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Challenges for circular bioeconomy in forestry: Analysis of socio-economic impacts of global change on the forestry sector

Ph.D. Thesis

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Prague

2024

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Forestry and Wood Sciences

Ph.D. THESIS ASSIGNMENT

Ing. Michaela Perunová

Global Change Forestry

Thesis title

Challenges for circular bioeconomy in forestry: Analysis of socio-economic impacts of global change on the forestry sector.

Objectives of thesis

The main aim of the dissertation thesis is to carry out analysis and evaluation of socio-economic impacts of global change on the forestry sector. Currently, it is a significant issue because we live in a world with limited resources, and forests represent an important source not only for the economy but also for society needs. The world's forests influence climate through physical, chemical, and biological processes that affect planetary energetics, the hydrologic cycle, and atmospheric composition. Therefore, the dissertation focuses on solutions in the circular bioeconomy as an important direction with great potential for the future. The main findings are being developed as a case study in the Czech Republic.

Methodology

Both the qualitative and quantitative methods will be used for the research. In the first year of the study, a detailed literature review and desk research will be carried out. Simultaneously, the methodology used will be specified in more detail. The statistical analysis will be based on regression analysis and input-output (I-O) analysis and a suitable model will be chosen to monitor the socio-economic impact. The relationship will expressed in the form of an equation or a model connecting the response or dependent variable and one or more explanatory or predictor variables. Advanced analysis and evaluation will be carried out and final model will be prepared.

Milestones:

1) academic year 2020/2021 – data collection, presentation of the first results

2) academic year 2021/2022 – data collection and the first analyzes, presentation of the results, publishing an article

3) academic year 2022/2023 – data collection, presentation of the results, publishing an article, continuation of the analysis

4) academic year 2023/2024 – final analysis and completion of the doctoral thesis.

The proposed extent of the thesis

At least 80 standard pages.

Keywords

Circular economy; forest bioeconomy; renevable resources; social impact; economic impact; adaptation measures; carbon sequestration

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Recommended information sources

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Expected date
2023/24 SS – FFWS – Doctoral Thesis Defense

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Prague on 08. 04. 2024

Declaration

I declare that this dissertation thesis Challenges for circular bioeconomy in forestry: Analysis of socio-economic impacts of global change on the forestry sector was composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where states otherwise by reference or acknowledgment, the work presented is entirely my own.

I agree to the publication of the thesis according to Act No. 111/1998 Coll. on universities as amended, regardless of the outcome of its defense.

Prague, 2024 Ing. Michaela Perunová

Acknowledgments

I would like to express my sincere gratitude to my supervisor assoc. prof. Jarmila Zimmermannová for the continuous support of my doctoral study and related research. I am sincerely grateful for her guidance, patience, motivation, and immense knowledge.

I would like to sincerely thank my close family, especially my parents, sister, and grandparents for their incredible support and trust in me during my entire doctoral study.

Abstract

The main aim of the dissertation thesis is to carry out the evaluation of the socio-economic impacts of global change on the forestry sector. To accomplish the key purpose, both the qualitative and quantitative methods were applied to the research and the following methods were utilized, namely literature review, desk research, data collection, time series analysis, comparative analysis, spatial data analysis, cartogram and cartodiagram method, and correlation and regression analysis. The objective of the dissertation thesis was achieved through three original research papers published in scientific journals with impact factors. The studies were consistent with the dissertation theme and focused on various aspects of socio-economic impacts of global change on the bioeconomy, including the forestry sector. The first study aimed to evaluate the development of the bioeconomy labour market in the Czech Republic. The second study focused on the explanation of the impacts of economic and financial instruments of the climate change policy on the development of the forest bioeconomy in the Czech Republic. The third study dealt with regional divergences and the impacts of financial support on the development of the forest bioeconomy in the Czech Republic. The dissertation thesis highlighted the priority of developing the social and economic aspects of the bioeconomy. The findings of the dissertation thesis can contribute to the development of national and regional bioeconomy strategies, economic and financial priorities, and the achievement of the European Green Deal vision. The results carry wider implications of the socio-economic impacts of global change on the bioeconomy, including the forestry sector, and the framing of further research agendas for the Czech Republic. The dissertation thesis and doctoral study completed the picture of the circular bioeconomy in the Czech Republic.

Keywords: forest bioeconomy; circular economy; renewable resources; social impacts; economic impacts; carbon sequestration, Czech Republic

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1 Introduction

The global challenges confronting humanity at present encompass climate change, the rapid depletion of natural resources, the degradation of ecosystems, and the significant loss of biodiversity that co-exist with the growth of urbanization and human population (IPCC, 2023). Overcoming these circumstances, it is essential to identify novel models for the production and consumption of commodities respectful of the planet's scarce resources (European Commission, 2022). As global demand for food, feed, biomaterials, and bioenergy resources continues to rise, there is an increasing likelihood of pressure on natural resources and conflicts between supply and demand.

In response to the challenges posed by this situation, modified economic models, which include the circular economy and bioeconomy, are expected to facilitate a shift towards a more sustainable future (Mougenot and Doussoulin, 2022). It is also important to emphasize the concept of green economy, bio-based economy, or Sustainable Development Goals, which are closely related to the concept of circular bioeconomy. All these initiatives have a shared vision to ensure the sustainable development of society and the well-being of current and future generations (European Commission, 2019a). Furthermore, it is the bioeconomy that has links to the concepts mentioned earlier and is considered to be an area with the potential to achieve the set of global challenges (Lier et al., 2018; Loiseau et al., 2016). Currently, the global challenge is to unlock the potential of the bioeconomy, not just in the forestry sector (Nabuurs et al., 2017).

Forests are generally accepted as a multifunctional natural resource and its economic, ecological and social importance lies in a wide range of market and non-market services (Merlo and Croitoru, 2005). Forests represent important objects of public interest and apart from timber provide many other ecosystem services (Wen et al., 2019; Putra et al., 2018; Antonelli et al. 2021). However, the forests have been significantly altered by human land use, and nowadays sustainable management should contribute to the adaptation and mitigation on climate change and provide environmental and social benefits (Harris et al., 2021; Kim et al., 2017). In the Czech Republic, forests and forestry sector face unprecedented challenges, such as climate change and the consequences of the bark beetle calamity that require a holistic approach and coordinated actions (Hlásny et al., 2021).

2 Objective

The main aim of the dissertation thesis was to carry out the evaluation of the socio-economic impacts of global change on the forestry sector in the Czech Republic.

Firstly, employment can be considered the leading social identifier of the bioeconomy. A trend of bioeconomy employment and forestry employment within the bioeconomy labour market was explored, and the evaluation of forestry employment drivers was examined.

Secondly, financial support can be identified as a crucial economic factor of the bioeconomy. The impacts of economic and financial instruments on the development of the forestry sector were examined.

Concerning the principal aim of the research, the following hypotheses were defined:

Null hypothesis ($1H_0$): There is no statistically significant relationship between economic growth and forestry employment in the Czech Republic.

Alternative hypothesis ($1H_A$): There is a statistically significant relationship between economic growth and forestry employment in the Czech Republic, with economic growth impacting either positively or negatively on forestry employment.

Null hypothesis ($2H_0$): There is no statistically significant relationship between economic and financial instruments and the development of the forestry sector in the Czech Republic.

Alternative hypothesis ($2H_A$): There is a statistically significant relationship between economic and financial instruments and the development of the forestry sector in the Czech Republic, with economic and financial instruments impacting either positively or negatively on the development of the forestry sector.

Null hypothesis ($3H_0$): There is no statistically significant relationship between national financial support and forest carbon in the Czech Republic.

Alternative hypothesis ($3H_A$): There is a statistically significant relationship between national financial support for the forestry sector and forest carbon in the Czech Republic, with national financial support for the forestry sector impacting either positively or negatively on forest carbon.

3 Literature review

Bioeconomy

A bioeconomy driven by biological inputs carries the potential to mitigate the consequences of climate change and enhance food and energy security while improving the well-being of humankind (Mougenot and Doussoulin, 2022). The European Union gives the following definition (European Commission, 2018) of the bioeconomy: *“The bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms, and derived biomass, including organic waste), their functions and principles. It includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources; and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy, and services.”*

Broadly, a coherent definition of the bioeconomy is still absent. Several characterizations were formulated in the field of differing stakeholders, resources, or geographical locations (Ellen MacArthur Foundation, 2013; Loiseau, et. al., 2016; D´Amato, et. al., 2017; Bracco, et. al., 2018; Ramcilovic-Souminen, 2018; Birner, 2018; Carus, et. al., 2018; Kardung, et. al., 2019; Mittra, 2020). Alongside the European meaning, countless definitions both at global and national levels were developed.

For example, bioeconomy definitions were created by the OECD (2009), the Food and Agriculture Organization of the United Nations (2021), the White House (2012), and the Global Bioeconomy Summit (2018). At the national level, there is a bioeconomy definition builded by the government of Italy (CNBBSV, 2019), Ireland (Department of Communication, Climate Action & Environment and the Department of Agriculture, Food and the Marine, 2019), France (Ministère de l'Agriculture et de l'Alimentation, 2021), Spain (Ministerio de Economia y Competitividad, 2021), Germany (BMBF and BMEL, 2020), Argentina (Ministerio de Ciencia, Tecnología e Innovación Productiva, 2012), and Malaysia (Bioeconomy Corporation, 2021).

Barañano and his team (Barañano, 2021) introduced the modified bioeconomy definition: *„The sustainable production and conversion of renewable biological resources and generated wastes into products and services, which fervently embraces ethics and circularity to simultaneously promote human well-being and nature conservation”.*

In detail, the European definition of the bioeconomy was launched in the first bioeconomy strategy in 2012 (European Commission, 2012) and later in the updated bioeconomy strategy in 2018 (European Commission, 2018). The revision established three principal lines of intervention to unlock the potential of the bioeconomy, namely:

- strengthen and scale up the bio-based sectors, investments, and markets,
- deploy local bioeconomies across Europe,
- understand the ecological boundaries of the bioeconomy.

Firstly, renewable resources, bio-based value chains and innovation, green public procurement, the environmental footprint of products, plastic-free oceans, and a thematic investment platform for a circular bioeconomy are covered. In the second area, can be observed a Strategic Deployment Agenda that supports a blue bioeconomy, rural areas, carbon farming, and education. The last domain concerns the establishment of a monitoring system to ensure comprehensive knowledge, data, and information on the European bioeconomy sectors.

Policymakers worldwide are striving to develop unique bioeconomy strategies that seem necessary to deliver economic, environmental, and social sustainability. On a national scale, bioeconomy strategies were discovered, specifically in Italy (CNBBSV, 2019), Spain (Ministerio de Economia y Competitividad, 2021), Finland (Luoma et al., 2011), Germany (BMBF and BMEL, 2020), and others.

The Czech Republic, likewise to Central and Eastern European countries, lacks a specific bioeconomy strategy at the national level. On the other hand, bioeconomy is incorporated in the first strategic plan for circular economy so-called Circular Czech Republic 2040, specifically in domain 3 - bioeconomy and food (Ministry of Environment, 2021). Besides, various policy materials covering the bioeconomy are available, such as the Strategic Framework of the Czech Republic 2030 (Ministry of the Environment of the Czech Republic, 2021), the Strategy of the Department of the Ministry of Agriculture of the Czech Republic with an Outlook up to 2030 (eAgri, 2023), Research and Innovation Strategy for the Smart Specialization of the Czech Republic (Ministerstvo průmyslu a obchodu, 2022), and The Czech Republic's Innovation Strategy for 2019–2030 (Úřad vlády, Rada pro výzkum, vývoj a inovace, 2019). To sum up, policy interventions should be geared towards the reduction of environmental pressures along the entire value chain and provide bioeconomy strategies (European Environment Agency, 2018).

Although the Czech Republic has no official national bioeconomy strategy, several initiatives aimed at supporting the progress of the bioeconomy can be observed. At the macroregional level, the Central-Eastern European initiative for bio-based agriculture, aquaculture, and forestry. The BIOEAST (2024) activities target (1) the establishment of a national circular economy and bioeconomy strategies, (2) creation of the value-added jobs, notably in rural areas, (3) the circular usage of biomass, and (4) evidence base support. At the national level, the Bioeconomy platform of the Czech Republic (2024) aims to (1) deepen knowledge related to the bioeconomy via research and education, (2) foster its practical implementation in the private and public sectors, and (3) contribute to sustainable development.

Bioeconomy is primarily rooted in the traditional sectors of the economy, namely (1) agriculture, (2) forestry, (3) aquaculture, and (4) the production of paper and wood-related goods. Nonetheless, innovative sectors are also included, bioenergy, biofuels, biotextiles, and biochemicals while their significance is strengthening over time (Ronzon et al., 2017). The study presented by Ronzon et al. (2015) segregated the national economies of the Member States following:

- agricultural bioeconomies (Romania, Greece, Poland, Slovenia, Ireland, and Croatia),
- agro-food industry and bio-based chemical industries (Netherlands, Belgium, France, Denmark, Germany, Italy, Spain, Luxembourg),
- forest bioeconomies (Finland, Sweden, Latvia, and Estonia),
- non-specialized bioeconomies (Bulgaria, Czech Republic, Hungary, and Slovakia).

Currently, the forest bioeconomy is gaining prominence and is part of a comprehensive set named the Fit for 55, targeting a series of proposed revisions and new initiatives to ensure the achievement of the climate-neutral vision (European Commission, 2021d). In detail, the New EU Forest Strategy (European Commission, 2021c) focuses on the cascading principle of biomass usage, forest restoration, financial support for forest owners and rural areas, and protection of forest ecosystems.

A circular economy, a regime in which waste becomes a source or input for further production while material and energy efficiency are maximized, has a major role in the transition to a low-carbon economy (European Commission, 2022). The circular economy replaces the original, linear economy, which operates on the principle where resources are turned into products, sold, consumed, and after a very short lifespan burned, or landfilled (Yang et al., 2023; Halog and Anieke, 2021). The bioeconomy, as a renewable segment of the circular economy, includes forestry as one of its priorities. Biodiverse and resilient ecosystems underpin a circular bioeconomy that delivers social well-being concerning the ecological boundaries of the ecosystems on which it depends (Palahí et al., 2020). The butterfly diagram, a system diagram of the circular economy, visualizes the flow of materials within the biological and technical cycle (McDonough and Braungart, 2002). In the biological loop, nourishment from biodegradable materials can be reinvested to help recover the environment (Ellen MacArthur Foundation, 2019).

Globally, renewable materials constitute roughly 25% of all material inputs (Circle Economy, 2023). Additionally, end-of-life materials flowing back into the global economy equated to 7.2% of all material inputs in 2023. Regarding the study by Bocken et al. (2016), four essential strategies, such as narrow, slow, regenerate, and cycle can contribute towards a more sustainable economic paradigm. To unlock the potential of the circular economy a holistic approach incorporating the economic, social, and environmental dimensions should be applied (Lozano et al., 2021; Reich et al., 2023).

Social aspects

According to the European Union calculations, the bioeconomy employs around 18 million people and by 2030 up to 2 million new jobs could be created (European Commission, 2018). The high employment numbers in the subsectors of the bioeconomy are the result of natural and geographical conditions (Drejerska, 2017). Drivers of bioeconomy job creation are the forestry, fishing, and wood sectors (Philippidis et al., 2014). Wood logging, the manufacture of wood products, and sectors using the by-product as a feedstock show the potential to boost bioeconomy employment (Jonsson et al., 2021). Comparing material and energy use of biomass, material utilization generates higher employment, mainly due to longer and more complex value chains (Carus, 2012).

Rakowska (2011) displays that tertiary education in the bioeconomy seems to be a crucial element in the development of an innovative and more sustainable society. The overview (Hetemäki et al., 2016) displays a significant need to increase academic research and education according to bioeconomy. The study (Ludvig et al., 2019) highlights the great potential of social innovations in the forest bioeconomy, which can provide economic, educational, and cultural opportunities and support people in rural areas.

The bioeconomy sectors seem to be crucial in the case of employment increment and household income at the national and regional levels (Dammer et al., 2017; Pașnicu et al., 2019; Jurga et al., 2021). To track the progress, several indicators were used, namely (1) the total number of bioeconomy employees and the bioeconomy share in the labour force (Efken et al., 2016; Piotrowski et al., 2019; Ronzon et al., 2020; Capasso and Klitkou, 2020), (2) labour productivity (Ronzon et al., 2017), (3) employment multipliers (Philippidis et al., 2014; Jurga et al., 2021); (4) direct, indirect and induced employment (Rajendran et al., 2016), (5) full-time equivalents (Debergh et al., 2016), and (6) location quotient (Ronzon et al., 2018).

Monitoring of social indicators provides important insight into the size, impact, and evolution of the bioeconomy (Kardung et al., 2019). At the same time, uniform tools, metrics, and indicators that can reliably measure the development and state of the bioeconomy are necessary (Kuosmanen et al., 2020). However, the monitoring indicators are hampered by a lack of statistical data (Parisi et al., 2016). To be able to monitor and measure the bioeconomy, it is essential to define the sectors belonging to the bioeconomy. Based on the NACE classification, there are several studies (Ronzonet al., 2017; Kardung et al., 2019; Efken et al., 2016; Piotrowski et al., 2019) which include various NACE sectors to measure and monitor the development of the social aspect of the bioeconomy.

Regarding studies focusing on the Czech Republic, besides the abovementioned studies (Ronzon et al., 2017; Philippidis et al., 2014; Pașnicu et al., 2019) there is research presented by Purwestri et al. (2020), and Hájek et al. (2020). However, studies lack attention directly to the bioeconomy labour market in the Czech Republic.

To sum up, research findings according to the bioeconomy labour force are constantly developing. However, a very low number of studies focused particularly on the labour market of the forestry sector were observed, especially in the Czech Republic (Sanz-Hernández et al., 2019). A notable knowledge gap exists in the current understanding of the employment potential of the bioeconomy in the Czech Republic.

Economic and financial aspects

Regarding scientific studies, the issue of economic and financial instruments and their impacts on the bioeconomy is not sufficiently analyzed. Studies focused on financial support of the bioeconomy that ensure economic, environmental, and social sustainability can be found (D'Amato et al., 2020). Financial instruments are crucial factors in achieving a climate-neutral economic system in the European Union by 2050 (European Commission, 2019a). Investments in research and innovation can improve European competitiveness and accelerate the transformation of the economy to a green and sustainable pathway (Ritter et al., 2024). At the European level, several economic and financial instruments to support and boost the bioeconomy are provided. Funding opportunities include the research and innovation program Horizon Europe 2021-2027, the European Circular Bioeconomy Fund, the Circular Biobased Europe Joint Undertaking, the European Structural and Investment Fund, and the European Fund for Strategic Investments.

Focused on bioeconomy, Horizon Europe 2021-2027 allocated in pillar 2 – Global challenges and European industrial competitiveness, namely in cluster 6 – Food, bioeconomy, natural resources, agriculture, and environment EUR 52.7 billion (European Commission, 2021b). The main aim of investments in research and innovation concerning food, bioeconomy, natural resources, agriculture, and environment is knowledge development, capacity building, and demonstrating innovative solutions to accelerate the transition to a more sustainable and circular system.

Economic and financial instruments can support also innovations (Lovric et al., 2020), the most frequent types are within the development of production methods, followed by innovations in goods and services. There are few innovation cases in the later stages of development, and more disruptive and complex innovations are usually more successful ones. Regarding the innovations in forestry, we can observe several studies focus on digitized forest management (Klitkou, 2021), wooden skyscrapers (Tollefson, 2017), drivers in forestry (UNECE, 2018), the role of new wood-based products (Hurmekoski, 2018), forest biomass (Bottcher, 2013), and new value chains and climate-smart forestry (Verkerk, et al., 2020). The study (Nayha, 2014) provides insight into existing traditional forest products, new forest products, bioenergy, and forest services.

The main types of financial instruments enabling bioeconomy development include taxes, tax relief, grants, subsidies, feed-in tariffs, loans, direct public funding, and tradable permits (Stichting Wageningen Research Netherlands, 2016). To assess the contribution of economic and financial instruments to the development of the bioeconomy, diverse variables were considered, in particular, environmental taxes (Zhurakovska et al., 2021; Sasaki, 2021), carbon payments (Kerr et al., 2012; Pukkala, 2020; Barua et al., 2012; Evison, 2017; Moiseyev et al., 2014; Caurla et al., 2013; Lauri et al., 2012), and national subsidies (España et al., 2022; Ersoy and Mack, 2012; Aoyagi and Managi, 2004; Jensen et al., 2022; van Valkengoed and van der Werff, 2022).

Simultaneously, there is no comprehensive system to support the development of the bioeconomy from initial research to the commercialization stage (Mubareka et al., 2023). Implementation of that system can ensure that the right financing solutions and targeted advisory support in the bioeconomy will be available. The lack of private investments is displayed, so the challenge to mobilize private financial sources to scale up innovations still exists (Becker et al., 2024). The risk-sharing finance facility presents a possibility to address the needs of bioeconomy projects and attract private capital (World Business Council for Sustainable Development, 2019). However, further barriers such as high and risky costs, a lack of bio-based technologies, uncomprehended policies, and customer perceptions of bio-based materials and products can be recognized (Borzacchiello et al., 2024).

National financial sources in the Czech Republic to support forestry are regulated by Section 46 of the Forest Act no. 289/1995 Coll. on forests and on the amendment and addition of certain laws. In the long term, the financial support mechanism is complex, imprecise, and administratively intensive, which reduces the overall effectiveness of financial support for forest owners in the Czech Republic (Ministry of Agriculture, 2022). Financial contributions for forest management granted from the budget of the Ministry of Agriculture provide a wide range of financial support for forestry (Ministry of Agriculture, 2023). Additionally, in the period 2020-2023, the National Recovery Plan (European Commission, 2019b) offered CZK 8 billion for Title B - financial contributions for reforestation, establishment, and tending of forest stands.

Except for the national programs named above, there are other possibilities open to forest owners, such as (1) subsidies for the protection and reproduction of the gene pool of forest trees, (2) support from the Agricultural and Forestry Support and Guarantee Fund, (3) services with which the state supports forest management, and (4) partial refund excise duty on diesel fuel consumed during forest management (Ministry of Agriculture, 2023).

Forest adaptation to climate change contribution was introduced in 2022, establishing a voluntary commitment beyond the binding requirements of the Forest Act for a period of at least five years. Currently, there is a short duration and a lack of data, however, it will be relevant to examine the effect of named contribution on the forestry sector.

State financial obligations under the Forest Act are a further option for the national financial sources for forestry. Four categories of mandatory expenditure can be identified, namely §24 improvement and strengthening of timber species, §26 costs for processing forest management plans, §35 improvement and damming of streams in forests, §37 activities of a professional forest manager. Based on the National Recovery Plan (European Commission, 2019b), CZK 300 million (EUR 12 million) between 2020-2023 was targeted for financial support under §35 of the Forest Act.

To sum up, a review of the existing literature reveals several avenues for further research as a knowledge gap is evident regarding the economic and financial instruments to support the bioeconomy in the Czech Republic.

Environmental aspects

The bioeconomy, in particular the forest bioeconomy, constitutes a component of a climate-neutral economy. Cumulative emissions of greenhouse gases are on the rise (Rae et al., 2021) and their concentration in the atmosphere continues upwards, driving up the global average temperature (Scripps Institution of Oceanography, 2023). The carbon budget and various emission scenarios are discussed, along with their impacts on ecosystems and humanity (IPCC, 2023; Kim et al., 2017; Giorgi, 2019; Hlásny et al., 2021). The Kyoto Protocol initiated the monitoring of national emissions of greenhouse gases (UNFCCC, 2023) and is not losing its relevance even in the effort to keep warming below 2 degrees Celsius (United Nations, 2016).

Forests are of great importance in the carbon cycle, as they participate in the process of photosynthesis (Keeling et al., 2011). Forests as net carbon sinks were examined by several authors, namely Kauppi et al. (2020), Assmuth and Tahvonen (2018), Meeussen et al. (2021), and Bradford (2011). Besides carbon sequestration and storage, other positive externalities and forest functions are explored (Wen et al., 2019; Putra et al., 2018; Antonelli et al. 2021; Mao et al. 2017; and Farkic et al., 2021).

Natural solutions for carbon storage in forest ecosystems were analyzed. Generally, monetary compensations constitute a significant positive incentive (Horne, 2006; Rämö et al., 2013; Markowski-Lindsay et al., 2011; Tian et al., 2015). Simultaneously, negative links with forest carbon were explored by Dickinson et al. (2012), Fletcher et al. (2009), Wade and Moseley (2011), and Khanal et al. (2017).

Finally, the mixture of policy materials and strategies that shape the direction of the development in the field of circular bioeconomy appears, namely the Paris

Agreement, the European Green Deal, or the Bioeconomy Strategy. European bioeconomy has the potential to create new green jobs, turn forests into value-added innovative products support renewable resources, and increase carbon storage. The bioeconomy is intended to scale up the bio-based sectors, unlock investments, and deploy regional bioeconomies. In parallel to fostering investment, the bioeconomy is stimulating the emergence of new high-skilled green jobs in rural and coastal areas. Supporting the bioeconomy has enormous potential to meet a major challenge to meet not only the European Green Deal (European Commission, 2019a) but also the Sustainable Development Goals (United Nations, 2015).

In summary, there is especially a knowledge gap in:

- studies to assess the development of socio-economic indicators of the bioeconomy,
- clear bioeconomy definition,
- clear identification of the bioeconomy sectors,
- comprehensive bioeconomy data and statistics,
- comprehensive bioeconomy education,
- comprehensive bioeconomy financial support.

Based on the literature review, it is obvious that there is an opportunity for improvement. There are still significant knowledge gaps in the European circular bioeconomy. The dissertation thesis and doctoral study completed the picture of the circular bioeconomy in the Czech Republic.

4 Methodology

4.1 Materials

Extensive secondary data was collected for the period 2000-2021. According to data linked with bioeconomy, various data sources were applied. The key data sources are Eurostat, the Czech Statistical Office, the Ministry of Agriculture of the Czech Republic, the Ministry of the Environment of the Czech Republic, the Energy Regulatory Office, the official websites of the European Union and the United Nations Framework Convention on Climate Change (UNFCCC), and data published in scientific studies (databases Web of Science, Scopus, etc.).

According to labour market data, the development of the bioeconomy relates to its subsectors. To identify the relevant data on employment in the bioeconomy in the EU-27 and the Czech Republic, two crucial sources of data can be found:

- Eurostat database (Eurostat, 2021) and
- Data-Modelling platform of agro-economics research (European Union, 2021a).

Based on the employment in the bioeconomy sectors, the thesis operates with specific sectors based on Ronzon et al. (2020), namely agriculture, forestry, fishing, the manufacture of food products, beverages and tobacco, the manufacture of bio-based textile, the manufacture of wood and wood products, the manufacture of paper, the manufacture of bio-based chemicals, the manufacture of bio-based pharmaceuticals, the manufacture of bioplastics, the manufacture of liquid biofuels and the production of bioelectricity.

Concerning employment data, the sectoral approach was used, and the key methodology has been carried out by the Data-Modelling Platform for Agri-Economic Research (European Union, 2021). Some sectors may be entirely biobased, whilst others are displayed as hybrid sectors and only the biobased part is included in the calculations. The sectoral approach is introduced in Table 1.

Table 1 List of pure and hybrid bioeconomy sectors

Bioeconomy sector	NACE Code
Agriculture	A01
Forestry	A02
Fishing	A03
Food, beverages and tobacco industry	C10; C11; C12
Bio-based textiles*	C13*; C14*; C15*
Wood products and furniture*	C16*; C31*
Paper and paper products	C17
Bio-based chemicals, pharmaceuticals and plastics (excl. biofuels)*	C20*; C21*; C22*
Liquid biofuels (bioethanol and biodiesel)*	C2014*; C2059*
Bio-based* electricity	D3511*

*hybrid sectors
Source: own processing, based on methodology European Commission (2021a).

According to economic and financial instruments, a mixture of data sources can be observed. Especially, two categories of data were obtained from the Ministry of Agriculture of the Czech Republic. First, several datasets were generally available from public repositories. Second, obtaining data regarding financial support for the forestry sector proved challenging. The data used are not widely accessible and are available only on request. From the extensive datasets obtained, selected data for the period 2000-2020 were extracted and harmonized. Searched data were divided into several categories, such as:

(1) national public financing
- state financial obligations under the Forestry Act,
- financial contributions for forest management granted from the budget of the Ministry of Agriculture,
- subsidy for protection and reproduction of the gene pool of forest trees,

(2) financial aid co-financed by the European Union
- Rural Development Programme 2007–2013,
- Rural Development Programme 2014–2020.

The comprehensive dataset contained financial flows with regional resolution. In particular, the nomenclature of territorial statistical units - NUTS level 3 (NUTS3) was chosen. The list of regions in the Czech Republic is set out in Table 2.

Table 2 Overview of the regions of the Czech Republic

NUTS3	Name	Abbreviation
CZ010	Prague, the Capital City	PRG
CZ020	Central Bohemian Region	CBR
CZ031	South Bohemian Region	SBR
CZ032	Plzeň Region	PLR
CZ041	Karlovy Vary Region	KVR
CZ042	Ústí nad Labem Region	ULR
CZ051	Liberec Region	LBR
CZ052	Hradec Králové Region	HKR
CZ053	Pardubice Region	PAR
CZ063	Vysočina Region	VYR
CZ064	South Moravian Region	SMR
CZ071	Olomouc Region	OLR
CZ072	Zlín Region	ZLR
CZ080	Moravian-Silesian Region	MSR

Source: authors, based on Eurostat (2023).

Turning to economic and financial instruments, additional sources of data were explored, notably Eurostat (Eurostat, 2022), Czech Statistical Office (CZSO, 2022), and Energy Regulatory Office (Energy Regulatory Office, 2021). These sources delivered secondary data on topics including:

- environmental investments in biodiversity,
- environmental taxes,
- price of European Union Allowance.

Besides this, additional data regarding the forest land, roundwood removals, gross domestic product, and wages/salaries can be observed. Concerning environmental inputs, the United Nations Framework Convention on Climate Change database (UNFCCC, 2023) covered greenhouse gas (GHG) emissions/removals from the Land Use, Land Use Change, and Forestry (LULUCF) sector. Figures regarding carbon fluxes consisted of selected sub-categories of the LULUCF sector, mainly:

- item 4.A, i.e. forest land,
- item 4.G, i.e. harvested wood products (HWPs).

4.2 Methods

To accomplish the key purpose, both the qualitative and quantitative methods were applied to the research. The following is a summary of the methods utilized.

Desk research

Desk research is an alternative term for secondary research (Manu and Akotia, 2021). Desk research is a method of the assembly, collation, and analysis of information which have been already published (Armstrong, 2002). Desk research allows to synthesize already available details from diverse sources, such as articles, books, reports, or databases (Kulachinskaya and Bencsik, 2023).

Data collection

The method of data collection was applied with the purpose of obtaining the inputs for pilot analysis and evaluation of the socio-economic impacts of global change on the forestry sector which are based on the data from the Czech Republic. According to the source (Joiner Associates Staff, 1995), data collection displays a five-step process that is able to ensure that the collected data are meaningful and appropriate for research needs. The first section looks at how to collect data to meet our data collection goals. Then we focus on developing operational definitions to define what we are trying to evaluate. The third section consists of a plan for data consistency and stability. Begin data collection and continuing to improve measurement consistency are the last parts of the data collection process. Data collection describes the systematic way of collecting and evaluating relevant observations or measurements from multiple sources (Groenland and Dana, 2019). Data collection is a fundamental component of all forms of research, analysis, and decision-making activities (van Delden et al., 2023).

Time series analysis

Time series analysis is a tool for examining and interpreting data points gathered over time (Nielsen, 2019). The main aim of the technique is to identify patterns and trends in a given data set (Palma, 2016). Data points are measured at regular intervals to find out changes over time intervals (Blume and Durlauf, 2016). Additionally, time can be seen as an essential variable as it provides evidence of links within the data (Bleikh and Young, 2014). Time series analysis requires robust data points to guarantee its consistency and reliability (Dinesh and Mangey, 2021).

Comparative analysis

Comparative analysis is a technique for enabling items to be compared and contrasted to detect commonalities and disparities (Perry, 2019). Comparative analysis takes the application of a concept, problem, theory, or question getting a more in-depth insight into the issue and framing the responses (Kahwati and Kane, 2018). Comparative analysis refers to the analysis of data to investigate the interaction of conditions with outcomes (Ge, 2019). Thorpe and Holt (2007) identified that comparative analysis involves a systematic process employed by evaluating and comparing two or more entities, variables, or possibilities in order to offer a structural decision-making basis.

Spatial data analysis

Spatial data analysis is a procedure of simulation of data with geographic characteristics (Kanaroglou and Delmelle, 2016). Spatial data analysis displays links that exist among objects, humans, or aspects through space (Brunsdon and Comber, 2014). The method turned out to be the backbone system for Geographic Information Science (Gokceoglu and Pourghasemi, 2019). Spatial analysis can be exploited to visualize both micro and macro place-based digital information (Fotheringham and Rogerson, 2008). This technique has considerable potential in tackling complex challenges such as the current global climate change (Maantay and McLafferty, 2011).

Spatial data analysis was performed using QGIS 2.26.3 software. The layer 'Boundaries' from the Topographic database of the Czech Republic (Data200) served as a topographic base. A regional analysis approach was undertaken to document regional differences in the allocation of national financial resources to the forestry sector in the Czech Republic. It was decided to utilize the terminology of territorial statistical units, specifically NUTS level 3 (NUTS3).

Cartogram and cartodiagram method

The cartogram and cartodiagram method represent a key method of economic geography simultaneously depicting several phenomena (Couclelis et al., 2011). The cartogram and cartodiagram method display a theme map of a collection of components (Fritz and Carver, 2016). Cartogram and cartodiagram method is a map illustrating geographical statistics of some sort, typically through shading, curves, or points (Kessler and Battersby, 2019). Cartogram and cartodiagram can be created as a unique map in the sense of its integration of statistical features with geographic positioning data (Ballas et al., 2017).

Correlation and regression analysis

Correlation analysis refers to a statistical method for the study of the relationship between two or multiple variables (Russell, 2018). It evaluates the intensity and direction of the relation by measuring the correlation coefficient, ranging from -1 to 1 (Agarwal and Kaushal, 2021). A correlation coefficient of 1 denotes a positive correlation, while -1 stands for a negative correlation. Nevertheless, correlation analysis does not mean causality (Marr, 2015).

As the data show a linear relationship and a normal distribution, correlation analysis was performed using Pearson's correlation coefficient (Zimmermannová et al., 2016). Bivariate correlation is adopted to achieve the correlation coefficient, a measurement that represents the degree of relationship between two linear variables (Armitage et al., 2014).

Subsequently, more complex regression analysis was performed, and regression models were built to be able to observe the partial relations of the variables (Cohen et al., 2014). Regression analysis is a method for investigating the functional relationships among variables (Arkes, 2023). The relationship is expressed in the form of an equation or a model connecting the response or dependent variable and one or more explanatory or predictor variables (Chatterjee and Hadi, 2006). In general, the regression analysis focuses on the relationship between a dependent variable and an independent variable (Hall, 2021). The dependent variable is called the regresand. The independent variable is called the regressor. The regression function combines a dependent and an independent variable (Hendl, 2012). The general regression equation (Thrane, 2019) is as follows:

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \ldots\ldots\ldots \beta nXn + u$$

In this equation, parameters β0 - βn represent regression coefficients that reflect the impact of the independent variable on the dependent variable. In each regression model, the variable Y represents the dependent while the X1 – Xn shows the independent variables. The parameter u represents a random element of the model.

Regarding the dependent variable (Y), forestry employment, forest land, wood biomass production, and forest carbon were established. Independent variables (X1 – Xn) can be divided into categories, such as gross domestic product, wages/salaries, environmental investments, environmental taxes, the price of European Union Allowances, national financial sources for forestry, and European financial sources for forestry.

Given the hypotheses previously determined, the following regression models were designed and tested:

- forestry employment model (FORE), dealt with the development of the forest bioeconomy,
- forest land model (FOLM), focused on the development of the forest bioeconomy,
- wood biomass production model (WBIOM), focused on the use of bioeconomy renewable resources, such as wood biomass,
- forest carbon model (FORCM), targeted at the environmental aspect, such as forest carbon storage.

4.3 Workflow

This dissertation employs several methodological approaches and the methodology is divided into various sections. The dissertation as a whole was evaluated according to the methods of description, systematic sampling, comparison, analysis, and synthesis. A workflow procedure has been implemented and is outlined below:

- literature review,
- examination of the bioeconomy labour market,
- examination of the economic and financial instruments,
- data visualization,
- final evaluation of results.

Firstly, a literature review was conducted by analyzing selected secondary sources and professional publications related to the socio-economic aspects of the bioeconomy. The literature search was categorized into the following subparts. The initial section addressed the fundamental elements of the bioeconomy and provided a knowledge base for further activities. The bioeconomy was evaluated at both the European and Czech levels, with particular emphasis placed on the definition, scoping, strategic frameworks, policy materials, and monitoring system.

Furthermore, bioeconomy-related concepts such as the circular economy and sustainable development were also considered. The second pillar explored the social dimension of the bioeconomy. Social aspects such as employment, green jobs, and education were investigated. The third pillar concerned the economic segment of the bioeconomy. In particular, the literature review focused on the analysis of economic and financial instruments, both at the European level and at the national one.

Secondly, an assessment of the bioeconomy labour market was carried out. In the first step, data collection and processing were applied and the data linked with bioeconomy employment were collected and analyzed. For each record, there were two kinds of data considered - textual and numerical. In specific, the particular items were as follows:

- NACE code,
- name of bioeconomy sector,
- number of employees.

In the next step, a quantitative approach was applied to evaluate the development of the bioeconomy labour market. For this, methods of time series analysis, sectoral comparative analysis, correlation and regression analysis were used. The following indicators were considered, such as:

- the share of the bioeconomy labour market in the total labour force,
- the evolution of employment in the bioeconomy labour market,
- changes in the structure in particular bioeconomy subsectors,
- drivers of the bioeconomy employment.

The aforementioned indicators were monitored in several categories, in detail European Union, bioeconomy groups, Visegrad Four countries, Czech Republic.

Thirdly, the evaluation of the effectiveness of the economic and financial instruments was realized. In the first step, data collection and processing were applied and various datasets were collected and analyzed, namely:

- price of European Union Allowance,
- environmental investments in biodiversity,
- revenues from environmental taxes imposed in forestry,
- forest land,
- roundwood removals,
- carbon fluxes in selected sub-categories of the LULUCF sector.

The subsequent stage displayed communication with the Ministry of Agriculture of the Czech Republic, specifically with the Department of Forestry Economic Instruments. Extensive datasets of financial flows in the forestry sector in the Czech Republic for the period 2000-2020 were obtained. The core financial flows were constituted by (A) national sources based on the Forestry Act No. 289/1995 Coll., on forests and on the amendment and addition of certain laws, and (B) European funds within the Rural Development Programme. An overview is given in Annex 1.

Regarding both groups of data, each record contained two kinds of data considered - textual and numerical. In specific, the particular items were as follows:

- number of financial contributions or subsidies,
- name of the financial contributions or subsidies,
- the amount of the contributions or subsidies,
- year,
- region.

In the next step, a quantitative approach was adopted to evaluate the impact of the economic and financial instruments on the development of the forest bioeconomy. Multiple methods were exploited, especially time series analysis, comparative analysis, correlation, and regression analysis. A series of indicators included:

- forest land,
- wood biomass production,
- forest carbon.

Fourthly, data visualization was utilized to examine the evolution of national financial sources within the forest bioeconomy in the Czech Republic. To demonstrate regional divergences in the allocation of national financial sources, spatial data analysis, the cartogram and cartodiagram method were employed. The following indicators were selected, concretely:

- regional differences in financial contributions for forestry granted from the budget of the Ministry of Agriculture per hectare,
- regional differences in financial contribution to mitigate the impact of the bark beetle calamity per hectare.

Finally, the evaluation of results was realized. Based on the findings of the preliminary analyses and pilot models, additional data were collected to ensure the completeness of the final form of the dissertation.

5 Results synthesis

The objective of the dissertation thesis was achieved through three original research papers published in scientific journals with impact factors (IF). The studies were consistent with the dissertation theme and focused on various aspects of the socio-economic impacts of global change on the bioeconomy, including the forestry sector.

The first study aimed to evaluate the development of the bioeconomy labour market in the Czech Republic, including the forestry sector (subchapter 5.1):

Perunová, M., Zimmermannová, J. (2022). Analysis of the forestry employment within the bioeconomy labour market in the Czech Republic. *Journal of Forest Science*. 68: 385-394. DOI: 10.17221/84/2022-JFS.

The second study focused on the explanation of the impacts of economic and financial instruments of the climate change policy on the development of the forest bioeconomy in the Czech Republic (subchapter 5.2):

Perunová, M. and Zimmermannová, J. (2023). Economic and financial instruments of forest management in the Czech Republic. *Front. For. Glob. Change*. 6:1237597. DOI: 10.3389/ffgc.2023.1237597.

The third study dealt with regional divergences and the impacts of financial support on the development of the forest bioeconomy in the Czech Republic (subchapter 5.3):

Perunová, M., Zimmermannová, J., Schovánková, T. (2024). Forest carbon and a regional perspective on the effectiveness of financial instruments within the forest bioeconomy. *Journal of Forest Science*. In Press.

5.1 Publication no.1: Analysis of the forestry employment within the bioeconomy labour market in the Czech Republic

TITLE:	Analysis of forestry employment within the bioeconomy labour market in the Czech Republic
TYPE:	Original Paper
AUTHORS:	Michaela Perunová and Jarmila Zimmermannová
JOURNAL:	Journal of Forest Science
YEAR:	2022
DOI:	10.17221/84/2022-JFS

https://doi.org/10.17221/84/2022-JFS

Analysis of forestry employment within the bioeconomy labour market in the Czech Republic

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Citation: Perunová M., Zimmermannová J. (2022): Analysis of forestry employment within the bioeconomy labour market in the Czech Republic. J. For. Sci., 68: 385–394.

Abstract: Climate change, biodiversity loss, and the increased occurrence of extreme weather events bring new challenges at a global level, not just in forestry. In response to the current situation, modified economic models such as circular economy, green economy, bio-based economy, or bioeconomy, are expected to move society towards a more sustainable future. The main aim of this paper was to evaluate forestry employment and its drivers within the bioeconomy labour market in the Czech Republic. The partial target was to provide a general view of the development of forestry employment within the bioeconomy labour market. The authors applied a mixed methods approach, using literature review, data analysis, correlation analysis, and regression analysis. A decreasing trend of the share of forestry employment in total bioeconomy employment and of the share of bioeconomy employment in the labour market in the Czech Republic was identified. Regarding the drivers of the forestry labour market, based on the results, employment in the forestry sector is positively dependent on wages/salaries and negatively dependent on GDP and forest land.

Keywords: bio-based economy; economic indicators; employment in forestry; regression analysis; Czechia

Global change (Watson et al. 1998) is often perceived as human-induced modifications in climate. Indeed, human activities have undeniably altered the atmosphere, and probably the climate as well. Non-human climate changes tend to be slower and less destructive than anthropogenic climate change. At the same time, most of the world's forests have also been extensively modified by human use of the land. Global climate change is predicted to bring a different climatic future to the world's major forest regions. The study (Kim et al. 2017) represents the impact of climate change on global forests and based on climate system modelling, concludes that climate mitigation can bring benefits as well as costs. Based on Hansen et al. (2001), consideration of climate, land use, and biological diversity is a key to understanding the forest response to global change.

The forest bioeconomy plays a significant role in capturing carbon in sustainably managed forest ecosystems and their products (Green Growth Knowledge Platform 2011). The forest bioeconomy can contribute to the Paris Agreement's aim to achieve a balance between anthropogenic greenhouse gas emissions by sources, and removals by sinks (UNFCCC 2015), by increasing the carbon stocked in forest land and in harvested wood products. A sustainable forest bioeconomy plays an essential role in the carbon cycle and provides essential environmental and social values. For the for-

https://doi.org/10.17221/84/2022-JFS

est bioeconomy, the most important challenges are to find innovative approaches to managing forest resources in a way that simultaneously increases wood and non-wood production (Marchetti et al. 2014).

Climate change, biodiversity loss and the increased occurrence of extreme weather events bring new challenges at a global level, not just in forestry. At the global level, the European Union has now taken the lead and critical objectives have been identified, such as ensuring the long-term competitiveness of European industry as well as climate neutrality by 2050. We can speak about this issue as highly topical and with a global impact. The Paris Agreement (United Nations 2015b), the European Climate Law (EU 2018/1999), the European Green Deal (European Commission 2019), and other environmental visions are being followed up by the latest Fit for 55 packages. A legislation revision aims to reduce net greenhouse gas emissions by at least 55% by 2030 (European Commission 2021), increase the adaptability of forests and the natural restoration of forests, as well as financially support sustainable forest management across EU countries. The New EU Forest Strategy for 2030 (European Commission 2021) can be considered as part of the package.

The sustainable economy policy package is complemented by the EU Bioeconomy Strategy (European Commission 2018), and the New EU Circular Economy Action Plan (European Commission 2020). Further, the US Sustainable Development Goals (United Nations 2015a), and the European Forests for biodiversity, climate change mitigation and adaptation (Science for Environment Policy 2021) have already been developed.

In the Czech Republic, the first strategic framework for the circular economy (Ministry of Environment 2021) was approved by the end of 2021. A significant area of interest of the Circular Czech Republic 2040 (Ministry of Environment 2021) is the development of the Czech bioeconomy, which should create new jobs across the European country.

Globally, pressure is increasing on the demand side for food, feed, biomaterials, and bioenergy resources, putting more pressure on natural resources. The transformation from a linear economic system to a more sustainable one has begun. We can observe modified economic models such as circular economy, green economy, bio-based economy, or bioeconomy. The circular bioeconomy has a significant impact on sustainable development. The bioeconomy (European Commission 2018) covers all sectors and systems that rely on biological resources, their functions, and principles. It interlinks land and marine ecosystems, all primary production sectors and all sectors using biological resources to produce food, feed, bio-based products, energy, and services.

Based on scientific literature (Ronzon et al. 2015), the national bioeconomies of the EU states can be divided into four groups of countries such as agricultural bioeconomies (Slovenia, Greece, Romania), agro-food industry and bio-based chemical industries (Italy, France, Germany), forestry bioeconomies (Finland, Sweden, Estonia), and non-specialised bioeconomies (Czech Republic, Slovakia, Hungary). Ronzon et al. (2020) defined the following subsectors of bioeconomy: agriculture, forestry, fishing, manufacture of food products, beverage and tobacco, manufacture of bio-based textile, manufacture of wood and wood products, manufacture of paper, manufacture of bio-based chemicals, manufacture of bio-based pharmaceuticals, manufacture of bioplastics, manufacture of liquid biofuels and the production of bioelectricity. Forestry represents the key sector of the bioeconomy.

In scientific studies focusing on bioeconomy issues, there is still a lack in this field. The most easily available scientific studies are national case studies. However, the socio-economic effects of the bioeconomy, such as employment, turnover, and GDP, have not been very well researched. For example, Carus (2012) provided an overview of the quantitative dimensions of the European bioeconomy and displayed the first-ever collection and analysis of bioeconomy data across the EU-27 Member States. The calculation of effects includes indicators such as the number of enterprises, employed persons, and value added. Subsequently, the high employment values in the individual bioeconomy sectors are caused by natural and geographical conditions in each country (Drejerska 2017). According to a study performed by Hetemäki and Hurmekoski (2016), at the European level is still a lack of studies that develop an area such as the forest labour market. Regarding the Jonsson et al. (2021) support of logging wood, the production of wood products, and sectors that use the by-product as a feedstock seem to be an opportunity to boost bioeconomy employment. Another study (Efken et al. 2012) assessed the macroeconomic

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impact of the bioeconomy in Germany and analysed four indicators such as the number of companies, employment, turnover, and gross value added. The study (CEPI 2012) refers to direct and indirect value added and employment in the European pulp, paper, and paperboard industry. On the contrary, Dammer et al. (2017) showed the new estimation of employment and turnover figures of the European bioeconomy. Regarding the multiplying effects of the bioeconomy (Mainar-Causapé et al. 2017), each EUR million spent on bioeconomy products newly generates 12 employed persons in the bioeconomy sectors, especially in agriculture, in the food and paper industry. The highest direct employment effects are represented by expenditure on forestry and agricultural products.

Regarding the studies focusing on the Czech Republic (Purwestri et al. 2020), opportunities for sustainable forest biomass and high-added value products opened in the forestry market. Based on the study performed by Hájek et al. (2021), health conditions in sectors such as forestry, agriculture, and food industries seem to be necessary for the development of a circular economy at the local level. Zimmermannová and Perunová (2022) evaluated employment and its trends in selected sectors of the bioeconomy as the main drivers of the labour market and identified GDP, wage, and subsidy development.

Based on the literature review, we highlight a lack of studies that would address the topic of forestry employment within the bioeconomy labour market in the Czech Republic. The analysis presented in this article will try to fill this gap.

MATERIAL AND METHODS

Material. To achieve the aim, various data sources were used, both from scientific databases and official institutional online sources. The essential data sources are represented by the data published in scientific studies (scientific databases Web of Science, Scopus, Research Gate, etc.), as well as the official websites of the European Union. For the period 2000–2020, detailed data connected with bioeconomy, bioeconomy sectors, features of such sectors, and forestry were used from the Eurostat database (Eurostat 2022), the Czech Statistical Office (CZSO 2022) and the Data-Modelling platform of agro-economic research (European Comission 2021). Table 1 shows the overview of all data/variables used for correlation and regression analyses presented in this paper, including abbreviations, units, and roles of the variables.

The key dependent variable is "employment in forestry". The "employment" is a suitable indicator characterising the labour market (Blais 1986; Samuelson, Nordhaus 2009). Regarding independent variables, they were chosen based on their expected influence on employment in forestry. Based on the labour market theory (Samuelson, Nordhaus 2009), wages and salaries influence employment and unemployment. Simultaneously, an increase in GDP represents transformation of the economy, increases in digitisation, and the creation of new jobs (Toth et al. 2019). It can cause the movement of employed people from forestry and other traditional sectors to other, up-to-date sectors. Environmental investments are necessary for transition to cleaner technologies (Toth et al. 2019). Together with subsidies (Blais 1986), they can support environmentally important sectors of the national economy, such as forestry. Forest land is an important indicator, wood is a renewable natural resource, and we can expect an increase in demand for this energy source (Hájek et al. 2021). Time represents the control variable.

The following Table 2 summarizes the parameters of variables described in Table 1. For each variable, minimum and maximum values, standard deviation, and the median are indicated.

Methods. The main aim of this paper is to evaluate forestry employment and its drivers within the bioeconomy labour market in the Czech Republic.

Table 1. List of variables

Variable	Abbreviation	Units	Role
Employment in forestry	*FORE*	thousand persons	dependent
Gross domestic product at market prices	*GDP*		
Wages and salaries	*WAGE*	current prices, million EUR	independent
Subsidies	*SUBS*		
Environmental investments	*INV*		
Forest land	*FORL*	ha	
Time	*TIME*	years	

Source: Authors' own elaboration

https://doi.org/10.17221/84/2022-JFS

Table 2. Overview of the data statistics

Variable	Minimum	Maximum	Standard deviation	Median
FORE	21	37.66	5.477	26.83
GDP	67 032.5	225 568.7	46 186.96	157 920.8
WAGE	19 989.3	77 380.2	16 662.85	50 328.5
SUBS	1 470.7	7 975.8	1 833.277	3 857.5
INV	596.7	1 604.4	250.520	939.64
FORL	2 637 289	2 677 329	12 458.08	2 657 376
TIME	2000	2020	–	2010

FORE – employment in forestry; *GDP* – gross domestic product at market prices; *WAGE* – wages and salaries; *SUBS* – subsidies; *INV* – environmental investments; *FORL* – forest land; *TIME* – time

Source: Authors, based on Eurostat (2022) and CZSO (2022)

Based on the above literature review and linking up with the paper objectives, the following research questions should be answered:

RQ1: Can we observe a decreasing trend of employment in the forestry sector within the bioeconomy labour market in the Czech Republic?

RQ2: What are the main drivers of employment in the forestry sector in the Czech Republic?

For the achievement of the main aim of our research and to answer the research questions, we used the following methods: literature review, data analysis, correlation analysis, and regression analysis.

To answer RQ1, the following methodological approach was used: based on the set target, the statistical data were collected, and the sectoral approach was applied. Regarding the statistical data, the main data sources for employment in the bioeconomy reported in the figures are Eurostat, the Data-Modelling platform of resource economics, and the Czech Statistical Office.

Focusing on the sectoral comparative analysis, changes in the structure of the employment in particular bioeconomy subsectors were analysed and compared. The key methodology was performed by the Data-Modelling platform of agro-economic research (European Commission 2021).

Considering the sectoral approach, employment data were listed by the NACE rev. 2 Classification. Agriculture, forestry, fishing, the manufacturing of food, beverage, tobacco, and paper were used as pure bioeconomy sectors. Other sectors, such as the manufacture of textiles, wearing apparel, leather, wood products, furniture, chemicals, pharmaceuticals, plastics and rubber, and electricity production, represent hybrid segments with a bio-based share of employment.

To answer RQ2, the following methodological approach was used: correlation analysis (Pearson's correlation coefficient) and regression analysis were carried out based on the above-described data (Tables 1 and 2). The authors use the linear regression models. The key one is the regression model MOD1 which calculates the relation between employment in forestry and all other variables.

The general regression equation of MOD1 is as follows [Equation (1)]:

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \beta 4X4 + \beta 5X5 + \beta 6X6 + u \quad (1)$$

where:

Y – employment in the forestry sector (FORE);

$\beta 0$–$\beta 6$ – regression coefficients that reflect the impact of the independent variable on the dependent variable;

u – random element of the model;

$X1$ – GDP (*GDP*);

$X2$ – wage (*WAGE*);

$X3$ – subsidies (*SUBS*);

$X4$ – environmental investments (*INV*);

$X5$ – forest land (*FORL*);

$X6$ – time (*TIME*).

Regression model MOD2 includes all variables like MOD1, except for *TIME*. MOD3 represents the more focused and statistically significant model. MOD2 and MOD3 are described in more detail in Results.

RESULTS

Employment in the forestry sector within the bioeconomy labour market. The changes in the structure in particular bioeconomy subsectors in the Czech

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Republic in 2010–2019 are presented in Figure 1; several categories were used, namely agriculture; food, beverage, and tobacco; forestry; wood products and furniture; paper; fishing and aquaculture; bio-based textiles; bio-based chemicals, pharmaceuticals, plastics, and rubber. The highest share of bioeconomy employment was represented each year by traditional economy sectors, such as agriculture; food, beverage, tobacco; wood products and furniture. Based on the results, about two-thirds of bioeconomy employment in the Czech Republic comes from agriculture and food, beverage, and tobacco.

Table 3 shows that the share of the bioeconomy sectors in the labour market in the reported period was approximately 7%–8%. The highest share was observed in 2012 (7.94%) and the lowest share in 2019 (7.31%). We can observe a declining trend. Consequently, the share of forestry in the bioeconomy labour market was around 5%–6%. The highest share of forestry in the bioeconomy labour market in the Czech Republic was observed in 2011 (6.98%). In contrast, its lowest value was in 2019 (5.42%). Based on the figures, a declining trend can be observed in the share of forestry in the bioeconomy labour market in the Czech Republic in the period 2010–2019.

Correlation analysis. Table 4 shows the results of the correlation analysis. The variables are described in more detail in Tables 1 and 2.

Focusing on employment in forestry (*FORE*), we can observe negative correlations with all other selected variables (*GDP*, *WAGE*, *SUBS*, *INV*, *FORL*, and *TIME*). To identify the drivers of the forestry labour market, we will use linear regression analysis.

Regression analysis. Table 5 presents models MOD1, MOD2, and MOD3 with forestry employment (*FORE*) as a dependent variable.

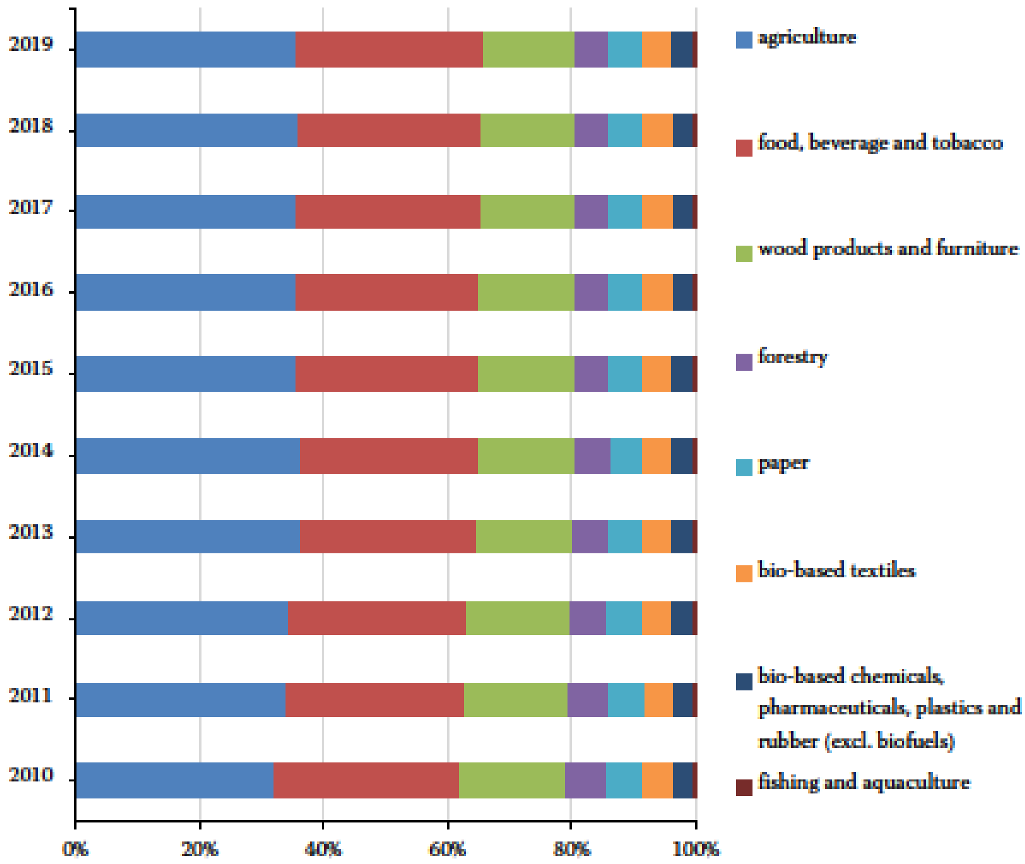

Figure 1. Changes in the structure of the bioeconomy employment in the Czech Republic in 2010–2019

Source: Authors' own processing, based on Eurostat (2022) and European Commission

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Table 3. Forestry in the bioeconomy labour market (%)

Year	Employed persons in total (thousand persons)	Employed persons in the bioeconomy (thousand persons)	Share of the bioeconomy sectors (%)	Employed persons in forestry (thousand persons)	Share of forestry in the bioeconomy sectors (%)
2010	4 885.200	385.535	7.89	25.96	6.73
2011	4 872.400	384.328	7.89	26.83	6.98
2012	4 890.100	388.348	7.94	24.64	6.34
2013	4 937.100	385.620	7.81	23.49	6.09
2014	4 974.300	384.186	7.72	22.61	5.89
2015	5 041.900	385.228	7.64	22.62	5.87
2016	5 138.600	383.281	7.46	21.50	5.61
2017	5 221.600	386.146	7.40	21.87	5.66
2018	5 293.800	395.281	7.47	**21.82**	5.52
2019	5 303.100	387.510	7.31	**21.00**	5.42

Source: Czech Statistical Office (2022), European Commission (2021), own processing

Table 4. Correlation analysis

Variable	*FORE*	*GDP*	*WAGE*	*SUBS*	*INV*	*FORL*	*TIME*
FORE	1	–	–	–	–	–	–
GDP	–0.943	1	–	–	–	–	–
WAGE	–0.933	0.996	1	–	–	–	–
SUBS	–0.944	0.939	0.949	1	–	–	–
INV	–0.805	0.728	0.723	0.790	1	–	–
FORL	–0.982	0.962	0.963	0.972	0.826	1	–
TIME	–0.980	0.968	0.969	0.973	0.823	0.999	1

FORE – employment in forestry; *GDP* – gross domestic product at market prices; *WAGE* – wages and salaries; *SUBS* – subsidies; *INV* – environmental investments; *FORL* – forest land; *TIME* – time
Source: Authors' own elaboration

Table 5. Regression analysis

Parameter	MOD1		MOD2		MOD3	
	sig.	coef.	sig.	coef.	sig.	coef.
X1 (*GDP*)	0.00542	–0.00017	0.004034596	–0.00017	0.00320889	–0.00016
X2 (*WAGE*)	0.00320	0.00055	0.002104713	0.000556	0.001759668	0.00047
X3 (*SUBS*)	0.52894	–0.00033	0.547242726	–0.0003	–	–
X4 (*INV*)	0.25074	0.00007	0.191729396	8.06E–05	–	–
X5 (*FORL*)	0.15738	–0.00064	6.99925E–05	–0.00052	1.03867E–07	–0.00048
X6 (*TIME*)	0.78291	0.27617	–	–	–	–
Constant	0.22402	1 159.86084	0.00005	1 405.418	0.00000	1 315.08900
Observ.	21	–	21	–	21	–
R^2	0.99167	–	0.99163	–	0.990408	–
Signif.	0.00000	–	0.00000	–	0.00000	–
DW	2.46538	–	2.374555	–	2.191986	–

MOD1–3 – model 1–3; *GDP* – gross domestic product at market prices; *WAGE* – wages and salaries; *SUBS* – subsidies; *INV* – environmental investments; *FORL* – forest land; *TIME* – time; *DW* – Durbin-Watson test
Source: Authors' own elaboration

https://doi.org/10.17221/84/2022-JFS

MOD 1 consists of all independent variables (*GDP, WAGE, SUBS, INV, FORL*, and *TIME*). The whole model is statistically significant, but not all selected variables are statistically significant.

MOD2 represents the same variables as MOD1, excluding *TIME* as the variable with the statistically lowest significance.

MOD3 represents variables with $P < 0.01$ statistical significance from MOD1 and MOD2 (*GDP, WAGE* and *FORL*). This last model MOD3 is the statistically significant model – all variables are statistically significant and the whole model is also statistically significant. *DW* was calculated for this model, and it is also acceptable (2.19). We can write the following regression equation:

$$Y = 1\,315.08900 - 0.00016X1 + 0.00047X2 - 0.00048X5 \quad (2)$$

Employment in the *FORE* sector is positively dependent on wages/salaries and negatively dependent on *GDP* and forest land.

DISCUSSION

The Czech Republic was identified in Ronzon's study (Ronzon et al. 2015) as a non-specialised bioeconomy, together with other Visegrad countries, namely Slovakia and Hungary. Considering the structure of the bioeconomy labour market in the Czech Republic in the observed period, we can confirm such a result. Based on the above-presented analysis, about two-thirds of bioeconomy employment come from traditional sectors of the national economy, such as (1) agriculture, and (2) food, beverage, and tobacco.

Regarding forestry, the share of forestry employment in the bioeconomy employment decreased in the observed period, it was 5.42% in 2019. This result is similar to the study performed by Toth et al. (2019). On the other hand, due to the Green Deal and new environmental policy, we can expect an increase in the number of new jobs in forestry. According to Philippidis et al. (2014), the forestry, fishing, and wood sectors represent segments with the most significant impact on the creation of new jobs in the European bioeconomy. Regarding Jonsson et al. (2021), support of logging wood, the production of wood products, and sectors that use the by-product as a feedstock seem to be an opportunity to boost bioeconomy employment.

Focusing on the drivers of employment in the forestry sector in the Czech Republic, there is a positive relationship between employment and wages/salaries, and a negative relationship between GDP and forest land. Social indicator (employment) as a dependent variable was used in many studies, such as Parisi and Ronzon (2016), Lier et al. (2018), Berkel and Delahaye (2019), Bracco et al. (2019), Kardung et al. (2019), Capasso and Kiltkou (2020), Alviar et al. (2021), and Ronzon et al. (2022). For example, Ronzon et al. (2022) concluded that modernisation, innovation, and employment reallocation are factors influencing changes in the development of bioeconomy employment. Some Northern and Western EU Member States are working on bioeconomy transformation through modernisation and structural changes in the national economies (Ronzon et al. 2021). However, Eastern and Central EU Member States are still in the early stages of a bioeconomy transition. Based on the last CBE JU policy (CBE JU 2022), a total of EUR 120 million will be dedicated to advancing competitive circular bio-based industries in Europe, including forestry. We can expect an increase in new jobs connected with renewable energy sources and/or bio-based products.

Regarding the methodology and methodological approach, correlation and regression analyses provide interesting and valuable results. On the other hand, the lack of quality primary and secondary data sources in suitable structure in forestry (Robert et al. 2020) appears to be a limiting factor for properly evaluating the forestry labour market. Simultaneously, there is a crucial need for innovative methods of measuring the development of the bioeconomy sectors (Sanz-Hernández et al. 2019), including forestry.

CONCLUSION

Forests are under tremendous pressure from global change. To tackle global challenges, it seems to be important to improve and innovate the way we produce and consume food, products, or materials. It requires investments, innovation, strategies as well as systemic changes across different economic subsectors, not just in the forest bioeconomy. Interdisciplinary science that integrates the knowledge of many interacting climate services of forests with the impacts of global change is necessary to identify and understand as yet unexplored

https://doi.org/10.17221/84/2022-JFS

feedbacks in the Earth system and the potential of forests to mitigate climate change. Concerning the forest bioeconomy, wood production can increase as long as we manage our forests sustainably. Then a sustainable forestry bioeconomy provides essential environmental and social values. From the environmental point of view, a sustainable forest bioeconomy can provide negative emissions or carbon sinks. Subsequently, employment can be considered the leading social identifier of the forest bioeconomy. The main aim of this paper was to evaluate forestry employment and its drivers within the bioeconomy labour market in the Czech Republic. The partial target was to provide a general view of the development of forestry employment within the bioeconomy labour market. Focusing on our research questions RQ1 and RQ2, we can conclude that there is a decreasing trend of the share of forestry employment in total bioeconomy employment in the Czech Republic with the share of forestry employment in the bioeconomy labour market being around 5%–6%. Employment in the forestry sector is positively dependent on wages/salaries and negatively dependent on GDP and forest land.

Monitoring and evaluating socio-economic indicators provide an essential insight into the size, impact, and development of the forestry bioeconomy. Based on the results, a significant knowledge gap still exists in the forestry bioeconomy labour market at both European and national levels. This research fulfilled the picture of the bioeconomy employment in the Czech Republic, especially in forestry.

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Zimmermannová J., Perunová M. (2022): Bioeconomy labour market and its drivers in the Czech Republic. Economics Management Innovation, 14: 33–46.

Received: June 29, 2022
Accepted: August 1, 2022
Published online: September 19, 2022

5.2 Publication no.2: Economic and financial instruments of forest management in the Czech Republic

TITLE: Economic and financial instruments of forest management in the Czech Republic

TYPE: Original Research

AUTHORS: Michaela Perunová and Jarmila Zimmermannová

JOURNAL: Frontiers in Forests and Global Change

YEAR: 2023

DOI: 10.3389/ffgc.2023.1237597

frontiers | Frontiers in Forests and Global Change

TYPE Original Research
PUBLISHED 03 October 2023
DOI 10.3389/ffgc.2023.1237597

Check for updates

OPEN ACCESS

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RECEIVED 09 June 2023
ACCEPTED 19 September 2023
PUBLISHED 03 October 2023

CITATION
Perunová M and Zimmermannová J (2023) Economic and financial instruments of forest management in the Czech Republic. *Front. For. Glob. Change* 6:1237597. doi: 10.3389/ffgc.2023.1237597

Economic and financial instruments of forest management in the Czech Republic

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The forest bioeconomy becomes a feature of a climate-neutral economic system, while effective financial support is crucial for sustainable forest management. The main goal of this paper is to explain the impact of economic and financial instruments on the development of the forestry sector in the Czech Republic in the period 2000–2020. For research objectives, the methods of literature review, data analysis, correlation analysis, and regression analysis were used. Several models were established and tested. This paper presents the forest land model (FOLM) and wood biomass production model (WBIOM). In the monitored period, there was an increase in forest land in hectares in the Czech Republic, which was positively influenced by environmental investments in biodiversity and negatively by subsidies from the Rural Development Programme and the price of European Union Allowance. Based on the FOLM model results, 100 million CZK (4.07 million EUR) of environmental investments in biodiversity would contribute to an increase of 228 hectares of forest land. Concerning wood biomass production in cubic meters, it was influenced positively by the whole mixture of economic and financial instruments, such as emission trading, environmental taxation, financial contributions for forest management, state financial obligations, and subsidies. Based on the WBIOM model results, an increase in the price of an emission allowance by 100 CZK Mg^{-1} (approx. 4 EUR Mg^{-1}) would increase wood biomass production by approximately 934,614 cubic meters. Generally, the economic and financial instruments in the Czech Republic have an environmental impact and can influence the forest bioeconomy, at least in the long-term period. Concerning the complex influence of the emission trading on the forestry sector in the Czech Republic, it is ambiguous—in the case of forest land rather negative, and in the case of wood biomass production positive. Therefore, focusing on the policy recommendations, we should underline economic and financial instruments connected with positive motivation in the forestry sector, such as grant schemas, subsidies, and investments in biodiversity.

KEYWORDS
financial instruments, economic instruments, forest management, subsidies, climate change, forestry, forest bioeconomy, Czech Republic

1. Introduction

Environmental and climate policy uses a number of environmental protection tools. The combination of economic and financial instruments, along with other mechanisms, is organized by countries depending on their environmental policy preferences. Financial support for forestry is an essential tool to drive the bioeconomy growth and is expected to shift society to a more sustainable economic regime (Libert-Amico and Larson, 2020). Firstly, financial support for the European bioeconomy is delivered through the Horizon Europe research and innovation program. Ten trillion euros are earmarked for the bioeconomy under Cluster 6–food, bioeconomy, natural resources, agriculture, and environment (European Commission, 2021b). Secondly, the European Circular Bioeconomy Fund (2021) targeted the European bioeconomy and the circular bioeconomy. Thirdly, the Bio-based Industries Joint Undertaking (2023) represents a 3.7 billion EUR public-private partnership involving the European Union and Bio-based Industries Consortium working on fostering bio-based research and innovation, taking the risk out of investing in innovative, circular bio-based production plants and engaging stakeholders along the value chains.

Following the results of Stichting Wageningen Research Netherlands (2021), the taxes, tax relief, grants, subsidies, feed-in tariffs, loans, direct public funding, and tradable permits represent major categories of economic and financial instruments that allow the promotion of the bioeconomy. The report (Leoussis and Brzezicka, 2017) underlines the role of financial support for landowners, and forestry owners. Bio-based Industries Consortium's (2017) report displays the synergy effects of funding programs across the European Union. In addition, financial instruments can also foster innovations. Development of production methods and innovations in goods and services are the most frequent ones (Lovrić et al., 2020). Another study published by Liagre et al. (2021) dealing with forestry financial support is observed.

Rapidly, human behavior has altered the climate system in recent decades (IPCC, 2022). In general, non-human climate changes are slower and less destructive than anthropogenic ones (Ford et al., 2012). The concentration of greenhouse gasses in the atmosphere has been on the rise since the pre-industrial epoch. It is evident that atmospheric carbon dioxide and global surface temperature are deeply interlinked (Webb et al., 2013). Climate change driven by human activities shifts a variety of climate system components (Kirilenko and Sedjo, 2007). Global warming has caused an observed higher frequency, intensity, and duration of extreme weather events, such as droughts, windthrow, heatwaves, etc (Scinocca et al., 2016). Regarding the AR6 Synthesis report (Intergovernmental Panel on Climate Change, 2023), the global surface temperature reached 1.1°C above 1850–1900 in 2011–2020. Moreover, the current economic system running on linear flows of materials and energy generates anthropogenic greenhouse gas and accelerates ongoing climate change. Climate models offer a variety of "what if" scenarios with insight into what the future might look like depending on human choices, helping to understand how the climate system works (Kim et al., 2017: Giorgi, 2019; Hlásny et al., 2021).

Globally, cumulative greenhouse gas emissions amounted to an average of 54.4 gigatonnes of CO_2 equivalent between 2010 and 2019 (United Nations Environment Programme, 2022), with the highest share represented by fossil CO_2, methane (CH_4), and nitrous oxide (N_2O). Global atmospheric CO_2 concentrations continued to speed up and achieved an annual average of 420 parts per million in 2022 (Scripps Institution of Oceanography, 2023). Forests contribute to the carbon cycle through photosynthesis. In the Keeling curve (Keeling, 1958, 1960; Keeling et al., 1976, 1996), CO_2 concentration reaches a peak in May and hits a minimum at the end of the growing season in September. Simultaneously, the annual CO_2 oscillations are repeating with a rising trend. While about half of the CO_2 from fossil fuel burning is in the atmosphere, the second half is dissolved in the oceans, driving down the pH (Keeling et al., 2011). For example, CO_2 emissions reconstructions over the past 66 million years provide a study by Rae et al. (2021).

Reversing this trend, multiple initiatives with a vision to decarbonise the economy have been launched. For example, in 2015, United Nations introduced 17 Sustainable Development Goals (United Nations, 2023). A sustainable pathway for forests and the forestry sector can be found notably in SDG 9—Industry, innovation and infrastructure; SDG 13—Climate actions; and SDG 15–Life on land. An analysis of the impacts of the sustainable development goals on forests and society is carried out in a publication by Katila et al. (2019).

Within the European Union, the Paris Agreement (United Nations, 2022) is designed to cut greenhouse gas emissions and limit the rise of global temperature. The Green Deal's vision is a climate-neutral European economy by 2050 (European Commission, 2019). The legal obligation to move toward climate neutrality is further defined in the European Climate Change Act (European Commission, 2021e). The Fit for 55 package (European Commission, 2021d) identifies milestones to bring down greenhouse gas emissions by 55% by 2030. Regarding forestry, the revision of the legislation calls for increased adaptability of forests and natural regeneration of forests, together with financial support for sustainable forest management. The new EU Forestry Strategy 2030 (European Commission, 2021c), part of the Fit for 55 package, requires cascading utilization of biomass and financial support for forest owners and rural areas. The sustainable economy policy package complements the first EU Bioeconomy Strategy (European Commission, 2012), the New EU Bioeconomy Strategy (European Commission, 2018), and the New EU Circular Economy Action Plan (European Commission, 2022a). Then the synergies of the various frameworks offer a way toward a more efficient transformation of the European economy.

The bioeconomy is a bridge linking the above concepts and a field with the capacity to face a series of global challenges. Various definitions of the bioeconomy can be recognized, based on different stakeholders, sources, or geographic locations (Carus, 2012; van Leeuwen et al., 2014; Loiseau et al., 2016; D'Amato et al., 2017; Wesseler and von Braun, 2017; Birner, 2018; Bracco et al., 2018; Ramcilovic-Suominena and Pülzlb, 2018; Mittra and Zoukas, 2020; Barañano et al., 2021; Kardung and Drabik, 2021). The European Commission presented the first bioeconomy definition in 2012 (European Commission, 2012) and later updated it in 2018 (European Commission, 2018). Alongside the European bioeconomy definition and strategy, we can observe countless others, mainly at the national level in Italy

(Comitato Nazionale per la Biosicurezza, le Biotecnologie e le Scienze della Vita [CNBBSV], 2019), Finland (Luoma et al., 2011), Netherlands (Langeveld et al., 2016), Germany (Federal Ministry of Education and Research [BMBF], and Federal Ministry of Food and Agriculture [BMEL], 2020), or Spain (Ministerio de Economia y Competitividad, 2021). Bioeconomy consists of traditional sectors (Ronzon et al., 2017), such as agriculture, forestry, aquaculture, and the production of paper and wood-related goods. On the other hand, innovative sectors emerged, especially bioenergy, biofuels, and biochemicals. A comprehensive summary of national bioeconomy policy developments since 2018 displays the EU Bioeconomy Strategy Progress Report (European Commission, 2022b).

As a renewable segment of the circular economy, the bioeconomy incorporates forestry as one of its pillars. Then, the forest bioeconomy becomes a feature of a climate-neutral economic system (Harrison et al., 2022). Besides carbon sinks in the form of carbon sequestration in soils and wood products, forests substitute fossil and non-renewable sources of biomass (Hetemäki et al., 2022). The economic, ecological, and social value of the forests, multifunctional natural renewable resources, can be seen in market and non-market services, such as water control, soil protection, climate regulation, recreation, landscape formation, and wildlife (Farnworth et al., 1981). In many cases, the valuable benefits provided by the forests are public goods and externalities. Forest ecosystem services analyzed Merlo and Croitoru (2005), Sisak (2006), Ciccarese et al. (2012), Börner et al. (2017), and Winkel et al. (2022). The current state of forests is summarized in the Global Forest Goals Report (United Nations Department of Economic and Social Affairs, and United Nations Forum on Forests Secretariat, 2021).

Although climate change is an issue that requires addressing and the bioeconomy, particularly the forest bioeconomy, is relevant, it is still not sufficiently recognized and promoted in some countries (European Commission, 2022b). In this respect, these are mainly Central and Eastern European countries, and the Czech Republic is one of them. Bioeconomy as well as forest bioeconomy, is dedicated to the sustainable management of natural resources, increased use of renewable resources (wood biomass), and the creation of new jobs while striving to adapt and mitigate climate change (European Commission, 2018). Unlocking the potential of the bioeconomy continues to be a worldwide challenge, not least in forestry (Hetemäki et al., 2022). For this reason, this study focuses on the Czech Republic and its analysis of the forest bioeconomy.

In general, the Czech Republic is classified as a non-specialized bioeconomy (Ronzon et al., 2015), and has not yet developed a bioeconomy strategy at a national level. However, there are several documents that address the bioeconomy in a marginal manner. For example, the Strategic Framework of the Czech Republic 2030 (Ministry of the Environment of the Czech Republic, 2021), the Strategy of the Department of the Ministry of Agriculture of the Czech Republic with an Outlook up to 2030 (eAgri, 2023b), Research and Innovation Strategy for the Smart Specialization of the Czech Republic (Ministerstvo průmyslu a obchodu, 2022), and The Czech Republic's Innovation Strategy for 2019–2030 (Úřad vlády, Rada pro výzkum, vývoj a inovace, 2019). The forest bioeconomy performs an essential task in such national strategies.

The Czech Republic operates a rather complex and extensive system of financial support for forestry. The core financial support scheme for forestry is composed of two principal funding sources: (1) national sources based on the Forestry Act No. 289/1995 Coll., on forests and on the amendment and addition of certain laws (eAgri, 2023a), and (2) European funds within the Rural Development Programme (Ministry of Agriculture, 2021).

In the case of the national sources, the ability to support forest management is specified in Section 46 of the Forestry Act. This establishes that the State, in particular through the Ministry of Agriculture, stimulates forest management by providing services and financial contributions or subsidies. We can monitor various subsidy programs (Ministry of Agriculture of the Czech Republic, 2022a) of the Ministry of Agriculture for forestry, such as (1) financial contributions for forest management granted from the budget of the Ministry of Agriculture; (2) state financial obligations under the Forestry Act–mandatory expenditures; (3) subsidies for protection and reproduction of the gene pool of forest trees; (4) support from the Agricultural and Forestry Support and Guarantee Fund; (5) services with which the state supports forest management; (6) partial refund excise duty on diesel fuel consumed during forest management. Table 1 shows the comprehensive summary of financial support from national sources for forestry in the Czech Republic.

TABLE 1 Summary of the financial support from national sources for forestry.

Financial support	Specific type
Financial contributions for forest management granted from the budget of the Ministry of Agriculture	Financial contributions for reforestation, establishment, and tending of forest stands Financial contributions for green and environmentally friendly technologies Financial contributions for the elaboration of forest management plans Financial contributions for forest protection
State financial obligations under the Forestry Act–mandatory expenditures	Improvement and strengthening of wood species Activities of a professional forest manager Costs s for processing forest management plans Improvement and damming of streams in forests
Subsidies for protection and reproduction of the gene pool of forest trees	Gene base support Support of plant parents, ortets, and clones Support for seed sets and clone mixes Support for the activities of the National Bank of Seeds and Explants of forest trees
Support from the Agricultural and Forestry Support and Guarantee Fund	Interest support (reduction of interest burden) of investment loans Direct provision of preferential forestry investment loans
Services with which the state supports forest management	Aerial liming and fertilization, including monitoring Aerial firefighting and fire brigade Monitoring and forecasting the occurrence and development of harmful agents Consultancy Other services
Partial refund excise duty on diesel fuel consumed during forest management	

Source: authors, based on Ministry of Agriculture of the Czech Republic, 2022a.

Concerning European funds within the Rural Development Programme, financial support is directed toward diverse aspects of forestry. Specific topics of financial support under the Rural Development Programme 2014–2020 and 2007–2013 are listed in Table 2.

Besides subsidies, the Czech Republic implements also other economic and financial instruments, such as emission trading (since 2005, as a part of EU emission trading system ETS), environmental taxation, and feed-in tariffs for renewable energy sources. Feed-in tariffs are distinguished, based on the type of renewable energy source, and are published every year by the Energy Regulatory Office of the Czech Republic.

The issue of financial support for forestry in the Czech Republic has been dealt with in several studies, namely Šišák (2007, 2013), Lojda (2014), Kotecký (2015), and Rinn and Jarský (2022). Subsequently, the Concept of State Forestry Policy until 2035 (Ministry of Agriculture of the Czech Republic, 2020) aims to increase biodiversity and ecological stability of forest ecosystems while keeping industrial manufacturing in line with ongoing climate change. Sustainable forest management and financial support for owners to manage their forests in a sustainable manner is therefore a long-term ambition. In general, the Ministry of Agriculture report (Ministry of Agriculture of the Czech Republic, 2022b) shows an analysis of the current state of financial support in the Czech Republic.

Financial support is necessary for the development of the forestry sector of the bioeconomy. On the other hand, other economic and financial instruments are also important and represent a suitable mix for influencing the behavior of economic subjects. Based on the literature review, the analysis of the simultaneous impact of all economic and financial instruments on the forestry sector in the Czech Republic is still missing. This study tries to fill this gap.

2. Materials and methods

2.1. Materials

For the period 2000–2020, we collected detailed secondary data regarding the impact of current economic and financial instruments on forestry in the Czech Republic. Forestry is represented by 2 indicators, the first is forest land in hectares, and the second is wood biomass production in cubic meters. Subsidies are represented by (1) national public financing of forestry (including state financial obligations under the Forestry Act, financial contributions for forest management granted from the budget of the Ministry of Agriculture, subsidy for protection and reproduction of the gene pool of forest trees) and (2) financial aid co-financed by the European Union (Rural Development Programme 2007–2013, Rural Development Programme 2014–2020). Regarding other economic and financial instruments, they are represented by environmental investments in biodiversity, environmental taxes, and the price of EUA (European Union Allowance). A variety of data sources were employed, in particular from the Ministry of Agriculture, Eurostat (Eurostat, 2022), Czech Statistical Office (Czech Statistical Office, 2022), and Energy Regulatory Office (Energy Regulatory Office, 2021). Table 3 gives an outline of all data/variables involved in correlation and/or regression analyses reported in this paper, specifying abbreviations, units, and the roles of the variables.

The first key dependent variable is "FOL," i.e., forest land, in total, in hectares. The second one is "WBIO," i.e., wood biomass production, in total, in cubic meters. These variables represent the forestry sector. Forest land is an indicator of the total area of forest and wood biomass production represents total roundwood removals.

Independent variables are selected with respect to their expected influence the on development of the forest bioeconomy. Specifically, independent variables describe economic and financial instruments currently applied in the bioeconomy sector in the Czech Republic, such as state financial obligations under the Forestry Act, financial contributions for forest management granted from the budget of the Ministry of Agriculture, subsidies for protection and reproduction of the gene pool of forest trees and Rural Development Programme, tradable emission allowances (the price of EUA) and environmental taxes (income from environmental taxes imposed in forestry sector).

Table 4 shows the expected impact of variables. Regarding the first dependent variable, forest land, we can expect a positive impact of all grants and subsidies (national public financing of forestry and Rural Development Programme), and a positive impact of environmental investments in biodiversity, similar to studies by España et al. (2022), or Rinn and Jarský (2022). Concerning the impact of revenues from environmental taxes and EUA price on forest land, we can suggest that it is not clear.

Based on Zhurakovska et al. (2021), an increasing tax payment results in an increased volume of harvesting, even though taxes are supposed to motivate the economic use of forest resources. Barua et al. (2012) demonstrate that forestry income taxes might be ineffective in limiting forest loss. On the other hand, carbon payments can effectively reduce forest clearing. It is similar to the results of Kerr et al. (2012), noting the effect of incorporating forestry into the ETS. However, Evison (2017) concluded that participation in the New Zealand Emission Trading Scheme (NZ ETS) is unlikely to deliver positive long-term effects on the forestry sector and appears not to be the appropriate instrument to encourage the planted forest increment. Pukkala (2020) analyzed the carbon pricing impact on optimal forest management and highlighted that rising carbon prices boost the rate of carbon sequestration. Moreover, a payment of 150 EUR per Mg^{-1} of carbon stored in forests would lead to a stop to cutting.

Focusing on the second dependent variable, wood biomass production, the expected impact of all grants and subsidies (national public financing of forestry and Rural Development Programme), and environmental investments in biodiversity is positive. Such expectation is based on Kanzian and Kindermann (2013), Moiseyev et al. (2014), and Locoh et al. (2022).

Wood biomass production represents roundwood removals as a native form of wood extracted from forests from planned harvesting and incidental logging (Forest Europe, 2020). Firstly, wood material can replace emission-intensive ones while storing carbon in long-lived harvested wood products (European Commission, 2021a). The positive effects of material replacement then depend on the substitution factor (Leskinen et al., 2018). The material use of wood brings opportunities for a circular bioeconomy and cascading use of wood biomass,

TABLE 2 Summary of the European funds within the Rural Development Programme 2014–2020 and 2007–2013.

Rural Development Programme 2014–2020		Rural Development Programme 2007–2013	
No.	Specific support	No.	Specific support
4.3.2	Forestry infrastructure	I.1.2	Investment in forests
8.1.1	Afforestation and reforestation	I.1.2.1	Forestry equipment
8.3.1	Implementation of preventive actions in forests	I.1.2.2	Technical equipment of the establishments
8.4.1	Restoration of forests after calamities	I.1.2.3	Forestry infrastructure
8.4.2	Flood damage repair	II.2.2	Natura 2000 payments in forests
8.5.1	Investment in the protection of ameliorative and reinforcing trees	II.2.3	Forestry-environment payments
8.5.2	Non-productive investments in forests	II.2.3.1	Improving the species composition of forest stands
8.5.3	Conversion of replacement tree plantations	II.2.4	Restoring forest potential after calamities and promoting the social functions of forests
8.6.1	Forestry machinery and technology	II.2.4.1	Restoring forest potential after calamities and introducing preventive measures
8.6.2	Technical equipment for wood processing plants	II.2.4.2	Non-productive investments in forests
15.1.1	Preservation of the stand type of the economic ensemble		
15.2.1	Protection and reproduction of the forest tree gene pool		

Source: authors, based on Ministry of Agriculture of the Czech Republic, 2022b.

TABLE 3 List of variables.

Variable	Abbreviations	Units	Role
Forest land	FOL	Hectares (Ha)	Dependent
Wood biomass production	WBIO	Cubic meters (m^3)	Dependent
Price of European Union Allowance	EUA	CZK Mg^{-1} CO_2	Independent
Environmental investments in biodiversity	INV	Million CZK	Independent
Revenues from environmental taxes imposed in forestry	TAX	Million CZK	Independent
State financial obligations under the Forestry Act (mandatory expenditures)	OBL	Million CZK	Independent
Financial contributions for forest management	CON	Million CZK	Independent
Subsidies for protection and reproduction of the gene pool of forest trees	SUB	Million CZK	Independent
Subsidies from Rural Development Programme	RDP	Million CZK	Independent
Time	TIME	Years	Control

Source: authors.

where closed loops of materials are created, the added value of inputs is maximized, and the lifetime of outputs is extended (Rüter et al., 2016). A synergy of wood biomass usage in downstream industries such as textiles, chemicals, and pharmaceutics is evident and boosts the forest-based bioeconomy (Martinez de Arano et al., 2018). Secondly, wood biomass in place of fossil fuels can achieve greenhouse gases (GHG) emissions cuts and assist in the decarbonisation of the economy (IUFRO, 2005). The value of wood biomass production is maximized by meeting both material and energy requirements using the same raw material (IUFRO, 2014). In this respect, scaling up GHG removals by harvested wood products, as well as decreasing GHG emissions by material and energy substitution can mitigate climate change (Nabuurs et al., 2017).

In terms of material and energy use of wood biomass, the following studies can be found, Martinez de Arano et al. (2018) deal with financing approaches for forest-based products. Lenglet et al. (2017) work with implications of subsidies and taxation on material flows within the forest wood supply chain. Based on raw wood products, Zhai and Kuusela (2022) highlight that taxes generate revenue while resulting in losses in the forestry sector.

TABLE 4 Expected impact of variables in FOLM and WBIOM.

Variable	Abbreviations	Expected impact	
		FOLM	WBIOM
Price of European Union Allowance	EUA	Not clear	Positive
Environmental investments in biodiversity	INV	Positive	Positive
Revenues from environmental taxes imposed in forestry	TAX	Not clear	Not clear
State financial obligations under the Forestry Act (mandatory expenditures)	OBL	Positive	Positive
Financial contributions for forest management	CON	Positive	Positive
Subsidies for protection and reproduction of the gene pool of forest trees	SUB	Positive	Positive
Subsidies from Rural Development Programme	RDP	Positive	Positive
Time	TIME	Positive	Positive

Source: authors.

TABLE 5 Overview of the data statistics.

Variable	Abbreviations	Minimum	Maximum	Standard deviation	Median
Forest land	FOL	2,637,289.00	2,678,804.16	12,967.29	2,658,606.50
Wood biomass production	WBIO	14,374,001.00	35,753,599.00	6,279,539.76	15,882,010.65
Price of European Union Allowance	EUA	41.64	1,355.69	312.67	336.37
Environmental investments in biodiversity	INV	177.63	1,549.00	368.93	422.58
Revenues from environmental taxes imposed in forestry	TAX	526.02	819.16	92.63	645.02
State financial obligations under the Forestry Act (mandatory expenditures)	OBL	185.90	306.90	35.79	237.80
Financial contributions for forest management	CON	176.00	8,187.00	1,923.52	356.5
Subsidies for protection and reproduction of the gene pool of forest trees	SUB	3.93	20.00	5.37	15,13
Subsidies from Rural Development Programme	RDP	9.72	625.95	217.42	403.63

Source: authors.

Jinggang and Peichen (2017) display that a higher carbon price would tend to higher forest carbon stocks. Concerning the impact of revenues from environmental taxes and EUA price on wood biomass production, we can suggest that in the case of taxation, it is not clear. Regarding EUA price, the expected impact is positive. Moiseyev et al. (2014) indicate that a high CO_2 price can support wood biomass production. Caurla et al. (2013) underlined that a carbon tax necessarily reduces consumer surpluses by pushing up the price of wood products. The combination of a carbon tax with sectoral policies is necessary. Based on Lauri et al. (2012), a higher carbon price can increase wood-based energy production. Sasaki (2021) concludes that facilitating global policies, upcoming sustainability markets, and financial stimulus via a carbon tax, environmental tax, and energy tax are able to promote sustainable forest management for long-term timber production and climate change mitigation.

Time represents the control variable. Based on statistics, the expected impact is positive (both forest land and wood biomass production increased in the selected period).

Table 5 summarizes the parameters of all variables described in Table 1. The minimum and maximum values, standard deviation, and median are given for each variable.

2.2. Methods

The main goal of this paper is to explain the impact of economic and financial instruments of the climate change policy on the development of the forestry sector in the Czech Republic in the period 2000–2020.

Keeping in consideration the main goal of the research, the research questions were set as follows. The first research question focuses on forest bioeconomy development (RQ1): Do current economic and financial instruments of the climate change policy have a positive impact on the development of the forest bioeconomy in the Czech Republic?

The second research question observes the drivers of bioeconomy renewable resources (RQ2): Are current economic and financial instruments of the climate change policy stimulating drivers for the increase in the use of bioeconomy renewable resources, such as wood biomass?

The third research question deals with the environmental effectiveness of selected policy instruments (RQ3): Are economic and financial instruments of the climate change policy environmentally effective?

To accomplish the research objectives, we followed the following workflow: (1) literature review and data collection; (2) quantitative analysis; (3) results evaluation and discussion.

Firstly, we conducted a rigorous literature review and collected the necessary data. The data are described in detail in the section "2.1. Materials." We adapted the data and time series to a format suitable for Excel.

In the next step, we performed quantitative analysis, specifically time series analysis, correlation analysis, and regression analysis. The data and time series were analyzed and their characteristics were evaluated. Since the data have a linear relationship and normal distribution, correlation analysis was performed using Pearson's correlation coefficient (Zimmermannova et al., 2016). The bivariate correlation is used to obtain a correlation coefficient that describes the measure of the relationship between two linear variables. Subsequently, we perform more complex regression analysis and construct regression models to observe also partial relationships of variables. Regression analysis enables to obtain the relationship between the dependent variables and all other variables.

Considering above-defined research questions, the following regression models were constructed and tested:

(1) forest land model (FOLM), focused in particular on the development of the forest bioeconomy;
(2) wood biomass production model (WBIOM), focused in particular on the use of bioeconomy renewable resources, such as wood biomass.

The regression equation of such models is as follows:

$$\mathrm{FOL/WBIO} = \beta 0 + \beta 1^{*}\mathrm{EUA} + \beta 2^{*}\mathrm{INV} + \beta 3^{*}\mathrm{TAX} + \beta 4^{*}\mathrm{OBL} + \beta 5^{*}\mathrm{CON} + \beta 6^{*}\mathrm{SUB} + \beta 7^{*}\mathrm{RDP} + \beta 8^{*}\mathrm{TIME} + u \quad (1)$$

where:

Y-FOL (forest land, in total, in Ha) or Y-WBIO (wood biomass production, in total, in m^3); X1—EUA (the price of the European Union Allowance); X2—INV (environmental investments in biodiversity); X3—TAX (revenues from environmental taxes imposed in forestry); X4—OBL (state financial obligations under the Forestry Act); X5—CON (financial contributions for forest management); X6—SUB (subsidy for protection and reproduction of the gene pool of forest trees); X7—RDP (subsidies from Rural Development Programme); X8—TIME (time in years); u—random element of the model.

Firstly, the model containing all economic and financial instruments (FOLM or WBIOM) was created. FOLM/WBIOM is the composition of all independent variables (EUA, INV, TAX, OBL, CON, SUB, RDP, and TIME). Secondly, alternative models were run to seek the statistically most significant model with a high index of determination.

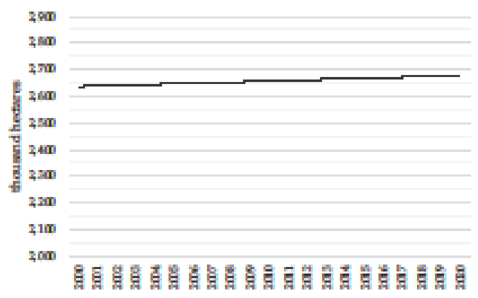

FIGURE 1
Development of total forest land in the Czech Republic. Source: authors, based on (Czech Statistical Office, 2022).

Finally, all results were verified using multiple tests. Based on the tests performed, the models were adjusted to be statistically significant, free of autocorrelation, and with a high degree of determination. In particular, the F-test and Durbin–Watson test were used to test the models developed. The F-test of overall significance examined the fit of the regression models. The Durbin–Watson test (DW) was performed to test for autocorrelation, using Durbin–Watson significance tables (Durbin–Watson Significance Table, 2023). The Durbin–Watson test is a frequently used method for testing autocorrelation, which generates a test statistic within the range of 0 to 4. If the value is close to 2, then the data indicates less autocorrelation. On the other hand, if the value is closer to 0 or 4, it implies stronger positive or negative autocorrelation, respectively.

The details of each model and the corresponding tests are described below in the section "3. Results."

3. Results

3.1. Forest land model

Firstly, Figure 1 provides the development of total forest land in the Czech Republic in the period 2000–2020. Regarding data, a positive trend is visible. In detail, forest land has a slight growing tendency, and 2.68 million hectares are indicated at the end of the monitoring period.

Secondly, all of the selected variables that were considered to affect forest land were chosen for correlation analysis. In Table 6, the outcome of the correlation analysis is presented. According to the correlation analysis findings, we notice a statistically significant negative correlation between FOL and TAX. Besides the above links, negative correlations with lower statistical significance exist, such as INV.

Statistically significant positive correlations can be seen in the case of SUB and control variable TIME. Besides the above links, positive correlations with lower statistical significance exist, such as CON, EUA, and RDP.

For regression analysis, the regression model FOLM was developed. Firstly, the model containing all economic and financial instruments (FOLM) was verified. Secondly, alternative models

TABLE 6 FOLM—correlation analysis.

	FOL	EUA	INV	TAX	OBL	CON	SUB	RDP	TIME
FOL	1								
EUA	0.3102	1							
INV	−0.5548	0.3700	1						
TAX	−0.7642	0.1626	0.1817	1					
OBL	0.0272	0.6517	0.3451	0.3403	1				
CON	0.4907	0.6546	−0.0248	−0.0487	0.6292	1			
SUB	0.8321	0.6417	−0.0560	0.0031	0.6370	0.4930	1		
RDP	0.2941	0.3663	−0.0985	0.3019	0.7925	0.4856	0.7268	1	
TIME	0.9991	0.3382	−0.5415	−0.7562	0.0394	0.5020	0.8442	0.3207	1

Source: authors.

TABLE 7 FOLM—regression analysis.

	FOLM		FOLM1		FOLM2	
	Sig.	Coef.	Sig.	Coef.	Sig.	Coef.
EUA	0.041	−0.761	0.000	−2.498	0.004	−0.809
INV	0.981	0.009	0.004	2.282		
OBL + CON + SUB	0.763	−0.016				
RDP	0.025	−1.002			0.008	1.038
TIME	0.000	2,047.933	0.000	2,053.154	0.000	2,045.343
Constant	0.000	−1,458,298.718	0.000	−1,469,452.780	0.000	−1,453,074
Observ.	17		13		17	
R2	0.999		0.999		0.999	
Signif. F	0.000		0.000		0.000	
Durbin–Watson test	1.722		2.180		1.747	

Source: authors.

TABLE 8 WBIOM—correlation analysis.

	WBIO	EUA	INV	TAX	OBL	CON	SUB	RDP	TIME
WBIO	1								
EUA	0.631	1							
INV	−0.145	0.370	1						
TAX	−0.350	0.163	0.182	1					
OBL	0.507	0.652	0.345	0.340	1				
CON	0.822	0.655	−0.025	−0.049	0.629	1			
SUB	0.722	0.642	−0.056	0.003	0.637	0.493	1		
RDP	0.558	0.366	−0.099	0.302	0.793	0.486	0.727	1	
TIME	0.721	0.338	−0.542	−0.756	0.039	0.502	0.844	0.321	1

Source: authors.

were run to seek the statistically most significant model with a high index of determination (FOLM1 and FOLM2).

Forest land model (FOLM) is the composition of all independent variables (EUA, INV, TAX, OBL, CON, SUB, RDP, and TIME). While the entire model is statistically significant, not all of the selected variables are statistically significant. The result of the Durbin–Watson test (DW) for FOLM is acceptable (1.722).

FOLM1 and FOLM2 represent selected variables with a statistical significance of $p < 0.05$. These models are statistically significant models—all of the variables are statistically significant, and the entire model is statistically significant as well. In Table 7, the outcomes imply a high coefficient of determination in both models. Meaning that for FOLM1 and FOLM2, the general formula that is specified explains more than 99% of the variance with less than 5% of random deviations. Variables with a p-value of below 5% are EUA, INV, TIME, and the constant (FOLM1) and EUA, RDP, TIME, and the constant (FOLM2). To the results of the overall F-test, the estimated regression forest land models are statistically

TABLE 9 WBIOM—regression analysis.

	WBIOM1		WBIOM2		WBIOM3		WBIOM4		WBIOM5	
	Sig.	Coef.	Sig.	Coef.	Sig.	Coef.	Sig.	Coef.	Sig.	Coef.
EUA	0.015	9,346.138								
TAX			0.044	42,667.350						
OBL					0.001	83,999.409				
CON							0.000	2,008.576		
RDP									0.049	11,193.506
TIME	0.002	776,395.806	0.000	2,177,209.912	0.000	678,486.466	0.003	398,034.953	0.003	817,573.294
Constant	0.002	−1,546,584,115	0.000	−4,392,833,128	0.000	−1,365,270,547	0,003	−783,415,440.5	0,003	−1,629,508,948
Observ.	17		13		22		22		17	
R2	0.835		0.864		0.865		0.896		0.805	
Signif. F	0.000		0.001		0.000		0.000		0.001	
Durbin–Watson test	1.262		0.784		0.614		1.050		0.584	

Source: authors.

significant at 5% (FOLM1 and FOLM2) levels of significance. The finding of the Durbin–Watson test (DW) for FOLM1 shows no positive autocorrelation (DW 2.180 > upper critical value 1.816), and for FOLM2 also no positive autocorrelation (DW 1.747 > upper critical value 1.710).

According to the FOLM1 outputs (Table 7), a statistically significant negative relationship between FOL and EUA and a statistically significant positive relationship between FOL and INV, and TIME is observed.

The following regression equation can be built:

$$Y\,(FOLM1) = -1,469,453.780 - 2.498\,EUA + 2.282\,INV + 2,053.154\,TIME + u \quad (2)$$

According to the FOLM2 outputs (Table 7), a statistically significant negative relationship between FOL and EUA and RDP and a statistically significant positive relationship between FOL and TIME is observed.

The following regression equation can be built:

$$Y\,(FOLM2) = -1,453,074 - 0.809\,EUA - 1.038\,RDP + 2,045.343\,TIME + u \quad (3)$$

Based on the results, it can be stated that in the monitored period there was an increase in forest land in hectares in the Czech Republic, which was positively influenced by environmental investments in biodiversity (CZK million) and negatively by subsidies from the Rural Development Programme (CZK million) and the price of EUA (CZK). Thus, 100 million CZK (4.07 million EUR) (Česká národní banka, 2023) of environmental investments in biodiversity would contribute to an increase of 228 hectares of forest land.

3.2. Wood biomass production model

All of the selected variables that were considered to affect wood biomass production were chosen for correlation analysis. In Table 8, the outcome of the correlation analysis is presented.

According to the correlation analysis findings, we notice a statistically significant positive correlation between WBIO, CON, SUB, EUA, RDP, OBL, and control variable TIME.

Besides the above links, negative correlations with lower statistical significance exist, such as INV and TAX.

For regression analysis, the following submodels were developed. Firstly, the model containing all economic and financial instruments was verified (WBIOM). Secondly, alternative models were run to seek the statistically most significant model with a high index of determination. Therefore, the following five submodels were developed: WBIOM1—EUA and TIME, WBIOM2—TAX and TIME, WBIOM3—OBL and TIME, WBIOM4—CON and TIME, and WBIOM5—RDP and TIME.

The results are presented in Table 9.

WBIOM1-WBIOM5 represents selected variables with a statistical significance of $p < 0.05$. These models are statistically significant models—all of the variables are statistically significant, and the entire model is statistically significant as well. In Table 9 the outcomes imply a high coefficient of determination in models. Meaning that the general formula that is specified explains almost 84% (WBIOM1), around 86% (WBIOM2), almost 87% (WBIOM3), almost 90% (WBIOM4), and almost 81% (WBIOM5) of the variance with less than 5% of random deviations. Variables with a p-value of below 5% are EUA, TIME, and the constant (WBIOM1); TAX, TIME, and the constant (WBIOM2); OBL, TIME, and the constant (WBIOM3); CON, TIME, and the constant (WBIOM4); and RDP, TIME, and the constant (WBIOM5). To the results of the overall F-test, the estimated regression wood biomass model WBIOM1-WBIOM5 is statistically significant at a 5% level of significance. The result of the Durbin–Watson test (DW) is acceptable only for WBIOM1, for other models WBIOM2-WBIOM5 the results show positive autocorrelation, and DW is under the lower critical value.

According to the WBIOM1-WBIOM5 outputs, the following regression equations can be built:

$$Y\ (\mathrm{WBIOM1}) = -1,546,584,115 + 9,346.138\ \mathrm{EUA} + 776,395.806\ \mathrm{TIME} + u \quad (4)$$

$$Y\ (\mathrm{WBIOM2}) = -4,392,833,128 + 42,667.350\ \mathrm{TAX} + 2,177,209.912\ \mathrm{TIME} + u \quad (5)$$

$$Y\ (\mathrm{WBIOM3}) = -1,365,270,547 + 83,999.409\ \mathrm{OBL} + 678,486.466\ \mathrm{TIME} + u \quad (6)$$

$$Y\ (\mathrm{WBIOM4}) = -783,415,440.5 + 2,008.576\ \mathrm{CON} + 398,034.953\ \mathrm{TIME} + u \quad (7)$$

$$Y\ (\mathrm{WBIOM5}) = -1,629,508,948 + 11,193.506\ \mathrm{RDP} + 817,573.294\ \mathrm{TIME} + u \quad (8)$$

On the basis of the results, it can be concluded that in the monitored period there was an increase in wood biomass production in cubic meters in the Czech Republic, which was positively influenced by a mixture of all economic and financial instruments, such as emission trading, environmental taxation, financial contributions for forest management, state financial obligations and subsidies. Thus, an increase in the price of an emission allowance by 100 CZK Mg^{-1} (approximately 4 EUR Mg^{-1}) (Česká národní banka, 2023) would increase wood biomass production by approximately 934,614 cubic meters.

4. Discussion

Based on the results presented in the previous chapter, we can focus on answering our research questions gradually.

> RQ1: Do current economic and financial instruments of the climate change policy have a positive impact on the development of the forest bioeconomy in the Czech Republic?

For this research question, the forest bioeconomy is represented by the indicator "forest land." The regression analysis results displayed a statistically significant negative relationship between forest land and the price of the European Union Allowance and Rural Development Programme. On the contrary, a statistically significant positive relationship between forest land and environmental investments in biodiversity was observed.

Regarding "forest land" variable, we expected a positive impact of all grants and subsidies (national public financing of forestry and Rural Development Programme), and a positive impact of environmental investments in biodiversity, similar to studies by España et al. (2022), or Rinn and Jarský (2022). Concerning the impact of revenues from environmental taxes and EUA price on forest land, we suggested that it is not clear, based on the scientific studies of Barua et al. (2012), Ersoy and Mack (2012), Evison (2017), Pukkala (2020), Zhurakovska et al. (2021), España et al. (2022), and Jensen et al. (2022).

Comparing expectations and results, the positive impact of environmental investments in biodiversity is visible; meanwhile, for the Rural Development Programme the negative impact is demonstrated. The total influence of national public financing is not clear. Contrary to expectations, the impact of the EUA price is negative. The impact of environmental taxes is not clear, which is consistent with the expectation.

Carbon payments can effectively reduce forest clearing, similar to the study by Kerr et al. (2012). Pukkala (2020) analyzed the carbon pricing impact on optimal forest management and highlighted that rising carbon prices boost the rate of carbon sequestration. Moreover, a payment of 150 EUR per Mg^{-1} of carbon stored in forests would lead to a stop to cutting. Based on Zhurakovska et al. (2021), an increasing tax payment results in an increased volume of harvesting, even though taxes are supposed to motivate the economic use of forest resources. Barua et al. (2012) demonstrate that forestry income taxes might be ineffective in limiting forest loss. Regarding forest land, the New Zealand Emission Trading Scheme (NZ ETS) is unlikely to generate positive long-term influences on the forestry sector and would not be the appropriate instrument to promote the planted forest expansion Evison (2017). Results (España et al., 2022) display a statistically and economically significant positive impact of government subsidies on forest cover, causing an expansion of the forested area by approximately 13% in comparison with the alternative scenario excluding subsidies. Similarly, the research (Ersoy and Mack, 2012) identifies that subsidies have a positive influence on the technical efficiency of public forestry firms. Further, Jensen et al. (2022) examine forest owners' voluntary subsidies in the presence of imperfect information. On the other hand, the study by Aoyagi and Managi (2004) concludes that government subsidies have a negative influence on the economic activity of the forestry sector and more subsidized entities have lower levels of efficiency.

Generally, the Czech Republic fits into the European temperate forest zone (Rivas-Martinez et al., 2004). Forest land area in the Czech Republic is constantly rising (Czech Statistical Office, 2022). In 2021, the area of forest land increased by 1,475 hectares compared to 2020. Hence, the total forest land area was more than 2.68 million hectares in 2021, representing around 35% of the land area (Ministry of Agriculture of the Czech Republic, 2022b). In the Czech Republic, management forests dominate, covering 74.1% of forest land. This is followed by special purpose forests (23.9%) and protective forests (2.1%). Considering the composition of the forests, coniferous forests (69.6%) predominate over broadleaved forests (28.7%). The most abundant coniferous species are spruce (48.1%) and pine (16%). For broadleaved forests, the dominant is the beech (9.3%) and oak (7.6%) The ownership scheme differs, while the majority of Czech forests are owned by the state (56%). This is followed by natural persons (19.12%), municipalities and municipal forests (17.19%), legal entities (3.41%), church forests and forests of religious societies (5.32%), and forest cooperatives (1.19%).

In summing up the perspective of the forestry sector in the Czech Republic, a further increment in forest land and economic and financial support can be expected. Regarding forest land, building on previous periods and positive trends (Ministry of Agriculture of the Czech Republic, 2022b) while strengthening the role of sustainable development and the bioeconomy, both at the national and European levels, is evident (Luoma et al., 2011; Carus, 2012; European Commission, 2012, 2018, 2019, 2021b,c,d,e, 2022a; van Leeuwen et al., 2014; Langeveld et al., 2016; Loiseau et al., 2016; D'Amato et al., 2017; Loiseau et al., 2016; D'Amato et al., 2017; Ronzon et al., 2017; Wesseler and von Braun, 2017; Birner, 2018; Bracco et al., 2018; Ramcilovic-Suominena and Pülzlb, 2018; Comitato Nazionale per la Biosicurezza, le Biotecnologie e le Scienze della Vita [CNBBSV], 2019; Federal Ministry of Education and Research [BMBF], and Federal Ministry of Food and Agriculture [BMEL], 2020; Mittra and Zoukas, 2020; Barañano et al., 2021; Kardung and Drabik, 2021; Ministerio de Economia y Competitividad, 2021; Harrison et al., 2022; Hetemäki et al., 2022; United Nations, 2022). According to the economic and financial instruments for the forest bioeconomy, there are crucial elements for moving forward, such as governmental support, oriented research, and technology development (Hájek et al., 2021). Therefore, new knowledge and innovations can be seen as a major driver of the forest bioeconomy progress. This is expected to stimulate an upturn in new jobs related to renewable energy and/or bio-based products (Perunová and Zimmermannová, 2022).

> RQ2: Are current economic and financial instruments of the climate change policy stimulating drivers for the increase in the use of bioeconomy renewable resources, such as wood biomass?

The outcome of the regression analysis indicated a statistically significant positive relationship between wood biomass production and the price of European Union Allowance, revenues from environmental taxes–in forestry, state financial obligations under the Forestry Act, financial contributions, and the Rural Development Programme. However, the DW test is acceptable only in the case of the price of European Union Allowance, other results/indicators show characteristics of autocorrelation.

Focusing on wood biomass production, the expected impact of all grants and subsidies (national public financing of forestry and Rural Development Programme), and environmental investments in biodiversity was positive. Such expectation is based on Kanzian and Kindermann (2013), Moiseyev et al. (2014), and Locoh et al. (2022). Concerning the impact of revenues from environmental taxes and EUA price on wood biomass production, we can suggest that in the case of taxation, it is not clear. Regarding EUA price, the expected impact is positive. Based on the following scientific studies Lauri et al. (2012), Caurla et al. (2013), Moiseyev et al. (2014), and Sasaki (2021).

Comparing results and expectations, the positive impact of all grants and subsidies (national public financing of forestry and Rural Development Programme) and EUA price is visible. Contrary to expectations, the influence of environmental taxes is positive. The findings are compatible with the summaries of various studies. For example, Moiseyev et al. (2014) indicate that a high CO_2 price can support wood biomass production. Caurla et al. (2013) underlined that a carbon tax necessarily reduces consumer surpluses by pushing up the price of wood products. The combination of a carbon tax with sectoral policies is necessary. Based on Lauri et al. (2012), higher carbon prices can increase wood-based energy production. Sasaki (2021) concludes that facilitating global policies, upcoming sustainability markets, and financial stimulus via a carbon tax, environmental tax, and energy tax are able to promote sustainable forest management for long-term timber production and climate change mitigation. In material utilization, wood biomass serves in the manufacture of all sorts of products as a raw material (Carus et al., 2010). In the circular economy, the cascading use of biomass (Keegan et al., 2013) occurs when biomass is converted to a final product and then reused at least one more time as materials or energy. Cascading use leads to increased resource efficiency if compared to direct energy use. Moreover, from an environmental point of view, long-living wood products provide long CO_2 sequestration, and subsequently cascading use can expand CO_2 sequestration (Hong et al., 2021).

> RQ3: Are economic and financial instruments of the climate change policy environmentally effective?

Based on our results, we can observe a relationship between some economic and financial instruments (subsidies, grants, investments, and emission trading) and indicators connected with the quality of the environment. The influence of the emission trading is ambiguous—in the case of forest land negative, and in the case of wood biomass production positive. Generally, the economic and financial instruments in the Czech Republic have an environmental impact and can influence the forest bioeconomy, at least in the long-term period.

According to van Valkengoed and van der Werff (2022) subsidies worked predominantly as an impulse to act. It seems that subsidy schemes are useful to stimulate early adopters who are already motivated to take action, rather than to mobilize individuals who are not yet willing to undertake concrete climate action. Regarding forest carbon, Evison (Evison, 2017) considered that the New Zealand Emission Trading Scheme (NZ ETS) is unlikely to achieve positive long-term effects on the forestry sector and seems not to be the appropriate tool to foster carbon sequestration by forests. Jinggang and Peichen (2017) show that a higher carbon price would drive higher forest carbon stocks and early tax/subsidy-induced net carbon storage diminishes.

Forests are a crucial carbon sequestration and storage contributor. Trees process carbon dioxide through photosynthesis and store carbon in woody biomass. Forests thus represent essential carbon sinks in the climate system. The difference between gross GHG emissions and gross GHG removals is the net flux, then based on the balance of gross flows, a net source (positive) or net sink (negative) is defined. Based on Harris et al. (2021), between 2001 and 2021, Czech forests emitted $12.6MtCO_2e$/year, on the other hand, removed $-19.8MtCO_2e$/year. This represents a net carbon sink of $-7.19MtCO_2e$/year. Forest carbon fluxes are further analyzed by Hansen et al. (2013) and Hong et al. (2021). Roughly, a larger forest area leads to a higher amount of carbon removed from the atmosphere, which seems to be an effective instrument in the effort to mitigate climate change. Long-life wood construction and furniture can be used as temporary carbon sinks (NOVA-Institute, 2017). In European forests, the biomass stock has increased since

1990, by about 1–2% per year, but its growth has stagnated due to aging processes, the rising impact of natural disturbances, and other climatic factors in the last years (Avitabile et al., 2023). Regarding environmental impacts, scaling up GHG removals by forest land and harvested wood products, as well as decreasing GHG emissions by material and energy substitution seems to be an effective way to mitigate climate change (Nabuurs et al., 2017).

In contrast, ongoing climate change is a driver of many changes in forest ecosystems, resulting in negative consequences, such as species distribution shifts or drought-related tree mortality (Mubareka et al., 2023). Forest disturbances are climate sensitive. For example, Seidl et al. (2017) provide an analysis of the impact of climate change on abiotic (fire, drought, wind, snow, and ice) and biotic (insects and pathogens) disturbances.

Conclusion

The main goal of this paper was to explain the impact of economic and financial instruments of the climate change policy on the development of the forestry sector in the Czech Republic in the period 2000–2020. To accomplish the research objectives, the following methods were applied: literature review, data analysis, correlation analysis, and regression analysis. Several models were established and tested, for example, the forest land models and wood biomass production models.

Regarding the findings, and to answer the research questions, a statistically significant negative relationship between forest land and the price of the European Union Allowance and subsidies from Rural Development Programme and a statistically significant positive relationship between forest land and environmental investments in biodiversity was observed (RQ1). Subsequently, a statistically significant positive relationship between wood biomass production and the price of European Union Allowance, revenues from environmental taxes in forestry, state financial obligations under the Forestry Act, financial contributions, and the subsidies from Rural Development Programme was found (RQ2). Overall, economic and financial instruments in the Czech Republic have environmental impacts and can determine the development of the forest bioeconomy. However, the impact of the emission trading on the forestry sector in the Czech Republic is ambiguous—in the case of forest land negative, and in the case of wood biomass production positive. Therefore, focusing on the policy recommendations, we should underline economic and financial instruments connected with positive motivation in the forestry sector, such as grant schemas, subsidies, and investments in biodiversity.

Regarding the following research, we should focus in more depth on the differences between urban and rural areas. The forest bioeconomy affects the carbon budget and has the potential to contribute to decarbonizing economies, and regions, hence mitigating climate change. In addition to environmental benefits, it also influences socio-economic aspects, such as employment. Economic and financial instruments are an integral part of the development of the forest bioeconomy in the Czech Republic, and their effective utilization is crucial. Therefore, a spatial analysis of current financial instruments in forestry with a focus on the regions of the Czech Republic is desirable.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MP and JZ: conceptualization, validation, writing—original draft preparation, writing—review, and editing. MP: methodology, software, formal analysis, investigation, resources, and data curation. JZ: supervision. Both authors contributed to manuscript revision, read, and approved the submitted version.

Funding

This research was funded by the Non-project Research of the Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague and the Non-project Research of the Faculty of Health Sciences, Palacky University Olomouc.

Acknowledgments

MP participated as part of a research effort to pursue doctoral studies at the Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Czech Republic.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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5.3 Publication no.3: Forest carbon and regional perspective on the effectiveness of financial instrument within the forest bioeconomy

TITLE:	Forest carbon and regional perspective on the effectiveness of financial instrument within the forest bioeconomy
TYPE:	Original Research
AUTHORS:	Michaela Perunová, Jarmila Zimmermannová, Tereza Schovánková
JOURNAL:	Journal of Forest Science
YEAR:	2024
DOI:	In press

Czech Journal of Forest Science
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To whom it may concern: Prague, 26 April 2024

This is to confirm that the manuscript "Forest carbon and a regional perspective on the effectiveness of financial instruments within the forest bioeconomy" (submitted as 24/2024-JFS), authors: Michaela Perunová, Jarmila Zimmermannová and Tereza Schovánková, has successfully passed through the review process and has been accepted for publishing in the Journal of Forest Science.

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Manuscript type: original paper

Forest carbon and a regional perspective on the effectiveness of financial instruments within the forest bioeconomy

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Abstract: The forest bioeconomy links to a climate-neutral economy for which effective economic and financial promotion is essential to sustainable development. The main purpose of the study was to examine the effects of financial support on the development of the forest bioeconomy in the Czech Republic in the period 2000–2021. Research objectives were met by applying literature review, time series analysis, spatial data analysis, cartogram and cartodiagram method, correlation analysis, and regression analysis. Firstly, regional divergences in financial flows were observed. Owing to the bark beetle calamity, the peak of the financial sources was detected in the Vysočina Region (CZK 4,658/EUR 190 per hectare), and the Olomouc Region (CZK 2,780/EUR 113 per hectare) in 2020. An upward trend - more than 6-fold growth of financial flows to forestry was found. Secondly, the forest carbon model was discovered and tested. Financial contribution for reforestation, establishment, and tending of forest stands increases net carbon sinks while financial contribution for green and environmentally friendly technologies increases net carbon sources. Regional carbon reservoirs offer the potential to contribute to climate targets and achieve sustainable progress.

Keywords: forest carbon; financial support; forestry; bioeconomy; circular economy; spatial analysis; regional analysis

INTRODUCTION

Environmental changes worldwide are speeding up and constitute considerable threats to society. Currently, the carbon neutrality of the European Union by 2050 (EC, 2019), compliant with the ambitions of the Paris Agreement (UN, 2022), is a global challenge and would require a long-term engagement, predominantly at the regional scene. Global greenhouse gas (GHG) emissions (IPCC, 2023), result from an unsustainable approach in energy usage, land use, and land-use change, consumption or/and production behavior across regions and national economics. The study by Rae et al. (2021) refers reconstruction of carbon dioxide emissions over the past 66 million years.

The long-term growing GHG concentration reached an all-time peak of 420 parts per million in 2021 (Scripps Institution of Oceanography, 2023). The amplifying feedbacks deflect the climate system in the same direction as the initial disturbance (Cramer et al., 2018). Global warming delivers negative repercussions in the form of extreme weather events, especially droughts, windthrows, heatwaves, etc. (Thrippleton et al., 2022; Scinocca et al., 2016). Finally, the carbon budget (Matthews et al., 2017) is a promising method for setting out the challenge of climate change mitigation.

The carbon cycle explains the flow of carbon into and out of the atmosphere and into living organisms (Porfirio et al., 2010). A cumulative effect displays net sources escalating carbon levels and concentration, due to a linear economy system (Tyson et al., 2001; Wesche and Armitage, 2014).

Anthropogenic carbon sources, such as burning fossil fuels and deforestation, have been increasing since the pre-industrial era (Ford et al., 2012). On the contrary, forests tend to be net carbon sinks (FISE, 2023; Keeling et al., 2011). However, forests can become a net carbon source due to unsustainable management (EC, 2023). Studies centered on forest carbon in specific regions were discovered, such as Zald et al. (2016), Liski et al. (2002), Moser et al. (2022), Miller et al. (2012), and Karppinen et al. (2018).

In each region, forests have different environmental features, states, biodiversity, and challenges in addressing climate change (UN Department of Economic and Social Affairs, and UN Forum on Forests Secretariat, 2021). Simultaneously, regions and their biogeographical characteristics are not stagnant throughout time. Because of climate change, adaptive management decisions could be made (Zimmermannova, 2009; Allen et al., 2010; CENIA, 2022). A range of closer-to-nature approaches are already in use, such as natural regeneration, leaving deadwood, and abandoning the use of pesticides (Hlásny et al., 2017). However, the philosophies are diverse from region to region (Larsen et al., 2022).

Moreover, ongoing climate change is placing pressure on building the forest's ability to flourish in the face of current and changing conditions, enhancing its resilience while storing carbon in trees as well as in the forest soils (IUFRO, 2014a).

Efforts at both regional and global scales are needed while synergies between climatic, forest-based, and societal policies will streamline the process (Nabuurs et al., 2017; Bowditch et al., 2022). The shift from fossil fuels to bioenergy or from carbon-intensive materials to biomass tends to mitigate climate change (IUFRO, 2014b). This requires the development of four key domains Rockström et al. (2017), such as investment, innovation, institutions, and infrastructure.

An integral component of sustainable development includes the bioeconomy concept at the European Union level (European Commission, 2018b). Bioeconomy is primarily rooted in the traditional sectors of the economy, namely agriculture, forestry, aquaculture, and the production of paper and wood-related goods. Nonetheless, innovative sectors are also included, namely bioenergy, biofuels, biotextiles, and biochemicals while their significance is strengthening over time (Ronzon et al., 2017). The study presented by Ronzon et al. (2015) segregates the national economies under (1) agricultural bioeconomies, (2) agro-food industry and bio-based chemical industries, (3) forest bioeconomies, and (4) non-specialized bioeconomies.

Currently, the forest bioeconomy is gaining prominence and is part of a comprehensive set referred to as the 'Fit for 55' package, a toolbox of proposed revisions and new initiatives to ensure that EU policies are aligned with climate targets (European Commission, 2021c). In detail, the New EU Forest Strategy (European Commission, 2021b) focuses on the cascading principle of biomass usage, forest restoration, financial support for forest owners and rural areas, and protection of forest ecosystems.

Alongside the environmental benefits of carbon capture and storage, multifunctional forests fulfill a countless array of ecosystem services, such as climate regulation, water control, soil protection, wildlife, recreation, etc. (Winkel et al., 2022; Börner et al., 2017; Masiero et al., 2018). Frequently, such advantages are delivered as public goods and externalities (Sisak, 2006) while the total economic value indicator attempts to reflect the aggregate quantification of beneficiaries (Merlo and Croitoru 2005). Topically, forest bathing of shinrin-yoku, as a mindful visit to the forest, improves human physical and mental health and prevents the development of various diseases (Wen et al., 2019; Putra et al., 2018; Antonelli et al. 2021; Mao et al. 2017; and Farkic et al., 2021).

The Czech Republic and its regions are a part of the European temperate forest zone (Rivas-Martínez et al., 2004). Forests cover 37% of the territory, approximately 2.68 million hectares in 2022 (CZSO, 2023). Considering the ownership structure, 54% is owned by the state, 21% by individuals, 16% by municipalities, and 9% by other owners. In addition, 74.1 % of Czech forest land is classified as management forests, while 23.9% as special purpose forests and 2.1% as protective forests. The tree species composition contains a significant proportion of spruce (48.1%), pine (16%), beech (9.3%), and oak (7.6%). The Czech Republic clusters into the non-specialized bioeconomy (Ronzon et al., 2015). However, social (Hájek et al., 2021; Perunová and Zimmermannová, 2022) and economic aspects (Perunová and Zimmermannová, 2023) of the forest bioeconomy can be seen. Additionally, the national financial support mechanism for forestry is imprecise, and administratively intensive, which reduces the effectiveness of financial flows for forest owners in the Czech Republic (MoA, 2020).

Typically, the Czech Republic is struggling with the unprecedented negative consequences of the bark beetle calamity (MoA, 2022), rated to be the most devastating in history (Brázdil et al., 2022). A switch from wind-driven to drought-driven outbreak dynamics was observed (Hlásny et al., 2021). For example, the study by Šafařík et al. (2022) provides insight into raw wood growing stocks and forecasts further cuttings according to coniferous stands in the Czech Republic. Secondly, Michalec et al. (2020) analyzed the sale of bark beetle-affected sawmill timber. Finally, Toth et al. (2020) display the relationship linking the incidental harvest volume and the drop in the price of spruce timber. Additionally, since 2015, there have been continuous increases in several indicators, such as the total volume of trees killed by bark beetles, and the total volume of salvage logging (CZSO, 2023; MoA, 2022). These are the principal drivers of the LULUCF sector emissions balance (IPCC, 2023), which have caused negative environmental effects. For this, forest restoration is one of the current regional challenges in the Czech Republic (MoA, 2019).

The literature review identified a range of studies dealing with national funding for forestry in the Czech Republic, for instance, Šišák (2002, 2007, 2013), Lojda and Ventrubová (2015), Kotecký (2015), Perunová and Zimmermannová (2023). The mentioned studies tracked national financial sources and/or other financial and economic instruments at the national level, with no consideration of regional differences. Simultaneously, the studies, such as Hlásny et al. (2021), Brázdil et al. (2022), Šafařík et al. (2022), Michalec et al. (2020), and Toth et al. (2020) examined bark beetle calamity in the Czech Republic, with no regard to regional disparities in financial support. To sum up, studies investigating regional aspects of the national financial sources and/or studies dealing with the economic aspects of bark beetle calamity emphasizing regional differences in the Czech Republic are still absent. This study tries to fill this gap.

MATERIALS AND METHODS

Materials

National financial sources are represented by financial contributions for forest management provided by the budget of the Ministry of Agriculture. The data utilized are not commonly available and are accessible on request. From the extensive datasets received, selected data were extracted and harmonized for the given monitored period.

Other data originated from public databases, including the Eurostat (Eurostat, 2023), the Czech Republic Statistical Office (CZSO, 2023), and the United Nations Framework Convention on Climate Change (UNFCCC, 2023). All figures have been converted according to the EUR/CZK exchange rate applicable on December 17, 2023 (ČNB, 2023).

To determine the impact of different national funding titles on forest carbon storage, several data were collected for the period 2000-2021. The data sources were the CZSO (2023), the UNFCCC database (2023), and the Ministry of Agriculture (data on request).

The presented model operates with GHG emissions/removals of selected sub-categories of the LULUCF sector, namely forest land and harvested wood products.

The independent variables depict the national financial sources implemented in the bioeconomy sector in the Czech Republic, such as financial contribution to the restoration of forests damaged by immission, financial contribution for reforestation, establishment, and tending of forest stands, financial contribution to an association of owners of small forest areas, financial contribution for green and environmentally friendly technologies, financial contribution for the elaboration of forest management plans, financial contribution for forest protection, financial contribution to mitigate the impact of the bark beetle calamity (Table 1).

The expected impact of all national financing sources is positive (Table 2). Such expectation is assumed from He and Ren (2023), Jinggang and Peichen (2017), Pukkala (2020), Dong-Ho et al. (2018), and Bowditch et al. (2022).

Forest carbon (Figure 5) displays a negative range between 1990-2017, which stands for the net sink, and carbon capture and storage in forests and harvested wood products (HWPs) is observed. The reverse tendency shows the timeframe 2018-2021, positive figures denote a net source boosting total GHG emissions.

Table 3 collects the parameters of all variables. The minimum and maximum values, standard deviation, and median are given for each variable.

Table 1 List of variables

Variable	Abbreviation	Units	Role
Forest carbon	FORC	megatonnes of carbon dioxide equivalent (MtCO2eq.)	Dependent
Financial contribution to the restoration of forests damaged by immission	A	million CZK	Independent
Financial contributions for reforestation, establishment, and tending of forest stands	B	million CZK	Independent
Financial contributions to an association of owners of small forest areas	C	million CZK	Independent
Financial contributions for green and environmentally friendly technologies	D	million CZK	Independent
Financial contributions for the elaboration of forest management plans	H	million CZK	Independent
Financial contributions for forest protection	I	million CZK	Independent
Financial contributions to mitigate the impact of the bark beetle calamity	L	million CZK	Independent
Time	TIME	years	Control

Source: authors.

Table 2 Expected impact of variables in FORCM

Variable	Abbrev.	Expected impact FORCM
Financial contribution to the restoration of forests damaged by immission	A	Positive
Financial contribution for reforestation, establishment, and tending of forest stands	B	Positive
Financial contribution to an association of owners of small forest areas	C	Positive
Financial contribution for green and environmentally friendly technologies	D	Positive
Financial contribution for the elaboration of forest management plans	H	Positive
Financial contribution for forest protection	I	Positive
Financial contribution to mitigate the impact of the bark beetle calamity	L	Positive
Time	TIME	Positive

Source: authors.

Table 3 Overview of the data statistics

Abbreviation	Variable	Minimum	Maximum	Standard deviation	Median
FORC	Forest carbon	-9,462,330.399	12,719,417.07	6,358,628.517	-7,180,636.361
A	Financial contribution to the restoration of forests damaged by immission	2,206,000	28,415,000	7,949,890.483	12,668,663.78
B	Financial contribution for reforestation, establishment, and tending of forest stands	100,621,043.4	1,405,096,249	287,694,414.3	222,662,500
C	Financial contribution to the association of owners of small forest areas	1,263,000	4,033,000	1,143,315.689	2,761,000
D	Financial contribution for green and environmentally friendly technologies	14,250,217.22	180,785,676	46,290,996.61	24,769,000
H	Financial contribution for the elaboration of forest management plans	1,900,000	82,300,000	25,318,568.87	29,564,735
I	Financial contribution for forest protection	1,154,956.852	116,321,104	33,015,060.2	3,150,000
L	Financial contribution to mitigate the impact of the bark beetle calamity	979,862,761.1	7,027,364,513	3,051,191,672	3,296,433,478

Source: authors.

Methods

The main purpose of the study is to examine the effects of financial support on the development of the forest bioeconomy in the Czech Republic in the period 2000–2021. With regard to the main target of the research, the following research questions were established.

The first research question deals with the development of selected national financial sources (RQ1): **Can we observe an increasing trend in the amount of financial flows to forestry in the Czech Republic?**

The second research question observes the regional aspect in the forest bioeconomy development (RQ2): **Can we observe regional differences in the amount of financial flows to forestry in the Czech Republic?**

The third research question focuses on the environmental aspect of the forest bioeconomy development (RQ3): **Do financial flows have a positive environmental impact in the Czech Republic?**

In order to meet the research objectives, a literature review, time series analysis, spatial data analysis, cartogram and cartodiagram method, correlation analysis, and regression analysis were applied.
Firstly, a comprehensive literature review and data collection were carried out. Data and time series were modified into a format suitable for Excel.
Secondly, quantitative analysis proceeded, such as time series analysis, spatial data analysis, the cartogram and cartodiagram method, correlation analysis, and regression analysis. The data and time series were analyzed together with their characteristics. Spatial data analysis was performed using QGIS 2.26.3 software. The layer 'Boundaries' from the Topographic database of the Czech Republic (Data200) served as a topographic base.
To demonstrate regional differences in the allocation of national financial sources, a regional analysis approach was used, especially the nomenclature of territorial units for statistics – NUTS level 3 (NUTS3) was applied. The list of the regions in the Czech Republic is introduced in Table 4.

Table 4 Overview of the regions of the Czech Republic

NUTS3	Name	Abbreviation
CZ010	Prague, the Capital City	PRG
CZ020	Central Bohemian Region	CBR
CZ031	South Bohemian Region	SBR
CZ032	Plzeň Region	PLR
CZ041	Karlovy Vary Region	KVR
CZ042	Ústí nad Labem Region	ULR
CZ051	Liberec Region	LBR
CZ052	Hradec Králové Region	HKR
CZ053	Pardubice Region	PAR
CZ063	Vysočina Region	VYR
CZ064	South Moravian Region	SMR
CZ071	Olomouc Region	OLR
CZ072	Zlín Region	ZLR
CZ080	Moravian-Silesian Region	MSR

Source: authors, based on Eurostat (2023).

A correlation analysis using Pearson's correlation coefficient was employed. Hence, a more complex regression analysis was developed and tested:

$$FORC = \beta 0 + \beta 1 * A + \beta 2 * B + \beta 3 * C + \beta 4 * D + \beta 5 * H + \beta 6 * I + \beta 7 * L + \beta 8 * TIME + u$$

where:
Y-FORC (forest carbon, in total, in MtCO2eq.); X1— A (financial contribution to the restoration of forests damaged by immission); X2— B (financial contribution for reforestation, establishment, and tending of forest stands); X3—C (financial contribution to an association of owners of small forest areas); X4— D (financial contribution for green and environmentally friendly technologies); X5 – H (financial contribution for the elaboration of forest management plans); X6 – I (financial contribution for forest protection); X7 – L (financial contribution to mitigate the impact of the bark beetle calamity); X8 – TIME (time); u—random element of the model.
First, the model containing all economic and financial instruments (FORCM) was developed. FORCM is the composition of all independent variables (A, B, C, D, H, I, L, and TIME). Second, alternative models were performed to identify the statistically most significant model with a high index of determination.

Finally, all outputs were validated via multiple tests. The F-test of overall significance investigated the adequacy of the regression models. The Durbin-Watson (DW) test was conducted to test autocorrelation employing Durbin-Watson Significance Tables (Durbin-Watson Significance Table, 2023).

RESULTS

Tendency in the financial instruments

Figure 1 displays the development of the amount and structure of financial flows to forestry in the Czech Republic in 2000-2021.

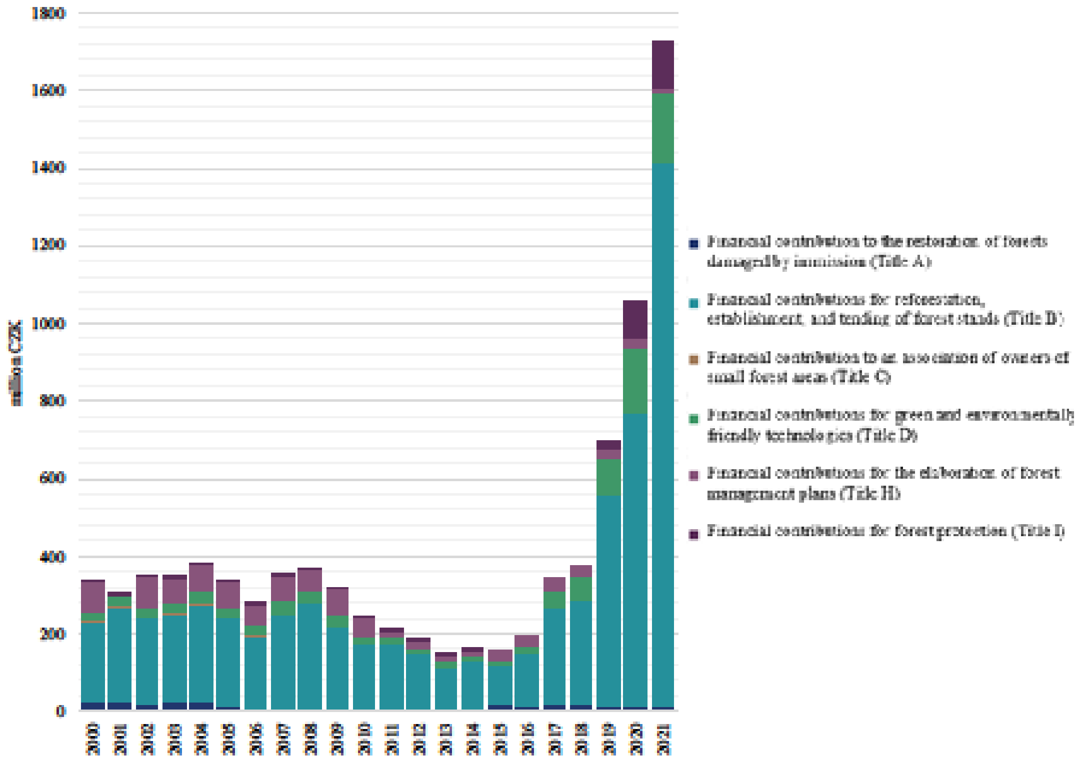
Based on the 2000-2009 results, the total financial support fluctuated from CZK 300 to 380 million (from EUR 12.23 to 15.49 million).

Since 2008, there has been a downward trend caused by the economic crisis and the decline in economic activity. In addition, several subjects were transferred under regional budgets, which restricted financial support for forestry since 2005.

In 2010-2016, the mean financial flows stood at CZK 185 million (EUR 7.54 million). Because of the bark beetle calamity, financial support increased in the period 2017-2021.

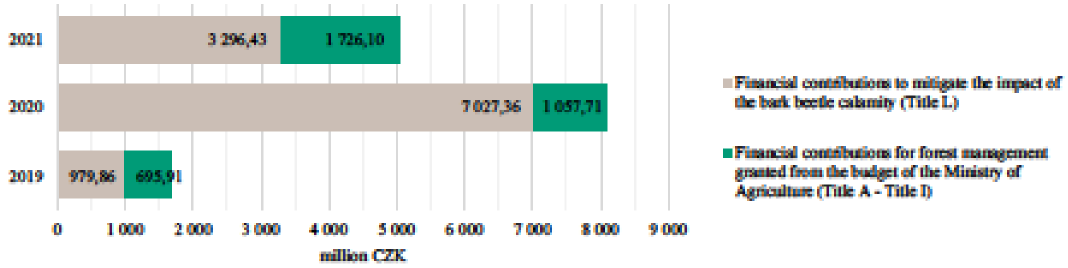
An all-time maximum of CZK 1,715 million (EUR 70 million) was recorded in 2021. According to the structure, the highest share (61% - 81%) represented Title B each year. Comparing the beginning and the end of the monitoring interval, two tendencies are visible, namely a downtrend for Title A, Title C, and Title H and an uptrend for Title B, Title D, and Title I.

Figure 1 Development of the amount and structure of national financial sources for forestry in the Czech Republic in 2000-2021



Source: authors, based on data provided by the Ministry of Agriculture.

Figure 3 Financial contributions for forest management granted from the budget of the Ministry of Agriculture in the period 2019-2021



Source: authors, based on data provided by the Ministry of Agriculture.

Regional differences in financial instruments (Title A – Title I)

An increase in national financial support flowing to forestry in 2000-2021 was found. Nevertheless, the national financial flows were not equally allocated across regions. For this, the indicator of the financial contributions for forestry granted from the budget of the Ministry of Agriculture (Title A – Title I) per hectare was set to detect regional divergences. In Figure 2, regional differences in financial contributions for forestry granted from the budget of the Ministry of Agriculture (Title A – Title I) per hectare are investigated.

Based on the findings in 2009, the highest financial contributions per hectare were received in the Central Bohemian Region (CBR) CZK 177/EUR 7.22 per hectare, and the Pardubice Region (PAR) CZK 165/EUR 6.73 per hectare. From 2010 to 2016, a fall in indicator was displayed in each region. Since 2017, the indicator continuously escalated across the regions and reached a historical level in the Vysočina Region (VYR) CZK 1,528/EUR 62 per hectare in 2021. In the reference period, the average national financial flows, Title A - Title I per hectare, were up approximately 4.5-fold.

Regional differences in financial instruments (Title L)

In the monitoring period, a bark beetle calamity occurred in the Czech Republic, which led to significant changes in the financial flows to the forestry sector. Figure 3 demonstrates that in 2019 the financial contribution to mitigate the impact of the bark beetle calamity (Title L) covered 58% of the national financial sources, which amounted to CZK 979.86 million (EUR 40 million). In the following year, the share of Title L rose to a peak of 87% (CZK 7,027.36 million/EUR 286 million) of the national financial sources. In 2021, Title L delivered CZK 3,296.43 million (EUR 134 million), approximately 66% of the national financial sources. Generally, there was a historical peak of the financial contributions for forest management granted from the budget of the Ministry of Agriculture (national financial sources) in 2020.

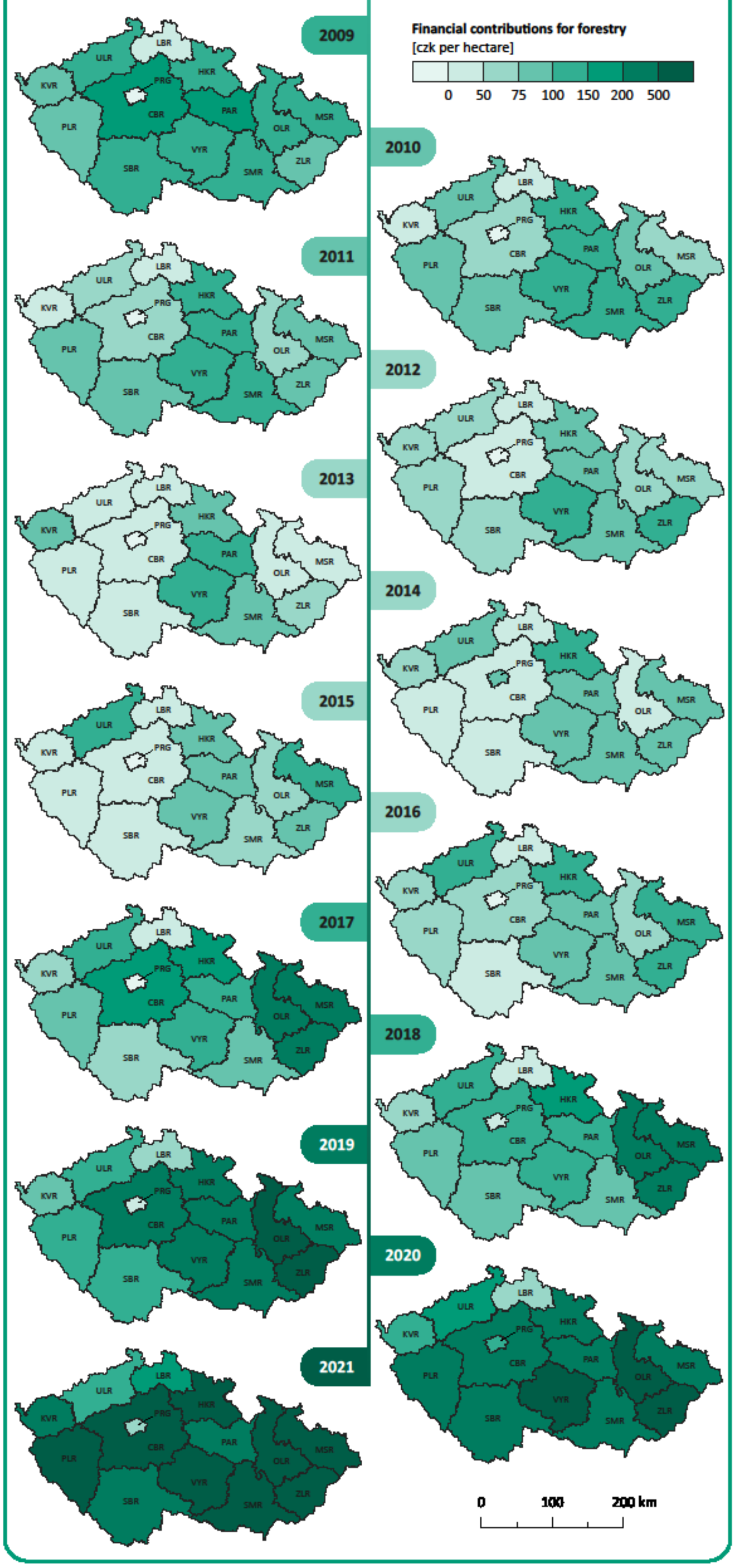
The indicator of the financial contribution to mitigate the impact of the bark beetle calamity (Title L) per hectare was set to detect regional divergences. In Figure 4, regional differences in the financial contribution to mitigate the impact of the bark beetle calamity (Title L) are illustrated.

Regarding 2019, the peak of indicator emerged in the Zlín Region (ZLR), and the Olomouc Region (OLR). This year, the Karlovy Vary Region (KVR), and Prague, the Capital City (PRG) were not applying. In 2020, a historical outlier was documented in the Vysočina Region (VYR) CZK 4,658/EUR 190 per hectare. Regions with an indicator on the scale of CZK 1,000-2,000 per hectare formed the most numerous category. Besides the Vysočina Region (VYR) achieved the strongest support in 2021 the South Bohemian Region (SBR).

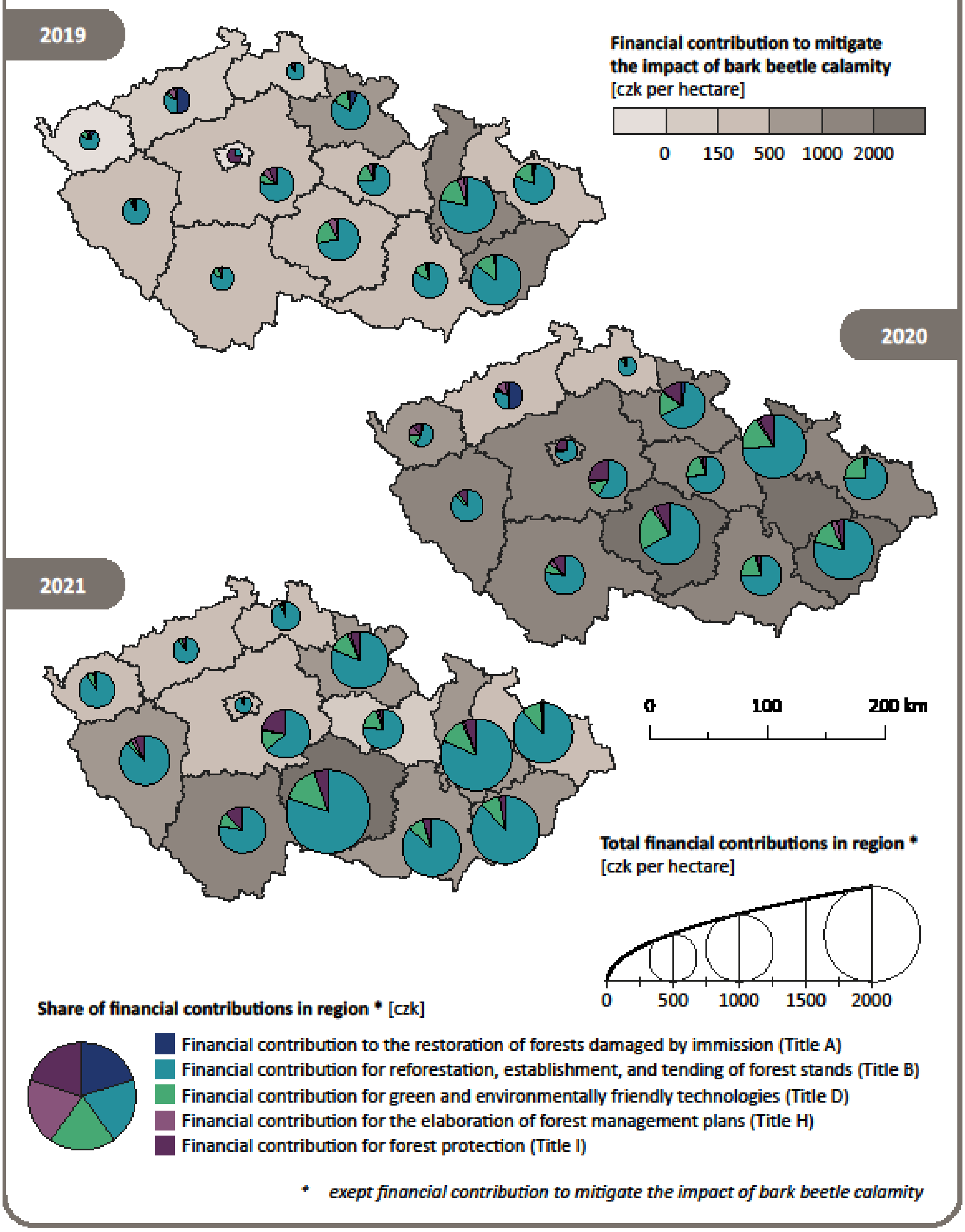
To sum up 2019-2021, the accumulated flows of Title L per hectare in maximum were observed in the Vysočina Region (VYR), the Olomouc Region (OLR), and the Zlín Region (ZLR). Indeed, the peak of both indicators, such as the sum of Title A - Title I per hectare and Title L per hectare, were granted in 2020 to the Vysočina Region (VYR), comprising 85% of Title L, 10% of Title B, and 4% of Title D.

Regional differences in financial contributions for forestry

granted from the budget of the Ministry of Agriculture (Title A – Title I) per hectare.



Regional differences in financial contribution to mitigate the impact of bark beetle calamity (Title L) per hectare and share of financial contributions (Title A – Title I).



Forest carbon model

Figure 5 deals with GHG emissions/removals of selected sub-categories of the LULUCF sector, namely forest land and harvested wood products (HWPs).

Environmentally, forestry remains a net source of GHG emissions as of 2018. The major contributor is the forest land subcategory (10.997 $MtCO_2eq.$), a consequence of the bark beetle calamity starting in 2015 and peaking in 2020. During such a period, random harvesting and clear-cutting dominated and the total volume of timber extracted rose rapidly. The Vysočina Region, Olomouc Region, and Moravian-Silesian Region lost the largest percentage of forest stands. Therefore, forest land was the fifth most impactful GHG emissions source in 2021.

Forest ecosystems thereby contribute 6.59% to the Czech total GHG emissions as a result of inappropriate management without close-to-nature elements, drought, global warming, loss of resilience, and bark beetle disturbance. The HWPs subcategory remains a GHG sink (-2.456 $MtCO_2eq.$) and decreasing total LULUCF sector emissions (8.358 $MtCO_2eq.$).

Secondly, all the selected variables that were deemed to influence forest carbon were sampled for correlation analysis. Table 5 shows the outcome of the correlation analysis. Sourced from the results of the correlation analysis, we noticed a statistically significant negative correlation between FORC and C. In addition to the above correlations, there are also negative correlations with lower statistical significance, such as A, and H. Statistically significant positive correlations occur for B, D, I, L, and the control variable TIME.

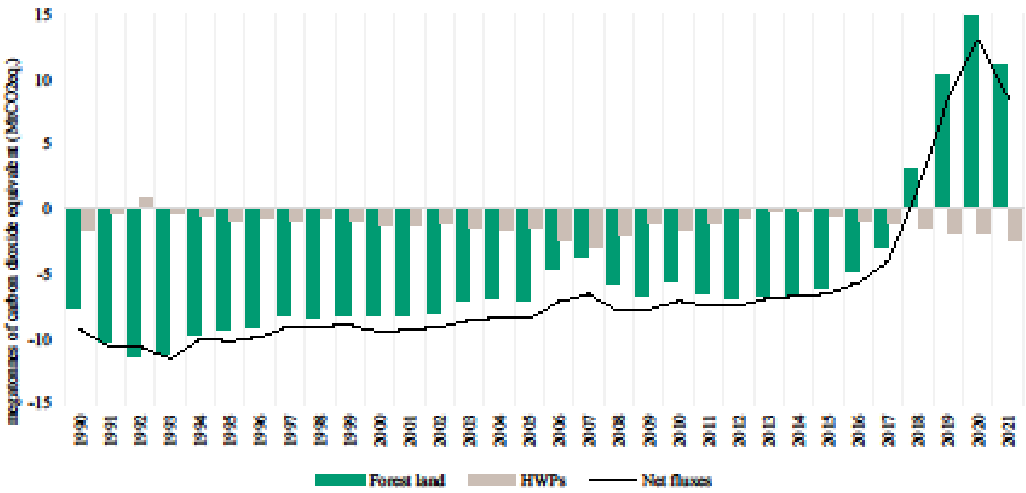
For regression analysis, the regression model FORCM was developed. FORCM consists of all independent variables (A, B, C, D, H, I, L, and TIME). While the entire model is statistically significant, not all of the selected variables are statistically significant. The result of the Durbin–Watson test (DW) for FORCM is acceptable (DW 1.861 > upper critical value 0.863).

FORCM1 represents selected variables with a statistical significance of $p < 0.05$. This model is statistically significant—all of the variables are statistically significant, and the entire model is statistically significant as well.

In Table 6, the outcomes imply a high coefficient of determination in the model. This means that for FORCM1, the general formula that is specified explains more than 99% of the variance with less than 5% of random deviations. Variables with a p-value of below 5% are B, D, TIME, and the constant (FORCM1).

To the results of the overall F-test, the estimated regression forest carbon model is statistically significant at 5% (FORCM1) levels of significance. The finding of the Durbin–Watson test (DW) for FORCM1 shows positive autocorrelation, and DW is under the lower critical value.

Figure 5 Development of the GHG emissions/removals of selected sub-categories of the LULUCF sector in the Czech Republic in 1990-2021



Source: authors, based on UNFCCC (2023).

Table 5 FORCM - correlation analysis

	FORC	A	B	C	D	H	I	L	TIME
FORC	1								
A	-0.0039	1							
B	0.7903	0.0371	1						
C	-0.7597	0.8328	0.0841	1					
D	0.9269	0.0449	0.9404	-0.3411	1				
H	-0.3940	0.1620	-0.2192	0.0097	-0.2714	1			
I	0.8486	0.0391	0.9470	0.7308	0.9656	-0.3471	1		
L	0.9373	0.1677	0.1009	0.0000	0.7047	0.2287	0.6337	1	
TIME	0.7665	-0.2918	0.4773	-0.8737	0.6043	-0.6591	0.6594	0.3796	1

Source: authors.

Table 6 FORCM - regression analysis

	FORCM		FORCM1	
	Sig.	Coef.	Sig.	Coef.
A	0.506	0.033		
B	0.013	-0.011	0.006	-0.011
C				
D	0.000	0.166	0.000	0.172
H	0.907	0.002		
I				
L				
TIME	0.015	277,814.887	0.002	247,637.603
Constant	0.014	-567,715,072.752	0.001	-506,566,127.350
Observ.	22		22	
R2	0.977		0.976	
Signif. F	0.000		0.000	
Durbin-Watson test	1.861		1.803	

Source: authors.

According to the FORCM1 outputs (Table 6), a statistically significant negative relationship between FORC and B and a statistically significant positive relationship between FORC and D, and TIME is observed.

FORCM1 refers to a model that simultaneously involves all 3 independent variables, namely B, D, and TIME. If separately (correlation analysis), the impact on forest carbon is positive, independent variables B and D both contribute to increasing GHG emissions to the atmosphere.

In the complex regression model (FORCM1), the reverse effect of the independent variable B is noted, suggesting a contribution to an increase in GHG removals from the atmosphere.

The following regression equation can be built:

Y (FORCM1) = -506,566,127.350 -0.011 B + 0.172 D + 247,637.603 TIME + u

Based on the regression analysis results, independent variable B (CZK million) contributes to increasing GHG removals from the atmosphere. According to forest carbon, forests fulfill the role of net sinks, and there is carbon capture and storage in forests and harvested wood products (HWPs).

Conversely, the regression analysis findings indicated that independent variable D (CZK million) and control variable TIME contribute to increasing GHG emissions to the atmosphere. According to forest carbon, forests fulfill the role of net sources.

DISCUSSION

RQ1: Can we observe an increasing trend of financial flows to forestry in the Czech Republic?

Firstly, in the period 2000-2021, there was an increasing trend of national financial flows to forestry in the regions of the Czech Republic. Due to the bark beetle calamity, financial support has sharply risen since 2017 and recorded an all-time maximum in 2021. In detail, two tendencies are visible, namely a downtrend for Title A, Title C, and Title H and an uptrend for Title B, Title D, and Title

I. According to the structure changes, the highest share (61% - 81%) represented Title B each year.
As the literature review pointed out, several studies work with national financial sources for forestry in the Czech Republic, for instance, Šišák (2002, 2007, 2013), Lojda and Ventrubová (2015), Kotecký (2015), Perunová and Zimmermannová (2023). Simultaneously, studies displaying the economic aspects of bark beetle calamity in the Czech Republic are still missing.
Based on Šišák (2002 and 2007), various mechanisms are available in forestry, especially ethical, normative, economic, and institutional, aiming for reasonable exploitation of forest resources in the Czech Republic. According to findings (Perunová and Zimmermannová, 2023), financial contributions for forest management granted from the budget of the Ministry of Agriculture are drivers for the rise in the utilization of bioeconomy renewable resources, such as wood biomass.
Subsequently, national funding sources can boost biodiversity conservation and sustainable forest management (Liagre, 2017). In addition, the study by Sevinc (2022) analyzed financial support in line with the behavior of forest owners. Leoussis and Brzezicka (2017) stressed the emergency of financial support for landowners and forest owners. According to Ohmura and Creutzburg (2021), the effectiveness of economic instruments will vary depending on the financial beneficiaries involved. Moreover, soft policy interventions, such as voluntary commitments, become slightly attractive, but depending on the type of forest ownership (Danley, 2019).
On the other hand, the study (Aoyagi and Managi, 2004) concluded that government subsidies adversely altered the economic outlook of forestry. In the Czech Republic, a proportionately high number of national financial titles and other resources are limited in total financial amount combined with difficult organization and administration (Šišák, 2013). Forestry makes a considerable impact on rural development and the Rural Development Programme seems to be a more effective tool than national financial funding (Lojda and Ventrubová, 2015). Based on Kotecký (2015), subsidies for afforestation in the Czech Republic are not optimal and seem to be targeted to areas with existing high forest cover. In certain regions, approaches are put in place to safeguard biodiversity, water, and climate regulation and recreation, although the social-environmental dimension remains far from balanced with the economic one (Sotirov and Arts, 2018; Mattioli et. al., 2024).

RQ2: Can we observe regional differences in financial flows to forestry in the Czech Republic?

Secondly, it can be concluded that national financial flows to forestry were not equally split among regions and regional divergences were investigated.
First, the indicator of the financial contributions for forestry granted from the budget of the Ministry of Agriculture (Title A – Title I) per hectare was applied (Figure 2). From 2000 to 2021, the average of the indicator was up by 447% while the indicator reached a historical level in the Vysočina Region (VYR) CZK 1,528/EUR 62 per hectare in 2021.
Second, the indicator of the financial contribution to mitigate the impact of the bark beetle calamity (Title L) per hectare was examined (Figure 4). In a summary of 2019-2021, the accumulated flows of Title L per hectare in maximum were observed in the Vysočina Region (VYR), the Olomouc Region (OLR), and the Zlín Region (ZLR). Indeed, the peak of both indicators, such as the sum of Title A-Title I per hectare and Title L per hectare, was granted in 2020 to the Vysočina Region (VYR), comprising 85% of Title L, 10% of Title B, and 4% of Title D.
Based on the literature review, studies investigating regional aspects of the national financial sources and/or studies dealing with the economic aspects of bark beetle calamity emphasizing regional differences in the Czech Republic are still absent. For example, Brázdil et al. (2022), Šafařík et al. (2022), Michalec et al. (2020) and Toth et al. (2020) examined bark beetle calamity in the Czech Republic, with no regard to regional disparities in financial support.
Previous forest management can be a precondition for existing conditions in forests and consequently influence pest outbreaks (de Groot et al., 2019). As a consequence of ongoing climate change, shifts in the disturbance regime caused by novel agents or overlapping of the historical range of variety occur (Turner and Seidl, 2023). Forest reorganization emerges as a phase determining the long-term shape of forest ecosystems, which can either persist or face regime shifts (Seidl and Turner, 2022). Falcone et al. (2020) suggest essential drivers to ensure a booming forest-based bioeconomy, including the circular principle. According to Hlásny et al. (2021), an

effective strategy to address bark beetle calamity is to reshape regional forest management.

RQ3: Do financial flows have a positive environmental impact on the forest bioeconomy in the Czech Republic?

Concerning this research question, the forest bioeconomy in our research is represented by the indicator "forest carbon". The regression analysis outputs reveal that financial contributions for reforestation, establishment, and tending of forest stands contribute to increasing GHG removals from the atmosphere. This implies beneficial environmental impact, as forests fulfill the role of net sinks, and carbon capture and storage in forests and harvested wood products (HWPs) is observed.

Conversely, the regression analysis findings indicated that financial contributions for green and environmentally friendly technologies contribute to increasing GHG emissions to the atmosphere. This implies adverse environmental impact, as forests fulfill the role of net sources, and carbon capture and storage in forests and harvested wood products (HWPs) are not observed.

Referring to the variable "forest carbon", we expected that all selected national financial sources lead to increasing GHG removals from the atmosphere, as a net sink, as in studies by He and Ren (2023), Jinggang and Peichen (2017), Pukkala (2020), Dong-Ho et al. (2018), and Bowditch et al. (2022).

According to the findings, till 2017 Czech forests acted as net carbon sinks, while in recent years had become a net source. Adversity is the effect of drought, especially on tree species planted outside their ecological optimum, and the subsequent attack of insect pests. Due to biotic disturbance, removals gradually rose from 2017, maximizing in 2020 (34 million cubic meters), and falling to around 23 million cubic meters in 2021 (CZSO, 2023).

These influence reforestation, which has led to the expansion of planting broadleaved tree species, intending to avoid monocultures over a large area at the same age. Currently, afforestation and reforestation activities are more intensive, with 40 thousand hectares in 2022 compared to 29 thousand hectares (2018) (CZSO, 2023). Long-term, coniferous tree species have been predominant, whereas in the period 2019-2021, the trend has changed. Considering the damaging impacts of the bark beetle calamity, the priority is on building more resilient forests, adapting to and mitigating climate change, and sustainably managing natural resources (Hlásny et al., 2017; Cramer et al. 2018; Thrippleton et al., 2023).

Financial support is a precondition to developing a support system for forestry carbon sinks (Bowditch et al. (2022). Subsidies can strengthen forest carbon capture and storage capacity and enhance the welfare of actors in forestry (He and Ren, 2023). A payment of EUR 150 per tonne of carbon sequestered in forests would bring a halt to cutting (Pukkala, 2020). The study (Jinggang and Peichen, 2017), focused on encouraging carbon capture and storage in forests through subsidy. The advancement of co-benefits, such as corporate social responsibility, social cohesion of regional communities, and positive environmental effects remains the key to enhancing the competitiveness of forest carbon credits (Dong-Ho et al., 2018).

Moreover, Kilgore et al. (2007) noted that financial stimulus appears to have the power to shape the decision-making of forest owners related to sustainable forest management and forest land utilization. The results (España, 2022) show that government subsidies constitute effective tools and appear to have aided the rise of forest areas. In the case of national financing mechanisms in small-scale forestry (Boscolo et al., 2010), innovation, knowledge sharing, and information exchange are crucial drivers for sustainable forest management.

The forest-based sector has several potentials in mitigating climate change. Firstly, notable forest carbon stocks/pools include forest soils and living wood biomass. Regarding living biomass carbon per hectare (Forest Europe, 2020), Central-West and Central-East Europe are the leaders. Secondly, in the long term, HWPs increase the carbon stock, while reducing forest sinks in the short and medium term (Pilli et al., 2015). Regarding forest land and HPWs, increasing afforestation and reforestation, reducing deforestation, and sustainable forest management are required. Thirdly, wood materials can reduce emissions by replacing emission-intensive ones while increasing removals by storing carbon in HWPs (EC, 2021a). The positive effects of material replacement then depend on the substitution factor. The material use of wood brings opportunities for a circular bioeconomy and cascading use of biomass, where closed loops of materials are created, the added value of inputs is maximized, and the lifetime of outputs is extended (Keegan et al., 2013).

Innovations, bio-based technologies, and bio-based materials are generators for the development of forest-based value chains and new business models (European Commission and Joint Research Centre, 2023). The synergy of wood biomass usage in downstream industries such as textiles, chemicals, and pharmaceutics is evident and boosts the bioeconomy. Finally, wood biomass in place of fossil fuels can achieve huge emissions cuts. According to the Czech Republic, the energy mix is transforming, with a 2030 target of 28-30% renewable sources, including wood biomass (EC, 2018a).

Regional forest carbon reservoirs offer benefits in a low-carbon economy, and a potential to contribute to climate goals. The target of the LULUCF sector represents -310 MtCO2eq. by 2030 (EP, 2023a), while the national goal of the Czech Republic is 1,228 ktCO2eq. (EC, 2022c). Moreover, Carbon Removals Certification (EP, 2023b) is an opportunity for the forest-based sector. Carbon capture and storage in restoring forests and in long-living wood materials and products constitute natural solutions for GHG removals under the certification framework (EP, 2023c).

CONCLUSION

The main purpose of the study was to examine the effects of financial support on the development of the forest bioeconomy in the Czech Republic in the period 2000–2021. Research objectives were met by applying literature review, time series analysis, spatial data analysis, cartogram and cartodiagram methods, correlation analysis, and regression analysis. Firstly, regional divergences in national financial flows were observed. Owing to the bark beetle calamity, the peak of the national financial sources was detected in the Vysočina Region (CZK 4,658/EUR 190 per hectare), and the Olomouc Region (CZK 2,780/EUR 113 per hectare) in 2020. An upward trend - more than 6-fold growth of financial flows to forestry was found. Secondly, the forest carbon model was discovered and tested. Financial contribution for reforestation, establishment, and tending of forest stands increases net carbon sinks while financial contribution for green and environmentally friendly technologies increases net carbon sources.

The limitations occurred, such as a varying number of financial contributions and the availability of the data and time series. The originality of the data, as datasets are not commonly available and are accessible on request.

Concerning the recommendations, policymakers should reflect on the key objective of financial contributions, i.e. emphasize the role of net carbon sinks or others. We would recommend that a regular evaluation of the economic and financial support provided should be carried out, including a regional scale, as it is obvious that the situation can differ. The forest bioeconomy links to a climate-neutral economy for which effective economic and financial promotion is essential to sustainable development.

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Received: March 11, 2024
Accepted: April 26, 2024

6 Discussion

The dissertation thesis is presented as a collection of original research studies, each of which contains a comprehensive discussion of the issue under investigation. The following is a brief summary and reflection of the most relevant outcomes of the scientific articles.

6.1 Development of the bioeconomy labour market

Regarding the findings, a diminishing tendency in the share of bioeconomy employment in the whole labour market in the Czech Republic was identified. The figures reflect values of around 7-8%, corresponding in absolute terms to 383-395 thousand employees. A more detailed insight into the bioeconomy labour market exhibits slight structural changes. A sectoral approach under the NACE rev. 2 classification yielded the conclusion that the traditional sectors of the economy, namely (1) agriculture, (2) food, beverage, tobacco, and (3) wood products and furniture constitute the largest proportion. Several pathways emerge in the individual subsectors of the bioeconomy. The bio-based electricity, liquid biofuels, bio-based chemicals, pharmaceuticals, plastics and rubbers, and fishing and aquaculture sectors recorded a growth rate. On the other hand, forestry, bio-based textiles, wood products and furniture displayed a negative trend. Thirdly, agriculture, food, beverage, and tobacco, and paper sectors held constant employment figures with no significant fluctuations.

As the results support the conclusions of the study (Ronzon et al., 2015), the Czech Republic belongs to the non-specialized bioeconomies. In the Czech Republic, the following sectors show powerful capacities, such as agriculture, forestry, chemistry, and food industries that can benefit the local labour market (Hájek et al., 2020). At the European level, the bioeconomy consists of more than 17 million employees with a turnover of EUR 2.5 billion. In general, agricultural activities provide a significant contribution to bioeconomy employment while there is a tendency for more capitalized segments, such as biochemicals and bioenergy to create relatively fewer jobs in the bioeconomy (Mainard-Causapé et al., 2017). Based on employment dynamics, it is anticipated that there will be an upturn in novel jobs related to renewable energy sources and/or bio-based products (Kardung et al., 2019; Lier et al., 2018). In contrast, a reduction in employment levels may have an imbalance effect on specific sectors, as skilled workers may leave and their non-replacement could bring discontinuity in the knowledge flow (Toth et al., 2021). It is suggested that the promotion of wood-based construction could be an effective way to enhance wood production and employment across the EU Member States (Jonsson et al., 2021). Additionally, carbon storage in harvested wood products (HWPs) and material substitution lead to climate mitigation solutions (Pilli, 2015). Therefore, several factors, including increased productivity and reduced demand for graphic paper, have contributed to the drop in employment in the wood-based sector (Robert et al., 2020).

With a focus on drivers, forestry employment in the Czech Republic was positively affected by wages/salaries and negatively impacted by gross domestic product and forest land. Over the period under focus, employment in the forestry sector decreased. However, positive fluctuations in employment were caused by the peak of the bark beetle calamity and activities such as logging and reforestation. According to the Czech Statistical Office (2023), the forestry sector employed approximately 13.6 thousand persons in 2022. The highest ratio of employees is typically in the private sector, followed by the public and municipal segments. Generally, the forestry sector is facing a permanent shortage of employees, especially for manual forestry positions, including middle management positions. Secondly, the upward trend in average wage in the forestry sector was observed. In 2022, the average wage in the forestry sector reached CZK 38.88 thousand, exceeding the average wage in the national economy. However, the high rate of inflation has reduced real wages in the forestry sector by more than 7%. It could be argued that the public sector has relatively high average earnings compared to other sectors.

Shifts in bioeconomy employment trajectories can be caused by modernization, innovation, and employment reallocation (Ronzon et al., 2022; Lovric et al. 2020). To promote employment opportunities in the rural bioeconomy, it is vital to foster multi-sectoral cooperation, business diversity, and education (Purwestri et al., 2020). The outputs (Dordmond et al., 2021) suggest that the setting up of quality institutions and the promotion of financial resources positively shape the creation of green jobs. Moreover, varying stages in the bioeconomy progress, including social aspects are present across the European Union (Ronzon et al., 2021; Patani et al., 2024). For example, in the Northern and Western Member States, a bioeconomy transition is underway, which is associated with modernization and structural changes in national economics. On the other hand, Eastern and Central Member States are still in the initial steps of a bioeconomy revolution. For this, the BIOEAST initiative was established to empower bioeconomy potential in 11 European countries. The macro-regional initiative is considered an essential part of the bioeconomy development in Central and Eastern Europe (BIOEAST, 2024).

Building an in-depth understanding of the existing and emerging jobs and skills needs of the European bioeconomy is necessary (Philippidis et al., 2014). Currently, green jobs and green skills remain poorly defined, making it challenging to compare trends across countries (Cedefop, 2019). In parallel, multiple definitions of green jobs can be found in the International Labour Organization (ILO, 2013), the United Nations Environment Program (UNEP, 2008), and the Bureau of Labour Statistics (2020). For this, the Green Jobs Initiative aims to examine the impacts of climate change on employment shifts and promote solutions for mitigation, especially in rural areas (ILO, 2019).

Green jobs show both higher levels of analytical skills and human capital indicators, such as non-formal education, or vocational education and training (Consoli et al., 2016). At the same time, the content of green jobs tends to be less routine than the content of non-green ones. Eco-innovation of products and services appears to be a driver in generating green jobs (Cecere and Mazzanti, 2017). Notable employment expansions are anticipated in resource recovery, earthmoving, and environmental research (Babugura, 2020). Based on Woods et al. (2023), public funds are factors related to the uptake of green jobs. Linkages between green jobs and sustainable development goals are evident (Sulich and Sołoducho-Pelc, 2022).

Regarding the forestry sector, *“green forest jobs provide forest-related goods and services while meeting the requirements of sustainable forest management and decent work”* (ECE/FAO, 2018). As the bioeconomy labour market evolves, green jobs have the ambition to thrive in non-traditional forestry-related sectors, especially in industries linked to new wood-based products, urban and social forestry, human health, or green chemistry (da Silva and Schweinle, 2022).

With a focus on the bioeconomy workforce, the composition of skills required is assumed to be changed, resulting in considerable tensions for a reaction from education and training. On the other hand, there is uncertainty about the scenarios surrounding further patterns of pathways in specific skills. Drivers of such uncertainty include the impossibility of accurately predicting human behavior in terms of the direction of environmental policy developments, as well as demographic or economic and environmental tendencies.

Moving the world towards sustainable patterns, both green reskilling and upskilling have a major role also in the circular economy and bioeconomy (Bozkurt and Stowell, 2016). Bioeconomy is expected to deliver up to a million green jobs, predominantly in rural and coastal areas (Ronzon et al., 2018). Unlocking such potential together with environmental and social benefits requires the proper combination of skills in the bioeconomy workforce. As the bioeconomy is not homogeneous, a diverse range of skills is needed to fulfill the requirements of particular sectors and regions (European Commission, 2022). Moreover, in the implementation of circular bioeconomy principles together with green skills and jobs, agents such as jobs, age, size, turnover, or sector can determine the success of economic units (Bassi and Guidolin, 2021). Based on European predictions, people with higher levels of qualifications are expected to keep rising in demand, while that for those with medium levels of qualifications seems to be constant.

Green skills can be termed as values, knowledge, experiences, attitudes, and abilities essential for green transformation (UNIDO, 2024; European Commission, 2020c). Boosting a net-zero resource-efficient economy, specific green skills can be needed and defined. Firstly, transdisciplinarity is frequently named as one of the core green skills, as global climate change requires a community-wide effort and a comprehensive perspective at the global scale (Jahn et al., 2012). Transdisciplinarity can be considered as an opportunity to converge scientific disciplines and promote know-how sharing, and capacity building (Sixsmith et al., 2021). Transdisciplinarity is able to stimulate multidimensional attitudes leading to analytical and problem-solving skills combining multiple viewpoints, assist in detecting possible synergies, and promote win-win responses (Miller et al., 2011). The transdisciplinarity delivers a holistic approach and generates a novel form of working that transcends the initial disciplinary frontiers (van Bewer, 2017).

Secondly, systematic thinking (Arnold and Wade, 2015) can be introduced as *"a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them to produce desired effects. These skills work together as a system".*

Moreover, long-term thinking (Chen et al., 2020) allows one to make investments to create things with lasting value. Collaboration (Mulligan and Nadarajah, 2008; Edelman, 2009) can provide dialogue among a variety of stakeholders regardless of geographies, cultures, and generations. Adaptability (Strachan et al., 2022) can refer to a continued desire to develop both dynamic and resilient schemes. Countless other green skills are defined, in detail what-if thinking, creativity, and awareness for continuous learning (Miller et al., 2010).

Circular economy and bioeconomy, as concepts of sustainable development, prioritize a balance between economic growth, social well-being, and environmental stewardship to transform the economy and move away from linear flows of energy and materials. The evolving bioeconomy and circular business models highlight technological aspects, namely Artificial Intelligence, Big Data, or advanced materials, which place additional pressure on the digital and technological skills of employees (Santoalha et al., 2021). The role of digital, quality management, and strategic thinking skills appears to be significant across Member States (Ramalho Ribeiro et al., 2023).

Currently, a mismatch is noted regarding the existing skills and the expected future skills that will be demanded in the bioeconomy sectors. This gap calls for an up-grading in the educational process. In the Czech Republic, a comprehensive bioeconomy education system is absent, stepping up from primary schools to higher education institutions. Nevertheless, individual courses are found targeting the bioeconomy or circular bioeconomy. At the European level, the European Bioeconomy University was established to build a knowledge-based bioeconomy and contribute to green transition (EBU, 2024). Vocational education and training is promoted as a kind of long-life learning across Member States. VET assists youth in finding first jobs and empowers adults to reskill or upskill and boost their careers (European Commission, 2020d).

Based on the European prediction (European Commission, 2021e), people with higher levels of qualifications are expected to keep rising in demand up to 2030, while that for those with medium levels of qualifications seems to be constant. However, developments are likely to be divergent across bioeconomy sectors. In the traditional sectors of the bioeconomy, medium and high -levels qualifications are anticipated as a requirement. Emerging sectors, such as bioenergy, biotechnology, or biotextiles, call for a deeper engagement of individuals with high-level qualifications.

To monitor the progress of the European bioeconomy jobs, a study by Ronzon et al. (2020) was developed. Based on the latest figures, there were approximately 17.19 million employees in the bioeconomy sectors across the European Union in 2021, whereas the sectors with the highest proportion included, (1) agriculture, and (2) food, beverage, and tobacco. Around 381 thousand employees were reported at the national level of the Czech Republic. The predominant sectors were also represented in the traditional bioeconomy sectors, namely (1) agriculture, (2) food, beverage, and tobacco, (3) wood products and furniture, and (4) forestry. Between 2008 and 2021 a downward trend in forestry (-23%), wood products and furniture (-28%), and bio-based textiles (-46%) is evident. In contrast, fishing and aquaculture and liquid biofuels marked an increment.

At the European level, the estimated evolution of the educational background of the population and the workforce is calculated (Cedefop, 2024). Overall, meaningful demographic changes will affect the labour force in the Czech Republic. For example, there should be a slight increase in the whole labour force, while the largest growth will occur in the over-60 age group. On the other hand, the 30-59 age category experiences a fall. In terms of gender, the female category tends to show higher growth. The 2021-2035 predictions suggest several trends for employment in particular sectors in the Czech Republic. For example, decline pathways can be observed in sectors, such as forestry (-1.2%), wood and wood products (-3%), and construction (-0.7%). In these sectors, medium-level qualifications display the highest decrease. The situation differs in sectors such as fishing (2.4%), water supply (0.1%), research and development (2.4%), and education (0.7%).

Circular economy and bioeconomy both contribute to delivering on the vision of the European Green Deal (European Commission, 2020a). The prognosis of the effects of the European Green Deal on employment (Cedefop, 2021) displays a 1.2% extra employment rise, certainly including disparities among sectors and urban and rural areas. Integral contributions to make in the transition to a low-carbon economy show highly skilled occupations, such as researchers. Additionally, positive dynamics of employment in engineering and administration services are anticipated.

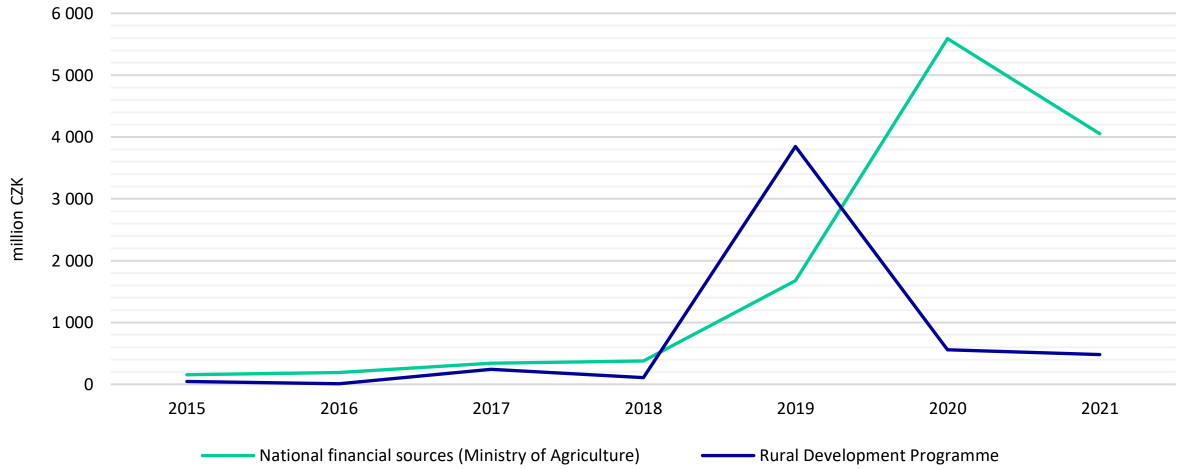
Finally, for the transition to a low-carbon system to be effective, it is necessary to build a green mindset (Shakil et al., 2023) across society and thus increase the willingness of stakeholders (OECD, 2014) to engage in global change. To flourish in the green and digital transition, a skills revolution is a precondition (European Commission, 2020b).

6.2 Impact of economic and financial instruments on the forestry sector

Regarding the results, both statistically significant positive and negative impacts of economic and financial instruments of the climate change policy on the development of the forest bioeconomy in the Czech Republic were observed. The forestry sector was presented by 3 indicators, namely forest land, wood biomass production, and forest carbon. In the period 2000-2021, a rising tendency was found in the case of the variables forest land and wood biomass production. Concerning forest carbon, the situation has shifted over time. Whereas until 2017 forests were removing more carbon dioxide than they were emitting, in 2018 this trend has reversed and forests have become a net source of carbon.

National financial sources, namely financial contributions for forest management granted from the budget of the Ministry of Agriculture and the Rural Development Programme have shown an accelerating pattern, mainly due to the bark beetle outbreak (Figure 1).

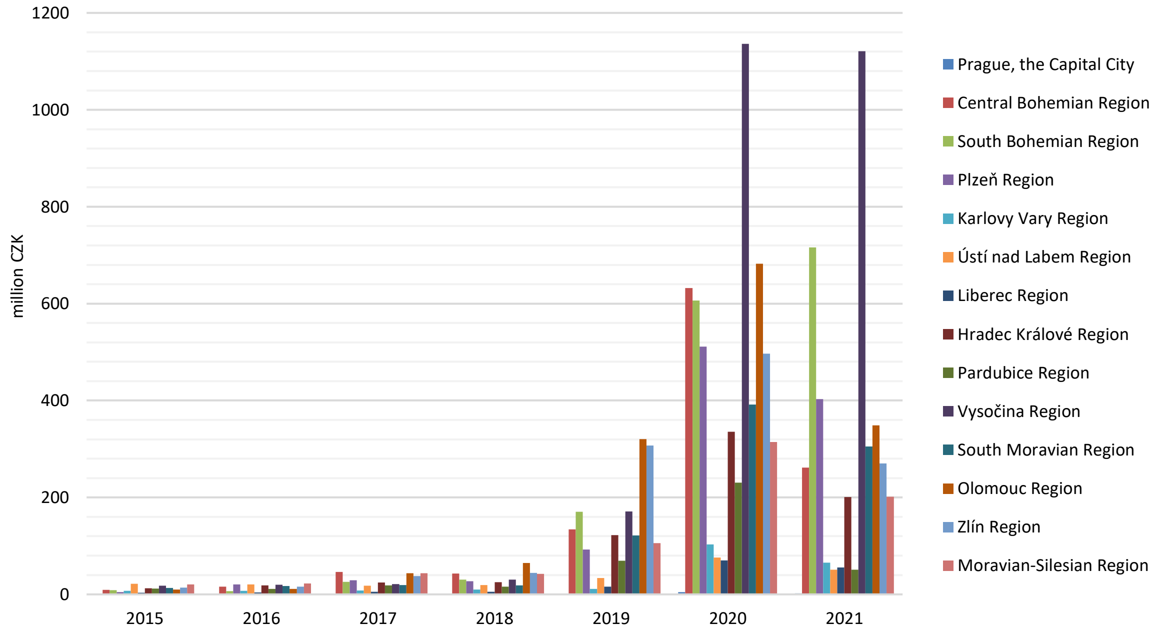
Figure 1 Development of the financial contributions for forest management granted from the budget of the Ministry of Agriculture and the Rural Development Programme



Source: author based on Ministry of Agriculture.

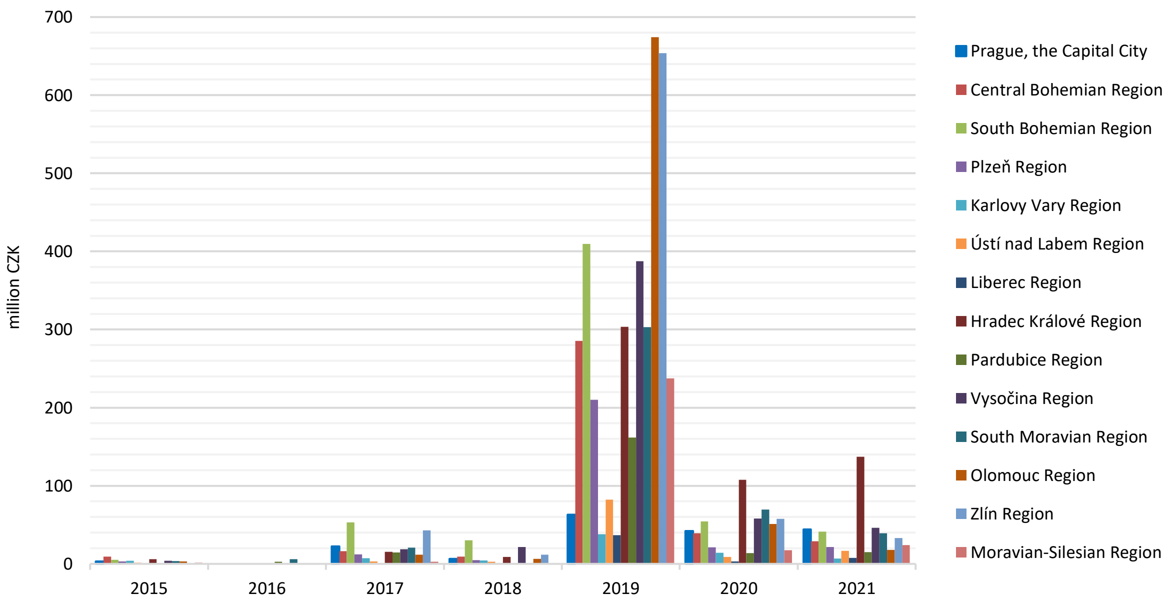
However, differences in funding flows across regions of the Czech Republic were examined a noted. According to a national financial source, the historical peak rate was recorded in the Vysočina Region in 2020 (Figure 2). Regarding the Rural Development Programme, a maximum value of support was achieved in the Olomouc Region in 2019 (Figure 3).

Figure 2 Financial contributions for forest management granted from the budget of the Ministry of Agriculture in the regions of the Czech Republic



Source: author based on Ministry of Agriculture.

Figure 3 Rural Development Programme in the regions of the Czech Republic



Source: author based on Ministry of Agriculture.

Forest carbon

Carbon storage in forests seems to be positively influenced by multiple factors, such as the profitability of wood production (Tian et al., 2015), high non-timber revenues (Miller et al., 2012), a large area of forest land (Khanal et al., 2017), an understanding of the precise impact of forests on the mitigation of climate change (Markowski-Lindsay et al., 2011; Miller et al., 2012), safeguarding of property rights (Rämö et al., 2013; Wade and Moseley, 2011), and innovative mindset of forest owners (Thompson and Hansen, 2013). Time emerges as an essential determinant as well (Koskela, 2011; Urquhart et al., 2012). Both willingness and motives for engaging in forest carbon storage are diverse across various types of forest owners. For example, subsidies are a vital criterion in the case of large-scale forest land ownership, however, as the educational background improves, subsidies move into the complementary category of advantage (Karppinen et al., 2018).

On the other hand, low levels of carbon pricing (Fletcher et al., 2009), insufficient promotion of carbon trade (Wade and Moseley, 2011), challenge to adhere to instructions (Wade and Moseley, 2011), and necessity of management expectations (Dickinson et al., 2012; Markowski-Lindsay et al., 2011; Khanal et al., 2017) are barriers that negatively interact with forest carbon.

The expansion of forest area is accompanied by a more substantial increase in forest carbon stocks per hectare (Kauppi et al., 2006). Hence, afforestation and effective forest management of the existing stands constitute elements improving the carbon sinks (Kauppi et al., 2020). Forest carbon can be affected also by factors, such as tree species, stand density, or selective harvesting methods (Assmuth and Tahvonen, 2018). Moreover, forest carbon levels may be greater in locations in close proximity to forest edges (Meeussen et al., 2021). The age of forest stands is influenced by the harvesting regime employed, which in turn leads to various regional carbon stock scenarios (Bradford, 2011).

Firstly, opposing approaches may occur, leaving forest stands to be grown further or cutting to store carbon in harvested wood products. Then, carbon sequestration should consider the quantity, longevity, and persistence of the carbon accumulated in the forests (Keith et al., 2014). Since the risk of forest damages arising from climate change-driven events persists (Bontemps, 2021). Additionally, the occurrence of extreme weather events, such as hurricanes, droughts, and windstorms disrupt the forests's function as carbon sinks (McNulty, 2002).

It is noted that there are linkages between the various disturbance events. Some events occurring in sequences may produce a synergy of their particular impacts (Gower et al., 2015; Harvey et al., 2013; Kleinman et al, 2019). On the other hand, the attributes of the first disturbance event can shape the characteristics of the event that follows (Simard et al., 2011; Stevens-Rumann et al., 2016). Therefore, it is vital to discover an understanding of the implications of disturbance history on the carbon storage capacity of forests (Bradford et al., 2008).

Linked to climate change, disturbance regimes alter and there are some ways that novelty can arise. First, it may be the consequence of disturbance regime properties, namely patch size, frequency, severity, or intensity moving outside their historical ranges of variation (Keane et al., 2009; Keeley and Pausas, 2022). Thereafter, forest ecosystems are disconnected from stability and the probability of regime shift scaling up (Turner and Seidl, 2023). Second, it could be the occurrence of new disturbance drivers, both abiotic (Grünig et al., 2023; Witze, 2020; Bergstrom et al., 2021; Holz et al., 2015) and biotic (Buotte et al., 2016; Herms and McCullough, 2014) ones.

Concurrently, novel responses of the forest ecosystems may take place after the disturbance events (Senf and Seidl, 2022; Falster et al., 2017; Hacket-Pain and Bogdziewicz, 2021). The main triggers of ecological answer variation can be classified as the condition of the ecosystem at the outbreak moment (Bowman et al., 2016), disturbance event characteristics and material legacies (Gill et al., 2022; Hoecker and Turner, 2022), post-disturbance forest management approach (Senf, 2019), as well as conditions of specific location (Hansen and Turner, 2019).

Reorganization can be identified as a crucial element of the recovery process that influences post-disturbance forest development. In that stage, both the structure and/or composition of the forest ecosystems can be changed, while resiliency can be maintained or a nonforest ecosystem is formed (Albrich et al., 2021; Zeppenfeld et al., 2015; Johnstone et al., 2020; Kitzberger et al., 2016). The nature of the disturbance event, the availability of seeds and resprouting, the presence of biotic and abiotic aspects, altered light regime or microclimate, and the presence of pests and pathogens are all variables driving the outcome of the reorganization (Seidl and Turner, 2022). Climate change has a great effect on the dynamics of the forest ecosystem, meanwhile, considerable uncertainty persists in the responsiveness of systems to these changes (McDowell et al., 2020).

Secondly, harvested wood products contribute to the mitigation via material and energy substitution. Firstly, the potential of wood biomass as a renewable source to substitute emission-intensive materials is significant, while simultaneously providing a temporary carbon storage facility (Carus et al., 2012). Application of wood biomass is opening up in sectors such as furniture manufacturing, and construction (Pilli et al., 2014). However, the proper application of the cascading principle is relevant (Keegan et al., 2013). Initially, inputs tend to be used to manufacture outputs with higher added value. During the product life cycle, the preference is to reuse the same raw material, although for producing a lower value-added outcome. Such a principle prolongs the residence time of biomass in the economic system, which pursues the rational usage of scarce resources and leads to increased efficiency (Hong et al., 2021). Meanwhile, the carbon footprint of the wood product needs to be tracked and evaluated from the beginning to the end-of-life stage (Jasinevičius, 2017). Life cycle assessment has a vital significance there (Hauschild et al., 2018).

Besides biomass carbon, forest ecosystems also facilitate soil carbon storage (Lal, 2005). The forest soils represent an integral component of the forest carbon budget (Liski et al., 2002). The type of soil has a significant impact on the amount of carbon stored within it. Forest soils occupy a particularly crucial position in this regard, in comparison to other soil types (Baritz et al., 2010).

For the above-mentioned, forests tend to be net carbon sinks (Forest Information System for Europe, 2023). Land use, land use change and forestry (LULUCF) sector usually add to the reduction of cumulative emissions, meeting the Paris Agreement target (United Nations, 2022), which replaced the Kyoto Protocol in 2020. Forest carbon reservoirs offer demonstrable benefits in climate questions and a low-carbon economy, and therefore LULUCF emissions and removals display a potential to contribute to climate goals. The European target of the LULUCF sector by 2030, as a net carbon sink, represents -310 MtCO2eq. of which the national vision of the Czech Republic is 1,23 ktCO2eq. (European Parliament, 2023a; European Commission, 2022c).

In the Czech Republic, total emissions between 1990-2021 continuously decreased by 41% and reported 118 MtCO2eq. in 2021, with the LULUCF sector contributing additional net emissions of 8.36 MtCO2eq. (UNFCCC, 2023). However, in closer detail, the transport and waste management sectors demonstrate an upward trend. Simultaneously, as a response to the bark beetle calamity, forest land was a net carbon source as of 2018. Across the Member States, the Czech economy is the fourth most emissions-intensive in the case of population and the second most emissions-intensive in the case of gross domestic product (International Energy Agency, 2023). Hence the appeals for decarbonization, circular economy, and bioeconomy to transform the economic system in the Czech Republic (Ministry of Industry, 2023; Ministry of Environment, 2021).

Forest land and wood biomass

Based on the impacts of the economic and financial instruments on forest land development several studies were observed. Instruments such as carbon payments (Pukkala, 2020; Kerr et al., 2012; Evison, 2017), taxes (Zhurakovska et al., 2021; Barua et al., 2012), and subsidies (España et al., 2022; Ersoy and Mack, 2012; Jensen et al., 2022; Aoyagi and Managi, 2004) were analyzed.

According to forest land, an extension of 1.5% was detected in the Czech Republic over the period 2000-2021 (CZSO, 2023). In detail, the forest land indicator was the highest for regions, such as the Liberec Region (43%), the Karlovy Vary Region (42%), the Plzeň Region (40%), the Zlín Region (39%), and the South Bohemian Region (37%) by the end of the reporting interval. The indicator exhibits an upward trend with a diminishing rate at the European level as well (Forest Europe, 2020).

Generally, the tree species composition contains a significant proportion of spruce, pine, beech, and oak. Based on the age category the drop was seen in category IV (61-80 years) at 13.3% in 2021 compared to 18.8% in 2000, and in category V (81-100 years) at 15.9% in 2021 compared to 17.3% in 2000 (Ministry of Agriculture, 2022).

Reforestation was influenced by the bark beetle outbreak, which has led to the expansion of planting broadleaved tree species, intending to avoid monocultures over a large area at the same age. For this, afforestation and reforestation activity are more intensive, with 40 thousand hectares in 2022 as against the 2008-2018 period with approximately 19-20 thousand hectares per year (CZSO, 2023). Long-term, coniferous tree species have been predominant, whereas in the period 2019 to 2021 the trend has changed, and more broadleaved tree species were planted. According to financial consequences, the national financial resources were boosted by CZK 8 billion from the National Recovery Plan to support reforestation (European Commission, 2019b).

Based on the impacts of the economic and financial instruments on wood biomass production, the following studies were found (Kanzian and Kindermann, 2013; Moiseyev et al., 2014; Locoh et al., 2022; Lauri et al., 2012; Caurla et al.; 2013; Sasaki, 2021). A mixture of instruments was examined, namely national subsidies, carbon payments, and environmental taxes.

Regarding the wood biomass production in the Czech Republic, the coniferous roundwood removals gradually rose, reaching a peak in 2020 with around 34 million cubic meters, and then decreased to around 23 million cubic meters in 2021 (CZSO, 2023). At the regional scale, the Vysočina Region, Olomouc Region, and Moravian-

Silesian Region lost the greatest proportion of forest stands during the bark beetle calamity. The indicator exhibits an upward trend with a diminishing rate at the European level as well (Forest Europe, 2020).

In the Czech Republic, the sale of significant volumes of wood biomass to foreign countries with low added value occurred. Furthermore, there is a shortage of a wood recycling infrastructure to guarantee the reverse flows and reuse of wood biomass and hence close the loop of renewable material. A further challenge is the adoption of eco-design for wooden products which would offer a longer lifetime and the possibility of reusing the material sustainably in a non-toxic recycling process (Reich et al., 2023). Concerning wood construction, regulatory restrictions hamper the growth of wood material utilization. In addition, there is a pressing issue to improve awareness across Czech society of the benefits of a circular bioeconomy and to stimulate demand for wood products. The potential of circular business models opens up here (Ellen MacArthur Foundation, 2019).

Specific indicators, such as forest land and roundwoood removals are integral factors of the sustainable forest management concept (Forest Europe, 2024). Monitoring and the management of such indicators can enhance the adaptive capacity and mitigation of forest ecosystems. The relevance of sustainable development is intensifying with declining forest health, soil and air pollution, extreme droughts and heat waves, expanded bark beetle infestations as well as forest fires.

Overall, diverse socio-economic scenarios will bring different levels of wood biomass production, which will imply alternative forest management approaches (European Commission, 2024). In the forestry sector, a challenge to find innovative management approaches persists (Rockström et al., 2017). A broad appeal to apply closer-to-nature approaches in forests, such as natural regeneration, leaving deadwood, and abandoning the use of pesticides, to prevent and prepare forests for a changing climate and boost their adaptive potential (Hlásny et al., 2017). The guiding principles of development are linked to the environmental, economic, and social pillars of sustainable development, namely wood production, biodiversity conservation, the protection of water quality, carbon sequestration, and storage (Muys et al., 2022).

Adaptive forest management that respects the productive function of forests, biodiversity, and other ecosystem services poses challenges for climate-smart forestry (Nabuurs, 2017). For forest owners, the concept of climate-smart forestry provides several indicators, however, stronger guidelines are needed (Bowditch et al., 2022). Moreover, to achieve positive macroeconomic impacts and emission reduction a stimulus by the public sector (CO2 taxes, and R&D policies) is necessary (van Meijl, 2016).

To sum up, according to the abovementioned results null hypotheses $1H_0$: There is no statistically significant relationship between economic growth and forestry employment in the Czech Republic, $2H_0$: There is no statistically significant relationship between economic and financial instruments and the development of the forestry sector in the Czech Republic, and $3H_0$: There is no statistically significant relationship between national financial support and forest carbon in the Czech Republic can be rejected.

7 Conclusion and recommendations

The main aim of the dissertation thesis was to carry out the evaluation of the socio-economic impacts of global change on the forestry sector. The aim of the dissertation thesis was achieved through three original research papers published in scientific journals with impact factors. The studies were consistent with the dissertation theme and focused on various aspects of the socio-economic impacts of global change on the bioeconomy, including the forestry sector.

Firstly, a general view of the development of forestry employment within the bioeconomy labour market as well as the evaluation of forestry employment and its drivers within the bioeconomy labour market in the Czech Republic were explored. A diminishing tendency in the share of bioeconomy employment in the whole labour market was identified. A more detailed insight exhibits slight structural changes and several pathways emerge in the individual subsectors of the bioeconomy. The traditional sectors of the economy, namely agriculture, food, beverage, tobacco, and wood products and furniture constitute the largest proportion and held constant employment figures with no significant fluctuations. The bio-based electricity, liquid biofuels, bio-based chemicals, pharmaceuticals, plastics and rubbers, and fishing and aquaculture sectors recorded a growth rate. On the other hand, forestry, bio-based textiles, wood products and furniture displayed a negative trend. According to forestry employment drivers, employment in the forestry sector was positively dependent on wages/salaries and negatively dependent on gross domestic product and forest land.

Secondly, both statistically significant positive and negative impacts of economic and financial instruments of the climate change policy on the development of the forestry sector in the Czech Republic were observed. The forestry sector was presented by 3 indicators, namely forest land, wood biomass production, and forest carbon. An increase in forest land was positively influenced by environmental investments in biodiversity and negatively by subsidies from the Rural Development Programme and the price of European Union Allowance. An increase in wood biomass production was influenced positively by the whole mixture of economic and financial instruments, such as emission trading, environmental taxation, financial contributions for forest management, state financial obligations, and subsidies.

According to the impact of national financial support for forestry on forest carbon, financial contribution for reforestation, establishment, and tending of forest stands increases net carbon sinks while financial contribution for green and environmentally friendly technologies increases net carbon sources. Additionally, an upward trend in national financial support for the forestry sector was found and regional divergences were observed. Owing to the bark beetle calamity, the peak of the national financial sources was detected in the Vysočina Region (CZK 4,658/EUR 190 per hectare), and the Olomouc Region (CZK 2,780/EUR 113 per hectare) in 2020.

On the basis of all the above results, it can be concluded that the main aim of the dissertation thesis was fulfilled. According to the obtained results, the following domains of recommendations for research and practice in the field of bioeconomy can be formulated.

Bioeconomy strategy development - bioeconomy strategy at the national level is a mandatory step for the integration of the concept into the economic system. The Czech Republic stands up to the challenge of developing a comprehensive strategic framework for the bioeconomy at the national level respecting regional disparities. The systematic promotion of local bioeconomies can generate new jobs, business opportunities, and socio-economic development not only in rural areas.

Bioeconomy monitoring system - to develop a comprehensive mechanism containing quantitative and qualitative data regarding the European bioeconomy. An essential parameter is to ensure comparability of data and a disaggregated insight at the national levels. A holistic assessment is needed that captures the economic, social, and environmental dimensions of the bioeconomy. The definition of the bioeconomy and the related definition of the bioeconomy sectors primarily need to be aligned. According to social aspects, qualitative details on bioeconomy employment by economic activity, gender, age, or level of education, are required.

Bioeconomy financial support - a comprehensive financial mechanism to promote the development of the bioeconomy from the initial research to the commercialization phase needs to be established. Investments in the bioeconomy can drive research and development, new jobs, innovative technologies, and products relying on renewable biomass, thereby diminishing dependence on scarce resources. Bioeconomy financial support can assist in the switch from a fossil-based to a more resilient economy while tackling critical environmental and social challenges.

Promote the transdisciplinarity - global change is a complex set of interacting agents, and this requires a transdisciplinary approach. The synergistic effect of disciplines will generate scope for holistic answers with novel solutions. A transdisciplinary attitude in the bioeconomy is demanded in various fields, especially in education, science and research, communication, policy-making, and elsewhere.

Stakeholders involvement - the transformation to a green economy requires effective communication with stakeholders with clear messages and devoid of greenwashing. The necessity for cross-sectoral communication is evident. The knowledge-based bioeconomy should foster socially engaged research to strengthen the willingness of stakeholders to collaborate toward change.

Youth engagement - a special status in the bioeconomy development is occupied by the young generation. The challenge is to raise awareness of concepts such as sustainable development and circular bioeconomy and to equip students with the green skills required for the future demands of the labour market. For youth engagement to be successful there is a pressing need to improve working conditions, especially in traditional bioeconomy sectors such as forestry, while ensuring equal opportunities and closing the gender pay gap within the whole bioeconomy labour force.

Bioeconomy education - education constitutes a bridge between current and future knowledge and skills demanded by the labour force. Ensure upskilling of existing skills, including green skills while reskilling for emerging bioeconomy sectors and associated new jobs, including green jobs. A novel education program and courses that will establish a set of skills, such as long-term thinking or adaptability, and will build a green mindset are the challenges. Moreover, promotes cooperation among educational institutions and enterprises as well as establishes or revises vocational education and training to fulfill shifting skills requirements.

International cooperation - to address global change, international cooperation can drive knowledge sharing, examples of good practices, and capacity building. International cooperation across the economic sectors at the macroregional and global levels is an essential factor in the bioeconomy development. Cooperation can stimulate economic growth by enhancing trade in bio-based products and establishing new markets. In the social sphere, international partnerships can contribute to the creation of new jobs, ensure that the bioeconomy benefits will shared worldwide, and reduce disparities between countries as well as regional inequalities within countries.

Cascading use of biomass - for the bioeconomy to be a sustainable path for progress, it requires circularity at its core. The challenge is to replace fossil-based and carbon-intensive materials with bio-based inputs. These biological resources such as wood biomass should be employed in a multiple cascade to extend their life cycle and increase efficiency of usage. Harvested wood products, such as furniture or constructions simultaneously boost carbon sinks, thus reducing overall emissions. In the synthetic cycle, it is then important to ensure reuse, repair, remanufacture, and recycling.

The challenge for the circular bioeconomy remains the closed energy and material loops. In the Czech Republic, a wood collection and recycling system needs to be built to ensure a reverse flow of wood biomass and to allow waste to become a resource for further production.

Circular business models - the bioeconomy represents a renewable segment of the circular economy and imposes models that are renewable and regenerative in design, use renewable energy, and avoid toxic chemicals. Setting up supply chains that encourage the circular use of bio-based materials and secure ethical production practices is crucial. Application of circular principles, such as waste valorization to transform waste into energy, materials, or chemicals, product as a service, product life extension, design for recycling, and modularity needs to be supported. Shifting to a circular bioeconomy calls for technological innovation, as well as a change in mindset and business behavior.

The findings of the dissertation thesis can contribute to the development of national and regional bioeconomy strategies, economic and financial priorities, and the achievement of the European Green Deal vision. The results carry wider implications of the socio-economic impacts of global change on the bioeconomy, including the forestry sector and the framing of further research agendas for the Czech Republic. The dissertation thesis and doctoral study completed the picture of the circular bioeconomy in the Czech Republic.

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List of abbreviations

CO_2	carbon dioxide
CZK	Czech crown
EU	European Union
EUR	euro
GHG	greenhouse gas
HWPs	harvested wood products
LULUCF	Land Use, Land Use Change and Forestry
$MtCO_2eq.$	megatonnes of carbon dioxide equivalents
NUTS3	nomenclature of territorial statistical units
UNFCCC	United Nations Framework Convention on Climate Change

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B.2.7 Non-productive investments in forests

B.2.8 Conversion of replacement tree plantations

B.2.9 Forestry machinery and technology

B.2.10 Technical equipment for wood processing plants

B.2.11 Preservation of the stand type of the economic ensemble

B.2.12 Protection and reproduction of the forest tree gene pool