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YSSP2026

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Proceedings from the Final Colloquium

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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 mentorship and guidance of IIASA scientists.

The Proceedings of the Final Colloquium comprises summaries of the research results obtained during the YSSP that were presented at International Institute for Applied Systems Analysis, Laxenburg, Austria on 24–25 August 2026.

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AGENDA

DAY 1	
GVISHIANI Room	
Session 1	Chair: Thomas Arnhold (POPJUS)
9:00 – 10:06	1) Anna Reckwitz – Freshwater Availability and Conflict Risk: The Role of Terrestrial Water Storage 2) Chantelle Ngwenya – The Intergenerational Transmission of Human Capital in Zimbabwe: A Dynamic Microsimulation of Educational Attainment Trajectories 3) Shahar Livne – The Continuity of Health System Response to Climate-Induced Food Insecurity in Malawi: Bridging Acute and Slow Onset Hazards with Routine Care 4) Tianxue Hou – Social Isolation Rather Than Loneliness as an Indirect Pathway from Depressive Symptoms to Subsequent Cognitive Impairment: Sex-Stratified Findings in Older Adults 5) Jen Hennenfeind – Ecosystem Intactness and Drought Effects on Internal Migration 6) Sara Ghebremicael – Differential Effects of Crisis on Agricultural and Non-Agricultural Households
BREAK	
Session 2	Chair: Roman Hoffman (POPJUS)
10:30 – 11:36	1) Alaa Dafallah – Examining Vulnerabilities and Resilience of Essential Maternal and Child Health Services amid Polycrisis in Sudan 2) Ola Adebayo – Why Does Exclusion Persist Despite Forward-Thinking Policies? Evidence from the Dwesa-Cwebe Marine Protected Area, South Africa 3) Stefani Rivić – Keeping Aluminium in Europe: An EU Policy Perspective Integrating Material Flows and Partial Economic Equilibrium Model 4) Rongqi Zhu – Evaluating the Distributional Effects of Policy-Driven Heat Pump Adoption 5) Xin Xu – Synergies of Reducing Global Nitrogen Pollution and Greenhouse Gas Emissions in Agriculture 6) Bowen Wang – Accounting for Dynamic Adaptive Capacity in Global Flood Risk Projections
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	BREAK
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	END OF DAY 1

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Session 7	Chair: Adrienne Etard (BNR)
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Session 8	Chair: Piotr Zebrowski (ASA)
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	BREAK

Session 9	Chair: Brian Fath (ASA)
15:00 – 16:06	1) Madhura Pawar – Collective Action Under Misinformation in Algorithmically Infused Social Network 2) Reason Mlambo – Explainable AI-based poverty assessment through knowledge-driven approaches 3) Esther Wairimu Kinyua – Modeling Medicinal Acacia for Sustainable Dryland Livelihoods 4) Federico Grossi – Assessing Structural Stability, Indirect Threat Exposure, and Conservation Action Coverage in Biodiversity Networks 5) Shiwei Chen – Quantifying Multiple Resilience Dividends of China’s Climate-Adaptive City Policy 6) Petra Bistričić – Financing Temperature Reversal: Financing Pathways & Policy Design
CLOSE OF PROGRAM RECEPTION IN CONFERENCE AREA	

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Population and Just Societies
(POPJUS)

Freshwater Availability and Conflict Risk: The Role of Terrestrial Water Storage

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IIASA Mentors: Roman Hoffmann (POPJUS), and Raya Muttarak (POPJUS)

Introduction.

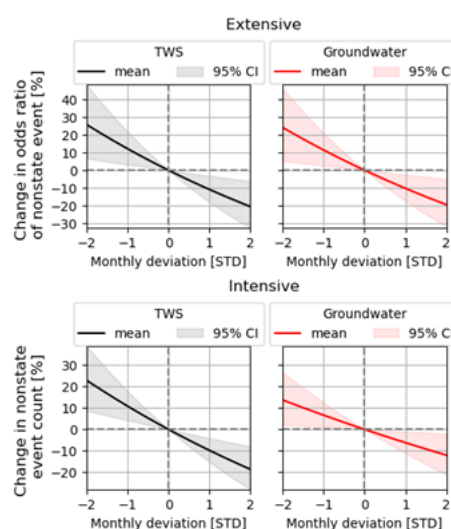
Experts generally agree that climate change will become an important driver of armed within-country conflict in the future (Mach et al. 2019). While the links between conflict and climate variables such as temperature and drought have been studied empirically, similar studies do not yet exist for terrestrial water storage (TWS), a separate essential climate variable. We address this gap and ask which socioeconomic circumstances moderate the conflict-water link, thus identifying potential adaptation levers for policy design.

Methodology.

We use global GRACE/GRACE-FO observations of TWS changes and nonstate armed conflict event data (UCDP) between 2002 and 2020, aggregated to first-level administrative regions. We combine a fixed-effects panel regression model, which uses within-region and within-year variation to identify plausibly causal effects, with a hurdle approach: the effect of TWS changes on onset of conflict (extensive change, logit link) is estimated separately from the effect on the increase in conflict events (intensive change, negative binomial model). Building on these models, we introduce regional characteristics (i.e., inequality, corruption, and democracy indicators) as moderating variables, revealing heterogeneous vulnerability patterns in the relationship between TWS changes and armed conflict risk.

Results.

We find that a negative shock in TWS of one standard deviation compared to the region- and month-specific average is associated with an increase in both nonstate conflict onset and nonstate conflict incidence of around 10% in that month. This is shown in the left column of the figure. After breaking down the TWS changes into their components, we find that this effect is consistent for the groundwater component, as depicted in the right column. The shaded areas mark the 95% confidence intervals. Further investigation of the heterogeneity of the effect suggests that the onset response is amplified in regions with comparatively high inequality (Gini index) or low electoral democracy (V-Dem index).



Conclusions.

We show a significant correlation between TWS (and specifically groundwater) decline and armed nonstate conflict onset and incidence. The heterogeneity analysis further implies that regions with low democracy or high inequality are particularly vulnerable to conflict onset associated with TWS decline. Remaining concerns about reverse causality will have to be addressed to strengthen these claims.

References

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The Intergenerational Transmission of Human Capital in Zimbabwe: A Dynamic Microsimulation of Educational Attainment Trajectories

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IIASA Mentors: Wolfgang Lutz (POPJUS), and Guillaume Marois (POPJUS)

Introduction. Studies on intergenerational transmission of human capital have shown that parental education, a proxy measure of human capital, is a strong predictor of children's educational attainment (Azomahou and Yitbarek, 2016). However, in developing countries, the effectiveness of this mechanism is largely impacted by prolonged socio-economic vulnerabilities which stall educational attainment (Alesina et al., 2021). This research evaluates the impact of maternal and paternal education on the intergenerational transmission of human capital in Zimbabwe.

Methodology. A dynamic microsimulation model is employed to simulate educational attendance and attainment trajectories of children aged 6-18 years between 2012 and 2030. The base population is the IPUMS 2012 Zimbabwe census microdata comprising jointly observed parent-child attributes, while the 2010 and 2015 Zimbabwe Demographic and Health Surveys are used to estimate education transition probabilities using logistic regression.

Results. The results demonstrate that maternal education is more crucial for improving educational attainment. First, compared to other parental education tiers, higher maternal education provides a protective effect against dropping out of school. Second, no or primary parental education results in roughly 74.0 per cent of children attaining no more than lower secondary education and only about 26.0 per cent attaining upper secondary education. However, a maternal secondary background translates to more children attaining upper secondary levels (91.8 per cent) and fewer stopping at the lower secondary level (7.3 per cent) whereas a paternal secondary background translates to 74.0 and 23.9 per cent of the same respective tiers. Finally, both higher maternal and paternal education levels translate to near universal upper secondary educational attainment, at 98.0 and 97.2 per cent, respectively.

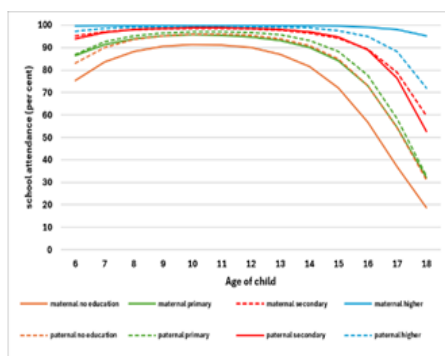


Figure 1. Probabilities of school attendance by age and parental education

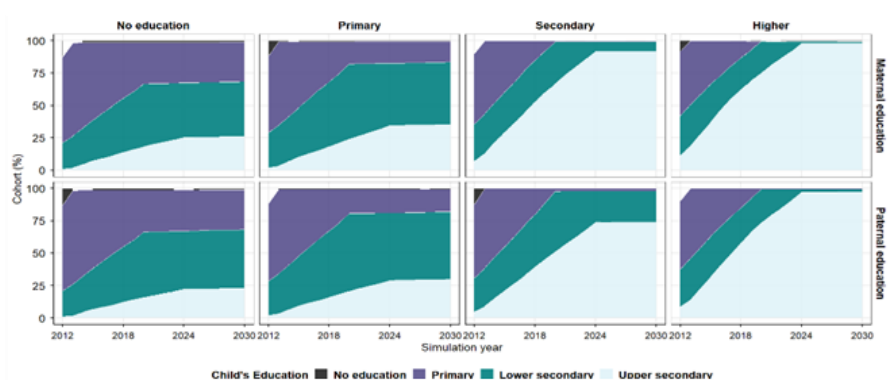


Figure 2. Educational attainment trajectories (2012-2030) by parental education

Conclusions. Overall, this research underscores the importance of secondary maternal education in ensuring early enrolment, shielding against premature dropout, and increasing upper secondary educational attainment. However, for parental education to effectively decouple children from generational inequality, policy must combine educational expansion with targeted interventions that avert other socio-economic gaps.

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The Continuity of Health System Response to Climate-Induced Food Insecurity in Malawi: Bridging Acute and Slow Onset Hazards with Routine Care

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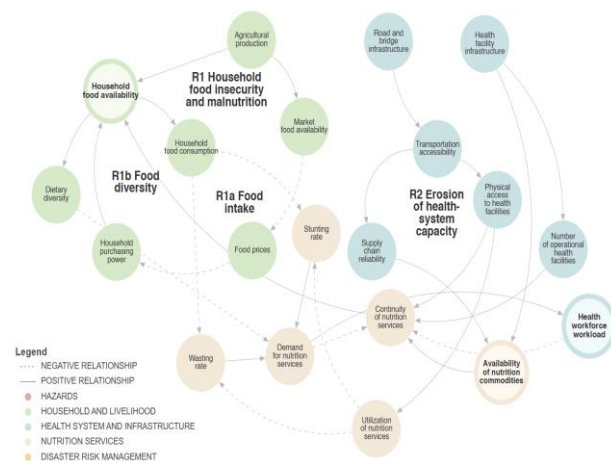
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Introduction. Multi-hazards present immense challenges for health systems in low-income countries, where limited resources and high disease burdens already constrain service delivery. Successive and overlapping climate-related hazards can simultaneously increase health needs and disrupt continuity of care. This study examines these specific pathways in Malawi, which experienced consecutive and overlapping cyclones, drought, and a prolonged cholera outbreak between 2022 and 2024. We focus specifically on nutritional care, which provides an important lens through which to examine the interaction between household vulnerability and health system capacity.

Methodology. In August and September 2024, we conducted 33 in-depth interviews with frontline healthcare providers, district-level health managers, and disaster risk management officers in two rural districts in Southern Malawi. Interviews explored emerging needs, health system effects, and interventions associated with each hazard. Through retrospective qualitative system dynamics analysis, we identified causal relationships and used them to develop causal loop diagrams by system level, district, and hazard type. We then integrated the diagrams to identify mechanisms shaping continuity of care.

Results. Two interconnected reinforcing mechanisms shaped continuity of nutritional care: (R1) increasing nutritional needs driven by declining household food availability, and (R2) erosion of health system capacity to meet those needs through increased workload and reduced availability of nutrition commodities. Multi-hazards increased staff workload by creating additional points of care and increasing disease burden. At the same time, damaged roads and storage facilities, together with resource redirection, disrupted the availability of nutrition commodities. Routine nutritional needs persisted, particularly as most households depended on subsistence agriculture, and acute malnutrition increased with each hazard.



Conclusions.

These findings demonstrate why continuity of nutritional care becomes increasingly difficult to sustain when routine health needs intersect with multi-hazards. Nutritional needs do not fit a rigid separation between routine and emergency care, as underlying needs persist while acute needs increase with each hazard. Resilient health systems therefore require moving beyond disaster-specific responses toward maintaining core functions across successive and overlapping hazards. Key leverage points include strengthening workforce capacity, expanding storage facilities in remote areas and strengthening supply chains, alongside interventions beyond the health system that address underlying household vulnerability to food insecurity.

Social Isolation Rather Than Loneliness as an Indirect Pathway from Depressive Symptoms to Subsequent Cognitive Impairment: Sex-Stratified Findings in Older Adults

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Introduction. Depressive symptoms and cognitive impairment frequently co-occur in older adults. Previous longitudinal studies have suggested associations in both directions, but the pathways underlying these associations remain unclear. Social isolation and loneliness represent distinct dimensions of social disconnection and may contribute differently to these pathways. However, research on the roles of social isolation and loneliness in these associations remains scarce. Whether these roles differ between women and men is also uncertain.

Methodology. We analyzed three consecutive waves of data from community-dwelling older adults participating in the National Health and Aging Trends Study. Generalized structural equation models were used to examine lagged associations between depressive symptoms and cognitive impairment in both directions. Separate three-wave mediation models were fitted for social isolation and loneliness, with the exposure measured in the first wave, the mediator in the second, and the outcome in the third. Adjusted models controlled for prior outcome status and sociodemographic covariates. Models were also stratified by sex. Sensitivity analyses further adjusted for health-related factors to assess the robustness of the findings.

Results. Depressive symptoms and cognitive impairment were longitudinally associated in both directions. After covariate adjustment, cognitive impairment was associated with higher odds of subsequent depressive symptoms (odds ratio [OR], 1.82; 95% confidence interval [CI], 1.29-2.56; $p = .001$), and depressive symptoms were associated with higher odds of subsequent cognitive impairment (OR, 1.58; 95% CI, 1.12-2.21; $p = .008$). Social isolation showed a significant indirect effect only in the pathway from depressive symptoms to subsequent cognitive impairment ($\beta = .31$; 95% CI, 0.06-0.57; $p = .016$). Loneliness did not significantly mediate either direction between depressive symptoms and cognitive impairment. In sex-stratified analyses, the indirect effect through social isolation was significant among women but not among men. Sensitivity analyses showed results consistent with the primary analyses.

Conclusion. Social isolation, but not loneliness, was associated with the pathway from depressive symptoms to subsequent cognitive impairment. The findings highlight the importance of distinguishing social isolation from loneliness when examining depressive symptoms in older adults with cognitive risk. Further research is needed to determine whether reducing social isolation can influence cognitive outcomes among older adults with depressive symptoms.

Ecosystem Intactness and Drought Effects on Internal Migration

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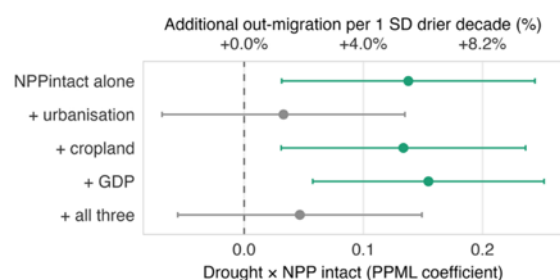
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Introduction. Drought increases out-migration worldwide, though contextual factors such as income and agricultural dependence shape the response (Hoffmann et al., 2024, 2020; Cai et al., 2016). However, the ecological context remains understudied (Hermans et al., 2023). While nature regulates water, soil moisture, and the stability of production under climate extremes, land degradation has reduced ecosystem productivity on 23% of global land (IPBES, 2018). Where ecosystems remain intact, households may have more options to adapt and stay. Conversely, these regions may depend the most on ecosystem productivity, so drought could affect them the most. We test whether ecosystem intactness changes the drought effect on out-migration.

Methodology. We model bilateral out-migration flows between admin-1 regions for 1992–2017 (N = 46,307 corridor years, 36,603 in the trailing specification). The outcome, annualised out-migration rate, is estimated through PPML models with corridor fixed effects and SE clustered at that level (Hoffmann et al., 2024). Drought is a 10-year SPEI12 mean preceding the out-migration year, dry coded (higher = drier). Ecosystem intactness is NPP_{intact} ($NPP_{\text{eco}}/NPP_{\text{pot}}$, Matej et al. 2025; $r = 0.79$, $\rho = 0.82$ with Biodiversity Intactness Index). We interact drought with intactness, and add urbanisation, cropland share and GDP per capita (long-term means) as competing moderators. Models include distance, contiguity, census-interval length and world-region-by-decade trends.

Results. Drought at origin significantly increased out-migration ($\beta = 0.117$, $p < 0.01$). In a 5-year trailing specification, regions with higher recent intactness showed lower baseline out-migration ($\beta = -4.53$, $p < 0.01$). In the structural specification, however, regions that were more intact than comparable agricultural regions responded more strongly to dry decades ($\beta = 0.138$, $p < 0.05$, Figure 1), roughly 5.6% additional out-migration per one SD drier decade, per one SD higher intactness. Specifically, a one-SD drier decade left the out-migration rate almost unchanged in degraded regions (-0.5%) and raised it by 11% in intact ones. This pattern held across all competing moderators except urbanisation (90% CI -0.069 to 0.135).



Conclusions. This is the first study to include a measure of ecosystem intactness in bilateral migration models. Contrary to a buffering hypothesis, intact regions did not provide a safety net during drought. They showed lower out-migration overall, but responded more strongly when dry decades occurred. Next steps map where this dependence concentrates, across world regions and socio-economic contexts.

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Differential Effects of Crisis on Agricultural and Non-Agricultural Households

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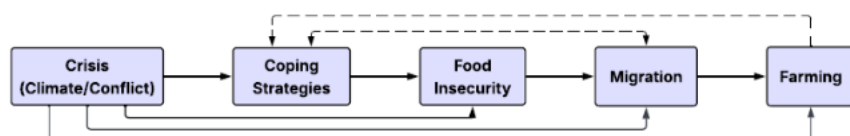
IIASA Mentors: Manya Oriel Kagan (POPJUS), and Sofia Badini (POPJUS)

Introduction. Food systems are increasingly affected by external crises, with political instability and weather extremes primarily driving acute food insecurity¹ through direct and indirect channels. These events can weaken institutions and agricultural systems through intersecting channels which then shape local adaptive capacity and decision-making. The relationship between changing weather and instability are particularly apparent in Ethiopia, where political instability is rising, along with inconsistent and unpredictable droughts and rainfall patterns – thus increasing population vulnerability well beyond the initial shock. This paper examines the differential relationship of shock on agricultural and non-agricultural households using longitudinal panel data.

Methodology. Nationally representative longitudinal survey data from the World Bank’s Living Standards Measurement Survey (LSMS) was used, linking two panel datasets to combine household-level and individual-level data on demographic characteristics, migration histories, and exposure to weather extremes and instability. The relationship between individual migration and household food security/coping strategies was regressed alongside self-reported exposure to conflict and climate shocks. External climate data from the European ReAnalysis (ERA5-Land) and conflict data from the Armed Conflict Location Events Dataset (ACLED) were then transformed into cumulative exposure measures of conflict and climate anomalies. Outcomes were aggregated to the household and enumeration area level, and were estimated using weighted ordinary least squares regression, logistic regression, and fixed effects regression – with clustering at the enumeration area.

Results. Climate and conflict were significantly correlated with food insecurity, with drought being the largest driver for agricultural and non-agricultural households. Crisis events were also correlated with greater use of coping strategies - significant for non-agricultural households; marginally significant for agricultural households. Food insecurity was a significant predictor of coping strategy use for agricultural and non-agricultural households, with effects almost twice as large for non-agricultural households. Alternatively, conflict was significantly associated with decreased longer-term (>6 months) migration for agricultural households, indicating a constraining effect on mobility within this subgroup. The relationship between longer-term migration and food insecurity was found to be significant for non-agricultural households and insignificant for agricultural households. Finally, longer-term migration was correlated with increased farm engagement for agricultural households, while short-term and permanent migration showed no reliable effect.

Crisis Pathways toward Food Insecurity and Migration



Conclusions. The relationship between crisis events and coping strategy use drives the food insecurity pathway, with shocks worsening conditions of food insecurity and increasing coping strategy use amongst agricultural and non-agricultural households. Individual migration, however, was only linked to food security for non-agricultural households. For agricultural households, crisis events (particularly drought) directly suppress longer-term mobility and farming capacity, independently, with positive relationships between migration and farming likely reflecting household access to resources or labor constraints. The results suggest that climate and conflict events act directly through household adaptive capacity and food insecurity, with subsequent impacts varying by livelihood.

References

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Examining Vulnerabilities and Resilience of Essential Maternal and Child Health Services amid Polycrisis in Sudan

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IIASA Mentor: Josephine Borghi (POPJUS)

Introduction. Since the onset of conflict in April 2023, Sudan faces multiple compounding shocks, resulting in the world's largest humanitarian crisis and severely disrupting the delivery of essential health services.¹ Understanding how compounding shocks affect the health system is essential for strengthening its resilience.² Therefore, this study aims to examine the effects of compounding shocks on the delivery and utilisation of maternal, newborn and child health (MNCH) services in Sudan, and identify key points of system vulnerability.

Methodology. This is a qualitative system dynamics study, drawing on a document review and 13 key informant interviews with stakeholders from the Ministry of Health and humanitarian organisations in Sudan. Transcripts were coded using purposive text analysis, extracting causal variables, relationships, and delays. Individual causal loop diagrams (CLDs) were developed, aggregated by service type into single CLDs, and analysed.

Results. Conflict is the main driver of disruption, propagating through 10 mechanisms across the health system, critical infrastructure systems, food security, and livelihood pathways. These include destruction of health facilities, erosion of health worker availability and capacity, and disruption of supply chains, water and power availability in facilities affecting supply of services. Damage to transport infrastructure, insecurity, breakdown of water and sanitation services, and loss of livelihoods affected demand-side dynamics. Effects compounded at key nodes of vulnerability, most prominently, capacity of health facility and personnel and willingness of mothers to seek care. Several reinforcing feedback loops were common across MNCH services, e.g., increased caseload straining facility and health worker capacity. For maternal health services, additional feedback dynamics were noted: diversion of funding towards emergency interventions reduced facility capacity to delivery routine antenatal care (ANC), while conflict-related factors affecting access to ANC increased substitution towards traditional medicine and home births, increasing downstream demand for emergency services. Delayed or unavailable emergency obstetric care in facilities further increased maternal complications and mortality.

Conclusions. Vulnerability in MNCH service delivery arises through interconnected supply- and demand-side mechanisms that converge on key nodes of system vulnerability, reflecting both system-wide constraints and service-specific dynamics. This evidence provides insights into leverage points where targeted interventions may deliver system-wide benefits across all MNCH services, and where service-specific interventions are required.

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Why Does Exclusion Persist Despite Forward-Thinking Policies? Evidence from the Dwesa–Cwebe Marine Protected Area, South Africa

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Introduction. South Africa experiences what may be considered a paradox of participation. In the post-apartheid era (1994-date), the country has established progressive and inclusive policy frameworks, yet ocean governance continues to be characterized by exclusion^{1,2}. Studies examining why exclusion persists have largely focused on either the institutional arrangement or the community experience³. This study examines how interactions between institutional arrangement and community experience may provide greater insight into the persistence of exclusion.

Methodology. The study combines Integrative Qualitative System Analysis with interpretive analysis to examine patterns of interaction between government and community perspectives. Government perspectives were represented through policy commitments and implementation practices, while community perspectives were represented through community expectations and lived experience. Interpretive analysis was used to examine the basis of these divergences. Data were collected from 10 relevant policy documents, in-depth interviews with four government officials and three community leaders, and focus group discussions with 43 fishers, women and traditional leaders across two communities, Hobeni and Cwebe, adjacent to the Dwesa-Cwebe MPA. Data were coded inductively.

Results.

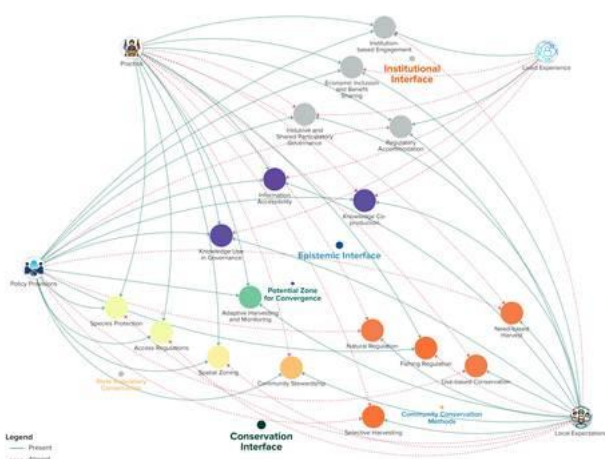


Figure 1 presents system interaction behaviour:

- **Institutional Interface:** This is the interface of governance, representation, and authority. The IQSM found convergence on presence of institutional participation but divergence on design, amount of authority and breadth of representation.
- **Epistemic Interface:** The interface of knowledge production, community and use. The IQSM found convergence on the relevance of Traditional Ecological Knowledge to ocean governance, divergence on interpretation, breadth of distribution and use.
- **Conservation Interface:** The interface for the practice of conservation. The analysis found

convergence on conservation goals, divergence on methods and stewardship of conservation.

The interpretive analysis shows that policy implementation architecture contains multiple participatory and engagement mechanisms, but these mechanisms do not necessarily produce the forms of representation, authority, influence and recognition that communities associate with meaningful participation.

Conclusions. As the Dwesa Case has shown, the establishment of a participatory mechanism does not necessarily transfer authority to that mechanism. The paradox, therefore, is that governance can become progressively more inclusive in its recognition of communities while remaining exclusionary in the distribution of representation, granting of epistemic authority, and recognized conservation stewardship.

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Economic Frontiers
(EF)

Keeping Aluminium in Europe: An EU Policy Perspective Integrating Material Flows and Partial Economic Equilibrium Model

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Introduction. Aluminium is strategically important for the EU's circular economy and resource security, being clarified as a critical raw material. Although recycling requires only about 5% of the energy of primary production, circularity is constrained by long building lifetimes, delayed scrap generation and imperfect sorting. These challenges are particularly relevant as construction aluminum demand is expected to grow through renovation and energy-efficiency investments. Existing studies either characterize the aluminum circle without accounting for economic behavior or evaluate recycling policies without considering physical stock and quality constraints. This model bridges these perspectives to assess how different circular economy policies affect recycling, material availability, and economic outcomes.

Methodology. We first conduct a material flow analysis (MFA) of aluminium in the EU construction sector to quantify physical stocks and flows. These physical flows are then translated into a partial economic equilibrium model by identifying the economic actors and market structures along the value chain and formulating their respective optimization problems. Rather than imposing a uniform assumption of perfect competition, we represent sector-specific market structures and link the actors through quality-specific scrap and secondary aluminium markets. This integration of physical and economic modelling is consistent with the integrated-MFA framework discussed by Baars et al. (2022) which highlights the value of combining MFA with complementary modelling approaches.

Results. The main result is a novel framework that integrates material flow analysis and economic equilibrium modelling while accounting for distinct market structures along the aluminium value chain. This allows physically consistent material flows and quality decisions to interact directly with firms' strategic behaviour. A key methodological contribution concerns the representation of heterogeneous scrap qualities. While a CES aggregator captures imperfect substitution between scrap qualities, standard CES optimization does not generally preserve the physical mass balance required by MFA. We overcome this discrepancy by introducing an explicit mass-balance constraint alongside the CES quality constraint, yielding a mass-consistent demand for individual scrap qualities. The resulting framework therefore integrates physical quantities, material quality, imperfect substitution, and sector-specific economic behaviour within one consistent modelling approach, providing a new basis for analysing circular material systems. The framework can thus support targeted, policy-relevant analyses of circular economy measures in the EU aluminium sector.

Conclusions. The methodological findings highlight the importance of explicitly integrating physical mass and quality constraints into economic decision-making. Further research at the interface of material flow analysis and economic modelling is therefore needed to ensure that policy assessments adequately reflect physical feasibility and provide robust guidance for decision makers. As a next step, the model will be calibrated and simulated to assess the effectiveness of alternative policy instruments and their interactions, providing realistic insights to support EU policy design.

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***Energy, Climate, and Environment
(ECE)***

Evaluating the Distributional Effects of Policy-Driven Heat Pump Adoption

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Introduction. Space heating accounts for approximately one-third of residential energy consumption, making the rapid scaling of electric heat pumps a cornerstone of global building decarbonization. Governments have introduced a range of incentives and regulations to accelerate heat pump adoption, yet deployment remains below the level required to meet climate targets. This study examines how the heat pump deployment gap can be reduced by accounting for building renovation dynamics and heterogeneous household technology preferences. It further investigates the distributional effects of policy-driven heat pump adoption across urban and rural areas and income groups.

Methodology. We couple empirically informed household heating technology preferences with the building energy model MESSAGEix-Buildings¹. First, nationally representative household surveys, such as the U.S. Residential Energy Consumption Survey, are used to estimate heterogeneous technology preferences across urban and rural households and income deciles using a multinomial logit model of levelized heating costs. Second, we extend MESSAGEix-Buildings by disaggregating households by income and separating renovation from heating technology adoption. Finally, we assess four policy pathways from 2020 to 2050: baseline, renovation and replacement, heat-pump incentives with fossil-fuel phase-out, and a combined policy package.

Results. Policy interventions reshape the U.S. residential heating technology stock (Fig. 1a). Heat-pump penetration reaches about 40% by 2050 under the baseline, while the combined policy package produces a synergistic effect, increasing penetration to nearly 80%. Adoption responses are similar across income groups in both urban and rural areas (Fig. 1b), whereas energy savings are unevenly distributed. Under the combined policy package, residential heating energy use declines across all income groups, with larger reductions among higher-income households, particularly in urban areas (Fig. 1c).

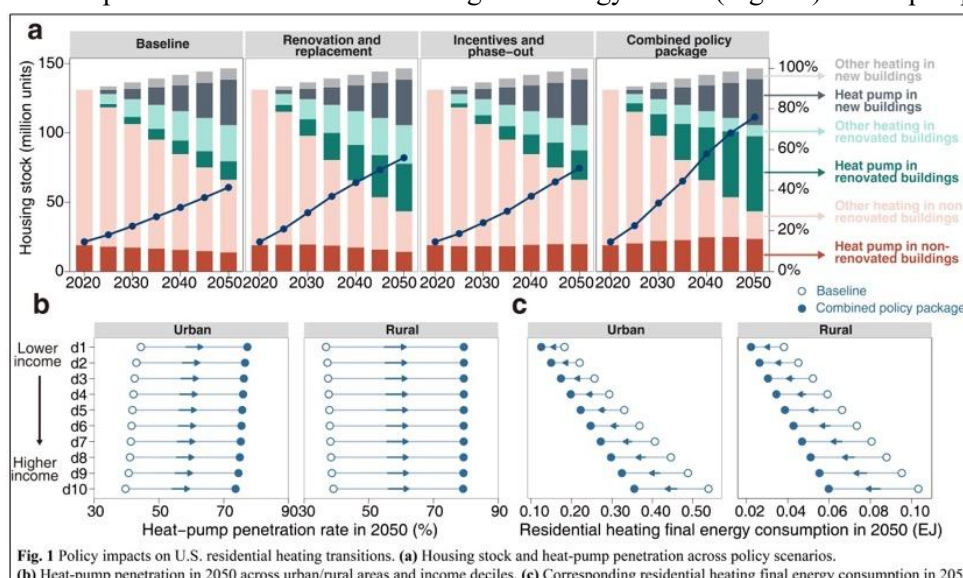


Fig. 1 Policy impacts on U.S. residential heating transitions. (a) Housing stock and heat-pump penetration across policy scenarios. (b) Heat-pump penetration in 2050 across urban/rural areas and income deciles. (c) Corresponding residential heating final energy consumption in 2050.

Conclusions. Integrating heterogeneous technology preferences into MESSAGEix-Buildings enables a more granular assessment of heat-pump policies and their distributional effects. Combining building renovation with economic incentives and phase-out measures can synergistically accelerate U.S. heat-pump deployment, while larger energy savings occur among higher-income households, particularly in urban areas. Future work will extend the framework to developing regions, where affordability and accessibility constraints may vary more strongly across income groups.

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Synergies of Reducing Global Nitrogen Pollution and Greenhouse Gas Emissions in Agriculture

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Introduction. Agriculture is a major source of greenhouse gases (GHGs) and reactive nitrogen (Nr), yet climate and nitrogen policies are often assessed separately. Because these emissions often arise from shared agricultural activities, coordinated management can generate co-benefits but also cross-pollutant trade-offs. These interactions vary across regions with production systems, emission profiles, mitigation options, and environmental damages. A globally consistent framework is therefore needed to link historical drivers, mitigation potential, and economic outcomes. This study develops an integrated CHANS-GAINS framework to identify cost-effective pathways for coordinated agricultural GHG-Nr mitigation.

Methodology. We integrated the CHANS carbon-nitrogen budget model with the GAINS assessment framework. Agricultural emissions of CH₄, N₂O, NH₃, NO_x, and N leaching/runoff were reconstructed for 166 countries during 1992–2022, and socio-economic drivers were assessed using country- and year-fixed-effects panel models. Meta-analysis evidence (CHANS) and validated practices (GAINS) were harmonized into a mitigation portfolio covering abatement efficiency, unit activity costs, and regional applicability. Pollutants were normalized into GHG-Nr equivalents (GNPeq) using country-specific damage/social-cost weights. SSP1-RCP1.9, SSP2-RCP4.5, and SSP5-RCP8.5 pathways with graded co-mitigation ambition were simulated to 2050, followed by regional synergy and cost-benefit analyses.

Results. From 1992 to 2022, global agricultural Nr emissions increased from 73.0 to 92.8 Tg N yr⁻¹, while GHG emissions rose from 5.7 to 6.6 Pg CO₂eq yr⁻¹. Population growth was the dominant upward driver, contributing 25.9% and 26.5% to the increases in Nr and GHG emissions, respectively, whereas improved nitrogen-use efficiency offset 12.8% and 11.7%. Under the SSP1-RCP1.9-strong mitigation pathway, integrated GNP emissions will decline to ~51 Tg GNPeq yr⁻¹ by 2050, 56% below 2022 levels (Figure 1). Co-mitigation profiles vary markedly across regions: the global GHG-to-Nr reduction ratio is 0.44, ranging from 0.21 in Europe to 1.21 in Brazil. All pathways generate positive societal benefits; the strong mitigation pathway achieves the highest global benefit-cost ratio of 7.2, with the largest net societal benefits in China, India, and Europe.

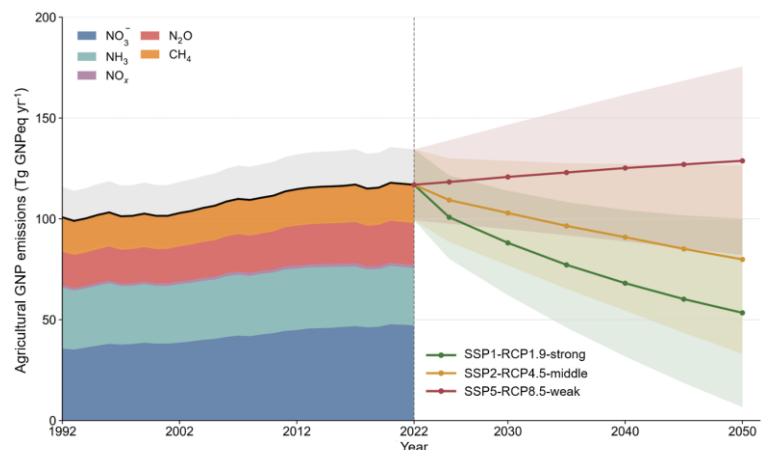


Figure 1. Historical and projected global agricultural integrated GNP emissions.

Conclusions. Coordinated agricultural GHG-Nr management can advance climate mitigation and nitrogen-pollution control while delivering substantial economic returns. Under strong mitigation, integrated GNP emissions could decline by more than half by 2050, with benefits exceeding implementation costs by over sevenfold. However, mitigation priorities should remain region-specific. Brazil, Latin America, and Sub-Saharan Africa exhibit relatively strong climate co-benefits from Nr reduction, whereas Nr-dominant regions require more targeted nitrogen-management strategies.

Accounting for Dynamic Adaptive Capacity in Global Flood Risk Projections

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Introduction. Future flood risk depends not only on climate-driven changes in hazard but also on societal adaptation. However, most global flood-risk assessments assume static adaptation, potentially biasing projections of future losses. This study develops a globally comparable indicator of protection-based flood adaptive capacity and projects its evolution under alternative Shared Socioeconomic Pathways (SSPs). To our knowledge, this is the first globally consistent set of SSP-based projections of protection-based flood adaptive capacity at the subnational level.

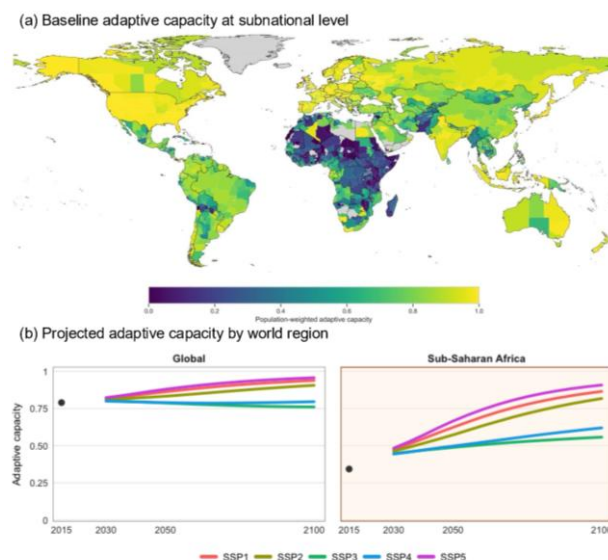
Methodology. We define protection-based flood adaptive capacity as the proportion of potential inundation depth avoided through existing flood protection. We derive the historical baseline by combining FLOPROS protection standards with ISIMIP2a flood simulations for 1971–2010 and applying a threshold-based procedure to determine residual inundation depth under protection. We then use a multilevel beta regression model to relate baseline adaptive capacity to socioeconomic predictors and project its trajectories under five SSPs from 2030 to 2100. To isolate the effects of alternative adaptation assumptions, we compare three scenarios: fixed physical protection, hazard-tracking protection, and socioeconomically evolving protection. For each future scenario, we translate projected adaptive capacity into residual inundation depth and combine it with exposure data and depth–damage functions to estimate direct economic losses.

Results. Historical adaptive capacity is lowest in the Sahel and East Africa, indicating substantial gaps between existing protection standards and potential flood hazards. Higher GDP per capita, urbanization, asset intensity, and stronger national governance are associated with greater adaptive capacity, whereas income inequality is associated with lower capacity. From 2030 to 2100, global adaptive capacity increases under SSP1, SSP2, and SSP5, remains broadly stable under SSP4, and declines under SSP3. Although adaptive capacity improves rapidly in Sub-Saharan Africa under several SSPs, the region retains the lowest capacity under all pathways. Under RCP8.5, annual flood losses in 2080 reach USD 1.1 trillion under fixed protection, compared with USD 701 billion under hazard-tracking protection and USD 497–672 billion under socioeconomically evolving protection. Relative to fixed physical protection, socioeconomically evolving protection reduces losses by 28–30% in 2030 and 39–55% in 2080.

Conclusions. Socioeconomic development pathways play an increasingly important role in shaping future adaptive capacity and flood risk. Compared with static adaptation assumptions, scenarios that account for evolving adaptive capacity produce substantially lower loss projections, although the benefits vary across regions and SSPs.

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Feasibility of Energy Transition Scenarios Under Mineral Supply Constraints

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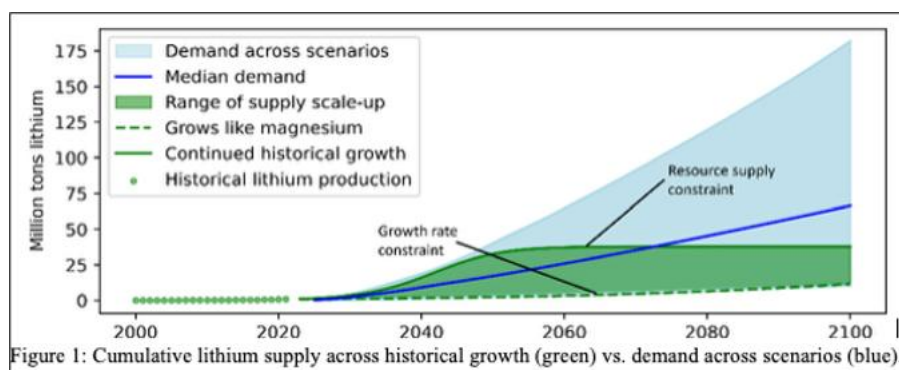
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Introduction. Scale-up of low-carbon energy technologies will require unprecedented increases in energy transition mineral (ETM) production (Rostami et al. 2024). The ability of ETM supplies to meet future demand will depend on many factors including available resources, supply chain complexity, political and social support, and sources of demand. We explore how models of ETM supply scale-up, informed by historical mineral production, can characterize the feasibility of future ETM demand across integrated assessment model (IAM) scenarios.

Methodology. (1) We model future supply of 32 ETMs using growth rates across historical mineral production (USGS 2026). We select a range of growth rates based on mining techniques, supply concentration, and sources of demand. (2) We multiply capacity additions of twelve low-carbon energy technologies (Huppmann et al. 2025), across IAMs and scenarios, and mineral intensities from literature to calculate ranges of future ETM demand. (3) We compare thousands of scenarios for differences in growth and magnitude of supply and demand of each ETM. (4) We characterize the growth rate- and supply-limited scenarios according to features from the scale-up models.

Results. Demand from low-carbon technologies for primary minerals like zinc, which have well-characterized resources and demand from many sectors, remains under 72% of the lowest supply model. Demand for primary minerals like lithium, used primarily for energy, may be limited by both



the magnitude and growth rate of ETM production, using magnesium as an analogy (Figure 1). Historically extracted from brine, magnesium grew at 3.8%, compared to 12% recent growth of lithium supply. Byproduct minerals, like indium, can be found plentifully in host ores, like zinc. However, growth of supply may be slow without incentives to extract it, like silver at 1.8%.

Conclusions. Policy solutions to ETM supply constraints depend on whether demand is growth rate-limited or resource supply-limited. Growth rate-limited scenarios have many policy tools to incentivize extraction of ETMs and reduce demand across technologies. Supply-limited scenarios require better ETM resource characterization. Policymakers can design targeted solutions for each ETM supply to more likely meet future demand.

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Quantitative Evaluation of the Effects of Temporal Resolution on VRE Integration and End-Use Electrification in Global IAMs

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Introduction. In power systems dominated by variable renewable energy (VRE), ensuring flexibility through dispatchable power generation, storage operations and managing curtailment, i.e. the amount of electricity from wind and solar that is discarded, is crucial to maintain a supply-demand balance. Energy system models and integrated assessment models (IAMs), such as MESSAGEix, feature low temporal resolution to ensure scalability across extended time horizons and sectoral coverage. Although these models utilise stylised integration constraints to model storage operations and curtailment at low temporal resolutions, potential misestimations remain because the emulated constraints in MESSAGEix have not been fully calibrated against high-temporal-resolution models^[1]. This research aims to identify these inaccuracies in low-resolution models using stylised integration constraints and proposes a new approach to capture power system operations with high fidelity within low-temporal resolution.

Methodology. We utilize the Multi-Regional Energy Chains Model, focusing on Japanese energy systems as a case study^[2]. This model has both high- and low-temporal-resolution variants: 1. we conduct a parametric sweep for photovoltaic (PV) and wind power penetration relative to demand to obtain high- resolution power system results. 2. based on model runs we create a lookup table (LUT) of curtailment rates, the capacities and operations of storage (battery, pumped hydro, and hydrogen) and dispatchable thermal generators, and the reduction in curtailment achieved via additional storage penetration. 3. we apply this LUT to the low-resolution model via emulation equations and compare the resulting power generation against those using the stylised renewable integration constraints from MESSAGEix-JPN model.

Results. The representative LUT for curtailment rates is shown in Fig.1. The power generation results under a carbon price of USD 350 for the year 2040 are shown in Fig.2. The low-temporal-resolution model using stylised integration constraints overestimates VRE generation, as well as battery and pumped hydro operations, while underestimating VRE curtailment. In contrast, our proposed LUT method accurately emulates VRE generation, curtailment, storage operations, and thermal generation. With this approach, generation errors are reduced by ~90% across these variables.

PV Penetration Rate [%]	Wind Penetration Rate [%]										
	0	10	15	20	25	30	35	40	50		
0	0%	0%	0%	0%	0%	1%	2%	3%	6%		
10	0%	0%	0%	0%	1%	2%	3%	4%	9%		
15	0%	0%	0%	1%	2%	3%	4%	6%	11%		
20	1%	2%	2%	3%	4%	6%	7%	9%	15%		
25	3%	4%	5%	6%	7%	9%	10%	13%	19%		
30	6%	7%	8%	9%	10%	12%	14%	17%	23%		
35	9%	11%	12%	13%	14%	16%	18%	21%	28%		
40	13%	15%	16%	17%	18%	20%	22%	26%	32%		
50	21%	23%	24%	25%	27%	28%	31%	35%	42%		

Fig. 1. lookup table for curtailment rate

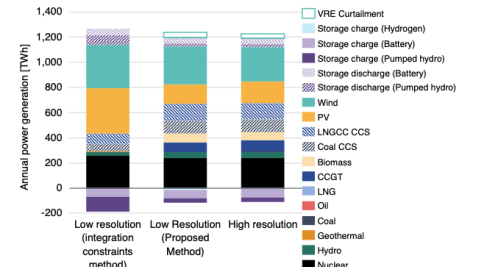


Fig. 2. Annual power generation

Conclusions. To enable operationally feasible scenario analyses of VRE and storage penetration, we developed a method that emulates high-resolution power system planning within a single annual-resolution model. This method emulates the annual power generation dynamics of a high-resolution model without increasing the computational burden associated with high-resolution modelling. Future work will explore applying this approach to global IAMs by expanding from a single-country, single-year focus to broader geographical, temporal, and VRE penetration scenarios.

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Assessing Future Energy System Resilience to Droughts and Heatwaves Across Global Mitigation Scenarios

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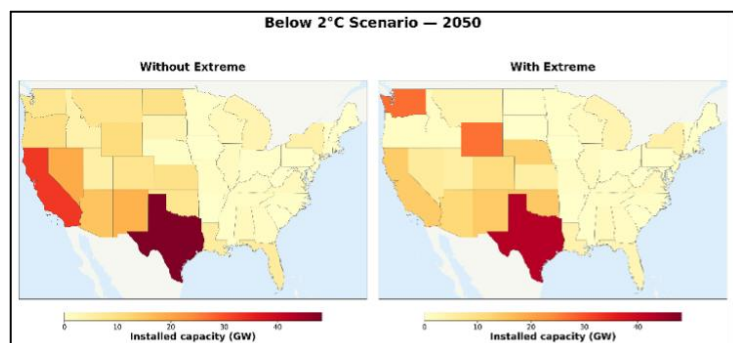
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Introduction. Energy systems are evolving to meet growing energy demand while decarbonizing to reduce greenhouse gas emissions. However, power generation remains highly water-intensive, making the sector vulnerable to water scarcity and extremes such as droughts and heatwaves (Otero et al., 2023). Climate change is projected to increase the frequency and severity of these extremes across many regions (Hari et al., 2020). While prior studies have examined drought and heatwave impacts on current energy systems, their impacts on future systems remain largely unassessed. This study evaluates future energy-system resilience under alternative decarbonization pathways by spatially downscaling MESSAGE integrated assessment model capacity trajectories – which resolve only macro-regional scales to plant level, since droughts and heatwaves operate at much finer spatial resolution.

Methodology. MESSAGE macro-regional capacity projections are downscaled to individual plant sites for coal, gas, oil and nuclear. Sites are selected based on water availability, population density, land suitability, protected areas, and climate risk and validated through historical hindcasting. Drought and heatwave impacts are assessed using water and temperature constrained generation. Alternative scenarios test sensitivity to key assumptions, including shifting technologies toward greater efficiency and transitioning cooling systems from water-intensive once-through to less-intensive cooling-tower designs, enabling assessment of how technology choices influence future energy-system resilience to water stress.

Results. The preliminary results indicate that the spatial distribution of downscaled power plants matches well with the observed PLATTS data for the hindcast years. Changes in the criteria used to determine future power plant locations can lead to different spatial distributions. For example, incorporating future climate extremes into the decision-making process results in lower installed in capacity in California compared with scenarios that do not account for future climate extremes.



Conclusions. Downscaling framework provides a robust framework for assessing where future power will be sited and how vulnerable it will be to water-related climate extremes.

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Justice Boundaries for Ocean Alkalinity Enhancement in Climate Scenarios

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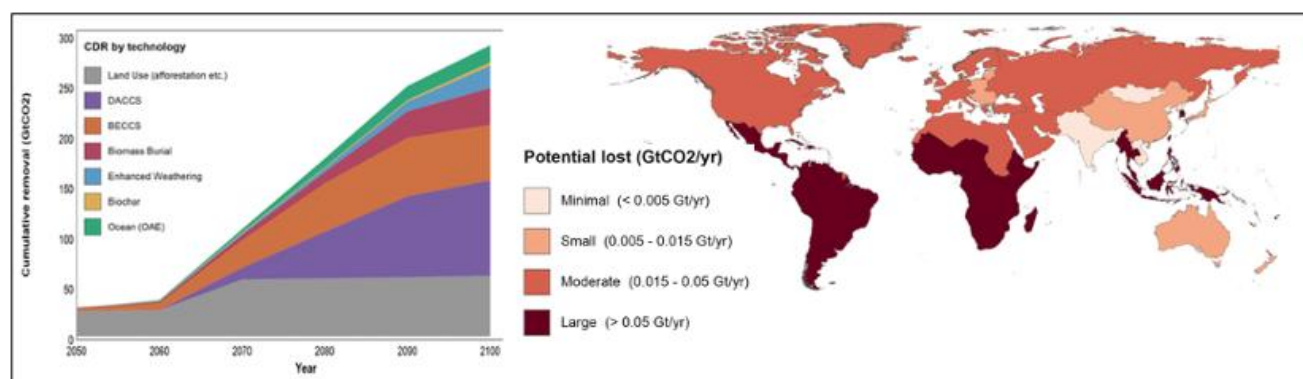
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Introduction. Carbon dioxide removal (CDR) is essential to climate mitigation, yet its justice implications remain underexamined. While conventional land-based and geologically stored CDR face rigid biophysical bottlenecks, Ocean Alkalinity Enhancement (OAE) emerges as a novel abiotic marine alternative offering a theoretical potential of 100 GtCO₂/yr; however, subduction and equilibration kinetics half actual delivery¹. Crucially, the ocean commons currently face a risk of unregulated deployment because the existing global governance landscape lacks the systemic guardrails required for marine interventions. To prevent intersectoral burden-shifting, we operationalize regional, justice-aware boundaries for OAE that complement established terrestrial sustainability protocols in MESSAGEix.

Methodology. To distinguish technical feasibility from the desirability of OAE deployment, we establish ethical showstoppers, grounded in environmental ethics theories and international agreements. We utilize the Nature Futures Framework² to map intrinsic, utilitarian or relational value baselines. By integrating a full spatial justice boundary – comprehensive of precautionary scientific designations, state reserves, and customary marine tenure, we enact epistemic and recognitional justice, rendering visible the ecological fragility and local sovereignty systematically overlooked by top-down governance.

Results. Under an 800 Gt carbon budget, unrestricted OAE contributes 17 of 294 GtCO₂ in cumulative 2100 CDR (5.8%). Applying a full spatial justice boundary reduces ~16% of global potential (0.68 GtCO₂/yr). Restricting the boundary to legal protections halves this to ~8% (~0.34 GtCO₂/yr), revealing how much recognitional justice is unaddressed by legal status alone. Regional impacts are highly uneven: Sub-Saharan Africa faces the sharpest absolute burden, losing 42% (0.38 GtCO₂/yr) of its potential, while Latin America faces a similar relative exclusion (39%) but loses 0.081 GtCO₂/yr.



Conclusions. Symmetrically integrating marine boundaries alongside terrestrial limits in MESSAGEix would enable comprehensive global sustainability runs — revealing how mitigation demand redistributes across the CDR portfolio depending on whether spatial boundaries are restricted to legal obligations or extended to precautionary protections, a distinction with direct consequences for policy design.

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Estimating the Temperature Response to Positive and Negative Carbon Emissions using Reduced-Complexity Climate Models

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Introduction. Remaining carbon budgets are a crucial tool in climate policy, estimating the amount of carbon emissions compatible with specific warming levels. Two climate metrics underpin these budgets, the Transient Climate Response to Cumulative Emissions (TCRE) and the Zero Emissions Commitment (ZEC). This framework can be enhanced with a third metric, the Transient Climate Response to cumulative carbon Removals (TCRR), capturing cooling from net negative emissions. Accurate estimates of these metrics are essential for effective carbon budget computation and overshoot assessment, as small differences can substantially affect compatible emissions. Here, we estimate these metrics using Reduced-Complexity Climate Models (RCMs) and assess their adequacy to provide such estimates.

Methodology. This study primarily relies on output from the third phase of the Reduced-Complexity Model Intercomparison Project (RCMIP3), whereby RCM simulations for almost a hundred experiments were compiled. Key to our approach is the computational efficiency of RCMs, which allows the generation of large simulation ensembles via simplified representations of the Earth system. We select a suite of idealised carbon experiments with different emissions levels and profiles, enabling a robust estimation of TCRE, ZEC, and TCRR. Additionally, output from more detailed, but crucially, more expensive Earth System Models (ESMs), is employed to identify potential discrepancies in model behaviour.

Results. Synthesising results across RCMs and experiments yields the following estimates (95% ranges): TCRE = 1.70 °C/TtC (1.14–2.72), ZEC at fifty years post-cessation = -0.07 °C (-0.33–0.19), and TCRR = 1.78 °C/TtC (1.17–3.14). TCRE and ZEC values are broadly consistent with previous literature, with likely estimates from the IPCC's last assessment report (AR6) being 1.0–2.3 °C/TtC and -0.3–0.3 °C respectively, supporting the suitability of RCMs for exploring these metrics. For TCRR, however, most RCMs exhibit strong reversibility, with several yielding TCRR values exceeding TCRE. This novel finding contrasts with most ESM results, which show TCRR values lower than TCRE. Our research suggests current RCM carbon-cycle formulations may not be adequately representing the progressive degradation of carbon sinks under persistent anthropogenic influence, particularly terrestrial ones, identifying future model development avenues.

Conclusions. This study provides robust estimates of three metrics central to carbon budget calculations, informing international and domestic climate policy and future assessments, including the upcoming IPCC Seventh Assessment Report. Per-model characterisation will guide future RCM development and uses. RCMs reproduce ESM temperature responses well under net-positive and zero-emission scenarios, but diverge under net-negative scenarios, with implications for their use in overshoot analyses. Future work should identify the source of this discrepancy and determine which models more plausibly represent the real Earth system, a question with direct bearing on the ongoing debate over overshoot pathways.

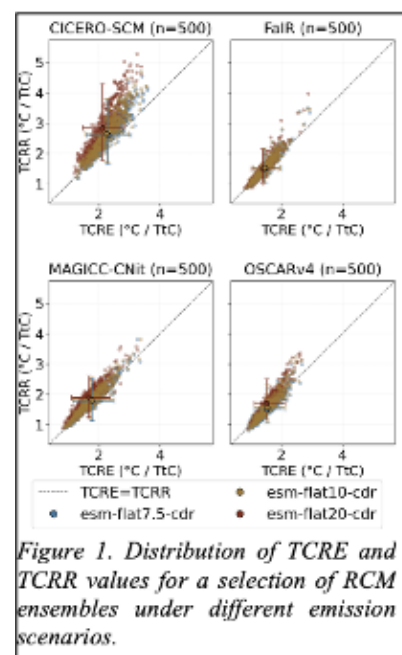


Figure 1. Distribution of TCRE and TCRR values for a selection of RCM ensembles under different emission scenarios.

Emulating Climate Mitigation Scenarios: Neural Surrogates and Reinforcement Learning for MESSAGE

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Introduction. Despite the intention of integrated assessment models (IAMs) to inform policy, their downstream application is often muddled by users treating sparse ensembles as statistical samples. Naturally, modelling infinitely many potential futures is impossible but current solvers are handicapped even further by the time a solution takes to run, the requirement for problems to be convex, and the deterministic nature of the results. This research set out to solve the first of those problems, using a machine learning surrogate of the underlying linear program to relieve the speed bottleneck. Over the course of the research, however, we realised reinforcement learning, used as an alternate solver, could tackle all three. As such, we developed both approaches.

Methodology. We built a MESSAGE-like system covering only the energy activity sub-problem: how much each technology generates, cost-optimally. This ran first as a single-period Austrian toy case, then across 129 countries (referred to as the n-country model), and finally intertemporally. Surrogates were trained on Austria and then the country pool and validated along three axes (See *Results*). The best n-country model predicted capacity utilisation fractions through a sigmoid layer, bounding activity by construction, with a price head supervised on LP duals and a differentiable Sinkhorn balancing step trained inside the network. For the intertemporal component, a reinforcement learning agent was rewarded not for choosing which technologies to use but which to invest in; the LP and the surrogate were each used inside it to decide activity within a period.

Results. Three primary results emerged: a validation table for measuring successful emulation, a functioning n-country surrogate, and converged RL agent for the intertemporal problem. The first was a precondition for the other as emulator validation has no settled standard. From a wider pool we settled on five metrics in three categories: regression (R^2), feasibility (bounds and energy-balance pass rates), and sensitivity (correlation between the surrogate's cost-response Jacobian and the LP's, and the diagonal of that correlation). The best n-country model achieved an R^2 of 0.98 and near-perfect feasibility, at 1.00 on bounds and 0.99 on sum, with a Jacobian correlation of 0.71, rising to 0.86 on own-price derivatives alone. When both the LP and the surrogate are batched, the surrogate is more than 300 times faster than the LP. The RL agent showed early promise: on the Austrian intertemporal problem, clearing activity through the LP, it converged on an investment schedule within 2% of LP-optimal result.

Conclusions. This research was a proof of concept, and it establishes MESSAGE sub-components can be emulated under validation spanning regression, feasibility, and sensitivity and much more quickly than the underlying LP. The research also demonstrates the potential of reinforcement learning as an alternate solver, addressing all three of the handicaps set out above: solve time, the convexity requirement, and determinism. Each component opens the door for widespread improvements in message and other like-solvers.

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Attributing Human Mortality from Compounding Dry and Humid Heat Events to Anthropogenic Climate Change in South Africa

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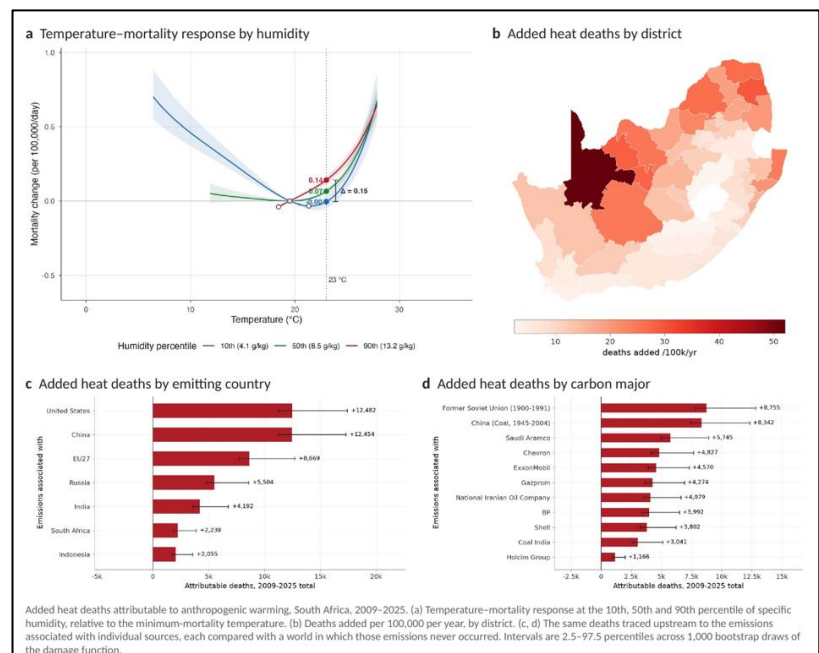
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Introduction. Climate change is increasing the occurrence of extreme heat events, with severe impacts on human health. Attribution science can quantify these impacts and trace them to their emission sources. Most attribution studies focus on climate hazards and are concentrated on data-rich, high-income countries. Regions facing the largest impacts remain under-researched. We address that gap for South Africa with the first end-to-end heat-mortality impact attribution. We ask what the relationship is between heat and mortality, whether humidity compounds it, how many excess deaths are attributable to all anthropogenic warming, and how many trace to individual emitters.

Methodology. Our source attribution pipeline follows three key steps: estimate the heat-mortality damage function; simulate a climate counterfactual without emissions; and apply the damage function to the factual and counterfactual climate worlds to estimate attributable excess mortality. To estimate the damage function, we regress daily mortality rate on a 4th order temperature polynomial interacted with specific humidity, with a 7-day lag and control for fixed effects to isolate plausible exogenous variation. We used 8.2 million death records from 2009 to 2025 and ERA5-Land climate data. We use MAGICC to translate emission scenarios into global warming levels followed by RIME-X to map that warming onto district climate variables. To isolate attributable deaths, we compare mortality across the factual and counterfactual climate worlds. We attribute mortality to emissions, and not responsibility to emitters.

Results. Over 2009-2025, South Africa would have experienced ~121,301 fewer heat deaths were it not for anthropogenic warming, and ~103,027 more cold deaths, a net of 18,274 additional deaths. There is unequal distribution of this burden across districts with heat death rates more pronounced in hot northwest and northeast. Humidity amplifies heat mortality. Results in the figures show the number of heat deaths attributable to emissions traced from countries and produces. Emissions were removed from 1990 for countries and 1965 for companies.



Conclusions. Anthropogenic climate warming has increased heat-related mortality in South Africa. Treating humidity as a modifier reveals an amplification that temperature-only models miss. Quantifying how many deaths are associated with emission sources adds evidence relevant to loss and damage discussions. The workflow we developed transfers to other socioeconomic outcomes and regional settings where outcomes data is accessible, and attribution evidence remains limited.

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Pollution Inequality and Sector Contributions across Post-Socialist European Countries

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Introduction. Despite air quality improvements across Europe since the 1990s, PM_{2.5} concentrations are approximately one-third higher in the lowest-GDP regions, which are primarily comprised of Central and Eastern European countries with legacies of socialism¹. After the fall of the Iron Curtain, socialist countries were left to rebuild their economies and transition from reliance on heavy industry, solid fuel usage, and delayed adoption of contemporary environmental standards. However, environmental improvements have varied throughout post-socialist countries, as geopolitical tensions, EU accessions, and climate policies have shaped the extent of widespread development². This project analyzes air quality improvement across measures of socioeconomic inequality for 20 post-socialist states from 1990 to 2025, to identify how emissions sectors have transformed pollution exposure across the region and which populations continue to bear the burden of exposure.

Methodology. PM_{2.5} concentrations and emissions contributions were calculated at the 1-degree grid cell level using IIASA's GAINS model for 1990 to 2025 (5-year timesteps). Concentration results were calculated as a population-weighted mean and stratified across income quintiles and urbanization gradients. Concentration and economic trends for each country were quantified as the ratio of mean PM_{2.5} to GDP per capita ($\mu\text{g}/\text{m}^3$ per \$1,000 int\$) and standardized using z-scores. Source-receptor transfer matrices attributed concentrations to seven aggregated sectors, retained as raw contributions and summing to the total concentration values.

Results. Across the study region, population-weighted PM_{2.5} exposure fell from 37.2 to 11.0 $\mu\text{g}/\text{m}^3$ (70.4% reduction) between 1990 and 2025. However, this decline was distributed unevenly across former geopolitical regimes, with former Yugoslavian states consistently showing higher concentration values, with a mean of 17.3 $\mu\text{g}/\text{m}^3$ in 2025, more than double the former USSR bloc. Former Yugoslavian states also have the largest range of exposure improvement, as their percent-change rate spans 68.9 points. EU members have reduced PM_{2.5} exposure by 65 to 82 percent since 1990. Power plant and industry sector emissions have decreased substantially between 1990 and 2025, and household combustion has become the largest source of exposure in all blocs. Within the former Yugoslavian bloc, the lowest-income quintile is exposed to 2.7 times as much household PM_{2.5} as the highest quintile and 2.9 times more from power plants.

Country	Bloc	EU	PM _{2.5} change	GDP change
Czechia	Other Eastern	Member	-82.4%	+350%
Slovakia	Other Eastern	Member	-81.8%	+436%
Latvia	USSR	Member	-75.3%	+508%
Lithuania	USSR	Member	-75.1%	+513%
Ukraine	USSR	Non-member	-74.8%	+149%
Slovenia	Yugoslavia	Member	-73.9%	+320%
Belarus	USSR	Non-member	-73.6%	+534%
Hungary	Other Eastern	Member	-73.5%	+420%
Poland	Other Eastern	Member	-71.7%	+723%
Moldova	USSR	Non-member	-71.3%	+176%
Croatia	Yugoslavia	Member	-70.5%	+415%
Estonia	USSR	Member	-69.6%	+571%
Bulgaria	Other Eastern	Member	-68.9%	+447%
Romania	Other Eastern	Member	-64.8%	+803%
Serbia	Yugoslavia	Non-member	-55.1%	+425%
North Macedonia	Yugoslavia	Non-member	-51.5%	+909%
Bosnia and Herzegovina	Yugoslavia	Non-member	-45.7%	+1839%
Montenegro	Yugoslavia	Non-member	-37.6%	+1314%
Albania	Other Eastern	Non-member	-24.9%	+775%
Kosovo	Yugoslavia	Non-member	-5%	+217%

Conclusions. Post-socialist states have improved their economies and air quality since 1990. However, these improvements have not occurred uniformly, with former Yugoslavian countries and non-EU members facing higher exposure burdens than others. Future work will explore sector emissions contributions in greater detail with linkages to policy development.

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High-resolution methane mitigation pathways in South Korea

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Introduction. Methane mitigation requires national pathways that identify both persistent sources and local implementation priorities. This study projects methane emissions from the covered sources in South Korea to 2050 and resolves their spatial distribution across 229 municipalities, linking energy transitions and non-energy measures to regional mitigation needs.

Methodology. MESSAGEix-ROK provides energy-combustion pathways; sector-specific activity projections and emission calculations represent agriculture, waste and selected industrial processes, drawing on IPCC inventory methods [1]. The NZ scenario reflects Korea's national carbon-neutrality plan and Global Methane Pledge objectives, using assumed measure effectiveness and uptake. Sector-specific activity shares and facility information allocate national emissions to municipalities. Energy fugitives are outside the study boundary.

Results. Covered emissions total 1,173.1 kt CH₄/yr in 2020. BAU reaches 1,094.2 in 2030 and 1,379.5 kt CH₄/yr in 2050; NZ reaches 697.7 and 830.2 kt CH₄/yr, respectively. NZ reductions from 2020 thus narrow from 40.5% to 29.2%. Managed-landfill measures and rice-water management account for 91.1% of the 2030 BAU–NZ difference. Agricultural activity growth and landfill emissions subsequently outweigh further energy reductions; agriculture supplies 75.2% of NZ emissions in 2050. Spatially, the ten largest municipal emitters' share falls from 25.7% in 2020 to 19.3% under NZ in 2030 (Figure 1), as landfill mitigation reduces emissions concentrated at major waste facilities, increasing the relative share of agricultural emissions distributed across municipalities.

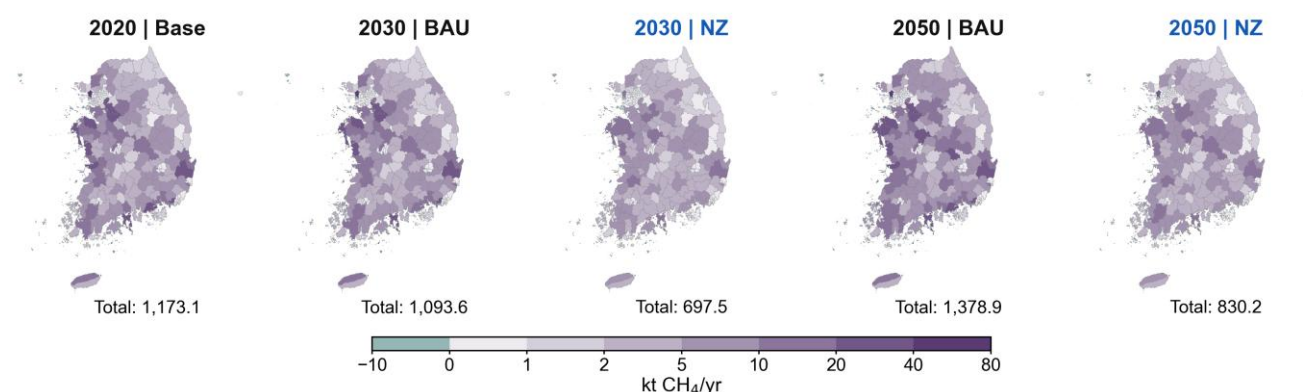


Figure 1. Spatial distribution of methane emissions in South Korea.

Conclusions. Near-term reductions depend on implementation: lowering assumed rice-water-management uptake to 30% and additional landfill-capture coverage to 50% raises 2030 NZ emissions to 837.9 kt CH₄/yr. Sustained mitigation requires verified capture performance at major waste facilities, coordinated feeding and manure measures in livestock regions, and water management in rice-growing areas. Additional measures beyond 2030 are needed to prevent activity growth from eroding earlier gains.

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Quantifying the demand-side mitigation potential of behaviour change in residential heating

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Introduction. Behaviour and lifestyle changes can make a substantial contribution to climate mitigation. However, integrated assessment models (IAMs) generally represent behaviour as static or exogenous, limiting their ability to capture how behavioural change evolves over time and influences future energy demand and transition. This study focuses on residential heating, where household decisions such as adjusting indoor temperatures, heat pump adoption, and insulation can affect both energy consumption and emissions. It aims to develop an endogenous representation of heating-related behavioural change and quantify its demand-side mitigation potential under a 1.5°C climate target.

Methodology. A self-developed, mechanism-based behaviour change model is coupled with the building sector energy model MESSAGEix-Buildings to represent evolving residential heating behaviours. The behaviour change model simulates how people move from perception and intention to real actions. These behavioural processes are passed to MESSAGEix-Buildings, where they influence household-level technology and building-related choices. MESSAGEix-Buildings then generates the corresponding adjusted residential heating demand, which is transferred to the MESSAGEix-GLOBIOM integrated assessment model (IAM) to assess the broader energy-system and emissions implications under different Shared Socioeconomic Pathways (SSPs) scenarios.

Results. The coupling exercise shows that different residential behaviours need to be represented through distinct pathways in MESSAGEix-Buildings. Temperature control, a typical direct saving behaviour, primarily affects realistic heating and cooling demand, while insulation and low-carbon housing influence building efficiency. Technology-adoption behaviours, such as efficient air conditioning and heat pumps, are mainly reflected through stock turnover and technology choices in MESSAGEix-Buildings. The implementation demonstrates that behavioural decisions can be consistently translated into changes in fuel/technology choices and building characteristics before being passed to MESSAGEix-GLOBIOM. It also highlights several areas requiring further refinement, including the treatment of interactions across multiple behaviours, consistency between assumptions in both behaviour change and build stock changes.

Conclusions. The coupled framework enables residential behaviour changes to be represented through explicit links to final heating energy demand, and then the wider energy system. Different behaviours are connected through behaviour-specific pathways, allowing a whole overview of impacts from behaviour changes. Further work will refine these pathways and improve the representation of interactions across multiple behaviours. Overall, the framework provides a basis for more realistic assessment of behaviour-driven demand-side mitigation.

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Empirically Calibrated Agent-Based Modelling of California Vehicle Choice

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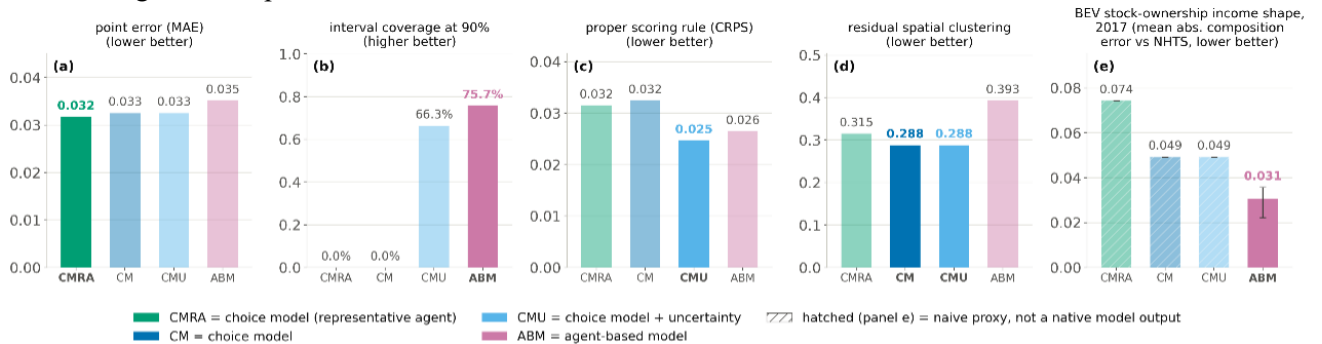
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Introduction. Agent-based models (ABM) offer a powerful framework for simulating complex systems of heterogeneous, interacting decision-makers (Hoekstra et al., 2017). However, they are difficult to calibrate, which limits their use for decision support (Windrum et al., 2007). This study applies neural simulation-based inference (SBI) to calibrate a large-scale ABM of household vehicle choice in California. It compares the ABM's predictive accuracy and uncertainty quantification against simpler fractional multinomial logit (FMNL) choice models.

Methodology. All models combine US Census data with public charging availability, political affiliation, rurality, and vehicle characteristics. They are calibrated to zipcode-level sales by powertrain from 2015-2024. The ABM runs on synthetic population data with fleet turnover and a used-vehicle market, and it estimates its parameters using SBI, extending work by Dyer et al. (2024). FMNL models are fit using maximum likelihood estimation. Models are scored on point accuracy, interval coverage, continuous ranked probability score (CRPS), residual spatial clustering, and the income distribution of battery electric vehicle (BEV) owners (how well they reproduce *who* chooses BEVs).

Results. BEV results are shown. Considering agent heterogeneity in models (all models except the representative agent variant, CMRA) and quantifying uncertainty (only CMU, the choice model with uncertainty, and the ABM) improve model performance: a small increase in point error (a) is outweighed by improvements in interval coverage (b), CRPS (c), residual spatial clustering (d) and the ability to recreate covariate relationships such as income (e). Compared with the choice model, the ABM has lower predictive accuracy but performs better at uncertainty quantification (b) and representing covariate relationships (e). Validation tools (not shown) attribute the ABM's residual misfit to model structure, not inference, offering a route to diagnose misspecification.



Conclusions. Model “performance” depends on the question asked: here, simpler models offer better predictive accuracy, while the ABM outperforms on uncertainty quantification. Agent heterogeneity drastically reduces residual clustering and error in reproducing the income distribution of BEV owners, at very low point accuracy cost. A realistic fleet turnover mechanism better represents who chooses which powertrain. In decision support contexts, ABMs can earn their complexity through distributional resolution and honest uncertainty, not point accuracy.

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Decent Living Standards, Climate Stress, and Child Undernutrition in India

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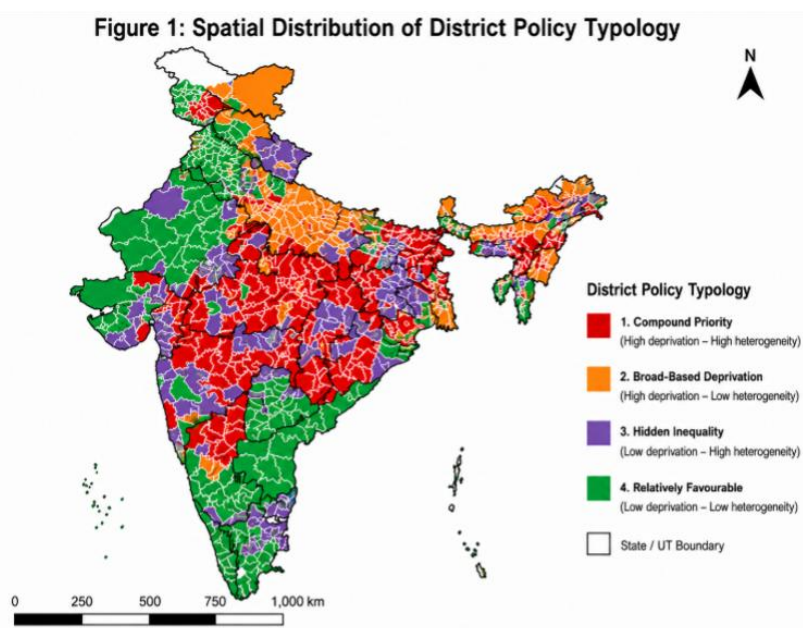
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Introduction. Child undernutrition remains a major public health challenge in low- and middle-income countries. Although household living conditions and climatic factors are independently associated with child nutrition, their joint influence remains poorly understood. Guided by the Decent Living Standards (DLS) framework (Rao & Min, 2017), this study examines how multidimensional household deprivation shapes child undernutrition in India, how hydroclimatic conditions modify this relationship, and how maternal nutritional status and district-level heterogeneity can inform targeted policy interventions.

Methodology. The study integrates household- and child-level data from the National Family Health Survey (NFHS-5, 2019–2021) with district-level Standardized Precipitation Evapotranspiration Index (SPEI) data. A multidimensional DLS Index was constructed for 636,699 households across 706 districts and linked with 214,026 children from 698 districts. Mixed-effects logistic regression was used to examine associations between DLS deprivation and child undernutrition, assess effect modification by dry and wet hydroclimatic conditions (SPEI-Dry and SPEI-Wet), and estimate the contribution of individual DLS domains. Generalized structural equation modelling was used to assess mediation through maternal BMI, while district-level heterogeneity was used to develop a policy typology.

Results. Household DLS deprivation was strongly associated with child undernutrition, with education, information, housing, and clean energy emerging as the most influential dimensions. Hydroclimatic conditions significantly modified the DLS–undernutrition relationship, while maternal BMI partially mediated the association, explaining 9.6% of the total effect. Districts with similar average deprivation differed substantially in within-district heterogeneity. Based on these two dimensions, four district policy typologies, Compound Deprivation, Uniform Deprivation, Hidden Inequality, and Relatively Favourable, were identified, providing an operational framework for geographically targeted nutrition and climate adaptation policies.



Conclusions. Household living standards are strongly associated with child undernutrition in India, with hydroclimatic conditions modifying this relationship and maternal nutritional status partially mediating the association. By integrating multidimensional household deprivation, climate stress, and district-level heterogeneity, this study provides a practical framework for identifying priority districts and informing geographically targeted, nutrition-sensitive, and climate-resilient interventions.

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Global Wildfire Projection under Climate Change

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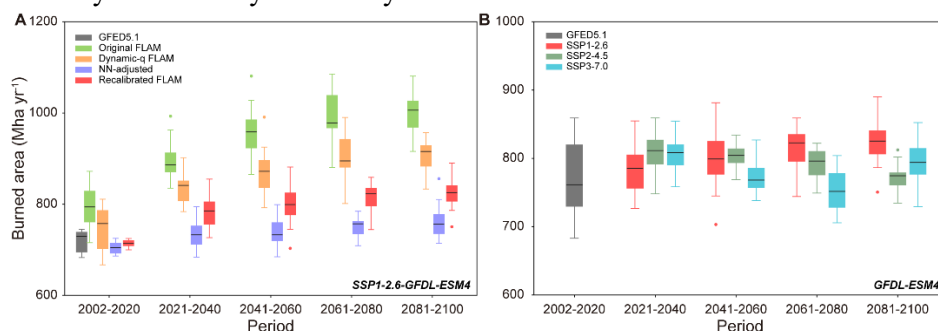
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Introduction. Wildfires are unplanned and uncontrolled fires in natural or semi-natural vegetation, shaped by interacting climatic, ecological, and human factors. Global burned area has declined overall in recent decades (Andela et al., 2017), but trends vary substantially across regions and ecosystems, while climate change continues to reshape wildfire patterns. Process-based models are therefore important tools for understanding fire mechanisms and projecting future changes (Krasovskii et al., 2018). This study focuses on the Wildfire Climate Impacts and Adaptation Model (FLAM), a process-based model for simulating historical wildfire activity and projecting future burned area. We dynamically calibrate key fire-spread and suppression parameters to improve agreement with observations and enhance the reliability of future wildfire projections.

Methodology. Building on FLAM, we develop a hybrid process–data-driven modelling framework. The fire suppression efficiency (q) generated by FLAM is dynamically represented using eXtreme Gradient Boosting, while a neural network adjusts the potential burned area (a) and the human fire suppression parameter (F_{supp}). These adjustments act as mechanistic corrections, absorbing influences that are difficult to represent explicitly in the process-based model. The dynamically estimated components are then fed back into FLAM to recalculate burned area, allowing the model to better match observations and improve the reliability of future scenario projections.

Results. Under SSP1-2.6 with GFDL-ESM4 forcing, the original constant- q FLAM projects a 2023–2100 mean burned area of 963 Mha yr⁻¹. Dynamic q reduces this to 879 Mha yr⁻¹, while the NN-adjusted and recalibrated- q estimates are lower at 747 and 808 Mha yr⁻¹, respectively. These correspond to mean reductions of 22.5% and 16.1% relative to the original FLAM, bringing the simulations closer to the GFED5.1. For future projections, the recalibrated model gives an average burned area of about 808, 793, and 780 Mha yr⁻¹ under SSP1-2.6, SSP2-4.5, and SSP3-7.0 during 2023–2100. SSP1-2.6 shows a weak increasing tendency; SSP2-4.5 gradually declines, whereas SSP3-7.0 decreases until the late century before recovering. These projections remain preliminary because they are currently based only on GFDL-ESM4.



Conclusions. The hybrid process–data-driven framework improves the agreement between FLAM-simulated and observed burned area, providing a more reliable basis for future wildfire projections. Our approach allows us to account for land-use change dynamics under each climate change scenario and their combined impacts on burned area, providing a more comprehensive basis for future wildfire projections. These improved projections can support more targeted wildfire management and adaptation planning under future climate scenarios.

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Reconstructing Global Fertilizer Product Use for Balanced NPK Management

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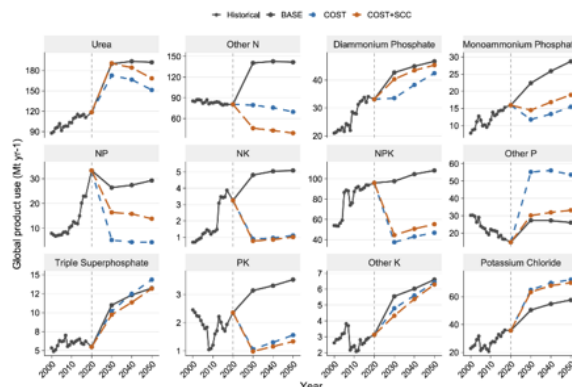
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Introduction. Mineral fertilizers sustain crop production by providing N, P and K elements, yet their product composition contributes to nutrient balance, expenditure and greenhouse-gas (GHG) emissions. Historical statistics are usually reported separately as products or nutrients, while many crop, economic and integrated models consider N, P and K balances independently. This limits assessment of feasible and affordable fertilization strategies in food-secure, low-nutrient surplus and low-carbon futures. To identify how product substitution can contribute to meeting crop N, P and K fertilizer demand while lowering fertilizer expenditures and GHG emissions during manufacturing and application, we develop a global spatially explicit framework that reconstructs national product portfolios and optimizes future product composition under agronomic and market constraints at 0.5° cropland grids.

Methodology. We harmonize country-year product use from IFASTAT and FAOSTAT into 12 fertilizer groups and use nutrient totals with product-specific N, P₂O₅ and K₂O contents to reconcile physical and nutrient accounts. Purchase prices and associated GHG emissions are compiled for fertilizer products across countries and years using published literature and datasets. Historical product mixes are then linked to two future fertilizer demand projections (baseline and soil-health-based), derived from the GLOBIOM model. For each demand scenario, we use a grid-level optimization to adjust future fertilizer product use to match N, P and K demands simultaneously while minimizing purchase costs (COST) alone or combined with the social cost of GHG emissions (COST+SCC).

Results. Global fertilizer product use increased from 325 Mt in 2000 to 452 Mt in 2020, with a growing share of compound fertilizers. High-income countries showed more balanced NPK use, while some upper-middle-income countries tended to over-fertilize. By 2050, under the soil-health-based demand projection, total demand increases to 659 Mt if assuming constant product shares, but the COST scenario reduces purchase cost by 38% and GHG emissions by 17% relative to the baseline. It shifts product use away from NP, NK, PK and NPK toward Other P, TSP and KCl. When a carbon price of US\$200 per t CO₂ is applied

(COST+SCC), purchase costs and the social cost of emissions are combined in a single objective; the resulting purchase cost is similar 35% lower and GHG emission is 33% lower than the baseline. This suggests that product substitution may be an important lever for sustainable fertilization strategies, with some trade-offs between climate mitigation and purchase costs reduction.



Conclusions. While the product composition of future fertilization strategies is routinely overlooked, our analysis shows that it can be a significant lever for reducing purchase costs and GHG emissions while maintaining crop nutrient demand. Our framework provides a practical basis for evaluating fertilizer policies, but future research is needed to incorporate endogenous product substitution into integrated models.

Aligning Nature Finance Objectives with Systematic Conservation Planning

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Introduction.

Nature finance mechanisms have become central tools for addressing global environmental crises such as biodiversity loss (UNEP, 2026). These mechanisms aim to promote nature-positive outcomes, yet remain disconnected from systematic approaches that identify where investments can deliver the greatest biodiversity benefits. Conversely, systematic conservation planning (SCP) has long supported cost-efficient and ecologically robust conservation decisions (Giakoumi et al., 2025), but rarely considers alignment with financial incentives, or risks. Here, we demonstrate how SCP can be integrated with nature finance through a case study for sustainable farming to identify where restoration investments can deliver the greatest ecological and financial benefits.

Methodology.

We apply a two-tier spatial optimization framework, implemented using the *prioritizr* R package, to guide farmland restoration investment decisions across a subset of farms in England. The first tier optimizes land allocation within individual farms, jointly maximizing biodiversity outcomes and farm production while integrating flood risk to determine how space is divided between restoration actions and continued agricultural use. This establishes the potential biodiversity and production outcomes achievable within each farm under alternative land-use configurations. These farm-level results provide the basis for a between-farm optimization tier, to prioritize farms for investments based on their potential to deliver biodiversity benefits and reduce flood risk.

Results.

Individual farms differed in their suitability for restoration, with some containing extensive areas for potential restoration actions, while others offered comparatively limited opportunities. Within farms, suitable restoration areas were unevenly distributed, for example with aggregations around areas relevant to flood-risk reduction. The resulting land-use configurations therefore varied among farms, reflecting differences in the availability and spatial distribution of restoration opportunities and the balance between biodiversity and agricultural production. At the between-farm level, these differences translated into distinct priorities for restoration investment. Farms varied in their potential to deliver biodiversity benefits and contribute to flood-risk reduction, such that farms offering the greatest opportunities for one outcome were not necessarily those offering the greatest combined benefits.

Conclusions.

Overall, our two-tier spatial optimization framework links within-farm restoration opportunities with between-farm investment priorities, identifying where restoration can deliver biodiversity benefits and reduce flood risk, thereby helping to reduce potential financial risks. Our findings demonstrate how SCP can be embedded within nature finance processes to support conservation investments that are both ecologically effective and financially credible.

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Supporting Agrohydrological Governance in Data-Scarce Regions with Inverted AquaCrop Modeling

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Introduction. Increasing hydrological extremes in developing regions (IPCC, 2021) are reducing the reliability of hydrological forecasts. Limited measurement of irrigation and rainfall introduces significant uncertainty in agro-hydrological analyses and water resource planning. High-resolution agro-hydrological data is critical for effective agricultural management, especially under climate change. The present study focuses on using plant growth indicators to simulate the soil moisture which will overcome the spatial resolution limitations of remote sensing and reanalysis products. The aim of the work is to leverage the agro-hydrological outputs of the inverse AquaCrop model to evaluate regional drought exposure, irrigation gaps, and other stress indicators under current and future climate change scenarios for cotton crop production.

Methodology. The AquaCrop model, inverted using the Covariance Matrix Adaptation Evolution Strategy (CMA-ES), was used to simulate seasonal irrigation requirements and soil moisture dynamics throughout the cotton crop growing season. Fifteen districts were selected in which cotton occupied >10% of the cultivated area based on SPAM 2020 and AICRP-Cotton datasets. ERA5-Land provided climatic variables. The yield-constrained inversion generated seasonal soil moisture estimates, Soil Water Deficit Index (SWDI), and Relative Water Content (RWC). Districts were clustered by climate and soil properties to assess field-scale water stress patterns during critical phenological phases.

Results. The three clusters formed based on climatic and edaphic factors are: Cluster 1, covering regions in North India; Cluster 2, covering Northwest India; and Cluster 3, covering central India. The inverse analysis revealed that the mean soil water content available during crucial phenological phases was highly variable, spanning from around 200 mm to above 450 mm. Cluster 1, which includes regions in North India, has a mean SWC of less than 300 mm during the flowering phase. Despite the higher SWC in Cluster 3, SWDI indicates Mild stress during the flowering phase. Cluster 2 has the least stress, with SWDI indicating surplus soil water availability in vegetative and reproductive phases.



Conclusions.

The study implements Inverse Crop simulation, a bottom-up approach for estimating seasonal soil moisture availability in cotton-growing regions of India. Analysis reveals North India faces acute water scarcity during the critical flowering phase, placing it at high risk of severe agricultural stress. Central India maintains adequate soil water content but experiences pronounced water stress during flowering, indicating high evaporative demand relative to available supply. These contrasting vulnerabilities require differentiated and adaptive water management strategies under current and future climate-driven hydrological stress conditions.

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Techno-Economic Allocation and Cost Minimization of Renewable Hydrogen and Syngas in Hard-to-Abate Sectors

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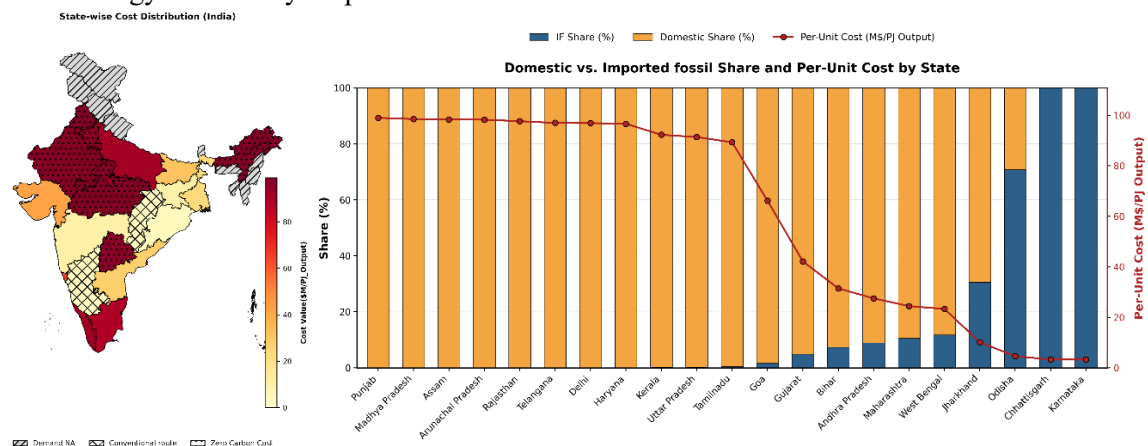
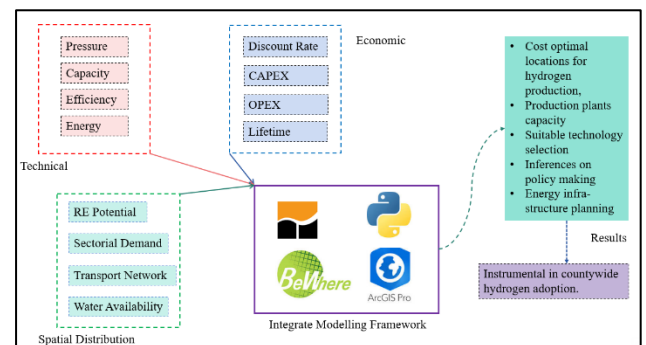
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Introduction. Integrating hydrogen and its derivatives into the existing energy landscape supports decarbonization, enhances energy security, and aligns with SDG 7: Ensure access to affordable, reliable, sustainable, and modern energy. However, adopting a new energy vector depends heavily on robust infrastructure and strategic planning, specifically the design of an optimal supply chain based on potential supply and demand nodes. To address this, the proposed problem focuses on facility location and cost minimization for hydrogen utilization in the fertilizer and refining sectors (produced via biomass gasification and electrolysis), while accounting for syngas utilization from coal gasification in the Indian steel industry.

Methodology. The problem was modelled as techno-economic cost minimization in the MILP formulation with the inclusion of spatial aspects. Figure illustrates the methodology in a schematic format.

Result. The supply chain cost was assessed to meet the demand for syngas in the steel sector and hydrogen in refineries and fertilizer industries, expressed in terms of million dollars per petajoule (\$M/PJ) of energy commodity output (syngas and hydrogen). A cost comparison was conducted for imported fossil feedstocks to meet the same demand. The results show that in the current base scenario, there are three instances: demand currently met by domestic resources (electricity, coal, and biomass), a combination of domestic and imported fossil resources, and entirely by imported fossil resources. The cost for these states ranges from \$98.99M/PJ to \$3.33M/PJ of energy commodity output.



Conclusion. A decrease in the imported fossil mix corresponds directly to an increase in the unit output energy cost. In the current scenario, for every 1 % decrease in the imported fossil fuel share, the estimated unit energy output cost increases by approximately \$0.48 M/PJ (equivalent to \$0.48 USD/GJ).

Climate, Governance, and Human-Elephant Conflict: A Coupled Agent-Based Model for Omo Forest Reserve, Nigeria

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Introduction. Human-elephant conflict in Omo Forest Reserve, Nigeria, emerges from interacting climate, land-use, governance, and livelihood pressures. Conservation actions that sustain elephants may also increase farm encounters and crop raiding, creating trade-offs for people and wildlife. This study develops a spatially explicit agent-based model (ABM) to examine how climate stress, logging, and enforcement jointly shape elephant persistence, farmer livelihoods, HEC, and protected-area habitat. The model integrates ecological and human decision-making processes and is grounded in fieldwork, spatial data, and climate forcing from Omo.

Methodology. The ABM uses a 500 m grid and monthly time steps, with elephant herds and heterogeneous farmers interacting across protected areas, farms, vegetation, and dynamic water. CHELSA rainfall, temperature, and potential evapotranspiration (Karger et al. 2017) drive drought, water, and heat stress. Behavioral rules draw on May 2026 fieldwork: six focus groups, 62 surveys, 12 key-informant interviews, one Baale interview, and GPS data from six communities. A full-factorial experiment combines three climates, three logging levels, and three enforcement levels. Preliminary results use 81 simulations (27 scenarios x 3 stochastic seeds).

Results. High enforcement is the strongest preliminary governance signal. Ranking management strategies within each climate places high enforcement in the top scenario for historical, future-low, and future-high climates, while the preferred logging level varies. Low HEC is not automatically desirable: some weak-enforcement scenarios record few crop raids because only about 5-15 elephants remain, whereas scenarios sustaining about 60-82 elephants retain greater crop-raiding pressure. Elephant persistence also declines under future climates even with high enforcement, indicating that enforcement buffers but does not eliminate climate-driven decline.



Figure 1. Equal-weight performance across elephant persistence, farmer income, low HEC, and habitat quality, ranked within each climate.

Conclusions. Effective enforcement is the most consistent management lever for elephant persistence, but conservation success can maintain crop-raiding exposure. HEC reductions should therefore be interpreted jointly with elephant abundance. Climate change reduces persistence, while preferred logging varies by objective and climate. Final inference will use the complete 270-run ensemble (10 seeds per scenario), with weighting sensitivity, Pareto screening, and uncertainty assessment.

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Collision or Avoidance: How Red Kites Navigate Europe's Wind-Energy Facilities

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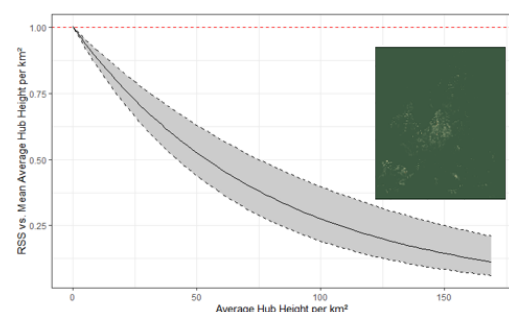
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Introduction. Wind power keeps expanding significantly in Europe to meet decarbonization targets. There are rising concerns, however, about accumulating bird losses, as turbine collisions are usually lethal. As a result, authorities are rapidly assigning mitigation measures that have not yet been empirically evaluated. The red kite is an ideal candidate to investigate how bird movement behaviour interacts with wind-power deployment. It is one of the large raptors that hunt or scavenge, and shows migratory and non-migratory behaviour. Its geographic range spans several EU members which allows international legislative action to improve mitigation measures. I investigated whether the presence and design of wind-energy facilities influenced movement behaviour at the European scale.

Methodology. I used GPS telemetry data¹ covering multiple countries which included tagging areas and migration routes, extending over the entire year. I combined these with a continental-scale dataset of wind-energy facilities providing location and technical characteristics. I used integrated Step Selection Analysis (iSSA) to analyse these data, investigating possible avoidance behaviour. iSSA examines and predicts habitat selection by comparing available and used habitat, taking movement restrictions into account². Specifically, I investigated whether wind-turbine density and turbine design (i.e., hub height, rotor diameter, capacity) influenced the movement decisions of the red kite, in particular looking at whether selection strength for an area was influenced by these variables.

Results. I found strong multicollinearity among hub height, rotor diameter, and power capacity. As a result, the final models included only one of these three variables at a time, together with turbine density. The best-performing models consistently showed a significant effect of hub height, while the other design variables were less distinct. Interactions between variables also showed no significant effects. Overall, hub height was the only turbine-design variable that significantly influenced red kites' movement behaviour. As

hub height increased, selection strength for the area decreased. Red kites thus preferred areas with turbines that had shorter masts, avoiding areas with taller turbines, independent of turbine density in the vicinity.



Conclusions. These results suggest that increasing hub height leads to increased habitat loss for the red kite. Conservation and collision-risk measures, especially repowering, should therefore be re-evaluated. Indeed, repowering replaces old turbines with fewer and more efficient models, typically with greater hub height. Previous non-empirical studies suggested that fewer, more efficient turbines would lower the risk of lethal collisions but did not account for habitat loss. Increased avoidance reduces collision risk, yet it also increases habitat loss. There is a need for future research to identify the distance at which avoidance begins relative to hub height, quantify the area of habitat lost, consider future wind-power developments locally, and compare impacts across species.

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EU pySRTS: Transplanting the Sub-Regional Timber Supply model to Europe

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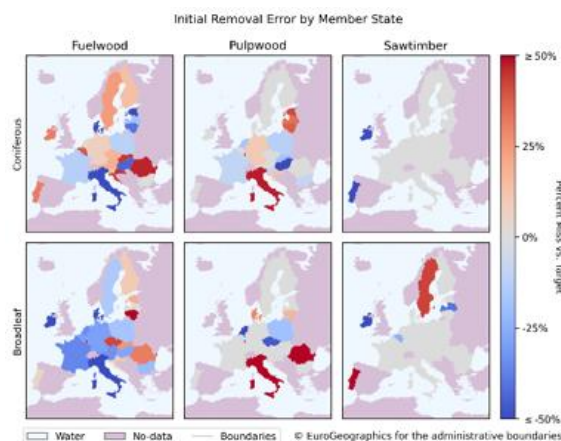
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Introduction. The Sub-Regional Timber Supply (SRTS) model is a forest economic model focused on the Southern United States (Abt et al., 2000). The next generation of the model, pySRTS, is ground-up rewrite focused on flexibility and modularity. The model operates at a local scale, considering the interaction between economic forces and ecological processes, allowing for detailed policy and scenario analysis of forest resources. This study aims to apply the model in the EU market, with individual countries serving as sub-regions, and explore the confluence of the European forestry sector, ecological and biological forces, and climate adaptation.

Methodology. The pySRTS model relies on detailed forest inventory and merchandising information to function. We link inventory data (Pilli et al., 2024 & 2026) with a DBH distribution dataset derived from PathFinder rasters (Miettinen et al., 2025). Removals are calibrated with FAOSTAT data (FAOSTAT, 2026). Several enhancements were made to the model including; settings for logging residues, a non-merchandised product type, and merchandising rules set by sub-region. When projecting future conditions, a new exogenous intra-forest land use change module shifts forested area towards ideal species composition targets.

Results. The addition of locally tuned merchandising rules was shown to dramatically improve model calibration. Compared with the 4 product projections, 6 products with local merchandising parameters produced a tighter fit to the FAOSTAT data and represented a broader cross-section of harvests. When considering climate driven forest adaptation targets (developed by IIASA), our projections showed forested area moving from conifer to broadleaf forest types. The market reacts to the increased availability of broadleaf inventory, driving prices down and inducing a shift in harvest patterns towards these forests.



Conclusions. We set out with two main goals for this research, 1) stand up and calibrate the pySRTS model in the EU and 2) develop projections of the EU forest resource and forestry sector under various LUC conditions. We developed a novel approach to construct DBH distributions and calibrated pySRTS with existing inventory data. The transition of forest composition via targeted replanting decisions highlights the impact climate-adaptation policy could have on European forests. We show that market forces react to these changes and harvests “chase” inventory availability, shifting current removal patterns away from coniferous forest types as then become scarcer.

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Low-Carbon Pathways for Global Water Scarcity Adaptation

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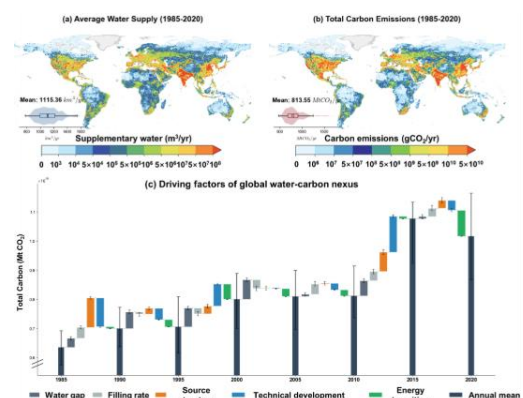
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Introduction. Climate change and growing water demand are intensifying water scarcity and reliance on supplementary water—additional water used to alleviate scarcity. Groundwater (GW) remains the dominant buffer, while four emerging sources—desalination (DE), wastewater reuse (WW), rainwater harvesting (RA) and inter-basin water transfer (IBWT)—are gaining importance but carry considerable energy and carbon costs. This study quantifies their role in water security, identifies carbon hotspots, and explores low-carbon adaptation pathways.

Methodology. A global 0.5° grid-level monthly framework was developed to quantify water, energy and carbon implications of five supplementary water sources (i.e., GW, DE, WW, RA, IBWT) during 1985–2020 and under 2050s. Water gaps, defined as unmet water demand after conventional surface supplies, were estimated using four hydrological and five climate models, combined with a global database of supplementary-water infrastructure and hydroclimatic conditions. Source-specific energy use was converted to carbon emissions using country-level electricity carbon intensity. Monte Carlo simulations capture uncertainty across climate-hydrology combinations, allocation processes and technology parameters. Future scenarios assess sustainable groundwater management, source expansion, water-use efficiency, technological improvement and electricity decarbonization.

Results. Supplementary water supplied $1115.4 \text{ km}^3 \text{ yr}^{-1}$ on average, filling 39.4% of the global water gap during 1985–2020. The share of emerging sources increased from 24.8% to 38.2%, but accounted for 70.8–84.1% of supplementary-water emissions, indicating a disproportionate carbon burden. IBWT and desalination had particularly high carbon costs, and the marginal carbon cost of scarcity alleviation increased by $7.1 \text{ g CO}_2 \text{ m}^{-3} \text{ yr}^{-1}$. A Water Security Dependence (WSD) index, combining water stress and dependence on supplementary water. Countries with both



above-median WSD and above-median emissions collectively account for 68.7% of global population, 73.1% of GDP and 74.1% of global crop production. By the 2050s, source expansion alone increases emissions by 19.8–21.4%, whereas combined efficiency gains, technological improvement and electricity decarbonization reduce emissions by 11.1–100.1% while maintaining water security.

Conclusions. Global water-scarcity adaptation is becoming increasingly carbon-intensive as emerging water sources expand. Low-carbon adaptation requires a shift toward lower water demand, sustainable groundwater use, efficient emerging sources and cleaner electricity, decoupling water-security gains from carbon emissions.

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Climate change alters groundwater–surface water connectivity, reshaping nitrate transport pathways

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IIASA Mentors Albert Nkwasa (BNR) and Rebekah Hinton (BNR)

Introduction. Climate change can alter watershed hydrology and nitrogen transport by modifying precipitation, evapotranspiration, runoff generation, groundwater recharge, and surface water-groundwater exchange. In agricultural watersheds, these shifts can change both the magnitude and timing of nitrogen export, particularly where shallow groundwater is strongly connected to streams. Nitrate can move through multiple surface and subsurface pathways and remain stored in aquifers before returning to streams (Tesoriero et al., 2009). Consequently, climate impacts should be evaluated using an integrated model that represents coupled surface and groundwater processes. This study assessed potential climate-change effects on watershed-scale hydrology and nitrogen dynamics using SWAT+ coupled with GWFLOW.

Methodology. The SWAT+ model (Bieger et al., 2017), coupled with the spatially distributed GWFLOW module (Bailey et al., 2020), was applied to the 346 km² Greensboro Watershed to simulate surface hydrology, groundwater flow, stream-aquifer exchange, and nitrogen transport. Following a 12-year warm-up (2006–2017), the model was calibrated for 2018–2020 and validated for 2021–2023 against streamflow, in-stream total nitrogen (TN), and groundwater heads. Four CMIP6 scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) were simulated with six GCMs. Ensemble changes were evaluated for near (2036–2050), mid (2061–2075), and far-future (2086–2100) periods relative to 2000–2014.

Results. KGE values were 0.49 for streamflow in both calibration and validation and 0.27 and 0.57 for TN, respectively. Historically, surface runoff and evapotranspiration corresponded to 56% and 44% of precipitation, while percolation corresponded to 7%. Recharge, boundary inflow, and stream seepage supplied 54%, 35%, and 10% of groundwater input, respectively, whereas saturation excess flow accounted for 91% of groundwater output. Ensemble-mean streamflow increased from 5.64 m³/s historically to 5.76–6.07, 5.88–6.32, and 5.76–8.15 m³/s in the near, mid, and far future. TN loads rose from 487 tons/yr to 553–581, 583–616, and 572–807 tons/yr, with NO₃-N driving most of the increase. Groundwater NO₃-N concentrations increased by 22–24%, 22–27%, and 9–30%, respectively. Under far-future SSP5-8.5, groundwater NO₃-N increased by only 9% as saturation-excess NO₃-N export rose by 79%, far exceeding the 8% increase in recharge NO₃-N input.

Conclusions. Climate change increased streamflow and nitrogen export by strengthening hydrologic connectivity among the soil profile, shallow aquifer, and channel network. Nitrate remained the dominant form of stream nitrogen export, while saturation excess flow was the principal pathway returning groundwater to surface water. Thus, a smaller rise in groundwater NO₃-N concentration does not necessarily imply lower nitrate delivery to streams when groundwater-to-surface-water fluxes intensify. Climate adaptation should therefore combine reductions in land-surface nitrogen inputs with management of nitrate leaching and shallow groundwater pathways, including riparian buffers, controlled drainage, and denitrification-enhancing practices. Absolute groundwater NO₃-N concentrations should be interpreted cautiously because groundwater nitrate was not directly calibrated.

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From FADN accounts to activity-based model input for policy impact analysis

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Introduction. Agricultural production models require activity-based input–output coefficients to represent heterogeneous farm production systems and their responses to policy changes. The Farm Accountancy Data Network (FADN) provides detailed microdata on farm resource endowments, financial accounts, and production, including crop areas, livestock numbers, agricultural outputs and yields. However, FADN does not directly provide the activity-based coefficients required for ex-ante policy impact analysis. This research addresses this gap by processing German FADN microdata and systematically mapping it with complementary activity-level data from CAPRI and KTBL, establishing a consistent data basis for input-output coefficient estimation and subsequent agricultural production modelling.

Methodology. German FADN on resource endowments, financial accounts, and agricultural production were processed and mapped to complementary activity-based data on input and labour requirements, prices, and costs from CAPRI and KTBL. Activities and variables across the three sources were systematically matched and harmonised with respect to definitions, units and aggregation levels. The resulting mapping links farm-level accounts and production structures to activity-specific technical and economic information, providing the data framework required for the estimation of activity-based input–output coefficients from FADN microdata and subsequent development and application of the agricultural production model PASMEG for Germany.

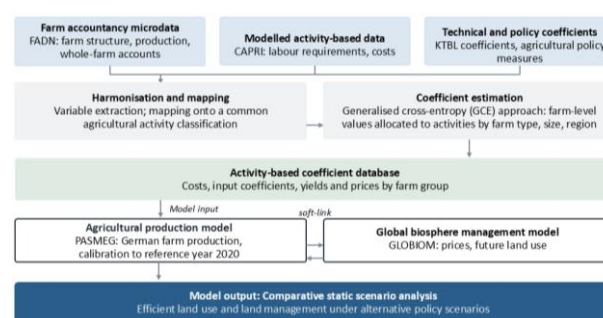


Figure 1: Conceptual overview of the project framework

Results. The project identifies which model parameters can be derived from observed farm data and where additional data or estimation is necessary. This framework thereby provides a data basis for two future applications: using the generalized cross-entropy approach to estimate activity-specific input–output coefficients for stratified farm groups and parameterising PASMEG. This creates a consistent link between farm heterogeneity and the activity-based representation required for agricultural production modelling.

Conclusions. The developed data framework bridges the gap between accountancy-based data in FADN and the activity-level data required for agricultural production modelling. Using FADN, CAPRI and KTBL provides a systematic and structured basis for representing heterogeneous farm production systems. Building on this framework, the next step is to develop an entropy-based approach that uses the mapped technical and economic information as a priori information to estimate input–output coefficients for different farm groups. These coefficients will support the further development and parameterisation of PASMEG and the analysis of policy changes.

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Geospatial Optimization of Municipal Solid Waste Management Systems: Environmental and Socio-economic Trade-offs

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Introduction. Municipal solid waste (MSW) management is an increasing challenge in rapidly urbanizing regions, where treatment infrastructure competes for land and creates environmental and social pressures. The performance of recovery technologies is strongly influenced by waste availability, transport requirements, plant scale, and spatial constraints (Ali et al., 2021; Bhowmick et al., 2024). This study applies a spatially explicit optimization framework to identify optimal locations, capacities, and technology pathways for MSW resource-recovery facilities accounting for geospatial aspects, population proximity, environmental constraints, and transport networks.

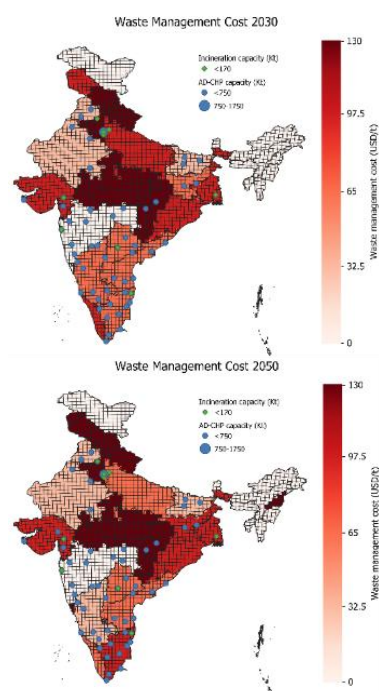
Methodology. A spatially explicit techno-economic assessment was conducted using the BeWhere model. MSW availability across India was estimated using population, state-specific MSW generation rates, and composition data. MSW management supply chain includes sorting and material recovery, followed by treatment through anaerobic digestion (AD), composting, and incineration. BeWhere applies mixed-integer linear programming to simultaneously optimize waste flows, transportation, technology selection, and location and capacity of facilities while minimizing total system cost. Scenario analysis was used to assess future waste availability, technology deployment, and environmental constraints.

Results. Preliminary results show that the cost of MSW management is relatively higher in Haryana, Madhya Pradesh, Chhattisgarh, and Telangana, compared with Rajasthan, Karnataka, and several northeastern states, reflecting spatial differences in feedstock availability, transportation, and treatment requirements. Comparison of the 2030 and 2050 results shows that the treatment network remains broadly distributed across major regions, while regional costs and technology deployment evolve over time. Total waste utilization increases by 15.70% between 2030 and 2050, indicating greater recovery of available feedstock. AD-CHP remains the dominant technology in both years, followed by AD-CBG, whereas incineration is selected at relatively few locations with smaller capacities, mainly because AD provides a lower treatment cost. Overall, the results highlight the importance of spatially differentiated MSW management strategies across India.

Conclusions. The spatial optimization highlights that cost effective MSW management in India requires region-specific infrastructure planning. Overall, AD emerges as the dominant treatment option, while incineration plays a more limited and localized role. The wide variation in state level waste management cost emphasizes the importance of feedstock distribution, transport requirements, and technology selection in shaping the optimal system.

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Signals of Agroecology: Linking Practices, Diets and Food-System Diversification

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Introduction. Food-system transition revolves around dietary change, however, such a disruption in consumption patterns would require a deep reorganization of farming systems. At the national level, the UK Food Strategy and Agricultural Transition Plan converge on themes such as supply resilience, sustainable growth, and healthier food environments, yet rarely resulting in shared interventions. Agroecology-based policy could bridge such gap (Tittonell et al., 2020), contingent on scaling the agroecological transition (AET) into large commercial farming settings. Assessing how widespread agroecological practices are, is the starting point for informing such interventions.

Methodology. Practice indicators were developed to capture AET from routinely collected farm survey data (FBS). Because practices differ in how much farm restructuring they require, two distinct families are built. Action-based indicators (cover cropping, companion cropping, legume leys) leave signals in farm data on how operations are carried out. Process-based indicators (crop-livestock integration, diversified cropping) capture land structure, synergies and feedbacks. Both map to different stages of AET. These indicators empirically calibrate the FABLE agroecology module by supplying adoption rates, practice bundles, and commodity mixes. Since FABLE outputs only national totals, blind to differences between adopting and non-adopting farms, a mathematical framework was built to recover how each group must change as adoption is scaled.

Results. Action-based practices are grounded in around 17% of farms (14–20%) and process-based practices around 12% (8–16%). Against a multidimensional agroecology score (TAPE), adopters emerge as a distinct subsystem: adopters score 1.6× higher overall, with process-based adopters driving the gap (1.8×). These indicators identify the commodities disproportionately affected by adoption in FABLE. The mathematical framework estimates how much of the modelled outcome depends on adopting and non-adopting farms converging in their commodity mix. Under a dietary-change scenario (EAT-Lancet), the new consumption dominates land-use patterns (−8.4% diet-induced change from BAU, −389 kha), while action-based practices spare 257 kha of agricultural land, with 2% of such savings conditional on diversification strategies. Diversification leaves a footprint even in such setting: action-based practices are, by design, efficiency measures with mild yield effects; adopters' diversification strategy should matter least - hence the 2% is effectively a floor, expected to rise for process-based indicators.

Conclusions. Secondary data signals let modelling imagine an agroecological future, but the conditions for reaching it lie in the farming system's own transformation dynamics, not in adoption alone. Continuous farm-level monitoring is the key for UK food-system interventions: identifying where policy should target diversification and integration alongside practice adoption is necessary to scale agroecology for healthier and more sustainable diets.

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Integrating Birch Timber and Early-Thinning Biomass Harvesting with Ecological Retention in Swedish Production Forest Management

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Introduction. Young forests in Sweden hold substantial but underused energy biomass, as early-thinning material is often left on site due to low harvest volumes and high extraction costs. Biomass harvesting can affect ecological values. This study examined whether early-thinning biomass harvesting can be combined with ecological retention, and assessed the resulting long-term economic returns, trade-offs, and retention costs.

Methodology. We compared business-as-usual (BAU) management with alternatives involving early-thinning biomass harvesting and modified thinning timing, and tested birch timber recovery at final felling as an additional revenue strategy. We assessed economic performance using land expectation value (LEV) over repeated rotations. We further quantified the economic cost of retaining green trees, broadleaves, high stumps, and deadwood at low and high levels to assess trade-offs with ecological retention.

Results. LEV varied considerably across management strategies, treatments, and site fertility. On average, alternative management performed similarly to BAU, indicating that modified thinning timing did not systematically reduce long-term returns. Birch timber recovery at final felling generally maintained or improved economic performance. No single strategy was consistently superior across comparisons (Figure 1). Fertility influenced the magnitude of returns. Alternative management, biomass harvesting, and birch timber recovery could match conventional management under several combinations. Ecological retention costs varied with type and intensity, with stronger retention generally more costly.

Conclusions. Overall, the results suggest that early-thinning biomass harvesting and higher-value utilization of birch can be combined with targeted ecological retention without substantially reducing long-term economic performance. The feasibility of such management depends particularly on the type and intensity of retention. This provides scope for management strategies that simultaneously mobilise currently underused biomass, improve birch utilization and maintain ecologically important forest structures rather than treating these objectives as mutually exclusive.

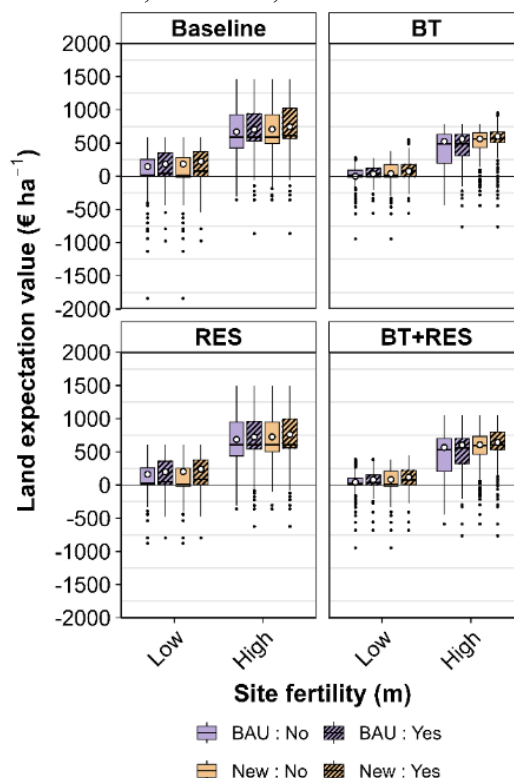


Figure 1. Land expectation value (LEV, EUR ha⁻¹) across silvicultural treatments at a 2.5% discount rate and Low and High site fertility. Treatments are Baseline, first-thinning biomass harvest (BT), residue extraction (RES), and their combination (BT+RES). BAU and New denote conventional and species-specific mixed-forest management, respectively; No/Yes indicate without/with birch timber recovery at final felling. Boxes show stand-level distributions and medians; black points are outliers and white circles are model-estimated means.

“Friction by Design”: Joint Water Assessment and Science Diplomacy on the Nile

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Introduction. This research examines the Strategic Water Resources Analysis (SWRA) under the Nile Basin Initiative (NBI) as a case of collaborative science diplomacy in a shared and politically contested river basin. Focusing on a decade-long joint water assessment through which nine Nile Basin countries sought to build a shared understanding of basin-wide water availability, use, future demand and management options, the study asks what the SWRA achieved, where it faced difficulty, and what lessons it offers both for future rounds and for scientific cooperation more widely, along the Nile and beyond.

Methodology. The study analyses the SWRA as an exercise in boundary work (see Gieryn, 1983; Guston, 2001), assessed against the criteria of salience, credibility, and legitimacy (Cash et al., 2003). It draws on eleven semi-structured interviews with individuals closely involved in the process, including country representatives, NBI technical staff and modellers, and international partners, alongside a review of NBI documentation. Interviews were analysed thematically, using a self-developed coding framework, based on the proposed conceptual framework and structured around the process, the tensions it revealed, its achievements, shortcomings, and uptake.



Figure 1 The SWRA Process

Results. Bringing multiple countries’ data and development plans onto a single shared platform inevitably gives rise to friction. This study treats the SWRA’s friction not as a failure of joint assessment but an inherent and often productive (see Tsing, 2005) feature of it: where engaged with, it becomes part of how countries build a common evidence base and a sense of ownership over the results. The study terms this “friction by design.” Assessed against the analytical framework, the SWRA scored highly on salience and drew legitimacy from its political mandate, producing the first basin-wide hydrological baseline, the first sharing of national development plans in an intergovernmental setting, and a shared methodology now informing investment planning. Yet challenges reflect a *legitimacy-credibility trade-off*, particularly where avoidance of tension constrained its technical credibility.

Conclusions. For future rounds of the SWRA, the findings point to sustained engagement of country modellers, clearer data and IT protocols and decision-ready communication. More fundamentally, bringing national data and plans onto a shared platform is bound to reveal disagreement rather than remove it. The objective is not to eliminate such friction, but to build the institutional capacity to manage it constructively – a lesson from which the wider practice of joint water assessment for science diplomacy can draw lessons.

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***Advancing Systems Analysis
(ASA)***

Why Some Communities Cope Better with Floods: Investigating Realized Flood Resilience in Southwest China

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Introduction. Flood risk is intensifying under climate change, making community resilience an urgent topic. Current literature mostly studies latent resilience through indicator systems of capacities, capitals, or resources. Yet in the face of actual floods, possessing resources does not mean they can be activated and translated into lower impacts and faster recovery. This leaves an important gap: evidence and integrated methods for quantifying realized resilience and identifying the factors that shape it remain limited (Chapagain et al., 2025). Focusing on flood-affected mountainous communities in Southwest China, this study asks: (1) How can realized flood resilience be quantified? (2) What are the most likely causes (adaptive capacities and adaptation measures) of high realized resilience?

Methodology. Using 1,463 valid household surveys from 63 communities and 29 expert surveys, we developed a hybrid framework combining recovery-curve estimation with Bayesian Networks (BN). First, we used survey data to estimate four parameters (robustness, response, recovery, and reconfigurability) to construct community recovery curves after flood events (Tang and Shen, 2024) and measure the loss triangle to represent relative resilience levels (Bruneau et al., 2003). Second, the BN presented probabilistic dependencies among adaptive capacities, adaptation measures, flood intensity, and realized resilience, enabling forward and backward inference. K-means and silhouette analysis discretized indicators into Low and High states. Structure learning used theory-constrained hill climbing with the K2 score; parameter learning used a K2 prior for observed nodes and constrained EM for latent nodes.

Results. Recovery curves varied across the 63 communities, with a mean recovery time of around 21 days. In backward inference, generic adaptive capacities, including income, livelihood diversification, social cohesion, and education, generally showed larger posterior probability increases than flood-specific capacities such as self-efficacy, local knowledge, and risk perception. Information communication was the exception. Among adaptation measures, household agricultural adaptation showed the largest percentage-point increase, whereas community flood management and household dwelling adaptation led in relative change. Forward inference showed the largest increases in the predicted probability of high resilience when community flood management and household dwelling adaptation were set to High. Income and information communication were the strongest capacity indicators.

Conclusions. This study offers a transferable methodological framework that moves from latent capacity indicators to realized recovery processes and captures probabilistic interdependencies among community resilience factors under uncertainty. The findings suggest that realized resilience is linked not only to adaptive capacities but also to their translation into concrete adaptation measures. The next step is to strengthen the robustness of the BN analysis.

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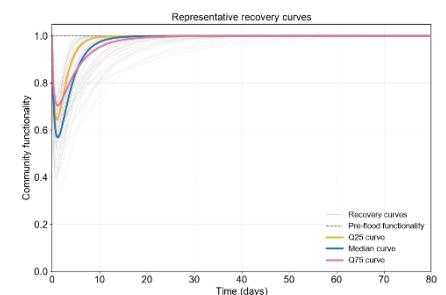
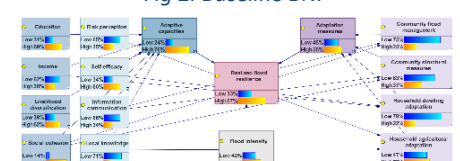


Fig 1. Estimated community recovery curves.

Fig 2. Baseline BN.



Extending OSCAR-fire: From Carbon to Multi-species Wildfire Emissions

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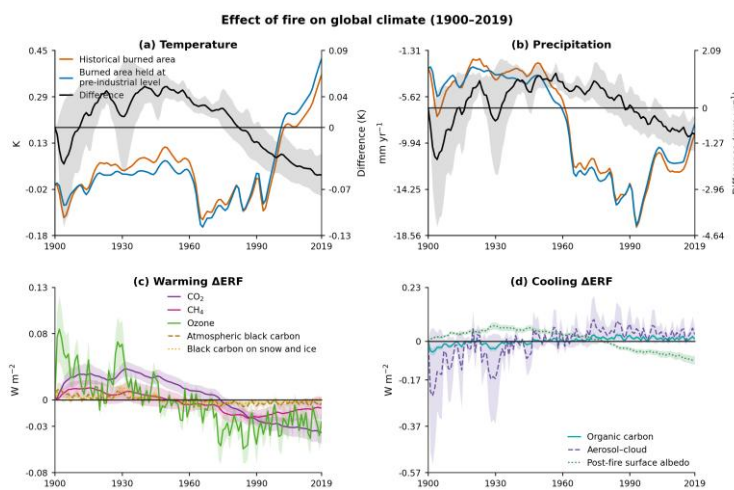
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Introduction. Wildfires are a significant disturbance to the Earth system, emitting a wide range of pollutants that influence atmospheric composition, radiative forcing, and ultimately climate (Li et al., 2025). These pollutants span greenhouse gases, aerosols, and reactive trace gases, each acting on different timescales and through different mechanisms, making their combined climate effect difficult to constrain (Zheng et al., 2023). Despite this complexity, most Earth system models treat wildfire emissions in a simplified way, limiting our ability to assess how changes in burnt area feed back onto the climate system.

Methodology. GFED5 wildfire emission factors are incorporated across biomes and fuel pools within OSCAR's framework to simulate multiple pollutant including aerosols, reactive gases, and greenhouse gases. Fire-induced albedo changes are parameterized from satellite-derived observations, with post-fire recovery tracked using biome-specific vegetation regrowth rates. Radiative forcing from both multi-pollutant concentration changes and albedo perturbations is then passed to climate module in OSCAR to simulate temperature and precipitation responses.

Results. Wildfire multi-pollutant emissions simulated by OSCAR broadly capture the regional patterns of the GFED5.1 assessment, with simulated global totals ranging from 60% to 81% of GFED5.1 values across species. Over 1900-2019, historically varying burnt area produces a small net warming relative to fixed preindustrial conditions on average. Aerosol-cloud interactions dominate the forcing response and drive most of the interannual variability, while burnt area albedo contributes a relatively larger signal, reaching around -0.08 W m^{-2} by 2019. The global temperature response averages around $+0.005 \text{ K}$ over the full period but shifts to approximately -0.055 K by 2019, consistent with the forcing trend. Precipitation responds in a similar direction.



Conclusions. This study shows that multi-pollutant wildfire emissions have a modest influence on the climate system, with aerosol-cloud interactions acting as the dominant forcing mechanism and burnt area albedo contributing meaningfully toward the end of the simulation period. Interannual changes in burnt area produce a weak net cooling effect on global temperature and precipitation. Burnt area variability therefore modulates the radiation budget and surface climate on interannual timescales.

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Shelterbelts Monitoring and Their Impact on Farmland Resilience

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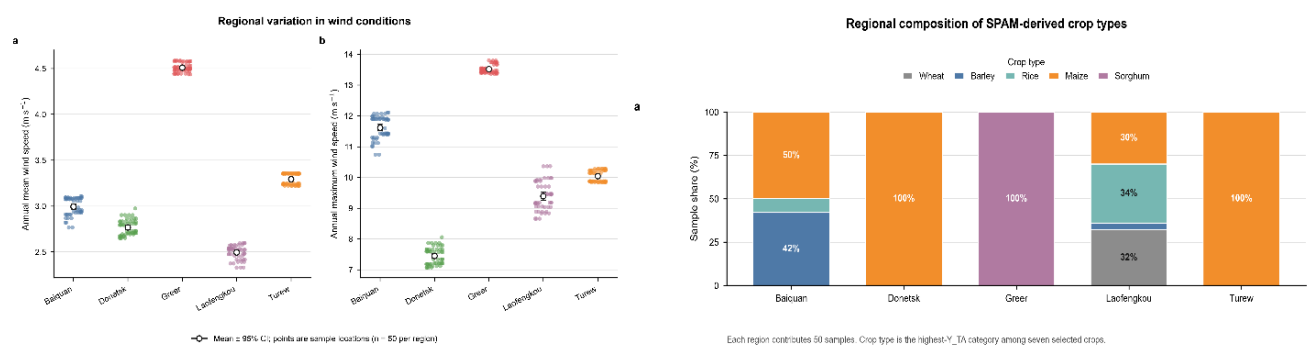
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IIASA Mentors: Juan Carlos Laso Bayas (ASA) and Milutin Milenkovic (ASA)

Introduction. Farmland shelterbelts are intentionally established linear woody vegetation systems located within agricultural landscapes and composed of trees, shrubs, or their combinations, whose primary purpose is to protect agricultural production by modifying wind, water, energy, and ecological processes in adjacent croplands. As a green farmland infrastructure, farmland shelterbelts hold significant importance for food security, biodiversity and the resilience of farmland. Now, the use of vision models for the comprehensive evaluation of farmland shelterbelts remains limited in existing research and when assessing the impact of shelterbelts on the resilience of farmland, farmland is always regarded as an entity without considering for its spatial heterogeneity. This study aims to establish a farmland shelterbelt assessment dataset by developing a scientific and reproducible evaluation framework for farmland shelterbelts. And try to Implement a knowledge-guided hybrid model for automated shelterbelt quality assessment in the future.

Methodology. Following a review of existing methods for monitoring and evaluating farmland shelterbelts, and several rounds of consultation with domain experts, we developed a preliminary expert knowledge-guided framework for assessing the protective effectiveness of farmland shelterbelt. The framework integrates shelterbelt structural integrity, connectivity and width with regional wind speed and wind-direction metrics, as well as crop susceptibility to wind damage, to provide a comprehensive evaluation of shelterbelt protection. Wind metrics were derived from the ERA5-Land dataset, whereas crop susceptibility to wind damage was inferred from crop-type data extracted from the SPAM dataset. Finally, the integrated data were uploaded to the Geo-Wiki platform for the annotation of comprehensive farmland shelterbelt protection assessments, thereby establishing an initial dataset.

Results. We extracted hourly 2020 eastward and northward wind components for the five study regions from the ERA5-Land dataset and derived regional annual mean wind speed, maximum wind speed, and the direction associated with the maximum wind speed (Fig. 1 left). Regional yield data from the SPAM dataset were then used to identify the dominant staple crop types and infer their susceptibility to damaging winds (Fig. 1 right). Region-specific sampling schemes were developed by integrating wind and crop characteristics. We randomly selected 50 sample points in each region, yielding a preliminary dataset for evaluating the protective effectiveness of farmland shelterbelts. This dataset will be used to train a calibration model and support its subsequent expansion.



Conclusions. This study established an integrated, expert-informed workflow for building a preliminary dataset to assess farmland shelterbelt protective effectiveness across five regions. Hourly ERA5-Land wind data characterized regional wind regimes, while SPAM yield data identified staple crops and provided a proxy for crop sensitivity to damaging winds. The resulting patterns revealed spatial variation in wind exposure and crop composition, supporting sampling designs. Fifty selected points per region produced a 250-point reference dataset for Geo-Wiki-based evaluation. This dataset can be used to train a calibration model for further sample expansion, ultimately producing a high-quality dataset for training a vision model and providing a foundation for assessing the protective effectiveness of farmland shelterbelts.

Power Grid Topology as the Binding Constraint on AI Data Centre Cascade Risk: Evidence from Texas

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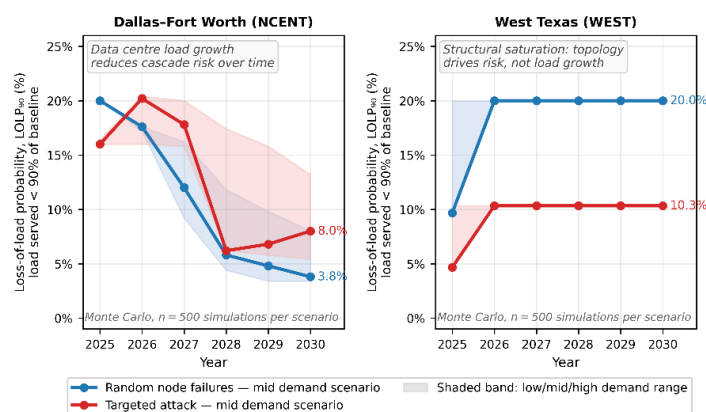
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Introduction. The rapid deployment of AI data centres is adding gigawatt-scale electricity demand into specific regions of the U.S. grid faster than transmission infrastructure can adapt. Unlike conventional loads, AI data centres are active grid participants: they can island, generate behind the meter, and draw synchronised demand surges. Texas hosts the world's largest concentration of this investment, connecting into regional grids of different architectures — a meshed network in the Dallas–Fort Worth corridor (NCENT) and a radial spoke network in the Permian Basin (WEST). This study asks whether and how grid topology, and the connection type of individual facilities, determine systemic grid risk from AI demand growth.

Methodology. A three-layer linearised power flow cascade model is constructed from regional subgraphs of the Texas2k synthetic grid, calibrated to 2025 summer peak: (1) transmission network, (2) data centre facilities mapped to grid buses using interconnection filings and regulatory permit records, (3) behind-the-meter generation differentiated by self-powered or grid-dependent withdrawal status. For each scenario, 500 Monte Carlo cascades simulate random and targeted substation failure, recording loss-of-load probability, mean load served, and cascade depth; cascade directionality covers both grid-to-facility propagation and facility-initiated disconnections. Nine scenarios vary demand growth (2025–2030), behind-the-meter generation coverage fraction, emergency backup duration, and new-entrant connection type.

Results. The two regions (NCENT and WEST) differ in structure: the former densely interconnected, the latter routing power through a handful of critical hubs. In NCENT, power-flow-weighted network analysis highlights four substations and eight transmission line pairs that most reliably trigger the deepest failures. AI load growth in NCENT reduces outage risk from one-in-five to one-in-thirty by 2030, as new facilities add redundant load paths. In West Texas, risk stays flat because vulnerability is set by how the grid is built, not by how much it carries. Among the interventions tested, only on-site generation coverage reduces risk — and only above a sharp 90% threshold. Demand flexibility and emergency backup extensions have no measurable effect. Data centres act as active risk agents: disconnection-triggered cascades elevate risk, and surviving facilities amplify severity by 13–53%. When new data centres connect to the shared grid rather than generating their own power, regional outage risk doubles.



Conclusions. Grid topology and connection type are primary drivers of AI data centre cascade risk. Interconnection rules should treat self-powered and grid-connected facilities differently, and siting standards should reflect grid structure, with topology-aware regulatory requirements calibrated to local cascade risks. Reliability standards should treat data centres as active participants in grid failures, and be updated to reflect their evolving operational role in grid dynamics. Beyond Texas, the risk mechanisms identified are applicable to regions where concentrated AI load meets constrained transmission infrastructure.

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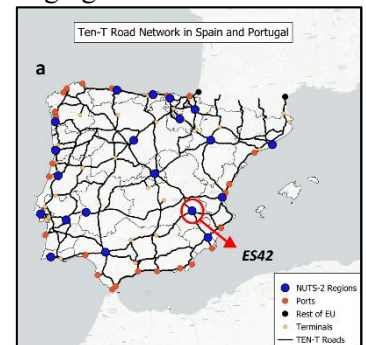
Supply-Chain Criticality of European TEN-T corridors under flood risk

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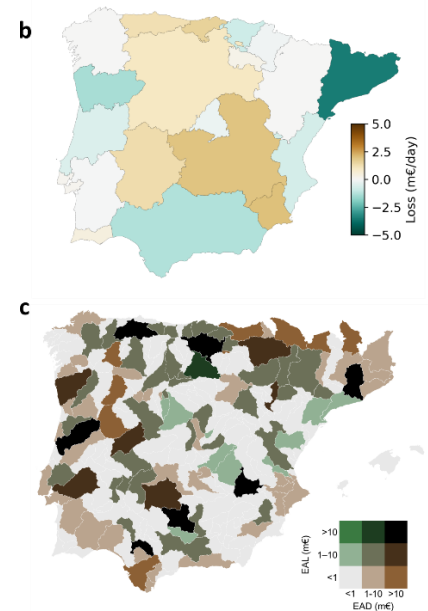
IIASA Mentor: Celian Colon (ASA)

Introduction. Natural hazards such as floods can disrupt transportation networks by damaging roads and impeding freight movement, thereby generating system-wide economic losses. Hence, adaptation of road networks to climate-related extreme events is imperative. However, conventional disaster risk (and adaptation) approaches often prioritize direct infrastructure damage while overlooking the economic consequences of network disruption (Colon et al., 2020). This research proposes a framework for assessing road criticality by integrating infrastructure damage modeling with transportation network and economic impact modeling. The framework is demonstrated using the Trans-European Transport Network (TEN-T) road network in Spain (ES) and Portugal (PT) (see Figure a).



Methodology. The framework comprises three modules: (a) a damage module estimating reconstruction costs, (b) a network module quantifying increased travel distances post-disruption, and (c) a Multi-Regional Impact Assessment (MRIA) (Vanniya Perumal et al., 2026) module estimating region-wide economic losses. Simulations across river catchments in ES and PT for different return periods generate estimates of Expected Annual Damage (EAD) and Expected Annual Loss (EAL) measures, for each catchment.

Results. We report two key findings. First, road network disruptions generate spatially differentiated regional impacts. Figure b shows the distributed effects for a flood event in Castile-La Mancha, Spain (see ES42 in Figure a). Regions along the disrupted corridors experience negative impacts, while less-dependent regions may benefit from supply-chain redistribution, depending on the extent of substitution possible. Second, the criticality map in Figure c shows that regions experiencing the greatest physical damage are not necessarily those generating the largest economic losses.



Conclusions. The study concludes that neglecting economy-wide effects can lead to incomplete assessments of road network criticality and, consequently, suboptimal adaptation decisions. By quantifying the broader economic consequences of network disruptions, our approach supports infrastructure resilience planning and the prioritization of adaptation measures. This framework can be extended to other transport modes and geographic scales to identify critical trade corridors.

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Innovating Disaster Risk Reduction through a Novel Population Health Resilience Index

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Introduction. Understanding disaster risk as a population health phenomenon is a global policy priority in disaster risk reduction (DRR), but existing indices rarely integrate population health comprehensively, treating health as a downstream outcome rather than a dynamic risk driver.¹ This study develops a conceptual framework grounded in systems-based models to operationalize a health-centered perspective through construction and validation of a novel Population Health Disaster Resilience Index (PHDRI).

Methodology. A county-level PHDRI was constructed and validated using the Southeastern US from 2013-2019, with 2016-2017 as the hurricane exposure period (N=1,054) following guidelines for formative index development.² Data from 8 publicly available sources reduced 316 potential indicators to 64 after expert review, analysis of missing data, transformation, directionality, and multicollinearity assessment.² These indicators were organized into 19 sub-categories across 5 domains based on the conceptual framework. Sub-category scores were variance weighted and aggregated into domain scores, which were aggregated into index scores with equal weights. The final index was symmetrically mean centered to range from -1 (high vulnerability) to +1 (high resilience) and categorized into 7 levels using 0.25, 0.5 and 1.5 standard deviations above and below the mean. Convergent validity was assessed by correlating PHDRI scores with pre-existing indices of vulnerability and resilience.

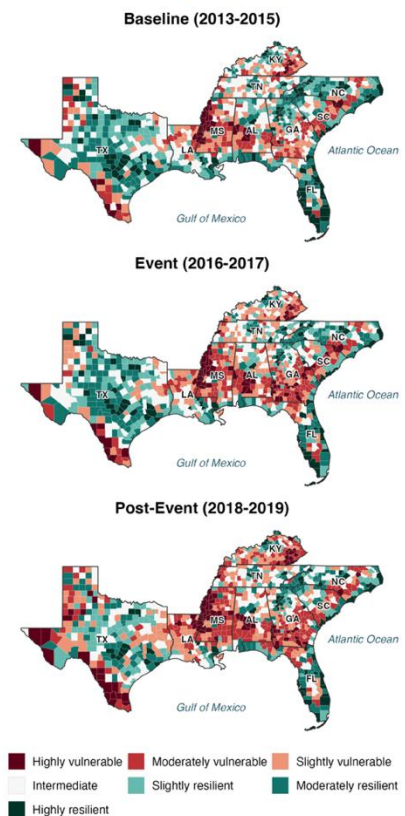
Results. At baseline (2013-2015), 45.4% of counties were slightly to highly resilient, 33% slightly to highly vulnerable, and 21.6% intermediate. After the 2016-2017 hurricane exposure and recovery (2018-2019), 364 counties became vulnerable and 96 resilient, with 32.2% slightly to highly resilient, 49.3% slightly to highly vulnerable, and 18.4% intermediate. These changes were significant ($p < 0.001$). PHDRI scores were moderately inversely correlated with social vulnerability index scores and positively moderately correlated with community resilience scores, validating and novelizing the PHDRI.

Conclusions. From 2013-2019, counties moved towards vulnerability, suggesting complex interactions between risk, exposure, vulnerability, and resilience. This analysis emphasizes the importance of population health characteristics in measuring vulnerability and resilience, as determinants of health also influence them. The index is not redundant with prior indices but has convergent validity, showing that adding population health characteristics doesn't override the meaning of vulnerability and resilience.

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PHDRI resilience-vulnerability categories, 2013-2019



EarthQuery: Active Learning in the Era of Earth Embeddings

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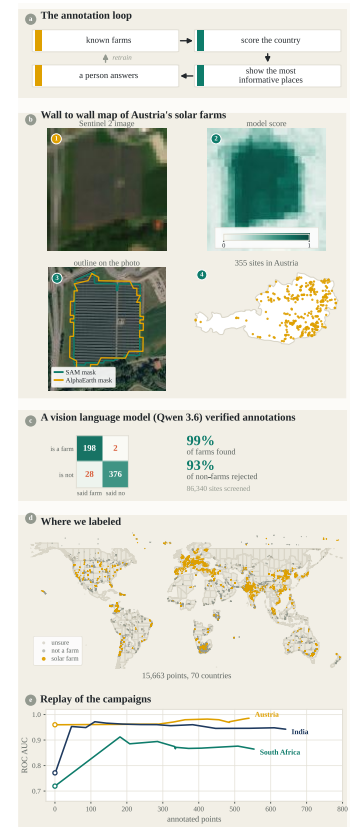
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Introduction. Earth Observation (EO) foundation models compress multi-sensor archives into globally queryable representations [1], reducing the need for repeated large-scale image inference during active learning. This study evaluated whether such embeddings can support a responsive citizen-science workflow that prioritizes informative samples, limits redundant annotation, and enables geographically robust mapping. EarthQuery, an end-to-end algorithm/web platform, was developed and evaluated using utility-scale solar farms as a rare-object case study.

Methodology. EarthQuery initializes a random forest using solar-farm candidates from Global Renewables Watch [3] that were screened and cleaned with vision-language models. The classifier operates on 64-dimensional annual AlphaEarth embeddings at 10 m spatial resolution. After each annotation batch, the newly collected human labels are added to the training set and the random forest is retrained, enabling iterative improvement. Candidate locations are identified through a Google Earth Engine coarse-to-fine procedure that estimates thresholds at 1.28 km, vectorizes candidates at 160 m, and refines selected peaks at 10 m. Simulations compared random, uncertainty, diversity, and combined exploration and exploitation strategies under 1% prevalence. Spatially blocked evaluations and campaign replays covered Austria, South Africa, and India. SAM converted Austrian score maps into polygons [2].

Results. EarthQuery was used to annotate more than 15,000 locations across 70 countries. A wall-to-wall solar-farm map of Austria was produced by combining AlphaEarth-based detection with a SAM-based segmentation workflow, resulting in 355 mapped sites. Global AlphaEarth vectors were subsequently analyzed in Austria, India, and South Africa, representing three distinct geographic and embedding-space regions. The analysis revealed substantial regional shifts in the embedding distributions and in the features associated with solar farms. Regions in which the embeddings represented local solar-farm characteristics well required fewer annotations. Regions with less representative feature space required more labels to distinguish farms from locally prevalent look-alike features (hard negatives).

Conclusions. The study demonstrates that embedding-driven active learning is effective for global-scale mapping, although its performance varies substantially among regions. Annotation budgets should therefore be adaptive: fewer samples may be sufficient when embeddings represent local solar farms well, whereas larger campaigns are required when regional shifts reduce representativeness. Vision-language models showed considerable promise as pseudo-annotators. SAM was effective for converting point-based detections into vector polygons, thereby reducing the need for annotators to digitize object boundaries manually. EarthQuery provides a state-of-the-art AL algorithm for EO, a practical framework for efficient, region-aware dataset curation and map production, substantially reducing the annotation budget and yielding datasets suitable for training deep learning models.



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Collective Action Under Misinformation in Algorithmically Infused Social Network

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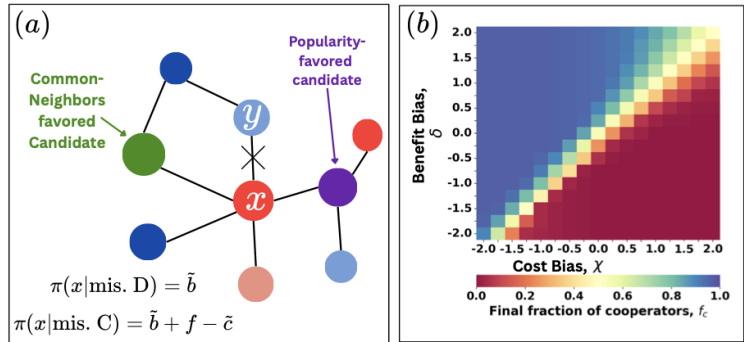
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IIASA Mentor: Nadejda Komendantova (ASA) and Tahereh Zobeidi (ASA)

Introduction. Collective action is essential for addressing societal challenges such as climate change and sustaining vaccination programs. Increasingly, people coordinate their actions through online social networks. Misinformation can distort how individuals perceive a collective problem, changing their willingness to contribute to their goal. At the same time, these platforms influence who users interact with by suggesting new social connections through link-recommendation algorithms. These biased user decisions and algorithmic interventions jointly reshape how cooperation evolves. However, their combined effects are not understood. We study this interaction using an evolutionary game-theoretic model of perception bias on static and evolving networks.

Methodology. We develop an evolutionary game-theoretic, coevolving agent-based network model in which behavior and social connections change over time. Users are informed when they perceive the true costs and benefits of contributing, or misinformed, where users perceive biased values. A cooperator pays a cost to contribute to the collective benefit, while a defector free-rides and contributes nothing. Through individual learning, users compare the outcomes of these strategies within heterogeneous neighborhoods and may switch strategies. The network evolves as users break ties and reconnect through link-recommendation algorithms.

Results. On static networks, cooperation depends on the direction of misinformation-induced perception bias. We call the bias unfavorable when misinformed users overestimate the cost and underestimate the benefit of contributing; this combination reduces cooperation, whereas the opposite increases it. Across the cost-benefit plane, a sharp diagonal transition appears because an increase in perceived benefit compensates for an increase in perceived cost. Even 10% misinformed users substantially reduce cooperation under unfavorable bias, especially when they occupy highly connected hubs. On evolving networks, we focus on this unfavorable bias. Common Neighbors restore cooperation by closing triangles around nearby users: small cooperative groups first become viable among leaf and low-degree users, then expand towards higher-degree users. Under Popularity, cooperation instead collapses. New connections concentrate around high-degree defector hubs, while leaf nodes remain attached to these hubs; consequently, the small cooperative groups that drive recovery under Common Neighbors cannot form, and cooperation therefore remains near zero.



Conclusions. Our findings show that the consequences of misinformation for collective action depend on the strength of the cost and benefit bias, size of the misinformed population, and its position within the social network. They also demonstrate that link-recommendation algorithms deployed by online platforms are not neutral: by reshaping users' connections, they can either counteract or exacerbate the effects of biased perceptions on cooperation. This highlights the need to evaluate link recommenders beyond predictive accuracy and engagement. Platform design should consider how recommendations affect misinformation, network structure, and the sustainability of collective action.

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Explainable AI-based poverty assessment through knowledge-driven approaches

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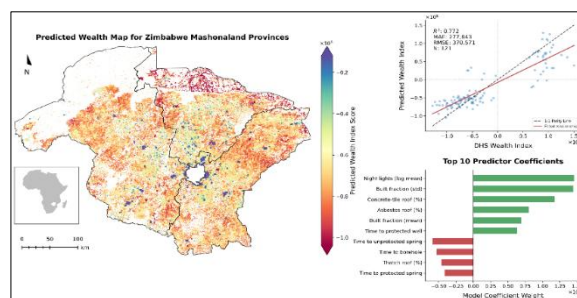
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Introduction. The scarcity of timely, fine-scale socioeconomic data constrains monitoring of Sustainable Development Goal 1 and the targeting of poverty-alleviation programmes. Earth Observation (EO) and machine-learning methods can address these gaps, but models based on raw imagery or unintuitive features are often difficult to interpret and may overlook local context. This research developed a knowledge-driven framework for poverty assessment in Zimbabwe using geospatial indicators. It examined roof-material, electricity access, settlement density, water accessibility and road-network density as transparent poverty proxies. Geospatial foundation-model embeddings and very-high-resolution imagery were also explored for automated roof-material classification and subsequent prediction of the DHS asset index.

Methodology. Field GPS labels for five roof classes (i.e. asbestos, concrete-tile, thatch, metal and unfinished building) were joined to Google Open Buildings footprints in three study areas within Zimbabwe totalling 5,896 buildings. Alpha-Earth embeddings were extracted per footprint to train Random Forest and XGBoost classifiers. The models predicted building-level roof-material classes, which were aggregated to pixel-level roof-material proportions across three Mashonaland provinces; national processing was restricted by computational overhead. Mean roof proportions and other spatial indicators were extracted within DHS cluster polygons from Mashonaland provinces and used in leave-one-out cross-validation ridge regression to predict the DHS asset index.

Results. Optimised Random Forest and XGBoost roof classifiers performed similarly under five-fold cross-validation. The best model achieved an accuracy of 0.71 and weighted-average F1 score of 0.52 when distinguishing five roof classes. Despite generally high performance, the models struggled to distinguish painted roofs. The optimised ridge regression model for predicting the DHS asset index achieved an R^2 of 0.77 under leave-one-out cross-validation. Night-time lights, built-up fraction, and the concrete-tile roofs emerged as the primary wealth predictors. While the wealth model effectively distinguished high-income urban neighbourhoods from low-income rural settlements, it showed limited resolution beyond this rural-urban divide. This aligns with the inherent characteristics of these geospatial features: built-up fraction and night-time lights exhibit strong signals in urban centres while negligible in sparse rural settlements. Similarly, strong correlation between concrete-tile roofs and wealth reflects their prevalence in affluent urban areas, contrasting with their scarcity in poorer rural regions where thatch often dominates.



While the wealth model effectively distinguished high-income urban neighbourhoods from low-income rural settlements, it showed limited resolution beyond this rural-urban divide. This aligns with the inherent characteristics of these geospatial features: built-up fraction and night-time lights exhibit strong signals in urban centres while negligible in sparse rural settlements. Similarly, strong correlation between concrete-tile roofs and wealth reflects their prevalence in affluent urban areas, contrasting with their scarcity in poorer rural regions where thatch often dominates.

Conclusions. This research demonstrates how locally meaningful geospatial variables can support transparent EO-based poverty assessment. It established workflows for classifying roof materials from Alpha-Earth embeddings, mapping proportion of roof-materials and using cluster-level roof proportions alongside other spatial indicators to predict the DHS asset index over small regions within Zimbabwe. Initial results show built fraction, night-time lights and concrete-tile roof prevalence emerging as the strongest wealth predictors, illustrating the value of interpretable features. Full national roof mapping remains constrained by computational overhead. Future work will optimise large-area processing, complete segmentation-model training and validation, and compare this knowledge-driven framework with data-driven EO-for-poverty baselines.

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Modeling Medicinal Acacia for Sustainable Dryland Livelihoods

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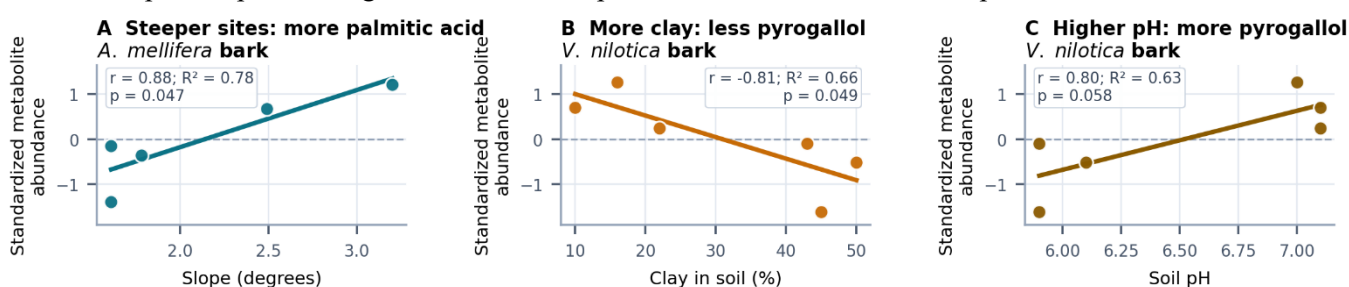
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Introduction. Medicinal Acacia trees support healthcare and livelihoods across African drylands, but harvesting occurs in ecosystems constrained by water scarcity, variable soils and slow recovery. A knowledge gap identified is whether environmental gradients consistently shape bioactive-metabolite production to inform prediction. This project tested whether soil conditions, water availability, topography, human pressure and tree size explain species- and tissue-specific chemistry measured by gas chromatography-mass spectrometry (GC-MS) in Makueni County, Kenya. The goal was to distinguish repeatable ecological signals from small-sample correlations and establish evidence from field observations to be incorporated into BioGeoChemistry Management Model (BGC-MAN).

Methodology. Ecological measurements of topography, soils, water availability, disturbance/browsing and tree dimensions were collected along six dryland transects in Makueni County. Bark and leaf extracts were profiled for compounds related to abiotic and biotic stressors using GC-MS. Samples were separated by tissue and species to preserve distinct metabolic responses. Metabolites with at least 4 occurrences per tissue and species were related to 13 predictors (standardized within species) using separate ordinary least-squares models. Candidate relationships were selected for consistency of direction under leave-one-out analysis and assessed using robust regression and 3,000 tree-level bootstrap resamples, to test whether a reported direction was retained when individual trees or model assumptions changed.

Results. From 468 screened metabolite-environment relationships, three were retained as the clearest directionally robust candidates (Figure 1). In *A. mellifera* bark, palmitic acid increased with slope. In *V. nilotica* bark, pyrogallol decreased with clay content and increased with soil pH. For each relationship, the direction was unchanged in leave-one-out analysis, agreed with robust regression and recurred in at least 98% of tree-level bootstrap resamples. No significant relationships were observed in the leaf samples.



Conclusions. The concentration of analysed metabolites in bark, and their cross-species divergence, argues against a single universal Acacia response. Instead, the findings point to selective, context-dependent environmental associations. Recent literature indicates that water stress can increase palmitic acid in plants¹ and that soil texture helps determine plant water-stress thresholds². Pyrogallol has been found in *V. nilotica*³, but the response against environmental factors is partially unexplored. Such relationships (if confirmed in future samples) should therefore enter BGC-MAN for targeted validation against species-specific independent samples. If confirmed, they could help identify environments associated with medicinally valuable chemistry and guide more sustainable sampling and harvesting.

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Assessing structural stability, indirect threat exposure, and conservation action coverage in biodiversity networks

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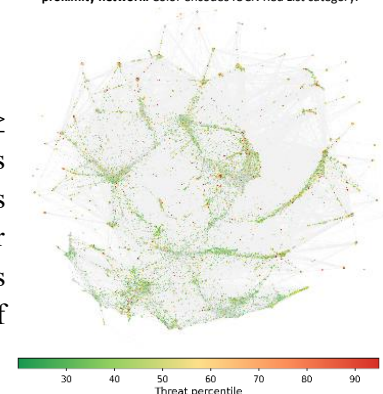
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Introduction. The direct drivers of the global biodiversity crisis are well documented, yet conservation frameworks assess species individually, prioritizing threat status, range size, or phylogenetic distinctiveness without accounting for the interaction-mediated dimensions of extinction risk. Species are embedded in networks of direct and indirect ecological interactions whose structure determines how perturbations propagate. Species-by-species approaches systematically miss the indirect and systemic vulnerabilities that emerge when both the socioeconomic and ecological interdependencies are accounted for.

Methodology. We build a bipartite species-habitat network (125,466 species, 13,101 country-habitat units) (Fig. 1), derived from IUCN Red List, treating habitat co-occurrence as revealing latent ecological "capabilities" species draw on, following economic complexity theory^{1,2}. Species-species proximity is derived via a two-step resource-allocation projection, capturing asymmetric ecological dependence as a directed, degree-normalized flow. Each species' ecological support is computed per habitat unit from these proximity weights. We simulate discrete extinction cascades: removing a species depletes co-occurring species' support, triggering extirpation below a collapse threshold τ . Structural and statistical validation (BiCM null-model testing, nestedness, taxonomic recovery, GloBI cross-referencing) confirms the network encodes genuine, non-random ecological structure beyond degree alone.

Results. Removal of nodes with high betweenness outperformed random, degree, IUCN-risk, PageRank, and HHI-based. Against random- and degree-based removal, it produced consistently larger cascades at high thresholds ($\tau \geq 0.8$), converging with both at low thresholds where near-total collapse occurs regardless of removal rule. The resulting top 5,000 cascade-critical species were robust across floors: 55% Data Deficient, 37% Least Concern/Near Threatened, and 94% of threat exposure undocumented. Nearly three-quarters (74%) have no conservation action, and among those that do, only ~13% of threats are addressed, highlighting a systemic mismatch between structural importance and conservation attention.

Figure 1. The largest connected component of the species proximity network. Color encodes IUCN Red List category.



Conclusions. We show that our species proximity network meaningfully captures ecological context and correlates robustly with real, documented ecological relationships. Structural bridging position, rather than raw connectivity or conservation status, consistently predicts a species' cascade impact across all thresholds and ubiquity levels tested. Critically, conservation attention is structurally misallocated: species whose loss would trigger the largest cascades are disproportionately Data Deficient or Least Concern, face heavy but largely undocumented threats, and mostly lack any assigned conservation action. This reflects not misclassification, but a systemic gap, as current prioritization, built on individual threat assessment, remains decoupled from network-level ecological importance.

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Quantifying Multiple Resilience Dividends of China's Climate-Adaptive City Policy

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Introduction. Cities concentrate climate risks, populations and critical infrastructure, yet adaptation finance remains constrained by the perception of adaptation as a cost of avoiding future losses rather than as an investment in systemic resilience. The Multiple Resilience Dividend (MRD) framework captures three dimensions of adaptation benefits—risk reduction, development unlocking, and social–ecological co-benefits—but provides limited quantitative insight into how these dividends emerge and why they vary across cities. We conceptualize urban adaptation as a process of capital reconfiguration, through which policy reshapes human, financial, physical and natural capitals and, in turn, influences MRD. Using China's Climate-Resilient City (CAC) Pilot Programme as a quasi-natural experiment, we examine whether adaptation generates MRD, why benefits differ across cities, and how capital configuration shapes these outcomes.

Methodology. Using panel data from 286 Chinese cities during 2005–2022, we construct an MRD index spanning risk reduction, development unlocking and social–ecological co-benefits. A Difference-in-Differences (DID) framework with city and year fixed effects is used to estimate the average policy effects, while a Double Machine Learning (DML) approach is applied to capture city-level treatment-effect heterogeneity. In addition, a k-means clustering algorithm is implemented to identify distinct urban capital configurations based on human, financial, physical and natural capitals. We further examine policy-induced changes in these four capitals and their relationships with MRD as well. Parallel-trend, placebo and other robustness tests are used to support the reliability of findings.

Results. China's CAC Programme increases MRD by approximately 3%, with the effect persisting throughout the post-policy period. The three dividends, however, unfold differently: the development dividend (MRD2) is most pronounced, rising from 8.7% contemporaneously to 11.2% after two lags; the risk-reduction dividend (MRD1) remains modest at 1.5–2.0%; while the social–ecological dividend (MRD3) emerges more gradually, reaching 4.9% at lag two (Fig. 1). Despite the positive average effect, DML reveals substantial city-level heterogeneity in policy responses. K-means clustering identifies distinct capital configurations, which, combined with the DML estimates, reveal systematic differences in policy effectiveness across city types (Fig. 2). For example, Cities with balanced, high-capacity capital portfolios show stronger responses, indicating that capital configuration shapes the extent to which adaptation translates into resilience gains. CAC also significantly strengthens all four capitals, whose positive associations with MRD point to capital reconfiguration as a potential pathway underlying heterogeneous adaptation benefits.

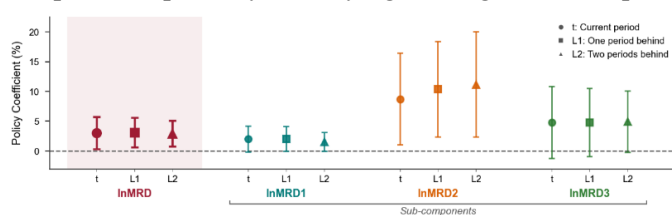


Fig. 1: Policy Effects by MRD

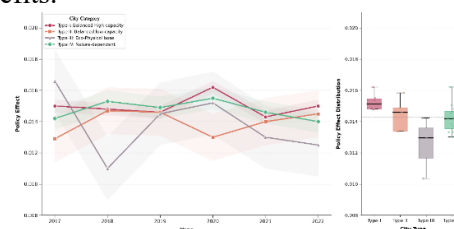


Fig. 2: Policy Effects by City Type

Conclusions. Climate adaptation generates persistent and multidimensional resilience dividends, extending beyond immediate risk reduction to development and social–ecological benefits. Yet these gains vary substantially across cities, with capital configuration shaping how effectively adaptation translates into MRD. These findings position urban capital reconfiguration as a key pathway for unlocking differentiated resilience benefits and inform more context-specific adaptation strategies.

Financing Temperature Reversal: Financing Pathways & Policy Design

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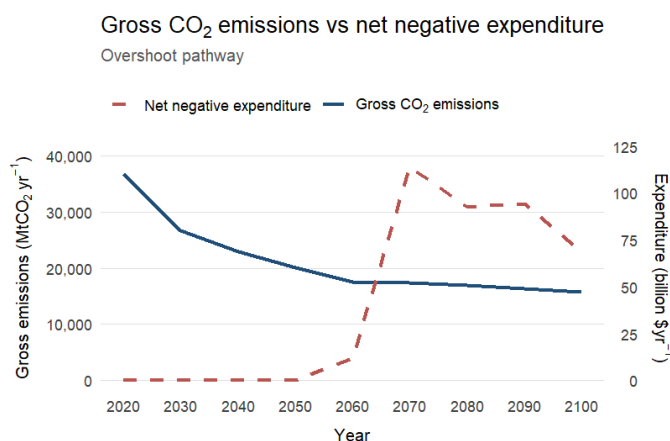
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Introduction. Exceeding 1.5°C has become virtually unavoidable, meaning that achieving the Paris temperature goal is now contingent on deploying sufficient net negative emissions to reverse temperatures following temperature goal exceedance [1]. Despite the growing prominence of CDR in mitigation pathways, large-scale deployment remains limited, and existing climate policy frameworks provide no credible mechanism for financing temperature reversal. The financing requirements are an unavoidable consequence of overshooting the 1.5°C target, but there has been limited investigation into how these financing requirements could be met. The research examines how alternative financing scenarios impact the scale of the costs and the ability to meet them, focusing particularly on the role that the fossil fuel industry may play in meeting the costs.

Methodology. The research adopts a scenario-based methodological framework, using a reduced-complexity model developed at IIASA which emulates several integrated assessment models [2]. Two sets of scenarios are developed, one considering contemporaneous policy designs and one considering intertemporal policy designs. Within each set, the scenarios examine the fossil fuel industry's ability to pay for net negative CDR deployment under different assumptions. The assumptions vary according to the fossil fuel industry's CDR infrastructure ownership, the type of CDR market in operation, and the industry's income from residual fossil fuel use.

Results. The figure illustrates one scenario in the contemporaneous policy set. A regulation is conceptualised under which the fossil fuel industry is required to finance net negative emissions from the point of net zero (2060). In this scenario, the fossil fuel industry does not own CDR infrastructure, instead needing to procure CDR at higher cost from the market while receiving no income from providing CDR for residual emission offsetting. Gross fossil fuel emissions remain relatively high until late in the century, allowing the industry to retain an income base. Despite the relatively high residual emissions, the figure highlights a tension: the financing requirement increases as gross fossil fuel emissions decline, reducing the potential income available to meet the temperature reversal costs. Alternative scenarios not shown here test how CDR ownership and different market designs alter this relationship, including whether CDR revenues can increase the fossil fuel industry's capacity to finance temperature reversal.



Conclusions. The results show the tension between a declining income base from residual emissions and increasing net negative financing requirements when the fossil fuel industry is required to pay. The scenario results demonstrate that the industry's ability to pay depends not only on the scale of residual emissions later in the century, but also on its role within the CDR market and the design of that market.

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