# Long-term scenario modelling for sustainable climate change mitigation and adaption

**Nadine-Cyra Freistetter**

Aalto University

Aalto University publication series
Doctoral Theses 252/2025

# Long-term scenario modelling for sustainable climate change mitigation and adaption

Nadine-Cyra Freistetter

A doctoral thesis completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Science, at a public examination held at the lecture hall M1 of the school on 05 December 2025 at 12:00.

Aalto University
School of Science
Department of Mathematics and Systems Analysis

**Supervising professor**
Professor Dr. Ahti Salo, Aalto University School of Science, Finland

**Thesis advisors**
Research Professor Dr. Tommi Ekholm, Finnish Meteorological Institute, Finland
Senior Research Scientist Dr. Antti-Ilari Partanen, Finnish Meteorological Institute, Finland

**Preliminary examiners**
Associate Professor Dr. Karl-Heinz Erb, BOKU University, Austria
Senior Research Scholar Dr. Stefan Frank, IIASA, Austria

**Opponent**
Director Professor Dr. Michael Obersteiner, University of Oxford, United Kingdom

Aalto University publication series
Doctoral Theses 252/2025



ISBN 978-952-64-2887-1 (paperback)
ISBN 978-952-64-2886-4 (pdf)
ISSN 1799-4934 (print)
ISSN 1799-4942 (pdf)

https://urn.fi/URN:ISBN:978-952-64-2886-4

PunaMusta Oy
2025

Aalto University

**ABSTRACT**

**Author** Nadine-Cyra Freistetter

**Name of the doctoral thesis** Long-term scenario modelling for sustainable climate change mitigation and adaption

**Article-based thesis**

**Number of pages** 129

**Keywords** foresight, impact forecast, optimal mitigation strategy, integrated assessment modelling

Global land systems can either mitigate or exacerbate climate change and its impacts. To utilise and protect land effectively, there is a need for timely, accessible foresight on land-based climate change impacts and mitigation strategies. This dissertation examines interactions between human-managed land systems and climate change through computational modelling and scenario analysis extending to 2100. Across four papers (I–IV), it delivers regional and global foresight under climatic and societal scenarios, and introduces two novel, lightweight, open-source models to bridge the gap between highly detailed, computationally expensive integrated assessment models and simple ones.

Specifically, **Paper I** investigates worst-case climate change impacts on hazardous driving and walking conditions in Northern Europe. Using a road surface energy balance model driven by regional climate projections, it is found that while the slip season may shorten with warming, its intensity could increase. **Paper II** presents the fast global land-use model *CLASH*, which integrates forestry, dynamic vegetation, and optimisation models into a single framework. A carbon stock maximisation experiment illustrates the utility of *CLASH*, reaffirming that reduced animal products consumption and tropical forest conservation are key mitigation levers. **Paper III** links *CLASH* to global energy, materials, and climate systems to form the complex yet lightweight integrated assessment model *SuCCESs*. A Monte Carlo experiment demonstrates its stochastic capabilities, revealing moderate sensitivity of fossil emissions and low sensitivity of land-use emissions to key parameters. **Paper IV** builds on Papers II and III, using *SuCCESs* to explore a wide scenario space informed by current uncertainties in land-based mitigation potential research. The analysis highlights critical system interactions, particularly between land and climate policy: When land is freed (e.g., via reduced product demand), policy must incentivise its use for mitigation. Conversely, if land use is constrained through preservation, mitigation incentives become redundant, as land-use change emissions are sufficiently avoided.

In summary, this dissertation pairs global climate mitigation with local impacts, underscoring the need for harmonised cross-sectoral policies. Future work is called to strengthen stakeholder integration and expand regional data to improve scenario relevance and policy robustness.

# Acknowledgements

This dissertation was made possible by funding of the Research Council of Finland, through the projects *Sustainable Climate Change Mitigation Strategies in Energy-Land-Material Systems (SuCCESs)* and *Health, Risk and Climate Change: Understanding Links Between Exposure, Hazards and Vulnerability Across Spatial and Temporal Scales*. The research work was carried out at the Finnish Meteorological Institute's climate research program, to which I extend my thanks for providing great facilities, equipment, and devotion to employee wellbeing. I also thank the Aalto University for having offered diversified education and support through all stages of my doctoral journey.

The realisation of this dissertation would not have been possible without many great researchers I was lucky enough to meet. My gratitude I owe to Prof. Tommi Ekholm, for giving me the chance to pursue my dreams. Thank you for always showing up, and for the many direct and indirect lessons you have taught me in research and beyond. I won't forget that *nobody really knows anything* and *in case of offense, assume stupidity over evil*. Warm thanks I also extend to Dr. Antti-Ilari Partanen for recruiting me after a very nice job interview, which foreshadowed your encouraging and empowering guidance style. Thanks to the entire climate systems modelling group, and in particular to Dr. Joonas Merikanto and Dr. Marje Prank for your insightful and heartfelt advice that often arrived without me even having to ask. I am also indebted to Dr. Erika Médus, my teacher and inspiration when I was starting a new job during the COVID-19 pandemic.

Furthermore, I wish to thank Prof. Hannele Korhonen and Prof. Annalea Lohila for always listening to the wishes and concerns of early-career researchers, and for supporting every idea with warmth and openness. I am thankful for the active early career community at FMI which gave a space for many relevant professional topics, and most importantly, for fun and friendship.

I am also grateful to Prof. Ahti Salo for acting as an approachable and supportive supervising professor. Thanks to Prof. Obersteiner for acting as an opponent, and thanks to Prof. Karl-Heinz Erb and Dr. Stefan Frank for devoting their time to the pre-examination of this dissertation. Thanks also to Prof. Liisa Kulmala and Prof. Ilkka Keppo for serving as advisors during the final stages of the doctoral research.

I am also thankful to the Research Council of Finland for supporting my participation in IIASA's young scientists summer programme in 2023 and thank my IIASA colleagues for reshaping my understanding of what research can achieve.

Furthermore, I would like to thank the INAR, most importantly Prof. Mari Pihlatie, Dr. Lukas Kohl, Dr. Janne Korhonen, and Prof. Timo Vesala for the most inclusive and fun pre-doctoral time I could have wished for.

I would not be where I am today without the many loving and caring people who shaped my life. My deepest heartfelt gratitude goes to my parents for nurturing my interests from the very beginning. For bearing my long absences. For coming to the rescue, big or small. For making me understand I could bolt and come home any day. Thank you, Mama, for teaching me empathy and creativity. Thank you, Papa, for making sure I get the best education. Thank you, Kiki for always being there, for following me to Finland, and delivering the best Animes in the right moments… and for telling only *a few* embarrassing childhood stories to my coworkers – I owe you a Momotoko Ramen. To my chatty Salama-companions, Arttu Väisänen and Quentin Bell, thank you for inviting me to your office – and letting me remodel it. Thank you for being such good friends. I really appreciate your humour, cleverness, and talents. Thanks also to the lunch/coffee break/after-work beers/crafting/gardening crews, for all the fun times giving me reason to not work from home. Thank you, Bini, TPh Stammtisch, and JENKS for making studying so bearable. You are the reason I have *good old days* to reminisce about. And finally, thank you Miguel for journeying and evolving together, every day. You remind me that the best things in life are worth fighting for and that slow-cooked meals are the most savoury.

To the people and moments that made this work possible.

Helsinki, August 15, 2025

Nadine-Cyra Freistetter

# Contents

# List of Publications

This dissertation is based on the following original articles which are referred to as Papers I–IV.

I. **Nadine-Cyra Freistetter**, Erika Médus, Marjo Hippi, Markku Kangas, Andreas Dobler, Danijel Belušić, Jukka Käyhkö, Antti-Ilari Partanen. (2022) Climate change impacts on future driving and walking conditions in Finland, Norway and Sweden. *Regional Environmental Change* 22, 58 (2022). https://doi.org/10.1007/s10113-022-01920-4

II. Tommi Ekholm, **Nadine-Cyra Freistetter**, Aapo Rautiainen, Laura Thölix. (2024) CLASH – Climate-responsive land allocation model with carbon storage and harvests. *Geoscientific Model Development* 17, 3041–3062. https://doi.org/10.5194/gmd-17-3041-2024

III. Tommi Ekholm, **Nadine-Cyra Freistetter**, Tuukka Mattlar, Theresa Schaber, Aapo Rautiainen. (2024) SuCCESs – a global IAM for exploring the interactions between energy, materials, land-use and climate systems in long-term scenarios (model version 2024-10-23). *Geoscientific Model Development* 18, 4805–4822. https://doi.org/10.5194/gmd-18-4805-2025

IV. **Nadine-Cyra Freistetter**, Tommi Ekholm, Ilkka Keppo, Antti-Ilari Partanen. (2025) Sensitivity of global land-based mitigation potential to land-use scenarios and interactions across sectors. Submitted for publication, May 2025. https://doi.org/10.21203/rs.3.rs-6573840/v1

# Author's Contribution

I. **Climate change impacts on future driving and walking conditions in Finland, Norway and Sweden**
Freistetter carried out the road surface model runs and data analysis and had the lead role in writing the manuscript. Médus carried out the regional climate model runs, for which Dobler and Belušić provided the global boundary data. Kangas and Hippi developed the road surface model its pedestrian index, respectively, and provided guidance on the model. All co-authors contributed to manuscript writing and editing.

II. **CLASH – Climate-responsive land allocation model with carbon storage and harvests**
Ekholm and Rautiainen formulated the model. Freistetter collected the data and developed the mathematical modelling for livestock systems and global food demand. Thölix performed the LPJ-GUESS simulations based on which Ekholm developed and parametrized the land-use representation of the model. Freistetter performed the model demonstration by defining the scenarios, carrying out the model runs, analysing results and writing. All co-authors contributed to manuscript writing and editing.

III. **SuCCESs – a global IAM for exploring the interactions between energy, materials, land-use and climate systems in long-term scenarios**
Ekholm designed the overall structure of the SuCCESs model. All authors contributed to the model development. Freistetter contributed to the model development by data collection and mathematical modelling of (1) the transportation sector including demand, emissions and technology options; (2) the remaining non-renewable energy carriers including their extraction costs and fugitive emissions by region; and (3) the variable renewable energy module with data provided by Ekholm. Additionally, Freistetter carried out (4) the linearisation of the non-linear functions for $CO_2$, $CH_4$ and $N_2O$ radiative forcing, (5) the validation and calibration of emissions produced in the model, and (6) the characterisation of properties of various energy production technologies. Schaber implemented CDR technologies and assisted the Monte Carlo

scenario experiment. Mattlar extended the materials module and tested the model. Freistetter and Mattlar developed a Python toolbox for analysing SuCCESs output. Ekholm carried out the model demonstration. Ekholm had the lead role in writing the manuscript. All co-authors contributed to manuscript writing and editing.

IV. **Sensitivity of global land-based mitigation potential to land-use scenarios and interactions across sectors**

Ekholm provided the original research idea. Freistetter designed and programmed the scenarios, carried out the model runs, analysed the results, and had the lead role in writing the manuscript. All co-authors took part in developing the structure of the paper and contributed to manuscript writing and editing.

# List of Abbreviations

| Abbreviation | Full name | Definition |
|---|---|---|
| AFOLU | Agriculture, Forestry, and Other Land Use sector | A sector in greenhouse gas accounting that includes emissions and removals from land-based activities such as crop and livestock farming, deforestation, afforestation, and land management. |
| A/R | Afforestation or Reforestation | The establishment of forests on previously non-forested (afforestation) or deforested (reforestation) land. |
| BECCS | BioEnergy with Carbon Capture and Storage | Energy generation process using biomass while capturing and storing the $CO_2$ emissions from the burning process; generates near-net-zero energy, and over long timescales, can even achieve net-negative emissions. |
| CCS | Carbon Capture and Storage | A climate mitigation technology that captures carbon dioxide ($CO_2$) emissions from sources like power plants or industrial processes and stores it, e.g. underground, to prevent it from entering the atmosphere. |
| CLASH | Climate-responsive Land Allocation model with carbon Storage and Harvests | A land use optimization model developed in this dissertation. It simulates vegetation growth and forest dynamics under climate change, accounting for forest age structure and climate impacts on productivity to inform land-based mitigation strategies. It also serves as the global land-use module in SuCCESs. |
| $CO_2$ | Carbon dioxide | A colourless, odourless greenhouse gas naturally present in the atmosphere, and the primary driver of human-induced climate change, released mainly through carbon-rich fossil fuel combustion and land use changes. |

| | | |
|---|---|---|
| DGVM | Dynamic Global Vegetation Model | A computer model that simulates global vegetation patterns and their interactions with climate, carbon, and land use over time. |
| FaIR | Finite Amplitude Impulse Response | Simple and idealised climate model that estimates future climate change based on greenhouse gas emissions, focusing on temperature and carbon cycle responses. |
| FMI | Finnish Meteorological Institute | Government agency responsible for gathering and reporting weather data and forecasts in Finland. Institute in which this dissertation was carried out. |
| GHG | Greenhouse Gas | Any gas that traps heat in the Earth's atmosphere, contributing to the greenhouse effect and climate change. The three greenhouse gases considered in this dissertation are carbon dioxide, methane, and nitrous oxide. |
| GLOBIOM | Global Biosphere Management Model | A global partial equilibrium land use model by IIASA that simulates competition for land use between agriculture, forestry, and bioenergy to assess environmental and economic impacts of land-based policies. |
| HCLIM | HARMONIE-Climate (HIRLAM–ALADIN Research on Mesoscale Operational Numerical weather prediction In Europe – Climate version) | A regional climate model based on the HARMONIE weather forecast system, developed for high-resolution simulations over Europe and used to assess local climate impacts and extremes. |
| IAM | Integrated Assessment Model | An economic model that combines climate, economic, and energy data to assess mitigation strategies, policy impacts, and sustainability pathways. |
| LPJ-Guess | Lund–Potsdam–Jena General Ecosystem Simulator | A process-based dynamic global vegetation model that simulates vegetation composition, structure, and function over time. It accounts for ecological processes while responding to changes in climate, $CO_2$ levels, and land use. |
| MAgPIE | Model of Agricultural Production and its Impact on the Environment | A global land-use and agro-economic model that links regional food demand and production with global environmental and economic dynamics, focusing on land-use change, greenhouse gas emissions, and food security. |

| | | |
|---|---|---|
| RCP | Representative Concentration Pathway | Greenhouse gas concentration scenarios used in climate modelling to represent different future levels of emissions. The RCPs used in this dissertation were RCP2.6, RCP4.5, and RCP8.5. |
| RCP 2.6 | Representative Concentration Pathway 2.6 | A low-emission climate scenario aiming to limit global warming to below 2°C above pre-industrial levels by 2100, requiring strong mitigation efforts limiting global warming to below 2°C. |
| RCP 4.5 | Representative Concentration Pathway 4.5 | A stabilization climate scenario where greenhouse gas emissions peak around 2040 and then decline, leading to a radiative forcing of 4.5 $W/m^2$ by 2100. It assumes moderate mitigation efforts and results in intermediate levels of global warming. |
| RCP 8.5 | Representative Concentration Pathway 8.5 | A high-emissions scenario with no significant climate policies, leading to continued rise in greenhouse gases and a radiative forcing of 8.5 $W/m^2$ by 2100, resulting in severe global warming. |
| SSP | Shared Socio-economic Pathway | Scenarios describing social, economic and technological global changes until 2100. The SSPs used in this dissertation were SSP1 and SSP2. |
| SSP1 | Shared Socio-economic Pathway 1 | A sustainable development scenario that emphasises green growth, reduced inequality, and environmentally friendly policies that support achieving climate goals. |
| SSP2 | Shared Socio-economic Pathway 2 | A "middle-of-the-road" scenario where current trends continue without major changes, resulting in moderate challenges to climate change mitigation and adaptation. |
| SuCCESs | Sustainable Climate Change mitigation strategies in Energy-land-material Systems | A lightweight integrated assessment model that simulates global land-use, material, and energy systems to evaluate climate change mitigation strategies; developed and used in this dissertation. |

# 1 Introduction

Recent assessments reveal that the world is not on track to meet the Paris Agreement's target of limiting the global mean temperature rise to well below 2°C (above pre-industrial levels) (Ripple et al., 2024; UNEP, 2024). This poses dangerous near- and long-term risks, and already visible consequences, to ecosystems and societies worldwide (IPCC, 2023a). It is therefore crucial for societies to anticipate the consequences of climate change on their regional habitations and livelihoods well in advance to hedge against risks (IPCC, 2023b, 2023c; World Economic Forum, 2024). Equally importantly, societies need to understand how their local environment can be shaped to help reduce the severity and frequency of climate change impacts (climate change mitigation and adaption) (IPCC, 2023d).

To support this understanding, climate change impact models and integrated assessment models (**IAMs**) use computational methods to explore possible societal pathways and inform policy decisions regarding mitigation and adaption (Harfoot et al., 2014; Michetti and Zampieri, 2014; Weyant, 2017). These models use scenarios to examine which actions could align global development with the Paris Agreement, and to evaluate the consequences of inaction (O'Neill et al., 2016). As land is the primary habitat and provider of livelihoods for most of the global population, much research attention has been given to better understand land-climate interactions: how life on land is impacted by climatic changes (impacts on land) and how land can help slow or reverse climate change (land-based mitigation) (Fawzy et al., 2020; Frank et al., 2021; Karki et al., 2023; Arora and Mishra, 2024). Such analyses reveal important synergies and trade-offs between mitigation strategies and other land uses (Burgess et al., 2012; Doelman et al., 2020; Zhao et al., 2024).

However, choosing between different types of models comes with trade-offs. IAMs are computationally efficient, thus allow large-scale scenario comparisons but typically lack the spatial and process resolution needed to capture complex land–climate interactions (Keppo et al., 2021). In contrast, detailed process-based models represent natural processes, such as cloud formation, ocean circulation, carbon cycle, cryosphere, or biogeochemistry in detail. They can represent nuances more accurately but are limited by high computational costs, especially when coupling with models of different sectors for an integrated assessment. A single scenario run may take days to weeks to complete on a high-performance computer. This creates a gap in current modelling practices. There is a need for medium-detailed models that are simple enough to explore a wide range of scenarios but sufficiently detailed to consider some of the complex and nuanced processes and interactions between systems.

In this context, a major modelling challenge is the trade-off between spatial and temporal resolution, process representation, and computational burden. Not only because of that, there is growing emphasis on regional-scale modelling for all parts of the world (IPCC, 2025). The focus on a small excerpt of the globe allows for more granularity that can better resolve biophysical and socioeconomic conditions, making model outputs more relatable and actionable for local policymakers while keeping the computational burden manageable (Gutowski et al., 2020). For example, high-latitude regions were shown to warm up to four times faster than the global mean, making local adaption planning particularly urgent (Rantanen et al., 2022). Nevertheless, regional processes are inherently linked to broader systems, and thus regional models require boundary conditions from global ones. Therefore, global and regional modelling go hand in hand in research, as they do in this dissertation.

The articles included in this dissertation explore the interactions between climate change and land in long-term scenario modelling until 2100 under the umbrella of computational efficiency, diving into relatable regional climate impacts in northern Europe, as well as developing a medium-detailed integrated assessment modelling framework and experimenting with globally optimal mitigation strategies under different conditions. The research was guided by three key questions (RQ1, RQ2, RQ3):

**RQ1.** **What impacts will climate change have on global human-managed land systems (including infrastructure) in the twenty-first century, and vice versa, what impacts can global land systems have on climate change mitigation?** (I, II, III, IV)

This research question is addressed from different angles throughout Papers I–IV. Paper **I** examines the climate change impacts on regional road infrastructure. Paper **II** assesses globally how changing consumption patterns affect land-based emissions with the help of our new dynamic land-use model. Paper **III** expands the land-use model to a full integrated assessment model, which is used in Paper **IV** to assess the mitigation potential of global land in over 800 scenarios combining six dimensions affecting land availability and emissions.

**RQ2. What is the optimal land-use strategy for mitigating climate change and its impacts while respecting all vital land services, such as food and biomaterial production and biodiversity protection?** (II, IV)

This research question is inquired in Papers II and IV. Paper **II** explores how changing demand for land-intensive products affects land use and forest structure across different biomes, using our newly developed land-use model. Paper **IV** builds on this by examining how various lifestyle choices and policy options, when combined, influence land use and land-use change. This analysis is based on over 800 six-dimensional scenarios using our fully integrated model of energy, materials, land, and climate systems.

**RQ3. How can the computational burden of long-term scenario analysis be lowered while enhancing the understanding of interactions between climate change and human-managed land systems?** (I, II, III, IV)

Papers I–IV address this research question across different domains. Paper **I** evaluates the added value of high-resolution modelling for climate impact analysis on northern European infrastructure, versus a lower resolution. Paper **II** develops a lightweight, spatially generalised land-use model (CLASH), optimising global land use within seconds. Paper **III** develops an equally fast global single-region energy-material-climate model (SuCCESs) and fully integrates CLASH. Paper **IV** applies SuCCESs created in Papers II and III and harnesses its low computational burden with a large-scale scenario exploration exercise.

The following sections summarize the work carried out during this dissertation. First, the theoretical background is presented, from emission sources to common computational modelling techniques in climate sciences and the global land squeeze problem. Second, the main results are summarised and discussed. Third, the conclusions and future scientific avenues emerging from this research are presented. After the references list, the appendix defines key terms used in this dissertation (*integrated assessment model* and *climate change-informed land management*). Finally, the original articles are attached in chronological order.

# 2 Background

## 2.1 Fundamental climate change indicators

This dissertation is grounded in the fundamental understanding that the relentless combustion of the carbon-rich fossil fuels oil, gas, and coal and the large-scale degradation of climate-regulating ecosystems such as forests, have led to a gradual but persistent increase in greenhouse gas (**GHG**) concentrations in the atmosphere (IPCC, 2023e). The altered concentrations have disrupted the Earth's energy balance, leading to a long-term energy surplus in the planetary system (IPCC, 2023f). This manifests as shifts in typical weather patterns and a sustained increase in average ocean and land temperatures, with far-reaching consequences for all systems dependent on climatic conditions (Jones and Mann, 2004; Norris et al., 2016; Savo et al., 2016; Sippel et al., 2020; WMO, 2025).

Climate refers to the average weather conditions in a given region over a few decades, with major climatological bodies agreeing on a thirty-year reference period called climate normal, currently 1991–2020, however with many studies still referring to the previous climate normal 1961-1990 for long-term climate assessments (WMO, 2017; NOAA, 2021; IPCC, 2022). Examples of climate information include the average snow depth in Rovaniemi on March 1st, the typical midday summer temperature in Zanzibar, or the average frequency of large-scale flooding in Dhaka within a climatological period. Like weather, climate is largely influenced by incoming solar radiation, thermal retention in the atmosphere, heat transport via large water bodies, land cover and topography, ice cover, and a range of atmospheric and ecosystem processes (IPCC, 2023g). The difference between current climatological values and those of the pre-industrial era (1850–1900) is referred to as climate anomaly. The accumulation of such anomalies across multiple variables, typically temperature, precipitation, and extreme weather frequency, is what is collectively understood as climate change. The current global temperature anomaly is approximately 1.34–1.41°C (WMO, 2025), just around a tenth of a degree away from the ambitious second Paris Agreement goal of limiting the global temperature rise to 1.5°C to avert the most severe climate change impacts on life on Earth (UNFCCC, 2015).

To restore climate stability, reducing emissions and enhancing carbon uptake are essential strategies. So far, the global carbon dioxide (**$CO_2$**) emissions from fossil fuel use and industries peak almost every consecutive year, hitting 36 $GtCO_2$ in 2024 (Deng et al., 2025). More than 75% of these emissions originate from the energy sector (including electricity and transportation) and further 14% from the agricultural, forestry, and land use (**AFOLU**) sector (Climate Watch, 2023). Thus, the energy and AFOLU sectors are important emission mitigation levers that gained special attention in the works of this dissertation.

## 2.2 Computational climate change foresight

Finding the most effective and efficient pathways to mitigate emissions and enhance carbon sequestration is a highly complex, multi-dimensional problem most effectively analysed through computational modelling. A computer model is a digital program with hundreds to hundreds of thousands of lines of mathematical expressions that describe laws and dependencies between variables in a simplified manner. As the underlying principles a model describes are not expected to change over time, they can be applied to past, present, and future. For example, a modeller can crudely estimate the temperature on top of a mountain at any point in time by programming the known relationship between temperature and altitude into the model and providing the temperature at sea level. Similarly, a computer model can be programmed to portray economic relationships, such as the price reaction to demand and supply. Computers solve these equations accurately and, in most cases, faster than humans.

The articles in this dissertation used two types of computer models: (1) climate and the related climate impact models, adhering to timeless physical laws that universally apply, for example, to the heat and moisture transfers in a medium such as the atmosphere or land surfaces, and (2) integrated assessment models, which approximate economic systems by simulating supply–demand dynamics and the influence of human activities on greenhouse gas emissions. Within both models, we used assumptions on future human activity that drives or mitigates future climate change. Such sets of assumptions are referred to as scenarios. Our scenarios analysed conditions until 2100, but longer simulations are possible and common (Lyon et al., 2022).

The Representative Concentration Pathways (**RCPs**) are widely used, expert-designed scenarios that describe potential future trajectories of GHG concentrations. Each pathway results in a specific level of additional heat trapped by the atmosphere in 2100, known as radiative forcing, which is influenced by societal emissions and climate policy choices (van Vuuren et al., 2011). More precisely, radiative forcing measures how much extra energy is retained on top of the Earth's atmosphere compared to pre-industrial times (1850–1900). As of now, this value is estimated at approximately +2.7 $W/m^2$ (IPCC, 2023h).

This dissertation employed three RCPs. RCP2.6 represents a Paris Agreement-aligned scenario with strong mitigation, limiting radiative forcing to 2.6 $W/m^2$ by 2100, and aiming to keep global warming below 2°C (vanVuuren et al., 2011). RCP4.5 is an emissions stabilisation scenario where emissions level off by mid-century, resulting in 4.5 $W/m^2$ radiative forcing in 2100 (Meinshausen et al., 2011). RCP8.5 acts as the worst-case climate change scenario in which little to no climate policy and extensive expansion of coal-based energy lead to severe warming and a radiative forcing of 8.5 $W/m^2$ in 2100 (Riahi et al., 2011).

The RCP scenarios are used to simulate future climatic conditions in climate models by providing founded assumptions for future atmospheric GHG concentrations. To complement with other future societal conditions, such as population, GDP, and demands for climate-impacting products and services, the five shared socio-economic pathways (**SSPs**) provide narratives and quantifications (Riahi et al., 2017). In this thesis, we predominantly used SSP2, the "Middle of the Road" scenario which represents a world where trends broadly follow historical patterns (Fricko et al., 2017). In an SSP2 world, the economy and population grow at a moderate pace, and society makes some progress toward sustainable development but not quickly enough to avoid moderate climatic, environmental, and social challenges. For Paper IV, we also used SSP1, the "Sustainability" scenario, as the basis for a sustainable meat consumption scenario (van Vuuren et al., 2017). The SSP scenarios are important for understanding how different societal choices lead to climatic outcomes by linking specific RCPs with economic indicators.

Both, RCPs and SSPs, are widely used in climate impact and integrated assessment modelling, with certain integrated assessment models (**IAMs**) simultaneously acting as the producers of these scenarios (Gidden et al., 2019; Pirani et al., 2024): The IMAGE model by PBL (Netherlands) was used to quantify the SSP1 narrative (van Vuuren et al., 2017), and MESSAGE-GLOBIOM framework by IIASA (Austria) quantified SSP2 (Fricko et al., 2017). These two models are among many established integrated assessment models worldwide (Calvin et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017) and shall example the two opposite sides of the spectra characterising different types of IAMs.

IMAGE is a recursive simulation model with hard-linked components in one framework (Stehfest et al., 2014). Recursive simulation means that the state of the economy, land use, and climate of a time step is dependent on the decisions made in the previous time step. Thus, the model has no foresight of how decisions will turn out in the next time step. This simulates decision-making in reality. A unified hard-linked framework means that the model components (modules) are internally linked, interdependent, and communicate seamlessly with each other within the same time step.

The MESSAGE-GLOBIOM framework on the other hand, comprises of five models, the MESSAGEix energy sector model and the GLOBIOM land-use model being the dominant ones. The five co-models iteratively provide input to each other until consensus among the models is reached. This means that a scenario runs multiple times with each co-model passing updated outputs back and forth until consistent (Krey et al., 2020; Awais et al., 2024). This process, which can be time consuming and computationally expensive, can be shortened by emulating a co-model, thus approximating outcomes beforehand to bypass the iterative steps. However, this can produce inaccuracies through human bias. Though being a cumbersome process, soft-linking still can be preferred over hard-linking when combining and harmonising already existing models would require too much work time, or the model would become too big, thus computationally expensive, to run.

Another difference to IMAGE's design, as opposed to recursive simulation, MESSAGE-GLOBIOM uses intertemporal optimisation as underlying algorithm. Optimisation is a mathematical method with which the exact input parameter values are found to maximise an outcome. Simple examples of an optimisation exercise would be finding the maximum area achievable with a twenty-meter-long fence; or minimising production costs in a factory that can produce three different products. In IAM settings, optimisation algorithms typically target minimal costs or maximum social welfare (Keppo et al., 2021). The optimisation becomes intertemporal, when the algorithm has perfect future foresight, thus knows the outcome of all actions in all time steps simultaneously and then chooses the optimal solution.

The models presented in Papers II and III, and used in Paper IV, are also intertemporal optimisation models. The land-use optimisation model CLASH (Paper II) maximises global carbon stocks, whereas the SuCCESs IAM (Paper III) minimises discounted costs for the global economy. While IMAGE and MESSAGE-GLOBIOM represent the world in twenty-six and eleven regions, respectively, SuCCESs v2024-10-23 is a point-sized global model not providing regional resolution, except for the ten major biomes for land use decisions in CLASH. Thereby, it saves considerable computational costs. The more complex a model is, and the higher its spatial and temporal resolution, the higher the computational expense for running a scenario. As a result, a scenario run with complex IAMs can take several hours to days depending on the computational infrastructure. Despite CLASH's and SuCCESs' relative complexity compared to simple IAMs, such as the pioneering IAM DICE (Barrage and Nordhaus, 2024), they achieve solution times of a few seconds using the CPLEX optimisation solver in GAMS.

The decision which side to take in the resolution versus granularity trade-off needs to be tailored to the intended use of the model's outputs. IAM outputs typically serve either directly as decision analysis tool or indirectly as input for other models. Land-use change projections produced by IAMs, for example, can be used to estimate land-use change impacts by impact models. The projected GHG emissions, and related indicators, such as atmospheric GHG concentrations, are particularly useful for a central type of models in climate sciences: climate models.

Climate models are built on complex mathematical equations that describe long-term physical, chemical, and thermodynamical processes influencing average weather patterns such as ocean heat uptake, large-scale oceanic and atmospheric circulations (e.g. thermohaline circulation, jet streams), greenhouse gas dynamics, and feedback mechanisms in ice and clouds (Müller, 2010). These processes operate over timescales of years to centuries and are critical for projecting long-term climate trends. Global climate models simulate the Earth's entire climate system using coarse spatial resolution (typically 50–250 km), while regional climate models focus on a specific part of the globe and use a much finer resolution (typically 1–50 km). Thus, regional climate models allow for more detailed simulations of local climate features such as mountains, coastlines, and extreme weather events (Rummukainen, 2010). They are usually driven by boundary data from global climate models, as global atmospheric states influence regional ones. This was also done in Paper I: global boundary data drove a regional climate model for the northern European domain.

Regional climate simulations are also especially useful for local climate change impact modelling. One of the key tools for impact assessments are energy balance models, which simulate the exchange of heat between the atmosphere and land surfaces to study temperature impacts on different surfaces (North, 2024). In Paper I, we used the FMI's road surface energy balance model RoadSurf to estimate climate change impacts on road infrastructure in northern Europe (Kangas et al., 2015). RoadSurf is usually an operational model driven by up-to-date weather data to predict hazardous (slippery) driving and walking conditions. But for Paper I, we drove RoadSurf with data from a regional climate model using boundary data from two different global climate models. This was done to cover a large portion of the range of estimated temperature and precipitation change over the century by different climate models (Lind et al., 2023).

The reason for the differing projections by different climate models is one of the subjects of investigation by model intercomparison projects. The last completed cycle for climate models (coupled model intercomparison project phase 6) involved more than one hundred models from over fifty modelling groups (Eyring et al., 2016; Touzé-Peiffer et al., 2020; Copernicus, 2021). No model is ever perfect – this is why weather forecasts sometimes fail, and models keep being developed. Model intercomparison projects then serve to compare models, learn from one another, and harmonise model accuracy. Among the known reasons for projection differences are varying levels of detail and complexity, differing scenario choices, foci, omissions, and biases, as well as diverting parametrisation choices. As all of these are human choices, slight differences in model design and their projections are always to be expected, thus, multi-model means often outperform individual models when compared to observations (Weigel et al., 2008; Bellucci et al., 2015; Ban et al., 2021).

Building on this understanding of model diversity and the value of diverse model insights, this dissertation contributes to the broader modelling landscape by developing and applying computational tools to generate foresight on climate change impacts and mitigation. The resulting insights and assets acquired aim to inform future decision-making. Most papers included in this dissertation address, at least in part, the interaction between climate change and human-managed land systems, including infrastructure. In contrast to the energy sector, where technologies for large-scale negative emissions have not yet reached sufficient maturity, the AFOLU sector, and land in general, can already contribute to carbon sequestration in a viable manner.

## 2.3 Climate change-informed land management

Planet earth harbours approximately 127 $Mkm^2$ of land mass, of which around 70% support vegetation on a significant scale. This area can theoretically be used for land-based climate change mitigation strategies that use the photosynthetic activity of plants to remove and store $CO_2$ from the atmosphere. Vegetation stores atmospheric carbon in their cell walls, and upon decomposing, deposits some of that for even longer-term storage in the soil. The rate by which this can happen mainly depends on climate and nutrients, which determines the productivity of the land. More productive land is typically settled on and utilized. For land to store as much atmospheric carbon for as long as possible, humans need to balance all services land can offer, including food, biomaterial, and bioenergy production, room for settlement and infrastructure, carbon sink and storage, biodiversity habitat, water filtration, recreation, and more, while halting pristine ecosystems destruction. This is also known as the *Global Land-Squeeze* problem (Searchinger et al., 2023; Erb et al., 2024). To converge towards such a balance, landowners and policy makers must be informed about expected climate change impacts on their regional land and about the best climate change mitigation and adaption options available to them.

Land-based mitigation strategies aim at enhancing land-based carbon uptake. Methods include afforestation and reforestation (**A/R**), climate-benefitting forest rotations, substitution of emission-intensive materials (such as plastics and cement) with biomaterials, greening of human-managed lands and structures, modern bioenergy, and bioenergy with carbon capture and storage (**BECCS**), among others (Roe et al., 2021). While these strategies contribute to climate change mitigation, they also stand in competition for land with food cultivation, animal husbandry, biomaterial extraction, and biodiversity preservation goals, among other human activity demanding land (Smith et al., 2013; Krause et al., 2018). Understanding the trade-offs and synergies among competing land uses is critical for designing effective climate policy. This challenge is often addressed through computational modelling including diverse sets of land use-affecting dimensions and strategies (Frank et al., 2021; Brack and King, 2021; Zhao et al., 2024). This dissertation contributed to this discourse using our IAM SuCCESs to analyse the global land-based mitigation potential across six land demand-affecting dimensions.

# 3 Main results and discussion

This section presents a compendium of main outcomes and points of discussion of the articles in this dissertation. **Table 1** is an overview over each paper's research objectives, methodology, and main results. Methodologically, all four studies employ interdisciplinary computational modelling and future scenario analysis for policy-relevant climate change impact and adaption foresight. While each study has a distinct focal area, they collectively contribute to a larger scientific discourse on land-based climate change impacts and mitigation.

**Table 1** Overview of publications

| Paper | Research objectives | Methodology | Main results |
|---|---|---|---|
| I | (1) Analysis of worst-case climate change impacts on hazardous driving and walking conditions (road surface temperatures, slipperiness, and zero-degree crossings) in Finland, Norway, and Sweden until 2100. (2) Comparison of the added value of high resolution (3 km) modelling versus coarser resolution (12 km). | (1) Utilisation of the Finnish Meteorological Institute's operational road weather forecast model RoadSurf, driven by the regional climate model HCLIM, with boundary data from two global climate models under the high-emission scenario RCP8.5, (2) with the high (AROME) and lower (ALADIN) resolution configurations of HCLIM. | (1) Average road surface temperatures increased significantly, reducing snow and ice on roads. The slip season shortened to December–February, but more zero-degree crossings led to increased slippery roads and pedestrian paths. (2) The computationally expensive 3km grid showed no added benefit over the 12km grid. |
| II | (1) Development of CLASH, a lightweight open-source partial-equilibrium land-use model that optimises forestry and land management inter-temporally and dynamically accounts for climate change. Modelling of the global land-based food demand and livestock sector. (2) Demonstration of a CLASH use case by analysing the impact of changing demands for land-intensive products on | (1) Emulation of the dynamic global vegetation model LPJ-Guess, incorporating managed forest age and carbon structure similar to dedicated forest models. Detailed modelling of global land-based food demands and livestock sector and associated emissions based on open data and demand projections. (2) Analyse trade-offs between carbon storage and production of wood, bio- | (1) Release of CLASH. (2) Increased animal product consumption had the most severe impacts on land, including increased agricultural emissions, increased harvesting of tropical forests, and decreased carbon uptake, even capable of making global land a net emitter. Furthermore, the optimisation algorithm chose Tropical-humid, Boreal, and Tropical-dry forests to maximise carbon |

| | | | |
|---|---|---|---|
| | land carbon stocks and forestry indicators. | energy, animal products, and food crops with CLASH. | stocks, and utilise Temperate-humid forests for product supply. |
| **III** | (1) Development of SuCCESs, a lightweight integrated assessment model utilising CLASH (Paper II), thereby integrating land, climate, energy, and materials to analyse long-term scenarios. (2) Deliver an easy-to-use python toolbox for analysing SuCCESs model output. | Integration of past and future energy demand, resource availability, technology options, emissions factors, economic parameters, and policy options into the open-source energy modelling system OSeMOSYS. Developing a climate module that translates emissions into climatic changes. Integrating climate and energy-material modules with the CLASH land-use model. | Release of SuCCESs and its results analysis toolbox, fully open source. SuCCESs provides a unique setup to the research community by combining intertemporal optimisation of hard-linked energy, land-use materials, and climate systems in a single region model. With its low computational burden, it is particularly suitable for large-scale scenario or stochastic analyses, demonstrated by a Monte Carlo experiment. |
| **IV** | Examination of the key determinants of the global mitigation potential of land under rising land pressures, harnessing the fast multi-dimensional and inter-systems capabilities of SuCCESs. Integration of six land-affecting dimensions into one framework to assess combined mitigation potentials, individual mitigation contributions, as well as synergies and trade-offs between the dimensions (i) emission taxation, (ii) dietary shifts, (iii) food distribution, (iv) biodiversity conservation, (v) biomaterial utilisation, and (vi) wildfire prevalence. | Implementation of scenarios in SuCCESs by (i) taking shadow prices of temperature-constrained model runs, (ii) adjusting demand for livestock products, (iii) constraining food distribution between biomes to 65%, (iv) restricting harvesting or converting pristine and mature managed forests to other land uses, (v) reducing graphic paper use or building 50% of new residential buildings out of wood, and (vi) adding an literature-based uncertainty range to CLASH's wildfire prevalence. This resulted in the analysis of 864 six-dimensional scenarios. | Emission pricing and reduced meat consumption had the biggest synergistic contribution to global mitigation potential, with nuanced influence of distributing food globally, reducing wood demand, and reducing wildfire activity. Without emission pricing, strict biodiversity protection mitigated as much as a global vegan diet but intensified forestry and deforestation on unprotected land. Reducing graphic paper demand had minor climate effects but decreased forestry intensity. |

Following are more in-depth descriptions of the main results relating to climate change-informed land management and the research questions of this dissertation. Interwoven are discussions of result validity and implications, where applicable.

## 3.1 Paper I

**Northern Europe to expect shorter but more slippery winters (**RQ1**)**

The road surface temperatures in Finland, Norway, and Sweden (**FNS**) were projected to increase strongly during the twenty-first century under the worst-case climate change scenario RCP8.5. The projection for 2041-2060 showed the most pronounced road heating in autumn and winter from September to February across the three countries, with average road temperatures rising 2.5–3.9°C, compared to the historical period simulated in this study (1986–2005). Regionally, however, changes can be even more pronounced. South-eastern Finland showed the most extreme changes of more than 5°C average road surface temperature increase during winter with GFDL's global climate model.

These temperature rises changed projected driving and walking conditions in the model. Freezing road temperatures were projected not to occur as often as they used to in the historical reference period. While road surface temperatures in FNS were below 0°C 43.5–46.9% of the time of a year in the period 1986–2005, for 2081-2100, this dropped to 23.9–29.7% of the time. This had consequences for snow and ice storage on roads and walkways. The model projected a noticeable decline in snow and ice on roads. During the entire cold season (September–May), roads were projected to be up to 30 percentage points more often dry than in the historical period. This made roads considerably less often hazardous to drive on.

However, in the historical period (1986–2005), road and sidewalk surface temperatures typically remained well below 0°C for extended durations during the cold season. The warming brings temperatures closer to the freezing point, resulting in more frequent and unpredictable fluctuations around 0°C and repeated freeze–thaw cycles, called here 0°C-crossings. Between 2041 and 2060, Finland and Sweden were projected to experience 1–4 fewer autumn days with at least one 0°C crossing, reflecting a delayed onset of cold temperatures compared to the historical period. In contrast, winter shows an average increase of 1–7 such days, driven by milder winter temperatures. Spring's 0°C crossings reduced by 1–7 days across FNS.

Due to the accumulation of 0°C-crossings in wintertime, the pedestrian mode of the road surface model projected an increase of water layered on top of ice on pedestrian sidewalks, which assume different cleaning and ice packing conditions. Water or snow on top of ice are the most slippery conditions encountered on sidewalks, causing many slip-related injuries in FNS. The decrease in 0°C-crossings in spring and autumn but increase in winter suggest the slippery season might become shorter, but more hazardous for pedestrians in the future.

For interpreting the results of this study, it is important to consider that it was produced with the worst-case climate warming scenario RCP8.5, which has been examined for assuming unrealistically high emissions until 2100 caused by an unlikely expansion of coal-based energy (Hausfather and Peters, 2020; Ritchie and Dowlatabadi, 2017). Therefore, these results should be regarded as upper extreme estimates and can serve as an orientation for the order of magnitude of changes to expect, especially around mid-century. Furthermore, the projections are averaged over large areas and time frames, which can vary considerably from year to year. Especially for the projected increases of repeated freeze–thaw cycles (zero-degree-crossings) it is important to consider that these can happen during short time periods, and within hyper-localized areas, which can significantly complicate managing hazardous driving and walking conditions. For example, while sun-exposed surfaces may remain above freezing, shaded areas, unaccounted for in the used model setup, could experience temperatures below 0°C. This omission likely underestimates the frequency of 0°C-crossings. These insights can help decision-makers in northern countries plan road maintenance, investments, and costs ahead of time, as freeze-thaw cycles pose a strain in road pavement and public health (Kwiatkowski et al., 2016, 2020).

### **Higher computational burden added too little value (**RQ3**)**

A full road surface model run with the lower resolution configuration (12km grid) of the regional climate model took about one month to run on the Puhti supercomputer (CSC, Finland) and produced a few terabytes of raw data. The high-resolution configuration (3km grid) posed a substantially increased computational burden to the infrastructure with three times longer run time and four times higher required storage space. The higher resolution only added value in topographically difficult regions, predominantly the Norwegian fjords and mountains. Therefore, the added value of the high-resolution configuration was insufficient to justify its use for a multi-country climate change analysis.

This pre-analysis enabled significant resource savings during the rest of the study, as our analysis examined at country scale, distinguishing only between northern and southern regions. However, for detailed regional analyses, for example on county level, higher resolution modelling may still offer substantial benefits. Focusing on a small sub-national region may keep the computational effort low even with a high spatial resolution, compared to the same resolution on a multi-country study.

## 3.2 Paper II

### Development of dynamic high-speed land use optimisation model CLASH (RQ3)

CLASH trades granularity for speed and flexibility, compared to detailed land-use models such as GLOBIOM or MAgPIE. This makes CLASH ideal for generating large numbers of global scenarios in the same time detailed models take for a few scenarios. This was achieved by keeping the spatial resolution at global, single-region level, only incorporating ten types of biomes to account for different ecological yields, on the one hand. On the other hand, ecological processes were emulated from a dedicated and complex dynamic vegetation model, run with different climate scenarios (see following section). This enabled the rapid climate-dynamic optimisation of land-use scenarios. Yet, what distinguishes CLASH from simplest models is the incorporation of detail around forestry and food production systems. The establishment of a forest age structure and associated carbon densities, along with differentiation between different types of livestock and animal-based products allows for a broader range of possible scenario designs.
Furthermore, CLASH can be run in stand-alone version or can be easily hard linked with other models, allowing for a fully integrated land use optimisation simultaneously with the coupled models' run.

### Emulation of vegetation model intrinsically accounts for climate change impacts on land (RQ1)

Climate change alters vegetation productivity through shifts in temperature, precipitation, and $CO_2$ concentration. The LPJ-GUESS dynamic vegetation model is a process-based model that accounts for important ecological processes such as photosynthesis, plant competition, growth, and mortality among different vegetation types based on many climatic and societal variables in high resolution. We ran this complex model under different climate change scenarios and represented all fitted functions over relevant ecological parameters, such as carbon density in a forest, with linear expressions to simplistically mimic the behaviour of LPJ-GUESS within CLASH. These fixed but time-varying values ensure that vegetation growth, yield, disturbance, and carbon sequestration potential vary with the climate scenario. This allows CLASH to evaluate land use strategies under evolving environmental conditions implicitly, based on the chosen parametrisation.

The LPJ-GUESS emulation reinforced findings that forests may gain increasing importance as carbon storages over the century due to the $CO_2$ fertilisation effect (Piao et al., 2020; Walker et al., 2021). In our RCP4.5 simulations, the fertilisation effect enhanced carbon density by 1.5–2 times, compared to a constant historical climate. The warming climate additionally boosted forest growth in cold biomes but slightly inhibited it in warm ones. Furthermore, $CO_2$ fertilisation was projected to strongly enhances crop yields in temperate biomes by up to 38% and tropical ones by up to 57%, higher than previously reported (Franke et al., 2020). However, this was consistent with LPJ-Guess' generally high sensitivity to $CO_2$ (Müller et al., 2015).

### Boreal and tropical forests maximise carbon storage in vegetation (RQ2)

To maximise global carbon stocks, the optimisation algorithm expanded and matured tropical-humid and boreal forests, harvested and regrew tropical-dry forests, and extensively cleared temperate-humid forests.

Tropical-humid forests (Amazon, central Africa, and Southeast Asia) were the most sensitive to livestock demand and carbon loss. A gigatonne of logging wood led to a carbon stock loss of ten gigatonnes (**GtC**), while reducing livestock demand increased carbon stocks by up to 100 GtC by 2100. These forests matured significantly, with a mean tree age of over 120 years.

Tropical-dry forests (central and south America, sub-Saharan Africa, India, and southeast Asia) showed a young mean tree age, below 20 years, reflecting extensive harvesting of mature forests and regrowth of younger ones. Despite net carbon gains, even small harvest increases led to major carbon losses, prompting the algorithm to limit their clearing.

Boreal forests (northern Europe, southern Canada, and Russia) had a semi-mature mean tree age of approximately 60 years, indicating selective harvesting. They were highly sensitive to wood demand and acted as fallback land under high livestock demand.

Temperate-humid forests (central Europe, eastern U.S., eastern China) lost around 40 GtC due to widespread clearing in most scenarios, making them minimally responsive to additional pressure. Biodiversity and wildfire effects were not included in these results.

While CLASH's aggregation of the entire global land into 10 biomes and six land-use classes allows fast computation, it is also important to recognise the associated caveats. The aggregation into biomes serves for the optimisation by vegetation but averages out important societal realities. It required creating an assumed representative person, lifestyle, and livestock for the whole world, largely influenced by data more available from highly developed countries. This may introduce biases and limit regional application.

Furthermore, the all-or-nothing approach of land use and land use conversion does not allow for combined land use classes, such as greening urban spaces or thinning of forests. This may produce partly inapproachable outcomes. Yet, these are caveats that CLASH shares with other simplified global models but with its medium-complex design offers a unique perspective for future land use scenario analysis.

## 3.3 Paper III

### Development of lightweight integrated energy-materials-climate-land model SuCCESs (RQ3)

SuCCESs provides to the research community a unique setup by combining intertemporal optimisation of hard-linked energy, land-use, materials, and climate systems in a fully transparent single model. The model hard-links the CLASH land use model (see Paper II) with extended versions of the FaIR simple climate model (v2.0.0) (Leach et al., 2021) and the open-source energy modelling framework OSeMOSYS (Howells et al., 2011). The entire model is 335 MB in size, solves in less than 10 seconds on an average laptop using the CPLEX linear programming solver with the GAMS programming language. A single scenario file requires only 23 MB of memory space. With its low computational burden, it is particularly suitable for analysing a large number of scenarios or stochastic analyses. We demonstrated this with a Monte Carlo sampling exercise (refer to section below).

### Land use emissions moderately sensitive to input parameters in SuCCESs (RQ1)

To assess the robustness of SuCCESs' estimates based on input parameters (which themselves are based on assumptions about the future), we conducted a Monte Carlo sensitivity analysis. In 1000 scenarios, twelve parameter groups, from costs to demands, were randomly varied by up to 20% around their default values. Land-related parameters included vegetation carbon density, crop yields, and forest fire probability, which were varied from their LPJ-GUESS parametrisations. Additionally, the scenarios were subject to four possible levels of radiative forcing targets in 2100, from no target (no climate mitigation) to low radiative forcing targets (high climate mitigation required).

While SuCCESs showed stronger sensitivity of fossil emissions to input parameters, land use emissions remained relatively stable across random parameter variations. Without mitigation incentives (no radiative forcing target), the spread of land-use $CO_2$ emissions based on input parameter variations was up to 5 Gt/year. Although there was no mitigation incentive, the cost-optimisation strove for net-zero land-use emissions between 2060 and 2100 in most scenarios. With radiative forcing targets, the spread among scenarios remained around 2.5 Gt/year, signalling a moderately low sensitivity to slight variations in input parameter assumptions. Under radiative forcing targets, land-use $CO_2$ emissions reached net-zero mostly between 2050 and 2080 and continued achieving net negative emissions thereafter, acting as a sink of up to -10 Gt/year.

The Monte Carlo experiment also showcased an important caveat from a land-based mitigation perspective, which SuCCESs shares with other prominent integrated assessment models: Giving the model the chance to achieve climate targets with utilisation of carbon capture and storage (**CCS**) technologies that are yet to be developed (Fuhrman et al., 2019; Fuss et al., 2014). This does not only foster over-confidence that future technologies will solve today's problems but also skews the true land-based mitigation potential of mitigation options we have today. Yet, global insights into mitigation potentials, timelines and extent of CCS technology and natural land-based mitigation needed can motivate investment and innovation into technology development and nature restoration.

## 3.4 Paper IV

**Large-scale scenario exploration uncovers cross-sectoral interactions and sensitivities (**RQ3**)**

We conducted a large-scale exploration of 864 climate mitigation-affecting scenarios, generated within two days of computation time on a standard laptop. This rapid turnaround was made possible by the SuCCESs model's exceptionally low computational burden, enabling broad and systematic testing across multiple interacting dimensions. Unlike many integrated assessment models that require long runtimes, using SuCCESs allowed to capture a wide range of trade-offs, synergies, and sensitivities between land-based mitigation strategies. This approach significantly improved the breadth of insights from scenario analysis and could improve the robustness of findings from other studies that did not incorporate as many dimensions.

**Livestock pastures key lever for land-based mitigation (**RQ2**)**

Livestock pastures present the most significant lever for optimising global land use. Currently, they cover approximately 25% of the world's land area, and importantly, this land is already under some form of human management. This creates a unique opportunity for transformation. Our land-use optimisation analysis showed that, regardless of whether there was a climate policy incentive in place, reducing pasture area emerged as an efficient land allocation strategy. While this result does not consider animal welfare or ethical farming, it highlights that underutilised pasture contributes to high costs and missed carbon sequestration potential. Reducing the climate burden of pasture fallowness should therefore be a clear priority.

One way to reduce pasture area is reducing the consumption of meat globally. Our results showed, however, that without explicit policy incentives, such as emission taxation, even a global shift to vegan diets did not lead to substantial climate mitigation gains as no cost-beneficial incentive for afforestation was in place. Neither did pasture abandonment preserve pristine (unmanaged) ecosystems without emission taxation, and global warming reached 2.7–3.4°C in 2100 in vegan-no emission tax scenarios – far from Paris Agreement targets, but very close to the omnivore diet scenarios' projected warming of 2.8–3.4°C. The only strong mitigation option in the absence of emission pricing was strict biodiversity conservation which avoided the land use change emissions from unrestricted deforestation, but lost significancy when combined with emission pricing.

Only when emission pricing was applied did the model reveal a much more powerful mitigation in vegan than in omnivore scenarios, as it was cheaper for the model to utilise abandoned pastures for emission mitigation than paying for the emission tax. This clearly demonstrated the synergistic impact of dietary change and climate policy. Therefore, global veganism in combination with emission taxation yielded temperature anomalies of under 1°C in 2100. But also slightly reduced animal product consumption following the SSP1 scenario ("flexitarian diet") combined with emission taxation were climate beneficial and helped keep the global mean temperature rise within Paris Agreement limits.

Thus, instead of leaving freed-up pasture idle, it must be actively managed, e.g., through afforestation, vegetation diversification, or sustainable repurposing. The same applied to other types of freed-up land in the model, such as freed cropland from shifting crop farming to the most productive climates and distributing food globally. The shifts enabled land-based mitigation even in scenarios with particularly tight competition for land (e.g., scenarios combining high meat consumption with strict biodiversity conservation and emission taxes).

In this land-use repurposing discourse, it is important to remind that the SuCCESs IAM follows an all-or-nothing land-use allocation approach. Nuanced and mixed land-use interventions, such as urban greening, forest densification and diversification, silvipasture, and agroforestry, are not modelled. However, recent studies emphasize that mixed land-use systems provide substantial benefits to climate and a variety of other ecosystem services (Baradwal et al., 2023; Cook-Patton et al., 2021). This is important because in practice, a global shift to veganism is not to be expected, but reducing in-use pasture fallowness lies within the range of possibilities. Furthermore, the results of this study should be seen as a sensitivity analysis of the land mitigation potential to land-use-related scenarios, and the numerical estimates interpreted as the maximum achievable mitigation at the extremes of possibilities.

### Climate impact integration projected lower afforestation sensitivity to wildfires (RQ1)

Wildfire activity is projected to increase in frequency and severity during this century (MacCarthy et al., 2023). SuCCESs, via its land use module CLASH, dynamically integrated climate change impacts on land and used intertemporal optimisation with perfect foresight of future wildfire activity. As a result, afforestation efforts were largely unaffected by moderate changes in wildfire extent, as the model favoured areas less prone to future fires. This revealed a lower-than-expected sensitivity of afforestation to fire disturbances and did not significantly reduce total afforestation potential as shown in Jäger et al. (2024). This reinforces that knowing which areas could experience changes in wildfire activity is crucial to afforestation/reforestation (**A/R**) planning. First, regionally declining wildfire prevalence might identify attractive areas for A/R and nature restoration. Second, areas that are becoming more prone to wildfires can either be chosen to be avoided or managed extra carefully for wildfire control.

# 4 Outlook and conclusion

This dissertation aimed to advance climate change research by contributing accessible and transparent foresight on alternative mitigation strategies versus inaction, bridging global and regional perspectives, under special consideration of lowering the computational burden of complex foresight-producing computer models.

In Paper **I**, we analysed the worst-case climate change impacts on land-based infrastructure in northern Europe and found less frequent but more severe slippery conditions, especially for pedestrians. In Paper **II**, we developed a land use optimisation model that emulates climate change impacts on vegetation like a DGVM and represents forest stands by age like a forestry model. We also presented a use case that showed that animal product consumption reduction and tropical forest protection had the biggest impacts on global carbon stocks. In Paper **III**, we fully integrated the land use model from Paper II with an energy-material-climate optimisation model and performed a Monte Carlo experiment to analyse its parameter sensitivity and demonstrate its low computational burden. In Paper **IV**, we used the models developed in Papers II and III to explore the determinants of the global land-based mitigation potential and found that releasing land (e.g., by demand reductions) only has climate benefits when incentive, i.e., emission penalty, is provided.

The collective findings of this dissertation highlight the far-reaching consequences of global inaction and absence of climate policy on climate change and its impacts. Meat-intensive diets, no protection of forests, and no climate policy caused a projected rise in global mean temperature of 3.7°C in our integrated assessment model. This rather abstract indicator can be made tangible locally with regional climate, energy balance, and impact models. Our results of projected intensifying freeze-thaw cycles on roads in high northern latitudes in a warming climate illustrates the diversity and highly localised nature of climate change impacts on land systems.

This dissertation focused on climate change impacts and mitigation strategies on land. One important side of climate change-informed land management is knowing expected climate change impacts on local land for designing adaption strategies. Like climate between boreal and tropical regions differ, so do climate change impacts. Looking ahead, this means it is crucial to rapidly strengthen regional climate, earth system, and impact modelling for diverse parts of the world. According to Berrang-Ford et al. (2021), there is yet little evidence for transformational human adaption to climate change across the world, and regional coverage and enhancing the understanding of adaption options are named as critical points for improvement. Providing more specific and accurate foresight on localised climate change impacts can inform and empower decisionmakers, as demonstrated by local climate change adaption initiatives for two Finnish regions that used insights from Paper I of this dissertation (Hämäläinen et al., 2022; Söderholm et al., 2024).

To build and improve models it is imperative to improve observational data. For Paper I, we validated historical road surface temperature observations before running future analysis to improve the confidence into our projections. In Finland, quality-checked data was available from road-embedded temperature sensors, so validation was easy and trustworthy. For the other countries, data was either scarce or the data quality was not guaranteed, making model validation for these countries limited. Similarly, while building models in Papers II and III, rich data availability, such as the FAOstat database for agricultural indicators, improved workflow and confidence in the representability of the corresponding module, while scarce open data availability, such as in the transport sector, prolonged the modelling process and decreased confidence. Therefore, improving data availability and quality for diverse sectors and underrepresented regions would be an imperative future research avenue for better monitoring and better models, ergo better foresight.

The other important side of climate change-informed land management is the integration of land-based mitigating interventions on as much land as possible while considering cross-sector interactions. While land-based mitigation is estimated to contribute median 10% of global mitigation until 2030 to limit global warming to 1.5°C with limited overshoot (Ganti et al., 2024), it does not remain uncontested. Dooley and Kartha (2018) argue that even nature-based carbon dioxide removal has risks being overestimated in potential or that their large-scale deployment might bring unexpected adverse societal impacts. Consensus reigns that rapid policy action is needed, and conventional land-based mitigation, such as A/R, are tangible now (Brack and King, 2021; Forster et al., 2025). In this decision conflict, agile scenario models can help generate insight on the most effective mitigation portfolios. Therefore, more scenario modelling frameworks for agile on-demand use should be developed. These should be able to more rapidly generate insights when and where they are needed for decision-making, as opposed to complex models partially requiring highly trained personnel, long preparation times, and high-performance computing infrastructure.

Scientists generally aim at progressing scientific understanding and accuracy of processes, yet often have hopes for impact beyond the scientific community. In the face of climate change-induced environmental crises, climate sciences bear a high relevance for public safety and policy with a diverse body of non-scientific stakeholders who climate scientists hope to inform (Calabria and Marks, 2024). In order to do so, climate sciences would benefit from ever-improving accessible communication and visualisation strategies (Shepherd and Lloyd, 2021). While this is not inherently part of the "climate scientist" job description, the field would profit from more individuals with a keen interest or training on communication strategies. This could also include co-designing climate information services together with stakeholders; for example, developing an accessible and attractive user interface for agile on-demand models mentioned above. The less distant scientists become to non-scientists, the more useful information and services scientists can produce for a highly-engaged yet divided global society (Dechezleprêtre et al., 2025).

In summary, this dissertation contributes to bridging scientific rigour with practical relevance by developing lightweight, transparent, and accessible modelling tools for climate change foresight. It highlights the importance of integrated thinking across scales, sectors, and disciplines, and underscores that both mitigation and adaptation must be informed by timely, localised, and reliable information. Looking forward, strengthening regional modelling, improving data infrastructures, and building inclusive, user-oriented modelling tools will be essential steps toward actionable climate science. Through continued interdisciplinary collaboration and stakeholder engagement, climate research can become an even stronger enabler of equitable and effective responses to the global climate crisis.

# 5 References


Arora, N.K., Mishra, I., 2024. Life on land: progress, outcomes and future directions to achieve the targets of SDG 15. Environmental Sustainability 7, 369–375. https://doi.org/10.1007/s42398-024-00330-y

Awais, M., Vinca, A., Byers, E., Frank, S., Fricko, O., Boere, E., Burek, P., Poblete Cazenave, M., Kishimoto, P.N., Mastrucci, A., Satoh, Y., Palazzo, A., McPherson, M., Riahi, K., Krey, V., 2024. MESSAGEix-GLOBIOM nexus module: integrating water sector and climate impacts. Geoscientific Model Development 17, 2447–2469. https://doi.org/10.5194/gmd-17-2447-2024

Ban, N., Caillaud, C., Coppola, E., Pichelli, E., Sobolowski, S., Adinolfi, M., Ahrens, B., Alias, A., Anders, I., Bastin, S., Belušić, D., Berthou, S., Brisson, E., Cardoso, R.M., Chan, S.C., Christensen, O.B., Fernández, J., Fita, L., Frisius, T., Gašparac, G., Giorgi, F., Goergen, K., Haugen, J.E., Hodnebrog, Ø., Kartsios, S., Katragkou, E., Kendon, E.J., Keuler, K., Lavin-Gullon, A., Lenderink, G., Leutwyler, D., Lorenz, T., Maraun, D., Mercogliano, P., Milovac, J., Panitz, H.-J., Raffa, M., Remedio, A.R., Schär, C., Soares, P.M.M., Srnec, L., Steensen, B.M., Stocchi, P., Tölle, M.H., Truhetz, H., Vergara-Temprado, J., de Vries, H., Warrach-Sagi, K., Wulfmeyer, V., Zander, M.J., 2021. The first multi-model ensemble of regional climate simulations at kilometer-scale resolution, part I: evaluation of precipitation. Clim Dyn 57, 275–302. https://doi.org/10.1007/s00382-021-05708-w

Baradwal, H., Ghosh, A., Singh, A.K., Jiménez-Ballesta, R., Yadav, R.K., Misra, S., Siddanagouda Sannagoudar, M., Kumar, S., Kumar, R.V., Singh, S.K., Yadav, D.K., Mahala, D.M., 2023. Soil nutrient dynamics under silviculture, silvipasture and hortipasture as alternate land-use systems in semi-arid environment. Forests 14, 125. https://doi.org/10.3390/f14010125

Barrage, L., Nordhaus, W., 2024. Policies, projections, and the social cost of carbon: Results from the DICE-2023 model. Proceedings of the National Academy of Sciences 121, e2312030121. https://doi.org/10.1073/pnas.2312030121

Bellucci, A., Haarsma, R., Gualdi, S., Athanasiadis, P.J., Caian, M., Cassou, C., Fernandez, E., Germe, A., Jungclaus, J., Kröger, J., Matei, D., Müller, W., Pohlmann, H., Salas y Melia, D., Sanchez, E., Smith, D., Terray, L., Wyser, K., Yang, S., 2015. An assessment of a multi-model ensemble of decadal climate predictions. Clim Dyn 44, 2787–2806. https://doi.org/10.1007/s00382-014-2164-y

Brack, D., King, R., 2021. Managing land-based CDR: BECCS, forests and carbon sequestration. Global Policy 12, 45–56. https://doi.org/10.1111/1758-5899.12827

Burgess, P.J., Rivas Casado, M., Gavu, J., Mead, A., Cockerill, T., Lord, R., van der Horst, D., Howard, D.C., 2012. A framework for reviewing the trade-offs between, renewable energy, food, feed and wood production at a local level. Renewable and Sustainable Energy Reviews 16, 129–142. https://doi.org/10.1016/j.rser.2011.07.142

Calabria, L., Marks, E., 2024. A scoping review of the impact of eco-distress and coping with distress on the mental health experiences of climate scientists. Front. Psychol. 15. https://doi.org/10.3389/fpsyg.2024.1351428

Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., Kim, S., Kyle, P., Link, R., Moss, R., McJeon, H., Patel, P., Smith, S., Waldhoff, S., Wise, M., 2017. The SSP4: A world of deepening inequality. Global Environmental Change 42, 284–296. https://doi.org/10.1016/j.gloenvcha.2016.06.010
Climate Watch, 2023. Historical Greenhouse Gas (GHG) Emissions.
Cook-Patton, S.C., Drever, C.R., Griscom, B.W., Hamrick, K., Hardman, H., Kroeger, T., Pacheco, P., Raghav, S., Stevenson, M., Webb, C., Yeo, S., Ellis, P.W., 2021. Protect, manage and then restore lands for climate mitigation. Nat. Clim. Chang. 11, 1027–1034. https://doi.org/10.1038/s41558-021-01198-0
Copernicus, 2021. Latest projections of future climate now available. [Press Release]. URL https://climate.copernicus.eu/latest-projections-future-climate-now-available (accessed 5.31.25).
Dechezleprêtre, A., Fabre, A., Kruse, T., Planterose, B., Sanchez Chico, A., Stantcheva, S., 2025. Fighting Climate Change: International Attitudes toward Climate Policies. American Economic Review 115, 1258–1300. https://doi.org/10.1257/aer.20230501
Deng, Z., Zhu, B., Davis, S.J., Ciais, P., Guan, D., Gong, P., Liu, Z., 2025. Global carbon emissions and decarbonization in 2024. Nat Rev Earth Environ 6, 231–233. https://doi.org/10.1038/s43017-025-00658-x
Doelman, J.C., Stehfest, E., van Vuuren, D.P., Tabeau, A., Hof, A.F., Braakhekke, M.C., Gernaat, D.E.H.J., van den Berg, M., van Zeist, W.-J., Daioglou, V., van Meijl, H., Lucas, P.L., 2020. Afforestation for climate change mitigation: Potentials, risks and trade-offs. Global Change Biology 26, 1576–1591. https://doi.org/10.1111/gcb.14887
Dooley, K., Kartha, S., 2018. Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. Int Environ Agreements 18, 79–98. https://doi.org/10.1007/s10784-017-9382-9
Erb, K.-H., Matej, S., Haberl, H., Gingrich, S., 2024. Sustainable land systems in the Anthropocene: Navigating the global land squeeze. One Earth 7, 1170–1186. https://doi.org/10.1016/j.oneear.2024.06.011
Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J., Taylor, K.E., 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development 9, 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016
Fawzy, S., Osman, A.I., Doran, J., Rooney, D.W., 2020. Strategies for mitigation of climate change: a review. Environ Chem Lett 18, 2069–2094. https://doi.org/10.1007/s10311-020-01059-w
Forster, J., Bindreiter, S., Uhlhorn, B., Radinger-Peer, V., Jiricka-Pürrer, A., 2025. A Machine Learning Approach to Adapt Local Land Use Planning to Climate Change. Urban Planning 10. https://doi.org/10.17645/up.8562
Frank, S., Gusti, M., Havlík, P., Lauri, P., DiFulvio, F., Forsell, N., Hasegawa, T., Krisztin, T., Palazzo, A., Valin, H., 2021. Land-based climate change mitigation potentials within the agenda for sustainable development. Environ. Res. Lett. 16, 024006. https://doi.org/10.1088/1748-9326/abc58a
Franke, J.A., Müller, C., Elliott, J., Ruane, A.C., Jägermeyr, J., Snyder, A., Dury, M., Falloon, P.D., Folberth, C., François, L., Hank, T., Izaurralde, R.C., Jacquemin, I., Jones, C., Li, M., Liu, W., Olin, S., Phillips, M., Pugh, T.A.M., Reddy, A., Williams, K., Wang, Z., Zabel, F., Moyer, E.J., 2020. The GGCMI Phase 2 emulators: global gridded crop model responses to changes in $CO_2$, temperature, water, and nitrogen (version 1.0). Geoscientific Model Development 13, 3995–4018. https://doi.org/10.5194/gmd-13-3995-2020
Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D.L., Obersteiner, M., Pachauri, S., Rao, S.,

Schmid, E., Schoepp, W., Riahi, K., 2017. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environmental Change 42, 251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004
Fuhrman, J., McJeon, H., Doney, S.C., Shobe, W., Clarens, A.F., 2019. From zero to hero? Why integrated assessment modeling of negative emissions technologies is hard and how we can do better. Front. Clim. 1. https://doi.org/10.3389/fclim.2019.00011
Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D.S., Dai, H., Hijioka, Y., Kainuma, M., 2017. SSP3: AIM implementation of Shared Socioeconomic Pathways. Global Environmental Change 42, 268–283. https://doi.org/10.1016/j.gloenvcha.2016.06.009
Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. Nature Clim Change 4, 850–853. https://doi.org/10.1038/nclimate2392
Ganti, G., Gasser, T., Bui, M., Geden, O., Lamb, W.F., Minx, J.C., Schleussner, C.-F., Gidden, M.J., 2024. Evaluating the near- and long-term role of carbon dioxide removal in meeting global climate objectives. Commun Earth Environ 5, 377. https://doi.org/10.1038/s43247-024-01527-z
Gidden, M.J., Riahi, K., Smith, S.J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D.P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J.C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E., Takahashi, K., 2019. Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. Geoscientific Model Development 12, 1443–1475. https://doi.org/10.5194/gmd-12-1443-2019
Gutowski, W.J., Ullrich, P.A., Hall, A., Leung, L.R., O'Brien, T.A., Patricola, C.M., Arritt, R.W., Bukovsky, M.S., Calvin, K.V., Feng, Z., Jones, A.D., Kooperman, G.J., Monier, E., Pritchard, M.S., Pryor, S.C., Qian, Y., Rhoades, A.M., Roberts, A.F., Sakaguchi, K., Urban, N., Zarzycki, C., 2020. The Ongoing Need for High-Resolution Regional Climate Models: Process Understanding and Stakeholder Information. Bulletin of the American Meteorological Society 101, E664–E683. https://doi.org/10.1175/BAMS-D-19-0113.1
Hämäläinen, R.-M., Halonen, J., Haveri, H., Prass, M., Virtanen, S., Salomaa, M.-M., Sieppi, P., Haahtela, T., 2022. Nature step to health 2022-2032: Interorganizational collaboration to prevent human disease, nature loss, and climate crisis. The Journal of Climate Change and Health 10, 100194. https://doi.org/10.1016/j.joclim.2022.100194
Harfoot, M., Tittensor, D.P., Newbold, T., Mcinerny, G., Smith, M.J., Scharlemann, J.P.W., 2014. Integrated assessment models for ecologists: the present and the future. Global Ecology and Biogeography 23, 124–143. https://doi.org/10.1111/GEB.12100
Hausfather, Z., Peters, G.P., 2020. Emissions – the 'business as usual' story is misleading. Nature 577, 618–620. https://doi.org/10.1038/d41586-020-00177-3
Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., Roehrl, A., 2011. OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development. Energy Policy, Sustainability of biofuels 39, 5850–5870. https://doi.org/10.1016/j.enpol.2011.06.033
IPCC, 2025. Decision IPCC-LXII-8. Scoping of the IPCC Seventh Assessment Report (AR7), SIXTY-SECOND SESSION OF THE IPCC. Intergovernmental Panel on Climate Change, Hangzhou, China.

IPCC, 2023a. Summary for Policymakers, in: Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 3–34. https://doi.org/10.1017/9781009325844.001
IPCC, 2023b. Key Risks across Sectors and Regions, in: Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 2411–2538. https://doi.org/10.1017/9781009325844.025
IPCC, 2023c. Decision-Making Options for Managing Risk, in: Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 2539–2654. https://doi.org/10.1017/9781009325844.026
IPCC, 2023d. Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781009325844
IPCC (Ed.), 2023e. Human Influence on the Climate System, in: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 423–552. https://doi.org/10.1017/9781009157896.005
IPCC (Ed.), 2023f. The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity, in: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 923–1054. https://doi.org/10.1017/9781009157896.009
IPCC (Ed.), 2023g. Changing State of the Climate System, in: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 287–422. https://doi.org/10.1017/9781009157896.004
IPCC (Ed.), 2023h. Annex III: Tables of Historical and Projected Well-mixed Greenhouse Gas Mixing Ratios and Effective Radiative Forcing of All Climate Forcers, in: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 2139–2152. https://doi.org/10.1017/9781009157896.017
IPCC (Ed.), 2022. Chapter 1.2.1: Working Definitions of 1.5°C and 2°C Warming Relative to Pre-Industrial Levels, in: Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Cambridge University Press, Cambridge, pp. 49–92. https://doi.org/10.1017/9781009157940.003
Jäger, F., Schwaab, J., Quilcaille, Y., Windisch, M., Doelman, J., Frank, S., Gusti, M., Havlik, P., Humpenöder, F., Lessa Derci Augustynczik, A., Müller, C., Narayan, K.B., Padrón, R.S., Popp, A., Van Vuuren, D., Wögerer, M., Seneviratne, S.I., 2024. Fire weather compromises forestation-reliant climate mitigation pathways. https://doi.org/10.5194/egusphere-2024-15
Jones, P.D., Mann, M.E., 2004. Climate over past millennia. Reviews of Geophysics 42. https://doi.org/10.1029/2003RG000143

Kangas, M., Heikinheimo, M., Hippi, M., 2015. RoadSurf: a modelling system for predicting road weather and road surface conditions. Meteorological Applications 22, 544–553. https://doi.org/10.1002/met.1486
Karki, L., Lieu, J., Xylia, M., Laub, M., Ismangil, D., Virla, L., Rahn, E., Bilbao, B.A., Indriani, S.N., Gallego, P.M., Suleiman, A.K.A., Schaldch, R., Takama, T., Silva, J.R.M. da, Johnson, F.X., 2023. Potentials and barriers to land-based mitigation technologies and practices (LMTs)—a review. Environ. Res. Lett. 18, 093003. https://doi.org/10.1088/1748-9326/ace91f
Keppo, I., Butnar, I., Bauer, N., Caspani, M., Edelenbosch, O., Emmerling, J., Fragkos, P., Guivarch, C., Harmsen, M., Lefèvre, J., Le Gallic, T., Leimbach, M., McDowall, W., Mercure, J.-F., Schaeffer, R., Trutnevyte, E., Wagner, F., 2021. Exploring the possibility space: taking stock of the diverse capabilities and gaps in integrated assessment models. Environ. Res. Lett. 16, 053006. https://doi.org/10.1088/1748-9326/abe5d8
Krause, A., Pugh, T.A.M., Bayer, A.D., Li, W., Leung, F., Bondeau, A., Doelman, J.C., Humpenöder, F., Anthoni, P., Bodirsky, B.L., Ciais, P., Müller, C., Murray-Tortarolo, G., Olin, S., Popp, A., Sitch, S., Stehfest, E., Arneth, A., 2018. Large uncertainty in carbon uptake potential of land-based climate-change mitigation efforts. Global Change Biology 24, 3025–3038. https://doi.org/10.1111/gcb.14144
Krey, V., Havlik, P., Kishimoto, P., Fricko, O., Zilliacus, J., Gidden, M., Strubegger, M., Kartasasmita, G., Ermolieva, T., Forsell, N., Guo, F., Gusti, M., Huppmann, D., Johnson, N., Kikstra, J., Kindermann, G., Kolp, P., Lovat, F., McCollum, D., Min, J., Pachauri, S., Parkinson, S., Rao, S., Rogelj, J., Ünlü, G., Valin, H., Wagner, P., Zakeri, B., Obersteiner, M., Riahi, K., 2020. MESSAGEix-GLOBIOM Documentation - 2020 release [WWW Document]. https://doi.org/10.22022/IACC/03-2021.17115
Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B.L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J.-P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., Biewald, A., Bonsch, M., Giannousakis, A., Kreidenweis, U., Müller, C., Rolinski, S., Schultes, A., Schwanitz, J., Stevanovic, M., Calvin, K., Emmerling, J., Fujimori, S., Edenhofer, O., 2017. Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. Global Environmental Change 42, 297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015
Kwiatkowski, K., Stipanovic Oslakovic, I., Hartmann, A., Ter Maat, H., 2016. Potential impact of climate change on porous asphalt with a focus on winter damage, in: Materials and Infrastructures 2. Wiley Blackwell, pp. 159–176. https://doi.org/10.1002/9781119318613.ch12
Kwiatkowski, K.P., Stipanovic Oslakovic, I., Ter Maat, H., Hartmann, A., Chinowsky, P., Dewulf, G.P.M.R., 2020. Modeling cost impacts and adaptation of freeze-thaw climate change on a porous asphalt road network. Journal of Infrastructure Systems. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000559
Leach, N.J., Jenkins, S., Nicholls, Z., Smith, C.J., Lynch, J., Cain, M., Walsh, T., Wu, B., Tsutsui, J., Allen, M.R., 2021. FaIRv2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration. Geoscientific Model Development 14, 3007–3036. https://doi.org/10.5194/gmd-14-3007-2021
Lind, P., Belušić, D., Médus, E., Dobler, A., Pedersen, R.A., Wang, F., Matte, D., Kjellström, E., Landgren, O., Lindstedt, D., Christensen, O.B., Christensen, J.H., 2023. Climate change information over Fenno-Scandinavia produced with a convection-permitting climate model. Clim Dyn 61, 519–541. https://doi.org/10.1007/s00382-022-06589-3
Lyon, C., Saupe, E.E., Smith, C.J., Hill, D.J., Beckerman, A.P., Stringer, L.C., Marchant, R., McKay, J., Burke, A., O'Higgins, P., Dunhill, A.M., Allen, B.J., Riel-Salvatore,

J., Aze, T., 2022. Climate change research and action must look beyond 2100. Global Change Biology 28, 349–361. https://doi.org/10.1111/gcb.15871
MacCarthy, J., Richter, J., Tyukavina, S., Weisse, M., Harris, N., 2023. The Latest Data Confirms: Forest Fires Are Getting Worse. World Resources Institute. https://www.wri.org/insights/global-trends-forest-fires
Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J.-F., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109, 213. https://doi.org/10.1007/s10584-011-0156-z
Michetti, M., Zampieri, M., 2014. Climate–Human–Land Interactions: A Review of Major Modelling Approaches. Land 3, 793–833. https://doi.org/10.3390/land3030793
Müller, C., Elliott, J., Chryssanthacopoulos, J., Deryng, D., Folberth, C., Pugh, T.A.M., Schmid, E., 2015. Implications of climate mitigation for future agricultural production. Environ. Res. Lett. 10, 125004. https://doi.org/10.1088/1748-9326/10/12/125004
Müller, P., 2010. Constructing climate knowledge with computer models. WIREs Climate Change 1, 565–580. https://doi.org/10.1002/wcc.60
NOAA, 2021. WMO Climate Normals.
Norris, J.R., Allen, R.J., Evan, A.T., Zelinka, M.D., O’Dell, C.W., Klein, S.A., 2016. Evidence for climate change in the satellite cloud record. Nature 536, 72–75. https://doi.org/10.1038/nature18273
North, G.R., 2024. Energy balance models in climate science. Current Opinion in Chemical Engineering 44, 101010. https://doi.org/10.1016/j.coche.2024.101010
O’Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G.A., Moss, R., Riahi, K., Sanderson, B.M., 2016. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geoscientific Model Development 9, 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016
Piao, S., Wang, X., Park, T., Chen, C., Lian, X., He, Y., Bjerke, J.W., Chen, A., Ciais, P., Tømmervik, H., Nemani, R.R., Myneni, R.B., 2020. Characteristics, drivers and feedbacks of global greening. Nat Rev Earth Environ 1, 14–27. https://doi.org/10.1038/s43017-019-0001-x
Pirani, A., Fuglestvedt, J.S., Byers, E., O’Neill, B., Riahi, K., Lee, J.-Y., Marotzke, J., Rose, S.K., Schaeffer, R., Tebaldi, C., 2024. Scenarios in IPCC assessments: lessons from AR6 and opportunities for AR7. npj Clim. Action 3, 1–7. https://doi.org/10.1038/s44168-023-00082-1
Rantanen, M., Karpechko, A.Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., Laaksonen, A., 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ 3, 1–10. https://doi.org/10.1038/s43247-022-00498-3
Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P., 2011. RCP 8.5—A scenario of comparatively high greenhouse gas emissions. Climatic Change 109, 33. https://doi.org/10.1007/s10584-011-0149-y
Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O’Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use,

and greenhouse gas emissions implications: An overview. Global Environmental Change 42, 153–168. https://doi.org/10.1016/J.GLOENVCHA.2016.05.009
Ripple, W.J., Wolf, C., Gregg, J.W., Rockström, J., Mann, M.E., Oreskes, N., Lenton, T.M., Rahmstorf, S., Newsome, T.M., Xu, C., Svenning, J.-C., Pereira, C.C., Law, B.E., Crowther, T.W., 2024. The 2024 state of the climate report: Perilous times on planet Earth. BioScience biae087. https://doi.org/10.1093/biosci/biae087
Ritchie, J., Dowlatabadi, H., 2017. Why do climate change scenarios return to coal? Energy 140, 1276–1291. https://doi.org/10.1016/j.energy.2017.08.083
Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J., Fricko, O., Frischmann, C., Funk, J., Grassi, G., Griscom, B., Havlik, P., Hanssen, S., Humpenöder, F., Landholm, D., Lomax, G., Lehmann, J., Mesnildrey, L., Nabuurs, G.-J., Popp, A., Rivard, C., Sanderman, J., Sohngen, B., Smith, P., Stehfest, E., Woolf, D., Lawrence, D., 2021. Land-based measures to mitigate climate change: Potential and feasibility by country. Global Change Biology 27, 6025–6058. https://doi.org/10.1111/gcb.15873
Rummukainen, M., 2010. State-of-the-art with regional climate models. WIREs Climate Change 1, 82–96. https://doi.org/10.1002/wcc.8
Savo, V., Lepofsky, D., Benner, J.P., Kohfeld, K.E., Bailey, J., Lertzman, K., 2016. Observations of climate change among subsistence-oriented communities around the world. Nature Clim Change 6, 462–473. https://doi.org/10.1038/nclimate2958
Searchinger, T., Peng, L., Zionts, J., Waite, R., 2023. The global land squeeze: Managing the growing competition for land. WRIPUB. https://doi.org/10.46830/wrirpt.20.00042
Shepherd, T.G., Lloyd, E.A., 2021. Meaningful climate science. Climatic Change 169, 17. https://doi.org/10.1007/s10584-021-03246-2
Sippel, S., Meinshausen, N., Fischer, E.M., Székely, E., Knutti, R., 2020. Climate change now detectable from any single day of weather at global scale. Nat. Clim. Chang. 10, 35–41. https://doi.org/10.1038/s41558-019-0666-7
Smith, P., Haberl, H., Popp, A., Erb, K., Lauk, C., Harper, R., Tubiello, F.N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J.I., Rose, S., 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Global Change Biology 19, 2285–2302. https://doi.org/10.1111/gcb.12160
Söderholm, J., Halonen, M., Mäntylä, I., Lehtonen, I., Tuomenvirta, H., Laapas, M., 2024. Ilmastonmuutokseen sopeutuminen Koillismaalla (Adapting to climate change in Northeast Finland). GAIA Consulting Oy (part of Sweco Finland Oy), Helsinki/Turku.
Stehfest, E., van Vuuren, D., Bouwman, L., Kram, T., 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model description and policy applications. Netherlands Environmental Assessment Agency (PBL).
Touzé-Peiffer, L., Barberousse, A., Le Treut, H., 2020. The Coupled Model Intercomparison Project: History, uses, and structural effects on climate research. WIREs Climate Change 11, e648. https://doi.org/10.1002/wcc.648
UNEP, 2024. Emissions Gap Report 2024. United Nations Environment Programme.
UNFCCC, 2015. The Paris Agreement.
van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Climatic Change 109, 5. https://doi.org/10.1007/s10584-011-0148-z

van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., van Meijl, H., Müller, C., van Ruijven, B.J., van der Sluis, S., Tabeau, A., 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environmental Change 42, 237–250. https://doi.org/10.1016/j.gloenvcha.2016.05.008
vanVuuren, D., Stehfest, E., den Elzen, M.G.J., Kram, T., van Vliet, J., Deetman, S., Isaac, M., Klein Goldewijk, K., Hof, A., Mendoza Beltran, A., Oostenrijk, R., van Ruijven, B., 2011. RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. Climatic Change 109, 95. https://doi.org/10.1007/s10584-011-0152-3
Walker, A.P., De Kauwe, M.G., Bastos, A., Belmecheri, S., Georgiou, K., Keeling, R.F., McMahon, S.M., Medlyn, B.E., Moore, D.J.P., Norby, R.J., Zaehle, S., Anderson-Teixeira, K.J., Battipaglia, G., Brienen, R.J.W., Cabugao, K.G., Cailleret, M., Campbell, E., Canadell, J.G., Ciais, P., Craig, M.E., Ellsworth, D.S., Farquhar, G.D., Fatichi, S., Fisher, J.B., Frank, D.C., Graven, H., Gu, L., Haverd, V., Heilman, K., Heimann, M., Hungate, B.A., Iversen, C.M., Joos, F., Jiang, M., Keenan, T.F., Knauer, J., Körner, C., Leshyk, V.O., Leuzinger, S., Liu, Y., MacBean, N., Malhi, Y., McVicar, T.R., Penuelas, J., Pongratz, J., Powell, A.S., Riutta, T., Sabot, M.E.B., Schleucher, J., Sitch, S., Smith, W.K., Sulman, B., Taylor, B., Terrer, C., Torn, M.S., Treseder, K.K., Trugman, A.T., Trumbore, S.E., van Mantgem, P.J., Voelker, S.L., Whelan, M.E., Zuidema, P.A., 2021. Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2. New Phytologist 229, 2413–2445. https://doi.org/10.1111/nph.16866
Weigel, A.P., Liniger, M.A., Appenzeller, C., 2008. Can multi-model combination really enhance the prediction skill of probabilistic ensemble forecasts? Quarterly Journal of the Royal Meteorological Society 134, 241–260. https://doi.org/10.1002/qj.210
Weyant, J., 2017. Some contributions of integrated assessment models of global climate change. Review of Environmental Economics and Policy 11, 115–137. https://doi.org/10.1093/reep/rew018
WMO, 2025. Monitoring global temperature for the Paris Agreement, in: State of the Global Climate 2024, WMO-No. World Meteorological Organization, Geneva, Switzerland, pp. 21–22.
WMO, 2017. WMO Guidelines on the Calculation of Climate Normals. World Meteorological Organization.
World Economic Forum, 2024. A 3°C world, in: Global Risks Report 2024. Geneva, Switzerland, pp. 42–49.
Zhao, X., Mignone, B.K., Wise, M.A., McJeon, H.C., 2024. Trade-offs in land-based carbon removal measures under 1.5 °C and 2 °C futures. Nat Commun 15, 2297. https://doi.org/10.1038/s41467-024-46575-3

# Appendices

## Appendix 1. Key terms of the doctoral thesis

### English

**Key Term:** Integrated assessment model

**Definition:** A computer-based framework that combines knowledge from multiple disciplines to assess the interactions between human systems and the climate system.

**Explanation:** Integrated assessment models (IAMs) link components such as energy systems, land use, economics, and climate processes to explore how policies and societal choices influence future greenhouse gas emissions and climate change. By integrating data and methods from disciplines like economics, environmental science, and engineering, IAMs allow researchers and policymakers to assess trade-offs, co-benefits, and long-term impacts of climate strategies. These models are used to develop global scenarios, including the Shared Socioeconomic Pathways and Representative Concentration Pathways, and to inform reports from the Intergovernmental Panel on Climate Change. While IAMs simplify complex systems, they provide valuable insights into how different development paths and policy decisions could shape climate outcomes and support evidence-based decision-making at national and international levels.

**Key Term:** Climate change-informed land management

**Definition:** The planning and use of land resources based on current and projected climate change impacts to enhance sustainability, resilience, and mitigation outcomes.

**Explanation:** Climate change-informed land management integrates climate science into decisions about how land is used for agriculture, forestry, conservation, and carbon sequestration. By aligning land-use practices with climate projections and mitigation goals, it supports long-term sustainability and contributes to both local resilience and global climate targets. It aims to reduce and abate greenhouse gas emissions, adapt to changing climatic conditions, and maintain ecological balance in human-managed land systems, such as croplands, pastures, managed forests, drained wetlands, conservation areas, and built environments. It involves both understanding and anticipating climate risks (e.g., extreme weather, temperature shifts, rising $CO_2$ concentrations) and making proactive decisions that support resilience and mitigation. This means landowners must be aware of likely and worst-case climate scenarios, equipped with knowledge about suitable adaptation and mitigation options, and ideally motivated (e.g., through policy incentives) to contribute to broader climate goals. This concept is increasingly relevant for modelling tools that assess the role of land systems in climate solutions and, subsequently, for evidence-informed policymaking.

## Suomi

**Avaintermi:** Integroitu arviointimalli

**Määritelmä:** Tietokonepohjainen laskentamalli, joka yhdistää tietoa useilta tieteenaloilta yhteiskunnan ja ilmastojärjestelmän välisten vuorovaikutuksien arvioimiseksi.

**Selitys:** Integroidut arviointimallit (IAM) yhdistävät komponentteja, kuten energiajärjestelmät, maankäytön, talouden ja ilmastoprosessit, jotta mallin avulla voidaan tutkia, miten politiikat ja yhteiskunnalliset valinnat vaikuttavat tuleviin kasvihuonekaasupäästöihin ja ilmastonmuutokseen. Yhdistämällä tietoja ja menetelmiä eri tieteenaloilta, kuten taloustieteestä, ympäristötieteestä ja tekniikasta, IAM:t antavat tutkijoille ja päättäjille mahdollisuuden arvioida ilmastostrategioiden keskinäisiä vuorovaikutuksia, sivuhyötyjä ja pitkän aikavälin vaikutuksia. Näitä malleja käytetään globaalien skenaarioiden, mukaan lukien jaetut sosioekonomiset kehityspolut (SSP) ja edustavat keskittymispolut (RCP), kehittämiseen sekä hallitustenvälisen ilmastonmuutospaneelin (IPCC) raporttien laatimiseen. Vaikka IAM:t yksinkertaistavat monimutkaisia järjestelmiä, ne tarjoavat arvokasta tietoa siitä, miten eri kehityspolut ja poliittiset päätökset voisivat muokata ilmastovaikutuksia ja tukea näyttöön perustuvaa päätöksentekoa kansallisella ja kansainvälisellä tasolla.

**Avaintermi:** Ilmastonmuutoksen huomioiva maankäyttö

**Määritelmä:** Maavarojen suunnittelu ja käyttö nykyisten ja ennustettujen ilmastonmuutoksen vaikutusten perusteella kestävyyden, sietokyvyn ja hillitsemistoimien parantamiseksi.

**Selitys:** Ilmastonmuutoksen huomioimaan käyttö integroi ilmastotieteen päätöksentekoon siitä, miten maata käytetään maataloudessa, metsätaloudessa, luonnonsuojelussa ja hiilensidonnassa. Yhdenmukaistamalla maankäyttökäytännöt ilmastoennusteiden ja hillitsemistavoitteiden kanssa se tukee pitkän aikavälin kestävyyttä ja edistää sekä paikallista sietokykyä että globaaleja ilmastotavoitteita. Sen tavoitteena on vähentää ja torjua kasvihuonekaasupäästöjä, sopeutua muuttuviin ilmasto-olosuhteisiin ja ylläpitää ekologista tasapainoa ihmisen hallinnoimissa maajärjestelmissä, kuten viljelysmailla, laitumilla, hoidetuissa metsissä, kuivatuilla kosteikoilla, suojelualueilla ja rakennetuissa ympäristöissä. Se sisältää sekä ilmastoriskien (esim. äärimmäiset sääolosuhteet, lämpötilan muutokset, nousevat hiilidioksidipitoisuudet) ymmärtämisen ja ennakoinnin että ennakoivien päätösten tekemisen, jotka tukevat sietokykyä ja hillitsemistä. Tämä tarkoittaa, että maanomistajien on oltava tietoisia todennäköisistä ja pahimmista ilmastoskenaarioista, heillä on oltava tietoa sopivista sopeutumis- ja hillitsemisvaihtoehdoista ja mieluiten motivoituneita (esim. poliittisten kannustimien kautta) osallistumaan laajempien ilmastotavoitteiden saavuttamiseen. Tämä käsite on yhä tärkeämpi mallinnustyökaluissa, jotka arvioivat maajärjestelmien roolia ilmastoratkaisuissa ja sitä kautta näyttöön perustuvassa päätöksenteossa.

## Svenska

**Nyckelterm:** Integrerad bedömningsmodell

**Definition:** Ett datorbaserat ramverk som kombinerar kunskap från flera discipliner för att bedöma samspelet mellan mänskliga system och klimatsystemet.

**Förklaring:** Integrerade bedömningsmodeller länkar samman komponenter som energisystem, markanvändning, ekonomi och klimatprocesser för att utforska hur policyer och samhällsval påverkar framtida växthusgasutsläpp och klimatförändringar. Genom att integrera data och metoder från discipliner som ekonomi, miljövetenskap och teknik gör IAM det möjligt för forskare och beslutsfattare att bedöma avvägningar, samfördelar och långsiktiga effekter av klimatstrategier. Dessa modeller används för att utveckla globala scenarier, inklusive delade socioekonomiska vägar (SSP) och representativa koncentrationsvägar (RCP), och för att informera rapporter från FN:s klimatpanel (IPCC). Medan IAM förenklar komplexa system ger de värdefulla insikter i hur olika utvecklingsvägar och policybeslut kan forma klimatresultat och stödja evidensbaserat beslutsfattande på nationell och internationell nivå.

**Nyckelterm:** Klimatförändringsinformerad markförvaltning

**Definition:** Planering och användning av markresurser baserat på nuvarande och prognostiserade klimatförändringseffekter för att förbättra hållbarhet, motståndskraft och utsläppsminskningsresultat.

**Förklaring:** Klimatförändringsinformerad markförvaltning integrerar klimatvetenskap i beslut om hur mark används för jordbruk, skogsbruk, bevarande och koldioxidlagring. Genom att anpassa markanvändningsmetoder till klimatprognoser och begränsningsmål stöder den långsiktig hållbarhet och bidrar till både lokal motståndskraft och globala klimatmål. Den syftar till att minska och begränsa utsläppen av växthusgaser, anpassa sig till förändrade klimatförhållanden och upprätthålla ekologisk balans i mänskligt förvaltade marksystem, såsom åkermark, betesmarker, förvaltade skogar, dränerade våtmarker, naturskyddsområden och bebyggda miljöer. Det innebär både att förstå och förutse klimatrisker (t.ex. extremt väder, temperaturförändringar, stigande $CO_2$-koncentrationer) och att fatta proaktiva beslut som stöder motståndskraft och begränsning. Detta innebär att markägare måste vara medvetna om sannolika och värsta tänkbara klimatscenarier, utrustade med kunskap om lämpliga anpassnings- och begränsningsalternativ och idealiskt motiverade (t.ex. genom politiska incitament) att bidra till bredare klimatmål. Detta koncept blir alltmer relevant för modelleringsverktyg som bedömer marksystemens roll i klimatlösningar och därmed för evidensbaserat beslutsfattande.

Business, Economy

Art, Design, Architecture

Science, Technology

Crossover

**Doctoral Theses**

**Aalto DT 252/2025**

ISBN 978-952-64-2887-1
ISBN 978-952-64-2886-4 (pdf)

**Aalto University**
School of Science
Department of Mathematics and Systems Analysis
**aalto.fi**