Evaluating Biodiversity Assessments in a Business Context

A Comparative Analysis of Data Requirements, Limitations and Applicability

Master's Thesis in Industrial Ecology

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Abstract

Biodiversity loss is one of the most pressing environmental challenges of our time, largely driven by land use and land use change in sectors like forestry. As regulatory frameworks increasingly require companies to assess and disclose their biodiversity impacts, the need for practical and data-compatible assessment methods grows. This thesis evaluates the practical feasibility of two LCA-based biodiversity assessment methods, GLAM (Global Guidance for Life Cycle Impact Assessment) and BioMAPS (Biodiversity Multi-Scale Assessments of Product Systems), in a business context within the forestry sector. Through a comparative analysis of data requirements and a qualitative study including interviews with supply chain actors, the study maps data availability, governance structures, and traceability across the tissue product supply chain. The findings show that GLAM is readily applicable given current data practices, as its requirements (land occupation area, geographic location, land use classification, and management intensity) largely align with data already collected for LCA and certification purposes. The spatially explicit version of BioMAPS offers greater ecological detail by incorporating management parameters such as deadwood volume, tree age, and biomass density, and assesses three spatial scales, but its implementation is constrained by limited data transferability along the supply chain. A key finding is that relevant biodiversity data often exists within upstream actors but becomes fragmented, aggregated, or inaccessible as materials move through industrial processes, such as pulp production. The study identifies a trade-off between ecological detail and practical applicability. While the spatially explicit version BioMAPS better captures biodiversity complexity in forestry systems, GLAM represents the more feasible option on short term. Both methods are expected to benefit from increasing data availability driven by EU Deforestation Regulation compliance requirements.

Keywords: biodiversity assessment, LCA, GLAM, BioMAPS, forestry, land use, data governance, supply chain, EUDR.

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Sofia Bergendahl and Vilma Strand, Gothenburg, May 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order. Additional variables used in equations are presented in Appendix A.2.

BRF	Biodiversity Risk Filter
CBD	Convention on Biological Diversity
CF	Characterization Factor
CO_2e	Carbon Dioxide Equivalents
CoC	Chain of Custody
CSRD	Corporate Sustainability Reporting Directive
DPSIR	Drivers, Pressures, State, Impacts, Responses
ECA	Equivalent Connected Area
EEA	European Environmental Agency
EEB	European Environmental Bureau
ES	Ecosystem Services
ESRS	European Sustainability Reporting Standards
EUDR	European Union Deforestation Regulation
FM	Forest Management
FPIC	Free, Prior and Informed Consent
FSC	Forest Stewardship Council
GBF	Global Biodiversity Framework
GBS	Global Biodiversity Score
GEP	Global Extinction Probability
GEZ	Global Ecological Zones
GIS	Geographic Information Systems
HCV	High Conservation Value
IBAT	Integrated Biodiversity Assessment Tool
IFL	Intact Forest Landscapes
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDI	Landscape Development Index
LUI	Land Use Intensity Index
MTI	Maximum Tolerable Intensity

NBSAP	National Biodiversity Strategies and Action Plans
NCP	Nature's Contribution to People
NDA	Non-Disclosure Agreement
OECD	Organisation for Economic Co-operation and Development
OEF	Organizational Environmental Footprint
PBR	Potential Biodiversity Risk
PCR	Product Category Rules
PDF	Potentially Disappeared Fraction of Species
PEF	Product Environmental Footprint
PEFC	Programme for the Endorsement of Forest Certification
RIL	Reduced Impact Logging
RSL	Relative Species Loss
SAR	Species-Area Relationship
SCBD	Secretariat of the Convention on Biological Diversity
SES	Social-Ecological Systems
SDG	Sustainable Development Goals
SIN	Special Indication of Nature Value
TNFD	Taskforce on Nature-related Financial Disclosures
UBR	Unified Biodiversity Risk
UNEP	United Nations Environment Programme
UNEP-WCMC	UNEP World Conservation Monitoring Centre

Contents

List of Figures

List of Tables

1

Introduction

The concept of biodiversity is defined as "*The variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part*" (Azuero-Pedraza & Thomas, 2024, p. 2). Biodiversity therefore includes variation, composition and interactions of species, rather than just their presence or absence, and includes differences in biological characteristics, ecological roles and relationships between organisms (Azuero-Pedraza & Thomas, 2024). As a result, biodiversity is not a binary concept, but rather dynamic and context dependent (Gaudreault et al., 2016).

Humans and society rely heavily on well-functioning ecosystems, and are dependent on biodiversity for food production, raw materials and the long-term functioning of these systems (Pascual et al., 2017). At the same time, human activities are one of the biggest influencing factors of the ecosystems and biodiversity (Coelho et al., 2025). This creates a complex relationship between dependence and impact.

Today, the loss of biodiversity is one of the most pressing global environmental challenges as a result of, inter alia, the current unsustainable land use in order to meet human demands. Despite this, limited focus and resources are currently allocated to addressing biodiversity loss. The five main drivers of biodiversity loss are described by The Secretariat of the Convention on Biological Diversity (SCBD) as: habitat loss and degradation, climate change, pollution and nutrient load, overexploitation and unsustainable use, and invasive alien species. (Hirsch, 2010)

The decline in biodiversity has far-reaching consequences for both ecosystems and human well-being (IPBES, 2019). This loss reduces nature's contributions to people (NCP), such as pollination, soil fertility, and the regulation of pests and diseases, which are essential for human health, sustainable food production, food security, and livelihoods (Gupta et al., 2024). Biodiversity therefore supports not only ecological processes and ecosystems, but societies as well.

Land use is one of the major drivers of biodiversity loss, meaning that companies handling large biomass flows, such as forestry and agricultural raw materials, indirectly affect biodiversity throughout the supply chain (Chaudhary et al., 2015). To reverse current trends, increased awareness is needed of how economic and strategic decisions are linked to impacts on the biosphere (Azuero-Pedraza & Thomas, 2024). Companies therefore need better tools and methods to assess where their activities have the greatest ecological impact and how mitigation measures can be implemented

(Damiani et al., 2023; ETC, 2021). This is not only important for ecosystems and societies, but also for the companies themselves, since they depend on resources sourced from forests and land (Maier, 2023).

Given the increasing need to incorporate biodiversity assessment methods into environmental evaluation frameworks, such methods have increasingly been integrated into Life Cycle Assessments (LCAs) (Damiani et al., 2023). LCAs are used to evaluate the environmental impacts of a product or service throughout its entire life cycle. LCA has a wide range of applications, and its results can support decision-making, policy development, and eco-labeling, as well as help identify opportunities to improve the environmental performance of processes across the life cycle (Baumann & Tillman, 2004). However, the integration of biodiversity-related indicators into LCA frameworks also introduces significant data requirements, as the applicability of such methods is closely linked to data availability and quality. This is particularly relevant in the forestry sector, where biodiversity impacts are tied to complex, multi-actor supply chains and where data is collected by many different actors for many different purposes (Barth et al., 2025). While existing research has evaluated biodiversity assessment methods from a methodological perspective, few studies have examined their practical feasibility in a business context, particularly with regard to data availability and supply chain traceability in the forestry sector. To address this gap, this study focuses on a global company operating within the paper- and pulp sector, here referred to as the company in focus. Through interviews and written communication with representatives from the company in focus and several upstream supply chain actors within the forestry sector, the study maps data availability, governance structures, and traceability across the tissue product supply chain. In particular, the study evaluates the feasibility of applying the biodiversity assessment methods BioMAPS and GLAM in a corporate LCA context, with a specific focus on data availability and supply chain traceability.

1.1 Data Requirements for Biodiversity Assessment

In order to apply biodiversity assessment methods on industrial activities, access to data from both open databases and companies is required. Data management then becomes an important aspect when trying to operationalize biodiversity assessments. It is not only a question of what data is needed, but also how the data is collected, stored and interpreted, and who within the organisation is responsible for and has access to it (Biodiversa, n.d.). In addition to data management, data governance is equally important. While data management focuses on how data is collected, stored and maintained, data governance manages the ownership, quality and transferability of data throughout its whole life cycle (Databricks, n.d.).

Methods that assess impact on biodiversity typically rely on a combination of environmental and organizational data. These types of data normally include information on what type of activity is conducted on the site, for example land use and material flows. Another type is the spatial information, which often involves data such as coordinates and exact sites where the activity is conducted. A more environmentally aligned type of data is the ecological information, containing the type of habitat, species within the area, as well as protected areas in proximity to the site. Lastly, one requirement is supply chain data, for example information regarding traceability and origin of product. (Barth et al., 2025)

Even though these types of data are often required when assessing biodiversity, the information does not come from one single source. The required data can be divided into two parts; external and internal. External data are for example statistics, measurements and values obtained from databases or datasets, regarding where different types of land is found in the world, or global averages. Internal data, on the other hand, is acquired from the company, found within their own systems and is more exact regarding their locations, volumes and areas. (Lammerant & Kisielewicz, 2018)

Performing this type of data collection and improving traceability has grown in focus due to the implementation of CSRD and EUDR. These regulations require companies to collect spatially explicit and traceable data, which can make it easier to implement methods with these requirements (Biodiversa, n.d.). This highlights the importance of evaluating biodiversity assessment methods not only based on methodological robustness, but also their compatibility with available company data.

1.2 Aim and Research Questions

The aim of this thesis is to assess the relevance and practical feasibility of two existing biodiversity assessment methods developed within an LCA perspective, applied in a business context, with a particular focus on data availability, traceability, and potential data gaps within an organization in the forestry sector. The study aims to examine and map the data requirements of the selected LCA-based methods and investigates the data governance, including how relevant data can be identified, traced, and combined across different organizational functions.

The project will aim to answer the following research questions:

- What data are required to apply selected biodiversity assessment methods, and how do these requirements relate to the type, resolution and structure of data available within the company?
- How can the required biodiversity-related data be located, accessed and integrated across different organizational functions and supply chain actors to enable the operationalization of the selected methods?
- What are the main limitations and uncertainties of the method and data, and how can possible data gaps be addressed when required data is not readily available?

1.3 Delimitations

One clarification of this master thesis is that no new methods for assessing biodiversity was constructed in the project. Only already existing methods for assessment was investigated based on available data.

This study focuses on methods connected to LCAs, which is used to assess environmental impacts throughout the entire life cycle of a product. Since biodiversity impacts often occur across complex supply chains, this perspective was found relevant for forestry-based products. In addition to this, since biodiversity assessments are under development, only the most recent LCA-based models were included in this study.

Another delimitation is that the main focus of this thesis is the forestry sector. This means that even though a company might use different materials and resources to produce their products, only the paper- and pulp based products are of interest in this project. One example is milk cartons, which are made from forest fiber but with the addition of a plastic lining. For this project, only the supply chain and management of data connected to forest fiber will be looked into.

In addition to narrowing the scope to the forestry sector, the upstream supply chain actors included in this study are primarily Swedish. This reflects a practical consideration, as Swedish companies proved more accessible to contact than larger, multinational actors operating in the same sector. Nevertheless, focusing on Swedish actors remains relevant from a broader perspective, as Sweden is one of the world's largest producers of forest products, accounting for a significant share of the world's pulp, paper, and sawn wood exports (Swedish Forest Industries Federation, n.d.). This suggests that findings and challenges identified within the Swedish forestry context may carry wider applicability across the sector internationally.

2

Background

This chapter presents the theoretical background relevant to the study, including biodiversity, biodiversity loss and its drivers, and relevant regulatory frameworks and certification systems. It also reviews biodiversity assessment approaches, particularly life cycle based methods, and describes the selected methods BioMAPS and GLAM, including their methodological frameworks, equations, and data requirements. The chapter also addresses data management and governance aspects relevant for the application of biodiversity assessment methods within companies.

2.1 Biodiversity

Biological variation and diversity has been a part of nature since the origin of life on earth. Despite biodiversity existing throughout the entire history of life, the term itself was not coined until recently. It was introduced in the late 1980s by Walter G. Rosen, who created it as a contraction of the words *biological diversity* (Sarkar, 2021). At that time, biological diversity was mainly understood and measured through metrics such as species richness, i.e. the number of species present in an area, which had already been established within ecology (Benton, 2016).

Today, biodiversity covers not only the number of species, but also the differences in their characteristics, functions and interactions with each other. While species richness provides a basic measurement, it does not capture the functional roles and ecological contributions of individual species within ecosystems (Gaudreault et al., 2016). Since a diverse set of functions allows ecosystems to better withstand disturbances and environmental change, a high level of biodiversity is a key factor for ecosystem stability and resilience (Schwartz et al., 2000).

To further understand the complexity of the concept, biodiversity is commonly described at three interconnected levels: genetic, species and ecosystem diversity. These levels are illustrated in Figure 2.1. Genetic diversity describes the variety of genes within a gene pool, and allows populations to adapt and persist over time. Species diversity reflects the number of different species within an ecosystem, and can make habitats more resilient, as an increased number of species can increase the functionality of an ecosystem. Ecosystem diversity captures variation across habitats and landscapes, which is important for maintaining ecological and environmental processes at larger scales (Winter et al., 2017).

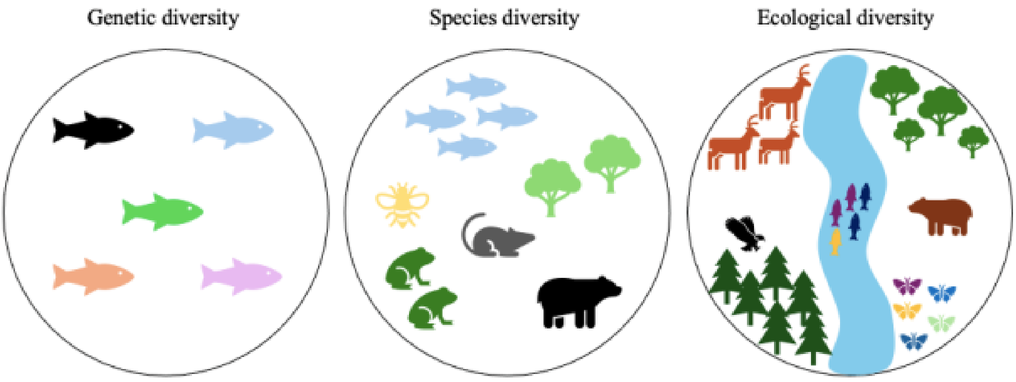

Figure 2.1: The three levels of biodiversity, from Larsson and Sjögren (2025)

2.1.1 Loss of Biodiversity

As previously mentioned, biodiversity has important functions for both humans and ecosystems. Despite its importance, there has been a 68% decrease of mammals, birds, fish, reptiles and amphibians between 1970 and 2016 (Manders et al., 2022). Due to this continuing decline, the loss of biodiversity is increasingly seen as a prominent risk to humanity, yet it is mainly driven by human activities (Damiani et al., 2023). The top drivers of biodiversity loss are the following:

- Habitat loss and degradation
- Climate change
- Pollution and nutrient load
- Overexploitation and unsustainable use
- Invasive alien species (Winter et al., 2017)

In addition to these drivers acting on their own, they also interact and reinforce each other through complex processes, making their combined effects on ecosystems and societies difficult to understand and predict (Chapin & Díaz, 2020). Among these drivers, habitat loss and degradation, primarily caused by land use and land use change, is widely seen as the dominant driver of biodiversity loss (Coelho et al., 2025; Scherer et al., 2023). Land use change transforms natural habitats into, for example, agricultural land, managed forests or urban areas, which often leads to reduced habitat quality. Even when land is not transformed, land occupation (ongoing use of the land for production) also changes the ecosystem, by reducing the species diversity and ecosystem diversity. Since land is a finite resource and demand for biomass is increasing, competition for space and resources puts pressure on and transforms ecosystems through expanding agricultural production, forestry, resource extraction and urbanization. Reasons behind these activities are linked to economic growth, consumption and global trade, which increase the pressures on land and natural resources. Because of this, biodiversity loss is not only an ecological issue, but is also connected to production and consumption systems and represents a central conflict between human activities and the conservation of biodiversity (Azuero-Pedraza & Thomas, 2024; IPBES, 2019).

2.2 Regulations

During the last decades, biodiversity loss and climate change has increasingly been recognized not only as environmental challenges, but also as risks to economic development and corporate value creation (Elliot et al., 2024; Evison et al., n.d.). As a response, regulatory frameworks have expanded on international and European level. This has placed growing responsibilities on companies to identify, measure and report their environmental impacts. The regulatory developments show a shift from voluntary sustainability communication to mandatory reporting, where companies need to demonstrate how their activities affect natural systems (European Commission, 2025).

This chapter outlines the key regulatory frameworks that the paper- and pulp industry is required to comply with, with regard to environmental and biodiversity reporting, as well as certification systems relevant to its operations.

2.2.1 International Agreements

At the international level, biodiversity governance is mainly shaped by agreements under the United Nations. Agenda 2030 includes 17 Sustainable Development Goals (SDGs), several of which relate to biodiversity. In particular, SDG 15, *Life on Land*, aims to protect and restore terrestrial ecosystems and halt biodiversity loss (United Nations, n.d.). SDG 15 supports the implementation of the Convention on Biological Diversity (CBD), which forms a central international framework for biodiversity conservation (CBD, 2026).

Under the CBD, the Strategic Plan for Biodiversity 2011–2020 introduced the Aichi Biodiversity Targets, which aimed to reduce biodiversity loss through national action (Amos, 2025). Although none of the 20 targets were fully achieved, the framework contributed to some progress, such as expanding protected areas (Secretariat of the Convention on Biological Diversity, 2020).

2.2.2 EU

Since the increasing recognition of biodiversity loss and its links to economic activities, the European Union has introduced a range of policies and regulations aimed at reducing environmental impacts and improving transparency in supply chains. Central strategies such as the European Green Deal and the EU Biodiversity Strategy for 2030 seek to decrease biodiversity loss and restore degraded ecosystems through a combination of conservation measures, restoration targets and regulatory instruments (European Commission, n.d.-a, n.d.-c). In combination with these broader policy goals, the EU has introduced several regulatory frameworks that require companies to collect and report environmental data related to their activities and supply chains (European Commission, 2025).

One such framework is the Corporate Sustainability Reporting Directive (CSRD), which requires large companies to disclose information about their environmental and social impacts in accordance with the European Sustainability Reporting Standards (ESRS) (European Commission, 2025; UNEP, n.d.). Within these standards, biodiversity is addressed through ESRS E4, which requires companies to report on their impacts and dependencies on biodiversity and ecosystems. To comply with these requirements, companies must gather and report data related to their operations, supply chains and environmental pressures, including land use, resource extraction and ecosystem impacts (EFRAG, 2022).

In addition to reporting requirements, the EU has introduced market regulations that directly target supply chains. One primary example is the EU Deforestation Regulation (EUDR), which aims to reduce global deforestation and biodiversity loss linked to the production of certain goods. The EUDR entered into force in 2023, but its application has been postponed until December 2026 to allow more time for companies and authorities to prepare and adapt (European Commission, n.d.-b). The regulation will apply to products such as wood, soy, cattle, palm oil, cocoa, coffee and rubber that are placed on the EU market. Under the EUDR, companies are required to conduct due diligence to ensure that these products are not associated with deforestation or forest degradation. Companies must therefore collect information about their supply chain, including the geographic coordinates of the land where raw materials are produced, as well as information on land use and production practices (European Commission, n.d.-e). To simplify due diligence reporting for companies, the European Commission has created an information system. Through this system, companies can submit their due diligence statements to authorities to demonstrate that their products do not contribute to deforestation. Examples of data submitted by companies include the exact geolocation of the source from which the material was harvested, along with other characteristics such as material description and quantity (European Commission, n.d.-d).

These regulatory developments highlight a growing demand for reliable environmental data within corporate supply chains (de Oliveira et al., 2024). As regulatory requirements expand, companies increasingly need robust methods to assess environmental impacts, including biodiversity impacts, based on spatially explicit data and traceable materials and supply chains. Because of this, the development of biodiversity assessment methods is becoming increasingly important (Gonzalez et al., 2026).

2.2.3 Certification Systems

To ensure that forest management is conducted in a responsible and sustainable manner, forest certification systems have been developed. This type of certifications is especially important to paper- and pulp companies since they purchase large amount of biomass from the forestry sector. There are different types of forest certification schemes, each with its own set of standards that companies must comply with. A common feature is the focus on conservation of biodiversity and its importance within forestry systems. This chapter briefly presents two common certification systems and their principles. (FAO, n.d.)

2.2.3.1 FSC

The Forest Stewardship Council (FSC) certification is a voluntary international sustainability certification system for forestry and forest-based products. FSC has comprehensive requirements for forest management and integrates ecological, social and economic aspects of the matter (FSC, 2020). The Swedish FSC board contains three chambers, economic, social and environmental, which all contain representatives from companies and organizations within the corresponding field (FSC, n.d.-e). To obtain FSC certification, forest owners must develop a forest management plan and keep documented routines describing how the forest is monitored and maintained over time. The certification also requires continuous documentation, revisions and follow-ups by third party certification bodies (FSC, n.d.-a, 2020).

FSC certification is divided into two main types, Forest Management (FM) and Chain of Custody (CoC). Forest Management certification applies to forest owners and verifies that forest management practices comply with FSC standards (FSC, n.d.-c). FSC FM certification includes several ecological requirements aimed at protecting managed forests. These include retention forestry practices such as leaving habitat trees and deadwood, setting aside a part of productive forest land for conservation and identifying and protecting key habitats and red-listed species. These measures aim to maintain biodiversity, strengthen ecosystem resilience and protect ecological functions in managed forests (FSC, 2013). In addition to ecological criteria, FSC FM certification also includes social and economic requirements, such as ensuring safe working conditions for employees and respecting the rights of local communities and indigenous people (for example the Sami population in Sweden). Furthermore, FSC FM certification also aims at conducting forestry in a way that is economically viable in the long term, ensuring the continuity of sustainable management (FSC, 2020).

FSC CoC certification is a traceability certification applied to companies in the supply chain and ensures that FSC-certified materials can be tracked through production and distribution. CoC certification requires documented procedures for purchasing, handling and selling certified materials, as well as systems to ensure that certified materials are correctly identified, tracked and controlled throughout the production and distribution processes. Organizations must maintain records related to certified material flows, and undergo regular third party audits to verify compliance. (FSC, n.d.-b)

There are three different product labels available within FSC; 100%, Mix and Recycled. All materials used in a product labeled with FSC 100% must come from a forest with FSC FM certification. The FSC Recycled label indicates that the material is recycled, but the raw material does not necessarily need to be certified. The FSC Mix label allows for a product to contain FSC certified material, recycled material and/or material marked with Controlled Wood (FSC, n.d.-g). Controlled

Wood applies to forest based material that is not FSC-certified, but has been verified to originate from acceptable sources. Examples of unacceptable sources are illegally harvested wood or wood from forestry which violates human rights. Controlled Wood allows companies to include non-certified material in their products, but does not guarantee compliance with ecological standards (FSC, n.d.-d).

Through these requirements for documentation, monitoring and traceability, FSC certification also generates data that can support biodiversity assessment and supply chain transparency. However, there is an ongoing debate regarding the forest benefits of nonindustrial private forest owners being certified. According to Laura et al. (2018), there is no correlation between forest certification and decreased forest degradation. Currently, there is a need for restoration of forests in order to halt the reduction of biodiversity and increase the resilience of forests. For actual improvements to happen, increased monitoring and strengthened enforcements are needed. (Laura et al., 2018)

2.2.3.2 PEFC

The Programme for the Endorsement of Forest Certification (PEFC) is an organization promoting sustainable forest management, providing both forest certification and labeling of forest-based products. Today, about 10% of the forest is certified globally, of which 75% is certified with PEFC (PEFC, n.d.-b, n.d.-d). The PEFC system includes two types of certifications: Sustainable Forest Management (SFM) certification and Chain of Custody (CoC) certification. SFM is applicable by forest owners and verifies that the forest management applies to the environmental, social and economic standards. Chain of Custody certification applies to companies throughout the supply chain and ensures traceability of certified material along the supply chain from forest to final product (PEFC, n.d.-b). Rather than functioning as one global standard, PEFC is an umbrella organization adapting national and regional forest certification systems. Before these systems can be endorsed by PEFC, they undergo assessments within PEFC's international Sustainability Benchmark. This ensures that the systems meets the environmental, social and economic requirements (PEFC, n.d.-a). The assessment is carried out by third party assessors, not by PEFC themselves. The assessors are PEFC registered and are independent consultants in the field of sustainable forest management (PEFC, n.d.-c).

2.3 Assessment of Biodiversity

Regulatory pressure and the resulting need for environmental assessment methods has grown. Addressing the drivers of biodiversity loss requires assessment methods that consider the impacts from a supply chain perspective, capturing impacts from multiple stages. One way to capture the full value chain is by using a life cycle perspective.

However, biodiversity impacts are inherently difficult to assess. Unlike climate change, which can be measured through standardized metrics such as greenhouse gas emissions, biodiversity is multidimensional and highly context-dependent, or more specifically site-specific, meaning that impacts and indicators measured at one location cannot easily be generalized or transferred to another (Gaudreault et al., 2016; Winter et al., 2017). Climate impacts can be aggregated, compared and integrated into regulatory instruments, while biodiversity impacts are more difficult to quantify and regulate (Maier, 2023). Furthermore, biodiversity can be described through several dimensions, such as species richness, functional diversity, and ecosystem structure. Consequently, different assessment approaches rely on different indicators. Therefore, the choice of method influence the resulting impact. Also, biodiversity and ecosystem services are difficult to assign monetary value, which makes them less visible in economic decision-making processes (Azuero-Pedraza & Thomas, 2024; Pascual et al., 2017). In addition to this, although biodiversity can be seen as a local problem, it has global consequences as ecosystems are interconnected through ecological processes. This interconnection complicates the allocation of responsibility and governance, which in turn limits the extent of how incorporated biodiversity is in environmental policies and assessments (Chaudhary et al., 2015).

Several Life Cycle Assessment (LCA) methods have been developed to evaluate biodiversity impacts from a life cycle perspective. However, many of these approaches have been criticized for not capturing the complexity of biodiversity and ecosystems. An alternative approach to the LCA-based methods are often referred to as ”beyond LCA” methods (Damiani et al., 2023). These methods typically focus on risk screening, footprint analysis, or ecosystem indicators rather than full life cycle modeling, and can complement LCA by addressing aspects of biodiversity that are difficult to capture within traditional Life Cycle Impact Assessment (LCIA) models (Crenna et al., 2020; Damiani et al., 2023).

Examples of beyond-LCA methods include the Global Biodiversity Score (GBS) and the WWF Biodiversity Risk Filter (BRF). GBS is a biodiversity footprint tool that links economic activities to biodiversity pressures across value chains, but relies heavily on aggregated economic and sector-level data, which may limit spatial resolution (CDC BIODIVERSITE, 2023; Schipper et al., 2020). In contrast, BRF is a risk screening tool that combines location-specific environmental data with industry dependencies to identify biodiversity-related risks. However, it focuses on risk identification rather than quantifying actual impacts, making it more suitable for prioritization than detailed assessment (Walsh, 2024).

These different methods shows that there is no single universally accepted method for biodiversity assessment. Instead, different approaches, such as footprint methods, risk assessment frameworks and impact assessment methods, are applied depending on the purpose, scale, and decision-making context. However, several companies use LCAs in their sustainability work and environmental reporting. This means that biodiversity methods compatible with LCA frameworks may be easier to implement in practice. Because of this, LCA-based methods will be the main focus going forward.

2.3.1 LCA-Based Methods

The methodology of an LCA study contains four main phases: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation and Results. The methodology is iterative, allowing for changes and refinement along the assessment process. In the first step of an LCA study, the intended application, functional unit, system boundaries and impact categories are defined. The LCI phase aims to structure a flow model of the technical system, and quantify the material and energy flows within the system boundaries, through collection of relevant data. In the LCIA phase, the flows are classified and characterized to assess their potential environmental impacts, for example by converting greenhouse gas emissions into carbon dioxide equivalents (CO2e) to express global warming potential. The last step is to interpret the results, often including hotspot and sensitivity analyses. (Baumann & Tillman, 2004)

One part of conducting an LCA is to translate data from the LCI into actual impacts. To achieve this, the impact categories are divided into midpoint and endpoint indicators. Midpoint indicators, for example acidification and eutrophication, are positioned earlier in the cause-effect chain and describe environmental mechanisms before the final damage is fully developed (Bare et al., 2000; Garrigues et al., 2012). Endpoint indicators, on the other hand, are positioned further along the same cause-effect chain and represent the resulting final damage to the environment (Bare et al., 2000). Endpoint indicators are often aggregated into the three common endpoint-categories: damage to human health, damage to ecosystem diversity and resource scarcity (Garrigues et al., 2012). By doing this categorization, impacts are represented in a more comprehensible way and can therefore be more easily incorporated in decision making (Bare et al., 2000).

If biodiversity assessment is conducted, it is commonly applied in the LCIA step of the LCA. In these biodiversity-related LCIA methods, flows from the LCI phase are translated into potential biodiversity impacts through multiplication with a characterization factor (CF). The CF reflects the potential biodiversity loss or risk per unit area at a given location, and depends on how the LCIA model characterizes the cause-effect chain and which indicators are chosen to quantify biodiversity, such as ecological vulnerability or species richness. CFs are often spatially differentiated since biodiversity impacts are dependent on location. Geographic location, such as country, region or ecoregion, is therefore used to determine the appropriate CF. Although CFs exist, they are not yet implemented in standard LCA software, meaning that additional effort and expertise are required to apply them in practice. (Maier, 2023)

2.4 Biodiversity Assessment Methods Included in the Study

In this section, the two biodiversity assessment methods are presented and methodologically explained, while their data requirements and applicability are further explored and analyzed later in the study.

2.4.1 GLAM

One of the chosen frameworks for assessing environmental impacts within LCA is the Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM) (Life Cycle Initiative, 2016). GLAM was initiated in 2013 by the Life Cycle Initiative, hosted by UN Environment. The project was launched as a response to the fact that LCIA for biodiversity assessment is a relatively young and rapidly evolving research field, with many methodological developments but few universally established standards. The first two versions of GLAM focused on specific impact categories and providing guidance on which indicators to use, while the currently developing third version aims to establish a comprehensive, consistent and global LCIA method (Life Cycle Initiative, n.d.-b).

GLAM covers multiple environmental impact categories within LCIA and focuses on identifying indicators and characterization models that can translate LCI results into potential environmental impacts. This is done through the use of CFs, that convert the inventory flows to impact indicators. The impact indicators can be evaluated at midpoint level, and further aggregated into endpoint indicators, represented as Areas of Protection (AoP). In GLAM, three AoPs are defined: ecosystem quality, human health and socio-economic assets. Impacts on biodiversity are addressed within the AoP ecosystem quality, where the impact is commonly expressed using the Potentially Disappeared Fraction of species (PDF). PDF represents the relative loss in species richness caused by environmental pressures, such as land use. When assessing biodiversity-related impacts, land use is a key midpoint category, as land occupation and transformation are major drivers of biodiversity loss. The CFs for the different midpoint indicators are provided by researchers within the corresponding field, and the CFs for the land use midpoint indicator are provided by Scherer et al. (2023).

Although GLAM aims to provide a comprehensive LCIA framework, the level of methodological development varies across different impact categories. While some categories are well-established and operationalized, others remain under development and are associated with higher data requirements and methodological uncertainty. Impacts related to biodiversity, especially those linked to land use, fall into the latter category. Although GLAM includes multiple impact categories, land use is the focus of this study due to its connection to forestry.

The third and current version of GLAM includes updated CFs that account for multiple species groups and land use categories. There are now five species groups covered (plants, amphibians, birds, mammals, and reptiles), five land use types covered (cropland, pasture, plantations, managed forests, and urban land) and three intensity levels (minimal, light, and intense) (Scherer et al., 2023). The intensities for managed forests are defined by Scherer et al. (2023a) and presented in Table 2.1. Species groups covered refers to the taxonomic groups for which CFs are currently available within GLAM. This means that biodiversity impacts are quantified for plants, amphibians, birds, mammals, and reptiles, based on changes in species richness. Other taxonomic groups, such as invertebrates, fungi, and microorganisms, are not explicitly included in the model due to limited data availability (Scherer et al., 2023). The included species groups are implicitly used as proxies for biodiversity.

Table 2.1: Intensities in the land use category managed forest in GLAM

Intensity	Definition
Minimal use (Reduced impact logging (RIL) forests)	Forests managed with RIL techniques designed to minimize impacts on biodiversity
Light use (Selectively logged forests)	Forests where only selected commercially valuable trees are harvested at a time such that the disturbance is not enough to markedly change the nature of ecosystem.
Intense use (Clear-cut forests)	Forests with extractive use, with both even-aged stands and clear-cut patches. The disturbance is severe enough to change the nature of the ecosystem.

As previously mentioned, one of the key drivers of biodiversity loss is land use and land use change. Going one step further in identifying underlying drivers, a major factor is that available habitat becomes fragmented. One key advancement in the more recent GLAM models is therefore the inclusion of habitat fragmentation, which means that a larger patch of land is divided into several smaller, separate patches (Scherer et al., 2023). This limits species' natural spatial pattering, hindering their movements across habitats and ultimately affecting their conditions for occupancy and fitness within an area (Hagen et al., 2012). Consequently, even if the total habitat area is large, it may not be fully accessible to different species due to fragmentation. This is incorporated into the method through the concept of Equivalent Connected Area (ECA), which shows how well different habitat patches are connected. ECA therefore represents the effective habitat area available to species when accounting for connectivity between patches.

The earlier versions of GLAM used Vulnerability Score (VS) to represent the susceptibility of species to extinction, based on factors such as threat status and range size (Chaudhary et al., 2015; Life Cycle Initiative, n.d.-a). More recently, VS has been replaced by Global Extinction Probability (GEP), which provides a more explicit and consistent estimate of the likelihood that local biodiversity loss leads to global species extinction. This harmonizes the biodiversity impact across different impact categories, improves comparability and links local biodiversity effects with global consequences (Scherer et al., 2023).

Spatial information is a crucial component of GLAM. The method uses the global terrestrial ecoregion framework defined by Olson et al. (2001) as its ecological basis for spatial differentiation. The map of these ecoregions can be seen in Figure 2.2. In GLAMs practical implementation (via Chaudhary et al. (2015)), the globe is further divided into 804 ecoregion units for which CFs are provided (Scherer et al. (2023), Supplementary information in Chaudhary et al. (2018)).

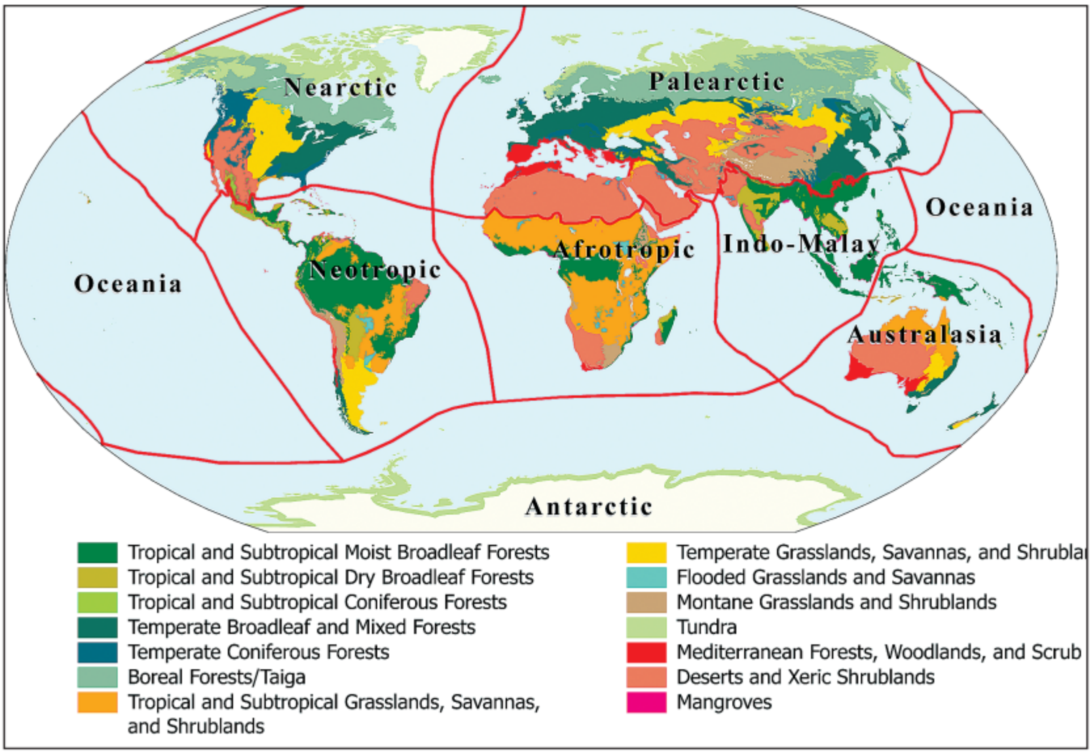

Figure 2.2: Ecoregions used in GLAM, the map was developed by Olson et al. (2001).

As previously mentioned, land use is considered a key driver of biodiversity loss in the GLAM framework. One common modeling approach to link land use to impacts on biodiversity is species-area relationship (SAR) models, where Chaudhary et al. (2015) use Countryside SAR. This approach accounts for the ability of some species being able to survive in human-modified landscapes. SAR estimates how species richness changes as the natural habitat is modified by human land use. How this concept is used within GLAM is further shown in the following section.

2.4.1.1 Method

Within the land use impact category, GLAM follows a cause-effect chain linking land use to potential biodiversity loss. First, land use activities alter the quantity and quality of habitat. This affects the suitable connected habitat area available for species, which is expressed through the concept of ECA. Changes in habitat are then translated into changes in species richness using species-area habitat relationships. Finally, these changes can be weighted by the GEP to estimate global biodiversity impacts. This chain is shown through mathematical formulas presented in this section. It is important to highlight that this is not the method conducted by the user, but rather the process conducted by the Life Cycle Initiative in order to compute the CFs.

ECA is calculated based on both the size of the land use patches and the probability that species can move between them. ECA can then be described by the following Equation 2.1:

$$ECA_{g,j,i,m} = (\sum_{x,y} A_{j,i,m,x} \cdot A_{j,i,m,y} \cdot p_{g,j,i,m,x,y})^{0.5} \tag{2.1}$$

Here i indicates land use type, j represent the ecoregion, g refers to the species group, and m indicates the intensity. A represents the areas of the patches x and y, and p shows the probability that species can move between these different patches. This concept means that two habitat patches that are geographically close, but separated by some sort of resistant land (for example urban infrastructure), will have a low connectivity, and therefore result in a lower ECA.

The suitable connected habitat area, H, is calculated by combining the ECA with habitat affinity, h, as can be seen in Equation 2.2:

$$H_{g,j} = \sum(h_{g,j,i,m} \cdot ECA_{g,j,i,m}) \tag{2.2}$$

Habitat affinity represents how suitable a specific land use type and intensity level is for a given species group, based on the relative species richness in different land use systems. For example, intensively managed cropland would have lower habitat affinity than minimally used pasture. Land use intensity is incorporated in this by scaling habitat affinity values. By using Equation 2.2, the two areas H_0 and H_1 can be calculated and then used in Equation 2.3. H_0 represents the land assumed to be in natural state and H_1 represents the current state of the land (Scherer et al., 2023).

The Relative Species Loss (RSL), expressing biodiversity loss at the regional level, *reg*, is calculated by using Equation 2.3:

$$RSL_{g,j,\mathrm{reg}} = 1 - \left(\frac{H_{g,j,1}}{H_{g,j,0}}\right)^{z(g,j)} \tag{2.3}$$

The parameter z corresponds to the slope of the SAR and determines how species richness change as habitat area decrease. (Scherer et al., 2023)

For land occupation impacts, the CFs are calculated as:

$$CF_{g,j,i,m,\mathrm{occ},\mathrm{reg}} = RSL_{g,j,\mathrm{reg}} \cdot \left(\frac{a_{g,j,m}}{A_{j,lu}}\right) \tag{2.4}$$

The parameter A represents the total regional land use area and a is an allocation factor that distributes the biodiversity impacts across the land use area.

For land transformation impacts, the CFs are calculated as:

$$CF_{g,j,i,m,\mathrm{tra,reg}} = CF_{g,j,i,m,\mathrm{occ,reg}} \cdot 0.5 \cdot t_{g,j,i} \tag{2.5}$$

where t is the regeneration time of a species group g in region j and land type i (Scherer et al., 2023).

The CFs are initially calculated regionally. To allow for comparison and aggregation at a global level, the regional CF can be weighted using the corresponding GEP, as shown in Equation 2.6. Here, the transformational or occupational CF is used in order to obtain the corresponding global CF.

$$CF_{g,j,i,m,\mathrm{glo}} = CF_{g,j,i,m,\mathrm{reg}} \cdot GEP_{g,j} \tag{2.6}$$

CFs for land occupation is expressed in PDF/m^2, and CFs for land transformation is expressed in PDF $\cdot$ yr/m^2.

The final step of the method is to translate occupational CFs into impacts through Equation 2.7:

$$PDF = CF \cdot Area[m^2] \cdot Time[year] \tag{2.7}$$

2.4.2 BioMAPS

The LANCA method, which is a land use-method, is focused on inter alia soil organic carbon and erosion resistance, and not specifically biodiversity (Bos et al., 2016). In order to represent ecological impact on biodiversity, the Biodiversity Multi-Scale Assessments of Product Systems (BioMAPS) method was developed within LANCA. BioMAPS is a method designed to support the assessment of biodiversity impacts within LCA. By analyzing biodiversity at the spatial scales global, local and regional level, the method helps to identify where negative impacts occur and supports the development of different mitigation methods. By doing this, the method can capture the negative impacts on biodiversity. (Maier, 2023)

Within BioMAPS, GIS is used to harmonize spatial biodiversity and land use datasets, perform overlay analyses, and identify areas with varying degrees of vulnerability to biodiversity impacts. The BioMAPS method includes the five land use categories cropland, plantation, pasture, urban and forestry (Maier, 2023).

The BioMAPS method can be applied at two different levels of detail and applicability:

- Using available CFs (Behm et al., 2023)
- Calculate CFs by using detailed data and equations

The first approach is less detailed and provides impact assessments at country level, excluding several important aspects of biodiversity. The published CFs are available for each country and land-use type, which in this case is assumed to be intensive forestry (Behm et al., 2023). Additional data requirements are area and time for land use occupation (Maier, 2023).

The second approach is more detailed and incorporates local characteristics of both the forest and the forestry management practices. This approach requires more extensive data and technical expertise. Although the increased level of detail demands more resources, it can provide a more representative and nuanced assessment of biodiversity impacts, which may add value for companies aiming to better understand and manage their biodiversity performance. Therefore, this study focuses on the second approach and investigates the calculation of CFs.

Since BioMAPS does not directly measure the loss in biodiversity, but rather quantify the potential risk or impacts from different land uses, it classifies as a midpoint-method. Meaning that it works at a middle stage in the cause-effect chain, linking land use pressures to biodiversity impacts through risk-based indicators.

The BioMAPS method is still under development and the CFs for biodiversity impact will be openly available in the next version (Fraunhofer IBP, n.d.). Despite it being under development, it is planned to be integrated in EU's environmental footprinting initiative, PEF, as part of the biodiversity impact category (Herrero & Laurentiis, 2025).

2.4.2.1 Spatial Scales

The BioMAPS method provides separate results from three spatial scales; global, regional and local. The results from each scale are then aggregated into a single point result. An illustration of the methodology and spatial scales can be seen in Appendix A.

Global Scale

The BioMAPS method addresses the global scale in LCA to help support decision-making regarding the geographical sourcing of resources. It provides information on the biodiversity risk associated with different locations by identifying areas of varying global importance for biodiversity conservation. These areas are derived from conservation frameworks and categorized into proactive (low vulnerability), reactive (high vulnerability, e.g. biodiversity hotspots) and irreplaceable areas (unique species or ecosystems). To operationalize this, the globe is divided into grid cells of 0.25x0.25 degrees (Maier, 2023). Biodiversity conservation maps are then converted into a grid-based format and overlaid within each grid cell. The degree of overlap between different conservation maps is used to calculate the biodiversity risk value per cell, resulting in a unified biodiversity risk map (UBR). The risk map is then combined with global land use data, allowing the assessment of whether and to what extent a specific land use type occurs in areas of high biodiversity risk. The results can be aggregated to larger spatial scales, such as countries, to support sourcing decisions (Maier, 2023).

One challenge in large supply chains is that companies often lack precise information about the exact location of land use. To address this, BioMAPS uses global land use models (e.g. based on datasets such as Hurtt et al. (2011)) to spatially allocate land use types. These land use types are overlaid with the global biodiversity risk maps. This process, referred to as regionalization, links land use types to biodiversity risk by calculating the share of each land use type occurring within areas of different biodiversity risk levels. As a result, it becomes possible to derive biodiversity risk factors for products even when only country-level information is available.

Local Scale

The goal of the local scale is to give support in decision making when it comes to deciding how land should be managed. This is done using a land use intensity index (LUI) and the biodiversity metrics of the area (e.g species richness loss).

The goal at this scale is to analyze the impact on biodiversity while taking into account as many taxa as possible, in order to avoid ”cross-taxon surrogacy”. Cross-taxon surrogacy means that one taxa is used as an indicator to represent the effects on biodiversity within an area, using this taxa as a surrogate for others. In order to include as many taxa as possible, BioMAPS uses data from the PREDICTS-database, which covers around 28700 different species. The biodiversity metrics from the PREDICTS-database are combined with the LUI to translate the area connected and used to convert the values to local impacts on biodiversity. The LUI value is also used to translate management parameters into land use intensities. (Maier, 2023)

Regional Scale

Between the global and local scale, lies the regional, where the focus is on the whole landscape where the local site is located. This means that the surrounding landscape composition is looked into, meaning the different types of landscapes surrounding the site and the share of remaining natural area. In order to get this information, BioMAPS uses two steps. The first is global land use models, that shows what land use types are statistically occurring in different parts of the world. The second step is the landscape development indices (LDI), which is a combination of the landscape composition and the locally calculated LUI.

2.4.2.2 Method

Having introduced the different spatial scales, the method of BioMAPS can be explained. Biodiversity risk factors (BR) are separately calculated for each of the spatial scales. The BRs are then aggregated in the calculation of CFs, according to Equation 2.8:

$$CF = BR_{globe} + \frac{BR_{locLUI}}{100} + BR_{regLDI} \tag{2.8}$$

The total potential biodiversity risk (PBR) is then calculated using the Equation 2.9, by multiplying the CF by the land use area and the duration of land use occupation:

$$PBR = CF \cdot Area[m^2] \cdot Time[year] \tag{2.9}$$

Global Biodiversity Risk Factor

To calculate the risk factor for the global scale, BR$_{globe}$, the following Equation 2.10 is used:

$$BR_{globe} = BR_{overlay} + PRA + Jenkins\ index \tag{2.10}$$

BR$_{overlay}$ represents the probability of land use types occurring within biodiversity risk areas, as defined by the Unified Biodiversity Risk (UBR) map, per grid cell. The proportion of these risk areas within each grid cell is expressed as PRA, which is derived directly from the UBR map. However, since not all land use occurs within areas prioritized by the UBR map, the Jenkins index is used to account for biodiversity values outside these risk areas. The Jenkins index is based on a gap analysis and reflects the share of threatened, endemic and total species in non-risk areas. To enable comparison between regions that are not identified as high-risk in the UBR map, a Jenkins biodiversity value is calculated to fill these gaps (Maier, 2023). It is constructed from three datasets, which together provide an estimate of biodiversity importance in otherwise unprioritized areas (Jenkins et al., 2013). In this way, the Jenkins index helps identify sites where land use would have the least negative impact on biodiversity. (Maier, 2023)

Local Biodiversity Risk Factor

To calculate the risk factor for the local scale, BR$_{loc,LUI}$, the following Equation 2.11 is used:

$$BR_{loc,LUI,forestry} = 12.396 \cdot LUI + 16.246 \tag{2.11}$$

The constants (12.396 and 16.246) are a result of an interpolation of a relationship between biodiversity risk and land use intensity within forestry. The local land use intensity, LUI, is calculated by Equation 2.12:

$$LUI_{\text{Land use type } i} = \frac{PI_i}{PI_{\max}} + \frac{PII_i}{PII_{\max}} + \frac{PIII_i}{PIII_{\max}} + \frac{PIV_i}{PIV_{\max}} + \frac{Pn_i}{Pn_{\max}} \tag{2.12}$$

P represents a specific management parameter, and max indicates the threshold value of that specific parameter. Each management parameter is standardized using fractions shown in Equation 2.12, and this standardization is referred to as benchmarking by Maier (2023). In the land use category forestry, seven management parameters are considered, as can be seen in Figure 2.3. A management parameter can have a positive effect on biodiversity, called a relief indicator, or a negative effect, called a pressure indicator. Since the effect can be either positive or negative, the size of the ”effectiveness” is the measurement. Figure 2.3 visualizes the parameters and their indicators for the land use category forestry.

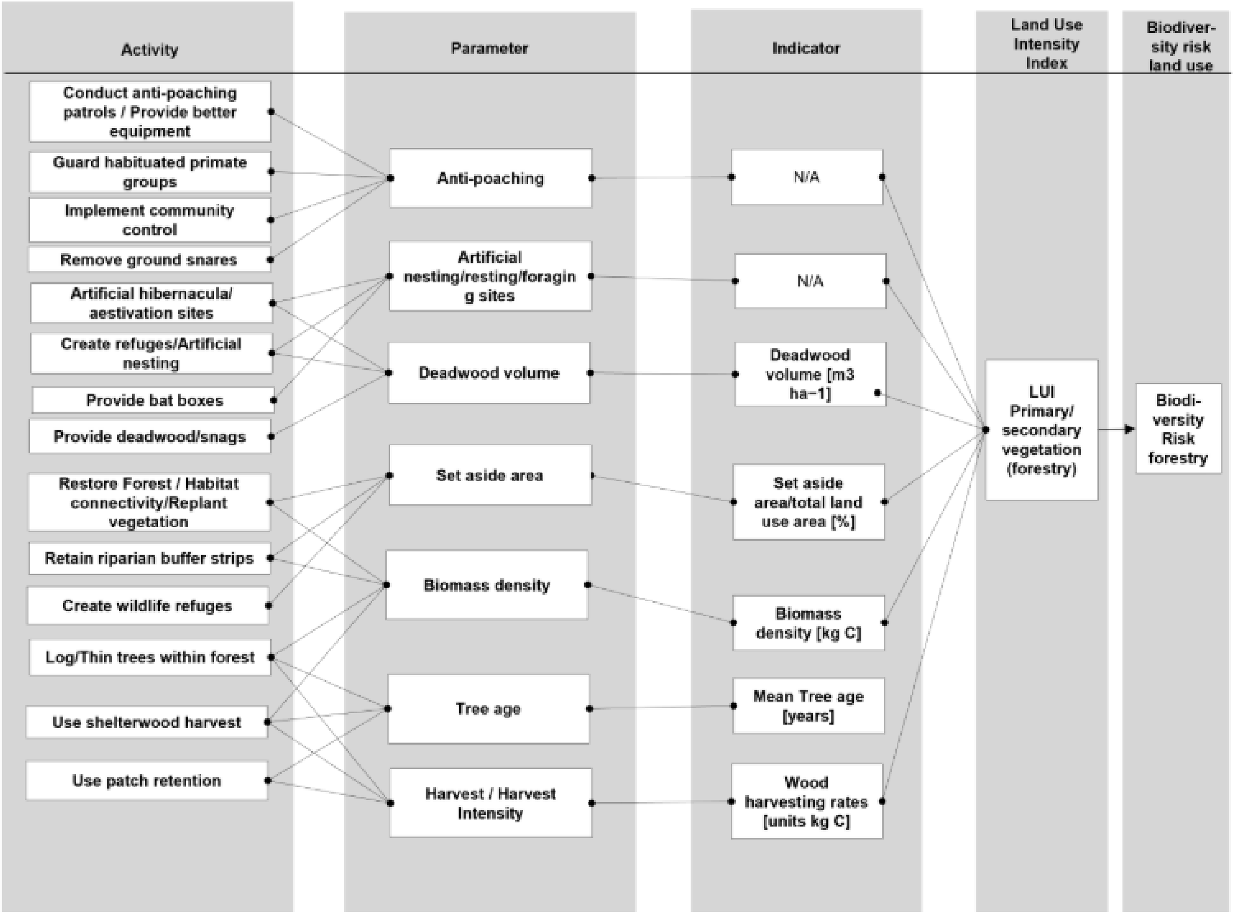

Figure 2.3: Management parameters for the land use type forestry, retrieved from Maier (2023)

Each parameter is classified according to the main drivers of biodiversity loss. Habitat Change and overexploitation are the two drivers covered by the management parameters in the forestry category. The parameters *anti-poaching*, focusing on illegal hunting and representing the driver Overexploitation, and *artificial nesting/resting/-foraging sites*, representing the driver Habitat Change, are not included yet in the calculation of LUI, since no well-established indicators could be found (Maier, 2023).

The management parameter *tree species/tree diversity* is presented in Maier (2023) but later excluded in the same study. This choice is not motivated by the author, however it is stated that no global data sets are found on the number and composition of native tree species in forests, so this is assumed to be the reason.

The included parameters are presented in Table 2.2.

Table 2.2: Forest management parameters included for land use category forestry, indicators, and data sources.

Management parameter	Indicator	Data source for background dataset *
Deadwood (DW)	Deadwood volume (standing and lying) [m^3/ha], relief indicator	Data available for European countries from Forest Europe; default value used for other countries
Wood harvesting rates (WH)	Wood harvesting rates as carbon per area [kg C/km^2], pressure indicator	Global grid cell datasets for primary and secondary forests (Hurtt et al., 2011)
Tree age (TA)	Mean tree age [years], relief indicator	Global grid cell datasets for secondary forests (Hurtt et al., 2011)
Biomass density (BM)	Biomass density [kg C/km^2], relief indicator	Global grid cell datasets for primary and secondary forests (Hurtt et al., 2011)
Set-aside areas (SetAside)	Share of set-aside forest area [% of total forest area], relief indicator	World Database on Protected Areas (UNEP-WCMC & IUCN)

* The background dataset is used in cases where primary data is not available and the company only knows country of origin (Maier, 2023)

For the land use category forestry, the LUI is calculated according to Equation 2.13. Each parameter is first standardized relative to a benchmark value. Pressure indicators (e.g., wood harvesting rates) increase with higher values, whereas relief indicators (e.g., biomass density, tree age, deadwood, and set-aside area) are inverted to reflect that higher values correspond to lower land use intensity.

$$\begin{aligned} LUI_{\text{Forest}}(i) = \frac{1}{5}\Big(\frac{WH_i}{WH_{MTI}} + \Big(1 - \frac{BM_i}{BM_{MTI}}\Big) + \Big(1 - \frac{TA_i}{TA_{MTI}}\Big) \\ + \Big(1 - \frac{DW_i}{DW_{MTI}}\Big) + \Big(1 - \frac{SetAside_i}{TotalArea}\Big)\Big) \end{aligned} \tag{2.13}$$

Here, i denotes the specific location. The resulting LUI value ranges between 0 and 1, where values close to 0 indicate low land use intensity and values close to 1 represent high intensity. This normalization enables comparison across regions and management systems. To enhance transparency, a detailed example of an LUI calculation is provided in Appendix B. This example also shows how the LUI value is used to determine the land use intensity class, in order to choose CF.

The Maximum Tolerable Intensity (MTI), representing the threshold, is generally calculated as seen in Equation 2.14, where *av* stands for average, and *SD* stands for standard deviation:

$$\begin{aligned} MTI = &\ \text{av(per land use type and GAEZ)} \\ &+ \text{av SD(per land use type and GAEZ)} \end{aligned} \tag{2.14}$$

However, GAEZ is not used in the land use category forestry due to its agricultural characteristics. Instead, Global Ecological Zones (GEZ) for Forest Assessment proposed by FAO are used (FAO, 2012). There are 20 different zones, classified based on climate, altitude and vegetation characteristics, as presented in Figure 2.4.

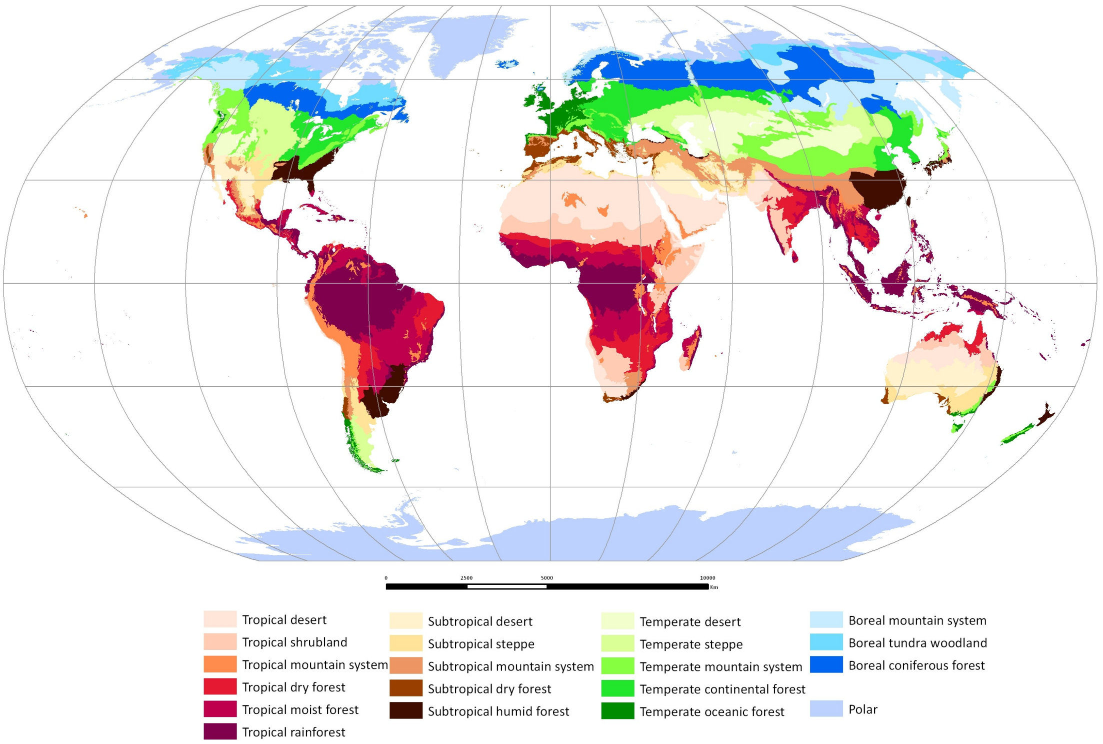

Figure 2.4: A map of the different Global Ecological Zones, retrieved from FAO (2012)

The MTI is defined more generally and is applied to other land use categories. It was developed by (Sattler et al., 2007) in a study on pesticide use. In the case of forestry, the same MTI Equation 2.14 is used to calculate benchmark values for each GEZ. The benchmark values are all provided by Maier (2023). The source of the data is not stated, however, since the data is given per GEZ, FAO is assumed to be the data source.

Regional Biodiversity Risk Factor

To calculate the risk factor at the regional scale, BR_{regLDI}, the following Equation 2.15 is used:

$$BR_{regLDItotal} = \sum_i (\%LU_i \cdot BR_{locLUI_i}) \tag{2.15}$$

$\%\mathrm{LU}_i$ represents the percent of land use i in the total area of influence, and BR_{locLUI} is the biodiversity risk depending on the land use intensity and given by Equation 2.12.

2.5 Supply Chain of Tissue Products

As mentioned above, land use is one of the drivers of biodiversity loss. One important aspect of land use is forestry, where trees are harvested and processed to produce, inter alia, tissue products. The process begins with forests and forestry operations, where wood is grown and harvested. The harvested wood is then transported to sawmills, where it is processed. During this stage, by-products such as wood chips and sawdust are generated, which can be used in pulp production. In addition to saw dust and wood chips, thinnings from the forest harvest is also used in pulp production (Suhr et al., 2015). The pulp is then used in tissue production, where it is transformed into tissue paper. This paper is further processed into different types of products, depending on the final use, such as toilet paper, paper towels or hygiene products. Certain products can also be recycled after their use-phase. After disposal, they can be collected and processed into recycled fiber. This recycled fiber can then be reintroduced into tissue production as an alternative raw material, reducing the need for virgin fiber (CEPI, 2021). A simplified representation of the supply chain is shown in Figure 2.5, highlighting the activities within the scope of this study.

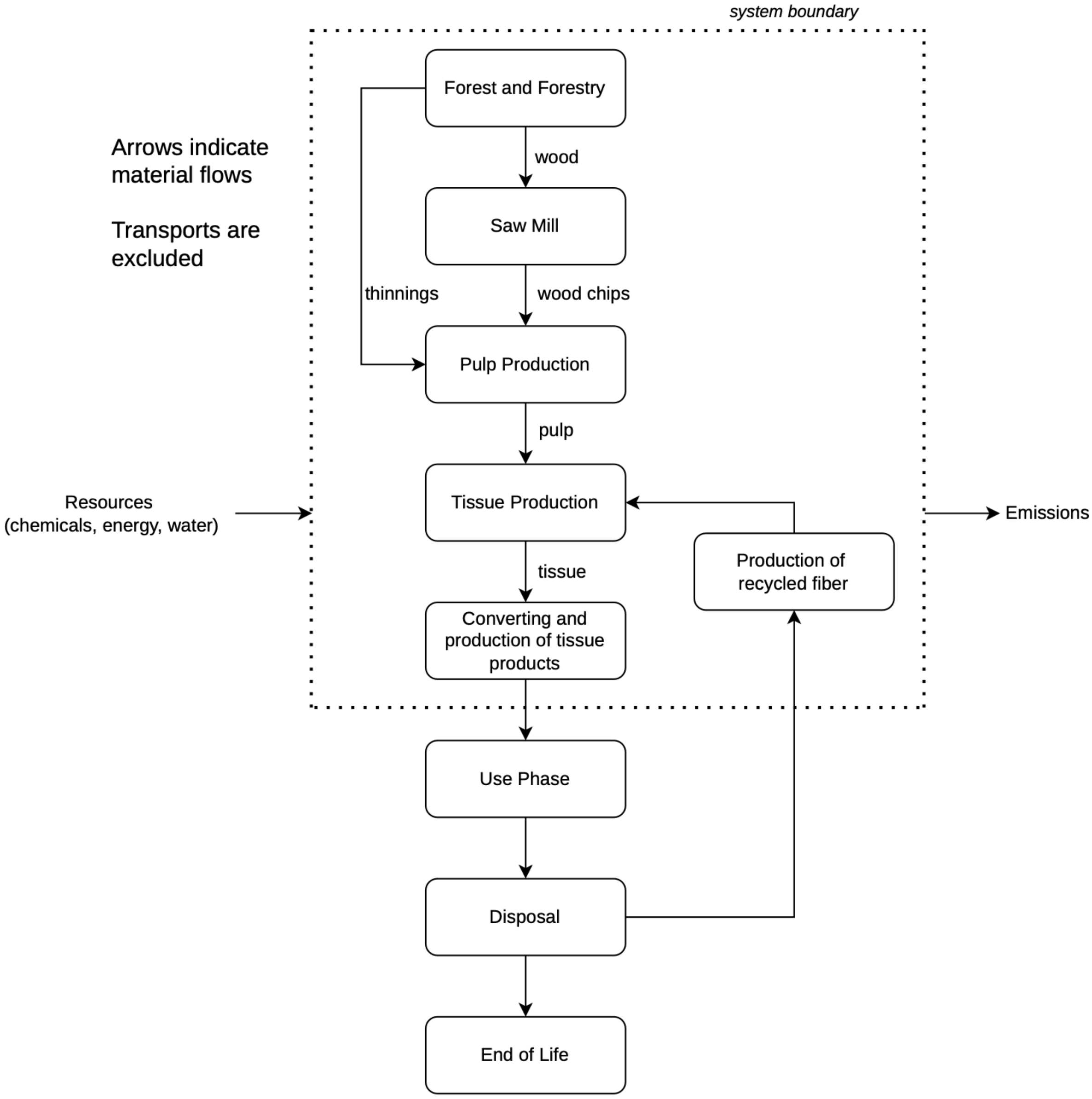

Figure 2.5: Mapping of the system for tissue production, as verified by the paper- and pulp company, including system boundary.

3

Methodology

This chapter describes the methodological approach applied in the thesis. The study follows a qualitative research approach, combining a comparative analysis with empirical data collection. First, literature was used to identify and analyze relevant biodiversity assessment methods in terms of their characteristics, data requirements, and applicability. Second, empirical data were collected through semi-structured interviews and written communication with companies and a scientific expert to investigate data management practices, data governance structures, and data availability across the forestry sector supply chain.

The thesis was conducted at IVL Swedish Environmental Research Institute, with supervision from both IVL and Chalmers University of Technology. The study focuses on a global company operating within the paper- and pulp-based consumer goods sector. The company has forestry-dependent global supply chains and production sites in multiple regions. Due to confidentiality, the company under study is not named and will hereby be referred to as *the company in focus*. Beyond the company in focus, the study also relied on information from other companies within the forestry sector.

The purpose of the study was to evaluate suitable biodiversity assessment methods that could be applied within the company in focus, considering available data and practical constraints.

3.1 Interviews and Online Communication

To understand the practical conditions for operationalizing biodiversity assessment methods, qualitative data were collected through interviews and online communication. The aim was to identify what types of environmental and supply chain data were available, particularly regarding forest-based material, geographical origin, traceability and reporting systems. All companies selected and included in the study are active within the forestry sector in Sweden, and operates at different levels in the supply chain. However, they do not necessarily have a customer-supplier relationship, but instead represent independent actors positioned at different stages of the forestry value chain.

Interviews were held with three representatives from companies within the forestry sector, one of which is the main company in focus. Additionally, one scientist knowledgeable within the subject of data management in forestry was interviewed as well. This was done in order to get a more in depth understanding of what type of data is typically collected and transferred along the forestry sector supply chain. In addition to the interviews, two companies were contacted via e-mail, where several questions regarding their data collection and management were answered in text. Another upstream company was also contacted but did not respond. Therefore, relevant information was instead gathered from their annual report.

The interviews were conducted in a semi-structured format, starting with predefined questions and themes, but with room for exploration of issues emerging during the interviews. This format allowed flexibility and deeper understanding of company-specific data structures and practices. The interviews were mainly held in Swedish and over Microsoft Teams, and the interviews were recorded with permissions of the interviewees. The recordings were transcribed with AI-tools shortly after the interviews to ensure accuracy of the information collected.

The interviews focused on understanding the companies' current sustainability data, data governance and management, and previous assessments of biodiversity impact. Particular attention was given to what type of data that is currently collected (e.g. for LCA and sustainability reporting), how they are collected and for what purpose they are used (e.g. internal follow-up, external reporting, decision making). See Appendices C, D, E, and F for interview guides.

The interviewees as well as the question respondents are presented anonymously in Table 3.1. The information gathered from these contacts formed the empirical foundation for the subsequent data mapping.

Table 3.1: Contacted people, their role and form of communication

Contact	Description	Communication type
Person A	Sustainability Specialist from the company in focus	Three interviews
Person B	Sustainability Reporting Director from the company in focus	Interview
Person C	Forest biologist at upstream forestry cooperation	Interview
Person D	Developer of forestry planning at upstream forest company	E-mail communication
Person E	Sustainability Manager at upstream forest company	E-mail communication
Person F	Scientist in deforestation and sustainable land use	Interview

3.2 Data Mapping

Building on the insights gathered through the interviews and online communication described above, a data mapping of the tissue supply chain was conducted. The process involved tracing how information moves through the supply chain by engaging with different actors at each stage. Through the interviews, data streams were identified and mapped to understand how environmental and biodiversity-related information is generated, transferred, and used across the system. This approach made it possible to localize the specific data required for the study and to clarify which actors are responsible for producing, managing, and reporting different types of data. In doing so, the mapping provided an overview of responsibilities within the supply chain and helped identify potential gaps in data ownership and reporting practices.

4

Results

The following results cover two areas: the data requirements of the two selected biodiversity assessment methods, and the data management practices and structures at the participating companies, as identified through the conducted interviews.

4.1 Data Requirements

The data requirements for the two selected methods were obtained from their respective articles, reports, and supplementary documentation.

4.1.1 GLAM

In order for a company to be able to assess their impact on biodiversity using the GLAM framework, specific data inputs are required to connect their activities to the recommended CFs. These inputs primarily relate to land use and spatial context. The data requirements for GLAM are summarized in Table 4.1 below. A total summary of the variables used can be found in Appendix A.

Table 4.1: Data requirements for GLAM, land use category forestry

Data	Unit and detail
Occupation Area * for PDF calculation (Equation 2.7)	[m^2]
Transformation Area * for PDF calculation (Equation 2.7)	[m^2]
Time of occupation for PDF calculation (Equation 2.7)	[years]
Location	Coordinates/Region, Preferably ecoregion
Intensity	Level: Minimal, light, intensive

* Transformation and occupation area are two independent impact pathways that can be applied separately. Since the company in focus treats forestry as continuous land occupation (reflecting that the same land has been under managed use over long rotation cycles) only occupation area is assessed here.

Regarding the intensity, forestry systems supplying the paper- and pulp industry in Sweden are best classified as intense use (clear-cut forests). According to the Swedish Forest Agency, forest management is dominated by even-aged systems in which stands are established through regeneration following clear-cutting and managed through a rotation of thinning and final felling (Skogsstyrelsen, 2020). This structure results in relatively uniform stands and a high volume of wood production, which aligns with the paper- and pulp industry's demand for consistent, large-scale fiber supply. This classification is also consistent with the land use definitions presented in the GLAM supplementary information, where clear-cut forestry systems are categorized as intense use (Chaudhary et al., 2018), see Appendix A.

The underlying data used to derive the CFs are collected from several global biodiversity databases. Species richness per ecoregion for vertebrates is obtained from the WWF WildFinder database, while species richness for plants is based on datasets from Kier et al. (2005). Vulnerability scores for vertebrates are derived from IUCN Red List and Birdlife, and vulnerability scores for plants are based on datasets from Kreft and Jetz (2007) and Kier et al. (2009). This species specific vulnerability data is used for calculation of GEP (Verones et al., 2022). Land use information used in the models is typically derived from Land Degradation Assessment in Drylands (LADA) database and anthropogenic biome classifications developed by Ellis and Ramankutty (2008). Modeling frameworks such as GLOBIO3 database is also used for CF development. (Verones et al., n.d.)

Through this data, the company can get their impact results in PDF, which represents the share of species that is at risk of disappearing.

4.1.1.1 Handling of Data Gaps

In cases where some required data are missing, there are functions within the GLAM framework for bridging the data gaps. For example, when data regarding the location of the site is missing, national-level aggregated factors are used as approximations. The country level CFs are calculated as area-weighted averages of the ecoregion CFs present within the country. For island nations, matching with ecoregions can be difficult, resulting in the use of the nearest neighbor method, taking an average of the three closest countries (Scherer et al., 2023).

In cases where the land use type is missing, the regional CFs from ecoregions within the biome are averaged. The averaged values are then scaled by the GEP of the ecoregion in focus to estimate its CFs. If the GEP is unavailable, an area-weighted average of GEPs from other ecoregions in the biome is used. (Scherer et al., 2023)

4.1.2 BioMAPS

In this section, both the simpler version with available CFs and the spatially explicit version of BioMAPS are explained, and their data requirements are presented.

4.1.2.1 Available CFs

This version of BioMAPS uses CFs provided by the Fraunhofer Institute. In this approach, predefined characterization factors are applied based on land-use category and geographical location, where country of origin is used. As a result, the amount of required input data is limited compared to the spatially explicit version of BioMAPS.

For this approach, data related to location, occupied area, and time of occupation are required in order to apply the relevant characterization factors. The CFs can be found via Behm et al. (2023). The required data inputs are presented in Table 4.2.

Table 4.2: Data requirements for BioMAPS, land use category forestry, using available CFs.

Data	Unit and detail
Occupation Area * for PBR calculation (Equation 2.9)	[m^2]
Transformation Area * for PBR calculation (Equation 2.9)	[m^2]
Time of occupation for PBR calculation (Equation 2.9)	[years]
Location	Country of origin

* Transformation and occupation area are two independent impact pathways that can be applied separately. Since the company in focus treats forestry as continuous land occupation (reflecting that the same land has been under managed use over long rotation cycles) only occupation area is assessed here.

4.1.2.2 Spatially Explicit CFs

The following Table 4.3 summarizes the data requirements for the spatially explicit version of BioMAPS, including data for the calculation of the different steps. A total summary of the variables used can be found in Appendix A.

Table 4.3: Data requirements for BioMAPS, land use category forestry, spatially explicit version

Data	Unit and detail
Occupation Area * for PBR calculation (Equation 2.9)	[m^2]
Transformation Area * for PBR calculation (Equation 2.9)	[m^2]
Time of occupation for PBR calculation (Equation 2.9)	[years]
Location	Preferably coordinates, but works with country of origin
Deadwood volume	Deadwood volume, standing and lying within the managed system [m^3/ha]
Wood harvesting rates	Wood harvesting rates as carbon per area [kg C/km^2]
Tree species diversity	Number of native tree species currently present in the forest stand
Tree age	Mean tree age of all trees in the forestry system during occupation [years]
Biomass density	[kg C/km^2]
Set-aside areas	Share of set-aside forest area [% of total land use area]

* Transformation and occupation area are two independent impact pathways that can be applied separately. Since the company in focus treats forestry as continuous land occupation (reflecting that the same land has been under managed use over long rotation cycles) only occupation area is assessed here.

The company in focus of the study uses pine and spruce as raw material in their products. According to the GEZ classification defined by FAO, these species are most common in the Boreal Coniferous forest and Temperate Continental forest zones. The corresponding benchmark values used in the calculation of LUI, see Equation 2.13, are provided by Maier (2023) and presented in Table 4.4:

Table 4.4: Benchmark (MTI) values for the relevant GEZ, provided by Maier (2023)

Parameter	Boreal coniferous forest	Temperate Continental forest
Wood harvest rates (WH_{MTI})	47357.53 [kg C/km^2]	47312.66 [kg C/km^2]
Biomass Density (BM_{MTI})	4.64 [kg C/km^2]	7.4 [kg C/km^2]
Tree age (TA_{MTI})	216.67 [years]	184.34 [years]
Deadwood volume (DW_{MTI})	100 * [m^3/ha]	100 * [m^3/ha]

* This value is independent of GEZ (Maier, 2023).

4.1.2.3 Handling of Data Gaps

The BioMAPS-method is developed to function despite data gaps at company level, through separating data into foreground data (primary data from the company) and background data (global statistics and models). Depending on the type of data available, BioMAPS can be applied using either foreground or background data. (Maier, 2023)

If the company does not have exact coordinates or information about the specific region of their site, BioMAPS uses global land use models (e.g. from Hurtt et al. (2011)) to estimate where production is likely to occur. These estimates are then overlaid with the UBR map to calculate an average risk factor for the country, based on the likelihood that a certain type of production occurs within global biodiversity risk areas. When exact sites are missing, it also becomes difficult to determine the surrounding landscape. In such cases, GIS datasets are used to analyze the average landscape composition of the relevant region, meaning that the LDI is calculated based on an average land distribution. If information on specific management parameters is missing, the global statistical databases, such as FAO, are used to calculate an average LUI for the relevant region. (Maier, 2023)

In addition to global statistics, averages and models, the BioMAPS method can also apply default values when certain data is missing. For example, if information on set-aside areas, deadwood volume or other management parameters are unavailable, standard values are used and provided by Maier (2023). To avoid underestimating impact, default values are chosen to represent a worst-case scenario for biodiversity, meaning parameters that reduce impact (such as deadwood volume or set-aside areas) are assigned low default values, while parameters that increase impact are assigned high default values.

4.2 Data Availability and Integration Across the Value Chain

From interviews with forestry companies at different locations in the supply chain, it has become clear that data necessary to perform biodiversity assessments are often available. Data collection is mainly done through questionnaires, forestry plans and certifications. However, if this data is collected, the reason is usually not to perform biodiversity assessments. Instead, data is collected in order to do LCAs, control the quality of the wood or simply to have general information regarding the forest characteristics. Despite the aim of the data collection, it can nonetheless be used when conducting biodiversity assessments.

4.2.1 Collection of Data

In this section, the three data collection methods obtained from interviews are presented. The methods are applied in different stages of the supply chain.

4.2.1.1 Certification Requirements

Certifications such as FSC FM provide data related to biodiversity, including requirements on retention trees, deadwood and protected areas. FSC CoC systems also enable tracking of material flows along the value chain. The majority of the interviewed companies require their suppliers to be certified, preferably FSC certification, which requires that all wood is sourced responsibly (FM) and is traceable (CoC). One step in acquiring the FSC FM certification is to have a forestry plan, which is described further in the following chapter. Additional requirements are:

- At least 5% of forest land must be set aside for conservation
- Additional 5% must be managed with adapted practices (prioritizing environmental and/or social values) requires that at least 50% of the total volume of trees is left after harvesting.
- Natural values must be preserved and enhanced (e.g. deadwood, old trees)
- Retention during harvesting (buffer zones, retention trees, high stumps)
- At least 10 trees per hectare must be retained when regeneration logging
- Forest products must be traceable from forest to final products, and all actors in the supply chain must comply with FSC standards (FSC, n.d.-f)

It should be noted that FSC FM certification does not prohibit clearcutting; rather, the above requirements are designed to mitigate its environmental impacts while still permitting conventional harvesting practices such as regeneration logging.

As described in Section 2.2.3.1, questions have been raised regarding the environmental effectiveness of certification systems, as their impact on Swedish forest conditions is not clearly demonstrated. This perspective was also reflected on by Person F, who expressed doubts about their overall usefulness and impact. At the same time, three of the examined upstream companies are part of the economic chamber of FSC Sweden and value their certifications highly.

4.2.1.2 Forestry Plan

One requirement for FSC FM certification is to have a forestry plan for the forest. The aim of conducting a forestry plan is to describe the characteristics of the forest by dividing it into different sections and set up a management plan. It also works as a tool for actions such as economic planning and certifications. In addition to collecting initial information, changes made in the forest sections must also be documented when implemented. Even if no changes has been made to the forest, the plan must be updated every ten years and, according to Person C, the old plans are typically not stored by the company. There is no set definition of what a forestry plan should contain, however it usually includes the following information for the sections:

- Development stage
- Mean tree age
- Site index (measurement of the forest productivity)
- Volume of biomass
- Tree species composition
- Recommended management actions (Skogsstyrelsen, n.d.)
- Area
- Soil moisture (Hushållningssällskapet, n.d.)
- Registered key habitats and other conservation forest areas
- Areas of special importance for reindeer husbandry
- Existing easements, conservation agreements and established nature reserves (Skogskunskap, n.d.)

4.2.1.3 Questionnaires

The company in focus uses questionnaires in order to collect necessary information from upstream suppliers. The two questionnaires relevant to biodiversity assessments are the LCA- and the pulp supplier questionnaire, where the LCA questions are sent out every other year while the one for the pulp suppliers is sent out every year. This information is then collected in separate databases, with limited availability for those not working within the relevant department. This information is not only important for the company to gather in order to track their impacts, but for the forestry owners as well in order to ensure the quality of their products. The data collected through these questionnaires include:

- Emissions to air and water (descriptions of how the emissions are measured)
- Certifications, FSC or PEFC (minimum requirement FSC Controlled Wood)
- Whether the supplier owns forest land or purchases from others
- Description of the raw material supply chain
- Which tree species are used, and their share of total volume
- Region of origin (in some cases, maps of origin, geospatial data)
- Description or flowchart of how raw material is tracked

- Harvesting
- Planting
- How the supplier works with biodiversity

4.2.2 Upstream Companies and Suppliers

The following chapter outlines the availability, governance and management of data in companies and organizations active upstream in the supply chain from the company in focus.

4.2.2.1 Upstream Actor

The company in focus has multiple upstream suppliers, one of them being one of Europe's largest private forest owner. Note that this company did not respond when contacted, and the information presented is therefore based on its website and annual reports. The company in question produces timber, pulp, packaging paper, and renewable energy. The company has implemented initiatives for enhancing forest biodiversity, with a focus on improving the precision, documentation, and transparency of conservation efforts. Progress is reported in the company's annual report. The company uses a set of indicators to measure and assess biodiversity, presented in Table 4.5:

Table 4.5: Biodiversity indicators used by upstream company.

Indicator	Unit / Description
Dead wood	[m^3/ha]
Older broadleaved trees	[m^3/ha]
Broadleaved trees	[m^3/ha]
Old forest (>140 years)	Share of productive forest area
Old forest with SIN (Special Indication of Nature Value)	Share of productive forest area

Furthermore, the company's minimum requirement for purchased raw materials is that they meet the FSC Controlled Wood standard. According to the 2024 annual report, 66% of the material was certified under either FSC or PEFC, while the remaining 34% met the FSC Controlled Wood requirements. By ensuring that all purchased material is at least classified as Controlled Wood, the company can maintain Chain of Custody certification and sell products under either FSC or PEFC schemes.

4.2.2.2 Upstream Actor Communicated Through Person C

Another upstream supplier interviewed in the study was Person C, who represents a member-owned forest association. Each member of the association typically owns relatively small forest areas, often around 50 hectares. A large share of the forest owners are certified according to FSC or PEFC standards, and many are double certified. Forest owners certified with FSC are required to maintain and report their forestry plans, including information presented in Section 4.2.1.2. The non-certified forest owners may report similar information, however it is not a requirement. In the case of not conducting a forestry plan, Controlled Wood is required and verified by the forest association. This implies that geographical origin of most wood flows is known, although the level of detail may vary. The forestry plans are not stored after updates, which limits the availability of time series data.

Several types of data available at the forest association are relevant for biodiversity assessment. Indicators related to forest structure were highlighted as important, for example volume and characteristics of deadwood, presence of older forest stands, tree species composition, and set aside areas. Dead wood was mentioned as a key indicator by Person C, due to its importance for species dependent on decaying substrates, and threshold values such as 20 m^3 per hectare are sometimes used as reference levels. Older forest stands can function as a proxy for ecological continuity, which is relevant to species that are sensitive to disturbances. The forest certifications require a minimum set aside area of 5%, and the members within the forest association typically set aside more than required. The average set aside area across the association is 8%. Person C emphasized that biodiversity indicators should be regionally adapted, since ecological conditions differ geographically. According to Person C, data based on global averages does not accurately reflect biodiversity conditions regionally and are strongly discouraged.

Traceability systems within the association are primarily designed to ensure compliance with certification requirements and regulatory frameworks. Raw materials can typically be traced from the forest to the industrial facility. However, once wood enters the industrial processes, particularly the pulp production, material from multiple locations are mixed. As a result, mass balance approaches are used, where certified and non-certified material flows are accounted for quantitatively, rather than physically separated. This implies that downstream actors can identify a set of possible forest origins rather than one specific site.

Overall, this actor holds spatially explicit information relevant for biodiversity assessment, particularly related to forest structure and management practice. The transfer of detailed data along the supply chain is limited by aggregation practices and the structure of traceability systems.

4.2.2.3 Upstream Actor Communicated Through Person D

One of the contacted upstream forestry companies, communicated through Person D, has operations at both forest level and saw mills. The company reported having extensive and detailed data related to forest management and land use. The available data includes land occupation and transformation, forest management activities, land use types and intensity, as well as high resolution geographical information. The majority of the data is stored in a forest stand register that covers the company's entire landholding. This register includes land classification, as well as both completed and planned management activities. The data in the forest stand register can be compared to the data collected by forestry plans.

In addition, several forest management parameters are recorded, including rotation periods, harvesting intensity, pesticide use, the share of protected or set-aside areas, and the degree of mechanization used in their operations. Historical data on management activities is available in internal systems, in some cases dating back to to the 1940s. Additionally, data retrieved from aerial photos from the 1960s is used to complement the dataset. However, the quality and reliability of the data decrease further back in time.

Data collection is conducted through a combination of remote sensing, field inventories and nature value assessments. The high level of data availability can partly be explained by the company's position in the value chain, as it operates both upstream forest assets and saw mills, while also sourcing raw material from private forest owners.

The collected data is used for reporting in accordance with CSRD, as well as for climate and sustainability reporting and FSC certification. A central function within the organization is responsible for compiling data from multiple sources. However, data obtained from suppliers is not shared with external actors. The company has also developed a plan for the implementation of EUDR. According to the Person D, the necessary data is already available, and the main challenge lies in integrating and structuring data from different sources.

4.2.2.4 Upstream Actor Communicated Through Person E

One of the contacted forestry companies operates at multiple levels in the supply chain, from owning forests to producing packaging products. The representative is referred to as Person E, and reported having broad access to forest-related data in cases where they are responsible for the harvesting operations. One distinction is that the company does not consider forestry activities as land transformation, but rather as ongoing land use, similarly to the company in focus. However, data on land occupation, land use type, geographical information and several management parameters, such as tree species diversity and tree age, is collected. Here, the level of detail varies depending on whether the forest is company-owned or privately owned, which also applies to wood harvesting rates. The company monitors this at country level and within special regions, while private forest owners are subject to more detailed rules and restrictions regarding their harvesting levels. Another management parameter is deadwood volume, which is inventoried before forest operations are carried out, but this data is not stored in their databases. Similarly, land use intensity is not systematically recorded.

The company highlights that when they are responsible for harvesting operations, they have access to extensive data and stores it in internal systems. However, when sourcing already processed wood or wood chips from saw mills, access to this type of data is limited. This also affects traceability, as detailed information is only available when the company manages the harvesting internally.

4.2.2.5 Visualization of Data Flows

Figure 4.1 illustrates the mapping of input data across the tissue supply chain. The interviewees, their companies' position in the supply chain and interconnectedness is also presented in the figure. The flowchart presents the required input variables to their corresponding data sources and indicates how data is transferred between supply chain actors. Blue dotted arrows represent direct data flows with measured values, while orange dotted arrows represent mixed, aggregated or indirect data, for example h (set-aside areas) that gives a minimum requirement value. There is also a blue dotted arrow between Forestry Plan and Certification, since it is required to obtain FSC certification. The green arrows represent the point in the process where each data collection method is applied.

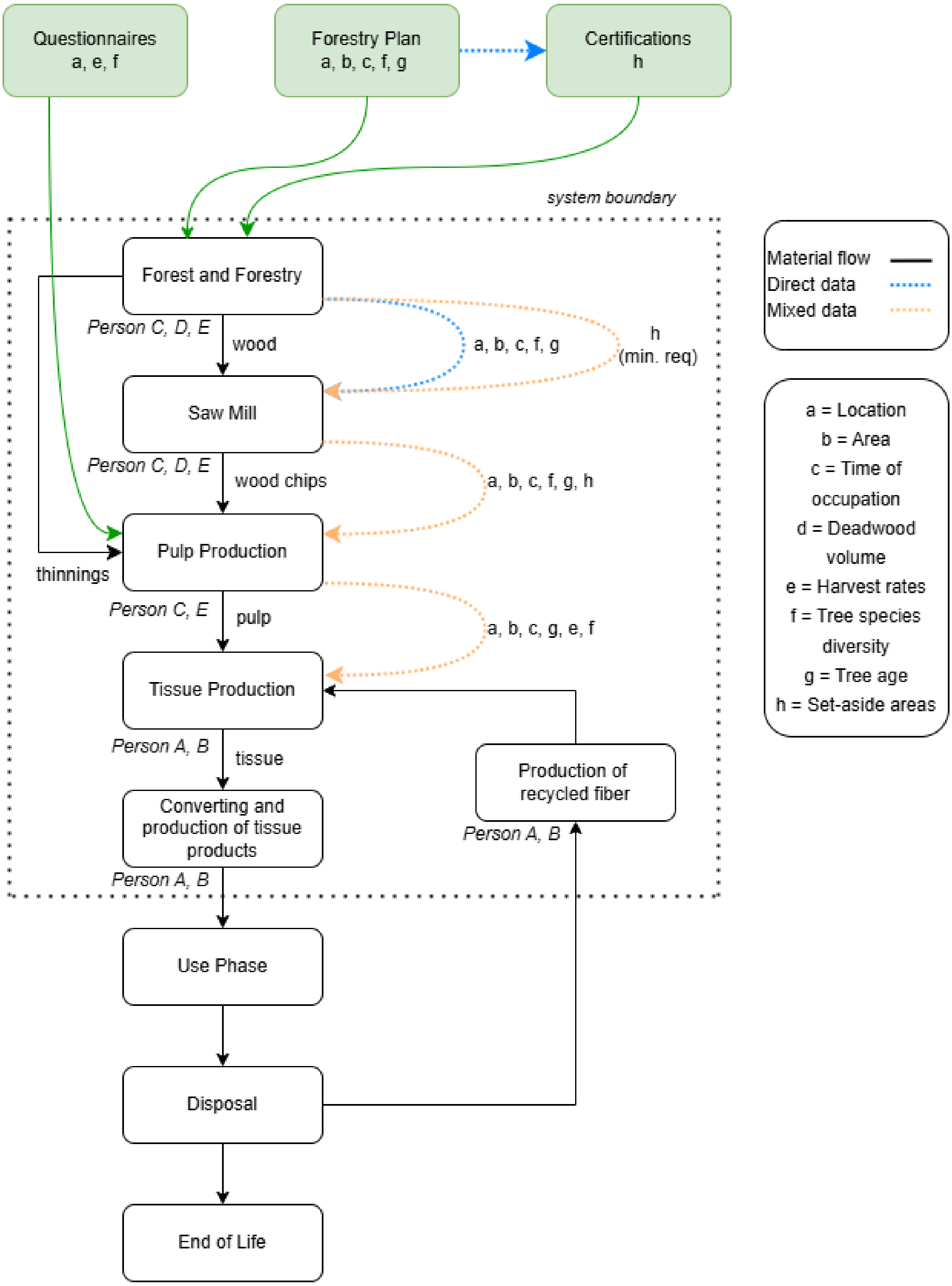

Figure 4.1: A mapping of the forestry system with data flows.

4.2.3 Data Management and Availability within the Company in Focus

In this section, the findings from interviews with Person A and B are presented, with regard to data management, data availability, as well as the company's internal policies.

4.2.3.1 Internal Access and Transferability of Data

As mentioned above regarding access to questionnaire data, the collected information is not openly available across the organization, according to Person B. Access is governed by a need-to-know-principle, meaning that only employees working within departments are granted access to specific datasets. Person A indicates that internal access to the data is generally not considered a barrier, as access can typically be arranged through internal approval processes, and in some cases supported by NDAs when confidentiality is required. However, this perspective is not fully shared across the organization. Person B highlights that internal NDAs and organizational structures can in practice limit data accessibility, as different departments are bound by separate confidentiality agreements. Different departments design and distribute their own questionnaires, and the responses are stored in separate internal databases. The databases include both qualitative and quantitative information, such as supplier certifications and origin-related data, and is structured in tabular formats supported by Power BI. Despite this structured setup, access to supplier identities and commercially sensitive information is typically restricted to specific departments and teams. This creates data silos and restricts the flow of information across functions, particularly when supplier data is considered sensitive.

The current questionnaires primarily collect general descriptions and qualitative information regarding supplier practices. Several parameters relevant for the biodiversity assessment methods are not systematically requested, although they may be known by suppliers. Person A indicates that such data could likely be obtained if requested, suggesting that the limitation lies more in current data collection practices than in data availability. The filling of other possible data gaps follows an iterative improvement process within the organization. Questionnaire responses are complemented by ongoing dialogue with suppliers through regular meetings, and verification is conducted through audits and controls as a part of the general supplier evaluation process. These processes are not limited to biodiversity-related data, but apply to broad quality related supplier information.

Both Person A & B point to external data availability as a more significant challenge. In particular, the ability to obtain relevant and detailed data from suppliers varies considerably depending on the supply chain structure. For example, traceability becomes more complex when forest fiber originates from a third party actors such as saw mills rather than directly from forest operations.

Geographical information on the origin of raw materials is available to some extent, typically at the level of regions or through supplier-provided maps. However, precise geospatial coordinates have not historically been required. This is expected to change with the implementation of EUDR, which will likely increase the availability of location-specific data. Even though the implementation of EUDR has been postponed, the company in focus is already in the process of implementing an EUDR database to ensure compliance and be prepared once the regulations enter into force, according to Person A.

Overall, the organization has a structured but evolving data management system with established processes for supplier data collection. While internal data governance is viewed by Person A as manageable and adaptable, the perspective of Person B highlights that internal fragmentation and confidentiality constraints can limit effective data use. Taken together, the findings suggest that both internal data accessibility and external data availability need to be considered when assessing the feasibility of implementing new biodiversity assessment methods.

4.2.3.2 Policy Requirements

In addition to collecting data through different questionnaires, the company in focus also referred to their policies, standards and codes of conduct to gain information regarding their suppliers, forest management and activities. However, these documents were not discussed in length and it is therefore unclear how and whether this data is systematically collected and stored or not. With this in mind, the following list contains requirements from the company's fresh wood-based fiber procurement policy.

- **Certifications and Standards**
  - FSC Chain-of-Custody (CoC) certification.
  - Compliance with FSC-certified or FSC Controlled Wood requirements.
  - Documentation of PEFC certification where applicable.
  - Adherence to the company's Code of Conduct and Global Supplier Standard (GSS).
- **Fiber Origin and Traceability**
  - Geographic location of fiber sources and specific wood species.
  - Sourcing data regarding Boreal forests, Intact Forest Landscapes (IFLs), and indigenous cultural landscapes.
  - High Conservation Value (HCV) assessment processes and field-level decisions.
  - Implementation of Free, Prior, and Informed Consent (FPIC) processes.
  - Full traceability documentation (from forest to mill, production, shipping, and delivery) for requested samples.
- **Environmental and Climate Data (LCA)**
  - Operational performance data: energy use, water use, and transport.
  - Emissions to air, water, and land.
  - List of chemicals used in production.
  - Greenhouse gas (GHG) emissions data (sub-scope 3.1) to support Science Based Targets.
- **Reporting and Progress**

  - Percentage of certified wood purchased relative to total volume.
  - Detailed plans and timescales for increasing the amount of certified fiber in the supply chain.
  - Reporting on forest degradation and peatland management.
  - Timely notification of any complaints or irregularities in the supply stream.
  - Responses to regular sustainability and raw material questionnaires.

4.2.3.3 Summary of Data Availability within the Company in Focus

The following Tables 4.6 and 4.7 show the availability of the data that is required for GLAM and BioMAPS. The tables provides an example of what data that is required for the land use category forestry, and available within the company, for a pulp-based product.

Note that the ecoregion presented in this example (PA0608 Scandinavian and Russian Taiga) reflects a specific case of tissue production using wood sourced from Sweden. For products with different geographic origins, the appropriate ecoregion would differ accordingly. Given that GLAM provides CFs for 804 ecoregions, the pairing of location to ecoregion is relatively straightforward when geographic data is available at regional or coordinate level, and even country-level data can be used to derive area-weighted average CFs as described in Section 4.1.1.1. All ecoregions available are presented in Supplementary information in Chaudhary et al. (2018).

According to Person A, land transformation is not assessed, in alignment with certification regulations. This means that Equation 2.4 is redundant in this case. As mentioned in Chapter 4.1.1, the intensity of the forestry is assumed to be intensive.

Table 4.6: Examples of data inputs required for GLAM, available within the company in focus

Data	Availability
Occupation Area for PDF calculation (Equation 2.7)	Gathered for LCA assessment
Time of occupation for PDF calculation (Equation 2.7)	Gathered for LCA assessment
Location	Ecoregion PA0608 Scandinavian and Russian Taiga for tissue
Classification	Forestry
Intensity	Intensive

Data on management parameters for BioMAPS are, as previously mentioned, not included in either questionnaires or certification documentation. Entries marked as "*Not currently available*" in the table refer to data that is currently unavailable to the company in focus, rather than data that is not collected at all. In several cases, the data exists upstream in the supply chain but is not transferred between actors. For example, data related to the deadwood parameter is collected by one of the upstream companies, but is no longer available once the pulp reaches the company in focus, as shown in Table 4.7.

Table 4.7: Examples of data inputs required for BioMAPS, spatially explicit version, available within the company in focus

Data	Availability
Occupation Area for PBR calculation (Equation 2.9)	Gathered for LCA assessment
Time of occupation for PBR calculation (Equation 2.9)	Gathered for LCA assessment
Location	Coordinate, not systematically collected
Deadwood volume	Not currently available
Wood harvesting rates	Retrieved in pulp supplier questionnaire
Tree species diversity	Retrieved in pulp supplier questionnaire
Tree age	Not currently available
Biomass density	Not currently available
Set-aside areas	A minimum of 5% can be assumed due to certification rules, but no exact data currently available

It should be noted that the area input required for PDF and PBR calculation is not directly available as a single data point, but rather needs to be calculated in the LCI. This LCI area represents the land area required to produce one functional unit, and is not equivalent to the total forest area described in a forestry plan. To derive the LCI area, two input data are needed:

- the productivity of the forest stand (site index, expressed in m^3/ha/yr, which is usually available in the forestry plan)
- the volume of wood required to produce one functional unit (which is available through production yield data, for example from LCA questionnaires)

The forestry plan thus provides one necessary input to this calculation, but the full derivation requires data from both the forestry and production sides of the supply chain. If wood from multiple origins with different productivity is mixed, as is common in pulp production, a weighted average productivity may need to be used, which introduces additional uncertainty into the area estimate.

5

Analysis and Discussion

In this chapter, the findings of the results are analyzed and discussed with regards to the aim and research questions.

5.1 Data Requirements and Availability

What data are required to apply selected biodiversity assessment methods, and how do these requirements relate to the type, resolution and structure of data available within the company?

As the study shows, the two assessment methods require different types of data, including management, spatial and ecological data as well as modeling and statistical data from global databases. The methods also differ in the level of detail required, which in turn affects how readily they can be implemented based on data currently available within companies.

GLAM shows a relatively high level of compatibility with data available within the company in focus. In practice, the method requires information regarding land occupation, geographic location, land use classification and management intensity needs to be provided in order to link activities to the recommended CFs. Much of this information is already collected through LCA processes, certification systems or forestry-related documentation. The main challenges are therefore not the absence of data, but rather difficulties related to internal accessibility, transferability and integration of data between organizational functions and systems, as well as the practical limitations of tracing data back to a specific harvesting location.

BioMAPS can be applied in two ways: either using available CFs at country level, or through the spatially explicit version which calculates CFs based on detailed management parameters. These two versions differ substantially in both data requirements and ecological detail. The version using the available CFs has data requirements comparable to those of GLAM, and is therefore equally applicable given the current state of data collection within the company in focus. The spatially explicit version, on the other hand, takes a more advanced and ecologically detailed approach by assessing biodiversity impacts across three spatial scales and incorporating several forest management indicators. This approach can provide a more nuanced assessment, and detailed assessments are sought after by companies, as highlighted by Person C. However, the increased methodological complexity comes with substantially higher demands on data availability that are not currently met within the supply chain.

From the perspective of data requirements and availability, both GLAM and the pre-calculated version of BioMAPS are applicable given the current state of data collection within companies, while the spatially explicit version of BioMAPS is constrained by the limited availability and transferability of detailed management data along the supply chain.

5.2 Traceability and Integration of Data

How can the required biodiversity-related data be located, accessed and integrated across different organizational functions and value chain actors to enable the operationalization of the selected methods?

Through interviews with the companies, it has become clear that relevant biodiversity-related data exists within organizations. However, this data is usually spread across the organization. Different functions collect different types of data for different purposes. For example, the sustainability department gather LCA-related information, while the supply chain department collects forest management data from suppliers. These datasets are often stored separately and are not directly accessible across departments, even though they are relevant to each other. However, the opinions of the interviewees vary regarding the accessibility, sharing and coordination of data internally.

One possible explanation for these differing experiences is the organizational position of the interviewees and their relation to the data flows. Different departments interact with different systems, suppliers and reporting processes, which affects their understanding of what data is available and how accessible it is. Interestingly, Person B, working directly with sustainability reporting, described difficulties in identifying and accessing relevant data across the organization. This suggests that the challenge is not necessarily the absence of biodiversity-related data, but rather limited internal coordination, communication and visibility between organizational functions. As a result, employees may have different perceptions of data availability depending on which part of the organization they operate within and which datasets they interact with in their daily work. However, the company in focus is implementing an internal database for EUDR compliance, which could improve the availability and structure of supplier and origin data across the organization.

The existence of multiple datasets collected for different purposes can pose a challenge when implementing biodiversity assessment methods. However, this situation may change with the implementation of EUDR, which has encouraged some companies to plan ahead through reviewing and increasingly integrating their current data systems. In addition to integrating different datasets, the amount of data regarding the origin of materials will drastically increase. This can benefit biodiversity assessment methods since they will not have to rely as much on estimates and proxies, as geographical location will be more available.

Despite the potentially increased detail of geographical data, the issue regarding the traceability and transferability of data in the supply chain still remains. Traceability is partly enabled through certification systems, for example FSC CoC, but in the case of paper- and pulp production, traceability becomes more complex due to the mixing of materials. These industrial processes reduce the spatial resolution of the data, which in turn limits the applicability of spatially explicit biodiversity assessments. This challenge is also linked to data transfer along the value chain. Upstream actors possess more detailed data regarding ecological characteristics and forest management, as they operate closer to the forest level. However, this does not necessarily mean that the data is easily transferable or usable for downstream biodiversity assessments. Different actors within the value chain collect and manage data for different purposes, such as operational forestry planning, certification compliance or sustainability reporting. As a result, the structure, level of detail and accessibility of the data may vary between actors. Information can therefore become simplified, aggregated or disconnected as it moves through the supply chain, making it more difficult for downstream companies to connect biodiversity-related data to specific products, sourcing areas or assessment requirements. One solution as described by Person C, is a mass balance approach applied to certified material. However, this solution can not give an exact measurement of the amount of certified wood in a product, but rather an estimate of the total amount of certified wood in the input.

This issue of transferability affects both GLAM and BioMAPS. However, GLAM can be applied using less detailed, regional data, while BioMAPS requires multiple, more detailed data input parameters that depend on high-resolution data. While this type of specific data often has shown to be available at the upstream supplier level, it is usually not accessible to the company once the product has been processed and moved further along the value chain. For example, according to Person C, it is difficult to determine what share of the wood chips that originates from a specific forest. However, since the company in focus uses a limited number of tree species in their tissue production, the ecoregions that the wood is retrieved from is limited. Despite this, these extensive data requirements make BioMAPS more difficult to implement within the forestry sector, where detailed data is not consistently transferred between actors. The implementation of BioMAPS may therefore require improved data sharing practices and increased transparency between actors and stakeholders. As a result of this, the main challenge is not to gain access to data within the company itself, but rather the transferability of sufficiently detailed data from upstream actors.

5.3 Limitations, Uncertainties and Data Gaps

What are the main limitations and uncertainties of the method and data, and how can possible data gaps be addressed when required data is not readily available?

The results show that both data-related and methodological limitations affect the applicability of the assessment methods. One of the main limitations is that not all necessary data is available at the required level of detail. Also, while some data exists within the company or among upstream actors, it is not always collected in a systematic manner. This is particularly clear for the management parameters required by the spatially explicit BioMAPS, where detailed ecological and management data are often missing or only partially available. This limits the ability to fully operationalize the method and may require the use of estimations and proxies.

Related to data limitations along the supply chain is the processing of wood. During this process, different tree species originating from multiple forests are often mixed. The paper- and pulp company in focus then purchases wood chips and sawdust from sawmills to produce pulp, which makes clear traceability of raw material origins difficult. As mentioned by Person C, one approach to improving traceability is the use of a mass balance system. This represents a general allocation problem in LCA when products are based on mixed-origin resources, similar to challenges seen in other impact categories. However, as previously discussed in Section 2.3, biodiversity is particularly sensitive to this limitation since impacts are highly dependent on context and location-based information, in contrast to more easily aggregated metrics such as greenhouse gas emissions.

In addition to broader organizational limitations, BioMAPS has methodological constraints. The LUI is based on scaling management parameters against benchmark values that may not reflect local ecological conditions, relying on assumptions that are not necessarily transferable across forestry systems. This may lead to an incomplete representation of site-specific management intensity. In addition, equal weighting of parameters can oversimplify their relative importance, resulting in similar LUI scores despite different ecological conditions. Furthermore, in Equation 2.8, the global risk component of BioMAPS is not normalized and may therefore dominate the overall result. This can underrepresent local impacts, meaning that regions with high biodiversity, such as the Amazon, may consistently yield high risk scores regardless of local management quality, potentially hiding improvements at the local level.

Another important finding lies in the differences in methodology of the the assessment methods. GLAM includes CFs for five species groups, for example plants and birds, but invertebrates, and more importantly, insects, are not included. This is a significant limitation in the assessment of biodiversity in forest ecosystems, as insects represents a major share of species richness and contribute to ecosystem functions. Plants and birds can provide an indication of habitat quality, but not fully capture the complexity and importance of insects. BioMAPS assess habitat requirements for insects when including management parameters such as deadwood and tree age. As a result, BioMAPS is better suited for assessing biodiversity impacts in forestry systems. The reliance on a limited set of species groups in GLAM implies that these groups act as proxies for overall biodiversity, which introduces uncertainty and risks to underestimate impacts.

One key difference between the two assessment methods is the units they use to measure biodiversity, where GLAM uses PDF and BioMAPS uses PBR. Both methods focus specifically on biodiversity impacts arising from land use, with a primary application in agricultural and forestry contexts. The purpose of PDF is to provide a quantifiable measure of biodiversity loss that can be compared across different types of environmental impacts. PBR, on the other hand, is a dimensionless index representing an aggregated risk to biodiversity. The aim of this approach is to support decision-making by identifying where actions are needed, rather than directly measuring species loss. In addition, PDF mainly focus on the species level, often looking at specific taxa, while BioMAPS' PBR aims to capture risks across all levels of biodiversity. While the ambition behind PBR is valuable, and potentially very useful if successfully applied, it is a metric specifically developed within BioMAPS. This raises some questions regarding its legitimacy, standardization and applicability in real-life company settings. This challenge is not purely technical, it also reflects a form of path dependency, where previously established indicator units and frameworks become embedded in industrial processes and reporting systems over time, making them difficult to replace regardless of whether newer alternatives offer improvements in certain respects. BioMAPS therefore faces an uphill battle simply by virtue of being new, even if it captures aspects of biodiversity that PDF does not. In contrast, PDF has been used before and was developed as a footprint metric for use in LCAs. It may therefore be easier to implement GLAM in companies that already conduct LCAs on their products, even though it presents a more simplified picture, not capturing important aspects such as functional diversity. This once again suggests that GLAM may be more practical under the current state of biodiversity assessment in companies, while the ambitious approach of BioMAPS could become more relevant in the future.

Overall, the analysis show that limitations do not only arise from data gaps, but also from the assumptions and structures of the methods themselves. Even with improved data availability, uncertainties remain due to how biodiversity is represented and modeled within the assessment approaches. This highlights that methodological constraints are inherent to the current state of biodiversity assessment and cannot be fully resolved by improved data availability alone.

5.4 Sources of Error

As can be seen in the results, several companies focus on certifications from FSC or PEFC to argue that their products are sourced sustainably and environmentally conscious. Despite limited evidence that certifications improve ecological conditions, companies place strong emphasis on them when describing their biodiversity efforts. It is worth noting that three of the companies included in the study are part of the economic chamber of the FSC board. This could imply that there is a bias toward this type of certification, especially since there has been an ongoing debate regarding the legitimacy of the certification.

Additionally, it is important to distinguish what type of information is actually provided from certification. While FSC CoC certification ensures traceability of materials through the supply chain, it does not include detailed ecological data on forest management. Such information is instead covered by FSC FM certification.

As a result, certification data alone may be insufficient for biodiversity assessment methods that require site-specific ecological or management data, limiting its usefulness for more detailed approaches.

In addition to availability, the quality and reliability of data introduce further uncertainty. Much of the results of the study is based on self-reporting from companies and suppliers, and there have been limited possibilities of verification. As a result, data may be reported as accessible and sufficient when in reality, it is not. This raises the possibility of reporting bias and introduces uncertainty into the results, where data availability and quality may be presented more favorably than the actual case, thereby affecting the reliability of the findings. Additionally, the company in focus requested to be anonymous in this report, which limited the inclusion of organizational details. This constraint might affect the reproducibility and transparency of the results.

Related to the reliability of the study is the comparability with similar research. As BioMAPS and GLAM are relatively new assessment methods, no studies with sufficiently similar designs were identified to allow for meaningful comparison of methodological approaches. In addition, no case studies applying either BioMAPS or GLAM in practice were found. This lack of empirical applications also limited the ability to verify whether the theoretical descriptions of the methods have been correctly interpreted and implemented. Consequently, the absence of comparable studies weakens the ability to validate the findings and may affect the interpretability of the results.

5.5 Further Research

The topic of biodiversity assessment is under continuous development, making further research inevitable. New emerging policy regulations, most importantly the EUDR, will expand the possibilities of biodiversity assessment, as requirements for supply chain traceability are likely to increase, potentially driving greater availability of spatially explicit data in practice. Therefore, further research is recommended to explore how the growing availability of geospatial data can be effectively utilized to improve biodiversity assessments.

One possible development is that the Information System that the European Commission will provide for the enrollment of EUDR (European Commission, n.d.-d) could include an integrated biodiversity impact or risk assessment tool. Such a tool could function in a similar way to the WWF Biodiversity Risk Filter, where biodiversity risk levels are derived primarily from geographic location and the ecological importance of the area. Since EUDR already requires geolocation of raw material origins, integrating a biodiversity risk indicator within the same system could provide companies with an initial biodiversity screening without requiring additional internal data collection. An important advantage of such an approach is that it would reduce the need for companies to independently collect and process large amounts of biodiversity-related data. Instead, risk assessments could be conducted within the same platform used for reporting geolocation data, thereby simplifying implementation and improving comparability between companies.

However, this approach raises several important questions. A key challenge concerns the temporal dimension of such assessments: if the screening is conducted after raw material extraction, it serves primarily a reporting function rather than a preventive one, meaning any biodiversity damage has already occurred. Furthermore, a meaningful biodiversity assessment requires knowledge of the baseline state of biodiversity prior to land use, which in itself is a complex and data-intensive undertaking. These limitations suggest that while such an integrated tool could improve comparability and reduce the burden of data collection, its value as a decision-support tool would depend heavily on whether assessments are conducted prospectively, before extraction takes place, rather than retrospectively for compliance purposes alone.

Both methods studied in this thesis fall under the category ”LCA-based assessment methods”. To fully capture the complex nature of biodiversity, future research could benefit from approaching the problem from multiple perspectives. Evaluating a company’s impact on biodiversity from a life cycle impact perspective in combination with for example a risk-based or economic perspective could provide a broader analysis and a more comprehensive evaluation.

A key limitation of these biodiversity assessment methods lies in the attempt to reduce a complex and multidimensional issue as biodiversity loss into one single aggregated metric. Biodiversity has multiple interacting dimensions, such as species richness, functional diversity, genetic diversity, spatial distribution, and temporal dynamics. Combining these aspects into one numerical score inevitably leads to a loss of information. One single resulting value will fail to capture ecological complexity and reflect variability in, for example, management practices and local conditions. Single value indicators are often requested in decision making contexts due to their simplicity and ease to interpret. However, this simplification and aggregation risks to hide whether a given score reflects moderate impacts across many indicators, or severe impacts concentrated in fewer. Consequently, relying on a single metric can create a false sense of precision and comparability. Further research is therefore needed to explore how indicators can better communicate uncertainty, variability and multidimensionality, while still functioning in corporate decision making contexts.

From a broader perspective, it would also be interesting to apply the two assessment methods to other sectors and industries besides forestry. Since the forestry sector has proven difficult when it comes to transferability along the supply chain, another sector would likely pair better with the data requirements of the chosen biodiversity assessment methods. In addition to examining different sectors, it would also be valuable to explore different types of data transfers within the supply chain. For example, economic data transfers could be analyzed as a basis for understanding how similar mechanisms might be applied to biodiversity-related data transfers.

Also, this study did not account for any organizational costs of implementation of the methods. Possible costs for licenses or programs are also excluded from the study. The economic aspects may influence the selection of method in practice and should therefore be considered in future research.

6

Conclusion

The aim of this thesis was to assess the relevance and practical feasibility of two biodiversity assessment methods in a business context, focusing on data availability, traceability, and data gaps within the forestry sector. The study analyzed the methods' data requirements and examined how relevant data could be identified, traced, and integrated across organizational functions.

The study focused on the two methods GLAM and BioMAPS, with particular attention given to the more spatially explicit version of BioMAPS. With the addition of local management parameters in BioMAPS, which rarely transfer downstream in the supply chain, it became clear that GLAM requires less data and is more readily applicable in a business context. Its approach is also largely compatible with existing LCA practices. It is however worth noting that using BioMAPS available CFs would result in similar data requirements for both methods.

The assessment also showed that data tends to disappear as wood is processed and aggregated throughout the supply chain. Once the material is processed and different wood sources are mixed to produce pulp, it becomes very difficult to connect relevant ecological data to the final material flows. Certification systems such as FSC CoC enable material traceability through mass balance approaches, but these provide estimates of certified material flows rather than exact measurements, and do not transfer the detailed ecological information needed for biodiversity assessments. Even when detailed ecological data exists at the forest level, such as deadwood volume, tree age, and biomass density, it becomes inaccessible once the material has passed through industrial processing.

Another key finding is that relevant biodiversity data exists within the company in focus, but is fragmented across departments that collect and manage it for different purposes. This suggests that the challenge is less about data absence, and more about the inability to connect existing datasets across organizational functions. As a result, employees in different departments may have fundamentally different perceptions of what data is available, depending on which systems and suppliers they interact with in their daily work.

A central conclusion regarding biodiversity assessments is that there is a fundamental trade-off between applicability and ecological detail. GLAM is more practical under current conditions, while the spatially explicit BioMAPS is ecologically more relevant, but currently difficult to implement given existing data flows in the forestry supply chain. This trade-off, however, is not unique to the two methods examined in this study. It reflects a broader and more fundamental tension in biodiversity assessment: the methods that are most ecologically meaningful tend to require data and contextual knowledge that is difficult to obtain in a corporate supply chain setting, while the methods that are practically feasible tend to simplify or approximate the very complexity that makes biodiversity difficult to assess in the first place. Regulations such as EUDR may improve data availability and supply chain traceability, but are unlikely to resolve these underlying tensions, as the challenge is not only one of data access but of the inherent difficulty of capturing ecological complexity within standardized assessment frameworks.

However, even with improved data availability, methodological limitations remain. GLAM excludes insects and other invertebrates from its species groups, which represent a major share of species richness and ecological function in forest ecosystems, meaning the included groups act as proxies that risk underestimating actual biodiversity impacts. BioMAPS, by contrast, captures habitat requirements for insects through management parameters such as deadwood and tree age, making it better suited for assessing biodiversity impacts specifically in forestry systems. Similarly, the LUI calculation in BioMAPS applies equal weighting to all management parameters, which may obscure important ecological differences between sites, and the global risk component can dominate the final result in ways that hide local improvements. These are not data problems, but reflect fundamental assumptions built into the methods themselves.

A further barrier to the adoption of BioMAPS relates not only to data availability, but to path dependency. PDF has become embedded in existing LCA frameworks and corporate reporting systems over time, meaning that GLAM benefits from institutional familiarity regardless of whether BioMAPS offers ecological improvements in certain respects. This structural inertia represents an additional challenge for BioMAPS beyond its data requirements, and suggests that wider adoption may depend as much on standardization efforts and regulatory uptake as on methodological development.

Overall, the feasibility of biodiversity assessment in the forestry sector is constrained not primarily by methodological complexity or lack of data, but by how data is structured, siloed within organizations, and disconnected from material flows as wood is mixed, aggregated, and transformed throughout the supply chain. The central challenge is therefore not simply that data disappears, but that the relationship between site-specific ecological information and the final product becomes increasingly difficult to maintain. Once wood from multiple forest stands is combined in industrial processes such as pulp production, biodiversity-relevant attributes can no longer be reliably attributed to specific material flows, even if the underlying data still exists somewhere within the supply chain. Improving biodiversity assessment in this context therefore requires not only better methods, but also improved data governance, integration within companies, and mechanisms for preserving the link between ecological information and material traceability across supply chain actors.

It should also be noted that the findings of this study are based primarily on self-reporting from companies and suppliers, with limited possibilities for independent verification. Data availability and quality may therefore have been presented more favorably than the actual case. Additionally, three of the interviewed companies are part of the economic chamber of the FSC board, which may introduce a bias toward FSC certification in how biodiversity efforts are described and assessed.

Furthermore, as both GLAM and BioMAPS are relatively new methods, no comparable empirical case studies were identified during this research. This limited the ability to validate whether the methods have been correctly interpreted and applied, and means that the findings should be read with this uncertainty in mind.

Ultimately, some of the limitations identified in this study are not merely technical or methodological, but reflect fundamental constraints in applying LCA as a framework for biodiversity assessment. LCA was designed to quantify and aggregate environmental impacts across a product's life cycle, which inherently favors impacts that are measurable, comparable, and expressible as a single score. Biodiversity, however, is place-specific, context-dependent, and shaped by complex ecological interactions that resist aggregation. Reducing biodiversity impacts to a single metric, whether PDF or PBR, inevitably loses information about ecological complexity, functional diversity, and spatial variability. This is not a limitation that more research or better data can fully resolve. This suggests that the challenge is not only one of data availability or methodological refinement, but one of fundamental fit, whether LCA-based approaches are the most appropriate tool for capturing biodiversity impacts at all, and whether complementary approaches beyond the LCA framework may ultimately be necessary.

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A

Appendix A: Tables and figures

Table A.1: Land use classifications for GLAM, retrieved from Table S1 Supplementary information in Chaudhary et al. (2018)

Land use type	Management type	Description
Natural habitat	None	Little or no human disturbance (pristine state)
Regenerating secondary vegetation	None	Little or no human disturbance
Managed (logged) forests	Minimal use (RIL)	Forests managed with reduced-impact logging techniques designed to minimize impacts on biodiversity
	Light use	Forests where only selected commercially valuable trees are harvested without major ecosystem change
	Intense use	Clear-cut or even-aged forests with severe disturbance altering ecosystem structure
Plantation forests	Minimal use	Mixed or extensive plantations with native understorey, no pesticide/fertiliser, no recent (<20 years) clear-felling
	Light use	Monoculture plantations of mixed age without recent clear-felling
	Intense use	Even-aged monocultures or plantations with recent (<20 years) clear-felling
Pasture	Minimal use	Low fertiliser/pesticide input and low stocking density allowing vegetation regeneration
	Light use	Either high input use or high stocking density causing disturbance
	Intense use	High input use and high stocking density preventing regeneration

Continued on next page

Land use type	Management type	Description
Cropland	Minimal use	Low-intensity farming: small fields, crop rotation, little mechanisation, minimal chemical input
	Light use	Medium intensity farming with some fertiliser, pesticide, irrigation, or mechanisation
	Intense use	High-intensity monoculture farming with strong inputs and mechanisation
Urban	Minimal use	Villages or extensive managed green spaces
	Light use	Suburban areas or small green spaces in cities
	Intense use	Fully urban areas with no significant green spaces

BioMAPS overview

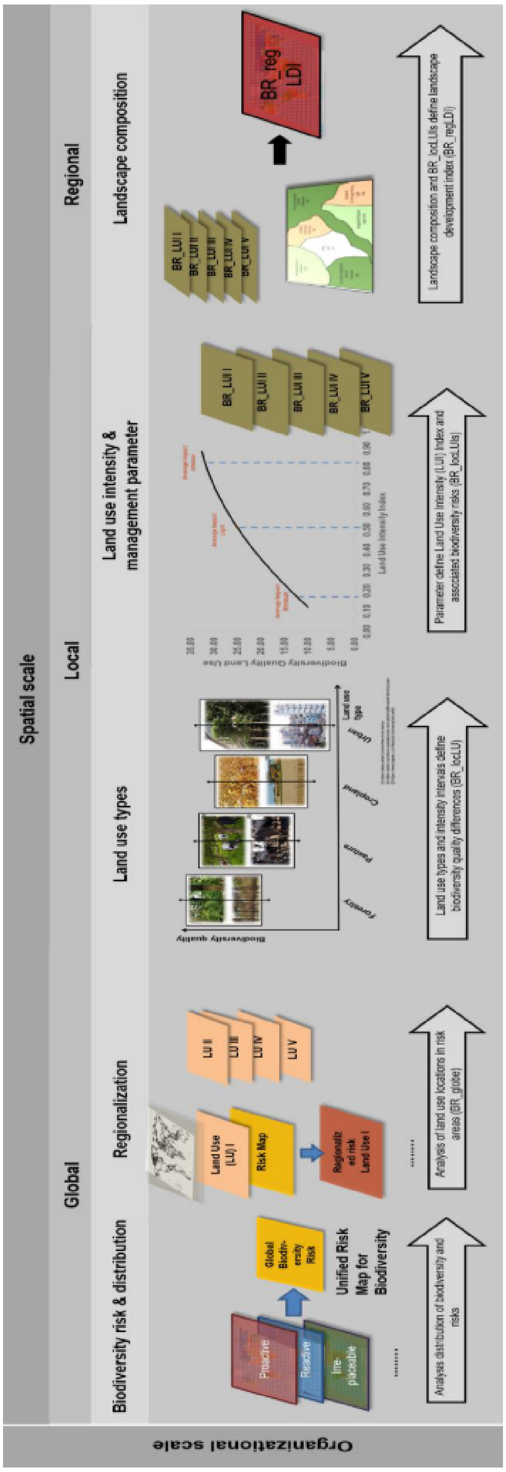

Figure A.1: BioMAPS overview retrieved from Maier (2023)

Table A.2: Variables used in the GLAM and BioMAPS equations

Variable	Equation	Definition
GLAM		
ECA	2.1	Equivalent Connected Area, effective habitat area available to species
$A_{j,i,m,x}$	2.1	Area of landscape patch
p	2.1	Probability of movement between patches for species
H	2.2	Suitable connected habitat area
h	2.2	Suitability of specific land use type and intensity level for a species group
RSL	2.3	Relative Species Loss, at regional level
a	2.4	Allocation factor distributing biodiversity impacts
$A_{j,lu}$	2.4	Total regional land use area
t	2.5	Regeneration time of a species group
GEP	2.6	Global Extinction Probability, probability that local biodiversity loss leads to global species extinction
BioMAPS		
$BR_{overlay}$	2.9	Probability of land use types occurring in biodiversity risk areas
PRA	2.9	Proportion of risk areas within each grid cell
Jenkins Index	2.9	Share of threatened, endemic and total species in non-risk areas
WH	2.12	Wood harvesting rates
BM	2.12	Biomass density
TA	2.12	Tree age
DW	2.12	Deadwood
%LU	2.14	Percent of land use in total area of influence

B

Appendix B: Calculation example of LUI for BioMAPS

This appendix presents a hypothetical calculation of the Land Use Intensity (LUI) for a managed forest, based on BioMAPS-related parameters and benchmark values. Equation B.1 is used for the calculation:

$$\begin{aligned} LUI_{\text{Forest}}(i) = \frac{1}{5}\Bigg(& \frac{WH_i}{WH_{MTI}} + \left(1 - \frac{BM_i}{BM_{MTI}}\right) + \left(1 - \frac{TA_i}{TA_{MTI}}\right) \\ & + \left(1 - \frac{DW_i}{DW_{MTI}}\right) + \left(1 - \frac{SetAside_i}{TotalArea_{MTI}}\right)\Bigg) \end{aligned} \tag{B.1}$$

Assumed primary data (numerators)

- WH_i: 180000 kg C/km^2
- BM_i: 3.2 kg C/km^2
- TA_i: 70 years
- DW_i: 20 m^3/ha
- $\mathrm{SetAside}_i$: 5 ha

The assumed primary data was selected to represent a realistic example of a managed boreal production forest with moderate management intensity. The values were chosen to illustrate how deviations from ecological reference conditions affect the final LUI score. The tree age reflects a common rotation period in managed boreal forests, while the deadwood value corresponds to the minimum threshold identified by Person C as important for many deadwood-dependent organisms. The set-aside area represents a limited but realistic conservation allocation within productive forest land.

Assumed benchmark values (denominators)

- Wood harvesting rate (WH_{MTI}): 473573 kg C/km^2
- Biomass density (BM_{MTI}): 4.64 kg C/km^2
- Mean tree age (TA_{MTI}): 217 years
- Deadwood volume (DW_{MTI}): 100 m^3/ha

- TotalArea$_{MTI}$: 50 ha

These assumed benchmark values are retrieved from Table 4.4 and represents Boreal coniferous forest conditions.

Step 1: Calculation of intensities

Wood harvesting (pressure indicator):

$$\frac{180000}{473573} = 0.38$$

Biomass density (relief indicator):

$$1 - \frac{3.2}{4.64} = 1 - 0.68 = 0.31$$

Tree age (relief indicator):

$$1 - \frac{70}{217} = 1 - 0.32 = 0.68$$

Deadwood volume (relief indicator):

$$1 - \frac{20}{100} = 1 - 0.20 = 0.80$$

Set-aside area (relief indicator):

$$1 - \frac{5}{50} = 1 - 0.10 = 0.90$$

Step 2: Aggregation of intensities

According to Equation B.1, the Land Use Intensity (LUI) is calculated as the average of the individual intensity scores.

Sum of intensities:

$$0.38 + 0.31 + 0.68 + 0.80 + 0.90 = 3.07$$

Total LUI:

$$\frac{3.07}{5} = 0.614$$

Interpretation

The resulting LUI value of 0.614 indicates that the forest is characterized by a *light intensity* management regime. The resulting LUI value is used to calculate the local biodiversity risk, as shown in Equation 2.11.

In this example, the deadwood-related intensity score of 0.80 reflects a relatively high impact, as it assumes that the forest only meets the minimum threshold of 20 m^3/ha required for many organisms, rather than the benchmark level of 100 m^3/ha. This illustrates how deviations from ecological reference conditions can significantly influence the overall intensity classification.

C

Appendix C: Interview guide: Sustainability specialist (company in focus)

The following interview questions were collected across three separate interview sessions (5 February, 3 March, and 18 March). The questions are grouped by interview occasion.

Interview 1 (5 February 2026)

- What types of sustainability data do you currently collect (e.g., for LCA, CSRD reporting, climate, forestry, raw materials)?
- How is data collected from your suppliers?
- For what purposes is the data currently used (e.g., internal follow-up, external reporting, decision-making, supplier dialogue)?
- Is there a central function or system where sustainability and environmental data are stored, or is the data distributed across different departments?
- What information do you have regarding the origin of raw materials (e.g., forest, pulp, fibre), such as country, region, or certification level?
- Do you have data on land use or land type linked to raw materials (e.g., forestry, plantations, natural forest)?
- Is there information available on changes in land use (e.g., harvesting, replanting, rotation periods)?
- Is eDNA something you currently use or have discussed using? How do you view its potential future application?
- Is there any data that is confidential and therefore not accessible to us, but which we should nevertheless be aware exists?
- At what geographical level is data available (global, country, region, or specific

coordinates)? What is the typical spatial resolution?

- Is time-series data available (e.g., historical data or annual updates)?
- How frequently is data updated?
- How did data collection and data availability change when the company was split into two separate entities?
- How interconnected are the two organizations today in terms of data sharing or operations?
- Have you previously tested or considered biodiversity assessment methods?
- In previous communication, Circhive and GLAM were mentioned. Are these still the primary methods of interest going forward?
- How significant are reporting requirements in influencing your choice of methods?
- Do you have any concrete case studies or datasets in mind that could be used to compare methods?
- Are there any other stakeholders or experts you recommend we contact?

Interview 2 (3 March)

- Do you have data on land use linked to your fiber flows, such as the share of natural forest, plantations, and managed forests? Do you have information on previous land use, for example whether land has been converted from natural forest to plantations? At what level is this data available (supplier, region, country)?
- Do you have access to area data (m^2 or hectares) linked to your raw material flows? Is it possible to link raw material volumes to a specific land area or region?
- Do you have information on forest management practices among suppliers (e.g., rotation time, thinning, harvesting methods, certification requirements)? Do you distinguish between different intensity levels of forestry practices, or is a uniform assumption applied across locations?
- **BioMAPS methodology**
  Occupation and transformation quantities:
    - Area of land occupation ($m^2 \cdot yr$)
    - Area of land transformation (m^2)

    - Specification of previous and current land use (e.g., primary forest → cropland)

  Spatial location:
    - Geographic origin of production
    - Preferably exact coordinates, otherwise country or region

  Land use classification:
    - Primary vegetation, secondary vegetation, cropland, plantation, managed forest, urban land

  Management parameters:
    - Fertilizer application (kg/ha)
    - Pesticide use
    - Livestock density (for pasture systems)
    - Harvest rate / rotation period (for forestry)
    - Share of set-aside or protected areas
    - Degree of mechanization
    - Urban green area share (for urban systems)

- **GLAM methodology**
  Occupation and transformation quantities:
    - Area of land occupation ($m^2 \cdot yr$)
    - Area of land transformation (m^2)

  Spatial location:
    - Ecoregion level

  Land use classification:
    - Cropland, pasture, plantations, managed forests, urban land

  Management intensity:
    - Minimal, light, or intense

- WWF Water Risk Filter is already used internally, according to previous discussions. What is your view on also using the WWF Biodiversity Risk Filter? The filters use the following data:

  Spatial location:
    - Coordinates or address of site

  Industry sector:
    - e.g., paper and forest product production

  Business importance:
    - Low, medium, or high — how is this determined?

- What types of sustainability and environmental data do you currently collect (e.g., LCA, CSRD, climate, forestry, raw materials)?

- Will the new data infrastructure be used solely for EUDR compliance, or also for other purposes?

- Which databases or data sources (e.g., Ecoinvent, IBAT) are used?

- At what geographical level is the data available (global, country, region, coordinates)?

- Are there regional differences in data availability or data quality?

- Are there differences in data availability between product types?

Interview 3 (18 March)

- **Certification**
  - FSC certification appears to be a central component of your work on sustainable forestry. At the same time, several large companies have discontinued collaboration with a specific upstream supplier due to concerns regarding environmental and social performance. How do you respond to this criticism?
  - You previously mentioned that you would stop sourcing from a specific upstream supplier if they were to leave FSC. Do you consider FSC certification to impose sufficiently strict requirements?
  - How do you think FSC should further develop or strengthen its requirements and auditing processes?

- **Questionnaires and traceability**
  - Which actors typically respond to supplier questionnaires (e.g., forest owners, sawmills, or other suppliers)?
  - At what level is traceability maintained in your documentation? Is material traceable back to a specific sawmill or down to a precise harvesting location?
  - The EUDR requires plot-level data. Do you currently have access to this level of detail?
  - Do suppliers from eucalyptus plantations use the same questionnaires as suppliers from conventional forestry?
  - How do data flows and reporting processes differ between plantation-based and conventional forestry supply chains?

- **Fiber policy and traceability**
  - Your fiber policy emphasises transparency regarding the origin of raw materials and environmental impacts. You also conduct random supplier checks where origin must be specified. How does this differ from the origin information already available in your regular reporting systems?

- **EUDR and confidentiality**
  - The EUDR will require exact geographic coordinates for harvesting areas, potentially increasing supplier identifiability. Do you see this as a confidentiality challenge? Have suppliers expressed concerns about this?

- **Biodiversity network**

  - You previously mentioned a biodiversity network involving representatives from brands and reporting teams. Is it possible to speak with someone from this network?

D

Appendix D: Interview guide: Sustainability reporting (company in focus)

The following questions were developed to explore data collection practices, reporting requirements, and challenges related to sustainability reporting within the company in focus.

- What types of data do you currently collect for sustainability reporting? Are there any data types that are particularly difficult to access?

- What do you see as the main barriers to obtaining more detailed data from suppliers?

- How are you currently working to prepare for the EU Deforestation Regulation (EUDR), particularly with regard to traceability and geographic data?

- What types of data do you collect in order to report according to ESRS E4 (biodiversity and ecosystems)?

- Are there any reporting requirements that you consider particularly challenging to fulfill based on the data currently available to you?

- Are there any types of data that are not currently collected but that you expect will be required in the future?

- How do you view data sharing within the organization? Do you have access to the data you need, even when it is distributed across different departments?

- We have reviewed a pulp supplier questionnaire. Do you use similar questionnaires as a tool for collecting data for reporting purposes?

- How do you currently work with biodiversity impacts? Which methods or tools are used to assess and measure these impacts?

E

Appendix E: Interview guide: Upstream suppliers

The following questions were developed to investigate data availability and practices related to the application of the GLAM and BioMAPS methodologies. These questions were sent prior to the interviews with Person C, D and E.

- We are examining data requirements associated with the GLAM and BioMAPS methodologies. Relevant parameters include, but are not limited to:
  - Area of land occupation ($m^2 \cdot yr$)
  - Area of land transformation (m^2)
  - Geographic information (country, region, coordinates, ecoregion)
  - Type of land use (e.g., plantation, managed forest)
  - Deadwood volume
  - Wood harvesting rates
  - Tree species diversity
  - Tree age
  - Rotation period
  - Share of protected areas / set-aside land
  - Degree of mechanization
  - Land-use intensity (minimal, light, intense)
- To what extent is this type of information generally available from your suppliers?
- Alternatively, is it more common that such parameters are estimated? If so, how are these estimations typically carried out?
- How do you collect data from your suppliers? At which organizational level is this data managed and processed?
- With regard to traceability documentation, at what level is traceability maintained? Is the raw material typically traceable back to a specific sawmill, or further down to a precise geographic location of the harvesting area?
- The EU Deforestation Regulation (EUDR) requires precise geographic coordinates for harvesting areas. Do you foresee this as a potential challenge from a

confidentiality perspective, for example in relation to suppliers' concerns about how geographic information is used or shared?

F

Appendix F: Interview guide: Scientific expert

The following questions were developed to explore data requirements, methodological assumptions, and system boundaries in models used for assessing land use impacts, deforestation, and biodiversity footprints.

- What type of input data is required in your research models in order to link deforestation to specific raw materials?

- Which types of data are the most difficult to obtain or associated with the highest level of uncertainty in your analyses?

- If similar methods were to be applied at a corporate level, what types of data would then be required from companies?

- How important is spatial data (e.g., satellite data, geospatial datasets) compared to statistical datasets or trade data in your modelling approaches?

- To what extent does the data typically available from companies (e.g., supplier information, purchase volumes, country of origin) correspond to the data required in footprint models?

- What are the main data gaps between academic research requirements and corporate environmental reporting practices?

- Are there any types of data that companies should collect but generally do not today?

- Do you consider it realistic that companies can collect the level of data required to produce robust deforestation or biodiversity footprints?

- Many land-use impact assessment methods rely on defining a reference situation or baseline. How do you think a reasonable reference state should be defined when analysing land use from a corporate or product perspective?

- Is it more appropriate to compare against a natural ecosystem, historical land use, or an alternative land-use scenario? What challenges do you see associated with each of these approaches?

- In some forestry systems, portions of land are set aside for conservation purposes. How important is it to include such set-aside or protected areas when assessing land-use impacts on biodiversity?
- If analyses focus only on productive land, is there a risk of underestimating the benefits of conservation set-asides? Could this also reduce incentives to preserve parts of the land?
- From a methodological perspective, how should set-aside or conservation areas be handled when assessing land use impacts in larger systems such as supply chains or national-scale models?

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