UNIVERSITY OF SOPRON
FACULTY OF FORESTRY

PHD THESIS

CLIMATE CHANGE MITIGATION STRATEGIES IN THE FORESTRY AND WOOD INDUSTRY SECTOR

ÉVA ILONA KIRÁLY

SOPRON

2026

University of Sopron Roth Gyula Doctoral School of Forestry and Wildlife Management Sciences

Head of the Doctoral School: Prof. Dr. Sándor Faragó

E1 Ecology and Diversity of Forest Ecosystems Program

Program Manager: Prof. Dr. Csaba Mátyás

Supervisor: Dr. Attila Borovics

Introduction and Scopes of the Research

As the impacts of climate change become increasingly evident and the international political landscape evolves, climate change mitigation has become a pressing global priority. The forest-based sector plays a unique role in addressing this challenge. Beyond reducing emissions, it can offset them through the natural, photosynthesis-driven carbon sequestration capacity of ecosystems, thereby capturing and storing carbon dioxide over the long term. In addition, wood—as a renewable raw material within the circular bioeconomy—can contribute to emission reductions in the industrial and energy sectors through both product and energy substitution effects.

In 2022, the *ForestLab* project was launched with the collaboration of all faculties of the University of Sopron. Its main objective is to map and assess the climate protection role and potential mitigation pathways of the Hungarian forestry and wood industry sectors. A key aim of the project was to develop a carbon balance model capable of comprehensively evaluating climate change mitigation strategies in forest management and the wood industry. This model provides a tool for examining the future carbon balance under various mitigation pathways. The modelling work involved contributions from several faculties of the University of Sopron as well as external researchers. My doctoral research formed part of this larger effort and sought to contribute to the advancement of the modelling process.

The outcome of this work was the creation of the *Forest Industry Carbon Model (FICM)*. Within this framework, I consider the development of the harvested wood product (HWP) and agroforestry sub-models to be my independent scientific contribution, which I have chosen as the subject of my doctoral dissertation.

The specific objectives of my doctoral research, in connection with the overarching aims of the *ForestLab* project, were as follows:

1. **To develop a harvested wood product (HWP) sub-model** that describes the carbon storage of wood products, as well as the carbon dioxide and methane emissions released at the end of their life cycle, in accordance with the methodology established by the Intergovernmental Panel on Climate Change (IPCC) for Greenhouse Gas Inventory Reports (GHG Inventories). A further objective was to quantify the emissions avoided through product and energy substitution.

2. **To test the HWP sub-model** by modelling a smaller product quantity at the company level and, subsequently, the national-level carbon balance of the HWP carbon pool.

3. **To develop an agroforestry sub-model** based on data from the National Forestry Database on shelterbelts and modelling their carbon balance in line with IPCC guidelines and GHG Inventory methodology.

4. **To evaluate the mitigation potential of agroforestry measures** by applying the agroforestry sub-model to shelterbelts.

Materials and Methods

Creation of the FICM HWP Sub-model

Maximizing the carbon storage capacity of wood products requires the integration of climate change mitigation considerations throughout their life cycle — from production and use to recycling and waste management. It is therefore essential to understand how product design, recycling practices, and different waste management technologies affect both carbon storage and emissions.

To support national-level analyses and company-level impact assessments of domestic wood products, I developed the harvested wood product sub-model of the Forest Industry Carbon Model. The sub-model was constructed in accordance with the methodological guidelines of the IPCC for the LULUCF (Land Use, Land-Use Change and Forestry) and Waste sectors. In addition to implementing IPCC equations, the model incorporates a self-developed recycling and waste-routing module.

The model consists of the following modules:

- **Module for Wood Products in Use**: Simulates the carbon stock and carbon balance of wood products throughout their lifetime until disposal.
- **Recycling and Waste Routing Module**: Tracks HWPs that become waste, which can follow three pathways: recycling, incineration, or landfill. The model allows the annual adjustment of waste distribution among these pathways. For the fraction allocated to recycling, it is also possible to specify how

the recycled material is reallocated across different product categories.

- **Waste Module**: Estimates emissions from bioenergy use and wood waste incineration, as well as carbon dioxide and methane emissions from wood waste disposal in landfills. The module can additionally account for variations in methane recovery efficiency at landfills.

- **Product and Energy Substitution Module**: Quantifies the emissions avoided in the industrial and energy sectors through product and energy substitution. The substitution effects increase in proportion to the production of wood products, particularly those with high added value and long service lifetimes. This module was developed on the basis of the comprehensive European-level analysis carried out by the European Forest Institute (EFI).

I parameterized the FICM HWP sub-model specifically for Hungary using data from the Central Statistical Office (KSH), the National Environmental Information System (OKIR), the National Waste Management Plan, and the National Greenhouse Gas Inventory Report.

Using this parameterization, I carried out two sets of analyses. (1) First, I performed product-level projections to examine the life cycle of a manufacturer's annual product volume. These analyses focused on the influence of product lifespan, recycling rates, and waste management practices on the carbon storage capacity of wood panels. To assess the magnitude of these effects at the company level, I modelled eight different scenarios for 200,000 m³ of particleboard, projecting carbon storage as well as carbon dioxide and methane emissions.

(2) Second, I conducted national-level carbon balance analyses for the entire HWP carbon storage pool, covering both the historical period (1985–2022) and the projection period (up to 2050). Within the projections, I assessed the carbon balance of domestic wood products under 11 different scenarios.

Creation of the FICM Agroforestry Sub-model

The LULUCF sector plays a vital role in offsetting greenhouse gas (GHG) emissions from the agricultural, energy, and industrial sectors. Agroforestry is a land-use and management system that integrates the cultivation of trees or shrubs into agricultural practices, interactively combining them with crop production or livestock husbandry. Such systems enhance the synergies between trees and agricultural activities, improving productivity, biodiversity, and environmental sustainability. In particular, agroforestry practices are an important means of increasing carbon sequestration and storage in agricultural landscapes.

For the development of the agroforestry sub-model, I analyzed data on domestic shelterbelts obtained through targeted queries from the National Forestry Database (2020 statistical state data). Data analysis was performed using Statistica software (version 14.0.1.25, Tulsa, OK, USA).

I assessed canopy closure and yield class distributions of shelterbelts by tree species group. These results provided the basis for the parameterization of the FICM agroforestry sub-model.

Using the sub-model, I then evaluated the climate change mitigation potential of a scenario in which the extent of Hungarian shelterbelts is doubled. Specifically, I calculated the total carbon sequestration and the average annual mitigation potential projected up to 2050.

Summary of New Scientific Results (Theses)

Following each thesis point, the scientific publications supporting the respective thesis are listed in a grey-shaded field.

1. Development of the FICM HWP Sub-model

I developed the FICM HWP sub-model to project the carbon storage and carbon balance of wood products. The model is fully consistent with the National Greenhouse Gas Inventory and the methodological framework of the IPCC. It quantifies the carbon stored in wood products, as well as the carbon dioxide and methane emissions released during incineration or disposal at the end of their life cycle. The model also incorporates the recycling of wood products. Through its product substitution module, it further estimates the emissions avoided by product and energy substitution.

Király É. et al. (2024). Climate change mitigation potentials of wood industry related measures in Hungary. Mitigation and Adaptation Strategies for Global Change, 29(6). http://doi.org/10.1007/s11027-024-10161-1

Király É. et al. (2024). Climate Change Mitigation Through Carbon Storage and Product Substitution in the Hungarian Wood Industry. Wood Research, 69(1), 72–86. http://doi.org/10.37763/wr.1336-4561/69.1.7286

Király É. et al. (2023). Modelling Carbon Storage Dynamics of Wood Products with the HWP-RIAL Model—Projection of Particleboard End-of-Life Emissions under Different Climate Mitigation Measures. SUSTAINABILITY, 15(7). http://doi.org/10.3390/su15076322

2. Impact of Climate Change Mitigation Measures on Particleboard End-of-life Emissions

Applying the FICM HWP sub-model, I assessed the effects of different climate change mitigation measures on the carbon storage of 200,000 m^3 of particleboard and on the associated carbon dioxide and methane emissions at the end of its life cycle. Among the mitigation measures, increasing the recycling rate proved to have the greatest impact. Extending the lifespan of particleboard also contributes to climate change mitigation, supporting the principles of cascade use, recycling, and the circular bioeconomy. Furthermore, I found that in the long term, landfilled wood waste represents a significant source of methane emissions, which makes incineration a more advantageous disposal option than landfilling.

Király É. et al. (2023). Modelling Carbon Storage Dynamics of Wood Products with the HWP-RIAL Model—Projection of Particleboard End-of-Life Emissions under Different Climate Mitigation Measures. SUSTAINABILITY, 15(7). http://doi.org/10.3390/su15076322

3. Historical Climate Change Mitigation Impact Assessment

Using the product substitution module of the FICM HWP sub-model and data from the National Greenhouse Gas Inventory Report, I found that between 1985 and 2021, 49% of the climate change mitigation impact of the forestry and wood industry sector was attributable to carbon storage in forests, 4% to carbon storage in wood products, and 47% to product and energy substitution effects.

Király É. et al. (2024). Climate Change Mitigation Through Carbon Storage and Product Substitution in the Hungarian Wood Industry. Wood Research, 69(1), 72–86. http://doi.org/10.37763/wr.1336-4561/69.1.7286

4. Business-as-Usual Scenario Projections

Using the FICM HWP sub-model to project the carbon balance of the national HWP pool under a Business-as-Usual scenario, I found that without additional climate change mitigation measures, the Hungarian HWP pool would become a net carbon source by 2047. To sustain continuous carbon sequestration, it is essential to implement further mitigation measures, particularly cascade use of wood products and circular bioeconomy approaches.

Király É. et al. (2024). Climate change mitigation potentials of wood industry related measures in Hungary. Mitigation and Adaptation Strategies for Global Change, 29(6). http://doi.org/10.1007/s11027-024-10161-1

5. National-Level Projections for HWP Carbon Balance

Using the FICM HWP sub-model, I carried out national-level projections of the domestic HWP carbon pool under 11 different scenarios. The most effective individual mitigation measures were extending product lifespans, increasing recycling rates, and raising the share of industrial wood through improved assortments or higher harvesting levels. When combined, these measures could deliver an average annual climate change mitigation potential of up to 1.5 Mt CO_2 equivalent for the period 2022–2050. This potential could be further enhanced if all harvested wood were processed domestically.

Király É. et al. (2024). Climate change mitigation potentials of wood industry related measures in Hungary. Mitigation and Adaptation Strategies for Global Change, 29(6). http://doi.org/10.1007/s11027-024-10161-1

Király É. et al. (2024). Climate Change Mitigation Through Carbon Storage and Product Substitution in the Hungarian Wood Industry. Wood Research, 69(1), 72–86. http://doi.org/10.37763/wr.1336-4561/69.1.7286

6. Estimating the Quantity of Wood Waste Burned in Households

Using the FICM HWP sub-model, I estimated the annual volume and energy content of wood waste burned in household heating appliances. The analysis indicates that more than 1.2 million m^3 of end-of-life wood products may be burned annually in households, corresponding to a heating value of 14 PJ. These results suggest that a substantial share (39%) of the biomass supply deficit identified in the Bio Screen CCE Project is not attributable to illegal logging, but rather to the combustion of wood waste in households.

Király É. et al. (2025). Estimating the amount and heating value of wood waste burned in households based on FICM HWP model output data. Acta Agraria Debreceniensis, 1, 79-84. https://doi.org/10.34101/actaagrar/1/15104

7. Development of the FICM Agroforestry Sub-model

I developed the FICM agroforestry sub-model, parameterized using data from the National Forestry Database and international literature. The model is consistent with the methodological framework of the IPCC and is suitable for projecting the carbon balance of shelterbelts. It quantifies carbon dynamics across multiple pools, including biomass, deadwood, litter, and soil.

Király É. et al. (2024). Carbon Sequestration in the Aboveground Living Biomass of Windbreaks—Climate Change Mitigation by Means of Agroforestry in Hungary. Forests, 15(1). http://doi.org/10.3390/f15010063

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Király É., & Borovics A. (2024). Preparatory study for carbon sequestration modelling of agroforestry systems in Hungary: The assessment of the yield class distribution of windbreaks. Acta Agraria Debreceniensis, (1), 73–78. http://doi.org/10.34101/actaagrar/1/13673

Király É. et al. (2024). Climate Benefit Assessment of Doubling the Extent of Windbreak Plantations in Hungary. Earth, 5(4), 654–669. http://doi.org/10.3390/earth504003

8. Climate Change Mitigation Impact of Doubling the Area of Shelterbelts

Using the FICM agroforestry sub-model, I evaluated the climate change mitigation effects of doubling the area of domestic shelterbelts. I found that the newly established strips would sequester a total of 913 kt of carbon by 2050, with an average annual mitigation potential of 144 kt CO_2 equivalent. This corresponds to approximately 2% of the average annual carbon sequestration of the Hungarian LULUCF sector. The largest share of this sequestration would occur in the biomass carbon pool of the shelterbelts.

Király É. et al. (2024). Climate Benefit Assessment of Doubling the Extent of Windbreak Plantations in Hungary. Earth, 5(4), 654–669. http://doi.org/10.3390/earth504003

Conclusions

In my doctoral research, I created two sub-models of the Forest Industry Carbon Model (FICM)—one for harvested wood products and one for agroforestry systems—to assess their climate-mitigation contribution within Hungary's forestry and wood industry sectors.

Application of the HWP sub-model demonstrated that both the carbon storage capacity of wood products and their product and energy substitution effects make a substantial contribution to improving Hungary's greenhouse gas balance. At the same time, the results revealed that under a Business-as-Usual scenario the carbon sink role of wood products would cease in the medium term and could even shift to a net source of emissions. This underscores the urgent need for new climate-protection measures grounded in the principles of the circular bioeconomy, with particular focus on extending product lifetimes, increasing recycling, and expanding domestic processing of industrial roundwood.

In addition, the FICM HWP sub-model enabled me to estimate the volume of wood waste burned in households, exposing a previously underexplored yet significant emission source. Tackling this issue is essential not only from environmental and climate-mitigation perspectives, but also within the framework of the circular bioeconomy, as eliminating household wood-waste burning is critical for the optimal use, reuse, and recycling of timber resources.

Through application of the agroforestry sub-model, I demonstrated that windbreak plantations not only enhance the stability of agricultural production but also provide significant carbon sequestration potential. Doubling their area at the national scale would generate considerable climate-mitigation benefits, thereby improving the carbon balance of the LULUCF sector.

Overall, my research confirms that the integrated management of the forestry and wood industry sectors is indispensable for meeting climate targets. The practical application of the developed models can contribute to improving the accuracy of the National Greenhouse Gas Inventory, provide a foundation for carbon certification under the EU Regulation on the certification framework for permanent carbon removals, carbon farming, and carbon storage in products (CRCF, EU/2024/3012), and support the development of climate-friendly forestry, agroforestry, and wood-industry strategies in Hungary.

Acknowledgements

I am deeply grateful to:

Dr. Attila Borovics

for supervising my doctoral research, for consistently providing guidance, and for always being available with advice and solutions to any questions or problems I encountered. I am especially thankful for his excellent lectures, which have been both highly insightful and deeply inspiring.

Dr. András Bidló

for introducing me, during my second year as an environmental engineering student, to the field of carbon sequestration, climate change mitigation, and the Greenhouse Gas Inventory. His support and example have inspired me to remain dedicated to this research area for almost fifteen years.

Dr. Zoltán Somogyi

for guiding me through the intricate details of the Greenhouse Gas Inventory. Beyond sharing methodological expertise, I am grateful for the opportunity to learn from him the nuances of using scientific English. His English-language works remain among my most influential readings. I also thank him for his guidance in matters of scientific ethics.

Dr. Péter Kottek

for first drawing my attention, as early as 2013, to the importance of carbon modelling in harvested wood products. I am also grateful for the collaboration we have shared, which has extended into many areas of life.

András Szepesi

for introducing me to the policy challenges of the LULUCF sector and for guiding my path into the Ministry of Agriculture.

Károly Wisnovszky

who was my first employer and a supportive mentor in the early stages of my professional career.

Gábor Kis-Kovács

for introducing me to the calculations of the Waste sector in the Greenhouse Gas Inventory. The knowledge I gained from him formed the basis of the waste module of the FICM harvested wood products model.

Dr. Endre Schiberna

for his support as head of department in fostering a supportive professional environment, and for encouraging my gradual engagement in university teaching and student supervision alongside my research activities.

Dr. Gábor Illés

for his valuable insights that have enhanced the scientific quality of our joint publications, and for his willingness to collaborate on the development of a forest projection integrating the impacts of climate change.

Dr. Péter Csépányi

for welcoming me into the Continuous Cover Forestry Section of the Hungarian Forestry Association and for everything I learned from him about the relationship between continuous cover forestry and climate action.

All colleagues at the Ministry of Agriculture

for their continuous support and cooperation, and for providing access to the data of the National Forestry Database for research purposes.

All colleagues at the Forest Research Institute

for welcoming me into their community and creating a supportive environment for both my research and daily work.

All colleagues at the University of Sopron

for the wealth of knowledge they imparted to me as an environmental engineering student, which laid the foundation for my career and for this research. I also thank them for supporting me in recent years as a colleague and for their contributions to my work.

List of publications

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