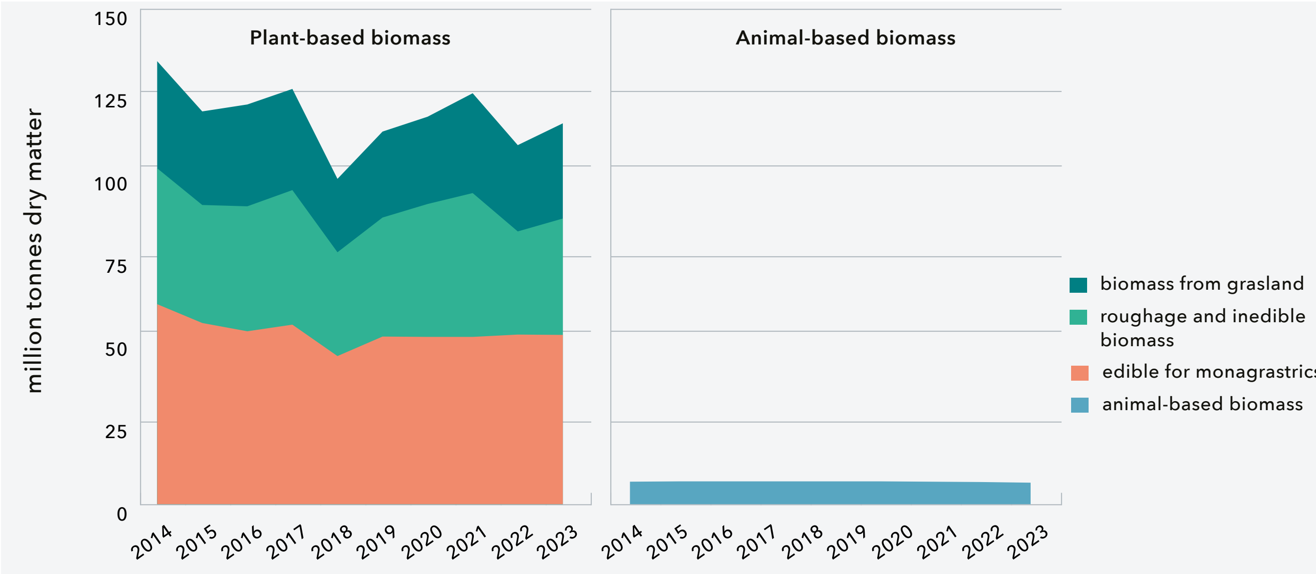
- **Plant-based biomass**: Biomass produced by photosynthesis from solar energy
- **Animal-based biomass**: Biomass produced by metabolism of plant-based biomass such as meat, eggs and milk
- **Processed biomass**: Processed and modified crop- and animal-based biomass (e.g. textiles).

To address these aspects, **all biomass flows are reported in dry matter** and categorised into plant-, animal-based and processed biomass. Plant-based biomass is further subdivided into biomass that can potentially be digested by monogastric animals and other biomass. Other biomass includes roughage that can only be digested by ruminants or hindgut fermenters and lignin-containing biomass that is inedible. A distinction is also made between roughage from grassland and roughage from arable land.

Trends in production and trade

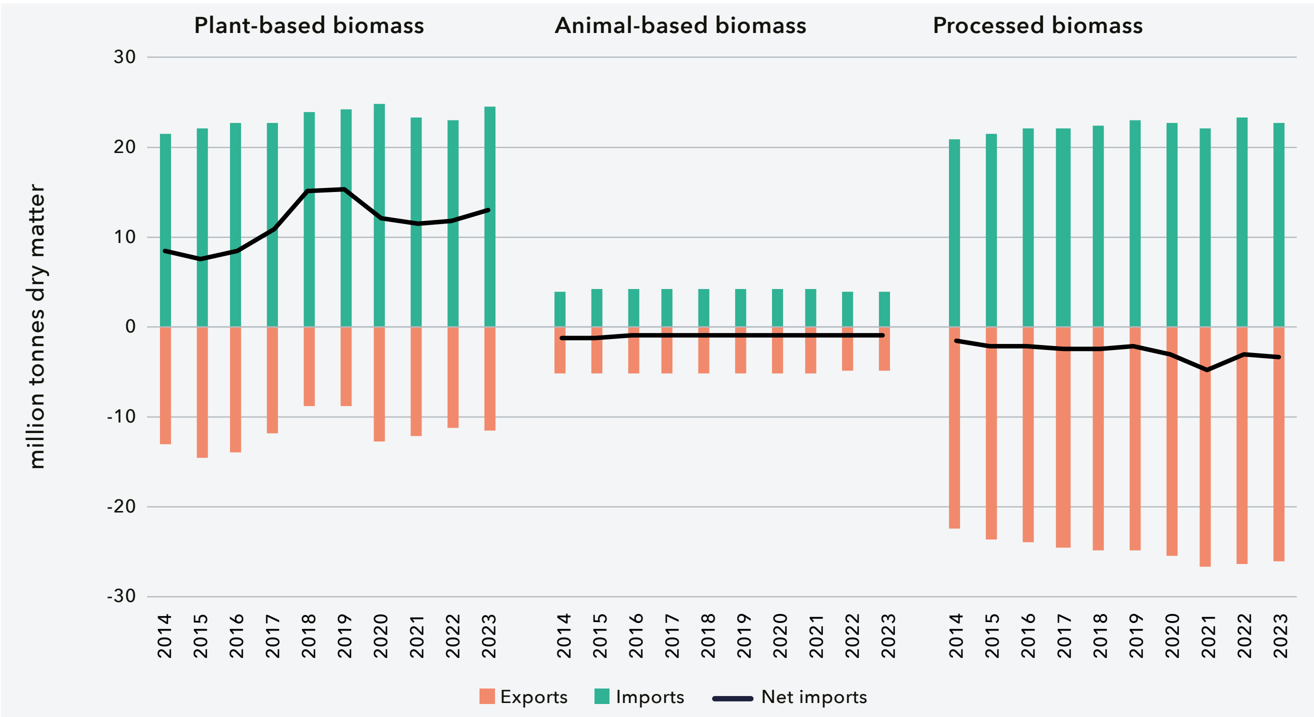
The amount of biomass produced over the last 10 years shows that the amount of plant-based biomass in particular is subject to fluctuations, e.g. due to weather conditions. In comparison, the amount of animal-based biomass produced has changed only slightly. The lowest

Figure 6.2 Agricultural biomass production in Germany



Source: Calculations based on data from Destatis

Figure 6.3 Foreign trade of biomass in Germany from 2014 to 2023



Source: Calculations based on Destatis

plant-based biomass yield was recorded in 2018, with a total biomass yield of 98 million t 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 t 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 t (Figure 6.2).

A look at the foreign trade volumes (Figure 6.3) 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 t 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 t in 2014 to 0.8 million t 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 t in 2021 and the lowest of 2 million t in 2014. **Overall, Germany is a net importer of biomass**. Net imports in the last 10 years ranged from **4 million t in 2015** to **12 million t in 2019.**

Key findings for 2020

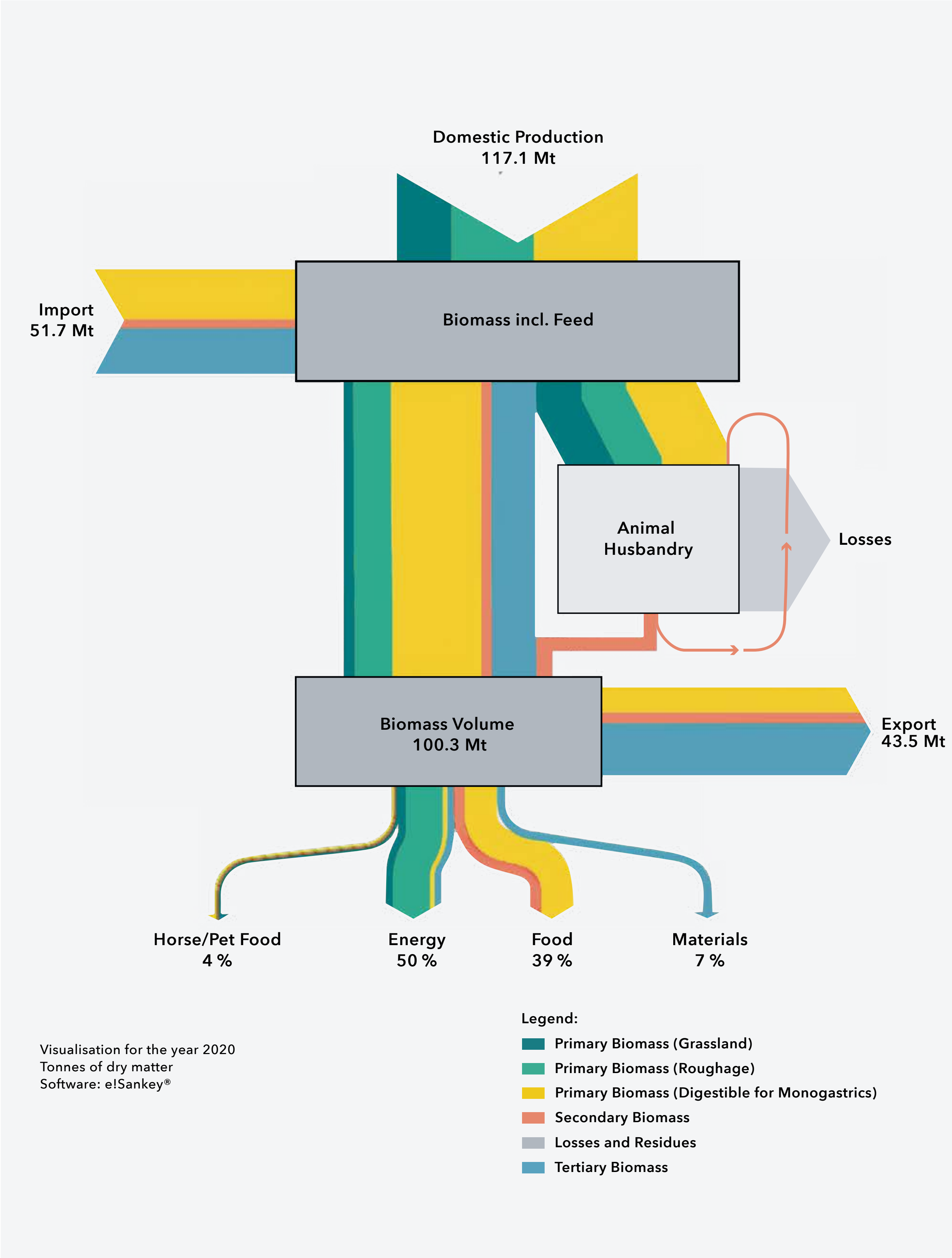
The total material flow for agricultural biomass in Germany in 2020 is shown in Figure 6.4. The chart includes all biomass that is reported as harvested in official statistics. This is only part of the agricultural biomass production, as plant parts that are generally not harvested, such as the roots of cereals, are excluded and by-products, such as cereal straw, are defined as residues and are only part of the total biomass flow in Germany (see Section 6.5).

- **The production of plant-based biomass amounts to 117 million t,** of which 67 million t and thus more than half (57 %) is accounted for by roughage and biomass inedible for monogastric animals. Permanent grassland contributed to domestic production with a biomass yield of 26 million t, representing 23 % of total primary biomass production and 40 % of roughage biomass production.
- **52 million t of biomass were imported**, of which 25 million t of plant-based biomass was imported. Furthermore, 4 million t of animal-based biomass and 23 million t of processed biomass are imported, which have a higher economic value due to their previous conversion from primary biomass.
- **75 million t of biomass was used as feed for animal husbandry**. 44 million t of the feed is roughage, which can only be consumed by ruminants or hindgut fermenters. 32 million t is feed that can also be fed to monogastric animals. In addition to plant-based biomass, 0.2 million t of animal-based biomass is used as animal feed. This is, for example, milk used to feed calves in dairy farming.
- **The output of animal production in 2020 was 7 million t dry matter** animal-based biomass, and is made up of meat (incl. offal), leather, milk and eggs. Other biomass flows such as manure used for energy production or as fertiliser and slaughterhouse waste are summarised as losses in this figure.
- **The total volume of non-feed biomass processed by the German bioeconomy was 100 million t**, consisting of plant-based, animal-based and processed biomass either produced domestically or imported. 43.5 million t or **43 % of this was exported in 2020** and the rest was consumed domestically.
- **Half of domestic consumption of non-feed biomass was used for energy**, whereby the different value of plant-based and processed biomass in particular must be taken into account. While the material flow of processed biomass is already biofuel (3 million t) and therefore a secondary energy source, plant-based biomass is the input material for biogas production, whereby part of the biomass is converted into unused CO_2 during biogas production or remains in agriculture as fermentation residue. If we consider the secondary energy source biomethane (methane content of the raw biogas) produced in biogas production instead, then the biomass used for energy is reduced from 23 million t of plant-based biomass to 6 million t of processed biomass.
- **39 % of the non-feed biomass was used for food**, of which 5 million t of the 21 million t, or **about one-quarter, was of animal origin.**
- **The proportion of material usage of non-feed biomass was 7 %** and includes textiles, leather and raw materials for the chemical industry.
- **Pet food (including horses) represents 4 % of the non-feed biomass used in 2020**. With a volume of 0.5 million t, the animal component of pet food accounts for around 7 % of domestic animal production.

Interim conclusions

In summary, it can be seen that **Germany is a net importer of biomass**, whereby the share of higher economic value, animal-based and processed biomass in exports is higher. In terms of dry matter, after the use of animal feed for livestock production, energy use is the most important utilisation pathway in terms of quantity. This is because of the high proportion of low-value roughage (grassland and cropland) among the forage and energy uses (e.g. for biogas production). Nevertheless, these two utilisation paths are associated with high mass losses and therefore offer potential for optimisation in order to enable the use of biomass for new applications.

Figure 6.4 German agricultural biomass flow in 2020



6.3 Forestry biomass

What is forestry biomass?

Figure 6.5 shows the detailed material flow of wood as well as flows of bark for 2020. The material flows have been calculated based on official statistics, data from the wood resource monitoring[36], information from industry federations and own estimates. The flow chart shows the raw material input into the first processing stage, the further trade and domestic consumption of semi-finished and finished wood-based products and the energy use of wood.

As shown in the total material flow (Figure 6.1), the supply of wood and wood fibres includes roundwood removals from the forest, including forestry residues, as well as recovered waste paper and recovered waste wood. In the more detailed material flow of this chapter, also residual flows of wood processing residues, wood from landscaping and bark are displayed. In contrast to Figure 6.1, **the unit cubic meter wood fibre equivalent m³(f) is used in the detailed wood flow analysis**. This unit describes the equivalent volume of the wood fibres or wood-based fibres contained in the product in the fibre-saturated state and is therefore comparable to the cubic meter under bark that is customary in forestry (Weimar 2011).

Key findings for 2020 and differences to 2015

In 2020, a total of **79 million m³(f) of roundwood was removed from the forest**. The increase compared to 2015 (69 million m³(f)) is mainly caused by increased fellings due to drought and bark beetle infestation. As a result of higher removals net trade changed significantly, from net imports of 5.5 million m³(f) in 2015 to **net exports of 7.0 million m³(f) in 2020**, mainly caused by changes in trade of coniferous roundwood.

After taking trade into account, domestic **consumption of roundwood totalled 73 million m³(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 panels (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), 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 m³(f) in 2020 compared to 2015. Within the production of sawnwood, **relevant quantities of wood processing residues (e.g. sawdust, wood chips) are produced**; 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, as a residue of roundwood processing, are also used as constituents for the production of growing media.

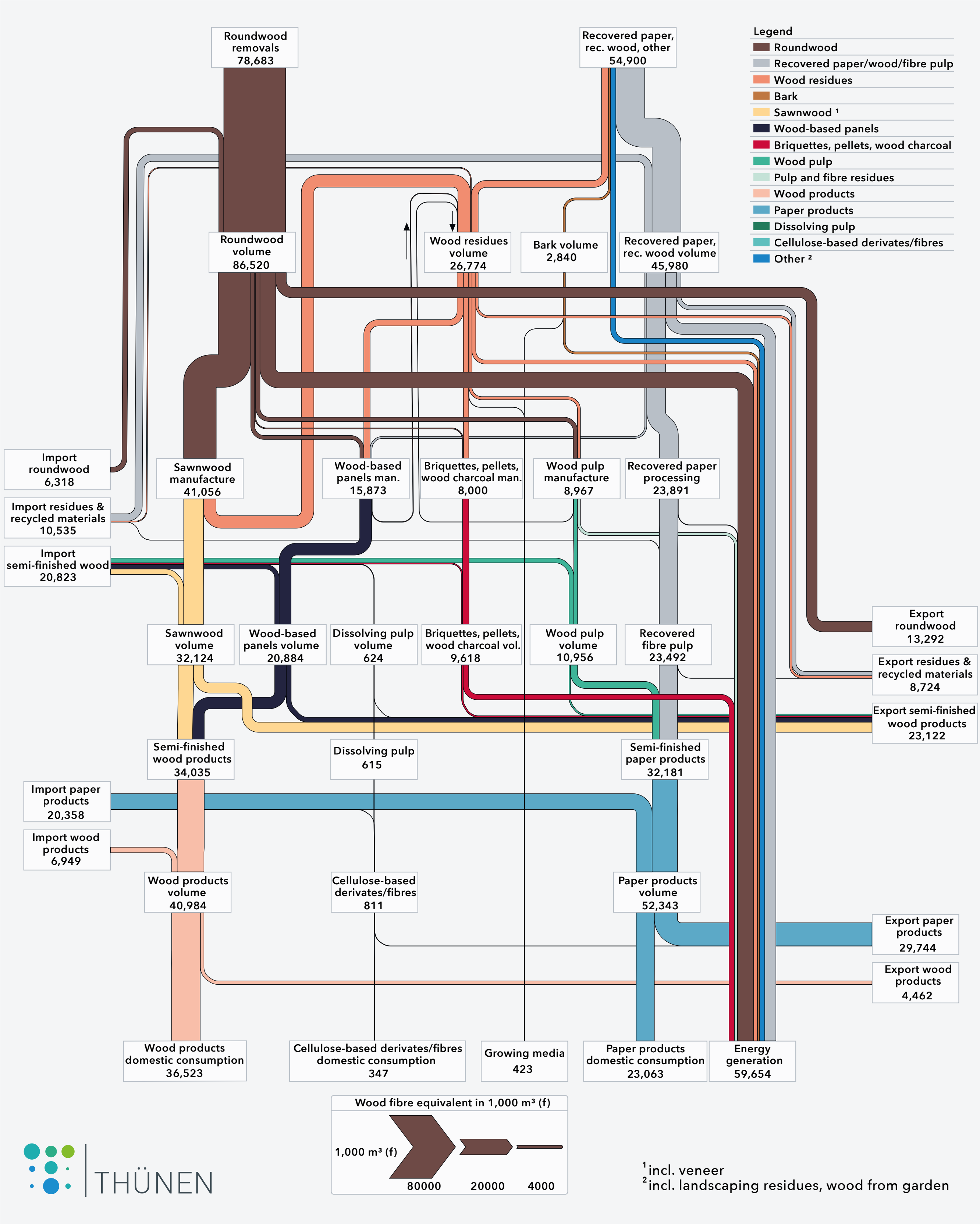
Dissolving pulp is not produced in Germany, but imported and further processed (e.g. regenerated cellulose). Biorefineries for production of various chemical compounds were not operating in Germany in 2020. However, the chemical sector is starting to shift toward biochemicals (see Section 3.3.2 and 4.3), and respective 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 m³(f).** Trade shows net imports of these of raw materials of about 3.8 million m³(f). Most of the recovered paper is processed and used for the manufacture of semi-finished paper and paperboard. 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 m³(f). For paper products, the consumption summed up to 23 million m³(f). For energy generation in private households and in combustion plants, about 60 million m³(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 m³(f) in 2020 while in 2015 net imports of 6 million m³(f) could be observed.

36 More information on the wood resource monitoring of Thünen Institute can be found here: https://www.thuenen.de/en/institutes/forestry/projects-1/rohstoffmonitoring-holz-1

Figure 6.5 Wood flow in Germany in the year 2020, in cubic metre wood fibre equivalents, m³(f)



Source: Schliemann 2024, Thünen Institute of Forestry, created with elSankey®

Key messages:

- Recovered materials of waste wood and waste paper comprise a significant share of the domestic supply of wood fibres.
- Domestic removals increased significantly due to salvage fellings caused by drought and bark beetle infestation.
- In total, Germany showed a net export of wood fibres of 14 million m^3(f) in 2020.

6.4 Aquatic biomass[37]

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 und Résimont 2007). In aquaculture, fish, crustaceans, molluscs and algae are farmed in controlled conditions. Freshwater fisheries includes commercial fisheries in lakes and rivers, which may comprise natural and artificial water bodies, such as quarry lakes and river dams.

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 fisheries and aquaculture products consumption fluctuate 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 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 fish rest raw material ranges between 30 and 85 %** (Rustad et al. 2011). This rest raw material is utilised for food and non-food purposes.

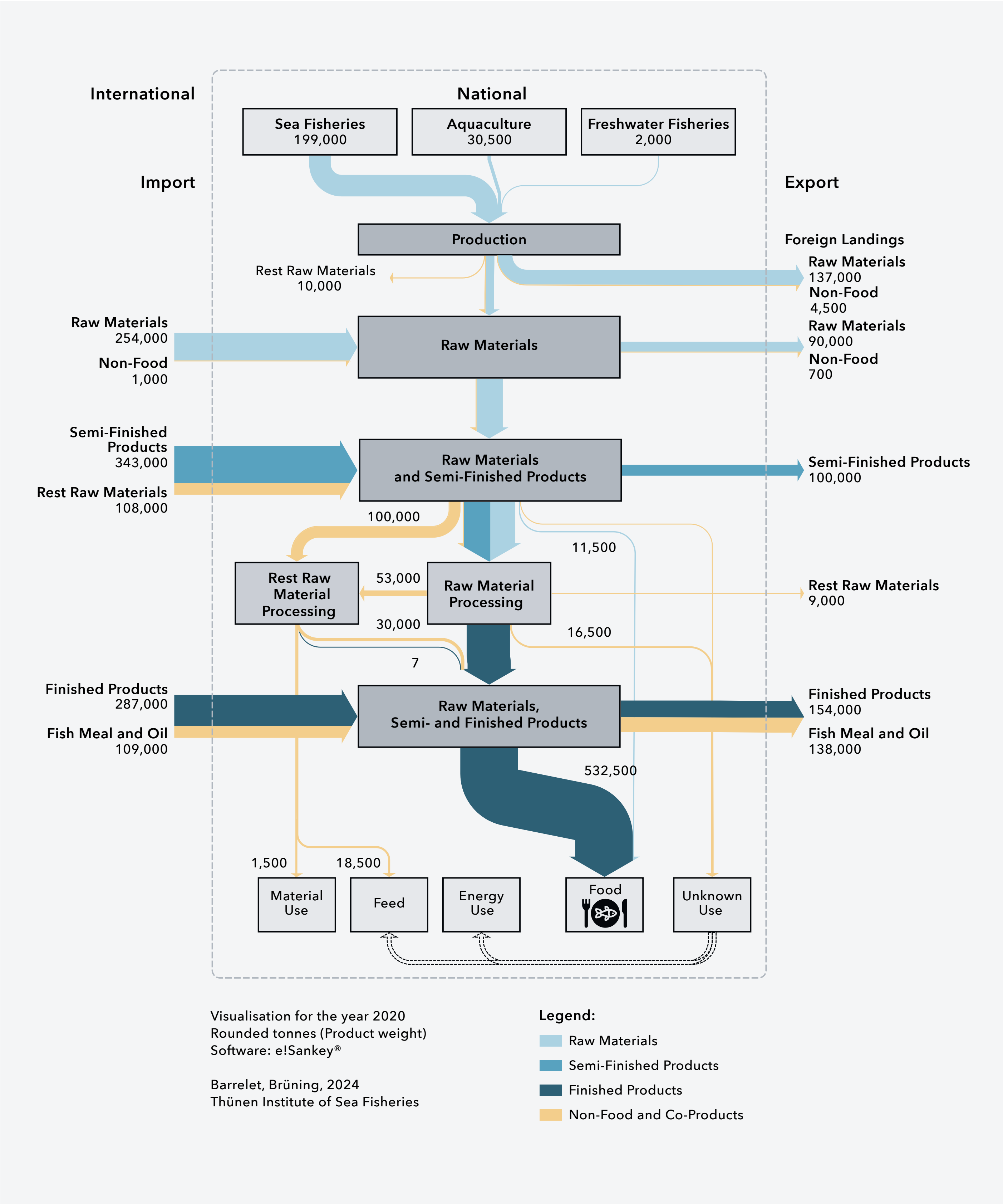
Key findings for 2020

In 2020, **production amounted to around 230,000 t of aquatic biomass** in Germany (Figure 6.6). Around 86 % stemmed from sea fisheries, 12 % was a result of aquaculture production and 2 % was 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).

37 More information on Salmon Rest Raw Material can be found in the forthcoming article "Salmon Rest Raw Material Flow — Assessing Resource Efficiency of Salmon Processing in Germany", which is currently in preparation.

Figure 6.6 Material flow of aquatic biomass in Germany (rounded for the year 2020)



Source: Thünen Institute of Sea Fisheries

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 t, followed by around 290,000 t of finished products (i.e. smoked, marinaded, battered fish and seafood and a range of convenience products) and 260,000 t of raw materials (whole or gutted fish, whole seafood). As regards **exports**, raw materials make up the largest share. It should be noted that of the approx. 230,000 t raw material exports, almost 140,000 t 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 t (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 t 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 t** in 2020. Of this, over 50,000 t went into rest raw material processing to produce fish oil and meal while another ~17,000 t 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 t were imported and merely 9,000 t exported. After the processing of co- and by-products, almost **30,000 t of domestically produced fish oil and meal were exported and nearly 20,000 t used in Germany**, with the largest share of over 18,000 t going into animal feed production (pet food, aquaculture and livestock feed), and only around 1,000 t 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 t would have been suitable for human consumption.

Trends (2020 compared to 2015)

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

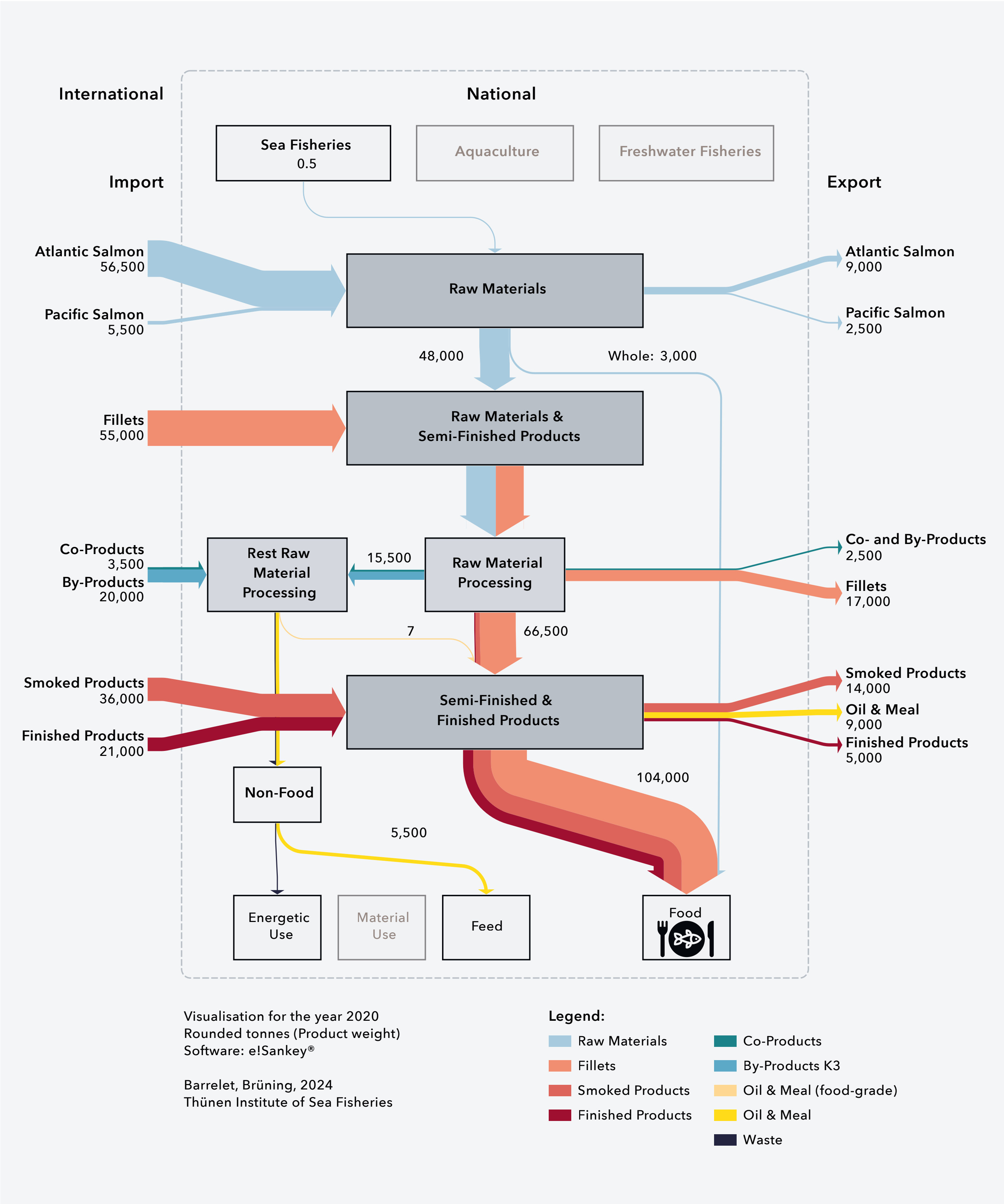
- Between 2015 and 2020 **German production saw a decline of 11 %,** primarily due to reduced harvest from sea fisheries. This reduced harvest can be attributed to drastic quota reductions in the Baltic Sea coupled with large fluctuations in the catch volumes of commercially vital brown shrimp.
- In contrast, high-seas fisheries have maintained stable catches while improving resource efficiency by utilising by-products for fish oil and meal production at sea and reducing fleet capacities without lowering catch volumes.
- The import volume of aquatic biomass 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).

Case study – Salmon:

Salmon was the most popular fish by consumers in Germany with a **market share of 19 % in 2020** (FIZ 2022). This product was **almost exclusively imported**, only 0.5 t 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 t of Salmon raw material were imported** and around 10,000 t exported (Figure 6.7). Nearly 3,000 t of whole salmon were sold directly, without further processing, the rest went into German processing plants, where over 65,000 t of finished products were produced. This resulted in almost 16,000 t of rest raw material, which went into further processing, along with over 20,000 t of imported rest raw material. After raw material and rest raw material processing over **100,000 t of final products** (whole, semi-finished and finished salmon products) were sold for human consumption, 5,500 t (salmon meal and oil) were used for animal feed and a very small fraction was disposed of and used for energy production.

Figure 6.7 Material flow for salmon production in Germany (rounded for the year 2020)



Source: Thünen Institute of Sea Fisheries

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. Further, the amounts of fisheries and aquaculture products resulting from processing and the amounts of final products going into consumption had to be estimated by balancing, taking into account a number of assumptions. Examining Salmon as one particular main commercial species in detail provided more precise information and helped identify gaps in the publicly available data (Figure 6.7). 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 in the MoBi project period.

Take-home messages

- Catches are continuously falling, which impacts self-sufficiency and, in turn, influences the entire German value chain.
- The German fleet would benefit from strengthening regional value creation of available resources.
- Rest raw material amounts can be calculated for all aquatic biomass and for the specific main commercial species.
- Data on aquatic biomass flows is available, but presents considerable gaps and imprecisions that can only be compensated by surveys and/or assumptions.

6.5 Secondary biomass

6.5.1 State and potentials[38]

What was assessed?

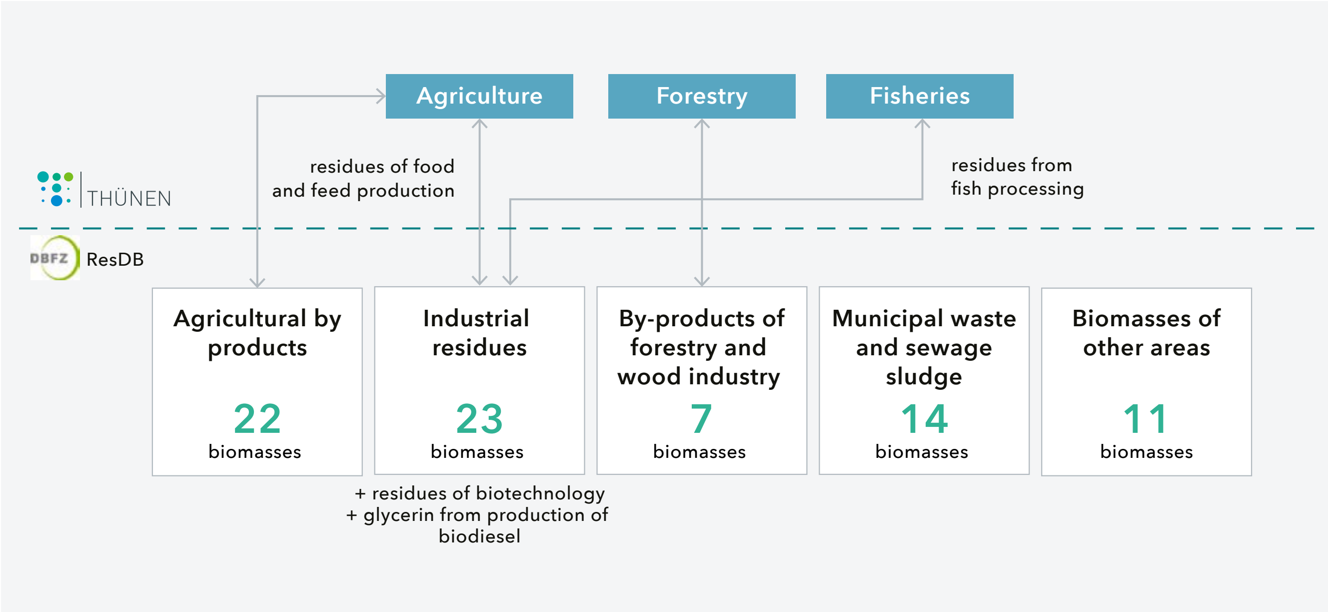
Cross-sectoral balancing of resource supply and use of secondary biomasses, i.e. biogenic wastes, residues and by-products, was consolidated and continued within the project "Monitoring of the Bioeconomy II part 2 (MoBi II 2)[39]. **Time series data** was collected for the period from **2010 to 2020.** This allows for a real monitoring of biomass flows in the sense that meaningful dynamics and trends — where they exist — can be identified and analysed. Unchanged from the beginning of the biogenic waste monitoring process, data were collected and aggregated to the potentials of 77 biomasses[38], which together cover the secondary resources of five comprehensive sectors, namely agriculture, industry, wood industry and forestry, municipal waste and sewage sludge, and biomasses from other areas (Figure 6.8).

It is important to note, data of secondary biomass reported in the previous sections, especially under 6.3 forestry and 6.4 aquatic biomass, can deviate from the potentials of biomass reported in this chapter. This is partly due to different categorisations, e.g. considering "waste paper" as forestry residues instead of municipal waste. The presentation of the entire spectrum of secondary biomasses of all relevant sectors involves some trade-offs between scientific depth and the practical accessibility of referable sources in order to facilitate a comprehensive and continuous monitoring.

The main frame of the online Resource data base "Biomass Monitor"[40] consists of ten levels of biomass potentials, including the main levels 'theoretical', 'technical', 'technical used' and 'mobilisable technical potential' (Brosowski et al. 2019). The difference between 'technical potential' and 'technical potential used' results in the 'mobilisable technical potential'. These three categories depict the first measures of circularity. The minimum and maximum values of each 'biomass potential' category

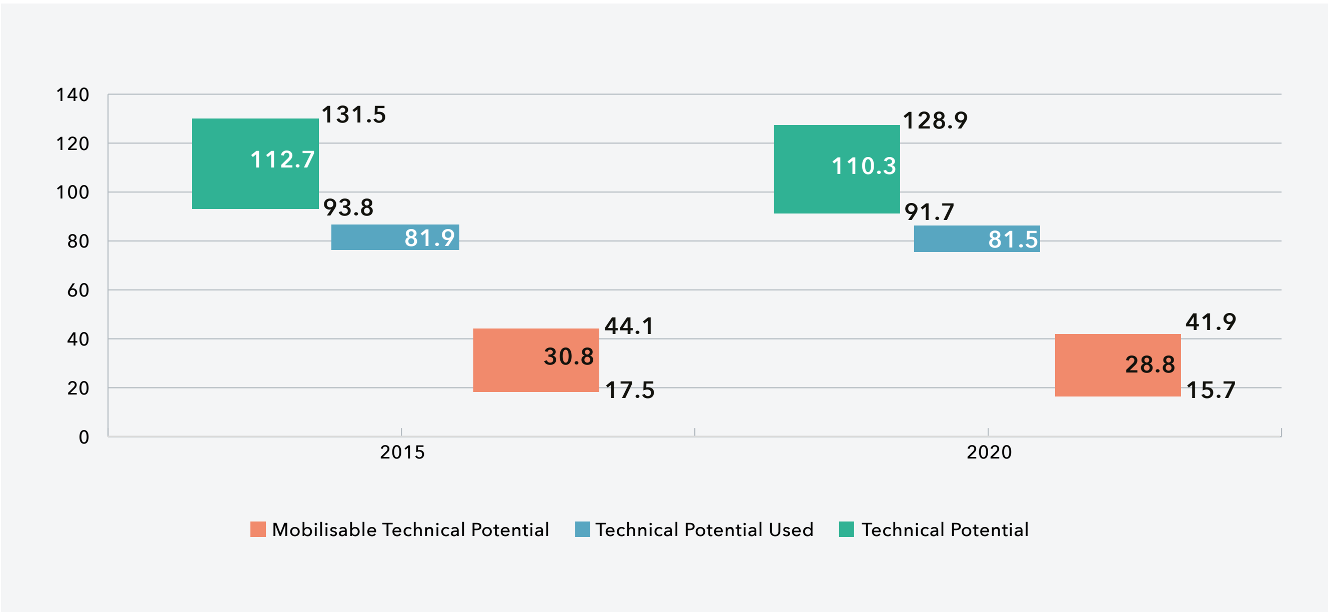
38 Terms and data presented in this section follow generally the terminology and calculations of biomass potentials as published by Brosowski et al. (2019). Most of the calculations remained unchanged in the currently updated version of the DBFZ Resource data base (ResDB) menu item "Biomass Monitor" for biogenic wastes, residues and by-products (https://datalab.dbfz.de/resdb/potentials). Adjustments in some sources and calculations were introduced during the consolidation process, which included implementation of new understanding and expertise of project partners (i.e. TI Forestry, Market Analysis, Sea Fisheries, and Witzenhausen Institute as well as Dept. Waste and Resource Management, Rostock University).
39 MoBi II lead by TI covered primary resources. MoBi II 2 of the DBFZ covered the comprehension of the secondary bio-resources.
40 See the database online at: https://datalab.dbfz.de/resdb/potentials

Figure 6.8 Sources and sectors of secondary biomasses



Source: DBFZ and Thünen Institute

Figure 6.9 Potentials of secondary biomass, i.e. biogenic wastes, residues and by-products, in Germany in the years 2015 and 2020 (in million tonnes of dry mass, Mt DM)



Note: A 2 % decrease in the overall technical potential effected mainly a reduction in the mobilisable technical potential.

are based on calculations using either the least or the highest factors, salvage rates, etc. for each single biomass. This results in a large range between minimum and maximum potentials, which illustrates the statistical uncertainty of used calculation elements. It also indicates, the results should be understood in the context of and in relation to one another instead of emphasising single data points. Accordingly, presentations of mean are a handrail in the middle of the wide ranges when comparing trends or between years.

Key findings

- **The 'technical potential' of total secondary biomass amounted to 91.7 – 128.9 million tonnes of dry mass (t DM) in 2020.** In 2015 the technical potential was 93.8–131.5 million t DM. It should be noted that this amount was recalculated based on some new adjustments and the findings thus differ somewhat to the results for 2015 given in the previous Pilot Monitoring Report (85.6 – 139.8 million t DM). As such, **the mean technical potential has decreased by about 2.4 million t DM from 2015 to 2020.**
- **The ratio of 'technical potential used' to 'mobilisable technical potential' increased slightly**. The 'technical potential used' ranged between 66–81 % in 2015 and 68–83 % in 2020.
- **The distribution of biomass uses between material production and energy generation slightly changed towards energy use**. The mean secondary biomass potential recovered for material production was 44.5 million t DM and 42.5 million t DM in 2015 and 2020, respectively. The corresponding input to energy generation was 32.4 million t and 32.8 million t DM in the same year sequence. However, the Biomass Monitor has four levels influencing the distribution between energy and material use: "used for material", "used for energy", "used for energy or material" and "data not clear". It must be noted that particularly the potential "used for energy or material" is so large that it might hide a different proportion.
- **The mean mobilisable technical potential decreased by 2.0 million t DM in 2020 as compared to 2015.** This was the result of the overall decrease in the technical potential and the slight shift to more use.

31 % of technical potential in 2020 was comprised of municipal waste and sewage sludge.

- **"Municipal waste and sewage sludge" remained the single largest contributor to 'technical potential', comprising 30 % and 31 % of the total biomass in 2015 and 2020.** In general, relative contributions of the five sectors to the technical potential of secondary biomass changed only marginally from 2015 to 2020. Forestry and agriculture collectively contributed 53 % and 52 % in 2015 and 2020, respectively. The sector "Biogenic residues from industries" showed only a slight decrease of less than 0.4 million t DM from 2015 to 2020; its relative contribution of 14 % did not change and moreover, its technical potential is virtually identical with its technical potential used. Gathering from the remaining land area not used for agriculture, forestry and the main areas where people work and live, the sector "Residues from other areas" contributed 3 % to the total secondary biomass in 2015 and 2020.
- **The usage share of manure and slurry (cattle and pigs) for energy purposes increased from 2015 to 2020**. While in 2015 about 28 % of the theoretical potential of manure and slurry (cattle and pigs) was used for energy purposes, this share increased to 41 % in 2020. The trend results from two counter-directional developments. While there is a factual increase of manure and slurry being used as input material for biogas plants, the overall livestock numbers decreased.
- **The three individual biomasses of waste paper, cereal straw, and green waste collectively contributed around one-third (33 %) to the mean technical potential** of secondary biomass in both 2015 and 2020. The contributions shifted slightly being 2015 vs. 2020 for waste paper 14 % vs. 13 %, 10 % vs. 9 % cereal straw, and 9 % vs. 10 % green waste.

- **Six biomasses contributed 84–85 % to the mean 'mobilisable technical potential'** in 2015 and 2020. The mean contributions of these biomasses (2015 vs. 2020) were cereal straw (16 vs. 15 %), solid cattle manure (19 vs. 14 %), cattle slurry (16 vs. 12 %), green waste (15 vs. 20 %), wood residues of coniferous forests (13 vs. 16 %) and of deciduous forest (6 vs. 7 %).

Interim conclusions

- The potential of secondary biomass for material and energetic use has slightly decreased rather than increased from 2015 to 2020. This sets the national potential of secondary biomass in contrast to the generally increasing demand for biogenic carbon sources including wastes, residues and by-products. However, there are still untapped potentials that need to be mobilised across the country, among them are the quota of (a) households connected to obligatory biowaste collection, and (b) the separate collection of spent cooking oils and fats. In addition, there are secondary bio-resources in the queue (from using insects and fungi for biowaste conversion, via microalgae cultivation on efflux of wastewater treatment, to faeces separation for nutrient recovery). Finally, larger availability and/or reallocation of secondary biomasses often includes options to supplement or substitute other resources.
- "Municipal waste and sewage sludge" is the sector with the largest single contribution to the total 'technical potential' of secondary biomass. This is followed by the technical potential of residues and by-products from forestry and the wood industry. Forest residues are increasingly used for forest conservation protecting the forests' vital functions and the many ecosystem services beyond wood production (see EU Regulations such as EU 2023c, the EU Biodiversity Strategy for 2030 (EU 2020), and the EU Nature Restoration Law (EU 2024)). Thus, municipal waste and sewage sludge is set to further increase its relative contribution. Secondary biomass resources of municipal waste are also reflective of societal developments. A large decrease in waste paper is obviously caused by a decline in print media, whereas the increase in green waste derives

from the renewed efforts of planting more greenery in urban areas. Further increments in green waste can be expected from more investments in green infrastructure for the necessary climate adaptation of cities (UBA 2021).

- Larger supply of secondary bio-resources and the trends associated with urbanisation could be promoted through better recycling of urban waste and sewage sludge. Thus, reinforcing selective collection and utilisation of urban waste is one unavoidable main task of German policy makers (across all regulatory levels and together with citizens) to achieve sustainability, climate change mitigation and social coherence. The solutions sought are not only of technical, but also of human nature. This is particularly important to maintaining balance in social responsibility. For example, while rural areas in general serve productivity, biodiversity, conservation and recreational purposes, large shares of the urban secondary biogenic resource are currently wasted or cannot be used to their full value owing to individual neglect and/or still missing awareness.

Key policy messages

- When considering raising the use of residues and wastes in Germany for future growing demand sectors (e.g. advanced biofuels in the transport sector, chemical sector, peat substitutes) three main options can be considered for future policy; first, implementing policy which addresses mobilisable (unused) potentials (e.g. cereal straw) more accurately (Brosowski et al. 2020); second, adjusting policy towards redirecting currently used potentials for other uses (e.g. redirecting incinerated shares of waste wood towards a material usage in the chemical sector; Fraunhofer-WKI 2024); third, allowing increased imports of biomass/bio-based products from residues and wastes (e.g. allowing import of biomethane within the EEG) as long as it is in line with the overarching strategic aim and principle purpose of using secondary biomasses.
- The trend of an increased usage of livestock manure for energy purposes positively contributes to the policy goal of supporting the fermentation of manure within the Climate Action Programme 2030 (BRg 2019).
- Realistic expectations in future secondary biomass resources ought to align with demographic developments. While secondary biomass resources from urban areas gain relative importance, their usage underlies regulations, e.g. the biowaste bylaw and the Fertilizer Directive (BRg 2022a, BRg 2022b, BMUV 2022), which limit the exploitation of the full potential. The underlying problem appears unsurmountable, i.e. the non-compliance to clean separation and disposal of biowaste by the waste producers (NABU 2023).

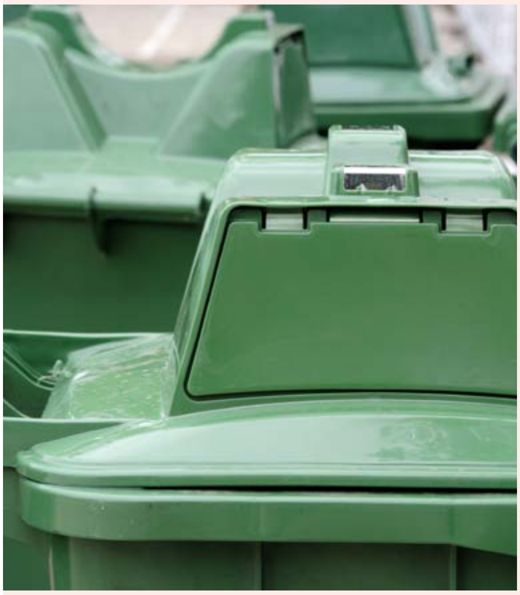
Incentivising people to make their waste usable offers the co-benefit of greater awareness for sustainable development.

- Although an uphill task, mobilising or even incentivising people to make their waste usable offers resources and the co-benefit of greater awareness for sustainable development. Possibly, concerted campaigning of federal, regional and municipal offices recognises the importance of the issue most convincingly. Also, co-design (e.g. Hölting et al. 2021) offers a contemporary approach in continuing the further development of the collection and higher value use of secondary bio-resources.

MONITORING CHECK BOX 8:

How are secondary flows and potentials determined?

Data for the DBFZ 'Resource data base "**Biomass Monitor**" is sourced from DESTATIS, The Federal Office of Agriculture and Food (BLE), producer syndicates, and individual publications. The aim is to source and develop 'dynamic data', which is defined as the annual amounts of raw material, product or produce from which residue derives. For this purpose, electronically accessible data are preferred over individual publications (including syndicate reports), in particular to ease the continuity of monitoring. **Calculations of potentials** are based on processing dynamic data with static factors, including technical recovery rates, waste proportions, and conversion rates (fresh to dry matter). Two **challenges** are the:



- Inconsistent reporting of biomasses in source data through time; and
- Verification of static factors, some of which derive from single publications or expert estimates only.

Accordingly, some caution is needed when interpreting data. **It is preferable to look at the data as a whole** and trends in context to one another, instead of selecting individual data points for isolated analysis.

As regards the specific assessments of **biomass flows**, also some assumptions have to be made. For example, in looking at rest raw material in the aquatic biomass sector, data also stems from DESTATIS, BLE, and the sector. However, statistics on processing outputs are only available at a highly aggregated level and not separated by biomass (e.g. agricultural ingredients, aquatic biomass). In this accounting, processing is a 'black box', with no consistent in- and output data at the same aggregation level available. For that reason, surveys are necessary to determine rest raw material quantities that go into processing and utilisations.

Altogether, better data availability and quality would strengthen monitoring capacities. To this end, the German government could **strengthen the automation of data exchange between various government levels and research institutions.**

6.5.2 Cascades, co-production and circularity: Concepts and challenges

Re-use and efficiency are central to the aims of developing a sustainable bioeconomy in Germany (See Section 2.1 as well as the National Bioeconomy Strategy (BMBF and BMEL 2020). This section describes **three relevant concepts for increasing the efficiency of biomass use by keeping it in circulation longer**—i.e. optimising sourcing from waste and residue streams. However, while these concepts are at the core of political strategies, a broad variety of methods to monitor circularity and its components still is being tested and discussed in the scientific literature. The diversity of biomasses and their uses contributes to the complexity of monitoring circularity, as well as the lack of consistent and comprehensive biomass flow data. Thus, there are still significant gaps. The ability to monitor them with reliable and robust data varies widely, depending on e.g. the residue stream, sector and degree of novelty. In general, data is not the focus of this section (data on residues and potentials are depicted in prior sections), rather the needs and implications for further developing monitoring tools geared toward conceptual aims.

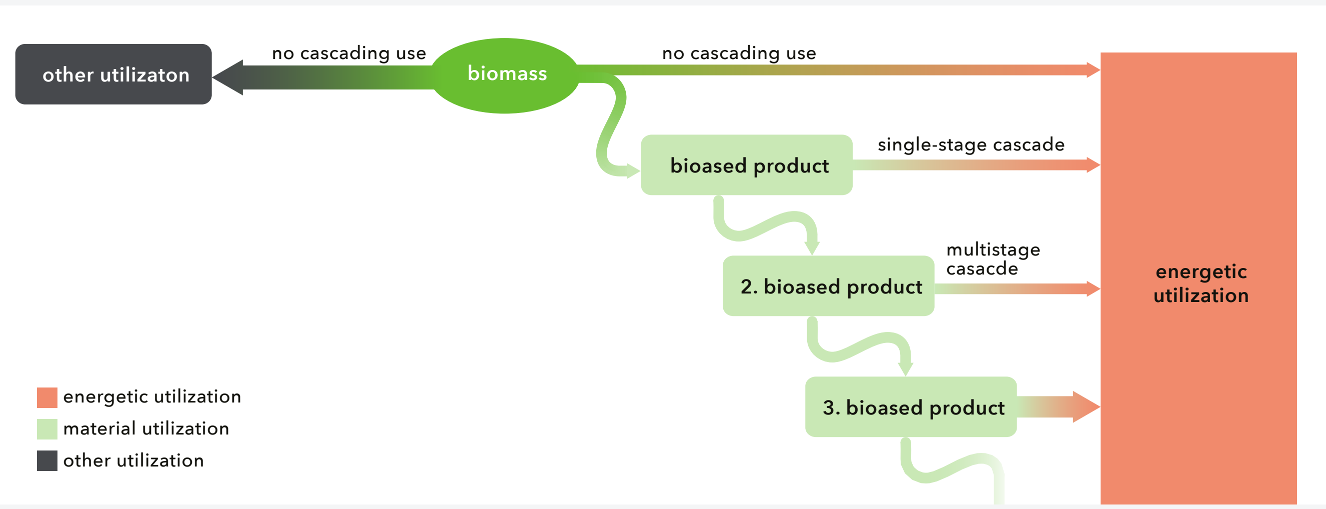
Cascading use

The concept of cascading use mostly relates to the material use of biomass, especially wood (Vis et al. 2016, Kalverkamp et al. 2017). However, the term 'cascading use' was not originally limited to biomass. It was first introduced by Ted Sirkin in the early 1990s and was defined as a „method for optimising resource utilisation through a sequential re-use of the remaining resource quality from previously used commodities and substances" (Sirkin and Houten 1994). As the concept was further developed, it became evident that different objectives could be pursued as regards 'cascading' (Fraanje 1997, Odegard et al. 2012):

- Cascading in time: The objective is to extend the duration of use in each cascade stage and/or to integrate as many cascade stages as possible
- Cascading in value: The optimum configuration of the cascade can be achieved by prioritising the highest possible value in each cascade and minimising the loss of quality between the individual cascades as far as possible
- Cascading in function: optimising the use of the individual (by-)products in a biomass flow.

In practice, it is not always possible to achieve all objectives at the same time. Moreover, if the focus is exclusively on one of these aspects, it can lead to conflicting objectives (Olsson et al. 2018). A loss in value is sometimes seen as a core element of cascading use (hence the Italian origin of the word **'cascare' – to fall**). This generally distinguishes it from recycling (Fehrenbach et al. 2017). However, that said, there are multiple definitions and deviations for describing the cascading use of biomass, which range from the optimised use of biomass (like in recycling) to the optimised use of by-products or waste.

Figure 6.10 Cascading use principal visualization



Sources: Adapted from Sirkin und Houten (1994) and Fehrenbach et al. (2017)

Circular economy

Although the concepts of „cascading use" and „circular economy" have developed in parallel, they remain surprisingly unconnected (Mair und Stern 2017). The circular economy concept is based on the „principle of Rs", where the design varies in detail and ranges from a short '3 R principle' (reduce, reuse and recycle) to a **'10 R principle'** (extended by one or more of the following terms: refuse, repair, refurbish, remanufacture, repurpose, recover, remine) (Reike et al. 2018). The concept has become increasingly popular in recent years, although there is not a universally valid and clear definition. Two review articles pointed to a total of over 300 different definitions (Kirchherr et al. 2023, Kirchherr et al. 2017). In contrast to the concept of cascading use, only around a third of the circular economy definitions contain a ranking or prioritisation of measures (Kirchherr et al. 2023) and the definitions of a circular economy increasingly focus on a system perspective (Kirchherr et al. 2017). Altogether, circular economy concepts are **strategies for extending the lifespan of resources** (Blomsma and Brennan 2017).

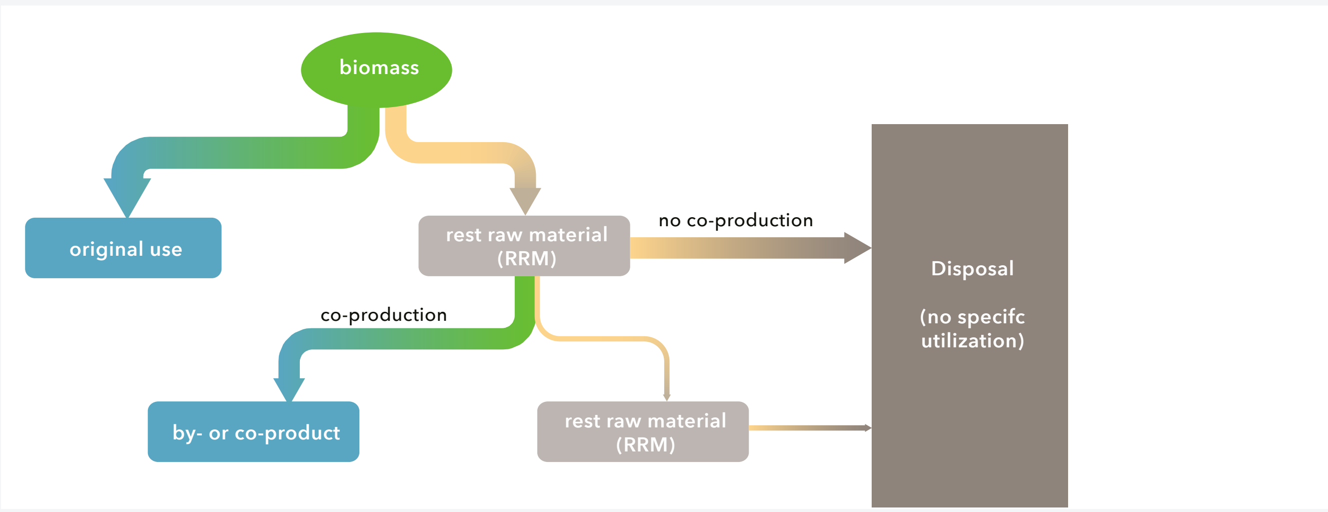
In reality, the utilisation of material leads to a loss of material (wastage, abrasion) and a loss of quality (mixing of materials, loss of structure) (Giampietro 2019, Cullen 2017, Figge et al. 2023). A special characteristic of biobased products is, that they **cannot be recycled as frequently as metals**, because the structure of the biomass wears out (Navare et al. 2021, Carus und Dammer 2018, Jarre et al. 2020). For example, the recycling process of paper shortens the fibres, which reduces the quality (Allwood 2014). This inevitable loss in quality explains why the concept of cascading use is often used for biomass (Navare et al. 2021).

For food waste, the options for a circular economy optimisation are varied, with the first priority clearly being prevention. The wasted food scale (Figure 6.11), developed by the U.S. Environmental Protection Agency, suggests that based on the overall goal of nourishing people, a scale can be used to determine the most preferable treatment of wasted food (U.S. EPA 2023). A similar evaluation tool was developed by the European Commission Joint Research Centre (Sanchez Lopez et al. 2020), based on a treatment hierarchy for food waste.

Figure 6.11 The wasted food scale: EPA's new ranking of wasted food pathways based on lifecycle assessment and circularity assessment

Source: US EPA 2023

Figure 6.12 Co-Production principal



Source: Thünen Institute for Sea Fisheries

Co-production

In the food sector, reutilisation of biomass is barely possible. For that reason, increasing biomass use efficiency primarily involves the utilisation of 'rest raw material' for producing a variety of value-added products (i.e. co- or **by-products** (Figure 6.12). This approach is also referred to as 'cascading in function', 'co-production' or 'coupled production'. It is the production of different functional streams (e.g. protein, oil and an energy carrier) from one biomass stream, thereby maximising the total functional use (Odegard et al. 2012). It describes the utilisation of material produced alongside the targeted raw material, which inevitably arises for natural or technical reasons. Resulting products can be of different types and qualities (Oenning 1997). Different production processes or systems can be combined in order to create synergies and thus improve overarching resource efficiency (Odegard et al. 2012).

Integration into bioeconomy monitoring

Research on strengthening these aspects in bioeconomy monitoring has shown that depending on the type and utilisation pathway of the biomass, different aspects need to be quantified.

If material re-use is possible, as is often the case with wooden products or textiles, **cascading** in time or circularity of the main product can be quantified in addition to the consideration of by-product utilisation (cascading in function). An extensive review of literature and methodologies has shown that a large number of methods exist for quantifying circularity and cascading use. Over 25 methods were considered for a bioeconomy monitoring. **Three approaches seem to be particularly appropriate and consistent with a monitoring based on material flow analysis**, and could be considered for integration in monitoring framework in the future:

- **Cascading Factor:** Focuses on the frequency a (wooden) raw material is used as an input, and can thereby substitute virgin material (Mantau 2012)
- **Cascade-use-potential:** Determines the potential of cascading use by comparing material vs. energetic use of primary and secondary raw material on the basis of time series (JRC 2023)
- **Biomass Utilisation Factor:** Simultaneously examines how much of a biomass and how often it was used within a bio-based life cycle or within a certain sector (vom Berg et al. 2022).

The field of research regarding cascades often focuses on the flow of materials in terms of the amount of the biomass itself. In the future, a stronger research focus could be directed at the flow of the chemical compounds or elements that make up the biomass. Such a focus could facilitate improved cascades and circularity options, in the context of overarching trends and monitoring of total resource requirements.

If the focus is on efficiency in production, as in the case of e.g. co-production for food, the focus of monitoring is on the quantification of rest raw material utilisation, as was done in Section 6.4 for aquatic biomass. In this case, a regular monitoring relies on the update of publicly available data on production and processing. Depending on the product or sector, this data can be difficult to come by and may require making assumptions (see Monitoring Check Box 8). Retrieving data on residues from the food sector is particularly challenging. This is in contrast to firmly integrated systems such as waste paper collection or deposit systems for pallets, where quantities are recorded.

Take-home messages:

- In the recent literature, multiple methods to monitor resource efficiency by quantifying cascades, co-production and circularity are tested and discussed. However, in practice, there is not one method applicable to all sectors, as data availability differs significantly.
- In the forestry and wood sector, data on flows of residues and recycled biomass are monitored via the wood resource monitoring which is now conducted as a permanent task at Thünen Institute of Forestry[41]. Based on this monitoring, data are available which can be considered also for further analyses on cascades, co-production and circularity within a bioeconomy monitoring.
- In the food sector increasing resource efficiency primarily involves the prevention of waste and the utilisation of industrial rest raw material for producing additional products. Official statistics on residues from food production are not publicly available. Approximations can be made based on expert knowledge from within the sector.
- The cascading use principal generally prioritises material use before energy use. Future monitoring of the bioeconomy needs to better reflect these flows and their trends in order to identify potential opportunities, hot spots and trade-offs.

BOX 2: CASCADING USE OF WOODY BIOMASS: CURRENT POLICY DEVELOPMENTS AND IMPLICATIONS

by Karl-Friedrich Cyffka, DBFZ

The current Revision of the **EU Renewable Energy Directive (REDII)** entails regulatory requirements regarding the principle of cascading use of woody biomass. Member states are asked to design support schemes for energy in a way that woody biomass is used according to its highest economic and environmental added value in the following order of priorities: first wood products, followed by extending the lifespan of wood products, reuse, recycling, bioenergy and finally disposal. Hence, **material use of woody biomass is generally prioritised over the use for energy production.** Nevertheless, deviation is possible to maintain the security of energy supply or if industry is quantitatively or technically unable to use woody biomass with higher economic and ecological added value (EU 2023a). The final execution of this principle and order of priorities will, however, depend on the national implementation into German law by May 2025.

Some potential challenges regarding prioritisation have been highlighted in the literature. For example, multi-product production facilities, like biorefineries, often produce a mix of material and energetic use products. For instance, the fermentation of poplar wood (e.g. from agroforestry systems), is performed in a technological process that produces a peat substitute (for material use) and biomethane (for energy use) (FNR 2022). Another example is the production of caproic and caprylic acid in biogas plants (Braune et al. 2017, 2021). As the EU foresees to increase the share of carbon used in chemical and plastic products to at least 20 % from sustainable non-fossil sources by 2030, it is likely that mixed material and energy production in biorefineries will increase (ECC 2021, The Government of the Netherlands 2024). To this end, greater certainty as regards the regulatory implementation of the cascading principle could help to promote investments. Price mechanisms and incentives for increasing the cascading use of e.g. woody biomass in the medium to long-term could also be effective (Schindler et al. 2023a).

41 For further information, please see here: https://www.thuenen.de/en/institutes/forestry/projects-1/rohstoffmonitoring-holz-1

7. Environmental footprints and sustainability scenarios

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Key findings

- The agricultural biomass footprint of German consumption was 4.1 t per capita in 2021. The two categories 'fodder crops and grazed biomass' and 'straw' combined make up around half of the footprint. Around 30 % of the biomass consumed is sourced from Germany directly, with another 21 % coming from the rest of the EU. The majority of rice, tobacco, spices, nuts and fibres come from outside Europe.
- The agricultural land footprint of German consumption was 468 thousand km^2 in 2021, with around 60 % comprised of grasslands and 40 % comprised of cropland. In comparison, the agricultural land area within Germany covers 166 thousand km^2, making the footprint of consumption 2.8 times higher. The largest land demands are related to grazing, especially in Argentina, Germany and the US. Two-thirds of the total footprint is on land associated with medium risk of soil erosion, with 1.4 % linked to high erosion risk.
- Historical trends show a decline in both the agricultural biomass footprint (24 % lower in 2021 than in 2000) and agricultural land footprint (38 % lower than in 2000). This decline is expected to continue in the future, as modelled in our reference scenario. Shifting diets toward recommended levels of meat and dairy could further reduce the agricultural biomass footprint, by another 13 %, and the agricultural land footprint, by another 14 %, compared to the reference scenario in 2050.
- The per capita German timber footprint for industrial use was estimated at 0.75 m^3 roundwood equivalents (excluding fuel wood). A little more than 80 % were found to stem from Europe. Future consumption levels in the reference scenario were shown to remain rather constant until 2050.
- The water footprint of the German bioeconomy was 451 m^3 per person in 2020, of which nearly 43 m^3 were irrigation water. Most of the water is used abroad (86 % of total water requirements), especially for irrigation (96 % of irrigation withdrawals), which mainly takes place in Spain, the US, Turkey, Iran, India and Greece. In particular rice, fruits and fibres are produced in regions with higher than average water stress levels. The water quality footprint can support monitoring the scarcity of clean water.
- Compared to global performance and with regard to long-term climate neutrality targets the climate footprint of the total German economy (12 t CO_2 equivalents per capita) and of the German bioeconomy specifically (1.85 t CO_2 equivalents per capita) were too high in 2021. Nonetheless, the climate footprint of the German bioeconomy was 35 % lower in 2021 than in 2000, and it shall continue to decrease in the reference scenario if binding climate neutrality targets are reached.
- Preliminary results on the biodiversity footprint, calculated here as a case study, shows that the biodiversity impacts of German consumption of Brazilian soybean increased by 134.3 % from the period 1997–2007 to the period 2008–2018, despite decreasing levels of imports. This was mainly a result of the expansion of soy-production areas into biodiverse landscapes.

7.1 Overview and scenarios

What are environmental footprints[42]?

Environmental footprints help to uncover the impacts of German consumption that are "hidden" by global trade and the spatial distance to the point of production. They also allow **comparisons between countries** on a per capita basis. In this sense, specific footprints deliver information on the distribution of specific global environmental burden, in particular to provide quantitative indicators underpinning discussions of responsibility, overconsumption and fair shares. For the German bioeconomy, the driving question is: to what extent are natural resources (agricultural biomass and land, forestry biomass, water) required for, as well as what climate and biodiversity impacts are associated with, the production and consumption of bio-based goods consumed in Germany?

The global multi-regional input-output dataset of the GLORIA database, release 057, was used to trace bio-based imports in all stages of production, i.e. commodities, semi-finished and finished products, back to the countries of origin of the raw materials (Lenzen et al. 2017, Lenzen et al. 2022). This is a change to the database used (EXIOBASE) in the pilot bioeconomy monitoring report (Bringezu et al. 2021a). GLORIA was chosen due to the much greater regional resolution, and to maintain consistency with UNEP reporting. It also allows a comparison of underlying data. The most recent data set in GLORIA is 2021. Central model equations are described in Bringezu et al. (2021b) and Helander et al. (2024).

What are the scenarios?

The **reference scenario** is largely based on continuity with regard to the influencing variables that are important for the development of the bioeconomy in Germany, Europe and the world. In terms of framework data, the scenario is predominantly based on trends and "business-as-usual" developments. Deviations from trend developments are taken into account when they are enshrined in law, as is the case with the energy transition in Germany and the EU (e.g. based on the Climate Protection Act and the Green Deal; see also Section 4.2). Also, international projections for the case of global production of agricultural commodities or material extraction (OECD and FAO 2023, UNEP 2024) are used instead of trend extrapolations in the reference scenario. The key assumptions for projecting the data set in ex-ante simulations into the future until 2050 are described in Lutz et al. (2024). General considerations on the scenario framework can be found in Lutz and Toebben (2023).

Simple what-if scenario elements showcase alternative pathways from the reference scenario. They aim to explore key levers for change by isolating parameters that could contribute to (or harm) a sustainable transition. While the focus of this report is related to the use of agricultural biomass, similar questions should be modelled for forestry in the future.

- **Dietary change:** An enhanced dietary shift toward less meat and dairy as aligned with dietary recommendations (see Section 4.1 for base data and assumptions)
- **Organic farming:** Enhanced demand for organic farming products. The "what if" scenario is to test the impact that 100 % organic farming in Germany by 2050 would have on the size of the land footprint. The assumption is that while ecological impacts decrease, organic farming results in lower yields (and consequently lower production quantities) compared to conventional farming (up to minus 45 % based on Röös et al. 2018) with further parameters in the supplementary information). The organic share will increase linearly until 2050.

The methods are described in more detail in Lutz et al. (2024). In general, individual parameters in the GLORIA-based MRIO model are adjusted for each case in a comparative-static analysis. There are no market reactions considered. This means, for example, that a decline in meat consumption in Germany does not lead to changes in demand (via changes in world market prices in other countries). If direct adjustments are assumed, such as an increase in demand for other food in the event of a fall in meat consumption, they are incorporated directly into the model (described in particular in Lutz et al. 2024).

42 The online, interactive footprint data explorer contains more information on the composition and calculation of footprints. Data is currently being updated from the pilot monitoring report to include the data presented in this chapter. Please visit: https://symobio.uni-kassel.de/?lang=de

7.2 Agricultural biomass footprint

What is the agricultural biomass footprint?

The agricultural biomass footprint quantifies how much biomass must be extracted worldwide to cover the German consumption of bioeconomy products. It includes all quantities of **primary** agricultural biomass in tonnes used for domestic consumption. In contrast to the tonnes of dry mass, as reported in Chapter 6, domestic extraction of biomass is reported in wet weight, i.e. the weight of the crop at harvest. The biomass harvested by agriculture, i.e. the plant-based agricultural biomass in Germany and internationally are included here. These material flows determine the extent of the various environmental impacts associated with them and also form the basis for calculating the land and water footprints.

Per capita consumption footprint

The German agricultural biomass footprint of consumption was **4.1 t per capita in 2021.** The year 2020 is distorted by the Covid-19 pandemic. Domestic production of agricultural biomass reached 2.24 t per capita in 2021. As stated above, it differs from primary biomass reported in Figure 6.2, as it is not converted to dry mass. As regards trade, 5.19 t per capita were associated with imports while 3.34 t per capita were associated with exports in 2021. A longer-term view clearly shows that the footprint of German agricultural biomass exports has increased significantly. In 2021, it was almost 2.5 times higher than in 2000. The footprints of exports and imports are also not identical to the exports and imports of agricultural biomass. They also include among others the biomass that was used as feed in meat imports and exports or in other food products, regardless of the country in which the biomass was originally grown. For example, if a German pig was fed with soy from Brazil and the meat is then exported to the UK, the soy is part of the footprint of German imports and exports.

Due to a change in the underlying database (see Section 7.1), the agricultural biomass footprint determined for 2015 is higher than that given in the pilot monitoring report, which was based on the EXIOBASE dataset (3.9 t per capita in Bringezu et al. 2021). Calculations based on a more recent version of EXIOBASE led to a footprint calculation of 5 t per capita in 2015 (Bringezu et al. 2021b). **In comparison to the GLORIA database, the orders of magnitude match up well**. Domestic extraction based on the GLORIA data has hardly changed compared to the data used in the first pilot report because it is based on production data from the German Federal Ministry of Food and Agriculture (BMEL). In contrast, **significantly higher levels of imports and exports were calculated based on the GLORIA dataset** compared to that used in the pilot report.

Historical evolution and composition of the total agricultural biomass footprint

The total agricultural biomass footprint in Germany was **341 million t in 2021**. It has fallen significantly over the last two decades, but with fluctuations. In 2021, the agricultural biomass footprint was **24 % lower compared to 2000**. This development is primarily driven by the decline in fodder crops and grazing as well as vegetables and fruit, while the footprint of other food products has changed only slightly.

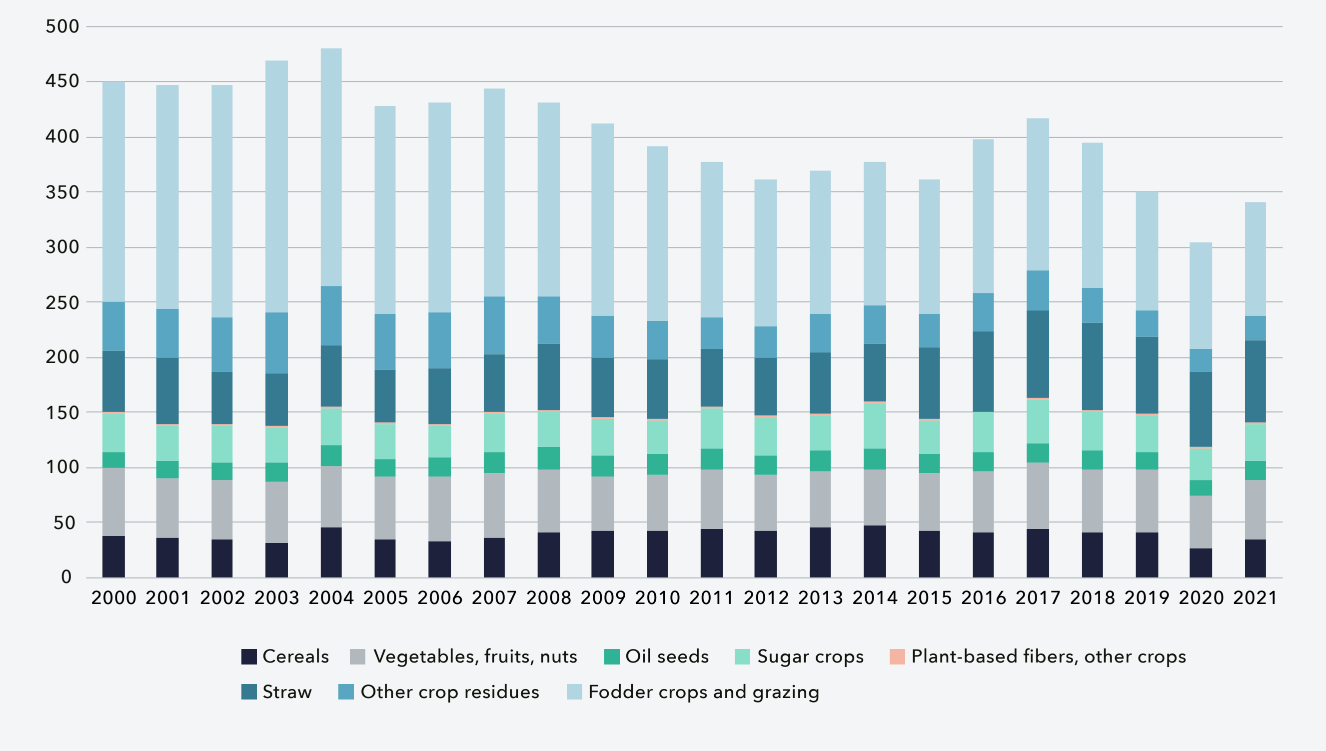
The most important agricultural products used in 2021 in terms of volume were **fodder crops and grazing** (103 million t), straw (74 million t), sugar crops (34 million t), cereals (35 million t), and vegetables, fruits and nuts (54 million t). Oil seeds (18 million t) and other crop residues (22 million t) are less important in terms of volume, while plant-based fibres and other crops only play a minor role with about 1 million t each.

Table 7.1 Development of the German agricultural biomass footprint between 2000 and 2021, tonnes per capita

	2000	2010	2015	2016	2017	2018	2019	2020	2021
Agricultural biomass footprint	**5.46**	**4.76**	**4.41**	**4.83**	**5.05**	**4.76**	**4.22**	**3.66**	**4.10**
Domestic extraction	2.75	2.52	2.59	2.55	2.62	2.29	2.27	2.26	2.24
Footprint of exports	1.37	2.17	2.44	1.81	1.55	1.88	2.46	3.06	3.34
Footprint of imports	4.07	4.41	4.26	4.10	3.99	4.36	4.40	4.46	5.19

Source: GWS based on GLORIA database; Population data stems from Riahi et al. (2017)

Figure 7.1 Agricultural biomass footprint of Germany from 2000 to 2021 in million tonnes



Source: GWS based on the GLORIA Database

The use of oils seeds and straw has increased between 2000 and 2021, while the use of other crop residues, fodder crops and grazing show above average decreasing trends. The development of the agricultural biomass footprint shows the consequences of the pandemic in the GLORIA data, which led to a significant decline in economic activity and international trade in 2020, while activities have increased again in 2021.

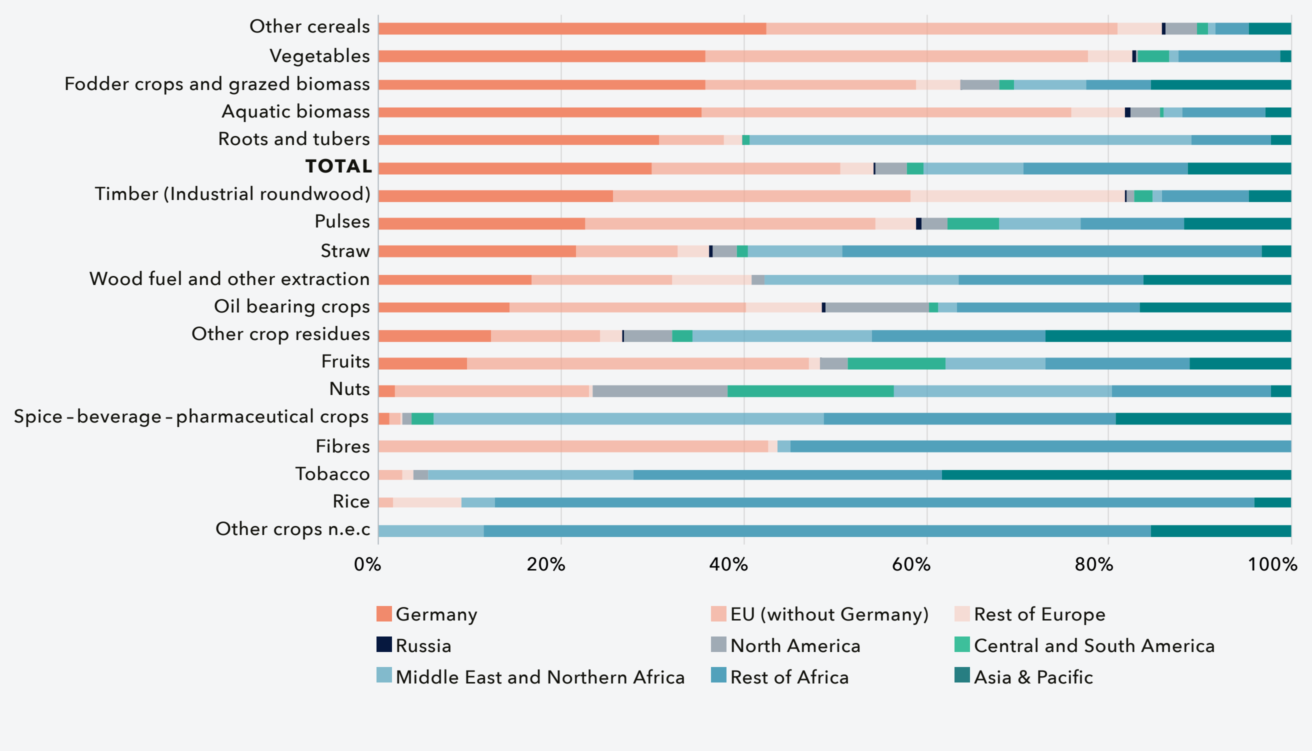
Origin of the agricultural biomass consumed in Germany

Figure 7.2 shows the regional distribution of the origin of agricultural biomass consumed in Germany in 2021. Overall, **30 % of the agricultural biomass footprint in 2021 came from Germany**, 21 % from the rest of the EU-27 and 4 % from the rest of Europe. The Middle East and Northern Africa, the rest of Africa, and Asia and the Pacific are also important supply regions.

The regional structure differs greatly for individual product groups. While wheat and other cereals, sugar crops, vegetables and fodder crop and grazed biomass are predominantly sourced from Germany and the EU, other agricultural products are more dependent on other parts of the world. The **majority of rice, tobacco, spices, nuts and fibres come from outside Europe**. North America has quite high shares for nuts and oil bearing crops, Central and South America for nuts and fruits. The share stemming from the Middle East and Northern Africa is high for spices, tobacco, roots and tubers, nuts, fruits, straw and other crop residues. The rest of Africa (sub-Saharan Africa) as well as Asia and the Pacific also play an important role in various product groups. The rest of Europe has some importance for oil bearing crops. Russia played only a minor role in 2021. In total, 11 % of the German agricultural biomass footprint comes from sub-Saharan Africa and 13 % from Asia and the Pacific.

Looking back to the year 2000, 34 % of the agricultural biomass footprint was sourced from Germany, while the rest of the EU (as currently defined by the EU-27) contributed 18 %. That implies that the shares stemming from the EU, including from Germany, have hardly changed between 2000 and 2021. In contrast, **the share stemming from the Middle East and Northern Africa in particular has risen sharply**; from 7 % in 2000 to 11 % in 2021. The share of Asia and the Pacific fell from 16 % to 11 % between 2000 and 2021.

Figure 7.2 Regional contribution to the German agricultural biomass footprint in 2021 in percent



Source: GWS based on GLORIA

Projected development to 2050 – Reference scenario

In the reference scenario, the agricultural biomass footprint **decreases** in the longer term. It decreases from 4.1 t per capita in 2021 to **3.9 t per capita in 2030** and **3.5 t per capita in 2050**. This would make the German agricultural biomass footprint almost equal to the global average, which is projected to reach 3.4 t per capita in 2050.

The reference scenario is based on the assumptions that, among other things, the demand for food in physical units in Germany will remain stable in the future, despite further economic growth. Meat consumption is modelled to fall slightly, while rice consumption increases in Germany. At the global level, worldwide biomass extraction is adjusted to meet the reference scenario from the Global Resources Outlook of the International Resource Panel (UNEP 2024). It is also assumed that material intensity will decrease somewhat in Germany and other producing countries in the future, i.e. less biomass will be required for one unit of the end products consumed, which can be achieved through better harvesting methods and less waste.

Wedge scenario – Changing diets

The dietary change scenario for Germany shows that reaching the German Nutrition Society (DGE) recommendations (see Section 4.1) by 2050 with a lower consumption of meat and dairy products has a particularly significant effect on the agricultural biomass footprint. It is **13 % lower in 2050 than in the reference scenario**. In comparison to 2021, it would **sink by 26 %,** reaching 3 t per capita in 2050.

Table 7.2 Development of the agricultural biomass footprint in the reference scenario compared to the 'wedge' dietary change in tonnes per capita

	2000	2010	2021	2030	2040	2050
Reference	5.46	4.76	4.10	3.90	3.68	3.50
Diets_DGE	5.46	4.76	4.10	3.63	3.27	3.04

Source: GWS, based on calculation with GLORIA database from 2000 to 2021, projections for 2030 to 2050.

Putting consumption into perspective – comparative benchmarks

Different types of comparisons help put the scale of German footprints into perspective. That said, a target range for quantifying sustainable consumption levels requires society-wide discourse, prioritisation, acceptance and decision making, in light of best available scientific evidence (see also the Monitoring Check box 9 regarding global benchmarks). In this report, multiple types of comparisons are made:

- Degree of self-sufficiency: In comparison to how much biomass Germany produced in 2021, the agricultural biomass footprint was around **83 % higher.**
- International comparison: An average of 3.1 t per capita of agricultural biomass were consumed worldwide in 2021. German consumption was thus almost **one-third higher** than the global average.
- Preliminary global safe and just benchmark: 2 t biomass (agricultural and forestry biomass) per capita[43] has been suggested in the literature as a sustainable limit for keeping global consumption levels within current planetary boundaries (Bringezu 2015). With an agricultural biomass footprint of 4.1 t per capita in 2021, Germany's consumption is **well over double** that suggested, proxy value (including forestry biomass would further drive overshoot).

Key messages

- The agricultural biomass footprint is a useful indicator to measure the global agricultural biomass extraction needed for German consumption.
- Efficiency increases and waste reduction all along the production chains together with dietary change as recommended by the German Nutrition Society are major levers to reduce the footprint.

7.3 Agricultural land footprint

What is the agricultural land footprint?

The agricultural land footprint quantifies the area of land, both domestically and in foreign countries, utilised by agricultural activities such as crop production and livestock grazing to meet the consumption of food, fibre and energy in Germany. The agricultural land footprint is determined based on modelled global maps with the LandSHIFT land-change model, depicting the location of agricultural land and the information from GLORIA used for calculating the agricultural biomass footprint.

The agricultural land footprint contains additional information that relates the utilised land to the local risk of soil erosion due to agricultural activities. This characterisation reflects that considerable global areas are subject to light and especially strong human-induced land degradation (FAO 2021). Evidence suggests during the last 6–7 decades over **35 % of arable land has been degraded due to human induced activities** (Gupta 2019). The calculation of erosion risk combines the global land-use maps with a map of soil erodibility by Gupta et. al (2024) and refers to the inherent susceptibility of soil to erosion.

Historical evolution and composition of the agricultural land footprint

Figure 7.3 shows the historical evolution of the agricultural land footprint of Germany and its development in the calculated reference scenario and wedges. In 2021, the total agricultural land footprint of the German bioeconomy was approximately **468 thousand km²**, of which 183 thousand km² related to cropland and 285 thousand km² to grassland.

The agricultural land footprint per capita in 2021 was around **5,635 m²** (Table 7.3). Around 50–60 % of German consumption was comprised of imported commodities. As a consequence, **the per-capita agricultural land footprint in foreign countries was 6.7 times higher than the domestic footprint** (4,903 m² compared to 732 m² in 2021).

There was a significant reduction of the agricultural land footprint over the past two decades, though the trend has exhibited fluctuations. Notably, the **agricultural land footprint decreased by almost 38 % between 2000 and 2021 from 752 thousand km² to 468 thousand km²**. This decline was primarily driven by

43 In a similar order of magnitude, Austria has recently set a target of 7 t per person for the entire economy (RMC including also abiotic resources like metals and sand. The Austrian footprint consist of 30 % biotic and 70 % abiotic materials. Assuming a proportional decrease between resource types, the target corresponds to approximately 2 t biomass (BMK 2020).

MONITORING CHECK BOX 9

Toward safe and just global benchmarks

Why are global benchmarks needed?

To set footprints in relation to *safe* and *just* consumption levels, benchmarks are needed that are compatible with long-term sustainable development within the carrying capacity of the Earth. Due to the increase in global trade and its displacement of resources (Steen-Olsen et al. 2012), it is not sufficient to consider only territorial environmental sustainability to achieve a balanced bioeconomy in a global context. To achieve multiple SDGs, consumption levels must be consistent with sustainable production capacities and be both *fair* and *just.*

Defining global benchmarks: State of the art

The definition of such benchmark indicators represents a significant area of research (Häyhä et al. 2016, Zhang et al. 2021). The challenge is twofold: First, defining global carrying capacities/sustainable limits for each indicator is far from trivial. For some indicators, thresholds can be scientifically demonstrated, such as for global warming where exceeding certain levels will trigger irreversible changes, such as the collapse of climate-regulating ice sheets (Armstrong McKay et al. 2022). For all indicators, judgments — based not only on knowledge but also on values — are needed to define how much risk and environmental degradation is acceptable. The interlinkages between the different footprint indicators, as well as conflicting sustainability dimensions and land use needs, add complexity to the definition of global benchmarks. The planetary boundaries concept aims to define global *safe* limits for nine earth processes (Richardson et al. 2023), for which also *safe* and *just* boundaries have been proposed (Rockström et al. 2023). Second, turning global limits into national consumption benchmarks includes additional ethical considerations and value-based decisions about how to define and operationalise a *just* share, both among the current population and between the current and future generations (Gupta et al. 2023).

Inclusion of proxy ranges in this report

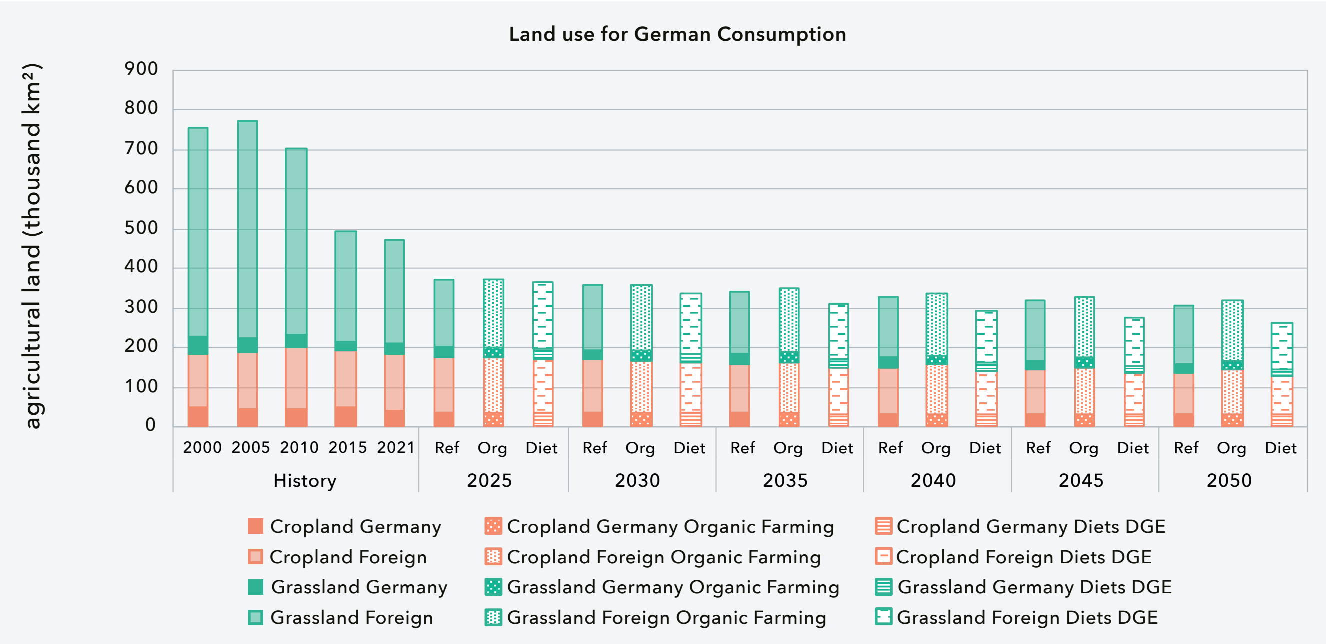
By using the best available estimates of global *safe* and *just* benchmarks given in literature, we have indicated the comparative order of magnitude of German consumption for agricultural biomass, forestry biomass and cropland. Nevertheless, we recognise that this is a work in progress and is indicative of the types of information needed to evaluate and quantify (over)consumption.

Next steps

Further developing global benchmarks requires an increased:

- Scientific effort to advance and synthesise available knowledge on global limits, including future modelling, and
- Active participation of citizens and stakeholders to address the normative aspects of benchmarks and ensure their legitimacy (Blum 2024).

Figure 7.3 Evolution of the German agricultural land footprint domestically and in foreign regions during 2000–2021, in thousand square kilometers, for the Reference scenario (Ref) and the Wedges Organic Farming (Org) and Diets according to the German Nutrition Society (DGE) (Diet), differentiated by cropland and grassland



reductions in the footprint of fodder crops, grazing, and the production of vegetables and fruit, while the footprint associated with other food products has remained relatively stable. Between 2000 and 2021, especially grassland use in foreign countries has decreased while cropland use only decreased slightly.

Looking at the **erosion risk** in 2021, 313 thousand km² (67 %) of the utilised agricultural land was located on areas at medium risk while 6,643 km² (1.4 %) was located on high risk areas. In comparison, agricultural land on medium risk areas in the year 2000 was 530 thousand km² (70 %) and 10,370 km² (1.37 %) on high risk areas.

Origin of the agricultural land used for consumption in Germany 2021

Figure 7.4 shows the German agricultural land footprint in the main sourcing countries in 2021, subdivided into the respective commodities. The country with the largest total agricultural land use is Argentina (89.5 thousand km²), followed by Germany itself (61 thousand km²), the USA (34.4 thousand km²) and China (27 thousand km²). The dominant land use that contributes to the footprint in Argentina, the USA and China is grazing. In comparison, **cropland has a much lower footprint.** The five most important foreign countries of origin where cropland imposed the largest part of the agricultural land footprint are India, France, Poland, Spain and the Democratic Repulic of the Congo. The crops with the highest land demands are oil crops, cereals, roots and tubers, fruits and spices.

Table 7.3 Development of the agricultural land footprint (sum of crop, pasture, Germany and foreign countries) in the reference scenario compared to the 'wedges' organic farming and dietary change in square meters per capita

	2000	2010	2021	2030	2040	2050
Reference scenario	9 140	5 971	5 635	4 269	3 919	3 683
Organic Farming				4 292	4 049	3 902
Diets DGE				4 003	3 486	3 161

Source: CESR, based on LandSHIFT results calculated based on the GLORIA database from 2000 to 2021 and modelled projections to 2050.

Projected development to 2050 – reference scenario and wedges

In the reference scenario, the agricultural land footprint decreases from 468 thousand km² in 2021 to **304 thousand km² in 2050** (Figure 7.3). This means a decline of the per capita footprint from 5,635 m² in 2021 to 3,686 m² in 2050 (Table 7.3). This development is primarily a result of reducing grassland use as a consequence of reduced meat consumption, in particular from ruminants. The reduction of cropland is lower and mainly caused by a decreasing sugar and wheat cultivation mainly by 2030, with a further slight decline by 2050. However, in some regions the footprint of fibre and nuts slightly increased.

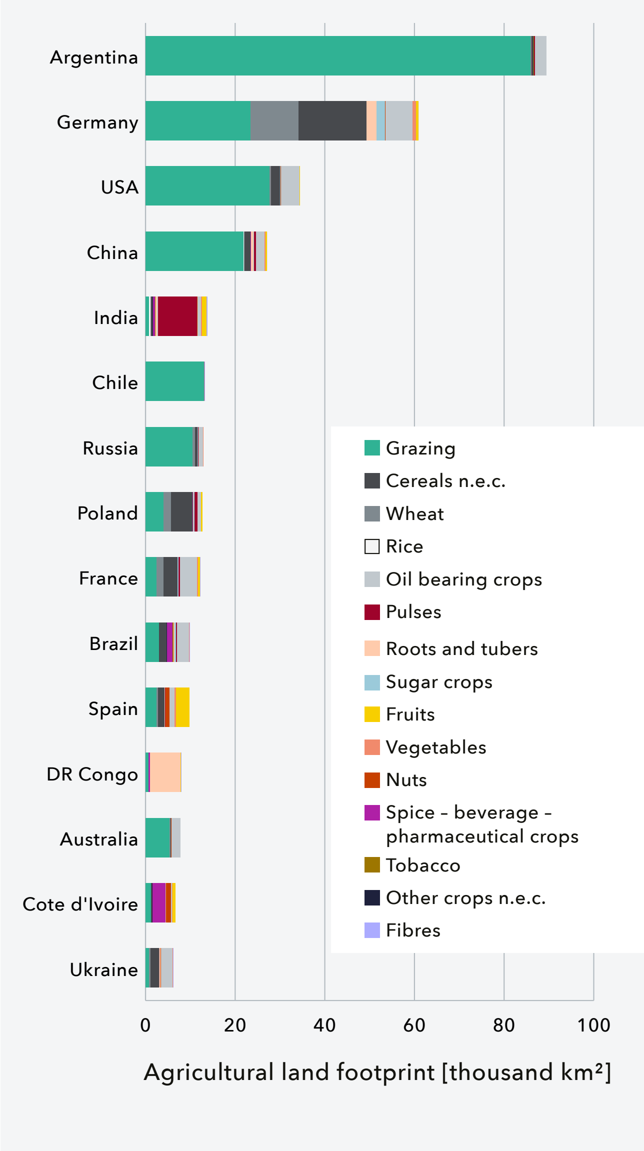
In addition the agricultural land footprint for the organic farming and the changing diets wedge were calculated until the year 2050 (Figure 7.3). We see significant discrepancies to the achieved reduction in the reference scenario. In the organic farming wedge, which is a theoretical what-if thought experient of 100 % organic farming in Germany, the agricultural land footprint in 2050 is 322 thousand km², **5.9 % higher** than the reference. This can be explained by the assumed lower crop yields under organic farming in Germany and corresponding higher land demands as well as substitution effects by international trade. In contrast, the Diets DGE wedge has a land footprint of 261 thousand km² in 2050, which is **14 % lower** than the reference, mainly due to the drastic decrease of grassland area used for the production of meat consumed in Germany. The per capita values are shown in Table 7.3.

Putting consumption into perspective – comparative benchmarks

In order to put the agricultural land footprint into perspective we compare the calculated values to results from the analyses conducted in context of the first pilot report, statistical data, and suggested benchmarks from the literature:

- Degree of self-sufficiency: The total land coverage for agriculture in Germany in 2021 was around 166 thousand km² (including domestic production for German use and for exports). The largest shares were comprised of cropland with 116.6 thousand km² and grasslands with 47.3 thousand km². In comparison, the German agricultural land footprint was **2.82 times higher**.
- International comparison: In 2021, the globally available cropland per person was 2,000 m² (FAO 2023a). The German per capita agricultural land footprint by cropland in 2021 was 2,208 m², which is around **10 % higher**.
- Preliminary global safe and just benchmark: A benchmark value for global sustainable use of cropland per person in the year 2050 is 1600 m² (Bringezu 2019). In the reference scenario, the German agricultural footprint by cropland per capita slightly surpasses this benchmark by 1.25 %. In the changing diets wedge the footprint by cropland is 5.5 % lower while in the organic farming wedge, the footprint is 12.5 % higher than the benchmark value.

Figure 7.4 German agricultural land footprint in 2021 by region and commodity, showing the most important source countries and their most important crops in terms of land utilised for German consumption



Key messages

- The agricultural land footprint is a useful indicator to measure the global agricultural land utilised for crop production and grazing needed for German consumption. It builds on the agricultural biomass footprint and helps to create a consistent picture of biomass use and corresponding area demands.
- 60.8 % of the agricultural land footprint in 2021 is comprised of grassland used for the production of meat and milk products.
- 68.4 % of the utilised land in 2021 is characterised by at least a medium risk for soil erosion. As soil degradation is a critical problem for sustaining agricultural production systems, on-farm measures to improve soil quality and to minimise soil loss should be actively supported as part of sustainable supply chains.
- In particular, dietary change is an important lever to further reduce the land footprint. Simple scenario analysis showed that the land footprint could be further reduced by 14 % compared to the reference scenario in 2050, which would make it possible to achieve levels of consumption under the global benchmark for safe and just consumption.

Due to relatively lower crop yields, in the first glance, organic farming seems to have negative effects on the agricultural land footprint in 2050: Full coverage (100 % of agricultural land under organic farming in Germany) would raise the footprint by 5.9 % compared to the reference scenario in 2050. Here it has to be noted that potentially positive effects on soil carbon, biodiversity of agricultural systems and reduced application of mineral fertilizer were not accounted for in the analysis.

7.4 Timber (industrial roundwood) footprint

What is the timber footprint?

The timber footprint quantifies the amount of primary wood raw material or roundwood that is harvested in Germany and elsewhere for the consumption of wood and wood-based products in Germany. The aim is to capture the amount of timber extracted annually as a proxy for the consumption of annual primary roundwood consumption (secondary flows of recycled material are not included) (Beck-O'Brien et al. 2022). The timber footprint corresponds to the agricultural biomass footprint as regards calculation methods, except that it concerns forestry-based biomass. In this report it is reported in cubic meters of roundwood equivalents under bark.

The GLORIA database is used to calculate the timber footprint for the **first time in this report**. As such while the method builds on approaches published in scientific literature (Egenolf et al. 2021, Egenolf et al. 2022; Bringezu et al. 2021b), there are still some **issues to work out**. In particular, there is insufficient differentiation in the GLORIA database as regards especially sub-sectors, unreliability in reporting of domestic extraction after 2018[44], a loss of precision due to the use of one conversion value[45], and uncertainties in the data specifically on fuel wood (especially as regards imports from countries that rely on high levels of wood for their own energy supply). For that reason, we limit the presentation of the footprint to industrial roundwood as a **preliminary estimation** and indication of **trends** (comparing developments of the footprint over time).

Despite the uncertainties and early stage of development and application, we decided to include preliminary results in particular to showcase the efforts toward further developing this approach. Because the footprint includes indirect upstream flows for imports (i.e. the wood used to produce the product imported) the indicator could be used in the future to help show the total burden of German consumption on forests across the Earth. It could also be used to compare German consumption levels to other countries' consumption footprints, as one advantage of the global database is that it can be used to calculate comparative footprints for multiple countries. Such a perspective complements the more detailed, comprehensive and reliable monitoring of specific forestry biomass flows developed and reported at a national German level (see Section 6.3).

44 The GLORIA database does not (yet) reflect the large increase in salvage harvesting between 2018 and 2021 as reported by German sources (see Chapter 6.3) as well as Destatis (2024c).

45 The timber footprint is calculated in GLORIA in tonnes and is converted to cubic meters roundwood equivalents (m^3 RE) using a conversion value of 1.61. This was done to maintain comparability with earlier timber footprint calculations and so that, in the future, footprint results can be compared with German and global forest growth data (requiring a further conversion to consider bark and harvest residues, not shown here—see also Egenolf et al. 2022).

Table 7.4 Development of the German timber footprint (industrial roundwood only) between 2000 and 2021, cubic meter roundwood equivalents under bark per capita

	2000	2010	2015	2016	2017	2018	2019	2020	2021
Timber (industrial roundwood) footprint	**0.97**	**0.80**	**0.77**	**0.75**	**0.80**	**0.82**	**0.76**	**0.72**	**0.75**
Domestic extraction (industrial roundwood)	0.60	0.72	0.68	0.65	0.65	0.78	0.83	0.97	1.00
Footprint of exports (industrial roundwood)	0.45	0.58	0.56	0.61	0.58	0.76	0.57	0.79	0.79
Footprint of imports (industrial roundwood)	0.83	0.66	0.60	0.70	0.73	0.80	0.50	0.55	0.54

Source: GWS based on GLORIA database; Destatis (2024) for domestic extraction from 2018 to 2021; Population data stems from Riahi et al. (2017)

Per capita consumption footprint (industrial roundwood)

The German timber (industrial roundwood) footprint of consumption is 0.75 cubic meters roundwood equivalents (m^3 RE) under bark per capita in 2021. According to the footprint concept, 0.54 m^3 RE per capita were imported, while 0.79 m^3 RE per capita were exported in 2021. Since 2019, Germany has developed from a net importer to a net exporter of industrial roundwood footprints, likely due to the strong increase in domestic extraction (as a result of forest damage). Domestic production for industrial roundwood reached 1.00 m^3 RE per capita in 2021, especially as wood damaged by drought and disease had to be harvested.

Historical evolution and composition of the timber footprint

The timber (industrial roundwood) footprint in Germany was 62 million m^3 RE in 2021 (Figure 7.5). It has fallen significantly over time, with fluctuations partly due to storm damage such as in 2007, which led to high domestic extraction in some years. The use of industrial roundwood has remained quite stable since 2004.

The findings depicted are lower than the timber footprint presented in the pilot report (Bringezu et al. 2021b, Bringezu et al. 2022) and in Egenolf et al. (2022), which included fuelwood and other extraction. For example, the total timber footprint of consumption based on Exiobase was calculated at 104 million m^3 RE under bark for 2021 (Egenolf et al. 2022). However, due to the different calculations, a direct comparison of the results is not possible.

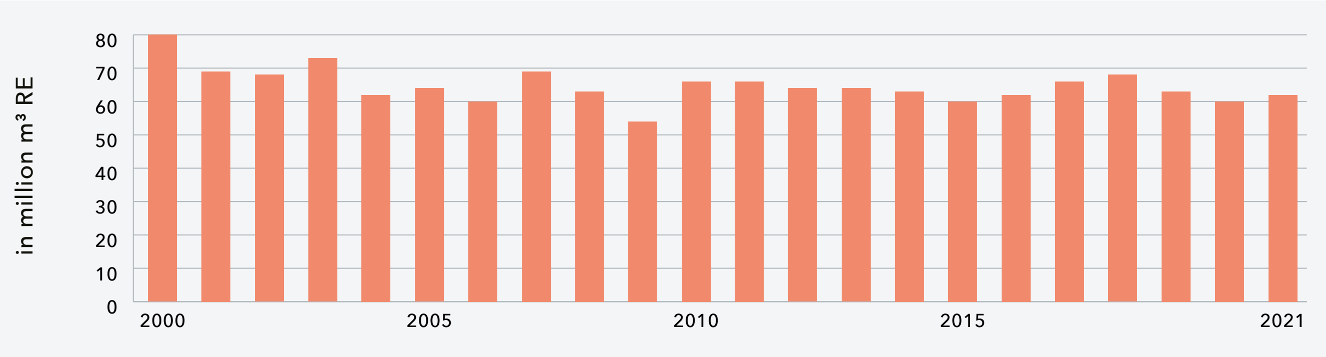
Origin of the industrial roundwood consumed in Germany

Figure 7.6 shows the regional distribution of the origin of primary timber consumed in Germany in 2021. Overall, 35 % of the timber footprint (industrial roundwood) in 2021 came from Germany, 40 % from the rest of the EU-27 and 6 % from the rest of Europe, which means that 81 % stemmed from Europe. Africa is an important supply region, which must be further examined in the future with a view to the detailed trade statistics for wood and wood products, because the calculated values appear (too) high. In comparison, Egenolf et al. (2022) calculated that 49 % of the total timber footprint in 2021 originated from Germany and 26 % from the rest of Europe based on EXIOBASE data.

Projected development to 2050 – Reference scenario

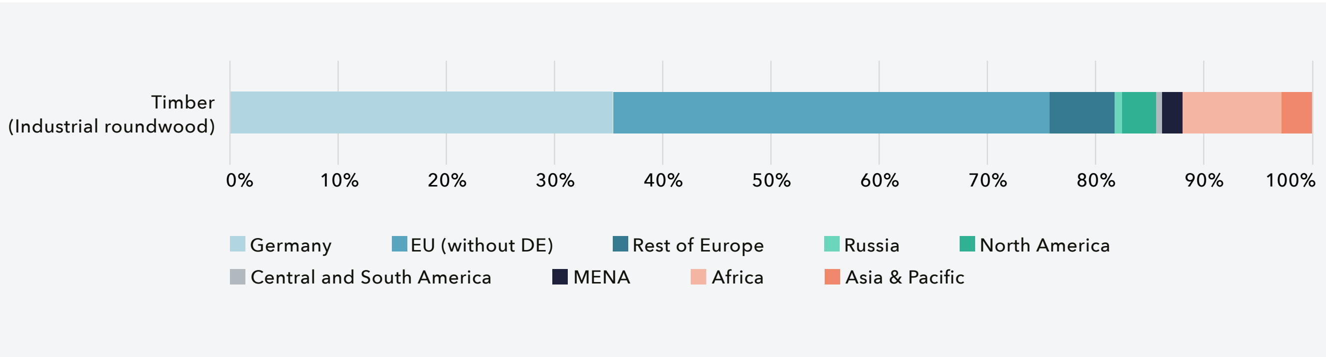
In the reference scenario, the timber (industrial roundwood) footprint remains almost constant in the longer term. It increases from 0.75 m^3 RE in 2021 to 0.76 m^3 RE in 2050. Under business-as-usual conditions, the demand for timber products is assumed to increase with GDP. On the other hand, there is also a certain increase in productivity in other countries, which largely offsets this increase. The various sustainability wedges considered so far have no major influence on the timber (industrial roundwood) footprint.

Figure 7.5 Industrial roundwood timber footprint of Germany in million cubic meters roundwood equivalents 2000 to 2021



Source: GWS based on GLORIA.

Figure 7.6 Regional contribution to the German timber (industrial roundwood) footprint in 2021 in %



Source: GWS based on GLORIA

Table 7.5 Development of the timber footprint (industrial roundwood) in the reference scenario in cubic meters roundwood equivalents per capita

	2000	2010	2021	2030	2040	2050
Reference	0.97	0.80	0.75	0.75	0.75	0.76

Source: GWS, based on GLORIA database from 2000 to 2021, projections for 2030 to 2050.

Key messages

- By tracking trends in consumption patterns as well as indirect flows connected to timber consumption, the timber footprint could contribute to monitoring Germany's contribution to pressures on global forests, as well as to grounding the discussion on how to prioritise consumption of forest-based wood in Germany. But to this end, the method and underlying database need improvement.
- Further work is needed to improve the reliability of the global database (especially as regards fuel wood and domestic extraction in Germany after 2018) as well as on conversion values and alternative options (for primary data) in order to be able to develop robust results for the total timber footprint. Fortunately, GLORIA is regularly updated and applied also by international institutions which opens up the possibility of improvements in this regard.

7.5 Water footprint

What is the water footprint?

The water footprint is comprised of the agricultural water used to grow the crops and crop-based goods consumed in Germany. It focuses on agricultural biomass grown both in Germany and abroad. The basic water footprint is comprised of two aspects:

- **Total water requirement:** equalling the total plant evapotranspiration during the growing period
- **Irrigation water withdrawals**: equalling the proportion of evapotranspiration that is not fed by rainfall

The **water quality footprint** has been developed to depict a third aspect related to theoretical water requirements, as well as agricultural production practices:

- **Virtual dilution volume:** is the amount of water needed to dilute the emissions of nitrogen, phosphorus and glyphosate applied to fields below certain thresholds

Water stress in the growing regions is considered by comparing hydrological water availability to human water use, i.e. water abstraction for households, irrigation and livestock, industry and energy production. A withdrawal-to-availability ratio of less than 0.2 is not considered as water stress, while between 0.2 and 0.4 a medium water stress situation is assumed and if 40 % or more of the available water is withdrawn, there is high water stress.

Germany's water footprint

The water footprint of the German bioeconomy in 2020 was **37 cubic kilometers (km^3)**, of which **3 km^3 were irrigation water withdrawals.** The difference (34 km^3) corresponds to the water that plants draw from the soil, i.e. rainwater. This information is important because this water consumption should be allocated to the end consumer, in this case the German bioeconomy. Until now, the focus of most virtual water assessments has been irrigation water. Rainwater, or so-called green water, was considered freely available. However, rainwater, like all other water flows in a catchment area, is part of the hydrological system and the use of water by humans in one place can have an impact on the entire system. We are therefore also presenting total water requirements here.

The per capita water footprint of Germany was **451** m^3, of which 43 m^3 were irrigation water.

Water footprint by growing region

The proportion of water consumed in Germany accounts for 14 % of the total water footprint. After Germany, the largest contributions came from the Ivory Coast, Brazil, Congo, Spain and Nigeria, each with around 5 %.

Germany accounts for only 4 % of the irrigation water footprint, meaning that relatively more irrigation water (96 % compared to 86 % of total water requirements) is used abroad. Water withdrawals for irrigation can additionally strain surface water and groundwater and should therefore be viewed as particularly critical. Spain, the US, Turkey, Iran, India and Greece are the countries that irrigate the most for the German bioeconomy. In Spain, Iran and Greece, irrigation accounts for well over 50 % of total water use.

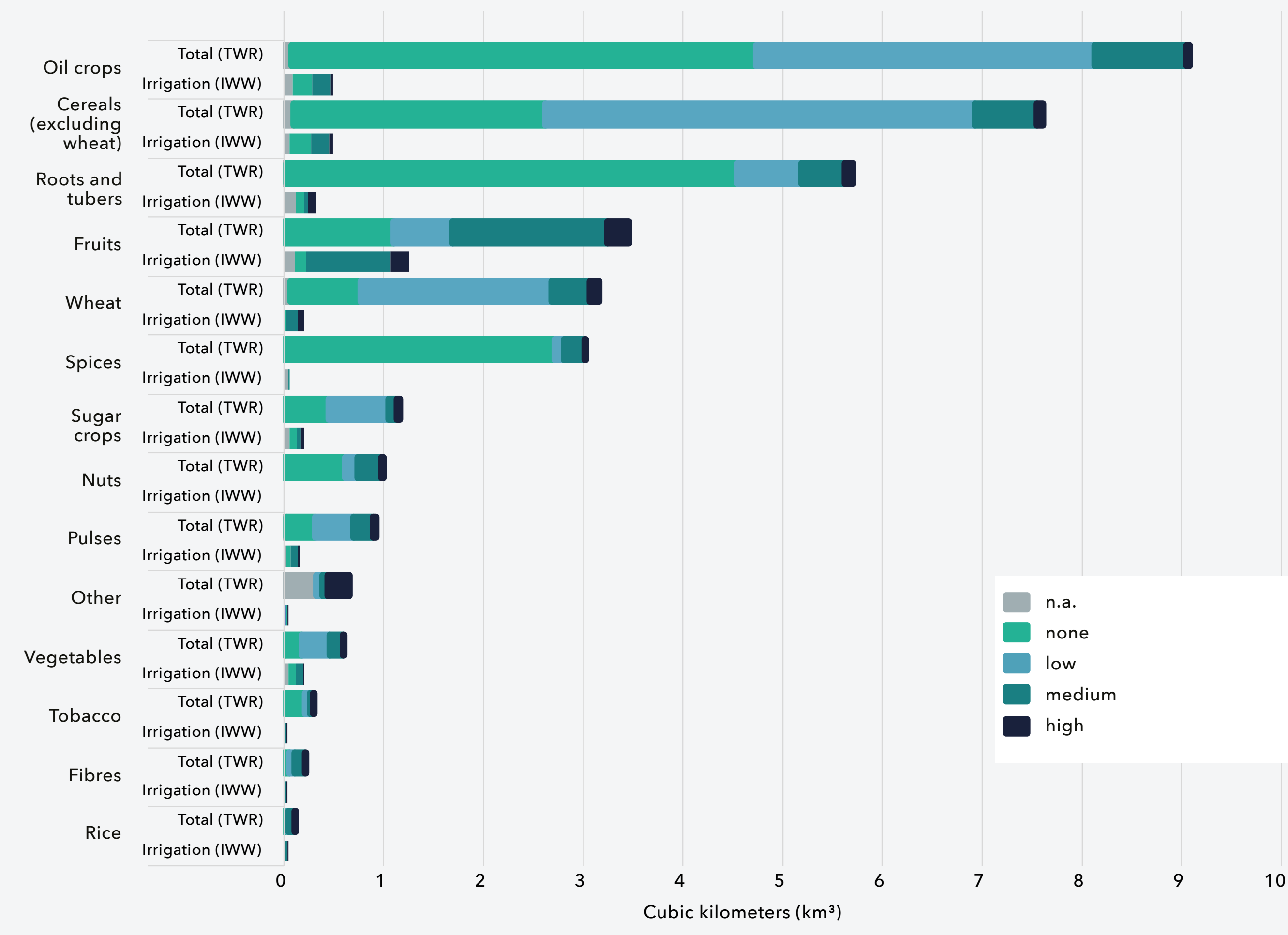
In 2020, **16 %** of the total water footprint of the German bioeconomy was associated with regions that suffer from **high water stress**, led by the countries Iran, Egypt, Pakistan, Tunisia, Lybia and Syria. In the countries with high water stress, the median share of irrigation in the total water footprint was 53 %, significantly higher than the median for all countries (40 %). As water withdrawals for irrigation represent an additional burden on the hydrological system, dependence on imports from already water-stressed countries could become even more problematic in the future, if climate change exacerbates water scarcity in these countries further.

Water footprint by crop class

In 2020 the highest total water footprint was associated with the cultivation of oil crops, followed by cereals (excluding rice and wheat), roots and tubers and fruits (Figure 7.7). Irrigation plays a particularly important role in the production of fruits, rice and vegetables, where the proportion of irrigation is between 33 % and 36 % and is significantly higher than for all other crops (maximum 17 %).

16 % of the total water footprint associated with the production of agricultural goods for the German bioeconomy takes place in regions with high or medium water stress. This applies in particular to rice (58 %), fruits (51 %) and fibres (47 %), where the proportion of production in water-stressed areas is significantly higher than the median of 19 %.

Figure 7.7 Total water requirement (TWR) and irrigation water withdrawals (IWW) of agricultural goods for German consumption by primary crop class in 2020



Note: Categorised by water stress level (shares from none to high; n.a. refers to Rest-of-World regions where no regional water stress information are available). „Cereals" here exclude rice and wheat which are reported separately.

Water quality footprint

In 2020, the total water volume needed to dilute the water pollution associated with agricultural production for the German bioeconomy was 4000 km^3, which equals 90 times the volume of the Lake Constance. Domestic German production accounts for 22 % of this, which is 20 times the volume of Lake Constance. Looking at the countries of origin, Germany is associated with high water quality footprints in 49 countries. The largest one is caused by agricultural production in Germany itself. With approximately 14,000 m^3 per German inhabitant, it is 300 times the German direct drinking water withdrawal per German inhabitant (GDW) of 46 m^3 a^{-1} (Schomberg et al. 2023). In the majority of the 49 countries supplying Germany, the footprint is more than twice the GDW. While most countries belong to Europe, countries from all continents are represented, showing the global relevance of water pollution linked to German activities.

Development to 2050

Between 2020 and 2050, a business-as-usual scenario shows that the water footprint of the German bioeconomy would slightly decrease and the proportion of countries in which crops are produced under water stress conditions remains rather equal. However, this may also be an effect of the limited data basis for calculating future water stress, which is based on many assumptions. Assuming a change in diets, the total water use would be reduced by 8 % to 33 km^3 in 2050 and the irrigation volume would be reduced by 7 %. In the purely organic farming scenario, however, water volumes would increase by 13 % for total water use and by 16 % for irrigation water by 2050. This makes it clear that from a water availability and use perspective organic farming should be implemented together with a simultaneous dietary shift to be successfully realised without entailing regional water scarcity or being limited by water shortages.

Key messages

The uncertainties of our global and economy-wide analysis are still large, mainly due to data gaps and assumptions made. Nevertheless, we regard our results as useful for the development of national monitoring to identify and monitor points in the supply chain of the German bioeconomy where most water is used quantitatively and qualitatively.

- To reduce Germany's water footprint decision-makers must be made aware of the hotspots of water use in the German agricultural supply chain.
- Promoting the bioeconomy should neither cause the emergence nor the increase in regional scarcity of clean water worldwide.
- Monitoring is necessary not only to assess and monitor the situation in hotspot areas, but in particular to review purchasing habits to avoid unintentionally exacerbating water stress in other regions.
- The water quality footprint could be a tool to help raise consumer awareness on the impacts of consumption habits on water pollution in other countries.
- The water quality footprint should be given particular importance when developing bioeconomy policies, as it has often been underestimated or not taken into account at all. Even despite the uncertainties associated with this indicator, water pollution can make a dramatic contribution to the scarcity of clean water. The scarcity of clean water should be prioritised, monitored and taken into account in decision-making processes.

7.6 Climate footprint

What is the climate footprint?

The climate footprint captures greenhouse gases (GHG) emitted globally associated with the production of (biogenic) goods consumed in Germany. Considered GHG are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in tonnes of CO_2 equivalents. GHG emissions are usually accounted for according to the territorial principle in accordance with the UNFCCC guidelines. A country's GHG emissions are emissions resulting from the combustion or extraction and distribution of fossil fuels, as well as from the production of other goods such as agricultural products. This production-side emissions data in GLORIA comes from the EU's global EDGAR database (https://edgar.jrc.ec.europa.eu/). They do not correspond exactly to the GHG emissions officially reported by the Federal Environment Agency for Germany, as they use an own uniform methodology for all countries. A big advantage of EDGAR is thus the uniform and detailed global coverage. GHG emissions include agriculture, buildings, fuel exploitation, industrial combustion, power industry, processes, transport and waste. **Land-use related changes and emissions from forestry (LULUCF) are not included.** A method to include land use change related emissions is currently being developed, with preliminary results demonstrating the potentially significant magnitude of these impacts on Germany's climate footprint (see Monitoring Check Box 10 following this section).

As with the other footprints, it is also possible to attribute GHG emissions to consumption activities. If a German family eats rice from Thailand, the GHG emissions generated during cultivation and transportation are attributed to the German climate footprint. The approach used for other footprints can also be used to determine the GHG emissions of the individual countries and the GHG emissions attributable to domestic final demand based on the GLORIA data, which are also referred to as the **climate footprint**. It includes the global emissions for final demand of bioeconomy goods in Germany.

Per capita consumption footprint

The German climate footprint of consumption of the bioeconomy was **1.85 t of CO_2 equivalents per capita** in 2021. Domestic production-related emissions of the German bioeconomy accounted for 1.05 t of CO_2 equivalents per capita in 2021. For the German economy as a whole the climate footprint was 12 t of CO_2 equivalents per capita, while German production accounted for 9.15 t of CO_2 equivalents in 2021. Thus, the bioeconomy climate footprint comprised around **15 % of the total German economy footprint** in 2021. If land use change related emissions were included, the footprint would be higher. Preliminary results find that around 0.5 t of CO_2 equivalents per capita in 2021 were attributed to German consumption abroad linked to annualised land use change (See Monitoring Check Box 10).

Table 7.6 Development of the German climate footprint and GHG emissions for the bioeconomy and the total economy between 2000 and 2021, tonnes of CO_2 equivalents per capita

	2000	2010	2015	2016	2017	2018	2019	2020	2021
Climate footprint bioeconomy	**2.83**	**2.25**	**2.00**	**2.07**	**2.00**	**2.03**	**2.02**	**1.75**	**1.85**
GHG emissions bioeconomy (domestic approach)	1.27	1.12	1.13	1.11	1.09	1.08	1.02	1.03	1.05
Climate footprint Germany total	16.26	14.48	13.52	13.93	13.82	13.85	12.68	11.56	12.00
Domestic GHG emissions Germany total	12.20	10.81	10.77	10.80	10.60	10.28	9.62	8.71	9.15

Source: GWS, based on calculation with GLORIA database from 2000 to 2021.

Historical evolution and composition of the climate footprint

The climate footprint of the German bioeconomy was 152 million t of CO_2 equivalents in 2021. It has fallen significantly over time, with a peak in 2003. In 2021, it was 35 % lower compared to 2000. While the CO_2 emissions and N_2O emissions have been reduced in the period by 22 % and 18 %, methane emissions have gone down by 55 % compared to the year 2000. Reasons for the reduction are that emission intensities (as emissions per production unit) have decreased drastically over time and there are some structural shifts away from high emission activities such as meat consumption.

Origin of the climate footprint of the German bioeconomy

Figure 7.8 shows the regional distribution of the origin of GHG emissions attributed to German consumption of bioeconomy products in 2021. Overall, 33 % of the climate footprint in 2021 came from Germany, 22 % from the rest of the EU-27 and 3 % from the rest of Europe. Of the other regions, North Africa and the Middle East (7 %), Asia and the Pacific (8 %) and the rest of Africa (15 %) are important regions, where GHG emissions are "imported" from.

The rest of Africa accounts for 20 % of CO_2 emissions, while the Middle East and North Africa, the rest of Africa, Asia and the Pacific play an important role in N_2O emissions. Almost half of N_2O emissions come from outside Europe. For methane, most emissions are imported from Asia and the Pacific, followed by the rest of Africa.

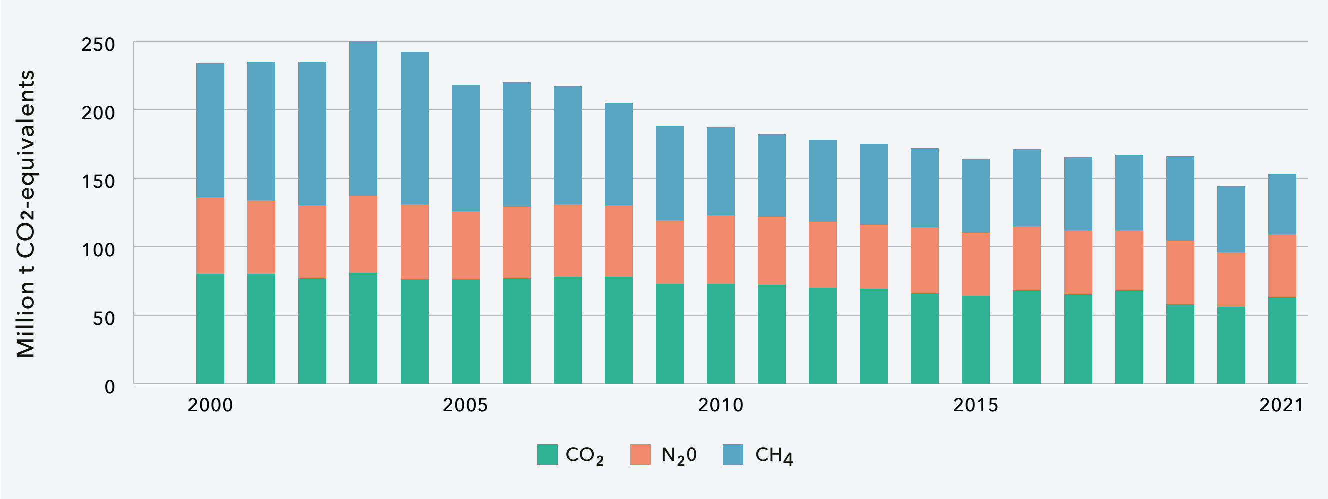
Compared to Bringezu et al. (2021a), where a climate footprint of the German bioeconomy of 1.9 t CO_2 equivalents is reported based on the EXIOBASE data for 2015, the climate footprint calculated with the GLORIA database is slightly higher with 2.0 t per capita.

Individual product groups according to the GLORIA classification with high contributions to the climate footprint of the German bioeconomy are growing leguminous crops and oil seeds (with 5 million t CO_2 equivalents in 2021), growing fruits and nuts (11 million t), growing beverage crops (6 million t), growing spices, aromatic, drug and pharmaceutical crops (6 million t), raising of cattle (10 million t), raising of swine/pigs (11 million t), raising of other animals and services to agriculture (18 million t), pulp and paper (3 million t), electric power generation, transmission and distribution (17 million t), distribution of gases (8 million t), and road transport (5 million t). Substitution with less GHG-intensive products such as from the bioeconomy, or in some cases decarbonization of production, are levers for reducing the climate footprint in the future.

Projected development to 2050 – Reference scenario and wedge Diets_DGE

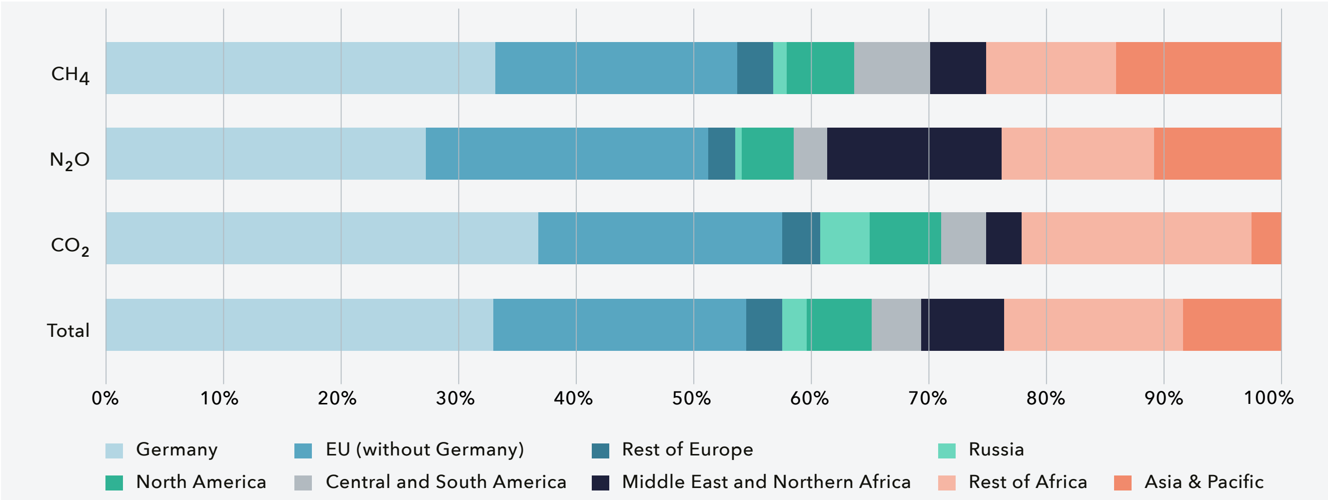
In contrast to other areas of the economy, for which structural constancy is (largely) assumed until 2050, in the area of energy and climate protection it is assumed that Germany and the EU-27 as well as the other countries participating in the EU ETS will achieve their binding climate neutrality targets by 2045 and 2050 respectively. For the rest of the world the development is adjusted to the Stated Policies Scenario of the recent World Energy Outlook (IEA 2023).

Figure 7.8 Climate footprint of the German bioeconomy in million tonnes of CO_2 equivalents from 2000 to 2021



Source: GWS, based on calculation with GLORIA database from 2000 to 2021.

Figure 7.9 Regional contribution to the German climate footprint of the bioeconomy in 2021 in percent



Source: GWS based on GLORIA

Table 7.7 Development of the climate footprint in the reference scenario in tonnes of CO_2 equivalents per capita

	2000	2010	2021	2030	2040	2050
Reference	2.83	2.25	1.85	1.34	0.96	0.71
Diets_DGE	2.83	2.25	1.85	1.22	0.82	0.59

Source: GWS, based on calculation with GLORIA database from 2000 to 2021, projections for 2030 to 2050.

In the reference scenario, the climate footprint will further decrease in the longer term. It will reach 1.34 t in 2030 and 0.71 t of CO_2 equivalents per capita in 2050. Dietary change according to the recommendations of German Nutrition Society (DGE) could reduce the climate footprint in the future further to 1.22 t in 2030 and 0.59 t of CO_2 equivalents per capita in 2050.

MONITORING CHECK BOX 10

Calculating land use change-related CO_2 emissions from biomass consumption in Germany

1. Method

Land-use change (LUC) has an impact on CO_2 accumulated in vegetation and soils. Changes in these sinks can be positive and negative, depending on whether more or less carbon is stored as in the previous year. The method for calculating CO_2 emissions from land-use change for a reporting year X associated with German consumption includes two steps:

a. **Carbon accounting:** Carbon accounting differentiates between a LUC-inventory period and a LUC-amortisation period (Maciel et al. 2022). The LUC-inventory period describes land-use change during Z years in a specific country before the reporting year X and the resulting total changes in carbon stocks in soils and vegetation. The LUC-amortisation period of Y years is used to annualise the total changes.

b. **Attribution:** The share of total annualised LUC-emissions in each exporting country attributed to German consumption in the reporting year X is equal the share of agricultural production exported to Germany from total agricultural production in the exporting country in year X. For example, if 5 % of total Brazilian agricultural production goes into German consumption in 2021, we attribute 5 % of the annualised LUC-emissions to Germany. This is a necessary simplification, as we cannot determine the exact spatial allocation of land-use change triggered by German consumption.

2. Implementation in SYMOBIO

For calculating the LUC-related carbon footprint for the reporting year 2021, we chose 20-year periods for LUC-inventory and LUC-amortisation (see Maciel et al. 2022). **In the first step,** we applied the LandSHIFT model (Schüngel et al. 2022) to generate global land-use maps for the years 2000/2001 and 2020/2021. Based on these grid maps, we determined for each GLORIA country/region the modelled land-use changes**. In the second step,** using a newly developed software tool that implements the IPCC guidelines for national greenhouse gas inventories (IPCC 2019) on grid level, we determined the associated losses or gains of carbon and converted these values to CO_2 emissions in each country**. In the third step,** we used GLORIA data on agricultural production in the exporting country and on biomass flows to German consumption (both in 2021) to determine the amount of LUC-related CO_2-emissions attributed to German consumption. So far, we do not account for changes in carbon stocks in other managed ecosystems such as forests.

3. Results

For the reporting year 2021, the annualised LUC-related emissions from German consumption within Germany amount to -327,065 t CO_2 (= -0.004 t CO_2 per capita), meaning that there is a relatively small carbon sink, e.g. due to afforestation or the net conversion of cropland to grassland. In exporting countries, we determined annualised emissions of 42,645,992 t CO_2 (= **0.53 t CO_2 per capita**) attributed to German consumption. The substantial emissions from imports indicate that Germany's consumption of imported agricultural products, such as soy, palm oil, or meat, has contributed to land-use changes abroad (or: *was located in countries that were characterised by land-use changes*) — most notably in regions like Latin America and Southeast Asia, where deforestation for crop cultivation or livestock production is prevalent.

4. Methodological considerations and gaps

Methodological considerations related to GHG emissions from land use change driven by agriculture include a more detailed representation of agricultural practices and further coordination with the calculations of the other GHG emissions as described above under climate footprint. A major gap of a complete climate footprint is the entire field of GHG emissions from forestry and forests, which has to be attributed to the bioeconomy.

Putting consumption into perspective – comparative benchmarks

The climate footprint of the bioeconomy must be considered against the background of the role of the bioeconomy in combating climate change. The bioeconomy is a key lever for reducing the GHG emissions of the fossil energy system. At the same time, the bioeconomy also generates GHG emissions and serves various other needs. One of the challenges is to greatly expand the contribution of the bioeconomy to combating climate change without the bioeconomy itself impacting climate change beyond long-term planetary boundaries while staying within other planetary boundaries, in particular as regards biodiversity loss related to land use change. The climate footprint of the bioeconomy must therefore be assessed in the overall context and together with other environmental footprints. In international comparison and with regard to long-term climate neutrality targets the climate footprint of Germany and of the German bioeconomy are currently too high.

- Germany's climate bioeconomy footprint was 76 % higher than German production-related bioeconomy GHG emissions in 2021
- The composition of the climate footprint indicates that adjusting meat consumption and energy use offer great potential to reduce the footprint by substitution by less GHG-intensive products or sometimes decarbonization in the future.
- Preliminary global safe and just benchmark: About 0.5 t CO_2 equivalents for the food system per person have been estimated in the literature (Steffen et al. 2015).

7.7 Biodiversity footprint

What is the biodiversity footprint?

The biodiversity footprint is a metric that quantifies the impact of biomass-based commodity production on biodiversity, focusing on how agricultural and forestry production affects species and ecosystems. It can be expressed as a 'production footprint' or as a 'consumption footprint'. The latter measures the production impacts on biodiversity that are embedded in the commodities consumed by a given country and sector, such as by the German bioeconomy. The methodology[46] is currently being developed and tested, with first results presented as a case study in this report.

The currently prototyped biodiversity footprint measures changes in the local persistence of the individual species and their habitats within larger ecosystems, which are impacted either by the displacement of habitat due to land conversion or by habitat degradation from intensified production practices. The footprint thus captures how both the expansion of production areas and the intensification of land use affect suitable habitats, and thereby threaten species survival and the integrity of ecosystems. The framework for calculating the biodiversity footprint enables a detailed understanding of the **link between consumption patterns in one region and biodiversity loss in production areas elsewhere**. The footprint can be flexibly calculated at different scales and levels of biodiversity and land-use sectoral organisation, in order to meet different end-user needs. For example, at the highest level of detail, impacts can be separately presented for each 10 × 10-km pixel and year, for each species and ecosystem type, for each commodity, and for land-use expansion and intensification. Alternatively, comprehensive biodiversity footprints can be calculated that reflect, for example, the cumulative impacts of production or consumption of all commodities on all vertebrates and all ecosystems worldwide over multiple decades.

Case study: Biodiversity impacts of German consumption of soy and sugar imported from Brazil

Brazil is the world's largest producer of both soybeans and sugarcane. Much of the Brazilian soybean production happens in Brazil's Cerrado, a global biodiversity hotspot, whereas sugarcane production is concentrated in the even more species- and endemism-rich Mata Atlântica biome (Myers et al. 2000). Germany's soybean imports from Brazil have been decreasing. They have more than halved from the 1997–2007 to the 2008–2018 period (from 12.9 to 5.8 million t; FAOSTAT 2024b). Meanwhile, Germany's imports of cane sugar have increased almost three-fold between the same periods (from 37.6 to 98.7 thousand t; FAOSTAT 2024b).

46 A scientific paper including details on the presented methods and workflow for calculating biodiversity footprints is currently in preparation for submission to a peer-reviewed journal. Please direct inquiries to carsten.meyer@idiv.de.

Based on the mere changes in German consumption of Brazilian commodities, one would expect that the biodiversity footprint of Germany's cane-sugar imports would have proportionally increased, while the footprint of Germany's soybean imports would have proportionally decreased. Yet, the opposite is true. The Brazilian biodiversity losses attributable to Germany's rising cane-sugar consumption **decreased by 87.1 %** from the 1997–2007 to the 2008–2018 period. The impacts of Germany's decreasing consumption of Brazilian soybean, in turn, **increased by 134.3 %** from the first to the second evaluation period. How are such counter-intuitive results possible?

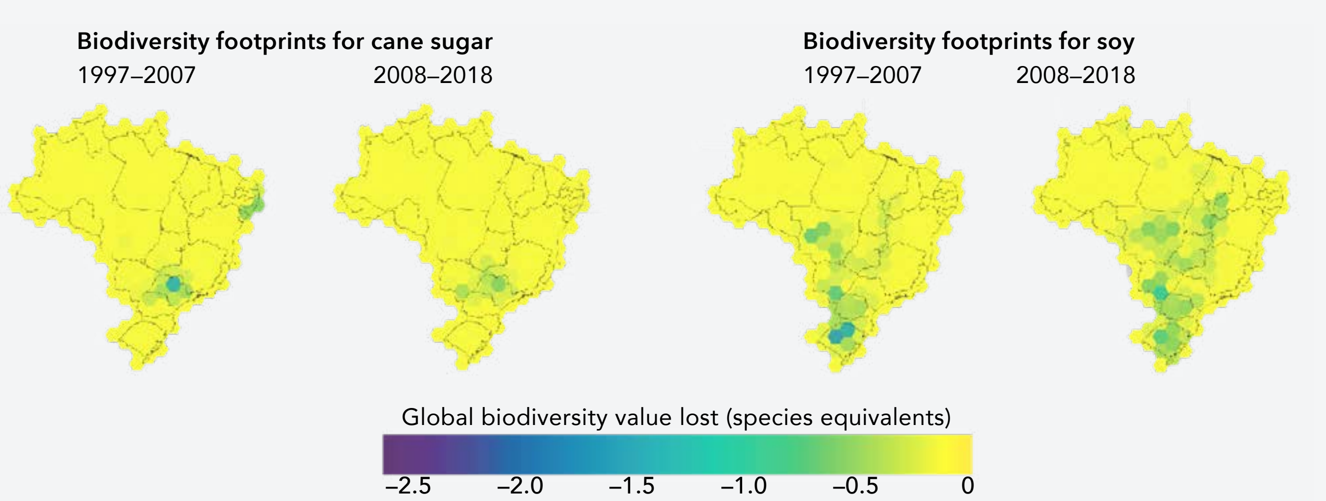
The reasons for these apparent paradoxes are the asymmetric changes in the production systems of these two crops as well as the differences in biodiversity that were exposed to these changes within the respective regions of Brazil. Both Brazil's sugarcane production and Brazil's soybean production increased substantially between these study periods (by 51.6 % and 98.4 %, respectively). Yet, Brazil's increase in sugarcane production was primarily due to intensification and expansion of sugarcane production within long-standing cropland areas of Brazil that had already been used fairly intensively during earlier decades. In contrast, Brazil's increase in soybean production mainly happened via the expansion of high-intensity soybean production systems into formerly much more extensively used, marginal agricultural regions in increasingly remote areas of the Cerrado (Zalles et al. 2019) that were originally used for producing other commodities (Figure 7.10).

Long-established agricultural regions typically have much less biodiversity that is both exposed and sensitive to threats from further agricultural land-use intensification than more recently opened agricultural regions (Melo et al. 2013). As such, **the replacement of extensive agricultural lands with more intensive soybean production systems in remote regions of the Brazilian Cerrado had a disproportionally higher impact on Brazilian biodiversity**. Before intensification, the agricultural landscapes had supported higher percentages of the original species assemblages, including many globally rare species, which had occupied larger and less heavily degraded habitat areas. Higher initial biodiversity values (cumulative persistence values across species) meant that more species were exposed to land-use intensification, and, those species were more sensitive to further intensification. This led to the disproportionately rapid decline in biodiversity values that is depicted by the footprint. In other words, the biodiversity impacts connected to Germany's consumption of Brazilian soy steeply increased, even though Brazilian imports to Germany more than halved. On the other hand, the biodiversity footprints of German consumption of Brazilian cane sugar strongly decreased relative to the earlier evaluation period, despite a substantial rise in consumption and despite the larger numbers of rare species that live in the Mata Atlântica biome, where Brazil's centers of sugarcane production lie. This is because most of the land-use-sensitive biodiversity had already been pushed back into protected areas and all but lost from the agricultural landscapes used for sugarcane production during earlier decades.

It is important to emphasize that even though the expansion of intensive soy production over formerly extensive agricultural landscapes translated into steeply increasing biodiversity footprints of German consumption of Brazilian soybean, this does not mean that Germany's biodiversity footprints could be lowered by sourcing more commodities from very extensive production systems, as the latter inevitably have much higher land footprints. The large biodiversity impacts of Brazilian soy production, which happened mainly via the expansion of intensive production modes over pre-existing agricultural landscapes, are still substantially smaller than the biodiversity declines that happened due to the loss of natural ecosystem areas at the deforestation frontier by new, extensively used agricultural lands, like cattle pastures and smallholder subsistence plots.

In this context, it is important to note that our case study of biodiversity footprints of Brazilian soy and sugarcane **only accounts for new biodiversity losses** driven by land-use expansion and intensification during a given evaluation period, which are attributed only to those commodities that are directly involved in the expansion and intensification processes (e.g., those that are produced on the agricultural areas in question during the evaluation period), and thus ignores more indirect effects. For example, our current approach to estimating biodiversity footprints does not attribute any historical impacts to commodities based on land-use legacies, i.e., historical biodiversity losses driven by land conversion are not partially attributed to commodities produced on those lands during later evaluation periods, even though the historical clearance of native woody vegetation co-facilitated the later production. Similarly, we **do not account for indirect land-use changes**, i.e., biodiversity impacts of new ecosystem conversions in frontier regions are fully attributed to whatever production system exists on the converted lands right after conversion (i.e., during that evaluation period), even though these systems may have been displaced from their original production areas

Figure 7.10 Changes in mammalian biodiversity values across Brazil due to production of sugarcane and soybean during the periods 1997–2007 and 2008–2018



Note: Biodiversity values are calculated by aggregating changes in persistence scores across species and their respective habitat areas within a given region (here: per hexagon cell).

by the expansion of more profitable commodity-production systems and thus 'pushed' deeper into the frontier (de Sa et al. 2013).

Nevertheless, such a biodiversity footprint presents a **complementary perspective** to analyses of other environmental footprints, such as agricultural land footprints or deforestation footprints. Besides considering biodiversity-related details such as fine-scale biogeographical gradients in species diversity species rarity, and the specific natural ecosystem types affected, the main factor differentiating this from these other footprints is the explicit consideration of land-use intensification effects.

Monitoring needs

It is crucial to invest in sufficiently reliable and detailed information. This includes both accounting for **spatial alignment of fine-scale biodiversity gradients with land-use patterns**, and for differences among biota of different agricultural production regions in terms of their **species' exposures and sensitivities to threats from land-use activities.** Global biodiversity maps are typically constructed by overlaying expert-drawn polygon (blob) maps that delimit the approximate outer boundaries of species' distributional changes, or by counting numbers of species known to occur within larger geographical areas like countries or ecoregions. In either case, such maps can only depict very broad-scale patterns but cannot inform (for most of the World) on differences in species assemblages among the specific regions within countries in which different agricultural commodities are produced, let alone on how many and which of those species may be exposed and sensitive to changes in agricultural production that were modelled or identified using fine-scale satellite imagery.

Credible estimations of biodiversity footprints of different agricultural commodities sourced worldwide require reliable time-series mapping of much finer-scale biodiversity patterns, and identifying those species and habitats that are likely to be affected. Both is possible, but **requires sophisticated data infrastructure and modelling tools that can integrate heterogeneous sources of biodiversity information, account for their inherent biases, and address associated uncertainties**. Taking shortcuts by relying on spatially coarse information or undifferentiated species counts leads to manifold over- and underestimations of regionally affected biodiversity which can reverse perceptions of relative impacts in different source regions, with the potential to mislead strategies to make supply chains more biodiversity-friendly.

Monitoring of biodiversity footprints needs to be further developed to **account for indirect land-use changes, spatial spillovers of biodiversity-harming agricultural inputs into nearby areas, and other indirect effects**. For any commodities whose total production areas in a given source region increase over pre-existing agricultural lands, or that tend to 'move' in to agricultural regions only after an initial period of agroeconomic opening and consolidation, the true biodiversity footprints will be substantially underestimated unless such indirect effects are considered.

Key messages

- The biodiversity footprint is intended to measure the impact of commodity consumption on species and ecosystems in a sufficiently reliable and comprehensive way to meet the monitoring needs of the German bioeconomy. As a new addition to more established environmental footprints, the biodiversity footprint exists as a prototype and its methodology and database are being further developed.
- The footprint captures biodiversity impacts of commodities in unprecedented detail, accounting for species-specific sensitivities and fine-scale exposures to land-use changes, and for effects of both land-use expansion and intensification via ecosystem displacement and degradation. To this end, it assimilates comprehensive biodiversity and remote sensing data using advanced machine-learning approaches.
- The presented case study for Germany's biodiversity footprints via commodity imports from Brazil demonstrates that this approach offers unique insights that vitally complement other environmental monitoring approaches such as deforestation monitoring and land footprints. The preliminary results underscore the key role of regional land-use dynamics (expansion, intensification, shifts) and biodiversity gradients and sensitivities, which can drive even greater footprint changes than mere changes in import and consumption volumes. This is demonstrated by a 134.3 % increase in the biodiversity footprint of Germany's consumption of Brazilian soy from 1997–2007 to 2008–2018, despite a 55 % decrease in imports.
- Effective and robust monitoring of biodiversity footprints depends vitally on spatially detailed and high-quality information on species and ecosystems. Simplistic biodiversity or proxy indicators cannot capture, nor sensibly attribute, biodiversity changes and are thus bound to mislead strategies for biodiversity-friendly supply chains. Integrating best-available data via sophisticated models allows the calculation of fit-for-purpose biodiversity footprint measures, like the prototype show here.
- Representative monitoring of the German bioeconomy's biodiversity impacts is highly feasible but requires additional investments in research and development projects.
- Given funding, the showcased approach to measuring biodiversity footprints can be extended to complete sets of agricultural and forestry commodities, source regions, ecosystem classes, and representative species groups. Moreover, the scales, foci and level of detail of footprint calculations are adaptable to meet diverse end-user needs. Further methodological refinements would be needed for a fair attribution of impacts that accounts for indirect effects.

MONITORING CHECK BOX 11

How is the biodiversity footprint calculated?

The currently prototyped method for calculating biodiversity footprints (Meyer et al. in prep.) follows a systematic workflow, loosely based on a workflow developed by Egli et al. (2018), that integrates detailed ecological and land-use data to quantify the biodiversity impacts of commodity production across spatial and temporal scales. It is applied for the first time in this report at a case-study level, focusing on selected crop commodities sourced from a selected source region. Pending further refinement, it could be applied to all crop commodities and their respective source regions, and also be extended to livestock and forestry commodities. The workflow follows several key steps, involving specific input data and modelling processes.

Input data collection

The first step involves gathering essential data on land-use changes and species' ecological requirements. Two primary types of land-use data are considered: (a) land-use expansion data, provided by satellite observations and/or land-use models, which detail the conversion of natural habitats into agricultural or forestry production areas, and (b) land-use intensification data, which capture changes in the percentage of the maximally achievable yields in a given region that are currently achieved within already cultivated areas, and which serve as a proxy for capturing intensification-associated management practices, such as increased pesticide or fertilizer use or higher livestock densities. On the ecological side, models of species distribution dynamics map the geographic areas where species occur and indicate the areas covered by the habitats providing the specific environmental conditions (e.g., vegetation type, altitude, proximity to water) that each species needs to survive. These datasets provide the foundation for modelling how production activities affect local habitats and species.

Modelling species-level impacts

The method uses the collected input data and models to estimate species-specific impacts of both land-use expansion and intensification. For land-use expansion, impacts are modelled by quantifying the area of natural habitat that is lost due to commodity production activities (e.g., conversion of forests to croplands). The loss of suitable habitat is linked to a reduction in local population persistence, based on the species' ecological requirements and the extent of habitat displacement. For land-use intensification, impacts are estimated by considering how changes in land-use practices typically associated with production increases degrade habitat quality (e.g., through pollution), reducing the suitability of remaining habitats for species survival. By combining these two types of impacts (expansion and intensification), the method calculates changes in the likelihood of local persistence for each affected species.

Aggregating impacts across regions and taxonomic groups

Once species-level impacts are calculated, the method aggregates these impacts to larger scales, such as larger taxonomic groups (e.g., all primates, all mammals, or all vertebrates) or broader geographic regions. To this end, the changes in local persistence across all species within a group or region, considering the area of habitat affected and the vulnerability of each species, are added together. Here, the global rarity of species is considered by relating local persistence changes to species' range-wide habitat areas and persistence scores. For example, if the aggregated persistence score across all species in a larger region decreases by a value of exactly 1, this might mean that one species went globally extinct, or that 50 species each lost 2 % of their range-wide habitat area. The result is a biodiversity footprint for the taxonomic group or region that reflects the cumulative impact of commodity production.

Attributing impacts to commodities and land-use sectors

The method links biodiversity impacts to individual commodities by tracing land-use changes associated with specific crops (e.g., soy, oil palm). By identifying the areas where these commodities are produced and assessing the biodiversity impacts in those regions, the method can attribute a biodiversity footprint to specific commodities. At the same time, impacts can also be calculated at the level of broader land-use sectors (e.g., all agricultural land) by aggregating the biodiversity effects of multiple commodities produced in the same region. This allows for a sector-wide assessment of biodiversity impacts driven by land-use changes. Pending further methodological adaptions, the workflow can be extended to comprehensively cover agricultural or forestry products (e.g., including livestock, timber, etc.).

Tracing impacts of production to consuming countries

Impacts attributed to the production of a given commodity can be further traced through the global supply chains to the places of final consumption (e.g., a given sector of the German bioeconomy), based on the trade relations and commodity flows represented in global databases like EXIOBASE or GLORIA and using the same general workflow also used to trace agricultural biomass and agricultural land footprints (compare sections 7.2 and 7.3).

Temporal tracking and change monitoring

The method is designed to capture biodiversity impacts over a specified period of time, such as annually or over multiple years. Land-use change data and species distribution models can be modelled for historical periods and can be updated periodically as more recent data become available, allowing the approach to track how biodiversity impacts evolve over time. By comparing results across different time periods, changes in the biodiversity footprint can be monitored, providing insights into whether the impact of commodity production on species persistence is increasing or decreasing.

7.8 Integrated findings and implications

This chapter has shown the dynamics of key environmental pressures associated with the German bioeconomy as well as potential levers to reduce them. This section summarises key scenario findings.

Footprint development – trend scenarios and alternatives

The **agricultural biomass footprint** exhibited a declining trend from 2000 to 2021. In the reference scenario it may be expected to fall from 4.1 t per capita in 2021 to 3.5 t per capita in 2050. In this scenario, it would exceed the global average (3.4 t per capita) by one-fifth in 2050. This corresponds to a high dependency from imports. Only 30 % of the biomass consumed is extracted within Germany, nearly half originates from outside Europe.

If the ongoing trend towards lower consumption of meat and dairy products would be enhanced to meet the German Nutrition Society (DGE) recommendations by 2050, the agricultural biomass footprint would be 13 % lower than in the reference scenario. Reaching 3 t per capita in 2050, it would still exceed the 2 t per capita reference value which has been suggested as a benchmark for total biomass extraction (agriculture, forestry, fisheries) to stay within planetary boundaries.

The **agricultural land footprint** decreased by almost 38 % between 2000 and 2021. This decline was primarily driven by reductions in the use of grassland in foreign countries. In 2021, 61 % of the agricultural land footprint comprised grassland. The largest meadows used for German consumption were in Argentina, the US and China, with each of them exceeding the extent of domestic meadows used to feed ruminants.

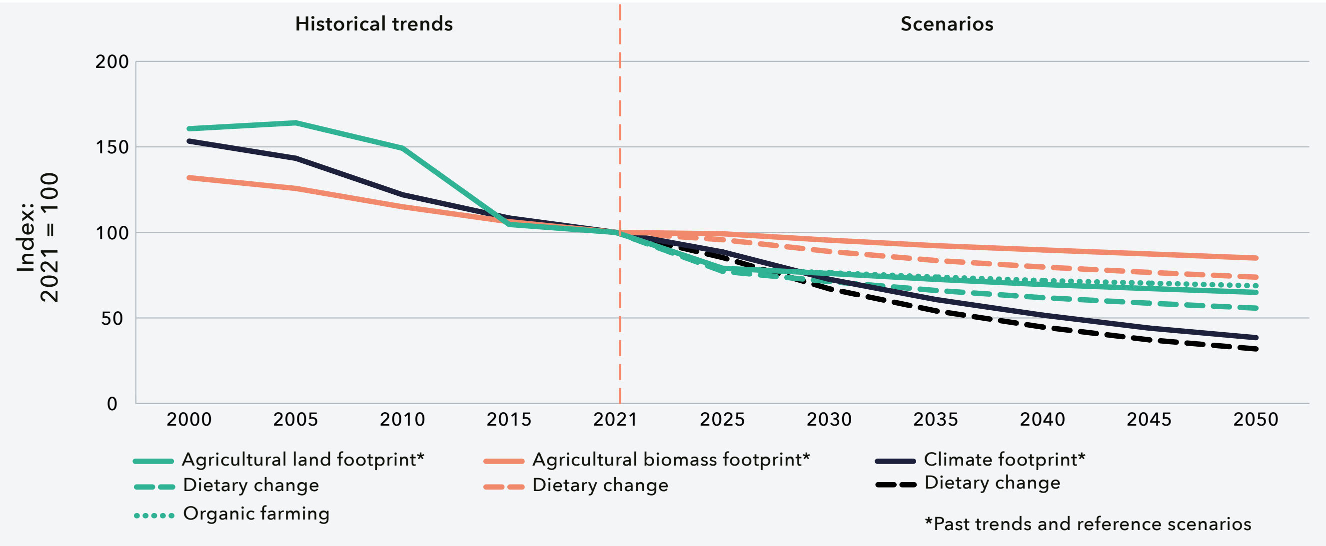
In the reference scenario, the agricultural land footprint might decrease from 5,635 m^2 in 2021 to 3,683 m^2 per capita in 2050. This development would primarily result from reduced grassland use as a consequence of reduced meat consumption, in particular from ruminants. Again, a shift to healthy diets could mitigate the agricultural land footprint further down to 3,161 m^2 per capita in 2050, i.e. minus 14 % compared to the reference scenario. If farming in Germany would switch to 100 % to organic, the agricultural land footprint in 2050 would reach 322 thousand km^2, or 5 % higher than the reference scenario (Figure 7.11)

As cropland has a much higher environmental impact than pasture land, its extension contributes in particular to degradation, often associated with low biodiversity, higher risk of erosion and nutrient pollution. The per capita agricultural land footprint by cropland in 2021 was 2,208 m^2, which is 10 % higher than the suggested reference value for sustainable resource use for 2030 (2,000 m^2) and 38 % higher than the reference value for 2050 (1,600 m^2). Under the reference scenario, the per capita agricultural land footprint by cropland in 2030 is projected to 1,999 m^2, it further declines to 1,621 m^2 in 2050.

A change to more healthy diets would reduce total water use by 8 % and irrigation volume by 7 % in 2050.

While the ***water footprint*** would hardly change in the reference scenario, a change to more healthy diets would reduce total water use by 8 % and irrigation volume by 7 % in 2050. Shifting to purely organic farming in Germany, however, would increase total water use by 13 % and irrigation water by 15 %. Thus, organic farming should be implemented together with a dietary shift, and care should be taken that regional water availability in the regions of origin of (shifted) imports are not compromised.

Figure 7.11 Historical and potential future developments of key environmental footprints of the German bioeconomy



Note: Trend line data is depicted in 5-year intervals

The ***climate footprint*** exhibited a significant reduction from 2.83 to 1.85 t CO_{2eq} per capita from 2000 to 2021, when accounted without land use change effects, with the decline becoming slower in the 2010er years. In the reference scenario it may be expected to reach 0.71 t CO_{2eq} per capita. Enhancing the path towards a healthy diet, German consumption would still induce 0.59 t CO_{2eq} per capita in 2050.

Overall, one-third of the bioeconomy climate footprint originates from within Germany. When land use change effects are included, the climate footprint could grow by an additional amount of 0.53 t CO_{2eq} per capita, totally emitted in the supply regions. This strongly indicates the relevance of trade flow interrelations of the German bioeconomy.

Effective levers and needs to combine policy measures

Reaching a **healthy diet** would have favourable impacts on most of the environmental footprints. The agricultural biomass footprint would be reduced in its major component, i.e. fodder and grazing; the agricultural land footprint would be diminished as grazing land is its dominant portion; the climate footprint would be reduced if less meat, especially from ruminants, and less dairy products were consumed; and due to a reduced land footprint, the biodiversity pressure by and large would indirectly be reduced (although it is important to note that the case studies also indicate that cropland expansion and/or intensification from e.g. pastures could have high impacts on biodiversity).

Reaching a healthy diet would have favorable impacts on most of the environmental footprints.

If German agriculture were to shift to 100 % organic farming, the agricultural land footprint would expand due to lower yields, although not as much as it could be reduced by a more healthy diet. Thus, shifting diets could also provide room for organic farming. Care is needed to ensure that the pressures to biodiversity in other regions do not grow, if Germany shifts toward less intensive agricultural production domestically. **Combined efforts to both reduce demands and promote more sustainable supply are essential**.

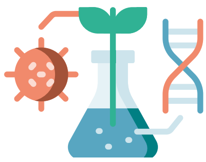
8. Conclusions

This report has presented indicators, trends and scenarios on the state and performance of the German bioeconomy. Our aim was to identify the challenges and opportunities that policy makers need to know in order to effectively steer the transition towards a circular and more sustainable bioeconomy. An overview of some of the key trends we identified is summarised here, followed by five key messages.

The trends and messages highlighted focus on the challenges ahead. This should not, however, detract from the big picture presented in this report—**the German bioeconomy is progressing, and our monitoring capacities are advancing along with it**. Noteworthy positive trends were observed—e.g. crop-driven deforestation for specific crops in hot spot regions is declining and meat consumption in Germany is going down. But, neither are happening fast enough. This is indicative of the broader challenge: how to reach the level and pace of change needed for developing a balanced bioeconomy, within a timeframe that matters for mitigating urgent humanitarian and environmental crises across the globe.

Trends to support: Scaling up critical levers for change

- 4 times as much biomass is used for feed than for food in Germany. Meat consumption levels are also at least 3 times higher than the dietary recommendations of the German Nutrition Society (DGE). While meat consumption is steadily declining in Germany, the pace and magnitude of change are not high enough to reach those recommendations before 2070. Reducing meat consumption is one of the biggest levers to lower Germany's global land pressures and make space for e.g. nature recovery or other forms of biomass use in the bioeconomy. Scenario modelling shows that if per capita meat consumption were reduced to 300 grams per week in Germany, the agricultural biomass footprint would be 13 % lower and the agricultural land footprint 14 % lower than in the reference scenario in 2050.



- Innovation in the areas carbon capture and use, agriculture 4.0, biotechnology, alternative proteins and biopharmaceuticals could be particularly relevant for developing Germany's future bioeconomy. They could contribute to, among other benefits, relieving the pressures of production, counterbalancing unavoidable emissions, raising biomass use efficiency, providing new functionalities (e.g antimicrobial properties, healthier therapeutics) and/or increasing competitiveness.
- From a global to local scale, prioritising conservation is urgent in areas where the destruction of natural ecosystems overlaps with high value nature areas, especially in places like the Amazon basin. Support is needed to mitigate threats amidst ongoing environmental pressures. This includes strengthening international agreements, continuing to invest in more sustainable supply chains for the German bioeconomy, and also lowering demand pressures for crops and products with large agricultural land footprints and particularly high risks of raising Germany's biodiversity footprint (such as soybeans).

- The monitoring of biodiversity in German forests reveals positive trends, with current and projected forest management practices generally conducive to improving habitat quality for species dependent on large trees and deadwood. However, scenario variations underscore the importance of carefully balancing wood extraction and conservation efforts to ensure biodiversity preservation and protection of ecosystem functions and services.
- German high-seas fisheries have stable catch results and made progress in resource efficiency, starting to produce fish oil and fish meal from by-products directly at sea while simultaneously increasing fishing efficiency as they reduced fleet capacities while maintaining catch quantities. This shift reflects broader efforts to enhance sustainability and value within the sector.
- The share of the German agricultural land footprint associated with medium to high risk of soil erosion has declined in absolute and relative terms since the year 2000. However, with two-thirds still associated with medium soil erosion risk in 2021, greater attention and a scaling-up of efforts to address soil degradation globally is needed.

Trends to watch:
Mitigating risks with counterbalancing measures

- On the one hand, there was a strong shift from the use of crop-based biofuels towards the use of 'waste'-based biofuels between 2020 and 2022, which is in accordance with Germany's policy goal of increasingly shifting the production of bioenergy towards residues and wastes. On the other hand, however, around 80 % of these residue- and waste-based biofuels were imported in 2022, with some of these imports entailing fraud risks. The production infrastructure for using advanced biofuel streams in Germany is also not yet being built, potentially limiting the capacity to make full use of the mobilisable potential of waste and residues estimated for Germany.
- The availability of secondary biomass (waste, residues and by-products) for material and energetic use slightly decreased rather than increased from 2015 to 2020. This sets national availability of secondary biomass in contrast to the generally increasing demand for biogenic carbon sources including wastes, residues and by-products. However, there are still untapped potentials that could be mobilised across the country, including e.g. increasing the quota of households connected to obligatory biowaste collection and the separate collection of spent cooking oils and fats.
- Drought and bark beetle infestations strongly impacted the forestry sector in recent years. Especially salvage harvesting increased, causing Germany to become a net exporter of roundwood in the 2020 assessment period. A comparison of scenarios indicates that especially future harvest potentials, in particular of conifers, could be significantly impacted if high rates of forest disturbance continue. This could affect capacities to meet demands in the bioeconomy with wood from German forests, in particular in e.g. construction with a preference for softwood. The occurrence of these natural disasters underscores the need to

support a structural shift in the composition of German forests—toward higher levels of deciduous species—as well as to support innovation for increasing the use of such species in German product markets.

- While aquaculture production is stagnating and high-seas fisheries remain stable, coastal fisheries in Germany are struggling to ensure their economic survival and would benefit from increased value added to their products by, e.g., regionalisation of the value chains and market establishment of under-utilised species.
- The bioeconomy is regarded as a key lever for reducing the GHG emissions of the fossil energy system. At the same time, the bioeconomy also generates GHG emissions in proportions higher than their contribution to value added and employment: The bioeconomy comprises at least 5 % of total gross value added, 7 % of total employment and around 15 % of the total climate footprint. Although the climate footprint of the German bioeconomy is declining, careful attention to land use impacts is still needed, in particular to prevent counteracting substitution benefits.
- The water footprint shows that the majority (86 %) of water use associated with the German bioeconomy occurs abroad, and that around 16 % of the water footprint currently stems from water-stressed regions. Close monitoring is needed to ensure that global water stress is not exacerbated by the development of the German bioeconomy. Moreover, the contribution of the German bioeconomy to water pollution (e.g. through over-fertilization and pesticide use beyond environmental thresholds) requires greater attention and prioritisation, with the water quality footprint providing one tool to this end.

Five key messages

1. Base policies on a systemic perspective

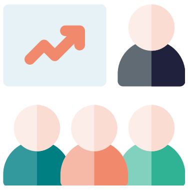
This report presented a multifaceted toolbox of methods to monitor the activities, impacts, performance and future outlooks of the German bioeconomy transition. Approaches ranged from monitoring product substitution effects at the micro level to linking environmental impacts abroad with national consumption patterns at the macro level. The evidence base provided — covering a multi-level, systemic perspective — should be considered when developing policies in order to minimise trade-offs, burden shifting, and unintended consequences.

- Effectively steering the bioeconomy transition in Germany requires taking overarching trends into account, considering both (a) trends in the German economy, e.g., the use of minerals, metals and other abiotic resources, and (b) the global context, e.g., trends such as the expected significant growth in global paper consumption to raise living standards in low-consuming countries. Footprints can help track comparative developments and quantify the overall effects of changed practices on both climate pressures and total resource requirements.

- While bio-based resources are potentially regenerative, they are not unlimited. Therefore, synergies and trade-offs between different biomass use options requires careful consideration. This is particularly relevant for decisions between material *versus* energy use. New policy strategies aim to prioritise the material re-use of biomass in cascades, with energy recovery as the final stage. However, biomass access between competing end uses is currently not equal. In comparison to the energy sector, the material use of biomass is generally more influenced by long-term strategies and less by regulatory frameworks and measures (such as quotas and price incentives). A more level playing field is needed as a first step toward incentivising cascading use. Investing in better monitoring capacities for cascades is also needed to identify and evaluate the trade-offs and potentials at different scales.
- As different climate change mitigation options may compete for biomass, demands in the economy should be weighed against ecosystem services and carbon sequestration capacities. A stronger focus on valuing ecosystem services beyond biomass provisioning is needed to help balance competing options for land and forest use. Payments for ecosystem services are one mechanism and could include aspects such as low fertilisation to uphold high-quality groundwater or reduced forest harvests to increase carbon sinks and/or habitat structures for rare and endangered species.

- Policy should not be based on a single indicator or perspective, but a blend of methodological approaches, like those depicted in this report (material flows analysis, life cycle assessment, remote sensing, innovation analysis, stakeholder participation, scenario modelling, etc.) in order to avoid spill over effects. For example, monitoring substitution effects faces the challenge that it relies on assumptions that may not fully capture real-world complexities, in particular as regards the scaling-up of product innovations. In this case, it is particularly relevant to pay attention to the limits and system boundaries when interpreting key findings for policy making. A sufficiently broad systems perspective, complementary approaches and cross-scale assessments are required.
- Some environmental indicators currently show positive trends across scenarios. While this is encouraging, careful management is still needed to optimise long-term outcomes. For example, the carbon sequestration capacity of certain compartments in natural systems, such as forest soils, may approach saturation over time, highlighting the need for diverse and flexible strategies in bioeconomy development that can be adapted over time to reflect new circumstances.
- Policy should focus not only on improving sustainable biomass production, but also on monitoring and promoting the sustainable processing and consumption of biomass-based products, including their use, re-use and avoidance when relevant (e.g. awareness raising as regards excess and sufficiency and incentivising business models that promote more efficient biomass use). Implementing cascading use requires investing in material re-use options at the beginning of the product life-cycle (design for recycling).

2. Remove barriers and invest in positive drivers



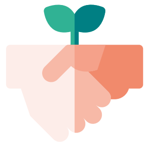
- Invest in education and skills development programmes to equip the German workforce, in particular in industry, with the necessary expertise in biotechnology, digitalization, and other bio-based and novel technologies needed to implement the future bioeconomy. Simultaneously, in light of declining employment in primary production sectors, provide support for rural development initiatives, such as fostering new creative business strategies (rural start-ups) related to bioeconomy goals. Promote a just transformation for affected communities by ensuring that the bioeconomy does not lead to precarious working conditions or intensify wage gaps.
- Create incentives for private sector investment in product and process innovation focused on smart, strategic and sustainable biomass use. Revisit existing misleading regulations, which e.g. act as a barrier to biomass access for especially material use, and develop supportive regulatory frameworks, including tax incentives and streamlined approval processes and regulations for bio-based products. However, make meeting sustainability criteria a prerequisite for funding to ensure responsible development. Avoid broad stroke measures that risk promoting overconsumption, instead favouring targeted approaches that encourage sustainable practices, accompanied by clear indicators to assess new value chains from the start.
- Foster the development of business models and infrastructures for re-use through investments in research and development. This should encompass technical, cross-cutting, and social innovation. Ensure that the quality of materials such as textiles, paper, and wood-based products is suitable for the transition to a circular bioeconomy, facilitating their repeated use and recycling.

3. Raise public awareness and participation

Technological innovations can contribute significantly to sustainability, but they must be complemented by behavioural changes and strategic prioritisation in biomass use. Engaging the public in both monitoring and policy-making processes fosters a more inclusive and effective transition to a sustainable bioeconomy, ensuring that diverse voices, fields of knowledge, values, interests and perspectives are considered in the process.

- Clarify that biological resources are overused in many places across the world. The agricultural land and agricultural biomass footprints, in particular, show that there is no sustainable capacity for increased total use of primary agricultural biomass in already high-consuming countries like Germany. Instead, inefficient and excessive use patterns must be adapted and the focus shifted to secondary biomass.
- Promote, e.g. in educational programs, the general message: "There is no 'waste', only secondary resources." This shift in perspective can encourage more sustainable practices.

- Improve collection processes and create incentives for citizens to participate in re-use initiatives. Clearly communicate these opportunities to the public. Consider using co-design approaches when developing and improving circularity-focused systems, especially as regards the re-use of urban 'waste'.
- Address social acceptance issues associated with the adoption of bio-based alternatives by raising awareness about overarching goals, risks and reasons for change.
- Support dietary change and food waste reductions. To this end, the targeted monitoring of dietary patterns, e.g. as part of German National Nutrition Monitoring, focusing in particular on meat and milk intake, could help political priority-setting and complement the ongoing food waste monitoring.



- Use footprints and other indictors to help facilitate social dialog and to develop a shared understanding of sustainable use and consumption in quantifiable terms—e.g. on how much is too much?
- Involve stakeholders in creating appealing visions of the future bioeconomy. This collaborative approach can help to identify not only policy priorities, but also contribute to developing monitoring in a credible, transparent and multi-perspective way.

4. Establish a regular bioeconomy monitoring

So far, research projects in Germany, like SYMOBIO 2.0 and MoBi II, have assessed the tools, data, and indicators available for monitoring the bioeconomy from a systems perspective, focusing on further developing both analytical methods and underlying data. This knowledge now needs to be used and directed toward the development of a regular bioeconomy monitoring, ideally characterised by a robust, comprehensive and manageable set of indicators that is useful for diverse groups of stakeholders (society, politics, business and science). To this end, gaps in data and indicators, e.g. in established statistics, must be addressed.

- The wider availability of official statistical data, in particular for research purposes, is crucial. This relates both to socio-economic data, e.g. raised in surveys covering bio-based shares, but for which certain base data is kept confidential, as well as environmental monitoring data, e.g. as regards remote sensing and environmental inventories. Currently, official statistics on e.g. residues from food production of aquatic biomass do not exist. Instead, monitoring relies on approximations based on expert knowledge. Both the reliability and timeliness of many bioeconomy monitoring indicators could be improved with better data access.
- Statistical classifications should be further developed and updated at regular intervals to better differentiate between bio-based and fossil-based sectors and products. Data are often available only at highly aggregated levels, which diminishes the capacity to account for smaller bio-based sectors or to monitor regional bioeconomy data (NUTS 1–3).
- The continuity of methodological approaches in statistical reporting is also essential. The disruption in 2018 of the time series for both gross value added and employment shown in this report hinders the ability to derive policy-relevant

implications regarding trends. The German Federal Statistical Office (Destatis) plays a fundamental role in this process and could benefit from increased support. This might also help to enhance the internationally comparable provision of resource footprint indicators (material, water, land).

- The spatial heterogeneity of impacts, such as the nitrogen balance per hectare when monitoring agricultural land, underscores the importance of considering regional variations in environmental impact assessments. National level reporting on larger-scale averages must be complemented by lower-scale monitoring at specific, e.g. regional scales, to detect critical local overshoots of environmental thresholds. Including indicators that can provide detailed information on spatial variations of impacts over time is necessary for comprehensive and cross-scale bioeconomy monitoring. The same is true for socio-economic impacts at disaggregated monitoring scales.
- Scenario modelling needs to expand to include relevant bioeconomy issues and priority indicators. Currently, water and biodiversity indicators are underrepresented in agriculture and forestry models. Given the observed effects of climate change and the requirements of the Nature Restoration Act, this is a critical gap. How future modelling can and should fit into the scope of a regular bioeconomy monitoring should be explored, with e.g. the core question being: Is sustainable development on track?
- To discuss and agree on a concise set of core metrics suitable for regular reporting, prioritisation and compromise is essential. Prioritisation requires broad stakeholder participation. Compromise may be necessary due to gaps between ideal indicators for bioeconomy monitoring and current monitoring capacities, which are in some cases under development and can only provide proxies at this time. The indicators provided in this report depict a potential core set of indicators on especially the status and environmental performance of the bioeconomy. Monitoring of socio-economic developments must be given more consideration overall. In the medium to long term, the whole physical economy might need to be monitored, using e.g. footprints, as there will be a need to use both biomass and minerals in a more sustainable manner.

5. Further support the development of modelling tools and monitoring capacities

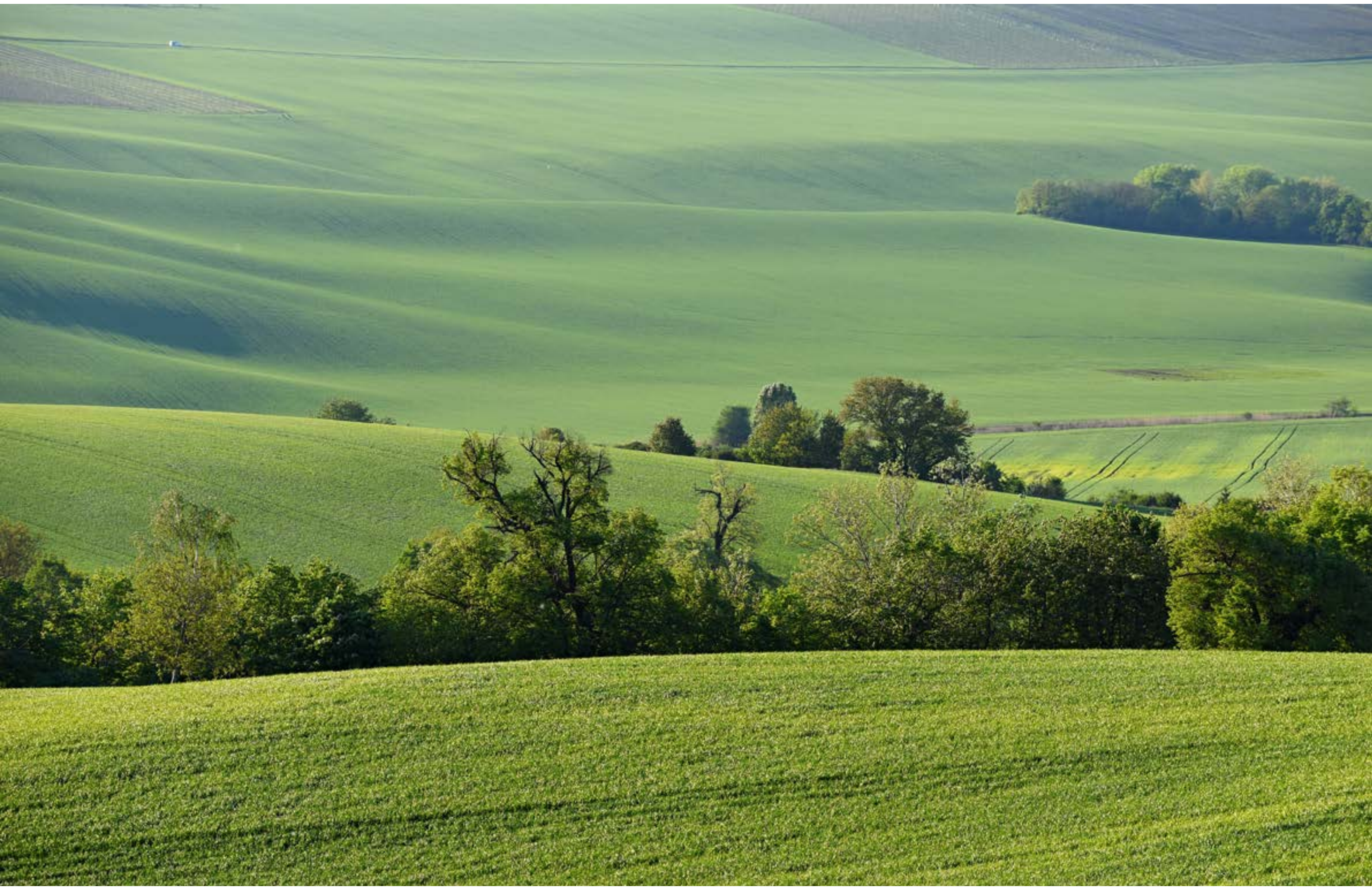
Multiple novel monitoring approaches were presented in this report. There is a pressing need to continue to maintain, expand and adapt existing modelling and monitoring capacities to specifically address core issues related to the bioeconomy. While some loosely related indicators and models have already been developed, they are not necessarily designed to tackle bioeconomy-related monitoring questions effectively. To better support strategic decision-making, it is essential to create fit-for-purpose indicators that align with the unique goals and needs of the bioeconomy. At the same time, it is crucial to reduce overlap and duplication in research efforts. By connecting bioeconomy monitoring to established and well-recognised monitoring systems, existing gaps in the monitoring landscape can be closed and understanding of interconnected topics is improved. Therefore, both types of analysis—improving new methods tailored to the bioeconomy and building links to established monitoring frameworks—should be further developed. This dual approach will facilitate a more comprehensive, concise and effective monitoring system that supports informed policy decisions in the bioeconomy sector.

- Monitoring biodiversity, and in particular biodiversity footprints, critically depends on additional funding. Sufficiently robust methods are in an earlier development phase compared to most other footprint indicators and still require additional refinements and adaptations to enable representative assessments across all commodities, sourcing regions, and ecosystems. Similarly, targeted data-mobilisation efforts are still needed to reduce attenuation bias in the modelling.
- In order to calculate robust bio-based shares based on production data, statistical information on physical quantities of biomass in products, not only monetary values of production, are needed. Thus, monitoring activities to quantify different types of biomass use in physical units should be extended. Such data would also provide the 'ground data' to better calibrate models and develop robust future scenarios.
- To ensure consistency and comparability across diverse models and scenario experiments in specific sectors (like for forestry) and the bioeconomy as a whole, common standards are needed. Scenario-based, long-term monitoring and modelling are essential for understanding complex ecosystem dynamics in the context of climate change, the global biodiversity crisis and bioeconomy development. To this end, a systematic, collaborative, model-based monitoring framework adhering to standard conventions and coordinating contributing models would facilitate the characterisation, comparison, and distribution of model outputs.
- A closer link between the potential of innovations and impact modelling is needed, in particular to address questions such as: What are the potential impacts of e.g. alternative proteins or digital innovation in agricutultural sectors on macro-economic sustainability performance? While direct impacts are (mostly qualitatively) covered in studies, those developments are hardly considered in modelling.

- What, how and when greenhouse gas emissions are included in the monitoring system, in particular as regards inclusion versus exclusion of land use change related impacts, needs greater transparency and further development, especially as regards defining system boundaries and the concept of carbon neutrality.
- Despite recent advances, the lack of disaggregated data at the supply chain level, especially in environmental statistics, remains a major shortcoming in monitoring impacts abroad connected to specific German imports. Future work should expand to cover additional commodities, geographical contexts, global supply chain stages (e.g. post-use), and other sustainability indicators including biodiversity and water use. Addressing data gaps, uncertainty, and lack of harmonisation in trade data and conversion factors are key challenges for further improvement of results.
- Increasing momentum and implementation of the bioeconomy is also driven by the states in Germany. Better spatial resolution in monitoring activities could help to improve cross-boundary cooperation and lever synergies between different regions.
- The water quality footprint as an indicator of scarcity of clean water should be further developed and prioritised.

- A semi-automated system using advanced remote sensing technologies has been developed for efficient and precise monitoring of crop-driven deforestation. It should be further operationalised (e.g. as an interactive web application), extended (both to specific crops and to determine contributions from the German bioeconomy) and used to promote sustainable agricultural practices, manage deforestation, and guide decisions about sustainable supply chains. Once validated and adjusted for automated workflows, the model can contribute to a functional and cost-efficient monitoring system without requiring extensive data collection.
- Multiple methods to monitor resource efficiency by quantifying cascades, co-production and circularity have been tested and discussed in the scientific literature. However, in practice, there is not one method applicable to all sectors, as data availability differs significantly. Further investment in monitoring capacities, e.g. as regards indicators on biomass utilisation efficiency, by-products and residues, are needed.
- To set footprints in relation to safe and just consumption levels, benchmarks are needed that are compatible with long-term sustainable development within planetary boundaries. Further developing global benchmarks requires both increased research to advance and synthesise knowledge on global limits (in units that are comparable to footprints) as well as the active participation of citizens and stakeholders to address the normative aspects of consumption benchmarks and ensure their legitimacy. Policy should use such benchmarks to help promote sustainable consumption at the national level.
- The overview of bioeconomy-related monitoring initiatives presented in this report, including existing indicators, models and tools, serves as a useful starting point for learning from and incorporating their experiences in further developing a comprehensive bioeconomy monitoring system. Greater attention to socio-economic related research activities, and filling gaps in these areas for the bioeconomy, is needed.

Altogether, policy plays a pivotal role in how the bioeconomy is implemented. It is crucial for creating an enabling environment that fosters bio-based innovations. At the same time, measures targeting increased biomass use can have far-reaching impacts on landscapes and resources, both within Germany and abroad. This has been demonstrated in several cases, such as on the impacts of biogas production in the Weser Ems region of Germany and of soybean cultivation in Brazil. As Germany moves forward with the bioeconomy transition, it is essential to carefully weigh potential future impacts against stated objectives to ensure a holistic and sustainable bioeconomy transition. This balanced consideration is vital for developing a bioeconomy that aligns with broader sustainability goals and minimises unintended negative consequences. In general, the footprint perspective shows there is no sustainable potential for increasing total primary biomass use, especially if consumption levels, e.g. of meat, remain so disproportionally high in Germany. Future efforts should focus on a smarter, more efficient and regenerative use of biomass. Monitoring the bioeconomy at the national level should continue to provide an overview of socio-economic and environmental performance.



9. Annex

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GENERAL ABBREVATIONS

AP	Acidification potential
CCU	Carbon Capture and Use
COC	Carbon opportunity costs
2D	2 Dimensional
3D	3 Dimensional
dbh	Diameter at breast height
DF	Displacement Factor
DM	Dry mass
DNA	Deoxyribonucleic Acid
DNP	Distance to nature potential
DPSIR	Driving forces, Pressures, State, Impacts and Responses
ESS	Ecosystem services
EP	Eutrophication potential
FAME	Fatty acid methyl ester
GDW	German direct drinking water withdrawal per inhabitant
GHG	Greenhouse Gas
Glulam	Glued laminated timber
GWP	Global Warming Potential
GWP_{100}	Total global warming potential
HCV	High Conservation Values
HDF	High Density Fibreboard
HEFA	Hydroprocessed esters and fatty acids
highD	High disturbances
IACS	Integrated Administration and Control System
LCA	Life Cycle Analysis
LCIA	Life Cycle Impact Assessment
LDF	Low density fibreboard
lowD	Low disturbances
LSU	Livestock unit
LULUCF	Land Use, Land Use Change, and Forestry
meanD	Mean disturbances
MDF	Medium-density fibreboard
ML	Machine learning
MRIO	Multi-regional input-output analysis
NGO	Non-governmental organisation
NUTS	Nomenclature of Territorial Units for Statistics
OSB	Oriented strand board
PBMA	Plant-based meat alternatives
PM	Particular matter
PMF	Particulate matter formation
POME	Palm oil mill effluent
R&D	Research and Development
RE	Roundwood equivalents
RNA	Ribonucleic acid
RPA	Revealed patent advantage
RS	Remote Sensing
SAS	Semi-automated system
SDG	Sustainable Development Goal
SMART	Specific, measurable, achievable, relevant and timebound
SME	Small and medium-sized enterprise
SNG	Synthetic Natural Gas
UCO	Used cooking oil

INSTITUTIONS, ACTS, AND COUNTRIES

BLE	The Federal Office for Agriculture and Food
BMEL	Federal Ministry of Food and Agriculture
BMBF	Federal Ministry of Education and Research
BMWK	Federal Ministry For Economic Affairs and Climate Action
CAP	Common Agricultural Policy
CEN	European Committee for Standardization
DBFZ	German biomass research centre
Destatis	The Federal Statistical Office of Germany
DGE	German Nutrition Society
EEG	Renewable Energy Sources Act
EU	European Union
EU ETS	European Emissions Trading System
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Statistics database
FNR	Renewable resources coordinating institution in Germany
GEG	German Buildings Energy Act
GRAS	Global Risk Assessment Service
JRC	Joint Research Centre of the European Commission
NEC	National Emission reduction Commitments
NECP	National Energy and Climate Plan

RED	Renewable Energy Directive
UBA	German Environmental Agency
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America

PROJECTS, MODELS AND SCENARIOS

BenOpt	Bioenergy optimization Model
BioSink	Impact of the use of forest biomass for energy in Germany on German and international LULUCF sinks
CAPRI	Common Agricultural Policy Regionalised Impact model
EDGAR	Emissions Database for Global Atmospheric Research
EFISCEN	European Forest Information Scenario Model
FABio	Forestry and Agriculture Biomass Model
FORMIT	Forest management strategies to enhance the mitigation potential of European forests
GLORIA	Global Resource Input Output Assessment
LISE	Livestock and Soil Emissions model
MoBi	Development of a systematic bioeconomy monitoring — Consolidation Phase
NVS II	The German National Nutrition Survey
ProRep	Projection report
SYMOBIO	Consolidation of Systemic Monitoring and Modelling of the Bioeconomy

UNITS

cm	Centimeters
CO_{2e}	Carbon dioxide equivalent
DM	Dry mass
ha	Hectare
kg	Kilogram
kha	Kilohectare
kt	Kilotonne
km^2	Square kilometer
m^3	Cubic meter
m^3(f)	Cubic metre fibre equivalent
mm	Millimetre
Mt	Million tonnes
MW	Megawatt
PJ	Petajoule
TWh	Terawatt-Hour
t	Tonne

CHEMICAL FORMULAS

CH_4	Methane
CO_2	Carbon dioxide
E2E	Ethanol to Ethylene
N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
P	Phosphorus
PEF	Polyethylene furan
PES	Polyester
PET	Polyethylene terephthalate

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