

Dissertationes Forestales 400

**Governing the forest-based bioeconomy: integrating
legal and deforestation-free trade and innovation as
drivers of sustainable supply chains**

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Academic dissertation

To be presented, with the permission of the Faculty of Science, Forestry and Technology of the University of Eastern Finland, for public criticism in auditorium BOR100, of the University of Eastern Finland, Yliopistokatu 7, Joensuu, on 11 December 2026, at 12 o'clock noon.

Title of dissertation: Governing the forest-based bioeconomy: integrating legal and deforestation-free trade and innovation as drivers of sustainable supply chains

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Dissertationes Forestales 400

<https://doi.org/10.14214/df.400>

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ISSN 1795-7389 (online)

ISBN 978-951-651-890-2 (pdf)

Publishers:

Finnish Society of Forest Science

Faculty of Agriculture and Forestry of the University of Helsinki

School of Forest Sciences of the University of Eastern Finland

Editorial Office:

Finnish Society of Forest Science

Viikinkaari 6, 00790 Helsinki, Finland

<https://www.dissertationesforestales.fi>

Van Brusselen, J. (2026) Governing the forest-based bioeconomy: integrating legal and deforestation-free trade and innovation as drivers of sustainable supply chains. *Dissertationes Forestales* 400. 46 p. <https://doi.org/10.14214/df.400>

ABSTRACT

To remain within planetary boundaries, global production and consumption must become more sustainable and biobased. The transition towards the biobased economy depends on the development of new uses of wood, increased material-use and processing efficiency, and development of new markets, while keeping supply chains legal and free of deforestation. The overarching objective of this thesis was to study how the forest-based bioeconomy can be driven by innovation and developed based on legal and deforestation-free supply-chains.

Regional analysis in North Karelia, Finland (Article I), demonstrates that while companies are generally oriented towards innovation, they face significant structural barriers. Innovation is hampered by regulatory complexity, financial limitations, and skilled labour shortages.

As the bioeconomy develops, the demand for forest resources is expected to increase. Due diligence and enforcement to ensure legal supply chains require scientific verification to combat fraud. A global market study (Article II) revealed that while 87% of stakeholders are aware of wood identification (ID) tools, their effective uptake is constrained by high costs, limited access to reference data, and technical gaps in countries with weaker governance.

In addition to requiring legal supply chains, the European Union (EU) Deforestation Regulation expands requirements to prove that products are sourced without causing deforestation. A quantitative risk framework (Article III) reveals that 17% of total EU wood-based import value is exposed to high-risk origins, with risk profiles varying significantly for each commodity. The results highlight where wood ID tools and intensified due diligence could focus to ensure market integrity.

By assessing company innovation and constraints in developing the forest-based bioeconomy, estimating the market capacity for wood ID technologies, and developing a tool for quantifying risk exposure of trade in legal and deforestation-free wood-based commodities, the research presented in this thesis offers tools and insights for private and public actors to govern the forest-based bioeconomy.

Keywords: wood identification, legal supply chains, trade risk, deforestation-free commodities, bioeconomy innovation, regional development

WORDS OF THANKS

I might have never ended up in Joensuu had it not been for Bert De Somviele, who returned with nice stories of a place where he had gone as an exchange student, and a poster of the European Forest Institute (EFI) hanging in the room where I started working on my engineering thesis at the University of Ghent's Faculty of BioScience Engineering.

Through the support of Andreas Schuck, I was able to start a traineeship at the EEFI and was hired soon after, which naturally had a huge influence on my career and life developments. Thank you very much mon cher André!

The themes addressed in this dissertation may seem diverse, but they are hardly as diverse as the variety of projects that I have encountered in almost a quarter of a century. Some topics have recurred in my curriculum, including, among others, all things related to trade data, FLEGT policy, and, more recently, bioeconomy development.

I am deeply grateful to my supervisors: Prof. Dr Pekka Leskinen for setting me on the path; Dr Pieter Johannes (Hans) Verkerk for his guidance and for reminding me of the benefits of functional pragmatism; Prof. Dr Jouni Pykäläinen for the support with the development of the regional bioeconomy research; and not least, thank you dear Prof. Dr Teppo Hujala for enthusiastic and engaging discussions and guidance all along the way.

I am deeply grateful for the thoughtful remarks and valuable suggestions provided by my pre-examiners, Prof. Dr Ahmad Maryudi and Emeritus Research Forester Jeffrey P. Prestemon.

I wish to sincerely thank Prof. Dr Markus Kröger for kindly accepting the invitation to serve as my opponent in the public examination of my doctoral dissertation.

I would like to warmly thank my co-authors for their contributions to the research articles: Fredric Mosley, Mathias Cramm, and Dr Diana Tuomasjukka (Article I); Mathias Cramm (once more!) and Dr Yitagesu Tekle Tegegne (Article II); and Johanna Klapper, Dr Raul de Paula Pires, and Janne Järvikylä (Article III).

Many thanks to the EFI for being such a wonderful place to develop professionally and for providing me with the opportunity to combine my responsibilities with the activities that have led to this manuscript, though any views expressed here are, of course, solely my own.

I extend warm appreciation to all my friends and dear colleagues whom I have had the pleasure of knowing and working with, and whom I look forward to continuing to work with in the future. A list of names would be long, and I would run the risk of forgetting someone. Those who are looking to find their name here, know that you are on my mind and in my heart, and please keep visiting me for lively conversations and cheerful musical sessions.

My heartfelt gratitude goes to my parents <3 who supported me when I went to Finland to begin my research, despite a consular forewarning that my leave may well take more than a year. I thank my sister Marian <3 for her cheerful and frequent visits. I thank my dearest daughter Linnea <3 for her wonderful charm and creativity; humour; bravery; and for providing me with berry pies, cakes, cookies, and smoothies to sweeten the process of completing this research.

And in closing, an ode to Finnish sauna, where it doesn't matter who you are and where you are from, where all are equal, in harmony, and subject to the same steam. Amen.

Noljakka, 15 September 2026

Jo Van Brusselen

LIST OF ORIGINAL ARTICLES

This thesis is based on data presented in the following articles, referred to by the Roman numerals I–III.

- I** Van Brusselen, J., Mosley, F., Cramm, M., Tuomasjukka, D. (2025) Companies' innovation approaches and barriers towards achieving their potential in the forest-based bioeconomy. *Scandinavian Journal of Forest Research*, 40(5–6), 303–320. <https://doi.org/10.1080/02827581.2025.2522719>

- II** Van Brusselen, J., Cramm, M., Tegegne, Y.T. (2023) Wood identification services in support of legal supply chains: A market study. *Sustainable Futures* 6 (2023) 100128. <https://doi.org/10.1016/j.sfr.2023.100128>

- III** Van Brusselen, J., Klapper, J., Järvikylä, J., de Paula-Pires, R. (2026) Risk profiles for deforestation-free and legal supply-chains of wood-based products. *Forest Policy and Economics*, 188 (2026) 103811. <https://doi.org/10.1016/j.forpol.2026.103811>

AUTHOR CONTRIBUTION

Jo Van Brusselen made comprehensive and leading contributions across all three peer-reviewed articles that form the basis of this dissertation, driving the research from its initial conception to final publication. In Article I, his contributions spanned conceptualisation, methodology and questionnaire development, data analysis, and manuscript writing and revision. In Article II, his contribution included conceptualisation, methodology and questionnaire development, data analysis, and manuscript writing and revision. In Article III, his contributions encompassed conceptualisation, methodology development, data curation and analysis, visualisation, and manuscript writing and revision. He is solely responsible for the compilation and writing of this thesis.

DECLARATION OF THE USE OF GENERATIVE AI

During the preparation of this manuscript, the author used Google Gemini Pro and Anthropic Opus 5 to assist with grammar and spelling of self-written text, and to improve the readability and language of the manuscript. All content was subsequently reviewed and edited by the author, who takes full responsibility for the final content.

STATEMENT ON RESEARCH ETHICS

Surveys were employed in Articles I and II. The surveys were conducted with professionals, who responded in their institutional or business capacity. Personal contact details were obtained from publicly accessible business directories and professional networks and were processed on the basis of legitimate interest under Regulation (EU) 2016/679 (GDPR). The personal information was used solely for the distribution of the questionnaires and reminders and did not form part of the results analysis.

Invitations stated the purpose of the respective study, the identity of the researchers, the research project, the research donor, the intended use of the responses, and the approximate time required; therefore, participation was considered to indicate informed consent. Participation was voluntary in all cases. Respondents were free to decline, discontinue, or leave individual questions unanswered, and partial responses were retained only where the respondent had submitted them.

Neither study involved sensitive personal data, minors, vulnerable groups, intervention in the physical integrity of participants, or deception. The research designs did not meet the criteria calling for ethical review, following the guidelines of the Finnish National Board of Research Integrity (TENK).

In Article I, respondents were able to indicate the level of confidentiality to be applied to their personal and company information, and the results are reported only in aggregated form by bioeconomy sector; no individual company is identifiable in any published output. In Article II, the underlying response data are confidential and not published; the results are reported by user segment and governance-quality group. Free-text responses were edited for fluency and translated where necessary and are quoted without attribution to an identifiable respondent.

Responses were collected through the QuestionPro (Article I) and SurveyMonkey (Article II) platforms and exported to the researchers' institutional storage at the EFI, where they are held under the institute's data management arrangements. Any project materials and data related to Article I need to be retained for at least 10 years from the project end date confirmed in the funding decision, upon which any personal data needs to be removed or erased in accordance with the EFI information and data retention policy. In the absence of a contractual retention period for the project materials and data referred to in Article II, personal data are retained only as long as necessary for the purposes for which they are processed, and erased thereafter, in accordance with the EFI Information and Data Retention Policy.

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ABBREVIATIONS

AAC	5-year percentage change in agricultural area
ANOVA	Analysis of Variance
EFI	European Forest Institute
EU	European Union
EUDR	European Union Deforestation Regulation
EU27	The 27 Member States of the European Union
FAC	5-year percentage change in forest area
FAO	Food and Agriculture Organization of the United Nations
FAR	A collective term for the indicators: 5-year forest area change, 5-year roundwood production change, and 5-year agricultural area change
FLEG	Forest Law Enforcement and Governance
FLEGT	Forest Law Enforcement, Governance, and Trade
FPIC	Free, prior, and informed consent
FRA	Forest Resources Assessment
FTE	Full-time equivalent
HS	Harmonised System (classification for commodities)
ID	Identification (specifically regarding wood identification tools)
KLRI	Korea Legislation Research Institute
NACE	Statistical classification of economic activities in the European Community (<i>Nomenclature statistique des Activités économiques dans la Communauté Européenne</i>)
OECD	Organisation for Economic Cooperation and Development
R&D	Research and development
RIV	Risk Index Value
RP	5-year percentage change in roundwood production (removals)
RTDI	Research, technology development, and innovation
RTDDI	Research, technology development, digitalisation, and innovation
SDG	Sustainable Development Goal
SME	Small- and medium-sized enterprise
UNDP	United Nations Development Programme
VPA	Voluntary Partnership Agreement
WGI	World Governance Index (World Governance Indicators)

1 INTRODUCTION

1.1 Background of the research

The world's forests are under considerable pressure from the impacts of anthropogenic climate change and from humankind's growing needs for food, wood, fibre, and other resources (FAO 2018; Bahar et al. 2020; Karsenty and Dieterle 2020; UNDP 2020). Richardson et al. (2023) demonstrated that six of the nine boundaries are transgressed, suggesting that Earth is now well outside the safe operating space for humanity. The planetary boundary for land system change, for which forest area is used as an indicator, is under critical strain (Richardson et al. 2023). The causes of forest decline include illegal logging and deforestation, often driven by agricultural expansion to meet increasing global consumption. Such processes are often exacerbated by unsustainable agricultural practices resulting in degradation of soil health (Pendrill et al. 2019, 2022; Jayathilake et al. 2020; Chen et al. 2024).

In response to widespread environmental degradation, policymakers have developed various strategic and regulatory frameworks. One policy approach focuses on the development of the biobased economy, which aims to reduce society's dependence on fossil materials by developing biobased alternatives while addressing resource and process efficiency, product durability, and waste reduction (Hetemäki and Hurmekoski 2020). Production can be decoupled from fresh raw material input by increasing the efficiency and utilisation of previously discarded materials from the production process (Lindner and Suominen 2017). The smart use of wood resources is one of the goals of the bioeconomy. It can be achieved by using wood to substitute fossil-based or more energy-intensive products, by prioritising material use over energy use, by valorising wood waste as a renewable raw material, and by developing innovative wood and fibre products, among other actions (European Commission 2018). While several multinational enterprises have taken leading roles in the development of new biobased products, the forest-based bioeconomy comprises many small- and medium-sized enterprises (SMEs) whose capacity for innovation is often constrained by regulatory burdens (European Investment Bank 2022; Barraza-Botet et al. 2026). However, these enterprises also have important roles to fulfil in the development of the bioeconomy. Therefore, it is important to assess how they may be open to research cooperation and innovation and what may act as constraints.

Along with development of the bioeconomy, the demand for raw wood materials is expected to increase, even if wood resources are used more efficiently through the use of sidestreams (previously discarded byproducts and, recycling and upcycling; Lindner and Suominen 2017; Verkasalo et al. 2019; Kallio and Schier 2021). While the European Union (EU) is self-sufficient regarding wood and wood-based products (Konstantinavičienė 2023; UNECE 2025), it remains one of the largest wood trading regions in the world.

Given the increasing demand for wood-based materials and the inherent environmental risks thereof, a second policy approach discussed in this thesis concerns how to ensure wood-based materials are responsibly sourced. This approach aims to use market leverage to reach policy objectives by denying products to the EU market when they originate from illegal logging, or when their production has caused deforestation or forest degradation (Piabuo et al. 2021; Hoare and Kanashiro Uehara 2022).

In the first decade of the 21st century, the EU was found to be a major importer of wood from illegal sources (Dieter et al. 2012). This led the EU to launch the EU Timber Regulation

(EUTR; EU 2010). The EUTR requires economic operators to implement due diligence to minimise the risk of trading wood-based products of an illegal origin to a negligible level. It also requires authorities to be able to verify wood species and origin, as stated in trade documents.

The EUTR, alongside comparable legislation in the United States, Australia, Japan, and Korea, has increased the need for wood identification (ID) expertise. This gave impetus to the development of science-based tools to unambiguously identify the tree species and geographical origin of wood-based products (Lowe et al. 2016; Low et al. 2023). However, an assessment was needed as to whether these tools were sufficiently known or used in the context of enforcement by competent authorities and in the context of economic operators as part of their due diligence.

In 2023, the EU launched its Deforestation Regulation (EUDR; EU 2023), requiring economic operators to prove that imported wood and certain agricultural products have had no link to deforestation or forest degradation. The EUDR called for countries to be benchmarked according to their risk of non-compliance, with the aim of aligning this risk with the due diligence requirements for economic operators and the enforcement requirements for competent authorities. While legality risk assessments have previously been implemented (Norman et al. 2017; Lin et al. 2021), when this study began, no benchmarking methodology existed yet in the context of the requirements put forward by the EUDR.

1.2 A role for the regional forest-based bioeconomy

The 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs) as well as the Paris Agreement provide an international policy framework to change the existing global economic model (Hermwille 2016; Hetemäki et al. 2020). Production and consumption need to be transformed so that we can live sustainably within our planetary boundaries (Bengtsson et al. 2018; Hetemäki et al. 2020; Richardson et al. 2023). The forest-based bioeconomy is a key component to transforming the global economy towards sustainability, through substitution of energy-intensive or fossil-based products with biobased alternatives, alongside the provision of ecosystem services such as carbon sequestration, water protection, and biodiversity (Hetemäki et al. 2020; Hassegawa et al. 2022a,b; Verkerk et al. 2022). This is recognised in the EU bioeconomy strategies, where forests are positioned as a pillar of European bioeconomy development (European Commission 2018, 2025a). This is to be achieved through the development of new biobased products, resource- and energy-efficient production processes, and new service models, in conjunction with market, regulatory, and institutional developments to facilitate the transition (Pelli et al. 2017; Hetemäki et al. 2020; Hassegawa et al. 2022a).

Greater reliance on biobased materials is expected to increase demand for roundwood. At the same time, sustainable forest management practices, technological improvements and efficient utilisation of wood could help address sustainability concerns (Lindner and Suominen 2017; Kallio and Schier 2021). This could be facilitated by meeting part of the demand for biomass inputs through previously discarded production waste (i.e., sidestreams), re-use of components, and recycling of end-of-life products (Verkasalo et al. 2019).

However, significant challenges remain in the development of the bioeconomy, particularly regarding raw materials and the innovation required in the design and manufacture of both existing and new processes and products (Hassegawa et al. 2022a). Innovations are defined as new or improved products or business processes, or combinations

thereof, that differ significantly from those previously produced or used by firms and that have been introduced to the market or brought into use. Innovation also encompasses the developmental, financial, and commercial activities undertaken by firms that are intended to result in an innovation (OECD/Eurostat 2018). These issues are relevant to the strategies related to the EU and Finnish bioeconomies (European Commission 2018, 2025a; Finnish Government 2022). Public and private initiatives have aimed to stimulate research, technology development, and innovation (RTDI), and this has been addressed in regional policy to a variable extent (Mosley and Van Brusselen 2023). However, relatively little is known about the openness of companies to innovation and the modalities that companies choose to achieve their innovation objectives and thereby maintain competitiveness in the evolving biobased economy.

Against this background, the Finnish region of North Karelia was chosen to study innovation at the company level. North Karelia is a heavily forested region, and its bioeconomy stakeholders are well acquainted with the bioeconomy concept. Innovation activities in the region have so far focused on wood-based construction, renewable energy and forest-based tourism (Briers et al. 2024). Organisations such as Business Joensuu, a business development company in the regional capital, Joensuu, play an important role in supporting new entrepreneurship, including in the forest-based bioeconomy. However, less is known about how established companies approach innovation.

1.3 Tools that support legally compliant wood trade

Illegal logging comprises ‘all practices related to the harvesting, processing and trading of timber inconsistent with national and sub-national laws’ (Kleinschmit et al. 2016, p. 14). Each year, 15%–30% of the total global trade in timber products, 50%–90% of logging in many tropical countries, and an total of 51–152 billion US dollars are estimated to be of illegal origin (Contreras-Hermosilla 2002; Interpol 2019). Although estimates on the size and importance of illegal logging vary considerably, are based on few systematic studies, include anecdotal evidence, and are sometimes speculative (Bösch 2021), illegal logging and related trade remain significant. Focusing on 37 timber exporting countries, Hoare and Kanashiro Uehara (2022) estimated that illegal timber exports represent 40–144 million cubic meters roundwood equivalent, accounting for 4%–14% of global exports, representing a value of 7–30 billion US dollars, for 3%–11% of global export value.

Illegal logging, associated trade, and corruption were identified as urgent concerns in the G8 Action Programme on Forests of 1998, and they remain so. Internationally, Forest Law Enforcement, and Governance (FLEG) was developed as a policy response (Colchester et al. 2006), while trade increasingly came to be seen as providing leverage that importing countries could use to require compliance with the law in countries of origin. This resulted in legislation in the United States, EU, Australia, Korea, China, and other markets (Tegegne et al. 2014; Dlamini and Montouroy 2017; KLRI 2017; Mukpo 2020). These Forest Law Enforcement, Governance, and Trade (FLEGT) instruments require economic operators to ensure that their wood-based products originate from legal supply chains.

Despite widespread efforts by more than 50 producer and consumer countries, illegal logging remains a concern, and competent authorities continue to uncover evidence of illegal activities (Bruch et al. 2019; Wiedenhoeft et al. 2019; Haag et al. 2020). They increasingly rely on modern methodologies to assist in identifying wood-based specimens in terms of both species and geographical origin. Methods capable of discerning multispectral, genetic,

isotopic, or other physical and chemical characteristics have been applied operationally to identify both the species and geographical origin of the wood in question (Lowe et al. 2016; Schmitz et al. 2020). By enabling such identification, these methods can support law-compliant operations, much in the same way that remote sensing can encourage forest owners to comply with forest legislation (Purdy 2010). The private sector must be able to demonstrate compliance with legal due diligence requirements. Economic operators can either implement their own due diligence or due care systems, or rely on, for example, third-party certification of chain of custody. Whichever option they choose, they can integrate ID technologies into their due diligence workflows in ways that optimise efficiency and effectiveness. This can also help minimise the impact on the wood products chain of custody (Kogler et al. 2021).

Competent authorities are responsible for monitoring and enforcing legislation. While monitoring tasks, such as by customs in harbours, require technology that can be deployed on the spot and produce results as rapidly as possible, enforcement tasks primarily require irrefutable evidence that can be used in court proceedings.

1.4 Quantifying the risk for deforestation-complicit wood trade

Deforestation resulted in the loss of 420 million hectares of forest worldwide in the 30 years since 1990 (FAO 2020), at a rate of almost 15 million hectares per year during 1990–2015. While the rate of forest loss slowed to 10 million hectares per year during 2015–2020 (FAO 2020), this still corresponds to an area approximately the size of Iceland or South Korea being lost each year. Agricultural expansion has a major impact on forest loss (Pendrill et al. 2019; West et al. 2025). West et al. (2025) found that 86% of global deforestation occurring between 2001 and 2022 can be attributed to crop and cattle production, while major economies, including the EU, are responsible for most commodity-linked deforestation.

In view of a market and policy drive towards responsible consumption and the economic leverage that consumers have on market requirements towards economic operators, the EUDR was adopted in 2023 (Regulation (EU) 2023/1115). The EUTR (Regulation (EU) 995/2010) remains in effect until 31 December 2028 for timber and timber products in its scope that were produced before 29 June 2023 and placed on the market from 30 December 2025 (Article 37(2) of Regulation (EU) 2023/1115 (EUDR), as amended by Regulation (EU) 2024/3234, European Union 2024). EUDR article 3 bars products from the EU market if they do not meet three conditions: (a) deforestation free, (b) harvesting and/or processing compliant with relevant legislation from the source to the market, and (c) covered by a due diligence statement.

Compared with the EUTR, the EUDR had a larger product scope that also comprises agricultural products that represent the largest share of EU-driven deforestation, including cattle; cocoa; coffee; palm oil; rubber; soya; and wood-based commodities such as articles of wood, pulp and paper, furniture, and prefabricated buildings (Pendrill et al. 2019; European Union 2023). Article 29§3 of the EUDR calls for the development of country benchmarking, attributing high, low, or standard risk to countries based on three criteria:

1. the rate of deforestation and forest degradation;
2. the rate of expansion of agriculture land for relevant commodities;
3. production trends of relevant commodities and of relevant products.

The European Commission called for the development of the benchmarking system through a service contract (European Commission 2023). However, the methodology presented in this work was prepared in parallel.

Due diligence requirements for countries labelled as low risk are simpler compared with the requirements for standard or high-risk countries. While the assessment of countries is separate from the due diligence requirements for economic operators, it is important to consider that the operators are required to provide adequately conclusive and verifiable information that ‘the relevant products are deforestation-free’ and that ‘the relevant commodities have been produced in accordance with the relevant legislation of the country of production’ (European Union 2023; see also Article III). Relevant legislation should cover issues such as (a) land-use rights; (b) environmental protection; (c) forest-related rules, including forest management and biodiversity conservation, where directly related to wood harvesting; (d) the rights of third parties; (e) labour rights; (f) human rights protected under international law; (g) the principle of free, prior, and informed consent (FPIC), including as set out in the United Nations Declaration on the Rights of Indigenous Peoples; and (h) tax, anti-corruption, trade, and customs regulations (European Union 2023; see also Article III). These issues, which should be addressed by economic operators in their due diligence assessments, are not addressed in the EUDR country benchmarking system. However, by including an indicator for the quality of governance, one could also consider these topics indirectly.

EUDR Article 10(3) also specifies that wood products covered by a FLEGT license will be considered in compliance with the legality requirement of EUDR Article 3(b) – while the deforestation-free aspect still needs to be demonstrated.

At the time of developing the methodology for Article III, no official EUDR country assessment had been developed. Norman et al. (2017) evaluated forest legality risk indices by combining several global governance and economic indices. Guan and Ip Ping Sheong (2019) identified high-risk wood origins based on the Corruption Perception Index proposed by Transparency International. Van Brusselen and de Paula-Pires (2019) combined the index proposed by Norman et al. (2017) with trade flow data. Lin et al. (2021) published an approach based on a reduced set of normalised indices. These indices did not rely on data that were specific to land use, land-use change, or the forest sector. However, EUDR country benchmarking requires that its three criteria related to deforestation and degradation, agricultural expansion, and commodity production trends be considered.

1.5 Aims of the research

The overarching objective of this thesis was to study how the forest-based bioeconomy can be driven by innovation and developed based on legal and deforestation-free supply chains. Through the development of empirical evidence and methodological tools that address key governance challenges across global, European, and regional scales, the thesis aimed: (i) to determine how research, technology development, digitalisation, and innovation (RTDDI) are incorporated into the business practices of regional forest-based companies, and what barriers may constrain these innovation processes; (ii) to identify and characterise the capacities, awareness, and drivers for effective uptake of legally verified methods in wood supply chains; and (iii) to develop and test a quantitative framework for assessing country-level risks of illegality and deforestation associated with EU imports of wood-based products. Together, these objectives provide a coherent analytical basis for understanding how

regulatory, technological and organisational factors shape governance and functioning of the forest-based sector.

Each article had its own specific aim and research questions:

- Article I aimed to develop a perspective on regional bioeconomy by assessing openness, barriers and constraints to innovation at the company level. It addressed two research questions: How are RTDDI integrated into business development practices of regional forest bioeconomy companies? What are the main barriers and constraints preventing the regional forest bioeconomy companies from realising the full potential of their economic activity?
- Article II aimed to assess the market for wood ID services in support of legal supply chains. It addressed four research questions: What is the awareness about wood ID technologies, both by economic operators and by law enforcement actors? What are the current capacities of wood ID technologies and the use thereof? What will be the need for wood ID technologies in the future? What are the current and projected drivers of demand for wood ID technologies and associated services?
- Article III assessed the risk exposure of EU imports of wood-based products in the context of the EUDR. It involved two research questions: How can a country-based risk index be developed and tested to guide enforcement and due-diligence efforts towards a deforestation-free market of wood-based products, inspired by the EUDR country benchmarking assessment criteria? What is the magnitude of potential risk exposure of the EU imports of wood-based products from outside the EU (extra-EU imports) and how does this differ for the main wood-based products?

2 MATERIALS AND METHODS

2.1 Companies' innovation perspectives for developing the regional forest-based bioeconomy (Article I)

2.1.1 Approach

The methodology consisted of four steps: definition of the bioeconomy sectoral scope for this study; identification of companies and compilation of economic data; development of a questionnaire and dissemination; and analysis of the company questionnaire results.

The sectoral scope of this study included producers of wood-based and non-wood forest products; manufacturers of forestry technology; and companies operating in RTDDI, information, and services sector. The forest-based bioeconomy was defined across 14 sectors, including a clarification of their linkages to corresponding classes of the statistical classification of economic activities in the European Community (*Nomenclature statistique des Activités économiques dans la Communauté Européenne* [NACE] Rev.2).

North Karelian companies were identified within the confines of the selected bioeconomy sectors, through expert knowledge such as from Business Joensuu, and with the online company directory Fonecta (Fonecta 2021). Macroeconomic data on turnover and employment were collected for these companies from the Kauppalehti online business intelligence portal (Kauppalehti 2024) to establish a baseline for regional economic performance.

A questionnaire was developed to gauge market expectations of North Karelian companies and their openness towards innovation. The questions collected information on the following topics: company profile; company turnover, former and future ten-year trends; employment level and trends towards 2030; cost structure; market orientation; RTDDI modalities; competitive environment and perceived industrial output capacity; realisation of market potential and identification of barriers and constraints thereto. The questionnaire was available in Finnish and English. A native Finnish-speaking member of the research team contacted companies to facilitate the data collection process.

2.1.2 Data

A total of 96 companies and contact details were identified for North Karelia. For these companies, data on turnover and employment were collected for the period 2016–2022. The survey yielded responses from 47 companies, consisting of 32 complete and 15 partial questionnaires. The number of responses therefore varies between questions. A link was maintained between the macroeconomic indicators and the survey responses as input to the analysis.

2.1.3 Analysis

The questionnaire was administered with the online QuestionPro platform. The results were stored and analysed in Microsoft Excel. Pivot tables were used to aggregate sectoral data. The data and trends are visualised using charts.

2.2 Wood identification in support of legal supply chains: A market study (Article II)

2.2.1 Approach

A combined-methods approach involving a literature review and an online expert survey was used to address the four research questions. The literature review was implemented to establish the context, to develop the survey in an informed manner, and to interpret the results of the survey. This review covered scientific papers; legislation; policy briefs; and reports from the corporate sector, international organisations, and non-governmental organisations that related to the topic of wood ID. The objective of the online survey was to elicit stakeholder perspectives on wood ID technologies and their existing and projected market demand (Article II). Responses were gathered using the online survey tool Survey Monkey (version 2019). Two wood ID technology user segments were approached through purposive sampling: potential users with an interest related to due diligence, and potential users with an interest related to law enforcement. The questionnaire responses were stratified based on the general governance condition in the respondent countries, determined by the mean of the rule of law index (World Justice Project 2022), the corruption perceptions index (Transparency International 2022) and the fragile states index (The Fund for Peace 2022). The countries were divided into two groups: countries with a governance ranking of ≤ 0.49 and countries with a governance ranking of ≥ 0.50 .

2.2.2 *Data*

The total pool of contacts was developed to obtain a representative balance of user segment, governance quality and geographical location. Complete questionnaires were received from 63 respondents, representing a response rate of 18%.

2.2.3 *Analysis*

The questionnaire allowed the collection of quantitative and qualitative data. Approximately half of the completed questionnaires were from respondents in countries with a higher governance ranking and half from countries with a lower governance ranking. Around two-thirds of the respondents had the due diligence perspective and one-fifth had the law enforcement perspective. The respondents' organisations mostly handled logs and sawnwood, although all main product groups were represented.

2.3 **Risk profiles for EU imports of deforestation-free wood-based products (Article III)**

2.3.1 *Approach*

This study used a three-part methodology: development of a risk index, selection of trade data and combination with risk categories, and quantification of EU imports by risk category.

The wood product-focused legality risk index addressed the key criteria of the EUDR's country benchmarking system: deforestation trend, agricultural expansion, and roundwood production. These were combined with a general quality of governance index, which is not explicitly required by the EUDR benchmarking criteria, although the EUDR refers to quality of governance in the context of a qualitative assessment that may influence the risk scoring. Quality of governance has also been linked with legality risk in previous studies (Brenton-Rule et al. 2016; Norman et al. 2017; Lin et al. 2021). In certain cases, forest legality legislation or legislative processes in trade-partner countries could increase the value of the risk index to the lowest tier of the low-risk category. Examples of this phenomenon include FLEGT Voluntary Partnership Agreements (VPAs) and EUTR-like legislation such as the U.S. Lacey Act. A proposed calculation approach resulted in possible scores for the Risk Index Value (RIV) ranging from 1 (highest risk) to 9 (lowest risk).

The calculation of the RIV was varied in two experiments. In the first experiment, the values assigned to trends in changes in forest area, agricultural land, and roundwood removals were varied by applying three different thresholds around the 'no-change' value. In the basic approach [$\text{FAR} \pm 0.000$], the centre point for scoring 5-year changes in forest area, roundwood production, and agricultural area (hereafter referred to as FAR) was set strictly at zero. Thus, a score of zero is assigned only when there is no change in the respective indicator (Article III). Because estimates of these indicators are subject to inherent uncertainty and error, two alternative thresholds were tested in a sensitivity analysis to assess their effect on the RIV calculation. The second approach [$\text{FAR} \pm 0.001$] allows for a band of 0.1% above or below the FAR value before a point is added to or subtracted from the RIV. The third approach [$\text{FAR} \pm 0.010$] allows for a band of 1% above or below the FAR value before a point is added to or subtracted from the RIV (Article III).

The RIV can be calculated as follows (Article III):

$$\text{RIV} = \text{WGI} + \text{FAC} + \text{RP} + \text{AAC}$$

- RIV (1, 2, 3, 4, 5, 6, 7, 8, or 9)
 - 7–9: low risk
 - 4–6: medium risk
 - 1–3: high risk
- WGI: World Governance Index (4, 5, or 6)
 - 6 for high governance quality ($66 < \text{WGI} \leq 100$)
 - 5 for medium governance quality ($33 < \text{WGI} \leq 66$)
 - 4 for low governance quality ($0 \leq \text{WGI} \leq 33$)
- FAC: 5-year percentage change in forest area (–1, 0, or +1)
 - +1 for an increasing trend ($\text{FAC} > x$)
 - –1 for a decreasing trend ($\text{FAC} < -x$)
- RP: 5-year percentage change in roundwood production (removals) (–1, 0, or +1)
 - +1 for a decreasing trend ($\text{RP} < -x$)
 - –1 for an increasing trend ($\text{RP} > x$)
- AAC: 5-year percentage change in agricultural area (–1, 0, or +1)
 - +1 for a decreasing trend ($\text{AAC} < -x$)
 - –1 for an increasing trend ($\text{AAC} > x$)
- $x \in \{0\%, 0.1\%, 1\%\}$

In the second experiment, the strictest approach from the first experiment [$\text{FAR} \pm 0.000$] was compared with an approach in which FLEGT licensing, FLEGT-like legislation, or engagement in VPA processes resulted in the assignment of a RIV corresponding to the lower level of the low-risk category (i.e., a RIV of 7).

The calculated RIV was overridden and increased to 7 when a country had signed or was negotiating a VPA with the EU, or when the country had legislation similar to the EUTR, provided that the calculated RIV was less than 7 (Article III).

Conversely, the calculated RIV was overridden and decreased to 3 when a country was subject to United Nations or EU sanctions banning trade in wood-based products, provided that the calculated RIV was higher than 3 (Article III).

The country-based RIV constitutes a categorical variable derived from the corresponding country-based continuous variables for the WGI, forest area change, roundwood production change, and agricultural area change (Article III). The distinctiveness of the nine RIV classes with respect to the corresponding FAR components was tested at the 95% confidence level using one-way analysis of variance (ANOVA; Article III). The test was conducted for each of the different approaches using IBM SPSS software.

2.3.2 Data

The WGI is updated yearly by the World Bank. It consists of the following sub-indices: Voice and Accountability, Political Stability No Violence, Government Effectiveness, Regulatory Quality, Rule of Law and Control of Corruption (Kaufmann and Kraay 2023). These topics very much resonate with the wider areas of implied governance interests expressed in the

EUDR. Normalised values of the WGI were used as the starting point in the calculation of the RIV.

The data for forest area, agricultural area, and roundwood production were sourced from FAOSTAT (FAO 2024). The FAOSTAT data are reported annually, but the annual values are typically interpolated between data points that are 5 years or more apart. The forest data in FAOSTAT are sourced from the FAO Forest Resources Assessment (FRA). National 5-yearly trends were calculated from FAOSTAT data for forest area, agricultural area, and roundwood production. These trend data were used to calculate the RIV. All required data were compiled to calculate the RIV for any country in the world for the year 2020.

The trade data were queried from the European Forest Institute (EFI) Forest Products Trade Flow Database (EFI 2024), which is based on United Nations COMTRADE data, which record global bilateral trade for commodities classified with the World Customs Organisation's Harmonised System (HS) classification. This particular database was used because these data are curated according to a procedure for estimating missing data as well as replacing data determined to be erroneous outliers. The data of interest are the imports of all wood-based commodities within the scope of Annex I of the EUDR, as imported by the 27 Member States of the European Union (EU27), from any other countries in the world, during the year 2020. The commodities of interest are classified into more than 300 products of the following HS chapters:

- HS44: 'Wood and articles of wood; wood charcoal';
- HS47: 'Pulp of wood';
- HS48: 'Paper and paperboard; articles of paper pulp, of paper or of paperboard';
- HS49: 'Printed paper materials';
- HS94: 'Wooden furniture and parts thereof; and prefabricated buildings of wood'.

2.3.3 *Analysis*

EU imports of wood-based products were queried, and the results were downloaded at the level of HS 6-digit-coded commodities for each country with which the products concerned were traded. The data included the EU-external country of origin, product code, EU importing country, quantity in metric tonnes, and value in US dollars, aggregated for the full reference year of 2020. These data were appended with the country-based calculated RIV by applying XLOOKUP table functions in Microsoft Excel. EU wood-based product import data are summarised by value, quantity, and number of extra-EU trading partners at the three levels of detail in the HS classification system (chapter level: 2-digit codes; heading level: 4-digit codes; and sub-heading level: 6-digit codes) by means of pivot tables.

3 RESULTS

3.1 **Companies' innovation perspectives for developing the regional forest-based bioeconomy (Article I)**

3.1.1 *Sectors in the regional forest-based bioeconomy*

The study region of North Karelia harbours a diverse range of companies that can be clustered into 12 bioeconomy sub-sectors and a total 29 NACE-compatible industrial activities.

Together, these companies achieved an annual turnover of 2.8 billion euros, with a full-time equivalent (FTE) of 4,200 employees (Article I, p. 4).

Five bioeconomy sectors each have 13–19 companies and jointly comprise 82% of the companies in this study and 63% of the turnover: ‘Forestry and logging’; ‘Manufacture and maintenance of forest related technology and machinery’; ‘RTDDI, information, and services sector’; ‘Wood-based construction’; and ‘Wood products manufacturing’ (Article I, p. 5).

3.1.2 *Integration of research, technology development, digitalisation, and innovation into business development practices*

A total of 35 North Karelian companies gave feedback on the importance of RTDDI for the development of their business; 69% considered RTDDI ‘important’ or ‘very important’ (Article I, p. 5). Of these, 21 companies provided additional concise information on the nature of their RTDDI investments over the past decade (Article I, p. 5). The reported areas include ‘development of electronic services and design programmes’; ‘automated data collection in log transportation systems’; ‘remote sensing, machine learning, software development for forest information systems’; ‘new accounting, invoicing systems using artificial intelligence’; ‘significant increase in technological automation’; and ‘new wood-based materials that can replace (e.g., tropical) hardwood species in acoustic applications’ (Article I, p. 7, Table 2).

Companies were asked which modality they preferred for implementing RTDDI processes. Thirty-two companies indicated reliance on one or another modality, 47% relied (though not always exclusively) on ‘in-house (own) RTDDI human resources and infrastructure’, and 21 companies (66%) involved ‘some form of external cooperation’ (Article I, p. 5). When asked about the funding for the RTDI, 30 companies indicated certain preferred funding modalities. Thirteen companies indicated that they relied only on private funding, whereas 17 companies indicated that they relied on a mix of private and other types of funding. Twelve companies indicated that they relied on mixed public-private funding (Article I, p. 6).

Thirty-one companies shared basic information on cost structures. While ‘Research and development costs’ represented an average of 9% of total costs, they formed a substantial share in ‘Wood products manufacturing’ (18%), ‘RTDDI, information, and service sector’ (25%) and ‘Forest-related technology and machinery’ (16%) (Article I, p. 6).

Of the responding companies, 75% achieved their turnover on the domestic market (Article I, p. 6). Overall, the ‘Wood products manufacturing’ sector achieved the largest share of turnover both domestically and in export markets. Although the share of the ‘Forest-related technology and machinery’ sector in domestic market turnover was relatively small, it represented the second largest exporting sector (Article I, p. 6).

Fourteen companies across seven sectors indicated they have recent or planned investments to increase output capacity, to innovate products or production processes (Article I, p. 6). The majority expected generally increasing markets ($n = 10$) to strongly increasing markets ($n = 2$). For nine of these companies, this could also be linked specifically to expectations of growing export markets (Article I, p. 6). In all sectors except the energy sector, at least half of the respondents indicated that they expected an increase of the export market over the next 10 years (following 2021; Article I, p. 6).

3.1.3 *Barriers and constraints preventing companies from achieving the full potential of their economic activity*

Thirty-three companies, representing eight sectors, indicated the types of barriers or constraints they considered to be in the way of realising their full potential. The top four categories were 'Legislative or regulatory' barriers (64%), 'Financial' (48%), 'Availability of suitable workforce' (39%) and 'Technological' barriers or constraints (36%; Article I, pp. 6–7). Other barriers or constraints that impact businesses were related to consumer preferences, exports, insurance restrictions, raw material resourcing, intellectual property management, or transportation issues (Article I, p. 7). The sectors where most categories of barriers or constraints were mentioned were 'Wood products manufacturing' and 'Forestry and logging' (Article I, p. 7).

3.2 **Wood identification in support of legal supply chains: A market study (Article II)**

3.2.1 *Awareness and willingness to understand wood identification technologies*

The vast majority of respondents (87%) had heard about wood ID technologies and services. However, most of them (94%) indicated a need to learn more about operational applicability, accuracy and costs of the applications (Article II, p. 3).

3.2.2 *The level of current capacity and uptake of wood identification technologies*

A significant proportion (44%) of respondents indicated that they have in-house wood ID capacities, and 36% indicated that they outsource for the services elsewhere. Most of the law enforcement respondents reported in-house capacities, which was a relatively higher proportion than the due diligence respondents. All of the remaining law enforcement respondents indicated that they intended to establish such capacity in the future if they did not already have it. The uptake of services was generally higher for respondents in countries with a higher governance ranking, while the proportion of desired future uptake of the technologies was higher in respondents from countries with a lower governance ranking (Article II, pp. 3–4).

The method that was applied by most respondents concerned basic wood anatomy (both microscopic and macroscopic), and this was also the method for which most in-house capacities were available. The next most applied method was wood anatomy based on machine vision. The most technologically advanced methods were also the ones for which services were being outsourced (Article II, p. 4).

In terms of frequency of reliance on wood ID technologies, 30% of respondents indicated that they had used them at least once a week and 13% once a month. Twenty per cent indicated that they were needed less than once a year, and another 20% indicated that they never used any wood ID technologies. There were clear differences between the due diligence and law enforcement user segments: less than 20% of due diligence respondents required wood ID technologies at least once a week, while more than 75% of law enforcement respondents required technologies at least once a week. Respondents from countries with a higher governance ranking generally indicated greater reliance on the wood ID services; however, the proportion of respondents using the services at least once a week was slightly

higher for those from countries with a lower governance ranking (32%) compared with a higher governance ranking (30%; Article II, p. 6).

3.2.3 *Future need for wood identification (in 5–10 years)*

When asked about the priority for which wood ID technologies should be applied, 85% of respondents indicated species verification and 72% indicated verification of geographical origin as the most important. While 69% of respondents already applied the technologies, this was expected to rise to 82% in the future (Article II, p. 6).

The importance of basic wood anatomy was expected to decline in favour of modern technologies, but wood anatomy would remain the most important approach used to determine wood species. The highest future expectation was given to machine vision-based ID, followed by genetics and stable isotopes analysis (Article II, p. 7).

Of all the products for which the technologies were applied, 63% of cases concerned sawnwood and logs. The respondents also mentioned more advanced products, some of which require highly specialised ID technologies (Article II, p. 6).

When asked to indicate the species for which the application of wood ID technologies should be a priority, the respondents mentioned species from all relevant continents, with 85% of the priority species being of tropical origin. However, priority species requiring the urgent development of reference material were mentioned for all forest-covered continents (Article II, p. 6).

Requirements: Five specific expectations clearly recurred in the responses: low cost, accuracy, ease of use, reliability of results, and speed of application. The methods that combine most, if not all, of these characteristics would be the most successful applications (Article II, p. 7).

3.2.4 *Drivers of demand for wood identification technologies and associated services*

‘Compliance with policy/legislation’ was seen by most respondents (83%) as an ever-growing driver for the demand of wood ID due to growing awareness about legislation, growing enforcement action, and increasing legislative requirements in the main consumer markets. ‘Certification compliance’ and ‘customer awareness’ were seen as drivers that would gain most from the ‘current’ time (53% of respondents) to the ‘future’ (75% of respondents). ‘Procurement requirements’ and ‘reputation management’ were also seen as important drivers both at the time of answering the questionnaire (63% and 60% respectively) and even more so in the future (75% and 73% respectively; Article II, p. 7).

‘Reputation management’ was considered more frequently as important by respondents from a country with a higher governance ranking, while ‘certification compliance’ and procurement requirements were considered more important by respondents from countries with a lower governance ranking. The respondents from countries with a lower governance ranking expected ‘Customer awareness’ to become much more important in the future (Article II, p. 7).

3.3 Risk profiles for EU imports of deforestation-free wood-based products (Article III)

3.3.1 Risk index

The RIV could be calculated for 181 countries for which data were consistently available from FAOSTAT and the WGI. The RIV could not be calculated for approximately 70 countries and non-sovereign territories that are otherwise represented in the COMTRADE dataset, typically small island nations. These countries and territories account for a modest proportion of extra-EU imports, representing 2% of total value and 1% of total quantity, respectively (Article III, p. 7).

The significance of the distinctiveness of the nine RIV classes was tested using ANOVA for each of the constituent components (WGI, forest area change, agricultural area change, and roundwood production change). For each of the three approaches – $[FAR \pm 0.000]$, $[FAR \pm 0.001]$, and $[FAR \pm 0.010]$ – ANOVA consistently shows that the WGI and forest area change demonstrate the most significant differences between the RIV (see Table 1). This is particularly clear between high-risk values, on the one hand, and medium- and lower-risk values, on the other hand. Agricultural area change values differ significantly between the RIV, but the differences are less distinct. No significant difference could be shown for roundwood production change values (Article III, p. 7).

Table 1 P-values resulting from analysis of variance (ANOVA) testing the distinctness of the Risk Index Value (RIV), including the World Governance Index (WGI), 5-year forest area change (FAC), the 5-year roundwood production change (RP), and 5-year agricultural change (AAC). Values smaller than 0.001 indicate a significant difference between the average data within the RIV class. Whiter cells show more significant differences, while greener cells indicate less distinct differences between classes. Part (a) shows the analysis results for the $[FAR \pm 0.000]$ approach, part (b) shows the analysis results for the $[FAR \pm 0.001]$ approach, and part (c) shows the analysis results for the $[FAR \pm 0.010]$ approach. (source: Article III, Table 2, pp. 6–7)

(a) ANOVA results for the $[FAR \pm 0.000]$ approach

P-Values_for_WGI_

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	0.178	0.216	0.003	<.001	<.001	<.001	<.001	<.001
RIV2	0.178	1.000	1.000	0.667	0.017	<.001	<.001	0.002	<.001
RIV3	0.216	1.000	1.000	0.589	0.012	<.001	<.001	0.001	<.001
RIV4	0.003	0.667	0.589	1.000	0.767	0.071	<.001	0.172	<.001
RIV5	<.001	0.017	0.012	0.767	1.000	0.981	0.111	0.935	0.011
RIV6	<.001	<.001	<.001	0.071	0.981	1.000	0.392	1.000	0.040
RIV7	<.001	<.001	<.001	<.001	0.111	0.392	1.000	0.973	0.728
RIV8	<.001	0.002	0.001	0.172	0.935	1.000	0.973	1.000	0.286
RIV9	<.001	<.001	<.001	<.001	0.011	0.040	0.728	0.286	1.000

P-Values_for_FAC

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	1.000	0.959	0.673	0.005	0.004	0.002	0.006	0.164
RIV2	1.000	1.000	0.986	0.678	<.001	<.001	<.001	0.002	0.174
RIV3	0.959	0.986	1.000	0.994	0.018	0.008	0.005	0.024	0.473
RIV4	0.673	0.678	0.994	1.000	0.224	0.196	0.087	0.172	0.815
RIV5	0.005	<.001	0.018	0.224	1.000	1.000	1.000	1.000	1.000
RIV6	0.004	<.001	0.008	0.196	1.000	1.000	0.994	0.993	1.000
RIV7	0.002	<.001	0.005	0.087	1.000	0.994	1.000	1.000	1.000
RIV8	0.006	0.002	0.024	0.172	1.000	0.993	1.000	1.000	1.000
RIV9	0.164	0.174	0.473	0.815	1.000	1.000	1.000	1.000	1.000

P-Values_for_AAC

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	0.994	1.000	1.000	0.826	0.751	0.488	0.649	0.956
RIV2	0.994	1.000	0.995	0.871	0.065	0.014	0.011	0.068	0.568
RIV3	1.000	0.995	1.000	0.999	0.368	0.177	0.101	0.286	0.856
RIV4	1.000	0.871	0.999	1.000	0.818	0.682	0.411	0.641	0.973
RIV5	0.826	0.065	0.368	0.818	1.000	1.000	0.999	1.000	1.000
RIV6	0.751	0.014	0.177	0.682	1.000	1.000	0.997	0.999	1.000
RIV7	0.488	0.011	0.101	0.411	0.999	0.997	1.000	1.000	1.000
RIV8	0.649	0.068	0.286	0.641	1.000	0.999	1.000	1.000	1.000
RIV9	0.956	0.568	0.856	0.973	1.000	1.000	1.000	1.000	1.000

P-Values_for_RPC

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	1.000	0.997	0.940	1.000	0.979	0.959	0.311	0.883
RIV2	1.000	1.000	1.000	0.952	1.000	0.988	0.974	0.252	0.916
RIV3	0.997	1.000	1.000	0.999	0.984	1.000	1.000	0.514	0.984
RIV4	0.940	0.952	0.999	1.000	0.819	1.000	1.000	0.852	0.999
RIV5	1.000	1.000	0.984	0.819	1.000	0.904	0.881	0.152	0.813
RIV6	0.979	0.988	1.000	1.000	0.904	1.000	1.000	0.626	0.995
RIV7	0.959	0.974	1.000	1.000	0.881	1.000	1.000	0.879	0.999
RIV8	0.311	0.252	0.514	0.852	0.152	0.626	0.879	1.000	1.000
RIV9	0.883	0.916	0.984	0.999	0.813	0.995	0.999	1.000	1.000

(b) ANOVA results for the $[FAR \pm 0.001]$ approach

P-Values_for_WGI

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	0.899	0.799	0.010	<.001	<.001	<.001	<.001	<.001
RIV2	0.899	1.000	1.000	0.048	0.002	<.001	<.001	<.001	<.001
RIV3	0.799	1.000	1.000	0.081	0.005	<.001	<.001	<.001	<.001
RIV4	0.010	0.048	0.081	1.000	0.983	0.120	0.013	0.015	0.005
RIV5	<.001	0.002	0.005	0.983	1.000	0.825	0.249	0.187	0.039
RIV6	<.001	<.001	<.001	0.120	0.825	1.000	0.942	0.812	0.227
RIV7	<.001	<.001	<.001	0.013	0.249	0.942	1.000	1.000	0.701
RIV8	<.001	<.001	<.001	0.015	0.187	0.812	1.000	1.000	0.916
RIV9	<.001	<.001	<.001	0.005	0.039	0.227	0.701	0.916	1.000

P-Values_for_FAC

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	1.000	0.985	0.600	0.009	0.007	0.003	0.008	0.215
RIV2	1.000	1.000	0.996	0.493	<.001	<.001	<.001	0.001	0.217
RIV3	0.985	0.996	1.000	0.922	0.006	0.002	0.002	0.010	0.440
RIV4	0.600	0.493	0.922	1.000	0.268	0.218	0.115	0.202	0.872
RIV5	0.009	<.001	0.006	0.268	1.000	1.000	1.000	1.000	1.000
RIV6	0.007	<.001	0.002	0.218	1.000	1.000	0.999	0.997	1.000
RIV7	0.003	<.001	0.002	0.115	1.000	0.999	1.000	1.000	1.000
RIV8	0.008	0.001	0.010	0.202	1.000	0.997	1.000	1.000	1.000
RIV9	0.215	0.217	0.440	0.872	1.000	1.000	1.000	1.000	1.000

P-Values_for_AAC

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	0.998	1.000	1.000	0.835	0.725	0.385	0.672	0.920
RIV2	0.998	1.000	0.976	0.768	0.860	0.011	0.003	0.061	0.525
RIV3	1.000	0.976	1.000	0.999	0.457	0.204	0.083	0.351	0.856
RIV4	1.000	0.768	0.999	1.000	0.865	0.680	0.292	0.703	0.964
RIV5	0.835	0.060	0.457	0.865	1.000	1.000	0.991	1.000	1.000
RIV6	0.725	0.011	0.204	0.680	1.000	1.000	0.992	1.000	1.000
RIV7	0.385	0.003	0.083	0.292	0.991	0.992	1.000	1.000	1.000
RIV8	0.672	0.061	0.351	0.703	1.000	1.000	1.000	1.000	1.000
RIV9	0.920	0.525	0.856	0.964	1.000	1.000	1.000	1.000	1.000

P-Values_for_RPC

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	1.000	1.000	0.966	1.000	0.999	0.932	0.408	0.919
RIV2	1.000	1.000	1.000	0.978	1.000	1.000	0.945	0.323	0.951
RIV3	1.000	1.000	1.000	0.992	0.999	1.000	0.972	0.384	0.968
RIV4	0.966	0.978	0.992	1.000	0.869	0.998	1.000	0.852	0.999
RIV5	1.000	1.000	0.999	0.869	1.000	0.995	0.794	0.183	0.877
RIV6	0.999	1.000	1.000	0.998	0.995	1.000	0.987	0.437	0.979
RIV7	0.932	0.945	0.972	1.000	0.794	0.987	1.000	0.949	1.000
RIV8	0.408	0.323	0.384	0.852	0.183	0.437	0.949	1.000	1.000
RIV9	0.919	0.951	0.968	0.999	0.877	0.979	1.000	1.000	1.000

(c) ANOVA results for the $[FAR \pm 0.010]$ approach

P-Values_for_WGI

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	0.991	0.983	0.146	0.004	0.006	<.001	<.001	-
RIV2	0.991	1.000	1.000	0.016	<.001	<.001	<.001	<.001	-
RIV3	0.983	1.000	1.000	0.012	<.001	<.001	<.001	<.001	-
RIV4	0.146	0.016	0.012	1.000	0.311	0.433	0.009	<.001	-
RIV5	0.004	<.001	<.001	0.311	1.000	1.000	0.853	0.023	-
RIV6	0.006	<.001	<.001	0.433	1.000	1.000	0.620	0.011	-
RIV7	<.001	<.001	<.001	0.009	0.853	0.620	1.000	0.208	-
RIV8	<.001	<.001	<.001	0.023	0.011	0.208	1.000	1.000	-
RIV9	-	-	-	-	-	-	-	-	-

P-Values_for_FAC

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	0.997	1.000	0.949	0.554	0.405	0.203	0.349	-
RIV2	0.997	1.000	0.936	0.014	<.001	<.001	<.001	0.003	-
RIV3	1.000	0.936	1.000	0.188	0.001	<.001	<.001	0.021	-
RIV4	0.949	0.014	0.188	1.000	0.805	0.494	0.137	0.610	-
RIV5	0.554	<.001	0.001	0.805	1.000	1.000	0.926	0.983	-
RIV6	0.405	<.001	<.001	0.494	1.000	1.000	0.764	0.986	-
RIV7	0.203	<.001	<.001	0.137	0.926	0.764	1.000	1.000	-
RIV8	0.349	0.003	0.021	0.610	0.983	0.986	1.000	1.000	-
RIV9	-	-	-	-	-	-	-	-	-

P-Values_for_AAC

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	1.000	0.998	0.998	0.475	0.721	0.264	0.514	-
RIV2	1.000	1.000	0.991	0.988	0.013	0.081	0.001	0.189	-
RIV3	0.998	0.991	1.000	1.000	0.079	0.351	0.009	0.423	-
RIV4	0.998	0.988	1.000	1.000	0.138	0.483	0.022	0.478	-
RIV5	0.475	0.013	0.079	0.138	1.000	0.991	0.996	1.000	-
RIV6	0.721	0.081	0.351	0.483	0.991	1.000	0.764	0.986	-
RIV7	0.264	0.001	0.009	0.022	0.996	0.764	1.000	1.000	-
RIV8	0.514	0.189	0.423	0.478	1.000	0.986	1.000	1.000	-
RIV9	-	-	-	-	-	-	-	-	-

P-Values_for_RPC

	RIV1	RIV2	RIV3	RIV4	RIV5	RIV6	RIV7	RIV8	RIV9
RIV1	1.000	1.000	1.000	1.000	1.000	1.000	0.990	0.735	-
RIV2	1.000	1.000	1.000	1.000	1.000	0.859	0.377	0.156	-
RIV3	1.000	1.000	1.000	1.000	0.997	0.967	0.558	0.232	-
RIV4	1.000	1.000	1.000	1.000	0.998	0.971	0.603	0.245	-
RIV5	1.000	1.000	0.997	0.998	1.000	0.659	0.189	0.098	-
RIV6	1.000	0.859	0.967	0.971	0.659	1.000	0.982	0.568	-
RIV7	0.990	0.377	0.558	0.603	0.189	0.982	1.000	0.891	-
RIV8	0.735	0.156	0.232	0.245	0.098	0.568	0.891	1.000	-
RIV9	-	-	-	-	-	-	-	-	-

3.3.2 Trade analysis – variation of FAR class bounds

Combining the RIV with the trade data produced the results shown in Table 2, which presents EU27 import values, and Table 3, which presents EU27 import quantities for wood-based products, summarised by Harmonised System chapter. The analysis covers a total of 51.7 billion US dollars in extra-EU imports, corresponding to 62.3 million metric tonnes (Article III, p. 7).

Table 2 EU27 import value (US dollars) of wood-based commodities traded in 2020, summarised by Harmonised System (HS) chapter and risk category: high (H), medium (M), and low (L). Values are shown as proportions of total traded value for three approaches to calculate the Risk Index Value, each using different class bounds for the FAR indicators. NN indicates that the country risk could not be determined. P indicates the number of 6-digit commodities classified under the HS (version 2017). Cells are colour-coded by percentage, from blue for the lowest values to red for the highest values. Due to rounding, percentages within a category may not sum to exactly 100%. HS chapter legend: HS44: 'Wood and articles of wood; wood charcoal'; HS47: 'Pulp of wood'; HS48: 'Paper and paperboard; articles of paper pulp, of paper or of paperboard'; HS49: 'Printed paper materials'; and HS94: 'Wooden furniture and parts thereof; and prefabricated buildings of wood'. (Adapted from Article III, Table 5)

HS	P	extra-EU import		Risk category (FAR $\pm$ 0.000)				Risk category (FAR $\pm$ 0.001)				Risk category (FAR $\pm$ 0.010)			
		value (USD)	Proportion of total	H	M	L	NN	H	M	L	NN	H	M	L	NN
44	105	12,361,168,661	24%	5%	13%	6%	0%	3%	14%	6%	0%	3%	17%	4%	0%
47	21	4,261,847,131	8%	5%	0%	3%	0%	3%	2%	3%	0%	3%	2%	3%	0%
48	101	9,617,321,807	19%	3%	8%	7%	0%	1%	10%	7%	0%	1%	10%	7%	0%
49	19	3,136,590,836	6%	1%	2%	3%	0%	0%	2%	3%	0%	0%	2%	3%	0%
94	3	22,324,507,926	43%	3%	34%	5%	1%	2%	35%	6%	1%	2%	36%	4%	1%
Total	249	51,701,436,361	100%	17%	57%	25%	2%	9%	63%	25%	2%	9%	68%	21%	2%

Table 3. EU27 import quantity (metric tonnes) of wood-based commodities traded in 2020, summarised by Harmonised System (HS) chapter and risk category: high (H), medium (M), and low (L). Quantities are shown as proportions of total traded quantity for three approaches to calculate the Risk Index Value, each using different class bounds for the FAR indicators. NN indicates that the country risk could not be determined. P indicates the number of 6-digit commodities classified under the HS (version 2017). Cells are colour-coded by percentage, from blue for the lowest values to red for the highest values. (Adapted from Article III, Table 6)

HS	P	extra-EU import		Risk category (FAR $\pm$ 0.000)				Risk category (FAR $\pm$ 0.001)				Risk category (FAR $\pm$ 0.010)			
		Total weight (Metric tonnes)	Proportion of total	H	M	L	NN	H	M	L	NN	H	M	L	NN
44	105	39,879,645	64%	7%	39%	18%	1%	4%	41%	18%	1%	3%	46%	14%	1%
47	21	9,504,031	15%	7%	1%	7%	0%	5%	3%	7%	0%	5%	3%	7%	0%
48	101	7,393,666	12%	2%	4%	6%	0%	1%	5%	6%	0%	1%	5%	5%	0%
49	19	359,400	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
94	3	5,201,084	8%	0%	7%	1%	0%	0%	7%	1%	0%	0%	7%	0%	0%
Total	249	62,337,827	100%	17%	50%	32%	1%	10%	57%	32%	1%	10%	62%	27%	1%

The strictest classification approach [$\text{FAR} \pm 0.000$] resulted in the highest proportion of trade allocated to the highest-risk category, with 17% of total value and 17% of total quantity. The less strict approaches reduced the value and quantity allocated to the highest-risk category to 9% of total trade value and 10% of total trade quantity. The more easily a country is retained in the ‘no-change’ class, the more countries ‘gravitate’ from both the high- and low-RIV categories towards the medium-RIV category (Article III, p. 7).

The HS chapters with the highest traded quantities are HS44 (Wood and articles of wood; wood charcoal), accounting for 64% of total extra-EU imports, and HS47 (‘Pulp of wood’), accounting for 15% of total extra-EU imports (Article III, p. 7).

The HS chapters that are most important in terms of traded value are HS94 (Wooden furniture and parts thereof; and prefabricated buildings of wood), accounting for 43% of total extra-EU imports, and HS44 (Wood and articles of wood; wood charcoal), accounting for 24% of total extra-EU imports (Article III, p. 7).

Wood and articles of wood, and charcoal (HS44) represent the largest overall quantity (64% of total imports), with 7% of its quantity classified as high risk. Specific high-risk segments include Fuelwood (HS4401), Industrial Roundwood (HS4403), and Sawnwood (HS4407), which together account for 80% of the imports of commodities in HS44 (Article III, p. 7).

Pulp of wood (HS47) represents the HS chapter with the highest proportional risk under the strictest risk classification approach [$\text{FAR} \pm 0.000$], with approximately 48% of the import quantity and 57% of the import value originating from high-risk countries. This is primarily linked to the HS headings for chemical wood pulp (Chemical wood pulp, dissolving grades (HS4702); Chemical wood pulp, soda or sulphate, other than dissolving grades (HS4703)) and Waste and scrap of paper and paperboard (HS4707). Under the less strict risk categorisation approaches – [$\text{FAR} \pm 0.010$] and [$\text{FAR} \pm 0.001$] – the proportion of Pulp of wood (HS47) import quantity assigned to the high-risk category was reduced to 35% under both approaches, while the proportion of import value assigned to the high-risk category was reduced to 35% and 34%, respectively (Article III, p. 7).

Wooden furniture and parts thereof; and prefabricated buildings of wood (HS94) comprise the highest total import value (over \$22 billion) but maintain the lowest proportional value in the high-risk category (approximately 4%–7%, depending on the approach used to calculate the RIV). Commodities in Printed Materials (HS49) are likewise consistently represented in the low-risk category (approximately 53% of value; Article III, p. 7).

3.3.3 *Trade analysis – inclusion of FLEGT considerations*

Acknowledging FLEGT licensing, the involvement of countries in a VPA process, or the presence of EUTR-like legislation results in a lower risk classification in the FLEGT-conscious approach. FLEGT licensing is currently applied only to trade in wood-based products from Indonesia and Ghana. Acknowledgement of FLEGT licensing alone (see [$\text{FAR} \pm 0.000$ | FL] in Table 4 and Table 5) therefore has a limited impact on the allocation of commodities to the low-risk category. The wider FLEGT-influenced risk-scoring approach, based on the assumption that future forest-sector governance in these countries will become de facto compliant with the EUDR, shows significant changes in the risk profiles of EU imports (see [$\text{FAR} \pm 0.000$ | LA] in Table 4 and Table 5 (Article III, pp. 8–9)).

Table 4. EU27 import value (US dollars) of wood-based commodities traded in 2020, summarised by Harmonised System (HS) chapter and risk category: high (H), medium (M), and low (L). Values are shown as proportions of total traded value for the basic approach to calculate the Risk Index Value [FAR $\pm$ 0.000] and two alternative approaches that adjust Risk Index Value based on FLEGT licensing [FAR $\pm$ 0.000 | FL] or VPA involvement and EUTR-like legislation [FAR $\pm$ 0.000 | LA]. NN indicates that the country risk could not be determined. P indicates the number of 6-digit commodities classified under the Harmonised System (HS17). Cells are colour-coded by percentage, from blue for the lowest values to red for the highest values. (Adapted from Article III, Table 7)

HS	P	extra-EU import value (USD)	Risk category (FAR $\pm$ 0.000)				Risk category (FAR $\pm$ 0.000 FL)				Risk category (FAR $\pm$ 0.000 LA)			
			H	M	L	NN	H	M	L	NN	H	M	L	NN
44	105	12,361,168,661	5%	13%	6%	0%	4%	13%	7%	0%	2%	12%	9%	0%
47	21	4,261,847,131	5%	0%	3%	0%	5%	0%	3%	0%	3%	0%	5%	0%
48	101	9,617,321,807	3%	8%	7%	0%	3%	8%	8%	0%	1%	7%	10%	0%
49	19	3,136,590,836	1%	2%	3%	0%	1%	2%	3%	0%	0%	2%	4%	0%
94	3	22,324,507,926	3%	34%	5%	1%	2%	34%	7%	1%	0%	31%	11%	1%
Total	249	51,701,436,361	17%	57%	25%	2%	14%	57%	27%	2%	6%	53%	39%	2%

Table 5. EU27 import quantity (metric tonnes) of wood-based commodities traded in 2020, summarised by Harmonised System (HS) chapter and risk category: high (H), medium (M), and low (L). Quantities are shown as proportions of total traded quantity for the basic approach to calculate the Risk Index Value [FAR $\pm$ 0.000] and two alternative approaches that adjust the Risk Index Value based on FLEGT licensing [FAR $\pm$ 0.000 | FL] or Voluntary Partnership Agreement involvement and EUTR-like legislation [FAR $\pm$ 0.000 | LA]. NN indicates that the country risk could not be determined. P indicates the number of 6-digit commodities classified under the Harmonised System (HS17). Cells are colour-coded by percentage, from blue for the lowest values to red for the highest values. (Adapted from Article III, Table 8)

HS	P	Total weight (Metric tonnes)	Risk category (FAR $\pm$ 0.000)				Risk category (FAR $\pm$ 0.000 FL)				Risk category (FAR $\pm$ 0.000 LA)			
			H	M	L	NN	H	M	L	NN	H	M	L	NN
44	105	39,879,645	7%	39%	18%	1%	6%	38%	18%	1%	3%	38%	22%	1%
47	21	9,504,031	7%	1%	7%	0%	7%	1%	7%	0%	5%	1%	9%	0%
48	101	7,393,666	2%	4%	6%	0%	2%	4%	6%	0%	1%	4%	8%	0%
49	19	359,400	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
94	3	5,201,084	0%	7%	1%	0%	0%	7%	1%	0%	0%	6%	2%	0%
Total	249	62,337,827	17%	50%	32%	1%	16%	50%	33%	1%	8%	49%	41%	1%

4 DISCUSSION AND CONCLUSIONS

4.1 Relation to the main scientific objectives

The overarching objective of this thesis was to examine how the forest-based bioeconomy can be driven by innovation and develop based on legal and deforestation-free supply chains. The three articles confirm that the conditions arise from the interaction between regulatory frameworks, technical and technological capacities, and organisational capabilities.

Article I addresses the first objective of this thesis by assessing innovation approaches and constraints in a regional forest-based bioeconomy. Many companies recognise the importance of RTDDI but face significant financial, regulatory, skills-related, and technological constraints. The heterogeneity of innovation modalities, with a preference for internally driven innovation, and a relatively low degree of engagement with academic partners, reveals structural challenges that may reduce the pace of the bioeconomy transition at the regional scale. A lack of skilled personnel was also indicated as a constraint for the availability of wood ID services (Article II).

Article II highlights that unbiased verification of legality can be achieved through mature, accessible and geographically representative wood ID technologies. Science-based wood ID tools are more easily accessible to due diligence actors and law enforcement agencies in countries with stronger governance. More technology-specific reference data are needed to increase the geographical resolution and species relevance of the tools.

Article III focuses on the development and testing of a country-based legality and deforestation risk index, inspired by the EUDR country assessment requirements. Governance quality and forest-area dynamics provide the strongest link to the calculated country RIV. EU import exposure varies considerably across commodity groups, with wood products (HS44) and wood pulp (HS47) having the highest proportions of quantity labelled as high risk. The risk index approach is a transparent and temporally reproducible framework that complements official EUDR benchmarking and informs which products and origins may warrant intensified due diligence or enforcement.

Commodities and products of tree species from countries labelled as high risk could also be prioritised for the development of reference data for wood ID technologies (linking Articles II and III). Country benchmarking may also be used to inform the prioritisation of third-country partnerships, facilitating targeted EU cooperation to enhance forest sector governance.

4.2 Companies' innovation perspectives for developing the regional forest-based bioeconomy (Article I)

Research, technology development, digitalisation, and innovation are important components for the development of regional bioeconomies. Companies in the study region were found to be engaged in product, process, organisational, and/or marketing innovation. The drivers for the innovations were market demand, technological advancements, environmental concerns, and supportive policies. Encouraging and fostering innovation within the bioeconomy sector can facilitate its resilient and sustainable development and enhance its ability to address future challenges.

While 69% of the companies considered RTDDI to be important or very important, not all production or process improvements can be achieved by companies on their own. Companies may depend on third parties particularly for digitalisation, automation, and mechanisation-based innovations. The sectors do not work in isolation and in practice cross-sectoral innovation links sectors such as 'RTDDI, information and services sector' or 'Manufacture and maintenance of forest related technology and machinery' as drivers of innovation in more downstream sectors such as 'Forestry and logging' and 'Wood product manufacturing'. It is important to recognise such interdependencies to ensure they are considered in the development of the region's innovation potential.

Proximity and connectedness of entities in innovation clusters can be beneficial to the adoption of innovations (Turkina and Van Assche 2018; Ferras-Hernandez and Nylund 2019). In this context, business acceleration services such as those provided by Business Joensuu have a strategic role in advancing collaboration between local partners, including universities, business, research institutes, networks and associations.

However, a significant number of companies relied solely on private funding for their RTDI activities. The preferred RTDI modalities concerned in-house resources, followed by innovation involving external collaborators and ideas. Two-thirds of the companies indicated that they involved some form of external cooperation to achieve their RTDDI goals. Only around 6% of companies indicated joint research and development (R&D) with academic institutions, which is a rather low share and seemingly a missed opportunity considering the availability of high-level forestry and bioeconomy education and scientific research in the region.

Companies indicated that they were affected by a range of constraints related to regulations, finances, raw materials, human resources, and technical aspects that prevented them from realising their full economic potential. These findings are consistent with the constraints identified in previous studies (Borgström et al. 2016; Bennich et al. 2018; Reim et al. 2019; Hasegawa et al. 2022b; Verkerk et al. 2022; Pender et al. 2023; Hetemäki et al. 2024).

Constraints pose challenges, implicitly requiring innovation to develop solutions that work around perceived impediments to economic success. They need to be addressed by coalitions of the most suitable actors, depending on the objectives they want to reach. Consideration could be given to helping to solve the workforce and expertise shortfall – for example, through the development of purpose-specific research and education for disciplines that are not currently catered to in the region. The products made in the region are also influenced by the available resources (Nørstebø et al. 2020; Barañano et al. 2022; Hyytiä 2022). In terms to wood-based material inputs, public and private forest management as well as valorisation of sidestreams, waste, and recycled material can influence sectoral development. Educational institutions have an important role regarding technical skills and human resources. Ultimately, innovation will benefit the companies driving innovation as well as the entire cluster of actors and stakeholders in the regional innovation ecosystem (Brege et al. 2010).

The findings suggest that innovation support services should be extended beyond start-up companies. This approach could make it possible to understand and serve the innovation needs of established companies. Replicating similar assessments in other regions and at regular intervals could support cross-regional comparisons and enable monitoring of temporal trends.

4.3 Wood identification in support of legal supply chains: A market study (Article II)

On the topic of awareness and willingness to buy, the majority of respondents were aware and still wanted to know more about wood ID methods, specifically about the cost, accuracy, and robustness of the method. However, this awareness cannot be generalised. For example, Köthke (2020) examined German economic operators and found that overall, awareness of the EUTR was low, but there was strong compliant behaviour among high-value operators. Transparency regarding technology maturity and cost needs to be improved and made available to potential user organisations or companies. Effective wood ID in the context of due diligence and law enforcement relies on access to reference data and technology. Appropriate access can be facilitated through international cooperation, development of interoperable databases and training in both methods development and technology application (Low et al. 2023).

The second research question concerned current capacities and uptake of wood ID technologies by public and private sector actors. Most respondents already engaged with wood ID technologies. The combination of in-house and outsourced capacity was lower for respondents from countries with a lower governance ranking; these countries would benefit from technology sharing mechanisms to help detect problematic trade closer to the source. For comparison, not all operators and competent authorities in the EU have the means to implement frequent testing. Wood ID capacities need to be developed in support of due diligence and law enforcement on the sides of the consumer and producing countries.

The third research question concerned the future need for wood ID. Based on the responses, the user base for all wood ID methods would expand by more than 20%, except for wood anatomy, which would still remain the most available method. The use of dendrochronological methods would remain more or less stable. The EUTR and EUDR utilise the leverage of the EU consumer market to influence governance in source countries, with the EUDR closing loopholes in the EUTR and increasing liability obligations (Köthke et al. 2023). Compliance with legislation was found to be the most important driver for EUTR compliance (Sotirov and Köthke 2024). Increased awareness of and striving for legal and transparent operations will likely also increase demand for wood ID methods.

Concerning the fourth research question on the drivers for demand of technology and services, ‘compliance with legislation’ would remain the most important driver for the demand of wood ID in the future, and all other drivers would also increase in importance. Compared with respondents from countries with a higher governance ranking, those from countries with a lower governance ranking assigned higher importance to the drivers. In 2018, five years after the EUTR went into effect, Köthke (2020) found that in Germany, only 28% of the examined operators had implemented the needed due diligence system. This corresponded to 70%–79% of the import value. This finding shows that many traders handle small volumes and values and when they do not even have the basic due diligence system in place, they may be less concerned about wood ID services. Integration of wood ID as part of a larger service offering that would include more comprehensive due diligence support. For example, wood ID may be made more accessible when offered in the context of the EUTR by so-called monitoring organisations.

Based on these findings, four recommendations can be proposed to increase the uptake of wood ID (Article II): i. First, scale up efforts for collecting and analysing geo-referenced wood samples to expand the global reference data and the functional applicability of various wood ID technologies. Prioritise species with protected status and those that are widely

traded. Second, promote the exchange of wood ID information, expertise, and technology among nations, organisations, and professionals. Third, increase the understanding of wood ID technology among those responsible for executing or implementing global forest-related rules and regulations. Finally, couple wood ID technologies more operationally as tools to help compliance with and enforcement of forest governance.

This study offers a reference point for the assessment of the wood ID market and imminent developments. Future research could aim to quantify the market purely based on the actual services implemented by public and private service providers following user segmentation types in relation to market volume and complexity.

4.4 Risk profiles for EU imports of deforestation-free wood-based products (Article III)

An alternative approach to assessing the risk profiles of EU trade partners and characterising the risk associated with imports of wood-based commodities was developed and analysed. The complexity of product sourcing is reflected in the number of trade partners per commodity type. Import values, quantities, and their ratio vary between products, partly depending on the commodity's position within successive value-added stages. The RIV was calculated using the WGI in combination with trends in forest area, roundwood production, and agricultural area. The differentiation between the RIV was determined primarily by the WGI, followed by forest area and, to a lesser extent, roundwood production and agricultural area. By incorporating indicators of countries' land-use change and production patterns, rather than relying solely on governance indices (as in Norman et al. 2017; Lin et al. 2021), the resulting RIV takes forest-sector legal and deforestation risks into account more explicitly than previous approaches.

The resulting country classification differs from the benchmarking outcome described by the European Commission (2025b). Under that approach, a country can be classified as low risk through one of three pathways: no net forest loss (≤ 0 kha/year; first pathway); deforestation below both a relative threshold of 0.2% and an absolute threshold of 70 thousand hectares of annual average forest area loss between 2015 and 2020 (second pathway); or zero or negative relative and absolute annual changes in cropland commodities, timber and cattle production trends, and the expansion of total agricultural land (third pathway; European Commission 2023). For the first implementing act, the methodology also allows countries to fall within +25% of the low-risk absolute and relative thresholds. High-risk countries are currently limited to those subject to United Nations Security Council or EU Council sanctions on imports or exports of the relevant commodities and products (European Commission 2025b). Countries that are not classified as either low or high risk are classified as standard risk. This produces a substantially different country classification from that obtained in the study discussed in this thesis.

The strictest calculation approach – [FAR ± 0.000] – resulted in more countries being assigned to the high- and low-risk categories, with 17% of total import value and 17% of total import quantity assigned to the high-risk category. As expected, the less strict approaches resulted in a greater proportion of countries being assigned to the medium-risk category, reducing the share of trade classified as high risk to approximately 9% of import value and 10% of import quantity. The choice of thresholds therefore has a substantial effect on the results.

At the product level, the analysis shows that Pulp of wood (HS47) carries the highest proportional risk, with up to 57% of its import value originating from high-risk countries under the strictest approach. By contrast, Wood and articles of wood (HS44) account for the largest overall import quantity (64%), but only 7% of this quantity is classified as high risk. This high-risk quantity is concentrated primarily in fuelwood (HS4401), industrial roundwood (HS4403), and sawnwood (HS4407). These high-risk product groups would therefore warrant the greatest scrutiny by competent authorities. Conversely, Wooden furniture and parts thereof and prefabricated wooden buildings (HS94), and Printed materials (HS49), represent high total import values, each exceeding 22 billion US dollars, but are consistently associated with lower risk categories. Research examining the relationship between deforestation and wood-based commodities, although not necessarily in the context of international or EU-bound trade, has identified logs (Hoare and Kanashiro Uehara 2022), charcoal (Sedano et al. 2020), and pulp (Hoare and Kanashiro Uehara 2022) as relevant commodities. With regard to illegal logging and trade, the volume of illegal log exports is estimated to have remained roughly constant between 2000 and 2018, although the countries of origin changed over this period (Hoare and Kanashiro Uehara 2022). The same authors estimate that illegal exports of sawnwood, mouldings, veneer, and plywood declined in both volume and value, primarily as a result of improvements in governance in Indonesia and Malaysia. These findings support the development of a multi-temporal index that can be regularly revised to reflect improvements in forest-sector governance.

Accounting for national forest-sector governance initiatives and legislation resulted in a significant shift in trade volume and value towards the low-risk category. Although the impact of current FLEGT licensing remains limited because it currently applies only to Indonesia and Ghana, a broader governance-based approach incorporating VPA involvement and EUTR-like legislation produces a substantial shift. For example, in the high-risk Pulp of wood (HS47) sector, accounting for these governance pathways reduces the proportion of import quantity assigned to the high-risk category from 48% to 35%.

Several limitations should nevertheless be acknowledged. Agricultural expansion does not necessarily occur at the expense of forest area. Similarly, an increase in roundwood production does not necessarily result in deforestation or a change in land use or land cover. Net-zero deforestation does not mean that natural forests have not been converted to plantations. Forests can also re-establish – for example, on agricultural land that was unsustainably cultivated and subsequently abandoned – while natural forest may simultaneously be converted to agricultural plantations. In plantation forestry, increases in roundwood production may also result from improved tree varieties or forest-management practices rather than from an expansion of the forest area.

Combining the RIV with trade data enabled the quantification of commodities by risk category and provided an indication of the products for which due diligence or enforcement may require greater attention. Regardless of the approach used to calculate the RIV, the largest proportions of import value and quantity were assigned to the medium-risk category. However, the RIV should not be interpreted as a guide for economic operators when deciding where to source their products. On-the-ground due diligence can reduce the risk of non-compliance to a negligible level.

4.5 Generalisability and transferability of the methods and results

The manner in which the findings can be applied more generally differs across the three studies. Many of the innovation constraints identified in Article I resonate well with challenges documented by other studies, such as regulatory complexity (Borgström and Mauerhofer 2016; Reim et al. 2019; Pender et al. 2023; European Investment Bank 2024), financial limitations (Bennich et al. 2018; Reim et al. 2019; D’Adamo et al. 2022; Salvador et al. 2022; Verkerk et al. 2022; Pender et al. 2023; European Investment Bank 2024), technological constraints (Kuhmonen et al. 2024), and labour shortages (Näyhä 2020; Verkerk et al. 2022). The study methodology provides an input for similar regional assessments as well as cross-regional comparison of bioeconomy innovation readiness.

The insights from Article II on wood ID technologies provide transferable lessons for improving efforts to verify legality by competent authorities and economic operators, even while regulatory frameworks and enforcement needs are evolving.

The RIV methodology of Article III can be generalised and transferred to any country-level context: the required data have global coverage, and they are open source. While the EUDR country assessment criteria guided the design of the RIV, the analytical framework can be adapted to enforcement or due diligence in other regional contexts, or to certification systems.

4.6 Policy, practice, and business implications

For regional development and business support actors, Article I identifies clear barriers that hinder forest-based SMEs from fully realising their potential. Tailored RTDDI support, stronger facilitation of university–industry outreach and collaboration, development of targeted skills, and more accessible innovation funding may be required to achieve this. This conclusion is consistent with the findings of Article II, where science–practice and public–private partnerships are needed to further develop and implement the wood ID methods.

For improved law enforcement and due diligence, Article II highlights the need for increased investment in reference datasets, interoperable databases, and capacity-building for wood ID. The RIV framework in combination with trade data (as in Article III) offers a practical tool to highlight commodity-embedded risk as well as overall risk related to country or regional imports. The tool can support prioritisation of customs controls and facilitate identification of needs for priority cooperation with higher-risk producing countries.

For economic operators, the findings show that the application of wood ID methods (Article II) as well as proactive supply-chain risk assessment (Article III) can provide substantial support for the assurance of legality and deforestation-free commitments. Operators can use the RIV to understand inherent risk exposures in their value chains and adjust their due diligence intensity or risk management accordingly.

4.7 Limitations of the research

Several limitations need to be acknowledged for each study. Article I is based on a voluntary company survey. The response rate was good, and the data were linked reliably to company register-based economic information. However, the relatively small number of companies

per sector precludes the ability to draw definitive comparative conclusions within or between sectors, although the observations provide a basis for future hypothesis testing with larger sample sizes. Respondent self-selection may have inclined firms at a certain stage of development to participate more than other firms, introducing nonresponse bias (Scheaf et al. 2023).

Article II relied on a purposive expert sample that did not provide equal representation of all market segments or geographic regions, despite global outreach. The uneven distribution of respondents may also over-represent organisations that were already aware of or engaged with wood ID technologies.

While FAOSTAT offers the benefit of a global database with continuously updated and harmonised assessments, the RIV calculation in Article III is constrained by overall data quality and temporal resolution. The annual changes in forest area and agricultural expansion rely on 5-year interpolated statistics. In some cases, political incentives may lead to a distortion of data reported by a country (Desiere et al. 2016). While problems with FRA data have been widely reported, the quality of forest monitoring data sources for national reporting to the FRA has improved significantly for the assessments covering the period 2005–2020 (De Sy et al. 2021). The RIV simplifies complex legal and deforestation dynamics into a set of aggregated indicators, and it is not a substitute for on-the-ground due diligence. The aim was to develop a tool as neutrally as possible. As Bowker and Star (1999) observed, however, standards and classifications can produce both winners and losers, and their development calls for moral reflection and caution regarding the consequences of applying them in practice.

4.8 Suggestions for further research

Research on bioeconomy innovation (Article I) could be expanded to examine the structural needs for and drivers of innovation and lessons learned at successive stages of innovation. This endeavour could examine movement from one technological readiness level to another, or from one business readiness level to another. This approach could help inform the design of more targeted policy interventions, including the most suitable support for the development of innovations.

Further research on wood ID technologies (Article II) could evaluate potential business models that would increase their uptake. Additional research is also needed to contribute to the development of open-source reference collections.

Incorporation of globally operational, geographically explicit land-use and forest area change datasets would strengthen the robustness of the RIV (Article III). It would be especially useful if the datasets included EUDR commodity-specific information. The integration of deforestation footprint data for EUDR commodities as well as other deforestation-linked commodities could be investigated. Greater attention to the development of forest plantations and plantation productivity may provide more balanced information compared with relying on roundwood production alone as an indicator.

4.9 Conclusions

This thesis has combined research on company innovation approaches, access to tools for legality verification, and wood sourcing risk assessment to advance knowledge and tools in support sustainable development of the forest-based bioeconomy.

While regional forest-based companies are oriented towards innovation and invest heavily in this area, their progress is impeded by structural barriers, including regulatory complexity, financial constraints, and a shortage of skilled labour. Furthermore, companies prefer to rely on in-house resources for R&D rather than engaging in external collaboration. Business development and innovation services could stimulate collaboration between industry and universities, facilitate access to innovation funding, and help to address labour skill gaps.

Although there is high awareness of wood ID technologies, their operational uptake is hindered by technological barriers and limited access to reference data, particularly in countries with weaker governance. Operational integration of wood ID technologies in due diligence processes could help companies comply with legal and deforestation-free requirements.

The intensity of due diligence or enforcement efforts can be moderated based on proactive supply chain risk assessment through quantitative evaluation of commodity- and country-based risk exposure. The level of risk exposure can differ greatly between commodities.

Taken together, this research demonstrates that legal, deforestation-free, and innovative forest-based value chains require progress in bioeconomy innovation management, technologies that facilitate legal verification, and risk-assessment tools. The findings from the three articles provide policymakers, competent authorities, and economic operators with market intelligence and tools to implement, monitor, and enforce legislation that governs the forest-based bioeconomy, contributing to ongoing efforts to strengthen the governance, transparency, sustainability, and resilience of the sector.

REFERENCES

- Bahar NHA, Lo M, Sanjaya M, Van Vianen J, Alexander P, Ickowitz A, Sunderland T (2020) Meeting the food security challenge for nine billion people in 2050: What impact on forests? *Glob Environ Change* 62, article id102056. <https://doi.org/10.1016/j.gloenvcha.2020.102056>
- Barañano L, Unamunzaga O, Garbisu N, Briers S, Orfanidou T, Schmid B, Martínez de Arano I, Araujo A, Garbisu C (2022) Assessment of the Development of Forest-Based Bioeconomy in European Regions. *Sustainability* 14, article id 4747. <https://doi.org/10.3390/su14084747>
- Barraza-Botet C, Nadal D, Rosen M, Winickoff D (2026) A comparison of the innovation and regulatory environments for biotechnology and biosolutions across the European Union and the United States. *OECD Science, Technology and Industry Working Papers* 2026/02. OECD Publishing, Paris. <https://doi.org/10.1787/1ec20342-en>
- Bengtsson M, Alfredsson E, Cohen M, Lorek S, Schroeder P (2018) Transforming systems of consumption and production for achieving the sustainable development goals: moving beyond efficiency. *Sustain Sci* 13: 1533–1547. <https://doi.org/10.1007/s11625-018-0582-1>
- Bennich T, Belyazid S, Kopainsky B, Diemer A (2018) The Bio-Based Economy: Dynamics Governing Transition Pathways in the Swedish Forestry Sector. *Sustainability* 10, article id 976. <https://doi.org/10.3390/SU10040976>
- Borgström S, Mauerhofer V (2016) Developing law for the bioeconomy. *J Energy Nat Resour Law* 34: 373–406. <https://doi.org/10.1080/02646811.2016.1200349>
- Bowker GC, Star SL (1999) Sorting things out: Classification and its consequences. The MIT Press. <https://doi.org/10.7551/mitpress/6352.001.0001>
- Brege S, Nord T, Sjöström R, Stehn L (2010) Value-added strategies and forward integration in the Swedish sawmill industry: positioning and profitability in the high-volume segment. *Scand J For Res* 25: 482–493. <https://doi.org/10.1080/02827581.2010.496738>
- Brenton-Rule EC, Barbieri RF, Lester PJ (2016) Corruption, development and governance indicators predict invasive species risk from trade. *Proc R Soc B: Biol Sci* 283, article id 20160901. <https://doi.org/10.1098/rspb.2016.0901>
- Briers S, Ackermann A, Linser S, Zivojinovic I, de Arano IM, Klapper J, Amato M, Osés MA, Orbe LB, Boscaleri F, Koivula S, Rinn R, Versyck J, Wallius V, Wieland S (2024) Shaping the bioeconomy: Public and private sector perceptions across European regions. *Curr Res Environ Sustain* 8, article id 100264. <https://doi.org/10.1016/j.crsust.2024.100264>

- Bruch C, Schang S, Pendergrass J, Fulton S, Moraga-Lewy N, Wright M, Swanson G (2019) Environmental rule of law - First global report. United Nations Environment Programme. ISBN 978-92-807-3742-4.
- Bösch M (2021) Institutional quality, economic development and illegal logging: a quantitative cross-national analysis. *Eur J For Res* 140: 1049–1064. <https://doi.org/10.1007/s10342-021-01382-z>
- Chen S, Woodcock C, Dong L, Tarrio K, Mohammadi D, Olofsson P (2024) Review of drivers of forest degradation and deforestation in Southeast Asia. *Remote Sens Appl Soc Environ* 33, article id 101129. <https://doi.org/10.1016/j.rsase.2023.101129>
- Colchester M, Boscolo M, Contreras Hermosilla A, Del Gatto F, Dempsey J, Lescuyer G, Obidzinski K, Pommier, D, Richards M, Sulaiman N. Sembiring SN, Tacconi L, Vargas Rios MT, Wells A (2006) Justice in the forest: Rural livelihoods and forest law enforcement. *Forest Perspectives* 3. Center for International Forestry Research (CIFOR), Bogor, Indonesia. ISBN 979-24-4618-4
- Contreras-Hermosilla A (2002) Law compliance in the forestry sector - an overview. World Bank Institute Working Papers, World Bank, Washington DC.
- D'Adamo I, Falcone PM, Imbert E, Morone P (2022) Exploring regional transitions to the bioeconomy using a socio-economic indicator: the case of Italy. *Econ Politica* 39: 989–1021. <https://doi.org/10.1007/s40888-020-00206-4>
- Desiere S, Staelens L, D'haese M (2016) When the Data Source Writes the Conclusion: Evaluating Agricultural Policies. *J Dev Stud* 52: 1372–1387. <https://doi.org/10.1080/00220388.2016.1146703>
- De Sy V, Nesha MK, Herold M, Garzuglia M, Pekkarinen A, Jonsson O, Duchelle AE, Branthomme A, Martius C (2021) An assessment of data sources, data quality and changes in national forest monitoring capacities in the Global Forest Resources Assessment 2005–2020. *Environ Res Lett* 16, article id 54029. <https://doi.org/10.1088/1748-9326/abd81b>
- Dieter M, Englert H, Weimar H (2012) Wood from illegal harvesting in EU markets: estimations and open issues. *Landbauforsch, Appl Agric Forestry Res* 4: 247–254.
- Dlamini C, Montouroy Y (2017) Governing Sustainable Forest Management Issues in Polycentric Governance: The EU FLEGT Action Plan as a Regulatory Catalyser. *Environ Law Rev* 19: 6–29. <https://doi.org/10.1177/1461452917691863>
- EFI (2024) Forest Products Trade Flow Database. European Forest Institute, Joensuu.
- European Investment Bank (2022) Forests at the heart of sustainable development - Investing in forests to meet biodiversity and climate goals. European Investment Bank, Luxembourg. <https://doi.org/10.2867/160826>

European Investment Bank (2024) Investment barriers in the European Union 2023: a report by the European Investment Bank Group. European Investment Bank. <https://doi.org/10.2867/45894>

European Commission (2018) A sustainable Bioeconomy for Europe: Strengthening the connection between economy, society and the environment. Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions. Brussels, 11.10.2018. COM(2018) 673 final.

European Commission (2023) Support contract for the establishment of a benchmarking system according to Article 29 of the Regulation on deforestation-free supply chains. Official Journal of the European Union, S 239 (December 12, 2023). Notice No. 751885-2023. <https://ted.europa.eu/en/notice/-/detail/751885-2023>

European Commission (2025a) A Strategic Framework for a Competitive and Sustainable EU Bioeconomy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Strategic Framework for a Competitive and Sustainable EU Bioeconomy. COM/2025/960 final. Eur-Lex: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52025DC0960>

European Commission (2025b) Commission staff working document on the methodology used for the benchmarking system. Accompanying the document Commission Implementing Regulation (EU) .../... of 22.5.2025 laying down rules for the application of Regulation (EU) 2023/1115 of the European Parliament and of the Council as regards a list of countries that present a low or high risk of producing relevant commodities for which the relevant products do not comply with Article 3, point (a). SWD(2025) 129 final.

European Union (2010) Regulation (EU) 995/2010 of the European Parliament and of the Council of 20 October 2010 laying down the obligations of operators who place timber and timber products on the market. Official Journal of the European Union, L 295, 12.11.2010, pp. 23–34. <http://data.europa.eu/eli/reg/2010/995/oj>

European Union (2023) Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010. PE/82/2022/REV/1. OJ L 150, 9.6.2023, pp. 206–247. <http://data.europa.eu/eli/reg/2023/1115/oj>

European Union (2024) Regulation (EU) 2024/3234 of the European Parliament and of the Council of 19 December 2024 amending Regulation (EU) 2023/1115 as regards provisions relating to the date of application. <http://data.europa.eu/eli/reg/2024/3234/oj>

Ferras-Hernandez X, Nylund PA (2019) Clusters as Innovation Engines: The Accelerating Strengths of Proximity. Eur Manag Rev 16: 37–53. <https://doi.org/10.1111/emre.12330>

- Food and Agriculture Organization of the United Nations (FAO) (2018) State of the World's Forests 2018 - Forest pathways to sustainable development. Food and Agriculture Organization of the United Nations, Rome, Italy. <https://openknowledge.fao.org/handle/20.500.14283/i9535en>
- Food and Agriculture Organization of the United Nations (FAO) (2020) Global Forest Resources Assessment 2020 (FRA 2020): Main report. Food and Agriculture Organization of the United Nations, Rome, Italy. <https://doi.org/10.4060/ca9825en>
- Food and Agriculture Organization of the United Nations (FAO) (2024) FAOSTAT – Food and agriculture data. Accessed during September–November 2024. <https://www.fao.org/faostat/en>
- Finnish Government (2022) The Finnish Bioeconomy Strategy - Sustainably towards higher value added. Finnish Government, Helsinki, Finland. <http://urn.fi/URN:ISBN:978-952-383-579-5>
- Fonecta Oy (2021) Henkilöt ja yritykset yhdestä hausta. [People and companies in one search]. <https://www.fonecta.fi/haku/yrityshaku/>. Accessed 3 October 2023.
- Guan Z, Kwee Fat Ip Ping Sheong J (2019) The Restricting Effects of Forest Certification on the International Trade of Wood Products. *J Sustain For* 38: 809–826. <https://doi.org/10.1080/10549811.2019.1607756>
- Haag V, Olbrich A, Heinz I, Helmling S, Sieburg-Rockel J, Koch G (2020) Identification of internationally traded timber at the Thünen Centre of Competence on the Origin of Timber. Presentation at the GTTN Futures Webinar on 17 September 2020 (invitation-only online event).
- Hassegawa M, Van Brusselen J, Cramm M, Verkerk PJ (2022a) Wood-Based Products in the Circular Bioeconomy: Status and Opportunities towards Environmental Sustainability. *Land* 11, article id 2131. <https://doi.org/10.3390/land11122131>
- Hassegawa M, Karlberg A, Hertzberg M, Verkerk PJ (2022b) Innovative forest products in the circular bioeconomy. *Open Res Eur* 2, article id 19. <https://doi.org/10.12688/openreseurope.14413.2>
- Hermwille L (2016) Climate change as a transformation challenge : a new climate policy paradigm? *Gaia* 25: 19–22. <https://doi.org/10.14512/gaia.25.1.6>
- Hetemäki L, Hurmekoski E (2020) Forest Bioeconomy Development: Markets and Industry Structures. In: Nikolakis W, Innes JL (eds) *The Wicked Problem of Forest Policy - A Multidisciplinary Approach to Sustainability in Forest Landscapes*. Cambridge University Press, Cambridge, pp 231–258.
- Hetemäki L, D'Amato D, Giurca A, Hurmekoski E (2024) Synergies and trade-offs in the European forest bioeconomy research: State of the art and the way forward. *For Policy Econ* 163, article id 103204. <https://doi.org/10.1016/j.forpol.2024.103204>

- Hoare A, Kanashiro Uehara TH (2022) Establishing fair and sustainable forest economies. Lessons learned from tackling illegal logging. Research Paper. Chatham House, the Royal Institute of International Affairs, London. <https://doi.org/10.55317/9781784135386>
- Hyttiä A (2022) Sustainable Development—International Framework—Overview and Analysis in the Context of Forests and Forest Products—Competitiveness and Policy. For Prod J 72: 1–4. <https://doi.org/10.13073/FPJ-D-20-00053>
- Interpol (2019) Global Forestry Enforcement. Strengthening Law Enforcement Cooperation Against Forestry Crime. Interpol, Lyon. <https://www.interpol.int/content/download/5149/file/Global%20Forestry%20Enforcement%20Prospectus%202019-web.pdf>. Accessed 15 June 2023.
- Jayathilake HM, Prescott GW, Carrasco LR, Rao M, Symes WS (2020) Drivers of deforestation and degradation for 28 tropical conservation landscapes. *Ambio* 50: 215–228. <https://doi.org/10.1007/s13280-020-01325-9>
- Kallio MAI, Schier F (2021) Editorial for the special issue “Towards the bioeconomy: The role of traditional and emerging products and supporting actions”. For Policy Econ 131, article id 102573. <https://doi.org/10.1016/j.forpol.2021.102573>.
- Karsenty A, Dieterle G (2020) “Wood Security”: The importance of incentives and economic valorisation in conserving and expanding forests. *Int For Rev* 22: 81–92. <https://doi.org/10.1505/146554820829523916>
- Kaufmann D, Kraay A (2023) Worldwide Governance Indicators, 2023 Update. <https://www.govindicators.org>. Accessed 26 June 2024.
- Kauppalähti (2024) Yrityshaku. [Company search]. <https://www.kauppalähti.fi/yritykset/>. Accessed 6 June 2024.
- Kleinschmit D, Mansourian S, Wildburger C, Purret A (eds) (2016) Illegal Logging and Related Timber Trade – Dimensions, Drivers, Impacts and Responses. A Global Scientific Rapid Response Assessment Report, IUFRO World Series. IUFRO, Vienna, Austria.
- KLRI (Korea Legislation Research Institute) (2017) Act on the sustainable use of timbers. Act No. 14657, of March 21, 2017. Statutes of the Republic of Korea. <https://klri.re.kr/>. Accessed 21 June 2023.
- Kogler C, Schimpfhuber S, Eichberger C, Rauch P (2021) Benchmarking Procurement Cost Saving Strategies for Wood Supply Chains. *Forests* 12, article id 1086. <https://doi.org/10.3390/f12081086>
- Konstantinavičienė J (2023) Assessment of Potential of Forest Wood Biomass in Terms of Sustainable Development. *Sustainability* 15, article id 13871. <https://doi.org/10.3390/su151813871>

- Kuhmonen I, Näyhä A, Solaranta M, Keränen J (2024) Can small and medium-sized companies increase the value added from wood-based side streams? *Silva Fenn.* 58 article id 23080. <https://doi.org/10.14214/sf.23080>
- Köthke M (2020) Implementation of the European Timber Regulation by German importing operators: An empirical investigation. *For Policy Econ* 111, article id 102028. <https://doi.org/10.1016/j.forpol.2019.102028>
- Köthke M, Lippe M, Elsasser P (2023) Comparing the former EUTR and upcoming EUDR: Some implications for private sector and authorities. *For Policy Econ* 157, article id 103079. <https://doi.org/10.1016/j.forpol.2023.103079>
- Lin JC, Lee JY, Liu, WY (2021) Risk Analysis of Regions with Suspicious Illegal Logging and Their Trade Flows. *Sustainability* 13, article id 3549. <https://doi.org/10.3390/su13063549>
- Lindner M, Suominen T (2017) Towards a sustainable bioeconomy. *Scand J For Res* 32: 549–550. <https://doi.org/10.1080/02827581.2017.1357329>
- Low MC, Schmitz N, Boeschoten LE, Cabezas JA, Cramm M, Haag V, Koch G, Meyer-Sand BRV, Paredes-Villanueva K, Price E, Thornhill AH, Van Brusselen J, Zuidema PA, Deklerck V, Dormontt EE, Shapcott A, Lowe AJ (2023) Tracing the world's timber: the status of scientific verification technologies for species and origin identification. *IAWA J* 44: 63–84. <https://doi.org/10.1163/22941932-bja10097>
- Lowe AJ, Dormontt EE, Bowie MJ, Degen B, Gardner S, Thomas D, Clarke C, Rimbawanto A, Wiedenhoeft A, Yin Y, Sasaki N (2016) Opportunities for improved transparency in the timber trade through scientific verification. *Bioscience* 66: 990–998. <https://doi.org/10.1093/biosci/biw129>
- Mosley F, Van Brusselen J (2023) Mapping Finland's regional forest bioeconomy plans. *Scand J For Res* 39: 20–29. <https://doi.org/10.1080/02827581.2023.2282087>
- Mukpo A (2020) China's revised forest law could boost efforts to fight illegal logging. Article on 19 March 2020. <https://news.mongabay.com/>. Accessed 21 June 2023.
- Norman M, Saunders J, Canby K (2017) National Governance Indicators, Relevance for the Regulation of the Trade in Illegal Timber. *Forest Trends, Information Brief*.
- Näyhä A (2020) Finnish forest-based companies in transition to the circular bioeconomy - drivers, organizational resources and innovations. *For Pol Econ* 110, article id 101936. <https://doi.org/10.1016/j.forpol.2019.05.022>
- Nørstebø V, Krøgli SO, Debella-Gilo M, Perez-Valdes GA, Uggen KT, Dramstad WE (2020) Identifying Suitable Bioeconomic Cluster Sites—Combining GIS-MCDA and Operational Research Methods. *Environ Model Assess* 25: 689–703. <https://doi.org/10.1007/s10666-020-09694-x>

- OECD/Eurostat (2018) Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation, 4th Edition, The Measurement of Scientific, Technological and Innovation Activities, OECD Publishing, Paris/Eurostat, Luxembourg. <https://doi.org/10.1787/9789264304604-en>
- Pelli P, Haapala A, Pykäläinen J (2017) Services in the forest-based bioeconomy - analysis of European strategies. *Scand J For Res* 32: 559–567. <https://doi.org/10.1080/02827581.2017.1288826>
- Pender A, Kelleher L, O'Neill E (2023) Regulation of the Bioeconomy: Barriers, drivers and potential for innovation in the case of Ireland. *Clean Circ Bioeconomy* 7, article id 100070. <https://doi.org/10.1016/j.clcb.2023.100070>
- Pendrill F, Persson UM, Godar J, Kastner T (2019) Deforestation displaced: trade in forest-risk commodities and the prospects for a global forest transition. *Environ Res Lett* 14, article id 055003. <https://doi.org/10.1088/1748-9326/ab0d41>
- Pendrill F, Gardner TA, Meyfroidt P, Persson UM, Adams J, Azevedo T, Bastos Lima AG, Baumann M, Curtis PG, De Sy V, Garrett R, Godar J, Dow Goldman E, Hansen MC, Heilmayr R, Herold M, Kuemmerle T, Lathuillière MJ, Ribeiro V, Tyukavina A, Weisse MJ, West C (2022) Disentangling the numbers behind agriculture-driven tropical deforestation. *Science* 377, article id eabm9267. <https://doi.org/10.1126/science.abm9267>
- Piabuo SM, Minang PA, Tieguhong CJ, Foundjem-Tita D, Nghobuoche F (2021) Illegal logging, governance effectiveness and carbon dioxide emission in the timber-producing countries of Congo Basin and Asia. *Environ Dev Sustain* 23: 14176–14196. <https://doi.org/10.1007/s10668-021-01257-8>
- Purdy R (2010) Using Earth Observation Technologies for Better Regulatory Compliance and Enforcement of Environmental Laws. *J Environ Law* 22: 59–87. <https://doi.org/10.1093/jel/eqp027>
- Reim W, Parida V, Sjödin DR (2019) Circular Business Models for the Bio-Economy: A Review and New Directions for Future Research. *Sustainability* 11, article id 2558. <https://doi.org/10.3390/su11092558>
- Richardson K, Steffen W, Lucht W, Bendtsen J, Cornell SE, Donges JF, Drüke M, Fetzer I, Bala G, von Bloh W, Feulner G, Fiedler S, Gerten D, Gleeson T, Hofmann M, Huiskamp W, Kummu M, Mohan C, Nogués-Bravo D, Petri S, Porkka M, Rahmstorf S, Schaphoff S, Thonicke K, Tobian A, Virkki V, Wang-Erlandsson L, Weber L, Rockström J (2023) Earth beyond six of nine planetary boundaries. *Sci Adv* 9, article id eadh2458. <https://doi.org/10.1126/sciadv.adh2458>
- Salvador R, Barros MV, Donner M, Brito P, Halog AB, de Francisco AC (2022) How to advance regional circular bioeconomy systems? Identifying barriers, challenges, drivers,

and opportunities. *Sust Prod Consumpt* 32: 248–269.
<https://doi.org/10.1016/j.spc.2022.04.025>

Scheaf DJ, Loignon AC, Webb JW, Heggstad ED (2023) Nonresponse bias in survey-based entrepreneurship research: A review, investigation, and recommendations. *Strateg Entrep J* 17: 291–321. <https://doi.org/10.1002/sej.1453>

Schmitz N (ed), Beeckman H, Blanc-Jolivet C, Boeschoten L, Braga JWB, Cabezas JA, Chaix G, Crameri S, Degen B, Deklerck V, Dormontt E, Espinoza E, Gasson P, Haag V, Helmling S, Horacek M, Koch G, Lancaster C, Lens F, Lowe A, Martínez-Jarquín S, Nowakowska JA, Olbrich A, Paredes-Villanueva K, Pastore TCM, Ramanantoandro T, Razafimahatratra AR, Ravindran P, Rees G, Soares LF, Tysklind N, Vlam M, Watkinson C, Wheeler E, Winkler R, Wiedenhoeft AC, Zemke VTh, Zuidema PO (2020) Overview of current practices in data analysis for wood identification. A guide for the different timber tracking methods. Global Timber Tracking Network, GTTN secretariat, European Forest Institute and Thünen Institute.

Sedano F, Lisboa S, Duncanson L, Ribeiro N, Siteo A, Sahajpal R, Hurtt G, Tucker C (2020) Monitoring intra and inter annual dynamics of forest degradation from charcoal production in Southern Africa with Sentinel – 2 imagery. *Int J Appl Earth Obs Geoinf* 92, article id 102184. <https://doi.org/10.1016/j.jag.2020.102184>

Sotirov M, Köthke M (2024) How and why do economic operators comply with EU Law? Analysis of firm-level responses to the EU Timber Regulation in Germany. *J Common Mark Stud* 62: 1594–1614. <https://doi.org/10.1111/jcms.13585>

Tegegne YT, Van Brusselen J, Tuomasjukka D, Lindner M (2014) Proposing an indicator framework for FLEGT voluntary partnership agreements impact monitoring. *Ecol Indic* 46: 487–494. <https://doi.org/10.1016/j.ecolind.2014.07.020>

The Fund for Peace (2022) Fragile States index. <https://fragilestatesindex.org/>. Accessed 15 July 2023.

Transparency International (2022) Corruption Perceptions Index. <https://www.transparency.org/cpi2019>. Accessed 15 July 2023.

Turkina, E, Van Assche A (2018) Global connectedness and local innovation in industrial clusters. *J Int Bus Stud* 49: 706–728. <https://doi.org/10.1057/s41267-018-0153-9>

United Nations Development Programme (UNDP) (2020) Human Development Report 2020. Chapter 2: Unprecedented - the scope, scale and speed of human pressures on the planet. <https://doi.org/10.18356/9789210055161c005>

United Nations Economic Commission for Europe (UNECE) (2025) Forecast of the Committee on Forests and the Forest Industry: Forest Products Production and Trade 2024-2025. United Nations Economic Commission for Europe, Geneva. <https://doi.org/10.18356/9789211067866>

- Van Brusselen J, de P. Pires R (2019) Forest Products Trade Risk of Trade in HS4407 by EU28 for the Years 2012 to 2016, Based on Validated UN COMTRADE Data and Forest Trends Governance indicator Assessment of 2017. European Forest Institute.
- Verkasalo E, Leppälä J, Muhonen T, Korpinen RI, Möttönen V, Kurppa S (2019) Novel industrial ecosystems and value chains to utilize side-streams of wood products industries – Finnish approach. *Pro Ligno* 15: 157–165.
- Verkerk PJ, Hasegawa M, Van Brusselen J, Cramm M, Chen X, Maximo YI, Koç M, Lovrić M, Tegegne YT (2022) The role of forest products in the global bioeconomy – Enabling substitution by wood-based products and contributing to the Sustainable Development Goals. Rome, FAO. <https://doi.org/10.4060/cb7274en>
- West C, Rabeschini G, Singh C, Kastner T, Bastos Lima M, Dermawan A, Croft S, Persson UM (2025) The global deforestation footprint of agriculture and forestry. *Nat Rev Earth Environ* 6: 325–341. <https://doi.org/10.1038/s43017-025-00660-3>
- Wiedenhoef AC, Simeone J, Smith A, Parker-Forney M, Soares R, Fishman A (2019) Fraud and misrepresentation in retail forest products exceeds U.S. forensic wood science capacity. *PLoS ONE* 14, article id e0219917. <https://doi.org/10.1371/journal.pone.0219917>
- World Justice Project (2022) WJP Global Rule of Law Index. <https://www.worldjusticeproject.org/rule-of-law-index/>. Accessed 15 July 2023.