YSSP24

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Proceedings of the Final Colloquium

Young Scientists Summer Program

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IIASA's annual three-month Young Scientists Summer Program (YSSP) offers research opportunities to talented young researchers whose interests correspond with IIASA's ongoing research on issues of global environmental, economic, and social change. From June through August each year participants work within the Institute's research programs under the guidance of IIASA scientific staff.

The Proceedings of the Final Presentations comprises summaries of the research results obtained during the YSSP that were presented at International Institute for Applied Systems Analysis, Laxenburg, Austria, on 23 August 2024.

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Proceedings Editors: Bek Ash (ECE), **Jennifer Bailey** (POPJUS), **Thomas Berger** (POPJUS), **Ted Buskop** (ASA), **Naud Loomans** (ECE), **Montserrat Koloffon Rosas** (SI), **Sowdamini Sesha Prasad** (BNR), **and Brian D. Fath**

	GVISHIANI ROOM and ZOOM*
9:00 – 9:15	**Welcome and Opening Remarks** Fabian Wagner, Capacity Development and Academic Training, Dean Brian Fath, Young Scientists Summer Program, Scientific Coordinator
	Session 1
1.1 09:15 – 09:40	Montserrat Koloffon Rosas - Transformations through partnerships for sustainable development: Leverage points in nexus governance Crystal Yu - Modeling age-specific migration schedules for U.S. States Anouk Brisebois - Climate risk and resilience in coastal Bangladesh: Differential experiences among migrant women and men at their destination Jaewon Son - Exploring the role of urban green spaces as nature-based solutions in Korea and Germany Thomas Berger - Sustainable transport systems: From pollution prevention towards just mobility transitions
1.2 09:45 – 10:05	Jakob Napiontek - Synthetic population of Germany Kedi Liu - Integrating air pollution health impacts on SSPs projection Julie Sojin Kim - Estimating fertility trends by state, education, and residence in India, 1990-2020 Jennifer Bailey - Estimating the impact of heat alerts on population mobility in California
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10:25 – 10:45	Break
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12:05 – 13:30	LUNCH
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3.3 14:20 – 14:35	Ruben Prütz - Spatial analysis of carbon dioxide removal implications focusing on biodiversity and land tenure Sowdamini Sesha Prasad - Integrating fed aquaculture into GLOBIOM to account for growing global feed resource competition Bingyi (Alex) Hou - Modelling Ontario Forest and mass timber in GLOBIOM-Forest
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	Session 4
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4.2 15:50 – 16:10	Haodong Wei - Exploitation of optical and radar data for improved mapping of diverse cropping patterns of paddy and upland fields in South China Oleg Sviridov - Defining carbon responsibility: A review of emission allocation methods Teresa Lackner - Energy-efficient housing and macroeconomics: Insights from a building sector-ABM model integration Todd Davies - Population ecology as a lens for competition law

4.3 16:15 – 16:30	Wen Yi - Arctic shipping emissions under multiple global-Arctic coupled scenarios Benjamin Goffin - Linking earth observations from the international space station to soil moisture and crop productivity Linara Arslanova - Pixel-level mapping of crop damages using space-born synthetic aperture radar
16:30	**Closing remarks** Karen Lips, IIASA Deputy Director

*Streaming: https://iiasa.zoom.us/j/93936510344
Passcode: YSSP2024

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Strategic Initiatives (SI)

Transformations through partnerships for sustainable development: Leverage points in nexus governance

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Introduction. The most comprehensive blueprint to date to govern sustainability globally is the UN resolution titled "Transforming our world: the 2030 Agenda for Sustainable Development" with its 17 Sustainable Development Goals (SDGs). SDGs are meant to be pursued through *transformative* interventions which shall be driven in collaborative partnership recognizing the integrated and indivisible nature of the Goals[1]. Since the agenda's adoption, thousands of partnerships working on SDG implementation have emerged, however, progress remains weak and insufficient in more than half of the targets, and in one third, progress has either stalled or even reversed[2]. This research aims to establish the *transformative potential* of partnerships working on an integrated implementation of the SDGs (nexus governance). An original operationalization of Donella Meadows' leverage points framework[3] is advanced and applied to assess a sample of 40 partnerships registered on UN-DESA's SDG Actions Platform.

Methodology. Using R, data from the UN-DESA SDG Actions Platform is scraped, and a dictionary-based text analysis is employed to determine the SDGs focus of partnerships registered on the Platform. Data for the analysis are delimited to partnerships addressing the 3 most popular SDG nexuses. The partnerships' transformative potential is coded on Atlas.ti through content analysis of the partnerships' descriptions. Additional variables on the partnerships' structural characteristics are also coded. T-tests and descriptive statistics are employed in the analysis to determine existing gaps in transformative ambitions, and explore the role of the partnerships' structural design.

Preliminary results. The most popular SDG nexuses targeted by partnerships on UN-DESA's Platform represent the climate-biodiversity nexus. Partnerships are found to have more than a single transformative ambition, meaning that most of them aim to push more than one leverage point. A few partnerships target high leverage points by aiming to change the goal of the system that they intervene, yet no partnerships seem to target the highest leverage points in the framework: changing the paradigm out of which the system arises, and transcending paradigms.

Conclusions and next steps. Partnerships are found to target leverage points all across the board, indicating high variation in their transformative potential. Finding some partnerships with high transformative ambitions is a hopeful sign, yet the highest ambitions (changing and transcending paradigms) remain largely unaddressed. The statistical analysis including structural variables is in progress, and the results will help establish whether certain design characteristics play a role in determining the partnerships' transformative potential. The assessment developed in this research can be generalized to determine the transformative potential of partnerships and similar governance forms implementing sustainability interventions, regardless of the issue areas in their focus. Future research will build on this study to determine the *transformative capacity* of partnerships.

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Population and Just Societies (POPJUS)

Modeling age-specific migration schedules for U.S. States

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Introduction. People often make moves in preparation for, or in response to, major life course events and transitions. This can include entering higher education, obtaining a job, marriage, family, and retirement. However, data on migration events and flows are often scarce and of varying data quality. Moreover, the dynamic nature of migration makes it an extremely difficult phenomenon to empirically study, much less predict. As migration becomes an increasingly important driver of population change in both national and subnational settings, it is imperative to have high-quality, granular migration data, as well as methods for informing and producing migration and population estimates and projections.

Methodology. Rogers and Castro (1981) observed that migration rates follow a regular pattern by age, and proposed that a multi-exponential parametric model could be used to capture these age-specific rates. However, this model is computationally difficult to estimate and only provides point estimates for a single time period. I propose a more flexible version of the Rogers-Castro model that allows for the joint estimation of multiple geographic units, multiple time points, and with uncertainty estimates. I illustrate this by producing age-specific estimates of in- and out-migration rates and counts, along with uncertainty ranges, for all U.S. states from 2006 to 2022.

Results. The use of a more flexible Rogers-Castro migration model parameterization and Bayesian computational approach are able to model diverse age-specific migration patterns with uncertainty for U.S. states from 2006 to 2022. The model not only captures spatiotemporal effects, accounts for potential data sparsity, but also provides sensible estimates and uncertainty ranges of age-specific migration rates and counts for all U.S. states. The data and model show the expected age-specific pattern in migration, with the highest levels of mobility occurring during the young adult ages. However, the magnitude and timing of migration can differ across states, suggesting location-specific factors likely influence some people to move and others to stay. Moreover, the results indicate inter-state retirement migration is not present in all states. For instance, retirement in-migration is prominent in Florida, Arizona, Nevada, and Delaware, but to a much lesser extent in other states.

Conclusions. The Rogers-Castro migration curve provides a reasonable parametric model for estimating migration rates by age. In combination with a Bayesian computational approach, which allows for the incorporation and sharing of information across geographic areas, time, and age, reasonable point estimates of migrant rates and counts and uncertainty ranges can be generated for subnational areas. Validation exercises suggest this modelling approach provides close to nominal levels of accuracy and coverage. The age-specific migration estimates and uncertainty measures generated using this approach can be used to inform estimation and predictions of age-specific migration for U.S. states and other subnational areas.

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Climate risk and resilience in coastal Bangladesh: Differential experiences among migrant women and men at their destination

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IIASA Mentor: Roman Hoffmann (POPJUS)

Introduction. In the context of climate change in Bangladesh, mobility may have the potential to enhance climate resilience (Etzold and Mallick, 2016). Yet, contextual factors shaping migrants' varied climate experiences are often overlooked. Moreover, women, who are the most impacted by climate change, are often under-studied, especially from an intersectional perspective (Boas, de Pater, and Furlong 2022). In this study, I draw from translocal social resilience, contextual vulnerability, and gender-sensitive vulnerability frameworks as analytical lenses to answer the following research questions: What contextual factors influence the risks and resilience of female migrants in destination areas in Bangladesh? How do gender differences intersect with other characteristics and contextual factors to shape differential climate experiences?

Methodology. I draw from two two-month periods of fieldwork conducted in 2023 and 2024 in Mongla, a coastal town and urban destination area in Bangladesh. During the first phase, personal livelihood history interviews were conducted with 24 migrant women. During the second phase, life history interviews were conducted with 22 of the initially interviewed migrant women and 10 interviews with their husbands to gain insights into their differential experiences of climatic events. Additionally, ten key informant interviews were conducted with local experts to gain deeper contextual information about the study site. Daily field observations supplemented these interviews to capture the participants and the broader community's behaviors in their daily context.

Results. Gender emerges as a crucial social factor that determines varying climate risks among people in Bangladesh. Yet, it is the intersection with other individual characteristics, including age, family situation, pregnancy status and health, economic condition and livelihood, and migrant status that contribute to differential climate risks between women and men and between women themselves. Additionally, contextual factors play an important role in influencing the extent of risk people are exposed to and their capacity for resilience. These include gender roles and norms and gendered embodied limitations and strengths that lead to differential economic opportunities, access to information and knowledge, networks and social capital, and resources and services between individuals and groups.

Conclusions. Climate change is predicted to cause an increase in internal mobility in Bangladesh by 2050, with an estimated 19.9 million people moving, mainly to already overcrowded cities. In this context, the number of women migrating will also significantly rise. This research highlights the need for more intersectional and context-specific approaches to climate resilience in mobility settings, particularly at urban destinations.

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Exploring the role of urban green spaces as nature-based solutions in Korea and Germany

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Introduction. Urban green spaces (UGS) serve as critical Nature-based Solutions (NbS), providing diverse ecosystem services that contribute to urban biodiversity, physical and psychological health, and play a crucial role in climate mitigation and adaptation, thereby enhancing overall urban sustainability. Despite the emphasis on NbS in international agreements and frameworks, the wider implementation of UGS faces many challenges which vary across different socio-cultural contexts. Consequently, this study selects Korea and Germany as case studies to analyze the distinct management approaches and policies in each context, thereby exploring potential learnings and cross-cultural insights.

Methodology. 30 semi-structured interviews were conducted in Korea and Germany, focusing on UGS planning and management, particularly on enhancing societal resilience and UGS ecosystems. 32 professionals including academia, government, and industry were selected using a mixed approach that combined purposive, theoretical, and snowballing techniques. For the purposive sampling approach, proficiency in UGS planning and management, professional affiliation, knowledge and expertise, experience, and geographical location were considered. Interview transcripts were analyzed using the MAXQDA software, with data categorized through systemic coding (Deterding et al., 2021). The analysis focused on i) policies that stakeholders mentioned at different governance levels, and ii) the enablers and barriers of UGS implementation.

Results. In Korea, the implementation of UGS is centralized, with cities adhering uniform national regulations while developing localized action plans accordingly. This contrasts with Germany's decentralized system, where state and local regulations often take precedence. Additionally, Germany's focus on international policies is more aligned with EU-level regulations rather than global frameworks. Interviewees in both countries identified effective communication and the logistical complexities of engaging diverse stakeholders as critical enablers and barriers, respectively. Korean interviewees emphasized the need for intermediary park managers and the challenge of demonstrating UGS policies' long-term value, while German interviewees highlighted issues with inadequate evaluations post-implementation. Korean interviewees acknowledged Germany's structured approach, while German interviewees commended Korea's efficiency and rapid changes. These findings underscore the centralized nature of Korea's approach versus the decentralized, state-specific focus in Germany.

Conclusions. The study concludes that while there are challenges in UGS implementation, the approaches in Korea and Germany offer valuable insights. In Korea, the centralized approach facilities rapid implementation, but it also highlights the challenges of demonstrating long-term value and limited time for further considerations. In contrast, Germany's decentralized system allows for tailed local regulations, aligning with EU-level policies, though it faces difficulties in understanding actions taken at a broader level and prolonged discussions without tangible outcomes. Effective communication and stakeholder engagement are critical enablers in both contexts, but the logistical complexities differ due to the governance structures. Securing resources remains a common challenge. By bridging research, policy, and community engagement, this study contributes to a more holistic approach in harnessing the potential of UGS as NbS. It underscores the need for collaborative efforts to create resilient and sustainable urban environments, drawing on the strengths of both centralized and decentralized systems.

Sustainable transport systems: From pollution prevention towards just mobility transitions

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Introduction. There is strong scientific agreement that for achieving strategic progress towards ecological, economic, and social sustainability goals, the transport sector must be fundamentally transformed. One promising approach towards achieving that goal lies in addressing mobility demand through integrating the Framework for Strategic Sustainable development with the Avoid-Shift-Improve (A-S-I) framework. Transforming mobility demand will come with conflicts, which themselves often result from different perceptions of just outcomes and processes across different stakeholder groups.

Methodology. To proactively identify and address potential justice-related conflicts, we explore what justice considerations come along with the three different levels of the A-S-I framework. To achieve this, we apply the IIASA/EQU Justice Framework (Hanger-Kopp et al., 2024) to a case specific context of regional and local transport system development in region Blekinge, Sweden. Multiple forms of justice are investigated to identify crucial justice aspects and a representative set of regional and local transport policies is systematically evaluated with respect to these identified crucial justice aspects.

Results. Transport system specific justice aspects have been identified for five justice dimensions, 1) distributional, 2) procedural, 3) corrective, 4) recognitional, and 5) transitional justice. We have identified five essential distributional metrics, physical space; access to places, goods, and services; access to (sustainable) means of transport; budget and monetary incentives; and human resources, knowledge and know-how and we reflect upon how these five identified metrics might be distributed according to different patterns and principles. With respect to the fairness of processes, we have identified two processes, distributional processes, having the above-mentioned distributional metrics in mind, and planning and decision-making processes, including discussions around the involvement of different societal representatives in shaping sustainable and just transport futures. Further, we have identified several relevant recognitional factors such as recognition with respect to demographics and socio-economic attributes; geographic context – urban versus rural (including a view on segregation); activities, trips, and needs to fulfill; security and safety; and transport modes. For translating these results into actionable knowledge for transport planners and decision-makers, a checklist with relevant justice-related questions along the levels of the A-S-I framework is proposed.

Conclusions. This study contributes to the understanding of what crucial justice aspects are and how and amongst whom they might be distributed when avoiding, shifting and improving mobility demand in regional and local transport systems. The results indicate who should be included in different processes, and how just procedures should be designed for reaching just outcomes. The in this study developed general guidance and tailored A-S-I checklist supports policymakers in proactively identifying and addressing potential conflicts and hence in shaping sustainable and just transport futures.

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Synthetic population of Germany

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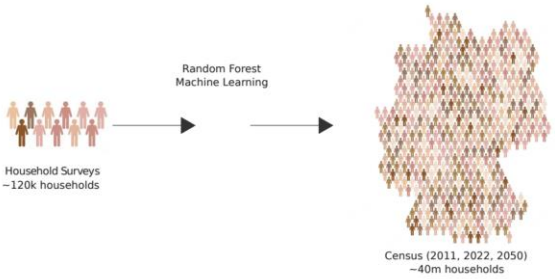
Introduction. The design and evaluation of climate change policies depends on accurate models of the future. This project provides a demographic dataset to advance these efforts in Germany. This synthetic population of Germany allows many characteristics of the German population such as household structure, education, employment or housing to be assessed for all 400 cities and counties. Based on this data, we can assess the demand for services such as housing now and in the future for each region and the corresponding impact on emissions, as well as model the impact of climate policies on different social groups.

Methodology. The synthetic population is based on two sets of data: household budget surveys and the census. The census is a comprehensive dataset for the whole of Germany, providing categorical totals for each region, such as the size of female population, people with a doctorate degree or single-family houses. However, census summary tables do not provide the relationship between these characteristics. The surveys provide detailed information about each household and its members. By training a random forest machine learning model on these surveys, we can understand the relationship between the characteristics and then predict the characteristics of all 41 million German households in 2022. These predictions are benchmarked to the boundaries of the census for each characteristic and region. The resulting dataset has both the comprehensive spatial coverage of the census and the relationship between the characteristics. By extending the modelling into the future, a 2050 synthetic census was created based on the German regional population and household projections

Results. Based on the 2011 and 2022 censuses, a synthetic population has been developed for both of the years. For more than 80 million people in more than 40 million households, it contains synthetic data on people's gender, age, marital status, citizenship, education, employment and housing. The code used to create this population, as well as the data itself, will be made openly available with the forthcoming publication. The data will allow many different applications, one crucial application is a high spatial resolution estimation of the German building stock by age and type, which is essential for modelling emissions from housing (Napiontek et al., 2024).



Conclusions. A first application of this methodology by Többen et al. (2023) has used people's responses on energy and fuel expenditure, as well as their primary energy source, to predict a large part of their carbon footprint and model how different households would be affected by different implementations of a carbon tax. The advantage of the synthetic population is that the high resolution allows the results to be stratified not only by region or income decile, but also by any custom group, for example to assess the impact on single mothers under 30 or widowers who own a house in the countryside. This approach allows much more precise design and evaluation of climate mitigation policies.

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Integrating air pollution health impacts on SSPs projection

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Introduction. Air pollution, particularly PM2.5, poses a significant and ongoing threat to global health. Although the impacts are well-documented, large-scale analyses comparing these effects across different climate and socioeconomic pathways, such as the Representative Concentration Pathways (RCPs), remain limited. Meanwhile, the Shared Socioeconomic Pathways" (SSPs) projections of demographic variables is working as an exogenous basis for current climate models systems, especially within the Integrated Assessment Model (IAM) frameworks. However, a crucial feedback loop from the climate and environmental factors to the SSPs is missing, leading to incomplete assessments of future health and well-being outcomes, especially when comparing SSP1 (sustainability) and SSP5 (fossil fueled development) that have similar population outcomes. This study aims to fill this gap by assessing the health impacts of PM2.5 within five SSP-RCP scenarios in 2020-2050, focusing on adjusting SSP5.

Methodology. We employed a multi-dimensional decomposition method to adjust all-cause mortality rates based on current SSPs, building on Dimitrova et al. (2021). The pathway-/location-/sex-/age-specific mortality is divided into two parts based on deaths share of diseases and adjusted differently: the first part related to the six diseases linked to PM2.5 is adjusted with corresponding relative risk change, and the second part with other causes of death remains unchanged. For SSP5, we introduced an adjustment for excess risk compared to SSP1. The relative risk curve data is from the GBD (2019) and Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) calculation. The SSPs projection population and mortality data are from KC et al. (2024).

Results. (1) Adjusted mortality projections indicate a decline in overall mortality for SSP1-RCP1.9 and -RCP2.6, driven by improvements in PM2.5 levels in most locations over the study period. In contrast, SSP5-RCP8.5 has an average placid increase in mortality while SSP3-RCP7.0 and show significant increases. Asian countries exhibit the most pronounced changes in mortality across different SSP-RCP scenarios. The elderly (especially those aged 85+) experience the most significant mortality shifts. (2) Cumulative deaths attributable to PM2.5 from 2020 to 2050 ranges from 109.8 million in SSP1-RCP1.9, SSP5-RCP8.5 results in 151.2 million deaths rather than 141.7 million after adjustment. Most health impact is 213.1 million in SSP3-RCP7.0. It appears that 68.5% of the cumulative deaths occur in the 55-80 age group across all scenarios. Regionally, India and China contribute approximately 56.4% to 60.7%. (3) For YLL, with individuals in SSP1-RCP1.9 losing an average of 17 days each year, compared to over 20 days in SSP3-RCP7.0 and SSP5-RCP8.5.

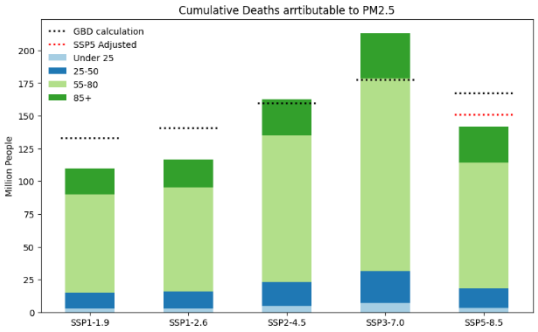

Figure 1 PM2.5-related Cumulative Deaths in 2020 - 2050.

Conclusions. SSP1 has positive health impacts while SSP5 and SSP3 show negative impacts from PM2.5 integration based on the adjusted mortality results. The health burden of PM2.5-related diseases is not only significantly different across different scenarios, but it also disproportionately affects the elderly population. Given the large population base in Asian countries and the relative difficulty in mitigating and adapting to air pollution, India and China are likely to continue suffering disproportionately from associated health impacts in all scenarios.

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Estimating fertility trends by state, education, and residence in India, 1990-2020

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Introduction. India stands at a pivotal moment in its demographic transition, where the remaining degree the country can harness its demographic dividend depends on 1) the pace of age structure change, primarily driven by the rate of fertility decline, and 2) the strategic investment in human capital through education, thereby enhancing the productivity of the workforce (Lutz et al. 2019). However, previous research on fertility decline has focused on national-level assessments, overlooking the vast heterogeneity in the determinants and pace of fertility decline within the country. This study fills this gap by providing a thorough depiction of fertility decline across geographic and sociodemographic subpopulations in India between 1990 and 2020.

Methodology. We estimated age-specific fertility rates (ASFR), total fertility rates (TFR), and birth counts by education and residence type of women across first-level administrative geography in India using data from 1,559,784 women between the ages of 15 and 49 from 5 rounds of the National Family and Health Survey (NFHS) conducted between 1992-93 and 2019-21 (IIPS 2024). The respondents were classified according to their residence location across 27 states and Union Territories (UTs), educational attainment based on the International Standard Classification of Education, and residence type classified as either rural or urban areas, as defined by the Census. The ASFRs were estimated from the expected count of births modelled using weighted Poisson regression with independent variables including year of the survey, age of the respondent, location, educational attainment, residence type, and their interactions. The estimated ASFR in each stratum was aggregated to estimate the TFR by location, age, and residence type, and the number of births for each stratum was derived by converting ASFRs to births using age- and sex-specific population data in the corresponding strata.

Results. Substantial variation in fertility levels and trends was observed across different states, educational levels, and residential areas in India between all observed years from 1990 to 2020. Total fertility rates decreased in all groups across states/UTs, education, and residence types during the observation period, with the rate of decline being faster among women living in high-fertility states/UTs and those with lower education levels. Women living in urban areas exhibited lower fertility rates compared to women with the same location and education levels in rural areas, and the urban-rural gap remained stable over the past three decades. An education gradient in fertility rates, where fertility was the lowest among women with higher education, was observed throughout the period. Despite the expansion of higher education during this period, birth counts were concentrated in the population with lower education levels living in rural areas.

Conclusions. This study is the first to comprehensively disaggregate fertility rates by first-level administrative geography, educational attainment, and residence type simultaneously in India using NFHS data. The findings reveal significant variation in fertility levels across subpopulations, with substantial gaps across education levels and rural-urban residence. The concentration of birth counts in rural regions and among lower education groups underscores the urgency of measures to provide educational resources and improve maternal and child health, such as improving access to safe water, sanitation, hygiene programs, and maternal health services in rural regions.

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Estimating the impact of heat alerts on population mobility in California

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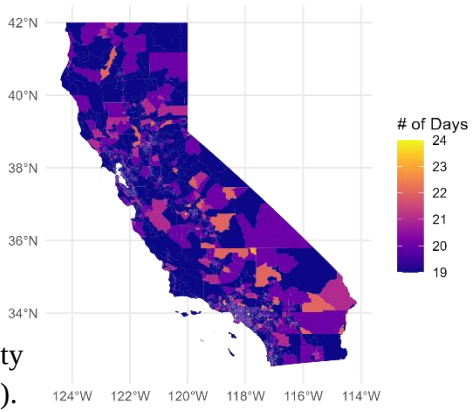
Introduction. Extreme heat is one of the most dangerous consequences of climate change and their expected increase in frequency and intensity threatens population health, with exacerbated risk due to existing disparities in exposure (Mora et al., 2017). In the United States, extreme heat is the deadliest weather hazard each year, surpassing the fatalities attributed to all other weather-related disasters combined (National Weather Service, 2023). In response, heat action plans use alerts to notify the public of deadly conditions and advise against exposure through suggesting limiting movements and time spent outdoors. While the necessity of assessing the effectiveness of these heat response systems is universally acknowledged, it is rarely done. High-resolution mobility datasets made publicly available to limit the spread of COVID-19 offer a novel approach to understand the influence of heat alerts.
Methodology. Daily surface minimum and maximum temperatures were obtained at population-weighted centroids from the high-resolution Gridded Surface Meteorological (gridMET) dataset and used to calculate extreme heat metrics. Heat alert information issued by the National Weather Service in California forecast zones was combined with mobile phone derived daily population and visitor flows to and from census tracts (Safegraph). The impact of heat alerts on mobility, as a measure of effectiveness, was estimated with a series of fixed effects panel models, using census tract and time fixed effects to account for unobserved spatial heterogeneity or confounding temporal trends. COVID-19 lockdown tier data was downloaded from the California Department of Public Health to control for impacts to mobility from stay-at-home orders in the state. Variables hypothesized to modify the relationship between heat alerts and mobility from the U.S. Census (2019) were included as interaction terms.
Results. As expected, during the warm months of 2019 and 2020, the inland and desert southwest areas of California experience warmer temperatures, while coastal areas tend to experience lower temperatures. The baseline Poisson linear panel regressions with fixed effects tested the response of the outflow rate, and the cubed root of total outflow and total inflow to heat alerts, including fixed effects for census tracts, day of the week, and year. The presence of a heat alert was found to reduce the daily outflow rate by 0.15%. Across all models, there were similar increases in mobility through the week, peaking on Friday, with a decrease in movement on Sunday compared to Monday. Counterintuitively, COVID lockdown tiers only reduced mobility when less restrictive tiers were in place (0.69% to 2.10% across outcomes). The most restrictive tier was shown to significantly increase flows by 0.26% or 0.78%. Temperature itself does not seem to impact mobility.



Number of days with maximum temperature at or above the 95th percentile temperature for census tracts in California (May-October of 2019 and 2020).

Conclusions. This research serves as the first of its kind to assess the impact of heat alerts on population mobility, using revealed, as opposed to perceived, behaviour change data adding to sparse alert effectiveness literature. Our findings show a small significant effect of heat alerts on reducing both outflow and inflow across census tracts in California during the warm months of 2019-2020. These findings can help local decision makers in assessing the effectiveness of heat early warning systems and can inform future research accounting for sub-population nuances to heat exposure and mobility.

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Economic Frontiers
(EF)

Waves of change: Understanding the impact of natural hazards on housing market dynamics and coastal evolution

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Introduction.
As climate change intensifies, the frequency and intensity of natural hazards are expected to increase. On the other hand, the population and economic development in hazard-prone areas continue to grow. Paradoxically, natural hazards can trigger residential redevelopment, which increases the footprint and places a higher value at risk for future hazards (Lazarus et al. 2018). Redevelopment often brings households with higher income to disaster prone regions. What drives the continuing growth in investment in housing capital on the coast against increasing climate change risk? By examining spillover effects of private investment in renovation, this work enhances our understanding of the impact of natural hazards on patterns of durable housing capital investment on the coast.

Methodology.
Following Rosenthal (2008), the age of housing stock serves as a measure of housing quality. A durable capital replacement model is developed, where landowners maximize lifespan profit from housing investments by choosing the optimal rebuild time and housing quality. Using empirically grounded parameter values from hedonic models, we simulate the evolution of housing market with or without natural hazard events.

Results.
We find that positive spillover effects from renovation can result in concentration of renovation activities within the neighborhood, which can be triggered by natural hazard events as well as concentration of individual renovation activities. Specifically, large scale renovation efforts increase housing price of properties within the same neighborbood, which provide incentives for nearby property owners to renovate as well. Thus, small amounts of hazard induced renovations can trigger full renovation within the neighborhood. Therefore, most properties in each neighborhood have ages within a 20-year window and exhibit wavy pattern over the long term, which matches our data in Miami-Dade County, Florida, USA. Neighborhoods with higher natural hazard risk tend to have higher long term housing quality and housing investment due to large-scale renovation triggered by natural hazards.

Conclusions.
In all, understanding such spillover effects and resulting coastal evolution due to natural hazard events are essential for informing coastal planners and addressing hazard-induced overdevelopment on the US east coast. As high income households are more likely to cluster in high-quality neighborhood until the neighborhood quality decays (Rosenthal 2008), natural hazard events and resulting renovation activities can lead to gentrification and long term coastal stratification. By examining the relationship between parameter space and evolution patterns, the study helps to identify potential hotspots in the future.

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Neighborhood environment and well-being disparities: The role of social infrastructure supply

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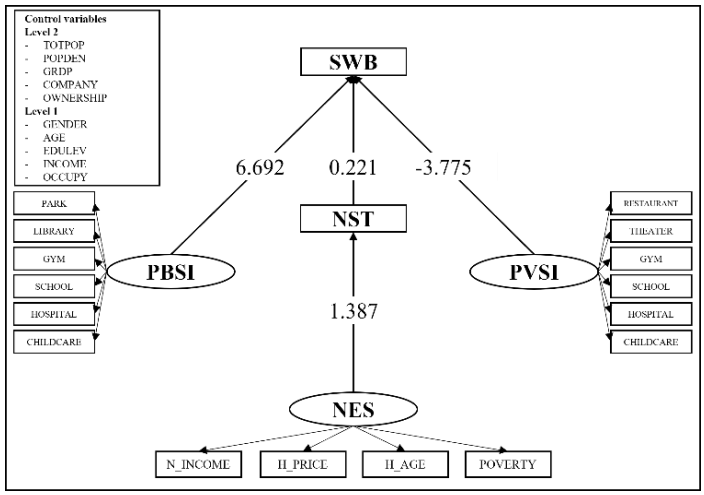
Introduction. To achieve well-being equity across regions, it is crucial to understand how well-being is shaped within urban systems. Despite substantial research on well-being, the neighborhood's role as a locus of impact has often been overlooked. Neighborhoods are the primary spatial units that significantly impact well-being. This study delves into how neighborhood economic status leads to well-being disparities. Specifically, it focuses on how differences in the provision of social infrastructure and levels of neighborhood satisfaction contribute to these disparities. Through empirical analysis, the study examines various pathways of well-being formation at the neighborhood level and discusses the policy implications.

Methodology. We use survey data from the Korean National Assembly Future Institute and officially published data from various Korean public institutions. Well-being is measured using the Cantril Ladder, and neighborhood economic status, treated as a latent variable, is examined for its role in shaping well-being. Social infrastructure supply and neighborhood satisfaction are key mediating parameters that explain these mechanisms. Social infrastructure is divided into private and public categories to better understand their distinct impacts on well-being. This distinction highlights how each type of infrastructure interacts with neighborhood economic status to shape overall well-being. An empirical analysis employs Bayesian multilevel structural equation modeling (MSEM) to estimate the impact of these key parameters, thereby identifying the direct and indirect pathways through which neighborhood economic status influences well-being.



Results. The preliminary results demonstrate the pathways through which neighborhood economic status (NES) influences subjective well-being (SWB). The analysis shows that NES significantly enhances neighborhood satisfaction (NST) ($\beta = 1.387$), which in turn positively affects SWB ($\beta = 0.221$). Additionally, public social infrastructure (PBSI) positively impacts SWB ($\beta = 6.692$), suggesting that improved public infrastructure provision is associated with higher well-being. In contrast, private social infrastructure (PVSI) exhibits a significant negative effect on SWB ($\beta = -3.775$), indicating that reliance on private infrastructure might be linked to lower levels of well-being. NES itself does not show a significant direct effect on SWB. These findings highlight the critical role of public infrastructure in promoting well-being and suggest that enhancing public services at the neighborhood level could help mitigate well-being disparities driven by economic status.

Conclusions. Given neighborhoods' critical role in shaping individual well-being, this study emphasizes the importance of understanding how different forms of social infrastructure—public and private—impact subjective well-being. The findings indicate that public infrastructure is key to enhancing well-being, while reliance on private infrastructure may be harmful. This research underscores the need for targeted public investments in neighborhood infrastructure to promote equitable well-being, highlighting the pathways through which neighborhood economic status influences well-being. These insights are essential for informing policies to reduce well-being disparities and ensure all communities access necessary social infrastructure.

The impact of air pollution on decent living standards: evidence from a district-level panel data

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Introduction. Air pollution, a major global cause of health issues and mortality, disproportionately impacts lower socio-economic groups due to their greater exposure and vulnerability to air pollutants. The developing countries are particularly vulnerable due to poor air quality regulations, polluting industries and vehicles, increasing elderly population and population density, rapid industrialization and urbanization and agricultural residual burning. Recent studies indicate that air pollution exacerbates socio-economic inequalities (Rentschler & Leonova, 2023). However, there is limited subnational evidence in India on how exposure to air pollutants disproportionately impacts poverty and well-being, majorly due to data constraints. Through this study, we propose a framework to better understand the intertwining of air pollutant levels and well-being by curating robust district-level panel data for India.

Methodology. We prepared district-level panel data for India by using the 4th (2015-16) and 5th (2019-21) rounds of the National Family Health Survey (NFHS) for the socioeconomic and health indicators and the district-level raster data at 1 KM spatial resolution, produced by Washington University using multiple satellite images for the air pollutant data (Siyuan et al., 2024). The analysis encompasses a final sample of 1312 observations for 656 harmonized districts of India spanning two years. The key outcome variable for the analysis is the Decent Living Standards Index (DLSI), which is constructed by adopting the Decent Living Standards framework (Rao & Min, 2018). We computed a DLSI at the household level followed by a mean DLSI at the district level. The DLSI is a composite measure constructed using 15 indicators of the following dimensions: household environment, household amenities, economy and education. The key predictor variable of the study is the concentration level of PM2.5 ($\mu g/m^3$) pollutant. The other variables of interest include the percentage of the urban population and median age. The panel fixed effects Ordinary Least Square (OLS) estimation is employed to examine the association of pollutant concentration and decent living standards.

Results. The results indicate that the mean of DLSI and air pollutant concentration levels are negatively associated. A unit increase in the concentration levels of PM2.5 decreases the mean DLSI score by 0.009 units. Even the relationship holds after controlling for age and urbanization. Thus, the hypothesis that exposure to higher concentration levels of air pollutants affects the living standard holds true. Previous research suggests that air pollution has significant adverse effects on morbidity, mortality, lost workdays, and children's education (Manisalidis et al., 2020). The other significant predictors of decent living standards include the median age and the percentage of the urban population.

Conclusions. Air pollution undermines health, economic stability, and environmental quality, all of which are crucial for maintaining and improving living standards. The concept of human well-being is a multidimensional construct covering economic, educational, health and household environment dimensions. This study shows that increasing concentration levels of air pollutants have a greater disadvantage in terms of well-being. From a policy perspective, this study highlights the importance of considering the heterogeneities at the sub-national level and adopting necessary regulations and air pollution mitigation strategies at the district level.

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Energy, Climate, and Environment (ECE)

Multi-model analysis on energy system achieving a complete phase-out of fossil fuels

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Introduction. The fossil fuel phase-out is essential to achieve the 1.5°C target, which was also agreed to "transition away from fossil fuels in energy systems" at the COP28. Recent studies have suggested that hydrogen-based energy carriers in combination with electrification and biofuels could reduce CO_2 emissions from hard-to-abate sectors and may theoretically enable the complete phase-out of fossil fuels. However, the configurations of zero-fossil energy systems remain unclear in previous studies. Here, we aim to reveal the changes in energy system configurations that achieve a complete phase-out of fossil fuels from the perspective of multiple energy systems models.

Methodology. We employed two energy system models: the *AIM-Technology model* and the *MESSAGEix* model. In the zero-fossil scenarios, constraints on the upper limits of fossil fuel supply were imposed, along with emission constraints equivalent to the 1.5°C target. These scenarios specify the years in which zero-fossil was achieved, set in ten-year increments from 2100 (DEF2100) to 2050 (DEF2050). We also employed the standard 1.5°C scenario (REF) without imposing zero-fossil constraints for comparison. In the zero-fossil scenarios, the MESSAGEix model determined fossil fuel supply endogenously, while the AIM-Technology model determined it exogenously (**Fig 1a**).

Results. Achieving zero-fossil influenced the penetration of hydrogen-based energy carriers (**Fig 1b**). In the AIM-Technology model, large-scale use of synfuels was required in the zero-fossil scenarios, where they accounted for about 10% of final energy by the time zero-fossil was achieved. In the MESSAGEix model, which lacks synfuels as a mitigation option, the phase-out of fossil fuels was achieved through the expanded use of electricity, hydrogen, and biomass. Both models showed an increase in power generation in the zero-fossil scenarios driven by the expansion of direct and indirect electrification compared to the REF scenario (**Fig 1c**). As a result, the cumulative system cost from 2025 to 2100 in the DEF2050 scenario increased by 4% compared to the REF scenario (**Fig 1d**).

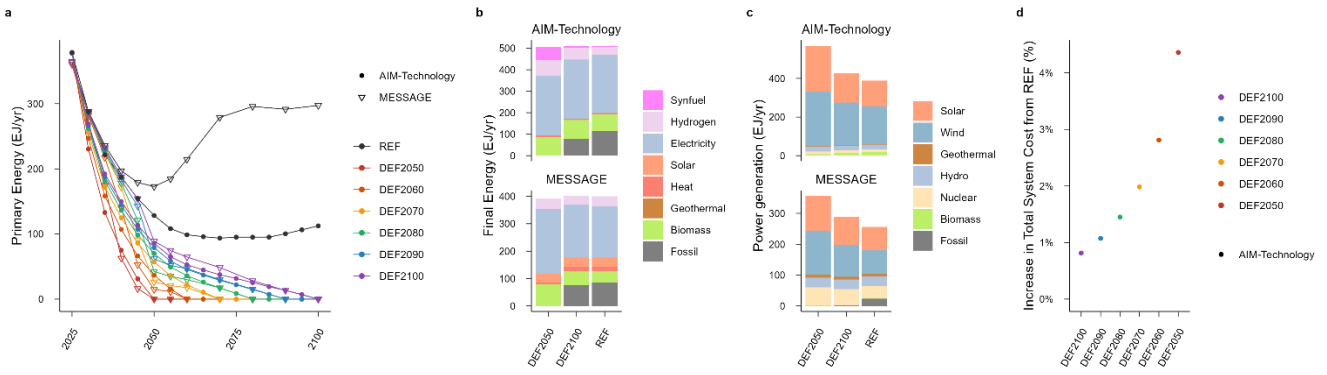

Fig. 1 a) Primary supply of fossil fuels. b) Final energy consumption in 2050. c) Power generation in 2050. d) Increase in cumulative system cost (2025 – 2100) from the REF scenario discounted by 5% per year.

Conclusions. Our findings suggest that expansion of direct and indirect electrification may make zero-fossil feasible within the scope of our models. However, although the concept of zero-fossil is straightforward, it must be noted that the zero-fossil scenarios are inefficient mitigation pathways, as reflected in the increased cumulative system costs. These challenges in the zero-fossil scenarios reinforce the need to reconsider, rather than simply advocating for a complete phase-out of fossil fuels, which sectors' fossil fuel consumption should be allowed to remain and be offset by CDR to achieve decarbonization more economically efficiently.

Quantifying the role of adaptive capacities in moderating climate damages

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Introduction. Addressing climate change requires rapidly scaling up investments across both mitigation and adaptation efforts. While Integrated Assessment Models have been instrumental in exploring mitigation pathways, progress on representing the role of adaptation has lagged behind. Understanding the extent to which adaptation can occur in the future is crucial for estimating adaptation investment needs, as well as the level of loss and damage needs. This project contributes to empirically understanding whether and how adaptive capacities (A.C.) - defined as the abilities of actors to adjust to potential climate impacts (IPCC WGII) - have played a role in moderating climate damages in the past. We also project how accounting for adaptation may lead to divergent climate futures.

Methodology. We start by testing whether adaptive capacities moderate damages by investigating how two groups of countries (i.e. those with a high vs low adaptive capacity), were differently impacted by temperature shocks in the past. We utilize a nonlinear damage function that relates temperature shocks to GDP growth as our baseline model (Burke et al 2015). We investigate the persistence of these impacts using local projections, a method which directly estimates the long-run response to a shock (Jorda 2005). To understand whether A.C. may explain attenuation of damages over time, we use 30-year rolling windows to test whether the shape of the damage function changes over time. Finally, we project future damages with differentiated estimates for Low vs High A.C. countries.

Results. After testing ten different indicators of adaptive capacity across four dimensions (governance, human capacity, social, financial), we find that two indicators have a statistically significant effect on moderating GDP damages: mean years of education and the level of financial development. Interestingly, widely used composite indices of adaptive capacity such as ND-GAIN did not significantly moderate damages from temperature shocks in the past. Figure 1 shows the differential impact of education on moderating GDP per capita growth rates. Countries with higher levels of education in colder climates marginally benefit from a 1C hotter year, whereas countries with lower levels of education are consistently negatively impacted across the temperature distribution. Projecting expected growth rates through 2100, we find that global average growth rates accounting for differential education levels may be 0.7 – 2 times baseline growth rates depending on the SSP scenario (SSP1-3).

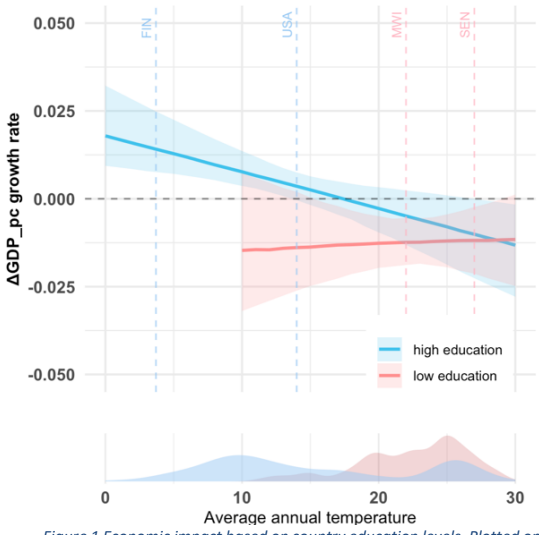

Figure 1 Economic impact based on country education levels. Plotted on y-axis is the marginal effect of a 1C hotter year on the GDP per capita growth rate. Bottom plot shows the temperature distribution of countries contributing to the regression estimates.

Conclusions. We conclude that adaptive capacity as measured by indicators of education and financial development have moderated damages from temperature shocks in the past. More work is needed to understand the causal channels of adaptive capacity, given high correlations across the A.C. indicators, income, and temperature. These findings may serve as a basis for incorporating adaptation in economic damage functions used to project future damages and understand inequalities in the impact of climate change on socioeconomic systems.

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Land use emission uncertainties for climate projections using the carbon-nitrogen coupled MAGICC

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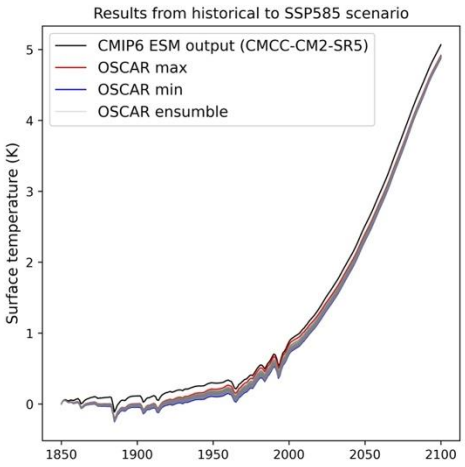
Introduction. The net flux from land use and land cover change (ELUC) represents the most uncertain component of the global carbon budget, despite accounting for over 10% of total anthropogenic emissions. This uncertainty arises from various factors, including discrepancies in model structures. The latest Global Carbon Budget 2022 highlights a broad range of cumulative ELUC estimates for 1850-2021: bookkeeping models report 140-280 GtC, while dynamic global vegetation models estimate 180 ± 60 GtC. This variability indicates the potential for even greater uncertainties in future emissions. Given that ELUC is a critical input for the MAGICC climate projection model, it has a direct impact on climate projection outcomes. Therefore, this study aims to assess how different sources of ELUC inputs influence climate projections across a range of scenarios, utilizing the established and refined nitrogen-carbon coupling within MAGICC.

Methodology. Reduced Complexity Models (RCMs) serve as emulators for Earth System Models (ESMs) by incorporating highly parameterized processes and components. The streamlined nature of RCMs makes them particularly suited for applications in ensemble projections and uncertainty analysis. MAGICC is a widely utilized RCM for climate and carbon cycle projections, with recent developments in nitrogen-carbon coupling calibrated to land surface models and CMIP6 ESMs. OSCAR is another RCM notable for its simulation of the net flux from land use and land cover change (ELUC). In this study, we utilize ELUC data from both the OSCAR ensemble results and CMIP6 ESM outputs to examine how uncertainties in these inputs influence climate projections.

Results. The surface temperature simulated by MAGICC using ELUC data from CMCC-CM2-SR5 is consistently higher than that using OSCAR throughout the historical period and into the SSP585 scenario. By the end of the century, the ESM ELUC results project a temperature increase of 5.066 K, compared to 4.892 ± 0.008 K (mean ± standard deviation) derived from the OSCAR ELUC ensemble. The temperature difference is particularly pronounced during the historical period, especially before 1975, indicating significant discrepancies in the carbon cycle representation during this time.



From the perspective of MAGICC model physics, the persistently higher temperatures observed with the ESM ELUC data can be attributed to two primary factors. First, the absolute ELUC values in CMCC-CM2-SR5 are higher than those in the OSCAR ensemble (2.5 to 6 GtC/yr vs. -1 to 3 GtC/yr), implying that the former estimates more carbon released from land use emissions. Second, larger ELUC values are associated with a greater reduction in net primary production (NPP) - the carbon assimilated by plants - under the assumption that deforestation directly decreases NPP. Both factors contribute to increased atmospheric CO_2 concentrations (1134.70 ppm with ESM ELUC vs.1080.87 ppm with OSCAR ELUC by 2100), leading to higher greenhouse gas forcings in scenarios with elevated ELUC.

Conclusions. The preliminary results show significant temperature differences (e.g., 0.174 K by 2100 in the SSP585 scenario) due to variations in ELUC inputs. These differences stem from direct ELUC variations and their impact on net primary production (NPP). To determine if these discrepancies are model- or scenario-specific, additional ESMs and scenarios will be included in the study. We may also compare integrated assessment model scenarios for a more comprehensive evaluation of ELUC-related climate uncertainty.

The implications of underdelivering and underestimating CDR

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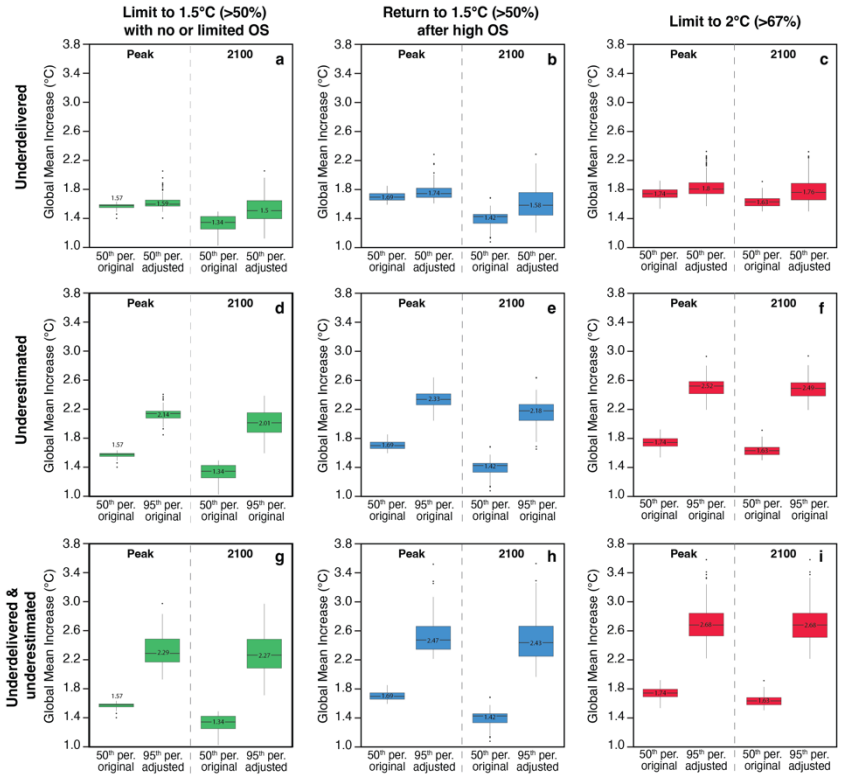
Introduction. IPCC scenarios that meet the 1.5 °C and 2 °C temperature targets rely heavily on carbon dioxide removals (CDR) to offset emissions from hard-to-decarbonize sectors, non-CO_2 and legacy emissions. These scenarios project cumulative CDR of 450–1150 $GtCO_2$ between 2020 and 2100, with some sequestering as much as 20 $GtCO_2$/yr in 2100. Presently, global sequestration is about 2 $GtCO_2$/yr from conventional afforestation and reforestation, and about 0.002 $GtCO_2$/yr from novel CDR technologies. Meeting scenario projections would require CDR to grow exponentially, which raises important concerns related to biophysical constraints and to the non-equivalence of emissions and removals for the climate system. Carbon storage limitations may mean we underdeliver on CDR, and the weakening of natural carbon removal processes may mean we underestimate CDR. Underdelivering or underestimating CDR could potentially lock us into a high-temperature pathway.

Results. In this project we used MAGICC to analyze the implications of underdelivering and underestimating modeled CDR amounts. We find important differences in global mean temperature increases by 2100 and at peak temperatures. If we do not meet modeled carbon sequestration levels ("we underdelivered"), then global mean temperature increase by 2100 could be 0.16 °C higher than expected. If, because of natural processes, there is a non-equivalence of emissions and removals (we "underestimated" CDR), then the median temperature increase by 2100 could end up being up to 0.86 °C higher than modeled. And if we underdeliver and underestimated CDR, global mean temperature increase by 2100 could be 1 °C higher than expected. These higher temperatures would have large human impacts.



Prospective scenarios for global mobility infrastructure and GHG emissions

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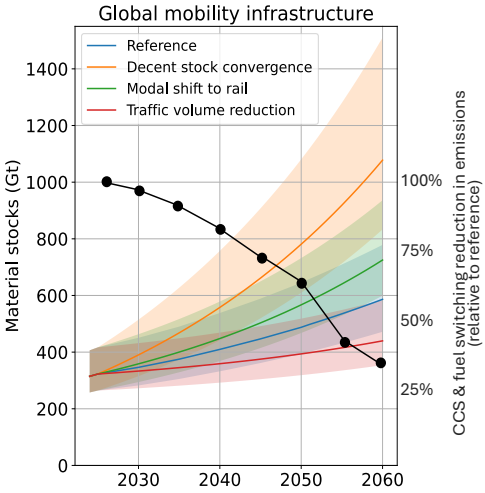
Introduction. Mobility infrastructure, comprising roughly one third of global material stocks[1], is a main driver of resource use with material and energy required for stock expansion, maintenance and replacement. At the same time, infrastructure facilitates well-being by providing the key service of moving people and goods. Due to globally increasing affluence, material demand for infrastructure expansion can be expected to grow substantially, requiring ever increasing amounts of natural resources. However, a global, regionally differentiated understanding of the future scale of mobility infrastructure expansion and embodied GHG emissions is currently lacking.

Methodology. To quantify future material demand, the stock-driven *GLOMIS* (GLObal Mobility Infrastructure Stocks) model was developed. GLOMIS quantifies material stocks for various infrastructure types based on crowd-sourced data. Stocks are extrapolated using traffic volume forecasts as a proxy. Based on annual stock changes and lifetime assumptions, material in- and outflows of stock expansion, maintenance and replacement are modelled, while material flows serve as inputs, or soft links, to the MESSAGEix-Materials model[2] which quantifies embodied emissions. To investigate option spaces, eight prospective scenarios (including a decent stock level convergence[3], a modal shift, and various supply-side measures) were developed.

Results. In 2024, material stocks in the mobility sector total 315 Gt, predominantly from road infrastructure. In a reference scenario, stocks would rise to 586 Gt by 2060, more than triple under a global convergence to decent mobility stock levels (92 t/cap), and double to 725 Gt under a modal shift to rail. A 25% traffic volume reduction would lead to 440 Gt of stocks. Average annual material flows are 8 Gt/a, 21 Gt/a, 12 Gt/a, and 4 Gt/a in these scenarios, respectively. First results for emissions show that emissions embodied in mobility infrastructure in the year 2060 could be significantly reduced by a combination of fuel switching and carbon capture and storage (CCS), cutting emissions by ~63% compared to the reference scenario. A traffic volume reduction alone would cut 2060 emissions by ~35%.



Conclusions. Demand- and emission-reducing measures have the potential to significantly soften the impact of increased material and energy use caused by projected mobility infrastructure expansion. With supply-side measures aimed at emission reductions alone, combined demand and supply-side measures could have the potential to mitigate emissions even further. A complete evaluation of the impact of both demand and supply-side measures is currently underway. Further research regarding material compositions of infrastructures and stock-service dynamics is needed to better project future resource use and emissions caused by infrastructure expansion.

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Developing machine learning-based $PM_{2.5}$ source-receptor relationships model

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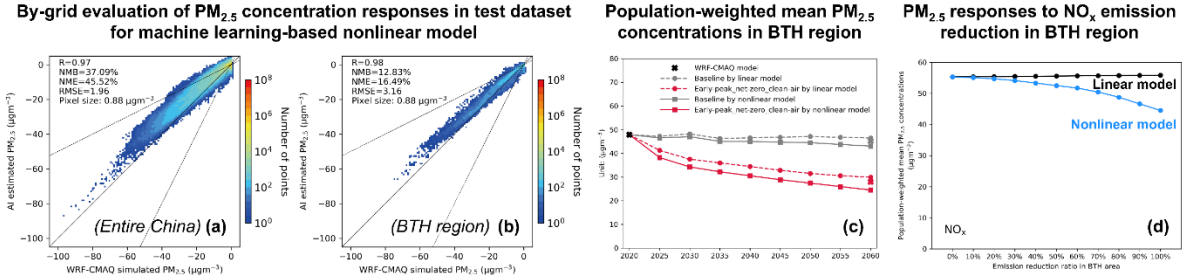
Introduction. The relationships between emission sources and receptor $PM_{2.5}$ concentrations (S-R relationships) are crucial to develop effective clean air policies. However, traditional chemical transport models (CTMs) that quantify these relationships are computationally intensive. Recently, simplified models were developed, but they were typically linear, overlooking the nonlinearity of atmospheric chemistry. This study developed a machine learning-based nonlinear model for China, with data from the Weather Research and Forecasting-Community Multiscale Air Quality (WRF-CMAQ) model. Then, it was compared with a linear model and WRF-CMAQ.

Methodology. We prepared a data set with ~600 emission reduction scenarios from WRF-CMAQ. Then, the machine learning model in a UNet structure was trained to obtain nonlinear $PM_{2.5}$ S-R relationships. For comparison, we developed a linear model following Amann et al. (2011) under the same WRF-CMAQ configurations. The nonlinear model, linear model, and the WRF-CMAQ model were compared in Beijing-Tianjin-Hebei (BTH) region under scenarios from Dynamic Projection model for Emissions in China (DPEC; Cheng et al., 2023).

Results. According to the by-grid evaluation in test data set (Figure a and b), the $PM_{2.5}$ responses estimated by the nonlinear model (y axis) were in good consistency with the WRF-CMAQ results (x axis) in China (R=0.97; NMB=37.09%; RMSE=1.96 μgm^{-3}) and BTH region (R=0.98; NMB=12.83%; RMSE=3.16 μgm^{-3}). The test data set included 126 different emission reduction scenarios of 5 pollutants (PM, SO_2, NO_x, NH_3, and VOCs) from 3 sources (power, industry, and other) in China. When applied to the DPEC scenarios in BTH (Figure c), the nonlinear (solid lines) and linear (dashed lines) model showed similar trend from 2020 to 2060 in both baseline (gray) and early-peak_net-zero_clean-air (red) scenarios. Specially, population-weighted mean $PM_{2.5}$ concentrations in 2060 were compared with WRF-CMAQ, indicating they were in good agreement. The discrepancies between them were mainly from the $PM_{2.5}$ responses to NO_x emission reduction (Figure d): under the same emission reduction ratio, the nonlinear model estimated more $PM_{2.5}$ reductions, causing the lower $PM_{2.5}$ concentrations in DPEC scenarios. The $PM_{2.5}$ responses to other pollutants were similar in linear and nonlinear models (not shown).



Conclusions. The nonlinear model can well estimate the $PM_{2.5}$ responses to emission changes of 5 pollutants (PM, SO_2, NO_x, NH_3, and VOCs) from 3 sources (power, industry, and other) in China. Under the DPEC scenarios in BTH, the $PM_{2.5}$ concentrations estimated by linear and nonlinear model were both close to those from WRF-CMAQ. The differences between linear and nonlinear models mainly stemmed from the nonlinearity of NO_x S-R relationship.

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Evaluating fluorinated greenhouse gas emissions and mitigation potential in China

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Introduction. Fluorinated greenhouse gases (F-gases) are rapidly growing contributors to global warming. Despite international efforts to phase down certain F-gases, further emission reductions are essential to meet the 1.5℃ climate target. Hydrofluorocarbons (HFCs), a major group of F-gases, are extensively used in sectors with delayed emissions, which are not fully regulated by current frameworks, but can be mitigated through lifecycle management, i.e. leakage prevention, recovery, recycling, reclamation and destruction. This study employs the GAINS modelling framework to quantify the mitigation potential through lifecycle management beyond the Kigali Amendment (KA), and to assess the associated costs. The findings contribute to the development of cost-effective mitigation strategies.

Methodology. Sectors with F-gas banks, including stationary (residential and commercial) and mobile air conditioning, industrial and commercial refrigeration, fire protection and foam, were studied. Three scenario sets were investigated: pre-KA (using macro-economic drivers from SSP1-5), KA, and improved management (implementing lifecycle management measures with cost constraints). Emissions and banks were estimated through dynamic material flow modelling, with uncertainty assessed using Monte Carlo analysis. Abatement costs of substance- and sector-specific lifecycle management measures were quantified using cost analysis within the GAINS modelling framework.

Results. Without the KA, annual HFC emissions from the studied sectors would reach 1.05 ± 0.01 ~ 1.69 ± 0.02 Gt CO_2-eq by 2060 under different SSP scenarios (see: Fig.1). Compliance with the KA would reduce the cumulative emissions during 2024 ~ 2060 from 27.94 ± 0.06 ~ 34.67 ± 0.08 Gt CO_2-eq down to 13.60 ± 0.04 Gt CO_2-eq, with the HFC bank peaking at 3.74 ± 0.06 Gt CO_2-eq in 2034. Implementing lifecycle management measures with marginal abatement costs below 10 USD/t CO_2-eq could further reduce the cumulative emissions by 7.21 Gt CO_2-eq, with total costs amounting to 16.6 billion USD. Reclamation is more cost-effective than destruction due to the tradable value of reclaimed substances. These measures are particularly economical when applied to larger equipment in the refrigeration and air conditioning sectors, while foam treatment remains the most expensive (see: Fig.2).

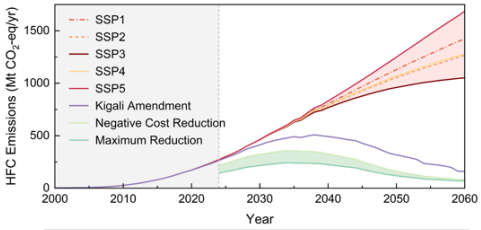

Fig. 1 Annual HFC emissions under different scenarios

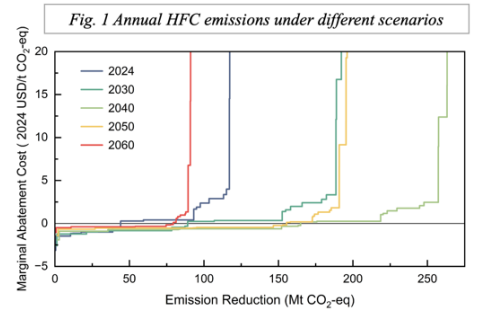

Fig. 2 Marginal abatement cost curves of F-gas lifecycle management

Conclusions. Through emission modelling, this study quantified the F-gas emission reduction achievable through the KA in China. Furthermore, combined with cost analysis, the study highlighted the substantial additional mitigation potential of lifecycle management, which could further reduce the emissions under the KA by more than 50% at relatively low abatement costs compared to other greenhouse gas mitigation measures. However, to fully harness the potential of lifecycle management, challenges beyond technological costs, such as infrastructure gaps, the absence of a robust market for reclaimed substances, and inadequate regulation and enforcement, must be addressed through policy incentives and market mechanisms.

Assessing the impact of air quality measures and climate change in Northeast Asia

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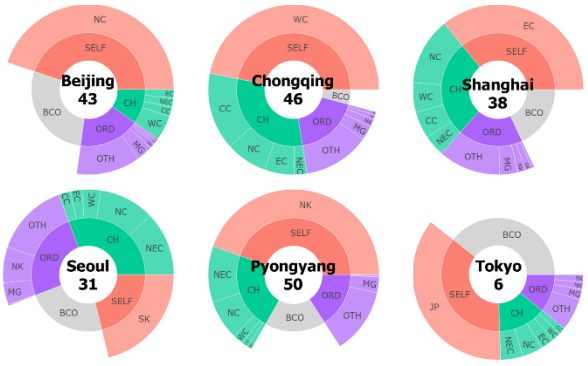
Introduction. Severe air pollution in Northeast Asia arises from a complex interaction of natural sources, long-range transport, and local emissions. Countries in the region have implemented various air quality measures, which studies have shown can significantly improve air quality. However, the effectiveness of these measures varies with meteorological conditions, making accurate assessment essential. Additionally, it is important to distinguish the contribution of each transboundary region to the air quality in the target area. This study aims to evaluate the effectiveness of these air quality measures, considering both local and transboundary effects, to better understand each factor's role in Northeast Asia's air pollution.

Methodology. We used the Community Multiscale Air Quality (CMAQ) chemical transport model (Byun & Schere, 2006) to simulate air pollutant concentrations. In this study, we set the meteorological data to 2020 to focus on the impact of future emissions on air quality. To project future emissions, we applied the AQNEA scenario (Base_CLE, NetZero_CLE, NetZero_MFR). Additionally, we employed the CMAQ-ISAM (Integrated Source Apportionment Method), a tagging method that tracks contributions from specific pollution sources to assess their impact on overall pollution levels. This approach allowed us to analyse both local and transboundary contributions to $PM_{2.5}$ and O_3 concentrations.

Results. In this study, we used the ASIA-AQv3 emission inventory, which is derived from the AQNEA inventory, to simulate air quality for 2020. The model accurately simulated concentrations of air pollutants. We focused on $PM_{2.5}$ concentration in January 2020, analysing air quality in Seoul, Beijing, Chongqing, Shanghai, Pyongyang, and Tokyo. We examined self-contribution (red), China (green), and other regions in the model domain (purple) and the numbers are $PM_{2.5}$ concentration ($\mu g/m^3$). Cities in China showed the highest levels of both local and regional contributions, while Seoul was significantly impacted by transboundary emissions, likely due to its downwind location. Tokyo had high local contributions but relatively low overall $PM_{2.5}$ levels, reflecting its lower base concentration. Pyongyang also showed high local contributions, although its emission data have higher uncertainties, necessitating further investigation. Future projected emissions using the AQNEA scenario indicated that the NetZero scenario could significantly decrease emissions and improve air quality. However, for North Korea and Mongolia, the Base scenario predicted increased emissions, likely due to ongoing development.



Conclusions. This study reveals the intricate factors influencing air pollution in Northeast Asia. Using the CMAQ model with AQNEA scenario projections, our results show significant contributions from Chinese cities to both local and regional pollution, while Seoul is heavily impacted by transboundary emissions due to its downwind location. The NetZero scenario projections suggest a promising reduction in emissions and improvement in air quality. In contrast, the Base scenario for North Korea and Mongolia predicts increased emissions due to ongoing development. This underscores the need for targeted policies and comprehensive management strategies to effectively address both local and transboundary air pollution challenges.

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Strategies for region-specific air quality improvement towards Beautiful China 2035 target

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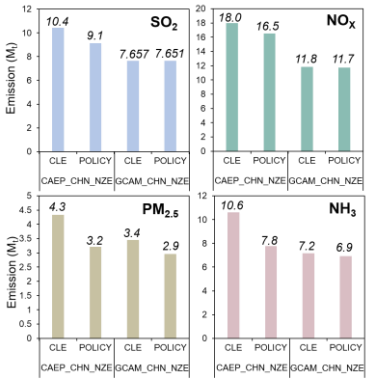
Introduction. Striving for the further improvement of environmental quality, China has embarked on building a "Beautiful China" characterized by clear air before 2035. However, previous studies often approached the formulation of air quality targets from a national perspective, making it challenging to achieve regional air quality targets with a cost-effective approach. This study aims to develop strategies for designing region-specific air quality improvement targets towards Beautiful China 2035 target, in the context of China's new climate change.

Methodology. We developed an integrated modeling framework that combines the GAINS, CAEP_CP, and GCAM models to assess the air quality co-benefits of decarbonization strategies through a cost-effectiveness approach, under the carbon zero target and the "Beautiful China 2035" air quality target. To explore the impact of key elements (e.g., responsibility, capacity, and potential) on the setting of provincial air quality targets, we used the Monte Carlo method with 10 thousand simulations. Then, the GAINS model is used to explore region-specific measures required to achieve the air quality targets, under the CAEP_NZE and GCAM_NZE scenarios.

Results. We find that under the CAEP_NZE and GCAM_NZE scenarios, CO_2 emissions will decline by 26.7% by 2035, driven by different progress in the energy transition. However, the different net-zero pathways have significantly distinct impacts on air quality. While GCAM_NZE could achieve the national air quality target of 25 μg m^{-3}, CAEP_NZE requires additional clean air actions to achieve this goal. Moreover, under the more ambitious national air quality improvement target of 20 μg m^{-3}, GCAM_NZE could yield further reductions of 6.2 Mt of NO_x, 2.8 Mt of SO_2, 0.9 Mt of $PM_{2.5}$, and 3.4 Mt of NH_3 compared to CAEP_NZE. Notably, the air quality improvements differ regionally between the two scenarios. For example, in GCAM_NZE, additional air quality improvement co-benefits of 7.6%, 8.8%, and 14.3% are observed in Tianjin, Hebei, and Inner Mongolia, respectively, compared to CAEP_NZE.



Conclusions. We explore strategies for developing provincial air quality improvement targets across China by 2035, under different pathways of carbon neutrality goal. Our findings indicate that more ambitious carbon neutrality policies would lead to greater co-benefits in pollution abatement, however, these benefits vary significantly across regions and sectors. Regions such as Hebei, Tianjin, and Shandong experience more substantial co-benefits under GCAM_NZE than CAEP_NZE, due to more ambitious net-zero actions. This suggests that the former would lead to cost savings in air pollution control. Therefore, we recommend integrated strategies that combine net-zero and clean air initiatives to achieve carbon neutrality and air quality improvement targets in the most cost-effective approach.

A double opportunity: Supporting pastoralism and climate in Kenya

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Introduction. In Kenya, pastoralism is the main source of livelihood supporting millions of people across the arid and semi-arid lands (ASAL) while playing an important role in ecosystem services. Despite the significance of pastoralist systems to food security and the environment, the livestock policy debate has often contrasted low-impact, extensive pastoralism with intensive livestock systems in western countries, to the detriment of the former in terms of productivity and climate efficiency. This results in inequitable generalisations that negate the important role of pastoralism in ecosystem services and supporting livelihoods where few alternative options exist. A more nuanced, balanced discussion of livestock sustainability is needed to address this inequality and can only be achieved with more specific research focused on the region.

Methodology. Leveraging the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, this research developed a novel bottom-up emissions inventory of national livestock enteric fermentation CH_4 emissions, with a focus on pastoral systems in Kenya using a feed-based Tier 2 methodology. Drawing on local knowledge from previously conducted social science research amongst pastoralists in East Africa, strategies that support pastoralist livelihoods, with a focus on urgent climate adaptation, were identified. The GAINS model was then used to understand how these strategies contribute, positively or negatively, to emissions reduction in comparison to a business as usual (BAU) approach.

Results. Using the feed-based Tier 2 methodology in GAINS, pastoral systems account for 44% of all livestock emissions while representing 72% of stock numbers in Kenya. The strategies identified to support local constructs of resilience in pastoral systems include mobility, fodder harvest and storage, anticipatory action, species diversification, Mazingira system, women support groups, public health and education, and disease prevention through vaccination. Based on literature availability, two strategies were selected for further quantifications of emissions: fodder harvest and storage, and disease prevention. Implementing both strategies from 2030 onward at a feasible adoption rate, annual enteric fermentation CH_4 emissions in 2050 would be 22% less in pastoral systems and 11% less across all livestock systems compared to the BAU approach. This means Kenyan pastoralist systems would emit 3,406kt CH4 less between 2030 and 2050, nearly double the country's total annual CH_4 emissions in 2020 based on the recent GAINS modelling.

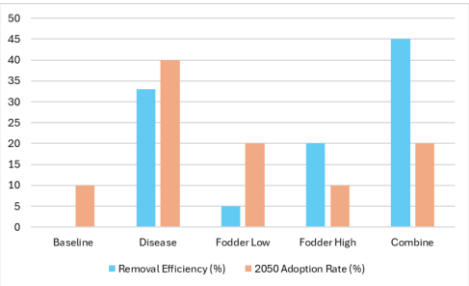

Figure 1: Removal efficiency and 2050 adoption rate of strategies in pastoral systems. strategies.

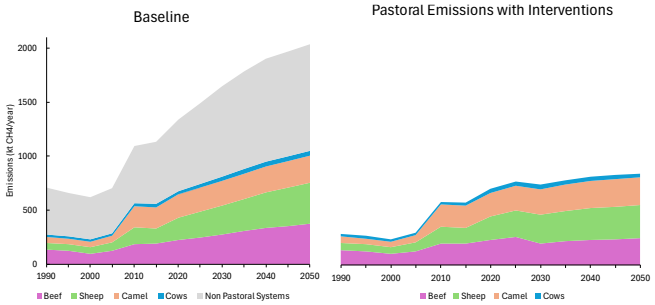

Figure 2: Enteric fermentation CH4 emissions 1990–2050 in Kenya in the baseline scenario and with adoption of strategies.

Conclusions. Given the important role of pastoralism in Kenya, it is important to find strategies that both support pastoralism and limit impacts on climate change. This research shows that disease prevention and fodder harvest and storage initiatives are interventions that can both support pastoralist livelihoods and limit future methane emissions. Further research is needed for a broader understanding of how institutional factors that empower pastoral systems, such as public health, education, anticipatory action, improved mobility and social capital, intersect with locally functioning climate adaptation pathways. Furthermore, significant differences in emissions were found when using empirical data from local regions to develop emissions inventories as opposed to default IPCC Tier 1 values. This reinforces the importance of accuracy in emissions estimates when developing policy recommendations.

A roadmap for future deployment of urban rooftop and utility scale photovoltaics in China from energy-water-land-carbon nexus perspective

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Introduction. About 75% of power generated globally is consumed within cities. Recent economic and technical advances have made city-integrated solar technologies increasingly attractive, including both utility-scale photovoltaic (UTSPV) and rooftop-scale photovoltaic (RTSPV). These two urban PV topologies generate unavoidable and distinct impacts such as land occupation, carbon emissions, and water consumption. However, the multiple interlinkages between urban PV systems and the energy-water-land-carbon nexus remain unknown, and city-to-city and regional heterogeneities are also complicated. This study hereby aims to reveal the energy-water-land-carbon tradeoffs of UTSPV and RTSPV to shape the evidence-based policy orientation for local government.

Methodology. We employed the MESSAGEix integrated assessment model to project the installed capacity of UTSPV and RTSPV in China, specifically under a 1.5°C global temperature target. To translate these national targets into actionable goals at the subnational level, we developed a "country-province-city" downscaling workflow including three approaches, which were the provincial-level extension of MESSAGEix framework, the multi-criteria decision analysis model, and the fixed-effects panel regression model. Based on the downscaled city-level installed capacity, we further integrated whole life cycle assessment and geographic information system to measure the energy, water, land, and carbon implications of deploying UTPSV and RTSPV in 349 Chinese cities.

Results. Throughout the stages from PV material production to disposal, RTSPV outperforms UTSPV with 1.1–1.5 times lower life cycle energy consumption, water usage, land occupation, and carbon emissions per GWh generation. By 2050, occupying 1.7% and 46% of the national potential area of UTSPV and RTSPV respectively, China's PV installation could promote 2.3 Gt of carbon mitigation and 20 billion m^3 of water saving (Fig 1). Out of the 30 provinces, Inner Mongolia's UTSPV and Jiangsu's RTSPV respectively show the highest potential for mitigating carbon emissions and reducing water consumption by 2050. While from the urban administrative boundary's perspective, 17% of the cities reach their capacity threshold for UTSPV and RTSPV potential areas. Capacity targets should be relocated to the rooftops and ground areas in neighboring cities and provinces to close these gaps.

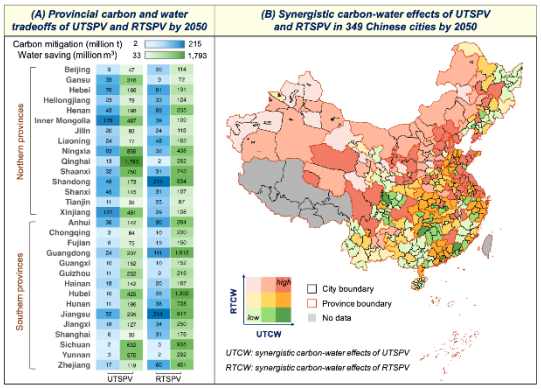

Fig 1. Carbon-water performances of UTSPV and RTSPV in China by 2050

Conclusions. This study provides a synopsis of progressively downscaling the national solar PV expansion targets to the provincial and city levels. Here the necessity of capacity adjustment is highlighted since urban installed capacity requirement might surpass local capacity potential, and we particularly call for the city governments to orient their local PV deployment based on the synergistic management of multiple resource elements and environment.

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Measuring household deprivation: From food poverty to national poverty lines

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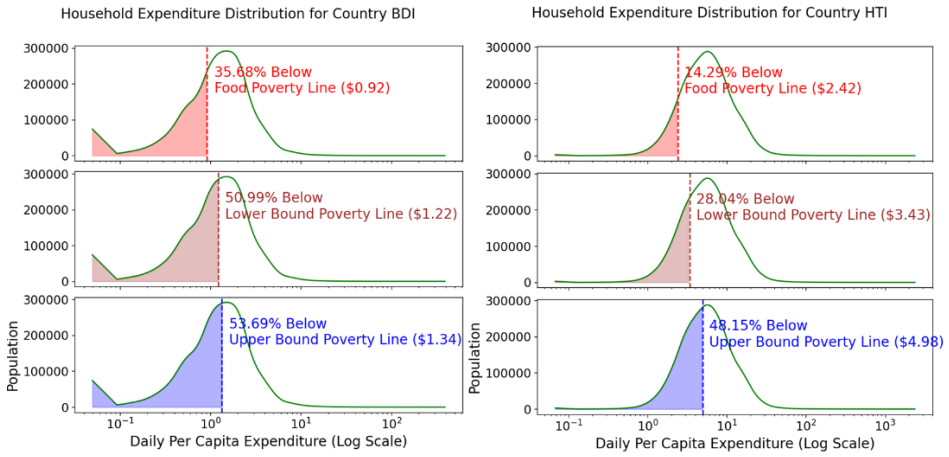
Introduction. The concept of absolute poverty is particularly critical for policy development in developing countries. Food is a fundamental indicator of absolute poverty, as it is typically the primary expenditure for poor households and a key factor in assessing their standard of living. This research aims to build poverty lines to measure household deprivation based on the food poverty line.

Methodology. Our approach considers different calorie prices across expenditure groups by using the mean calorie intake and the Coefficient of Variation of caloric intake from FAO and the global expenditure dataset with 201 expenditure bins from World Bank, reflecting subnational differences in food purchasing. From this, we determine national food and total poverty lines, comparing different methods. The food poverty line represents the minimum cost of food necessary for survival, based on the dietary energy requirement and cost per kilocalorie. The lower and upper bound total poverty lines are derived by adding non-food expenditure to food poverty line by comparing total and food expenditure. The research also analyzes the impact of economic growth and income redistribution on poverty alleviation.

Results. (1) Among 108 analyzed countries, Burundi, Iraq, Rwanda, and Haiti are facing severe poverty with more than 10% of population's total expenditure per capita lower than their food poverty line. For some countries, the international poverty line of $2.15 (2017 PPP) falls below the national poverty thresholds, suggesting the need to use national poverty lines in policy-making to effectively address poverty. (2) The analysis shows that targeted food and total poverty eradication requires a modest increase in total expenditure, ranging from 3% to 18% in 4 countries mentioned above. (3) Economic growth alone with current inequality level is insufficient for poverty reduction: the benefits of growth do not trickle down equally to the poor; even with 100% growth, severe poverty persists. (4) Nearly perfect domestic income redistribution can lift households above the poverty line in all the countries studied.



Conclusions. Food poverty lines can be built more accurately by considering different calorie price across expenditure groups. Targeted poverty reduction intervention like domestic income redistribution is necessary and promising in poor countries even with negative economic growth.

Attributing extreme events by income decile

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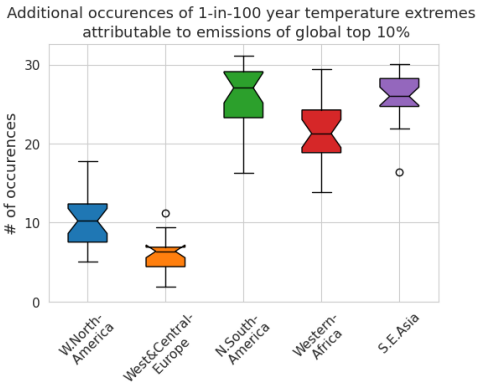
Introduction. Climate change presents significant inequalities in its causes and impacts. In 2019, private consumption and investments of the wealthiest 10% made up 48% of global emissions, while the bottom 50% contributed just 12%[1]. In addition, there is a spatial disparity in climate impacts, meaning those who have contributed the most are often not the ones worst affected. This raises questions about how climate policies can be designed fairly, particularly concerning the emerging costs for adaptation and loss and damage. Our study contributes to the discussion on fair climate policies by assessing how greenhouse-gas emissions attributable to the wealthiest share of the population over the period 1990-2019 have influenced the occurrence probability and intensity of present-day monthly temperature and precipitation extremes as well as drought conditions.

Methodology. Studying extreme events requires extensive data amounts, while traditional climate models only offer limited amounts of data due to computational constraints. Our modelling approach relies on a novel, emulator-based modelling chain that allows us to overcome computational constraints. First, we construct emissions pathways with and without contributions from wealthy population groups (specifically, the wealthiest 10% and 1% globally and in China, India, the US, and the EU27). Next, these pathways are converted into a large ensemble of global mean temperatures using the simple climate model MAGICC[2] and subsequently translated into gridded temperature and precipitation data through the Earth System Model emulator MESMER-M-TP[3]. We build on the framework of extreme event attribution[2] for an emitter-specific attribution of climate extremes at the grid-point level.

Preliminary Results. We find that 55% of the increase in global mean temperature since 1990 is attributable to the wealthiest 10%. In addition, the emissions attributable to the top 10% have strongly influenced occurrence rates and intensities of local temperature extremes, here defined as 1-in-100 year events in a pre-industrial climate, across the globe. We identify a large set of locations in which more than 60% of the additional occurrences are attributable to the wealthiest 10% and we report a large spatial disparity.



Conclusions. Our computationally efficient workflow is a flexible and robust tool to quantify how individual emissions influence the probabilities and intensities of climate extremes. This study is a first use case. Our findings demonstrate that emissions associated with the wealthiest population groups have disproportionally driven global temperature increases and intensified extreme weather events. The disparity between the drivers and effects of extreme climate impacts underscores the urgent need to integrate justice considerations into policy making. Targeted climate strategies should not only effectively mitigate risks but also ensure fair distribution of costs and responsibilities - addressing the needs of those most vulnerable to climate change.

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Quantifying the potential of energy communities in the Netherlands

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Introduction. Energy communities (ECs) have been crucial in accelerating the energy transition, with over 22,000 projects involving 2 million people in the EU since 2000 and rapid growth in the last decade (Schwanitz et al., 2023). ECs can enhance public acceptance, bolster local economies, and support decentralized energy systems. Despite their importance, there is a knowledge gap regarding their quantifiable impact on future energy systems and potential strategies to accelerate their adoption. Existing models often overlook the role of ECs in driving social tipping dynamics. This study, focusing on the Netherlands, aims to bridge this gap by modelling the development of ECs, evaluating key growth dynamics, and refining policy strategies to boost their adoption.

Methodology. In this study, we further developed the BENCH model (Niamir et al., 2020), an empirically validated agent-based model simulating households energy decisions and behavioral change. The model has been enhanced by incorporating collective household decision-making, based on the well-established Institutional Analysis and Development framework (Ostrom, 2011). The model was calibrated using data on drivers for EC participation in individual households and national data on EC development. Finally, the model was used in scenario analyses to assess key dynamics in EC development and the effectiveness of policy strategies to promote their growth.

Results. The development of ECs depends on the interaction between EC initiators, project initiators, and members. Initially, altruistic enthusiasts drive EC creation and renewable energy projects, but success hinges on sufficient household participation. Network effects and word-of-mouth can accelerate EC growth, leading to mainstream adoption. We designed several scenarios to test the impact of various socio-cultural and institutional settings, and policy measures in the Netherlands. The preliminary results show two key potential bottlenecks. First, if not enough people join ECs, initial projects may fail due to lack of investment. Second, reliance on volunteers limits scalability. To overcome this, ECs must professionalize, enabling them to hire employees and reduce the communal effort required for project expansion, especially during large-scale deployment. Effective policy measures can help mitigate these challenges, ensuring sustained growth and impact.

Conclusions. The adoption of ECs is a complex, non-linear process where small changes can significantly impact outcomes. Initial conditions, like early enthusiasm from key individuals, can trigger tipping points if enabling conditions are met. Effective strategies include enhancing public awareness and professional capacity of ECs. These alleviate bottlenecks in the number of interested households and dependency on volunteers. When these strategies are in place, ECs can show exponential growth, becoming key players in renewable energy generation. Ongoing research will explore network designs, the strength of status quo bias, and interactions between commercial developers and ECs to further understand their development.

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Biodiversity and Natural Resources (BNR)

Impact of mega dam construction on watershed carbon balance

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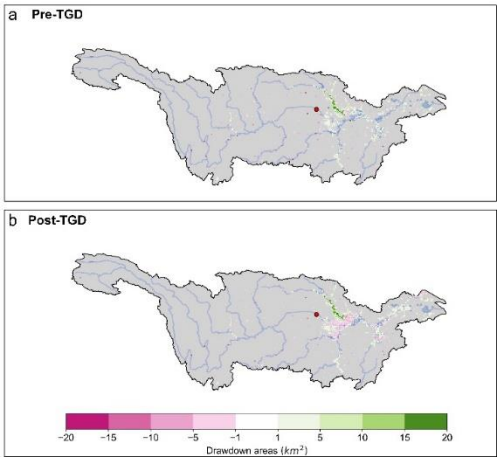
Introduction. Drawdown areas due to dam construction and operation are considered hotspots of carbon emissions[1]. However, dams can also significantly influence downstream water levels and associated carbon emissions from river floodplains, which has not been considered in previous studies. The Yangtze River Basin stands as one of China's most vital river systems, with the world's largest dam-the Three Gorges Dam (TGD), being a significant hydroelectric facility within this basin[2]. This study aims to investigate the impact of the construction and operation of the TGD on carbon emissions, focusing specifically on the potential effects of dam-related inundation dynamics on downstream water levels and carbon emissions from river floodplains under climate change.

Methodology. We simulated the long term (from historical period to future scenarios) GHG emission interfaces by coupling the corrected CWatM[3] 5min resolution runoff output for the Yangtze region, using the best-fitting TGD release curve, to the CamaFlood dam module, which generates dam parameters at 5min resolution. The results of greenhouse gas emissions from reservoirs in the Three Gorges region were obtained by calculating various greenhouse gas emission fluxes gathered with the associated emission interfaces. Our formulae were employed in order to ascertain the impact of the establishment of large dams on the carbon balance of the regional watershed, with comparisons made to natural scenarios.



Results and Conclusions. Following an extensive period of time-series simulations, it was determined that the commissioning of the Three Gorges Dam on the Yangtze River had a significant impact on the carbon balance of the entire Yangtze River basin. In comparison to the period preceding the operation of the Three Gorges Dam (Left figure), the post-2003 Yangtze River Basin has exhibited a reduction of approximately 25% in the drawdown area, with an average size of 2,483 km². In contrast, the carbon emission fluxes (658.825 gC m-2y-1) in the Yangtze River Basin's drawdown are higher than those at other emission interfaces, such as the Yangtze River Basin. When this portion of carbon emissions, which has been overlooked in previous studies, is taken into account, the overall carbon balance of the Yangtze River Basin appears to shift towards a carbon source compared to the pre-Three Gorges operational period. It is anticipated that more pronounced trends and uncertainties in carbon balance estimates for the Yangtze River Basin will emerge under different future scenario outcomes as climate change intensifies.

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A coupled Citizen Science and Nature-based Solutions (CS-NbS) approach - Implementation driver and barrier analysis: The case of TEvap in Brazil and Iran

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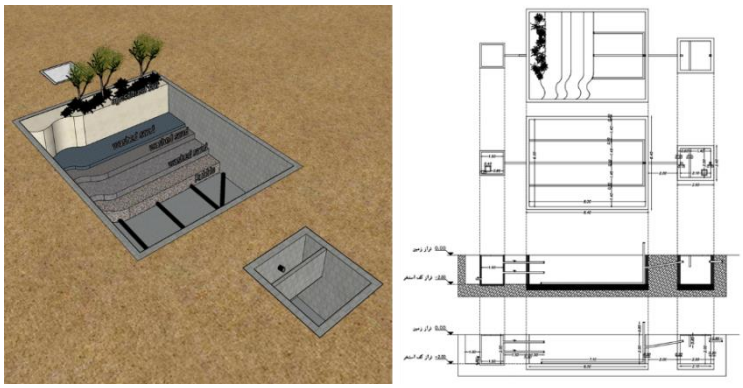
Introduction. Adopting Nature-based Solutions (NbS) for recycling water and nutrients in wastewater is crucial amid escalating threats to water and food security but requires the participation of informed stakeholders. Citizen science (CS) activities can raise environmental awareness and facilitate informed decision-making. This study investigates the drivers and barriers to adopting a coupled CS-NbS approach in rural Brazil and Iran, focusing on evapotranspiration tanks (TEvap).

Methodology. The study reviewed literature and conducted workshops and interviews to develop a citizen science protocol for TEvaps. Social network analysis, semi-structured interviews, and fuzzy cognitive mapping were used to understand implementation drivers and barriers. The study also leveraged stakeholder meetings and modeling to showcase evidence of the transformative potential of CS-NbS under upscaling scenarios.

Results. As a result, manuals and a data collection protocol for citizen science were developed—a trainer training workshop built capacity for the local organization of scoping workshops. Planned semi-structured interviews aim to gather input on local stakeholders' perceived drivers and barriers, and a fuzzy cognitive mapping concept has been developed to capture the relationship and magnitude between identified drivers and barriers. Furthermore, a preliminary TEvap model has been conceptualized, focusing on water balance and evapotranspiration.



Conclusions. The output of this research is expected to inform transformative policies for agri-food systems through harmonizing human-natural systems. CS-NbS showcases how inclusive participation in circulating the output of agri-food systems through WASH and NbS can provide input for sustainable and resilient agri-food systems. Upon continuation, citizen science data from various case studies could provide valuable information for long-term research.

Figure 2: Evolved TEvap design for black and greywater treatment

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The interactive impacts of climate change and policy on urban development in drylands

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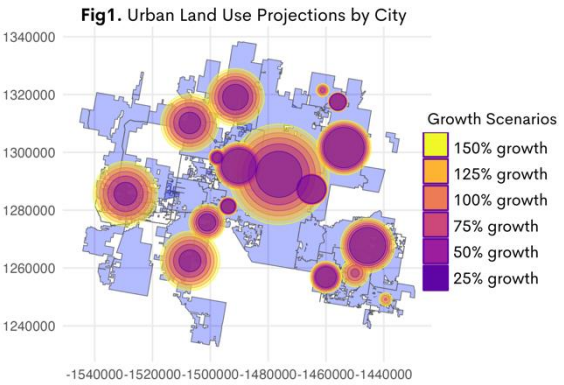
Introduction. Dryland cities are continuing to expand despite water scarcity, which can be exacerbated by climate change. To date, we lack an adequate understanding of the combined impacts of climate and policy on water sustainability and urban development. Using the Phoenix Metropolitan Area (PMA) as a case study, I addressed the following research questions: 1) How much urban development (i.e., urban population and land use expansion) can be supported by regional water supplies? 2) Which water-saving policies are required for sustainable urban development? and 3) How does climate change impact policy requirements?

Methodology. To link urban development with water availability, I used WaterSim5, a system dynamics model designed to project water supply and demand under climate and policy scenarios in the PMA. The study considered eight urban development scenarios, ranging from 0–150% of the regional population growth projected by the U.S. Census Bureau. For each growth scenario, I investigated groundwater levels in 2060 in response to factorial combinations of climate (severe vs. no impacts on water supply) and policies. The policy options ranged from "do nothing" to progressively implementing water-saving strategies including improving indoor, outdoor, and agricultural water use efficiency, using wastewater, reducing agricultural area, and augmenting water supply through coastal desalination. Next, I used historical relationships to estimate the urban land use area associated with each population growth scenario.

Preliminary Results. Population and urban land use projections for each PMA city and growth scenario are shown in Fig. 1. Climate and policy had major impacts on how much urban population growth and urban land use expansion can be sustainably accommodated in the PMA. With no climate impacts on river flows, scenarios ranging from 25–125% of the projected population growth required no policy interventions to maintain at least 80 years of groundwater supply throughout the simulation period. However, the maximum growth scenario required all water-saving policies to maintain at least 80 years of groundwater supply. Under severe climate impacts, the 25% population growth scenario required water use efficiency improvements to maintain 80 years of groundwater. The 50% and 75% growth scenarios required increased water use efficiency and wastewater use. The 100%, 125%, and 150% growth scenarios required all water-saving measures to maintain 80 years of groundwater supply.



Future Directions. To simulate urban land use expansion that is constrained by regional water supply, I still need to input the urban land use estimates into the Future Land Use Simulation (FLUS) model. Key challenges that must be overcome are accounting for the feedback between the location of urban growth (i.e., infilling vs. edge expansion) and water availability, as well as the relationship between population density and water availability.

Simulating water-limit crop yields and water scarcity under climate extremes using PyAEZ-CWatM coupled model: A case study of Bhima Basin

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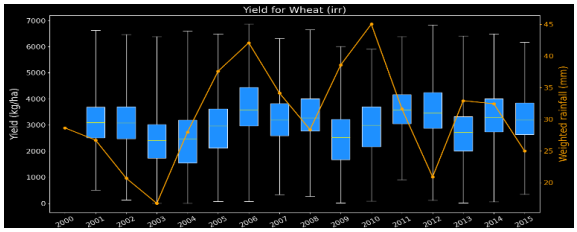
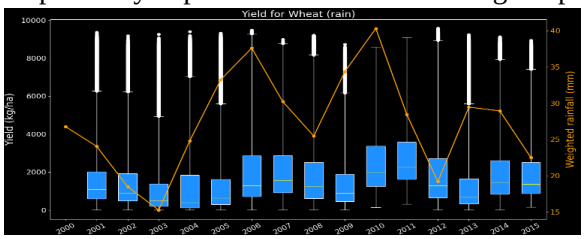
Introduction. The agro-hydrological coupling model can overcome the limitations of standalone hydrological or agricultural models and is an excellent tool for studying water scarcity and crop yields in climate extreme years. Agro-ecological model PyAEZ simplifies soil water balance, assuming constant soil moisture and neglecting runoff and deep percolation (Fischer et al., 2021), limiting its simulation performance. The Community Water Model (CWatM), with detailed soil moisture dynamics, calculates irrigation water availability. Therefore, the coupled PyAEZ-CWatM model can simulate water-limited crop yield under precise soil moisture conditions, which is crucial for understanding the water-crop relationship.

Methodology. CWatM simulates the complete daily soil water content in three soil layers, including infiltration, preferential bypass flow, soil moisture redistribution, and actual irrigation water, which PyAEZ does not consider. By transmitting the crop-specific ratios of actual to potential evapotranspiration, PyAEZ can receive more accurate hydrological fluxes. Subsequently, to ensure consistency in the time series of flux transmission, we standardized the crop calendars between PyAEZ and CWatM. PyAEZ calculates the crop cycle based on the crop calendar used by CWatM (i.e., the actual crop calendar). Finally, we enabled PyAEZ to accept multi-year climate data inputs and perform long-term continuous simulations instead of simulating single years individually.

Results. The box plots, respectively, show the interannual yield variations of wheat under irrigated and rainfed conditions, with the lines representing the weighted average of annual rainfall in the Bhima basin with the crop's area ratio. From the figures, we can draw the following main conclusions: First, PyAEZ-CWatM effectively captures the response of crop yields to water limitations under both irrigated and rainfed conditions. The interannual yield variations of wheat show a strong correlation with annual rainfall variations. In some extreme drought years, such as 2003 and 2012, the yields of wheat significantly decline. Second, compared to irrigated conditions, the interannual relative yield changes under rainfed conditions are more considerable in dry years. Third, for crops that grow across calendar years such as wheat, the yield primarily depends on the rainfall during the planting year.





Conclusions. This project completes the technical coupling from CWatM to PyAEZ to simulate water deficit yield. This is more than a one-way coupling, as much of the AEZ crop-growth methodology has now been embedded inside CWatM. The results indicate that PyAEZ-CWatM model shows great simulation performance under climate extremes. The dynamic coupling of PyAEZ with CWatM strengthens the water-crop interaction, significantly improving the crop model's accuracy in yield simulations, particularly in extreme drought years.

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The threat to biodiversity from bioenergy expansion in Europe

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Introduction. An expansion of bioenergy is deemed necessary to reach European climate targets. Forest biomass will continue to play an important role in the provision of European bioenergy, accompanied by a substantial increase in the use of purpose-grown energy crops. The amount of land needed to grow energy crops and trees in the future varies alongside possible socio-economic pathways, but the associated land-use changes are predicted to impact biodiversity. Thus, better predictions about how land-use changes relating to bioenergy production could impact biodiversity are important for energy, land-use and conservation planning.

Methodology. We focus on species in Europe that are associated with croplands or forests and are globally threatened according to the IUCN Red List. We use a species distribution modelling (SDM) framework (Jung, 2023) to investigate the suitability of bioenergy cropland and forestry throughout the range of each species. We then project how the suitability of land across Europe may change for threatened species in scenarios that project increases in bioenergy up to 2050, derived from the GLOBIOM model. The scenarios we test originate from the BIOCLIMA project and include: the EU "Fit for 55" climate-action pathway (FF55), a high biomass demand scenario relying on an increase in permanent cropland and forests (BIOM), a scenario with low biomass demand – from forests (LOW_LULUCF) – and a business-as-usual (REF) reference scenario (Visconti et al., 2024).

Results. The SDMs revealed divergent and species-specific responses to future expanding bioenergy cropland and forestry cover. For example, habitat suitability increased with bioenergy cropland and forestry availability for 53% and 39% of species, respectively. Furthermore, when considering all the species modelled, bioenergy cropland reduced habitat suitability less than other (i.e. annual) cropland. The future scenarios projected both increases and decreases in habitat suitability for threatened species within their contemporary ranges. In the BIOM and FF55 scenarios, there were more losses in suitable habitat than in the LOW_LULUCF and the REF scenarios in 2050. The LOW_LULUCF scenario projected the most gains in habitat suitability in 2050 of all the scenarios.

Conclusions. The results suggest that increases in biomass demand for bioenergy could impact habitat suitability for threatened species, with negative or positive effects depending on the species. Permanent bioenergy cropland could have more beneficial impacts for threatened species than other cropland. However, the responses of threatened species to intensive forestry expansion are likely more nuanced. Overall, scenarios relying on higher biomass demand are likely to have more detrimental effects on habitat suitability than those with lower biomass demand. Further work will expand the analyses to non-threatened species and investigate the links between different species groups (e.g. taxonomic groups, cropland- or forest-preferring species, species' traits) and responses to bioenergy expansion.

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What will control the forest's fate? including belowground nitrogen processes into the plantfate model to investigate possible limitations on aboveground productivity

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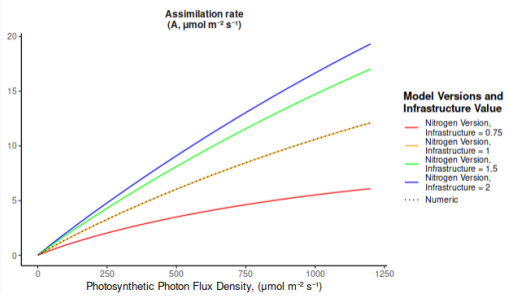
IIASA Mentors: Elisa Stefaniak (BEC, BNR) and Oskar Franklin (AFE, BNR)

Introduction.

As nitrogen limited environments boreal forests' response to climate change cannot be understood without considering the impact of nitrogen (N) on photosynthesis. To do this I extend the P-Hydro optimal stomatal control model (Joshi, 2022), which accounts for optimal water use in assimilation (A), to consider the effect of optimal N uptake on A. I examine two aspects of this process: (1) the biochemical effect of N on A through its effect on the A cycle limiting processes, which are limited by the parameters Jmax and Vcmax, and (2) the belowground infrastructure (OBJ) responsible for the N uptake (i.e. roots and symbionts like mycorrhizae).

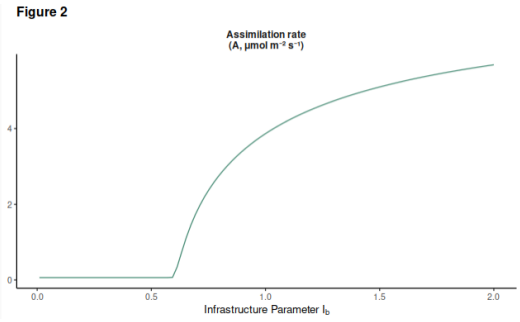
Figure 1



Methodology.

I extended the objective function (F) of P-Hydro to include the I_b and a relationship between needle N content and Jmax and Vcmax. Needle N content is assumed to be linearly related to Jmax and Vcmax (Fransson et al 2024) while I_b is assumed to reduce the cost of maintaining Jmax and Vcmax. This gives $F \sim A_j - \frac{b}{I_b}N$. The new formulation is then tested by running the extended P-Hydro model with different values of I_b and examining its effect on the optimal nitrogen content in the leaves and thus assimilation levels.

Figure 2



Results.

Assimilation increases with light availability and the size of the belowground infrastructure (I_b, Figure 1). However, the marginal benefit of I_b on assimilation also decreases with size (Figure 2).

Conclusions.

With this formulation I captured the saturating effect of investing in I_b on leaf nitrogen allocation and assimilation. I will then apply this new photosynthesis formulation to the PlantFATE whole tree and forest structure model to examine the difference and trade-offs in whole forest biomass distribution when assuming that assimilation is maximised in a leaf with respect to nitrogen and water use (these results will be presented in final report).

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Large regional differences in impacts of agriculture on arthropod biodiversity worldwide

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Introduction. Insects are reported to be in rapid decline worldwide, driven principally by changes in land use and climatic conditions. At the same time, insects provide many important services that benefit agriculture, including pollination and biological control of crop pests. Although changes in biodiversity have been demonstrated to vary largely between world regions [1], spatial heterogeneity in biodiversity responses is often neglected in global analyses. To better aid local conservation efforts, a better understanding of regional trends is needed. This project investigates regional differences in responses of arthropod biodiversity to agricultural land-use intensity. While historic land-use change is expected to explain much of this variation, my results suggest that positive biodiversity responses in Europe are driven by a small number of agricultural specialists, many of which are non-native species.

Methodology. Biodiversity responses were statistically estimated using generalised linear mixed models (GLMMs) fitted on arthropod records from the PREDICTS database, which contains worldwide, site-level species occurrence and abundance data and information on land use type and intensity. Data on non-native species in Europe were obtained from the European Alien Species Information Network. Due to the importance of many arthropods to agricultural ecosystem services, biodiversity responses were investigated for three intensities of agricultural land use. The analysed dataset contained 11,571 arthropod species across 7,054 sites worldwide.

Results. Worldwide, total arthropod abundance and species richness decline strongly with increasing agricultural land use intensity relative to a primary vegetation baseline: Total abundance is 35.6% lower [95% CI: 27.3–42.2%] and species richness is 30.9% lower [26.5–35.2%] in high intensity agriculture. Geographically, however, declines associated with higher agricultural land use intensity are primarily restricted to tropical regions. Changes in non-tropical regions are less negative and may even be reversed completely. In Europe, total abundance is 85.3% higher in minimal-intensity agriculture than in primary vegetation [49.8–125.7%] and species richness is 11.1% higher [1.3–20.8%]. Further analysis shows that the results for Europe are driven by a small number of agricultural specialists (ca. 3.6% of EU arthropods in the PREDICTS database) and that many of these are non-native species (35.6%). Conversely, non-native species comprise 18.7% of species that are specialists in primary vegetation.

Conclusions. This project highlights stark regional differences in biodiversity responses of arthropods to land use. Although previous studies have found notable differences in responses between tropical and non-tropical regions, such differences are typically discussed qualitatively, positing differences in historical land-use change and sensitivity of species [1]. Here, I have shown that the positive responses of arthropods in Europe to increasing agricultural intensity are driven by a small subset of abundant and largely non-native agricultural specialists. These results suggest that although biodiversity responses to changes in land use may not be negative everywhere, positive changes may be driven by a small number of opportunistic species that mask declines in the majority of species.

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Exploring the implications to area of habitat from global mining land use change

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Introduction.

Land use change is predicted to drive habitat conversion and loss of terrestrial biodiversity. Growing demand for battery metals will amplify this, driving global expansion in mining activities and associated impacts into more biodiverse regions. However, mines are generally not included in global land cover maps, and are typically mis-classified as various types of natural habitat, leading to potential underestimation of land-use impacts on biodiversity in large-scale assessments. Therefore, the overarching aim of this study is to assess the impacts of mine footprints on the available habitat of range restricted mammals and herptile species globally.

Methodology.

Mining areas (Maus et al. 2022; Tang and Werner. 2023) were overlayed with habitat classification maps (Jung et al. 2020) to determine the habitat types that occur within mine footprints of two mining land use datasets. The Maus et al. (2022) dataset was selected, to provide a more comprehensive estimate of mining impacts on species habitat, and overlayed with area of habitat maps (Hanson, 2024; Lumbierres et al. 2022) of mammal and herptile species, which had a known extent of occurrence (EOO) of <50,000 km^2, a threshold aligning with the IFC's Guidance Note 6 for biodiversity conservation and sustainable management of natural resources.

Results.

Analysis of habitat classification within mining polygons (Figure 1) revealed that >75.8% percent of mining areas were classified as a natural land cover class, with a maximum of 24.2% classified as anthropogenic, while not identified specifically as mining. 7,272 species were identified to meet the EOO criteria, with 1,694 selected that had habitat overlapping with mining areas. Across all taxonomic groups analysed, the mean proportion of habitat removed was 0.6% (CI: 0.4-0.7%), with 13 species having >10% of their habitat removed. Across IUCN Red List Categories, critically endangered species were found to have the highest average proportion of habitat removed at 3.5% (CI: 0.7-6.3%).

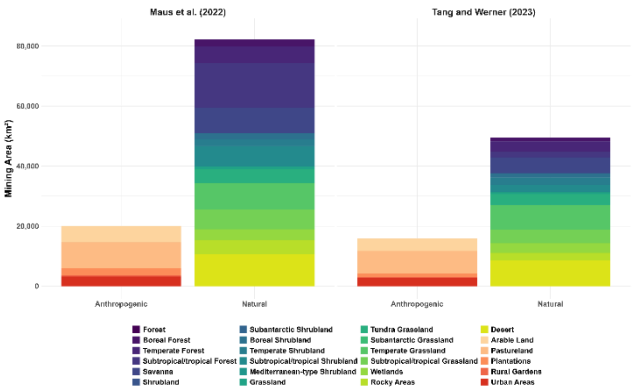

Figure 3. Habitat classification within mining polygons (Maus et al. (2022) left; Tang and Werner (2023) right), as classified by Jung et al. (2020).

Conclusions.

Current habitat classification maps fail to incorporate mining land use, overestimating the available habitat for terrestrial species. This analysis has showed the importance of including mining in biodiversity assessments and identified species that may require additional monitoring and potentially improved conservation efforts due to their exposure to mining threats.

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Spatial analysis of carbon dioxide removal implications focusing on biodiversity and land tenure

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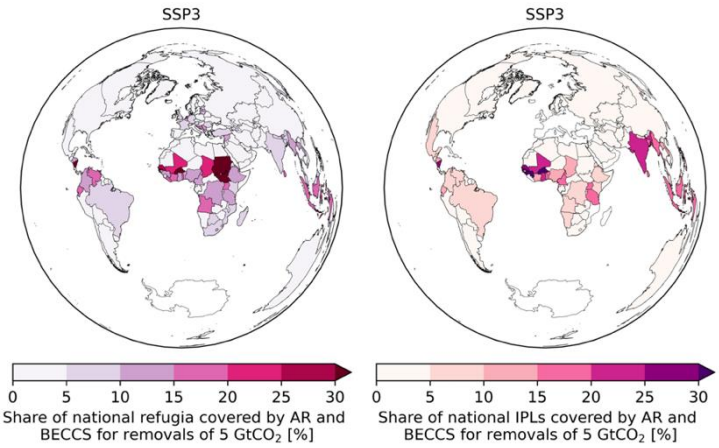
Introduction. Due to the ongoing delay in decisive emission reductions, and as more and more countries pledge net-zero CO_2 targets, carbon dioxide removal (CDR) is gaining relevance and attention. Currently, ambitious mitigation pathways, produced by integrated assessment models, primarily rely on removals via bioenergy with carbon capture and storage (BECCS) and afforestation, which require substantial amounts of land to meet scenario-implied removal scales. This land demand could have consequences for biodiversity and land managed or controlled by Indigenous Peoples, limiting the sustainable scaling potential. By combining spatial data on the climatic suitability of a multi-taxa species ensemble, land tenure data, and data from two models on bioenergy croplands for BECCS and afforestation, we can evaluate and compare the distribution of CDR land allocation within biodiversity refugia and Indigenous Peoples Lands.

Methodology. To assess land-related impacts of CDR on remaining biodiversity refugia at 1.5 °C and Indigenous Peoples Lands for a given removal level, we considered six existing datasets, namely (i.) a map of biodiversity refugia; (ii.) a map Indigenous Peoples Lands; (iii.-iv.) maps of afforestation and BECCS croplands across various scenarios and derived from the models GLOBIOM and AIM; (v.) removal timeseries for afforestation and BECCS for the same scenarios and model families as the land use data; and (vi.) a map of country-level administrative boundaries. We combined the removal data and land use data to approximate land demand for a given removal via afforestation and BECCS. Next, we overlaid the CDR land demand maps with the maps showing biodiversity refugia and Indigenous Peoples Lands. Ultimately, we compared how CDR's land demand within biodiversity refugia and Indigenous Peoples Lands varies across SSPs and models.

Results. We find that substantial amounts of land within remaining biodiversity refugia and Indigenous Peoples Lands are allocated for the deployment of afforestation and bioenergy croplands for BECCS. Countries of the Global South are especially affected – in some cases, more than 30% of national refugia or Indigenous Peoples Lands are allocated for CDR deployment, as shown in the figure, based on SSP3 in GLOBIOM. We also find that the land intensity differs across SSPs, despite the same removal level, with SSP3 showing higher land demand for CDR than SSP2 or SSP1. The results rely on preliminary input data and may change throughout the ongoing analysis.



Conclusions. While CDR deployment may be optimal in temperate and tropical zones in countries of the Global South regarding carbon uptake potential, deployment costs, and albedo change, it raises vital questions regarding common but differentiated responsibilities to act on global warming – especially when CDR is expected to come with negative side effects. While BECCS is commonly not considered beneficial for biodiversity, afforestation may benefit habitat conservation if native and diverse tree species are used and adjusted to baseline land cover. Potential CDR deployment within lands managed or controlled by Indigenous Peoples is contingent on their meaningful engagement and safeguarding of Indigenous Peoples' self-determination, rights, and futures.

Integrating fed aquaculture into GLOBIOM to account for growing global feed resource competition

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Introduction. Globally, over 3.2 billion people rely on aquatic foods or blue foods for nutrition and food security, and this number is expected to increase as population increases and dietary preferences evolve, but also through efforts to reduce the environmental impacts of livestock production. The sustainability of this sector will depend not only on the development of aquaculture to alleviate pressures on marine resources, but also on the environmental impacts of aquaculture systems, including interactions with the land resource to provide plant-based feed to aquaculture systems. To date, integrated food system modelling frameworks have been instrumental in investigating multidimensional sustainability challenges but lack full integration of the marine, aquaculture and agricultural sectors. In this study, we develop and apply the fish module of the GLOBIOM model (Havlik et al. 2014) to explore how multi-sector pressures change under different aquaculture growth scenarios.

Methodology. The fish module in GLOBIOM is incorporated similarly to already present terrestrial commodities and is linked to terrestrial production via demand for crops as feed for finfish aquaculture. We used a nutrient mass-balance approach to calculate nitrogenous (N) waste from aquaculture farms to use as inputs into the GLOBIOM fish module. We collated feed conversion efficiency data for aquaculture species groups, N content and N digestibility data for aquaculture feeds from various data sources. We then explored how nitrogenous waste output changes under different aquaculture growth scenarios.

Results. *Preliminary* results estimate lower nitrogenous waste per unit of salmon produced by 2050. A case study of Norway, a leading Atlantic salmon producer, predicts that the soy requirement to produce 1,000 tonnes of salmon in 2050 will be 2.3 times higher than in 2000, while the corresponding nitrogenous waste from on-farm production is calculated to be 25% less than in the year 2000 (NOTE: this estimate doesn't currently include nitrogen waste/runoff from crop production to make the aquaculture feeds).

Conclusions. The study contributes to the development of the fish module in the GLOBIOM model, in order to better comprehend the future sustainability of blue foods and land-sea connections. We will examine the greenhouse gas emissions, spatial use and water consumption associated with aquaculture, and the broader impacts of the agricultural sector to conduct a multi-sector analysis of trade-offs associated with different aquaculture growth scenarios.

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Modelling Ontario Forest and mass timber in GLOBIOM-Forest

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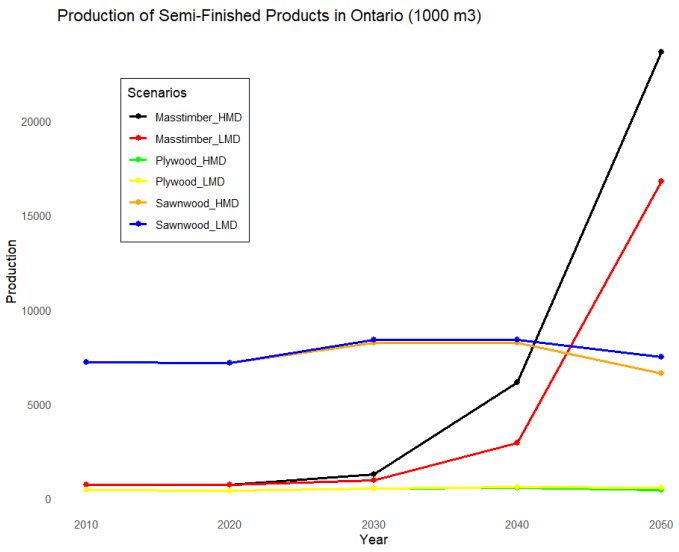
Introduction. As the global warming is intensifying, decarbonization has been given high priority in the development of most industries. Mass timber, a novel construction material made from sawlogs through pre-fabrication has a high potential in reducing carbon emission and construction time in the construction sector compared to concrete and steel. Moreover, mass timber has many advantages over conventional light wood frame due to better fire resistance, higher strength, and allowing the use of low-quality wood as feedstock. However, the development of the mass timber industry in Ontario is hindered by the limited market size and the imbalance between supply and demand. To investigate the effects of increased mass timber demand on market price, land use, international trade, and carbon benefits, we run GLOBIOM-Forest under different RCP, SSP, and alternative scenarios of mass timber use to inform policy making.

Methodology. This study is conducted in GLOBIOM-Forest, which is a simplified version of GLOBIOM, with more detailed forest sector and one product representing the agricultural sector (Lauri et al., 2021; Havlík et al., 2011). Ontario is added to the model as an independent region based on the geographic boundaries, and thus directly interacting with the rest of the world. We added mass timber as a new semi-finished product that consumes coniferous sawlogs and being a part of construction materials. Moreover, we calculated the bilateral trade data of forest products in Ontario and updated the transportation costs in the same region according to the distance between each grid and the closeted sawmill. In addition to the existing scenario sets, we introduced a new category of the mass timber demand in the future and increased the spatial resolution of the model in Ontario and the rest of Canada to 50x50 km for more accurate results.

Results. As the price of mass timber is higher than sawnwood and plywood that both consume coniferous sawlogs, the production of mass timber would crowd them out. At low mass timber demand (LMD) scenarios (exogenous demand shifter), the price and trade of mass timber would not be affected as it is more economical to produce less sawnwood and plywood to satisfy the mass timber demand. However, under high demand of mass timber (HMD), the price of mass timber would increase substantially, and Ontario starts to import mass timber from other regions. Price of sawnwood and plywood would increase under both LMD and HMD.



Conclusions. There is no doubt that future demand of mass timber will be increasing in Ontario. Due to the high value of mass timber, the growth of the demand would affect the production of competing products such as sawnwood and plywood, bringing challenges for industries utilizing them. Under a certain level of demand, the market can hold the price of mass timber thus saving costs for developers. The Ontario forest could satisfy substantial demand of mass timber without importing from other countries, suggesting a high potential of the development of this industry.

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Evaluating climate change impacts on single and double cropping systems in Brazil

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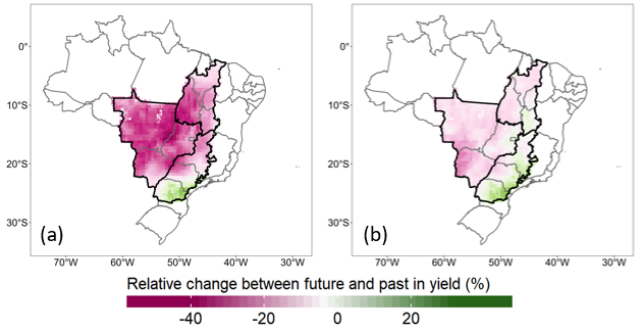
Introduction. Adapting agricultural practices to climate change has become a crucial focus for ensuring global food security. One promising strategy is the adjustment of crop calendars, which has shown potential in boosting yields in single cropping systems by aligning planting and harvest times with favorable climate conditions. While single cropping systems have been extensively studied, research on both the benefits and specific challenges faced in double cropping systems under these changing conditions remains underexplored due to the complexity of crop interactions and the limited availability of global data. As a major breadbasket of the world, Brazil's soybean-maize double cropping system provides an insightful case study to explore these impacts in detail. The findings can contribute to the sustainability and resilience of double cropping for food production in a changing climate both regionally and as a prototype for global studies.

Methodology. We collected key data on soybean and maize, including gridded suitable planting windows (Abrahao and Costa, 2018), harvested areas, cultivars, and yields. Using 0.5-degree climate data, we estimated the actual growing seasons based on potential heat units and calculated climate features such as precipitation and moisture deficit days during the growing season and reproductive phase. These analyses were conducted for both past conditions and future scenarios, including two Shared Socioeconomic Pathways (SSP126 and SSP585), to understand how temperature and precipitation shifts may affect crop growing seasons. Finally, we employed a crop model emulator CROMES (Folberth et al., 2024), which integrates the EPIC-IIASA model and the CatBoost algorithm, to simulate crop yields and determine the impacts of climate change on the yield variability within double cropping systems.

Results and Conclusions. The crop model emulator effectively demonstrates how varying climatic conditions and agricultural practices interact to influence both past and future soybean productivity. Using past soybean data as a baseline, both double and single soybean systems exhibit similar patterns in climate indicators and yield changes over time. However, yields under SSP585 are projected to decline more significantly compared to SSP126, particularly in major double cropping areas (Figure 1). Figure 1a shows yield relative changes for double cropping soybean with a medium maturity cultivar planted on a medium sowing date under SSP585 between 2070-2100, while Figure 1b shows results for single soybean under the same scenario. The results indicate that double soybean cropping is likely to be more heavily impacted than single soybean. This can in addition also affect the subsequent maize crop's planting window and yield.



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Development of the harvested wood product model to support the "New Bauhaus" concept in South Korea

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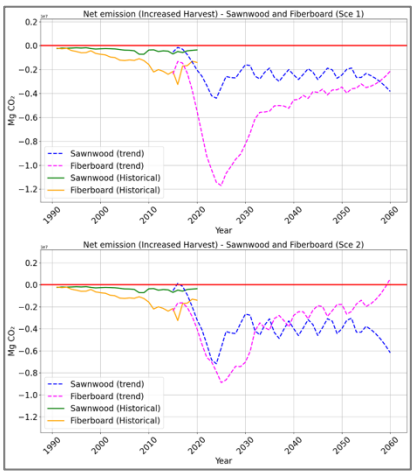
Introduction. Harvested wood products (HWPs) are one of means for coping with climate crisis by international community. Long-lived HWPs can significantly contribute to carbon storage, although harvesting wood decreases the carbon pool within forests. Therefore, sustainable wood usage is essential for enhancing carbon stocks with sustainable forest management considering forest environment. In this study, we estimated the harvested wood volumes, focusing on their application and carbon stocks and carbon sink in semi-finished products such as sawnwood and fiberboard, with an emphasis on their use in construction. Additionally, we identified optimal spatial locations for wooden buildings in South Korea.

Methodology. The study used results from Korean dynamic forest growth model, which incorporates the effects of climate change and forest management. The model provides estimates of harvested wood volumes, categorized into three classes based on log qualities: construction, furniture, and packaging. Construction logs were further divided into structural, temporary and interior materials, each with different half-lives. In addition, we identified wood usage pattern and ratio of domestic timber use to establish baseline scenarios about wood usage with two scenarios to enhance usage of sawnwood for construction. Finally, building characteristic and population scenarios were used to identify spatial locations for wooden buildings in South Korea.



Results. The wood usage ratio for domestic timber was determined through a national survey, which identified the following split: sawnwood for construction (20%), furniture (0.2%), and packaging (62%); and fiberboard for construction (80%), furniture (98.8%), and packaging (38%). Net emissions from harvest varied depending on the scenarios analyzed. Notably, Scenario 2 (high ratio of sawnwood) demonstrated that HWPs play a significant role in sequestering carbon for longer periods compared to Scenario 1 (mid ratio of sawnwood). South Korea has set a target to utilize wood products to achieve a carbon sequestration of 2.2 $MtCO_2$ by 2050. Our projections suggest that carbon sinks could reach approximately 5.10 $MtCO_2$ under Scenario 1 and 5.13 $MtCO_2$ under Scenario 2, assuming total usage of domestic wood. If the analysis assumes a 50% reliance on imported wood, the carbon sink values could be approximately 2.55 $MtCO_2$ under Scenario 1 and 2.56 $MtCO_2$ under Scenario 2.

Conclusions. The carbon sink potential of harvested wood products (HWPs) is closely tied to both their usage and forest management practices. To meet carbon reduction targets, it is essential to actively promote the use of wood products, particularly those that contribute to long-lived HWPs. Additionally, identifying suitable locations for wooden building activities can support the goal of carbon neutrality while also fostering market recovery in underpopulated areas of South Korea. Furthermore, it could be used for empirical data for trading the wood products between South Korea and other countries.

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Assessing the climate effects of management options in drained northern peatlands: long-term simulations with the ForSAFE-Peat model

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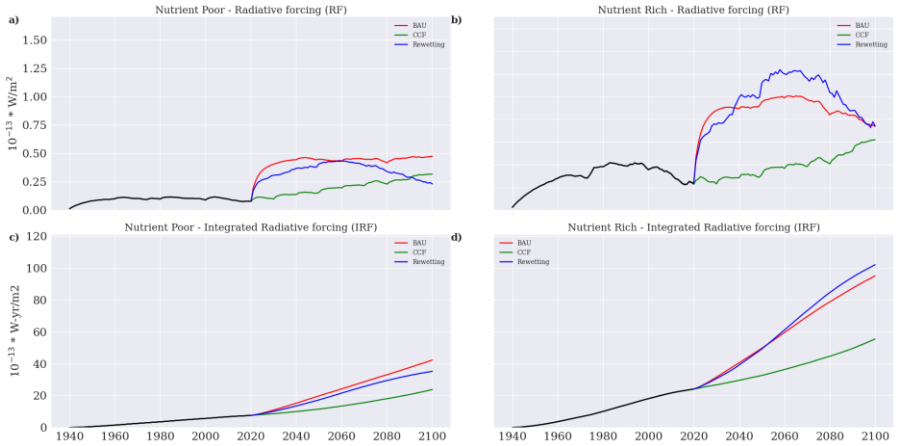
Introduction. Peatlands have been extensively drained for conventional forestry in northern Europe. While drainage reduces methane (CH_4) emissions, it increases carbon dioxide (CO_2) release, often converting these soils into net carbon sources. Nutrient-rich peatlands can also experience elevated nitrous oxide (N_2O) emissions. Continuous cover forestry (CCF) and ecological restoration through rewetting have been proposed as strategies to mitigate these effects on climate, though long-term data on greenhouse gas (GHG) fluxes in these systems remain limited. In this study, we employed the ForSAFE-Peat model to simulate GHG dynamics under conventional forestry (BAU), CCF, and rewetting across contrasting nutrient conditions**.**

Methodology. Simulations were conducted across contrasting nutrient levels (C/N ratios of 45 and 25) over 160 years. A conventionally managed, drained, and afforested peatland was modeled under historical climate conditions (1940-2020). Three management scenarios (BAU, CCF, and rewetting) were compared under future climate conditions (2020-2100). The fate of harvested wood products was incorporated into the GHG balance. Model outcomes were validated against field data on net ecosystem exchange, methane emissions, nitrous oxide emissions, and groundwater levels. Radiative forcing (RF; W/m^2) and integrated radiative forcing (IRF; $W\text{-}yr/m^2$) were used to assess the effect on climate of different management strategies.

Results. Previously drained peatlands contributed to atmospheric warming under all management strategies and nutrient conditions, as reflected by positive RF and IRF values. However, CCF consistently outperformed BAU across different nutrient levels and evaluation metrics. The climate impact of rewetting was nutrient-dependent; by 2100, rewetting under nutrient-poor conditions results in a 50% lower RF compared to BAU, while under nutrient-rich conditions, rewetting yields a similar RF to BAU. Rewetting's climate benefits generally improved over time, contrasting with CCF's declining efficacy. Despite rewetting's lower final RF in nutrient-poor scenarios compared to CCF, IRF analysis highlighted CCF's superior effect on climate.



Conclusion. CCF appears to be the most promising strategy to mitigate the effect on climate of currently drained afforested peatlands in northern latitudes over the next few decades. While CCF may face long-term limitations due to reduced nitrogen mineralization compared to BAU, it offers more immediate climate benefits. Although rewetting may eventually result in a net cooling effect, as indicated by simulation trends, it requires over 60 years to materialize, limiting its feasibility as a rapid climate change mitigation measure for the current century.

Advancing Systems Analysis (ASA)

Tele-coupled biodiversity loss from a perspective of input-output analysis

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Introduction. The post-2020 biodiversity framework targets call for a significant reduction in the number of endangered species. Although climate change will increase the extinction risk for a considerable number of species, minimizing additional pressures from human activities is crucial for maintaining ecosystem function. In today's increasingly globalized economy, international trade chains accelerate the degradation of habitats and biodiversity loss far from where resources and services are finally consumed. Measuring trade-related, telecoupled biodiversity loss holds profound importance in advancing the collective pursuit of global conservation goals.

Methodology. An Environmental-Extended, Multi-Regional Input-Output (MRIO) Model is used to estimate tele-coupled biodiversity loss. First, sectors of the MRIO are linked with specific biodiversity threats based on the IUCN red list. Second, the species distribution range is used to match the MRIO across countries of concern, by calculating a species threat coefficient for each region and sector. Third, MRIO analysis is used to estimate tele-coupled biodiversity loss. Here, we take all red-listed mammals, amphibians, reptiles and plants into consideration (n=19252).

Results. Due to the interconnectedness of global economic activities, telecoupling relationships cause 25.64%–29.22% of biodiversity threats. Brazil, Australia, the United States, and China have a higher number of endangered species, and also contribute significantly to local biodiversity threats. United States, China, Japan, and European countries cause greater biodiversity threats through imports compared to other countries. In contrast, the threats associated with exports are more significant in Madagascar and Australia. The 198 countries are divided into four groups according to the World Bank's income classifications. On average, middle-income countries have higher local losses, high-income countries have higher import-related losses, and low-income countries have higher export-related losses.

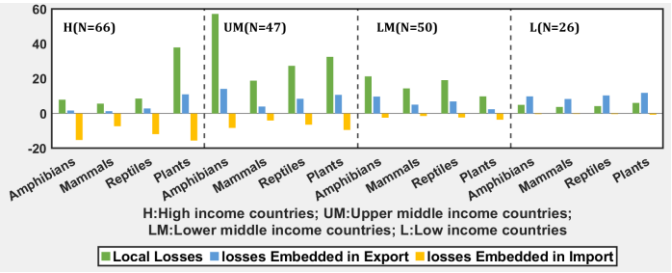

Fig1. The average biodiversity loss across the four categories of countries(N is the number of countries).

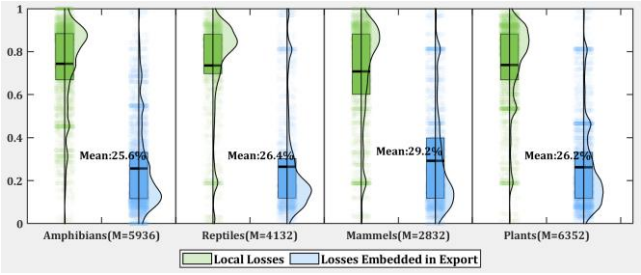

Fig2. Biodiversity threats for each species both locally and embedded in trade (M is the number of species).

Conclusions. International trade imposes telecoupling species threats and leads to biodiversity loss. What requires further attention is that some species face higher export-related threats. High-income countries should reduce biodiversity loss through their import consumption, while low-income countries, where export-related impacts are greater than local parts, should receive support for biodiversity conservation policies, such as the establishment of protected areas.

The fiscal benefits and trade-offs of adaptation infrastructure investment

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Introduction. Climate change leads to rising frequency and intensity of extreme weather events. These hazards present significant threats to economies at a systemic level (Stern, 2006). They can severely damage infrastructure and cause adverse effects on fiscal stability (Mechler *et al.*, 2010). Investing in climate-resilient infrastructure is critical in reducing the impacts of climate risks. However, the adaptation finance gap remains large, estimating up to 366 billion USD per year (UNEP, 2023). Many countries also have limited fiscal capacity, making optimal adaptation (Hall *et al.*, 2012) a priority to balance the benefits of adaptation and financing costs. Building on previous works, this research aims to quantify the fiscal benefits of infrastructure adaptation across countries and hazards and estimating their optimal levels of adaptation.

Methodology. The research methodology consists of four blocks. First, countries are selected (Jamaica, Thailand, and Rwanda as first case studies) based on their macroeconomic characteristics, geography, and frequency of exposure to natural disaster risks. Second, natural hazard scenarios are constructed using the Global Infrastructure Risk Model and Resilience Index to estimate the climate impacts on infrastructure assets. Third, infrastructure investment financing strategies are designed to evaluate their trade-offs across the options. Fourth, these profiles and sets of scenarios are introduced as inputs into the International Monetary Fund's macroeconomic model to estimate the fiscal impacts of natural disasters on the macroeconomy.

Results. Using Jamaica as the first case study, three types of investment pathways were introduced: (1) constant annual investment (e.g., 0.1% of GDP for the first five years, (2) increasing annual investment (e.g., 0.1% in year 1 to 0.5% in year 5), and (3) decreasing annual investment (e.g., 0.5% in year 1 to 0.1% in year 5). The initial results show that when an external shock similar to a 1-10 tropical cyclone wind was introduced in year 6, the benefits of investing in adaptation infrastructure in terms of GDP loss reduction can range from 1.30% (0.1% annually) to 9.84% (0.6-1.0% incremental annual investment) when compared to no investment. Similarly, for a 1-100 tropical cyclone wind, the benefits increase, ranging from 1.43% to 11.0%.

Conclusions. While the research is in its very preliminary stage, it demonstrates that investing in resilient infrastructure can reduce the impacts of GDP loss. The next steps include (1) demonstrate the trade-offs between investment benefits and financing costs to estimate the proportionate level of adaptation investment, (2) compare the benefits across financing and hazard (intensity) options, (3) analyse other macroeconomic-fiscal indicators beyond GDP loss, (4) modify the shock timing, and (5) include multiple countries for a cross-country analysis. The research implications will better inform fiscal-constrained governments on the relationship between the economic benefits of adaptation and the scale of investment required for a more climate-resilient economy.

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Evaluating flood risk for resilience improving of urban multi-modal transportation networks

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Introduction. Urban multi-modal transportation networks (e.g., interconnected metro, tram) are vital for socio-economic development and citizens' well-being. However, susceptibility to natural hazards, especially floods frequently occurring due to climate change, requires further research on how floods impact urban transportations, aiming to mitigate infrastructure malfunctions and societal disruptions. An in-depth exploration of urban transportation resilience must consider the direct aftermath of the event and its reconstruction period. Disruptions due to floods not only cause socio-economic losses during the event and directly after, but also amplify losses with a prolonged recovery period. To bridge this gap, our study scrutinizes the resilience of urban multi-modal transportation under floods, simulating the damage and recovery of stations affected by floods with different return periods.

Methodology. To achieve the research goals, focusing Amsterdam's subway and tram network, the initial step is to construct a multi-modal transportation network. We obtain and preprocess all geospatial data of subway and tram stations and tracks from OpenStreetMap. The network is simplified, and transfer edges are added at transfer stations to create a fully connected undirected network. The starting and ending stations of each line are paired to form OD pairs for simulation. Afterwards, we simulate urban multi-modal transportation under flooding. Flood scenario data from Klimaateffectatlas is combined with the transportation network model to analyse system risks using travel time, distance, and station usage frequency under different flood return periods. The third and last step simulates the recovery process. Composite weights for each station are generated based on network topology and station usage frequency. Stations are restored one by one according to weight ranking to test OD pair connectivity, identifying key stations that enhance network resilience during recovery.

Preliminary Results. We explored Amsterdam's subway and tram network, creating a fully connected network with 291 stations, 409 edges, and 524 OD pairs. Flood return periods of 100, 1,000, 10,000, and 1,000,000 years were considered. Without floods, all OD pairs are reachable with an average travel time of 70.85 minutes. When analysing the relationship between the number of affected stations and OD pairs, we find that they are positively correlated. The more stations are affected, the more OD pairs are interrupted, indicating that the system flood risk in this scenario is greater. However, the average travel time of the network has no obvious relationship with the two indicators above, because not all routes in the remaining accessible OD pairs will increase their travel time. In some cases, even the travel time of all remaining OD routes is consistent with normal conditions, so that the average travel time is even reduced. In addition, when analysing the changes in key stations from the perspective of station usage frequency, it is found that if there are no transfer routes near the failed station and its previous and subsequent stations, the usage frequencies of the three consecutive stations will become zero, indicating that the OD pairs passing through these stations are not accessible, which shows the key role of the failed station in the system.

Conclusions. The above analysis shows that combining the flood return period to analyse the risk of urban multimodal transportation networks can more accurately identify the relationship between the impact of stations and OD on accessibility. Besides, this research framework can obtain the changed rules of critical elements, thereby guiding the strategic choice of priority reconstruction during the recovery period. In the next step, we will consider the OD weight, and then combine the topological structure and system function to simulate the priority recovery strategy of critical stations under the composite weight and explore effective measures to improve the resilience of urban multimodal transportation.

Lessons from COVID-19 regarding resilience principles in social-ecological systems: An exemplary participatory study

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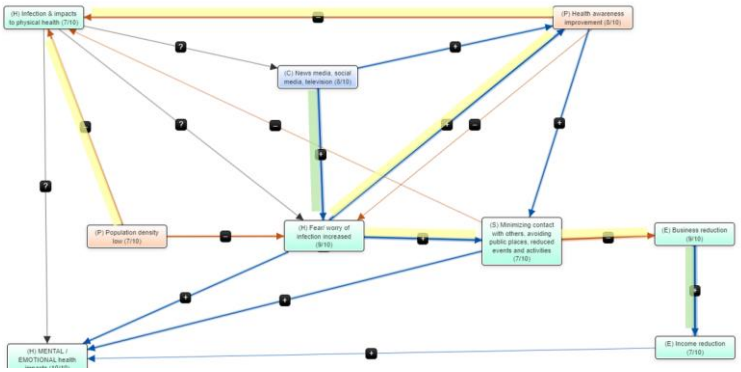
Introduction. The complex global impacts of COVID-19, resulting from direct and indirect social and the biophysical interactions, provide a rare opportunity to explore how such interactions affect societal resilience, i.e., the capacity to cope and maintain its defining characteristics. We examine whether generalised principles, which have been associated with social-ecological systems (SE-S) resilience, such as diversity, redundancy, and social capital, contributed to societies' capacity to endure and manage the pandemic. This project developed the methodological foundation for a comparative case-study analysis in collaboration with research sites affiliated with networks for long term SE research (LTSER).

Methodology. In collaboration with Changhua LTSER, Taiwan, we collected available regional information for indicators of COVID-19 (e.g., excess mortality, bankruptcy, school days lost), and background socio-economical and spatial-environmental characteristics (e.g., demographics and healthcare capacity). Additionally, we interviewed diverse local stakeholders (N=10) using Mental Modeler software to build causal loop diagrams reflecting their mental models of COVID-19 impacts, contributing factors, and relationships between them. Nodes were clustered in an inductive iterative process, and the maps were aggregated to produce one fuzzy cognitive map (FCM) which indicated participants' level of agreement regarding nodes and causal links between them. The FCM and the collected data were shared with the stakeholders in a group-meeting to facilitate discussion and validate the FCM. We are currently conducting a thematic analysis of the meeting outputs to adjust the FCM and to induce narratives that reflect the principles of SE-S resilience.

Results. (A) The aggregated FCM includes 17 nodes and 42 links (density 1.544, 2.47 link/node): 9 nodes of high agreement level (7-10/10, connected by 18 links) and 8 nodes of medium agreement level (4-10/10, connected by 24 links). (B) 5/10 stakeholders included "mental health - fear" among "top 3 main impacts of COVID-19 on the region"; 4/10 stakeholders included "negative impact on tourism". (C) Driving nodes are 'low population density', 'close community', and 'media'. Receiving node is "mental/emotional health". The most central node is 'fear', followed by "minimising contact, avoiding public places, reduced events/activities".

Conclusions. This study aims to provide a nuanced understanding of societal resilience factors to guide future research and governance. The central role of "close community" and "low population density" as well as the prominence of "media", "fear", and "minimising contact", reflect the resilience principles of social capital and connectivity. The impact on tourism highlights the need for diversity of business sectors.



FCM of LTSER Changhua, Taiwan, depicting the nodes of high agreement level (orange = positive; blue = contributing factor), and causal links of high (green highlight), medium (yellow highlight), and low agreement.

Plausibilistic climate impact storylines framework: Risk priorities in an uncertain future

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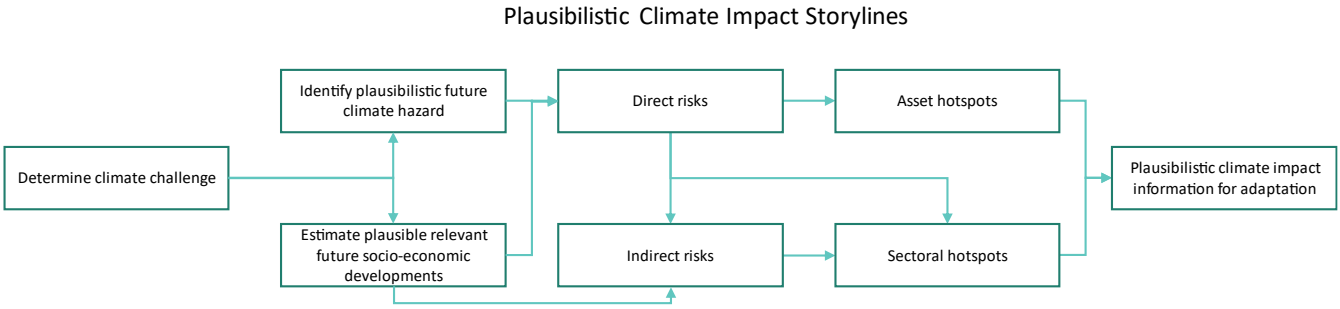
Introduction. In a changing climate, flood risk is a key risk throughout Europe (IPCC, 2022; EEA, 2024), necessitating regional actions. However, action is complicated by uncertainties in climate projections and socio-economic developments. Meanwhile, limited resources are available, and regions cannot adapt to all possible futures. Therefore, we propose a framework for developing Plausibilistic Climate Impact Storylines to aid priority setting in adaptation planning by providing a set of plausible future scenarios for probabilistic hazards and their direct and indirect impacts. The framework bridges full probabilistic and event storyline methods by exploring multiple facets of uncertainty while still estimating the likelihood of disasters in a plausible future. The approach is illustrated using a real-world flood case in the Lielupe basin in the Baltic states.

Methodology. To uncover the adaptation priorities for the future, we first determine the climate challenge for the region, and then plausibilistic climate futures are combined with plausible socio-economic developments for the hazard and sectors of interest. The storylines are used to obtain both direct and indirect risks across the collection of futures. To thoroughly explore future hazard changes, plausibilistic climate storylines are created using the scenario clustering approach of Buskop et al. (2024). Meanwhile, plausible socio-economic trends from SSP projections are used to adjust the exposed asset values and sector interactions in economic input-output tables. Lastly, sectors and regions are grouped into hotspots highlighting priorities.



Results. For the Lielupe basin, plausibilistic hazards can change both the location and the intensities of priority hotspots, while plausible socio-economic changes mainly alter the intensities of hotspots but do not create new priority locations. We also find that sectoral dependencies and stresses during disasters change in SSP scenarios. The impact of domestic supply interruptions becomes smaller when more goods are being imported, while demand change in the construction sector causes significantly higher stresses on local producers and imports in scenarios of decreased domestic manufacturing and increased property values.

Conclusions. Our study shows that plausibilistic storylines uncover varying direct and indirect risk information, allowing for a broad view of priority sectors and regions across the uncertainty space. The framework can be applied to different regions and climate challenges since open-access global datasets are used to create the storylines and can be extended to other hazards and risk mechanisms. This study advances climate risk literature by providing a framework to create quantitative plausibilistic scenarios that can be used in the adaptation planning process.

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Exploitation of optical and radar data for improved mapping of diverse cropping patterns of paddy and upland fields in South China

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Introduction. Due to favourable hydro-thermal conditions, there are remarkably diverse intra-annual cropping patterns of paddy and upland fields (CPPUs) in South China, e.g., single/double-cropping paddy fields and paddy-upland rotations. However, due to urbanization, industrialization, and climate change, the cultivation areas of different CPPUs in South China have undergone drastic changes over the past few decades. These changes in CPPUs may have potential impacts on food security and the ecological environment, both within China and beyond. To address these knowledge gaps, information on the accurate spatial distribution over time of CPPUs is essential. This study aims to develop a new method to integrate spaceborne Sentinel-2 (S2) multispectral images and Sentinel-1 (S1) synthetic aperture radar (SAR) images to accurately map CPPUs in South China, where the occurrence of cloudy and rainy weather is frequent.

Methodology. We first derived time-series vegetation index data and backscatter data using S1 and S2 satellite images, respectively, to analyze and obtain the critical annual time-series phenological features needed to identify different CPPUs. Then, the optimal multispectral- and SAR-based classification features were individually input into a Gaussian Mixture Model (GMM) to derive the probability that a pixel belongs to a certain class. Subsequently, we developed a method for dynamically assigning weights to S1-based and S2-based classification probabilities based on S2 optical data availability. Finally, the classification results from the different satellite data sources were fused in a weighted manner, using the field survey samples to validate the final CPPUs classification results.

Results. We found that the key classification features of different CPPUs were highly related to the flooding signals from the satellite data during the rice transplanting period. Specifically, the number of transplanting periods in a year as well as the specific time period can be used to accurately classify different CPPUs. Additionally, the classification based on multi-source data fusion outperformed the models that used only S2 optical data or S1 radar data (as is typically done now). Furthermore, the direct transfer of the proposed method to another test area also yielded improved classification results.

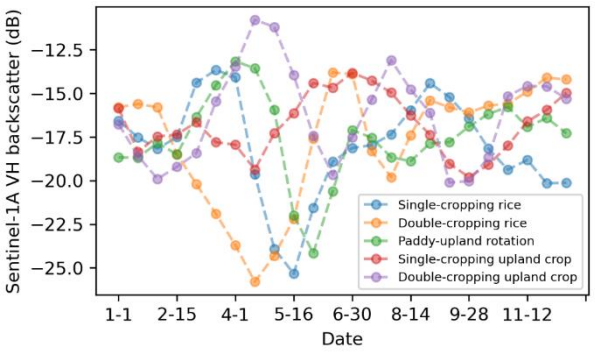

Fig. 1. *Time-series radar backscatter curves.*

Conclusions. This study reveals that the fusion of optical and radar data can effectively tackle the issue of missing optical images in cloudy and rainy-weather regions. The proposed method that integrates GMM and dynamic weighted fusion enables fast and accurate mapping of diverse cropping patterns at large scales in comparison to existing methods. The map of CPPUs derived from this research can provide critical information for supporting agricultural decisions regarding water management and adjustments to crop planting.

Defining carbon responsibility: A review of emission allocation methods

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Introduction. The problem of carbon dioxide emissions remains one of the major global warming issues today. One of the cornerstone questions of this problem is who should pay for existing emissions. Emitting entities are increasingly held liable for their emissions, but there is no unique way of determining what emissions an entity should be responsible for, nor what these entities are (companies, consumers, the whole countries, etc.). There are many different approaches by which these emissions can be allocated to agents and "fairness" rules that are supported by these approaches. In the literature, the most popular type of approaches are indicator-based, which use some economic variable as an indicator for attributing emissions. Even though indicator-based approaches have been developing over the past 20 years, there is still no structural approach to their definition and study.

Methodology. The paper defines indicator-based allocation rules (IBARs) of historical emissions as a mathematical object. We show that IBAR can be represented as a chores problem with weighted agents. In this setting, the formulation of IBAR boils down to a choice of three things: the indicator (as the weights of the agents), the disutility functions of the agents and the distribution rule. To select an indicator, we propose a list of axioms to ensure that the indicator does not distort information about the contribution of each agent and formulate 'beneficiary pay' and 'ability to pay' principles for the problem of allocating historical emissions.

Results. We claim that the main indicator-based allocation rules in the literature can be represented as an allocation rule in chores problem with homogeneous disutility functions of the agents and different weights (indicator values) that satisfies the weighted no-envy rule. The main result of the paper states that to satisfy the 'beneficiary pay' or 'ability to pay' principles, IBAR must use a person-based indicator. Moreover, there are conditions under which the two principles coincide and IBAR satisfies each of them, but they are too stylized and hardly can be accepted for real life. Nevertheless, these conditions provide us with a measure of the difference between "beneficiary pays" and "ability to pay" rules. Similarly, our axioms show how the error of an indicator that does not satisfy them can be measured, which creates the possibility for comparison.

Conclusions. This project proposes one of the possible ways to structure the task of allocating historical emissions. It defines indicator-based allocation rule as a mathematical object and suggests a set of axioms for indicator selection. One of the next steps may be to study heterogeneous disutility functions that can catch the effects of emissions on different agents.

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Energy-efficient housing and macroeconomics: Insights from a building sector-ABM model integration

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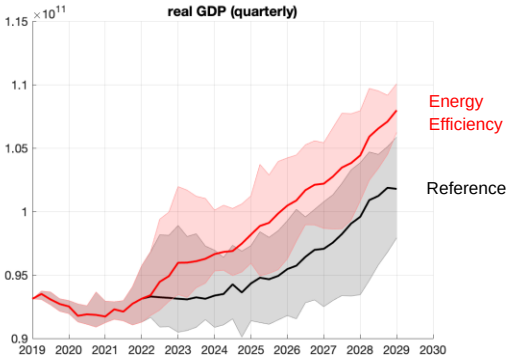
Introduction. Buildings play a major role in climate change mitigation. In the EU, they account for 40% of final energy consumption and one third of total energy-related GHG emissions. The largest energy mitigation potential relies on the renovation of existing buildings which will constitute the majority of the building stock by 2050. However, historic investment needs to more than double to meet the EU's 2030 emission reduction targets. To close this investment gap, the EU's legislative framework tasks national governments with developing renovation plans and policy measures. Understanding the associated economic opportunities and risks is critical, especially given the ongoing recovery from the pandemic, subsequent surge in inflation, and low willingness to invest due to (geo-)political uncertainties. This project explores the economy-wide impacts of demand-side interventions to reduce residential heating and cooling emissions in Austria, where economic recovery remains sluggish amid a continuing recession in the manufacturing and construction sectors.

Methodology. We integrate a macroeconomic agent-based model (Poledna et al., 2023) and a building sector model MESSAGEix-Buildings (Mastrucci et al., 2021) to conduct a scenario-based analysis contrasting the effects of ambitious demand-side interventions (Energy Efficiency) – which target electrification, fuel shifts as well as technology and energy efficiency improvements – against a reference scenario assuming the continuation of current measures (Reference). MESSAGEix-Buildings captures endogenous investment decisions of heterogeneous households and estimates energy demand for heating and cooling over 2020-2030. Macroeconomic effects of investment in dwellings and related changes in energy demand are evaluated in the macroeconomic model.

Results. Higher investment in the Energy Efficiency scenario provides an economic stimulus due to increased demand for insulation and construction material, heating systems and building services. It leads to an expansion of the domestic construction and manufacturing industries and boosts employment. Moreover, it causes feedback effects to other parts of the economy including a negative effect on the balance of payments and consumption shift due to reduced energy bills. Overall, ambitious demand-side measures are associated with higher GDP.



Conclusions. This study is among the first to systematically integrate a building sector and a macroeconomic model, investigating the largely unexplored economy-wide impacts of energy efficiency investment. Ambitious demand-side measures to reduce residential heating and cooling emissions are not only essential to reach emission reduction targets but also hold the potential to boost economic performance.

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Population ecology as a lens for competition law

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Introduction. How can we characterize the competitive process in an economic context, and what metrics can quantify the constraints faced by firms? These questions are increasingly important to competition law as economies become more dynamic and interconnected. Yet competition authorities find that existing analytical tools, mostly derived from classical economics, struggle to address them. This project observes that economics is not the only discipline studying competition. Ecology offers a well-developed framework for understanding competition that complements economics, which this project aims to leverage in the context of competition law.

Methodology. The project has two elements. Conceptually, it proposes that there are strong similarities between economic and ecological competition. It constructs a mapping between the two domains by proposing that just as species can survive and reproduce within a certain range of environmental parameters, firms are able to execute their business models only when enabling conditions are met and certain resources are available in their market environment in sufficient quantities. Competition arises because multiple firms rely on the same set of resources. Practically, the project operationalises this insight to build consumer-resource models of economic competition and applies metrics from population ecology to quantify the degree of competition that different firms face. The European Commission's recent Google Shopping case is used as a case study to explore the application of these techniques.

Results. The project conceptualises economic systems as a multi-layer network of resource stocks, where each layer represents stocks of a single resource, for example consumer demand or supplies of inputs. Firms generate flows between these stocks based on their production possibilities and their ability to satisfy demand, thus moving resources around the networks. Together, these stocks and flows represent the topology of the competitive playing field. This way of modelling markets allows for ecological metrics to be applied in economics settings. For instance, a coefficient of competition between two firms is defined as the ratio of their rates of resource uptake from the environment. Furthermore, conceptualising firms as a set of resource flows allows for economic activity to be represented as a set of ordinary differential equations which can be investigated analytically or numerically to understand market dynamics. The Google Shopping case, where Google promoted its own service while demoting rivals, was modeled using these techniques. The model demonstrated that Google's self-preferencing behavior reduced consumer flows to rival sites, which decreased Google's coefficient of competition while increasing it for its competitors.

Conclusions. This project has built the foundations for a bridge between theoretical systems ecology and competition law. It has mapped concepts from the former to the latter and demonstrated their application in the context of the ongoing Commission's Google Shopping case. Now that these foundations are built, the next steps are to cross-pollinate more concepts from systems ecology into competition law, particularly those pertaining to the open nature of the competitive process and how the competitive playing field changes over time.

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Arctic shipping emissions under multiple Global-Arctic coupled scenarios

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Introduction. The increasing importance of the Arctic region in global maritime trade and the need to address all sources of emissions for effective climate change mitigation underline the significance of shipping emission projections in the Arctic. Addressing the intricate challenge of estimating future Arctic shipping emissions requires interdisciplinary methods that integrate complex multidimensional factors. However, existing studies fall short to account for a diversity of driving factors behind the Arctic shipping emissions, often overlooking the complex interplay between Arctic socio-economic scenarios and maritime decarbonization trends. This oversight results in a significant disparity in the current scientific understanding of the future shipping emissions in the Arctic.

Methodology. This study first employs a Computable General Equilibrium (CGE) model to simulate future bilateral trade flows between all countries. Next, by integrating different technological scenarios, we establish future maritime emission pathways. Subsequently, we develop Global-Arctic coupled scenarios by incorporating a range of factors related to the socio-economic development of the Arctic, including infrastructure investments, Arctic technologies, Arctic governance, etc. Following this, an Arctic shipping cost assessment model is constructed. Coupled with a route network optimization, this model evaluates whether the port-to-port routes will shift to the Arctic region under different Global-Arctic coupled scenarios. Finally, we estimate the impact of the opening of the Arctic shipping routes on the global maritime emissions.

Results. Our model estimates that to achieve net-zero emissions by 2050, the international shipping industry must phase out all orders for conventionally fuelled vessels by at least 2025. By integrating global scenarios with the unique socio-economic factors of the Arctic, we developed Global-Arctic coupled scenarios. Two representative scenarios were selected: the Cooperative scenario, characterized by the fastest decarbonization rate, limited climate change, and an open and cooperative Arctic governance; and the Obstructive scenario, characterized by a slower decarbonization rate, extreme climate change, and a securitized Arctic governance, as shown in Figure 1. Our model indicates that, in the obstructive case, the cost of Arctic shipping routes remains high, leading to reductions in international shipping CO_2 emissions by 50, 53, and 63 million tons in 2030, 2040, and 2050, respectively. In the cooperative case, with significant technological advancements and the sharing of Arctic routes, the cost of Arctic shipping routes is lower resulting in reductions in international shipping CO_2 emissions by 54, 20, and 5 million tons in 2030, 2040, and 2050, respectively.

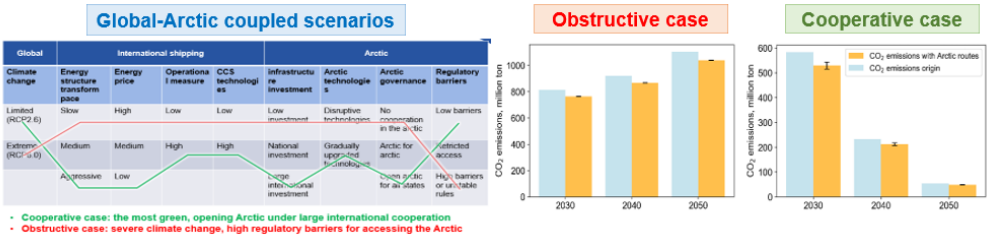

Figure 1: The Global-Arctic coupled scenarios developed in this study and international shipping CO_2 emissions under the two selected representative scenarios (the Obstructed scenario and the Cooperative scenario).

Conclusions. This study developed a coupled Global-Arctic maritime emission model and constructed integrated scenarios incorporating a broad range of factors such as trade, fuel, energy efficiency, and shipping costs. The opening of Arctic shipping routes can only reduce international shipping carbon emissions by 6-9% by 2050 comparing with the case where there is no Arctic shipping routes at all. It should be highlighted that while this study accounted for a broad range of factors and considered alternative scenarios for each of these factors, other uncertainties, not included in this model, such as the ship building price are likely to widen the uncertainty range for the emission reduction. Incorporating these uncertainties will be the next step in this research.

Linking earth observations from the international space station to soil moisture and crop productivity

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Introduction. Driven by climate change, some agroecosystems will face exacerbated water scarcity in the coming years, calling for the accurate monitoring of crop-water stress. Since its launch in 2018, the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) measures the Thermal InfraRed (TIR) radiation emitted from the Earth's surface. The Evaporative Stress Index (ESI), a core product of ECOSTRESS, quantifies plant stress based on the principle that well-irrigated crops are cooler than water-deprived vegetation. Because of its irregular orbit around the Earth, ECOSTRESS returns over a particular location at different times of day, providing snapshots of conditions across the diurnal cycle. To this day, there has been limited research testing the accuracy of ESI at different overpass times.

Methodology. My research examined ESI over parts of the United States, specifically throughout agricultural areas in Kansas. I leveraged the WorldCereal data set (recently co-produced by IIASA using crowdsourced training and validation data) to obtain the extent and irrigation status of cropland areas (Van Tricht et al., 2023). I selected more than 500 maize parcels encompassing over 37k pixels from ECOSTRESS, and employed a multivariate linear regression model to compare how variations in ESI align with information from other sensors such as the Landsat 8 Operational Land Imager (OLI) and the Terra Moderate Resolution Imaging Spectroradiometer (MODIS).

Results. This analysis revealed that the ESI varied substantially within an individual parcel and between nearby fields. I also found contrasting snapshots in ESI based on the overpass times (i.e., morning vs afternoon) and the retrieval algorithm used (i.e., Priestley-Taylor vs Atmosphere Land Exchange Inverse). Despite these differences, my research demonstrated that spatial variations in ESI could be linked to other remotely sensed indices ($p<0.05$). Going further, I showed that ESI was more closely aligned to spatial patterns in the environment than coarser observations from predecessors like MODIS.

Conclusions. My work demonstrated that variations in ECOSTRESS ESI could help explain patterns in vegetation health and serve as an early indicator of suboptimal crop productivity. These findings also confirmed that the high-resolution snapshots provided by ECOSTRESS added value beyond the information obtained from previous sensors. Ultimately, this project provided new insights into the diurnal sampling provided by ECOSTRESS, its significance and limitations for future TIR sensors in support of agricultural monitoring.

Acknowledgments. This work was made possible by a fellowship from the National Academies of Sciences, Engineering, and Medicine (NASEM) U.S. National Committee for IIASA, with funds from the National Science Foundation (NSF Award OISE 1663864).

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Pixel-level mapping of crop damages using space-born synthetic aperture radar

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Introduction. Yield losses from extreme weather events have increased due to climate change, with significant economic impacts (EEA, 2023). Yet less than one-third of these losses are typically insured, highlighting the need for improved damage mapping. By developing a data-driven model for mapping crop damage using space-borne Synthetic Aperture Radar (SAR) data acquired independently of weather and daylight conditions, we aim to enhance insurance models and yield predictions, ultimately supporting farmers and insurers in better managing and mitigating risks.

Methodology. Random Forest regression was utilized to model the relationship between multiple predictors such as SAR backscatter products, topography and weather-related information, and the percentage of damaged crop coverage for each 10 m Sentinel-1 pixel. The training and validation data were derived from high-resolution multitemporal UAV data.

Results. Cross-validation showed lower to moderate accuracy (R^2=0.44) with a tendency to underestimate high-range values (>0.3) (Fig.1, c), likely due to an unbalanced distribution of the training data, with more samples in the lower range (Fig.1, b). To improve this, bootstrapping and sample binning during sampling are being considered. Feature importance showed that differentiating damage types based on crop vitality (vital vs. dry, damaged crops) before damage occurs is crucial for modeling (Fig.1, a and c). Weather factors like wind speed, air pressure, relative humidity, and sensor and topographic parameters (relative orbit, local and global inclination) are also significant.

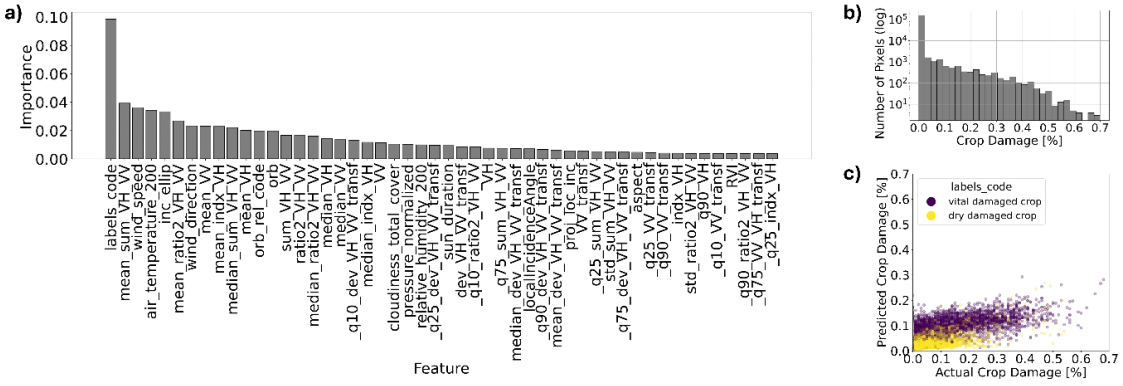

Figure 1: a) Feature importances of the model; b) Distribution of values used for model training; c) Actual versus predicted values of the damaged crop.

Conclusions. The study demonstrated the potential of using the Sentinel-1 data modeled with the machine learning technique - Random Forest - for pixel-level crop damage mapping. While it focused on developing a regressor for damaged crops, predictions can be strengthened by building regressors for additional agricultural patterns. Furthermore, this approach could be extended to map the often-occurring hail damage in Canola and boar damage in Corn.

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