IAM COMPACT

Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action

29/07/2025

D5.9 – Climate action in the sustainability spectrum - Update

WP5 Expanding – Resilient, inclusive, and sustainable recovery and development

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

The report will be used to guide consortium partners on how to assess the progress of Sustainable Development Goals (SDGs) in the IAM COMPACT modelling suite and reinforce modelling capacity to include biodiversity dimensions and uncertainty analysis of investments towards SDGs. It can also be beneficial to modelling teams and other researchers beyond the consortium, illustrating how decarbonisation can be achieved in conjunction with sustainability.

3. Short summary of results (<250 words)

This report presents progress in developing sustainable decarbonisation pathways that integrate biodiversity, material use, and biophysical constraints, while aligning climate action with broader sustainable development goals (SDGs). Section 1 updates a prior assessment of SDG coverage across IAMs, using an expanded survey of indicators derived from literature and UN sources. Modellers reviewed indicator representation and proposed additions, confirming continued use of previously reported metrics. Section 2 discusses how climate mitigation strategies optimised across environmental and socioeconomic goals can deliver strong biodiversity co-benefits, particularly through land conservation, while highlighting the need for more integrated approaches to fully capture trade-offs and synergies in the AFOLU sector. Section 3 shows the state-of-the-art in the application of the 2030 Agenda in IAMs, highlighting epistemic barriers to fairly representing the social dimensions of gender, peace, international partnership implications. Section 4 documents two stakeholder-informed studies: one using the WILIAM model to evaluate land-use impacts of solar PV and forest bioenergy expansion in the EU, and another applying the CLEWs framework to examine energy, water, and food security in Ethiopia. Section 5 explores the effects of dietary shifts toward plant-based and low-ruminant consumption, in terms of improved nutrition, reduced emissions, water stress, and food costs, and biodiversity promotion; regional strategies yield faster benefits compared to global targets, underscoring the need for supportive social policies. Finally, Section 6 outlines ongoing efforts to improve IAM capacity for tracking SDG progress alongside climate mitigation, strengthening the policy relevance of IAM-based analysis.

4. Evidence of accomplishment

This report, plus a preprint and a journal publication as follows:

Rodés-Bachs, C., Sampedro, J., Van de Ven, D., Horowitz, R., Pardo, G., and Zhao, X. (2025) Environmental and societal implications of transitioning to sustainable diets. https://doi.org/10.21203/rs.3.rs-5346673/v1.

Nikas A (2024) Projecting progress in sustainable development goals vis-à-vis climate action in climate-economy models[1]. PLOS Clim 3(7): e0000449. https://doi.org/10.1371/journal.pclm.0000449

[1] https://zenodo.org/records/12760230

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Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

NTUA – National Technical University of Athens	EL
Aalto – Aalto Korkeakoulusaatio SR	FI
AAU – Aalborg Universitet	DK
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Bruegel – Bruegel AISBL	BE
CARTIF – Fundacion CARTIF	ES
CICERO – Cicero Senter for Klimaforskning Stiftelse	NO
E3M – E3-Modelling AE	EL
KTH – Kungliga Tekniska Hoegskolan	SE
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UPRC – University of Piraeus Research Center	EL
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Executive Summary

The IAM COMPACT task linked to this report seeks to develop sustainable decarbonisation pathways that incorporate biodiversity, material use, and biophysical constraints, while positioning climate action as a cross-cutting priority across the full sustainability spectrum. It aims to align climate action with sustainable development by evaluating the integrated co-benefits (and potential trade-offs) of climate-neutral pathways and policies that address a range of SDGs. Currently, IAM-driven pathways tend to focus narrowly on climate action, energy efficiency, industry, and infrastructure, with limited attention given to other environmental and social dimensions.

Section 1 updates a previous assessment conducted in D5.8[2] to map the coverage of the SDGs in IAM COMPACT models. Using the same survey approach, modelling teams were asked to review and cross-check which indicators their models represent. The updated Excel-based template required modellers to indicate the presence, representation type (exact or proxy), model variable name, and measurement units for each indicator, and allowed them to suggest additional indicators. All previously reported indicators remain in use, with no removals or modifications reported.

Section 2 integrates the Global Change Analysis Model (GCAM) with downscaling tools and the Potential Species Loss (PSL) indicator to assess biodiversity outcomes under various mitigation pathways. Unlike typical post-scenario biodiversity analyses, it applies the concept of marginal SDG-emissions-reduction values (MSVs) to estimate the sector-specific impact of mitigation on SDG 15 (Life on Land) through land use–driven species loss. To support policymaking, the study combines GCAM with portfolio analysis to identify optimal sectoral mitigation strategies that account for biodiversity, poverty reduction, and economic development simultaneously.

Section 3 presents a four-step methodology combining the WILIAM model with scenario analysis and Stochastic Multicriteria Acceptability Analysis (SMAA) to evaluate SDG outcomes and stakeholder preferences. Three alternative global scenarios were developed and simulated, showing improvements in multiple SDGs and limiting temperature rise to 1.84°C by 2050. However, SDGs 8 and 17 perform better under business-as-usual trends and continued warming beyond 2050 highlights the need for bottom-up policy integration. The *Energy transition with Environmental Considerations promoting policies in the land-use sector (EC)* scenario emerged as the most acceptable to stakeholders. The study also identifies critical challenges in standardising SDG representation across IAMs, particularly for social dimensions, calling for harmonisation efforts similar to IPCC emissions protocols.

Section 4 documents a stakeholder workshop with representatives from key institutions to discuss the land use impacts of decarbonisation pathways, particularly under scenarios with high renewable energy penetration. Two studies were then derived from the workshop: one using the WILIAM model to assess the environmental and land impacts of large-scale solar PV and forest-based bioenergy in the EU, and the second applying the CLEWs framework to examine resource access and food security challenges in Ethiopia, a rapidly growing country facing energy and water access issues and high levels of hunger.

Section 5 assesses the global and regional benefits of shifting toward plant-based diets or reducing ruminant meat consumption using GCAM, an Integrated Assessment Model. Results show that such dietary transitions improve nutrition by increasing protein and fat intake and enhancing dietary energy adequacy, while also lowering greenhouse gas emissions, air pollution-related deaths, water scarcity, and food costs. Additionally, they promote re/afforestation and biodiversity, though regional trade-offs may occur. Regional, tailored efforts are shown to deliver quicker benefits than uniform global approaches. The findings highlight the importance of social policies to support sustainable dietary

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changes for both health and environmental gains.

Section 6 discusses six ways, in which the capacity to evaluate progress in SDGs vis-à-vis efforts to mitigate climate change using IAMs is currently being enhanced to offer robust and actionable policy prescriptions that may place climate policy in a holistic sustainable development context.

Contents

Table of Figures

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1. Capacity to assess SDGs in the IAM COMPACT models: update

1.1 Mapping of the SDG indicators

This exercise, framed in Subtask 5.6.1, serves as an update of the same enquiry conducted a year ago among the modelling teams of the project to map the coverage of the Sustainable Development Goals (SDGs) onto the IAM COMPACT model ensemble. To this end, the same surveying process has been carried out, sending a template to the modelling teams, so that they can cross-check the indicators that their models use to represent the SDGs.

Similar to the first iteration, the list of indicators proposed in the template come from a comprehensive literature review performed during the 1st Policy Response Mechanism (PRM) cycle (see Section 1.2 of D5.8[3] – Climate action in the sustainability spectrum (Frilingou et al., 2024)). Even though the original template was indeed extensive, feedback from the modellers showed that some SDGs were still overlooked, so to improve this underrepresentation, the list has been expanded with some more metrics, mostly derived from the official set of indicators provided by the United Nations (UN)[4].

Given that the UN indicators are often challenging to model, they have been slightly modified to ease their representation. These small tweaks have been tested in WILIAM (UVa's and CARTIF's IAM) and then proposed to the other models. Additionally, the template also covers some of the indicators that the modellers identified as missing in the first phase (the template was open for partners to flag indicators that their models included, but which were not listed as selectable).

The procedure for filling in the template has consisted of the same process, an Excel file in which the modelling teams had to tick whether the indicator was available or not, whether the representation was exact (same formulation as the original indicator) or through a proxy, the name of the variable within the model and, finally, the measurement units. The survey has again been open to suggestions for new indicators not considered in the template. It should also be mentioned that it was asked whether any indicator that was modelled in the first iteration had been modified or removed, but the answer was negative in all cases. The first table included in **ANNEX I** (Table AI-1) presents the new list of indicators, of which those that are new inclusions are shown in bold.

1.2 Analysis of the results – update

The set of indicators has been expanded from 93 to a total of 116, thus improving the analysis of the SDG coverage by the IAM COMPACT models. In most cases, this increase has been fruitful, since the modelling teams have indicated that some of the new indicators are available features in their models, making the new template more comprehensive than that of the 1st PRM cycle. The bar chart in Figure 1-1 illustrates the evolution of the metrics covered by the models over the two PRM cycles and it is clearly noticeable that WILIAM presents the highest number of SDG indicators, which makes sense as it has been the IAM on which the indicators were tested.

[3] DOI https://doi.org/10.5281/zenodo.12649184
[4] https://unstats.un.org/sdgs/indicators/indicators-list/

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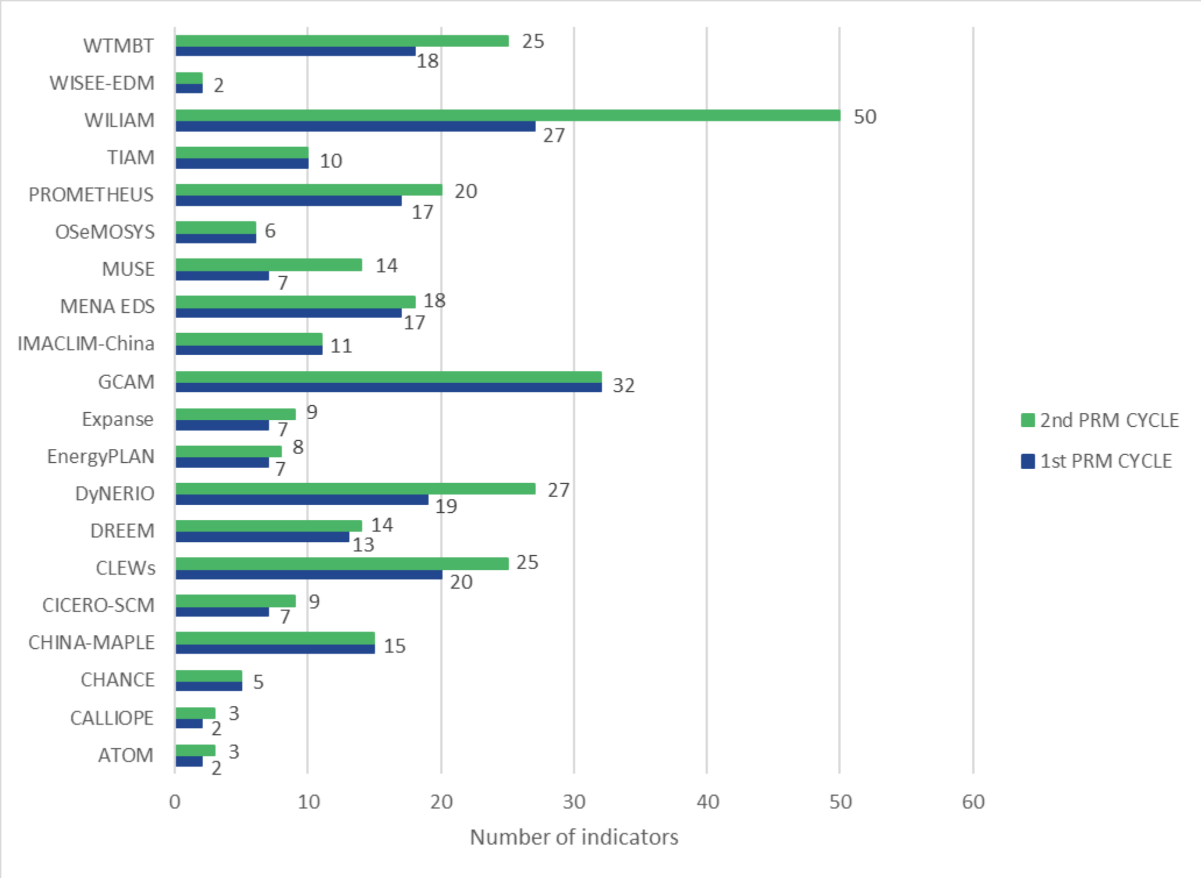


Figure 1- 1: Number of SDG indicators covered by each IAM COMPACT model in the 1st and 2nd PRM cycles

Once the results are analysed, it becomes apparent that the coverage varies significantly: while some SDGs, such as SDG7, SDG13, and SDG9 are represented by many models, others like SDG16 or SDG5 are only marginally covered. This uneven distribution reflects the classical orientation of models, which traditionally focus on energy, climate, land-use, technology and macroeconomic development, often tied to emissions pathways and policy scenarios.

In contrast, goals that involve legal, or socio-cultural dimensions are harder to quantify and integrate into model structures. These aspects may require qualitative approaches, different perspectives on how to model their indicators and to increase availability and resolution of relevant data.

Figure 1-2 shows the mapping of SDGs across the 21 IAM COMPACT models. In brackets next to each SDG is the number of models capable of representing at least one of the indicators included in the template.

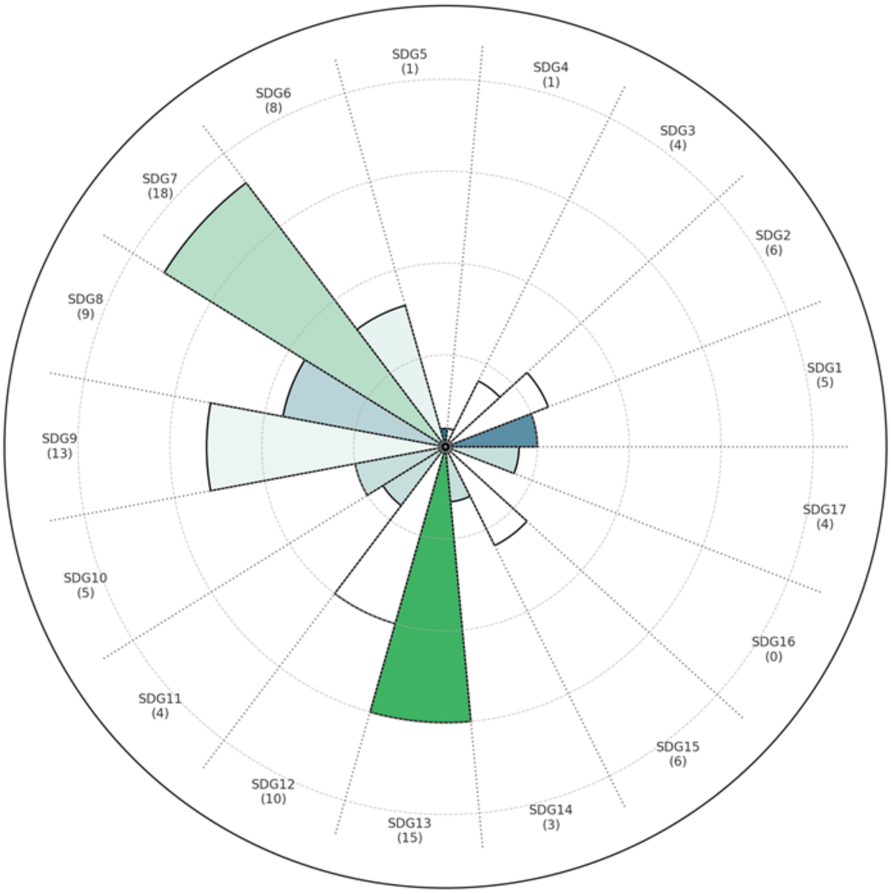


Figure 1- 2: Distribution of SDG coverage across the IAM COMPACT models. In brackets the number of models representing each SDG.

The most relevant conclusion that can be drawn from this exercise, both from the 1st and 2nd PRM cycles, is that justice, equity and education dimensions must be at the core of the next developments of IAMs, which also aligns with newer EU calls. A successful energy transition and climate-responsibility shift cannot be based solely on which is the most efficient green technology or how much new forest area is planted, but on how governments and, above all, citizens are keen to embrace these initiatives and structural changes, and how to overcome the potential negative effects that might make people sceptical about them.

Figure 1-3 demonstrates this unbalanced distribution in the SDG modelling, where economic, environmental and resource goals are comprehensively addressed, while social and institutional issues are barely touched upon.

	PEOPLE				PROSPERITY				PLANET INTEGRITY			SUSTAINABLE RESOURCES				PEACE, INSTIT.	
	1	3	4	5	8	9	10	11	13	14	15	2	6	7	12	16	17
CHANCE	✓			✓	✓		✓							✓			
IMACLIM-China	✓				✓	✓			✓					✓			
GCAM	✓	✓				✓		✓	✓	✓	✓	✓	✓	✓	✓		
MUSE					✓	✓			✓					✓			
TIAM						✓			✓					✓			
CLEWs						✓		✓	✓		✓	✓	✓	✓	✓		✓
DyNERIO					✓	✓	✓				✓	✓	✓	✓	✓		✓
WILIAM	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Calliope						✓			✓					✓			
China-MAPLE					✓	✓			✓			✓	✓	✓			
EnergyPLAN						✓			✓					✓	✓		
EXPANSE		✓			✓		✓		✓		✓			✓			
MENA-EDS						✓			✓				✓	✓	✓		
OSeMOSYS									✓					✓	✓		
PROMETHEUS					✓	✓			✓				✓	✓	✓		
DREEM (TEEM)	✓	✓						✓	✓					✓	✓		
ATOM (TEEM)														✓	✓		
WISEE-EDM						✓											
WTMBT					✓	✓	✓				✓	✓	✓	✓			✓
CICERO-SCM									✓	✓							

Figure 1- 3: SDGs represented by each IAM COMPACT model

1.3 References

Frilingou, N., Keppo, I., Zamanipour, B., Mateo, A., Ferreras, N., Hernando, G. P., Miguel, L. J., Nikas, A., Koasidis, K., Horowitz, R., Rodés-Bachs, C., Rouhette, T., & Arto, I. (2024). *IAM_COMPACT_D5.8_Climate_action_in_the_sustainability_spectrum*. Zenodo. https://doi.org/10.5281/zenodo.12649185

United Nations (2025). *Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development – 2025 Review* https://unstats.un.org/sdgs/indicators/indicators-list/

2. Biodiversity, material resources, and biophysical limits: update

Authors: Theo Rouhette, Dirk-Jan Van de Ven

2.1 Introduction

In recent decades, rapid growth in socio-economic activities has often come at the cost of environmental degradation along with overexploitation of material resources. These activities are contributing to an extraordinary rate of species loss over the past century (Ceballos et al., 2015; Leclère et al., 2020). A major consequence of this growth is the expansion of land use for urban development, agriculture, and forestry. These land use changes (LUC) have historically driven habitat destruction and ecosystem decline (Winkler et al., 2021). Research consistently identifies agriculture—especially crop cultivation—and overexploitation, such as intensive logging, as key contributors to biodiversity loss, especially within biodiversity-rich regions (Jaureguiberry et al., 2022). Climate change is not only an additional driver of biodiversity loss but also a threat multiplier. Rising global temperatures threaten species' habitats directly (Chaudhary & Mooers, 2018) and may become the leading cause of biodiversity decline in the coming decades (Pereira et al., 2024).

To respond to these challenges, ambitious agenda have been established globally to foster human well-being within planetary boundaries by adopting two landmark international agreements: (1) the Paris Agreement's goal to prevent dangerous anthropogenic climate change by limiting global temperature increase by 2100 to well-below-2°C and pursue efforts to stay below 1.5°C (UNFCCC, 2015), and (2) the Sustainable Development Goals (SDGs) to accelerate sustainable development across the world. Several SDGs have been shown to interact significantly with climate change and biodiversity loss, demonstrating how are highly interconnected and dependent on one another, with a range of interactions implying both potential trade-offs and synergies between individual SDGs (Soergel et al., 2021).

In particular, climate mitigation strategies focused on the agriculture, forestry and land uses (AFOLU) sector have become central to achieving the goals of the Paris Agreement, as they can enhance carbon sequestration in soils and vegetation (Searchinger et al., 2018). However, these same strategies can conflict with conservation efforts, particularly when they involve large-scale bioenergy crops or monoculture plantations, potentially harming terrestrial biodiversity (Jung et al., 2021). While achieving Paris Agreement-compatible mitigation levels requires deep transformations in virtually every sector, the actual contribution of each sector, such as AFOLU, has been widely debated precisely due to multiple trade-offs that are implied in such a distribution.

These potential trade-offs require harmonising efforts to curb greenhouse gas emissions and enhance carbon sequestration with initiatives aimed at minimising biodiversity impacts. Such alignment is critical not only for environmental integrity but also for improving social and economic outcomes and enhancing human well-being (O'Brien et al., 2025). Particularly, the AFOLU sector features an important negative emissions potential to offset emissions in the so-called "hard-to-abate" end-use sectors (Fuhrman et al., 2024), achieved through afforestation/reforestation of large land areas, which however does not come without risks and potential impacts for biodiversity. Such biodiversity loss can, in turn, undermine key ecosystem functions, including carbon storage which can further undermine the effectiveness of land-based mitigation.

Despite the importance of these interactions, only a limited number of studies have explored how future global land use changes driven by climate mitigation policies could impact biodiversity at regional scales. Biodiversity metrics have been developed to conduct such integrated assessments, including the Potential Species Loss (PSL) which estimate species committed to extinction due to habitat loss, while accounting for their geographic range (endemism) and adaptability to human-modified landscapes (Chaudhary & Brooks, 2018; Chaudhary & Kastner, 2016).

Building on these metrics, scenario-based models can play a crucial role in projecting future biodiversity outcomes and ecosystem service impacts. Integrated Assessment Models (IAMs) are valuable tools for identifying potential synergies and trade-offs among global sustainability goals such as the SDGs, the Paris Agreement (PA), and the post-2020 Global Biodiversity Framework (Pörtner et al., 2021). By covering all energy-consuming and GHG-emitting sectors (including AFOLU), and usually with decent technological detail, IAMs are well-suited and commonly applied to the question on which sector should mitigate what share. They have been used to explore trade-offs between carbon sequestration, biodiversity conservation, and food security (Prudhomme et al., 2020), as well as to examine the environmental benefits of dietary shifts toward plant-based consumption (Kozicka et al., 2023).

This study addresses several gaps in current literature. Our research integrates the Global Change Analysis Model (GCAM) (Calvin et al., 2019) with downscaling tools and the PSL indicator to evaluate biodiversity outcomes under multiple mitigation pathways. Rather than a post-scenario analysis on biodiversity impacts as most of the literature in this field, our analysis applies the concept of "marginal SDG-emissions-reduction values" (MSVs), introduced by Fujimori et al., (2020), and estimates the marginal impact of mitigation in each sector on the "Life on Land" SDG (SDG 15) through the PSL driven by land use changes. To provide a policy-relevant decision tool that integrates optimisation across non-climate goals within the IAM exercise (Nikas, 2024), our study then applies an established combination between the Global Change Analysis Model (GCAM) and portfolio analysis (PA) (Forouli et al., 2020) to estimate optimal allocations of sectoral mitigation efforts considering biodiversity impacts along with metrics of poverty and economic development.

2.2 Methods

The methodology is based on GCAM, a dynamic-recursive, partial equilibrium IAM that facilitates the analysis of interactions among human-earth system dynamics covering water, agriculture and land use, energy, climate, and economy (Calvin et al., 2019). The energy system encompasses primary energy resource production, energy transformation, and final energy demands, including international trade in energy commodities. The land use module categorises land based on vegetation cover types across 32 geopolitical regions and 235 water basins, resulting in a total of 384 distinct land-water regions. Land allocation and the use of specific technologies are calculated through a logit-based choice model and depends on the profitability of the competing technologies (McFadden, 1974). All protected land types cannot undergo conversion to other land types. GCAM is used to generate land use change (LUC) projections across 32 global regions for all the modelled climate mitigation scenarios.

The LUC projections are downscaled to a higher spatial resolution (0.5° × 0.5°) using the Demeter tool (Vernon et al., 2018). Demeter is a land use spatial downscaling model that disaggregate land use results from Integrated Assessment Models (IAMs) to produce gridded products with a resolution set by the base map. In this study we use the default base map to downscale global land use projections for eight different land types (forest, shrub, grass, pasture, tundra, rainfed crops, irrigated crops, and an aggregation of rock, ice, and desert). Demeter uses a hierarchical allocation process that first allocates land use types with stricter spatial requirements—such as irrigated cropland—before assigning more flexible land types like rainfed agriculture or natural vegetation (Chen et al., 2019). This spatial granularity allows for more accurate overlay with ecological datasets such as species distributions and biodiversity metrics.

The resulting gridded land use data are then aggregated at the ecoregion level, generating ecologically meaningful spatial units suitable for assessing biodiversity impacts. The 804 terrestrial ecoregions based on Olson et al., (2001), are areas with similar geographically and ecologically characteristics and with similar levels of solar radiation and precipitation patterns. Their boundaries align closely with the original extent of natural communities before significant land-use alterations and have been widely used in recent years for key biogeographical and macroecological research.

The Characterization Factors (CFs) developed by Chaudhary & Brooks, (2018) which serve as biodiversity impact metrics are also provided at the ecoregion scale. These CFs are derived using the countryside species-area relationship (cSAR) model. They quantify the Potential Species Loss (PSL) per unit area across five broad land use categories—forestry, plantations, cropland, pastureland, and urban land—each evaluated under three levels of management intensity. The CFs reflect aggregated species loss across five major taxonomic groups: mammals, birds, amphibians, reptiles, and plants. They incorporate species-specific responses to land use, including affinity to specific land types, levels of endemism, and threat status, based on historical data from the IUCN Red List of Threatened Species. Biodiversity impacts are computed by multiplying the area of land use change within each ecoregion-land use category combination by the corresponding CF. Notably, conversions to land use types classified as natural vegetation are assumed to have a CF of zero and are therefore considered to have no negative impact on biodiversity. The PSL indicator of each scenario is estimated with the following equations:

$$LUC_{l,r} = A_{l,r,2050} - A_{l,r,2020}$$
$$PSL_{l,r} = LUC_{l,r} \cdot CF_{l,r}$$
$$PSL = \sum_{l} \quad \sum_{r} PSL_{l,r}$$

Where *A* is the area in ha, *LUC* is the land use change between 2050 and 2020 in ha, *CF* is the aggregated characterisation factor in species loss per ha, *PSL* is the net potential species loss of the scenario, *l* are the managed land uses, and *r* are the ecoregions.

We estimate the PSL indicator across a range of mitigation scenarios with varying sectoral shares of the total mitigation target. The sectors covered include: industry, energy supply, AFOLU, transportation, buildings and DAC (direct air capture). To identify maximum sectoral potentials, we use the AR6 scenario database (Byers et al., 2022) and construct sectoral ranges for a National Policies (NPi) baseline, as well as sectoral ranges for 2ºC, 1.7ºC and 1.5ºC compatible scenarios until 2050. We combine this information with actual data on sectoral emissions up to 2020 from EDGAR to decompose future sectoral emissions in the NPi baseline and climate target scenarios. For the NPi baseline, we account for scenarios with name tags related to current or national policies. For the climate targets, we select scenarios with median warming by 2100 of 1.71-2.0ºC for 2ºC compatible scenarios, 1.51-1.7ºC for 1.7ºC compatible scenarios, and 1.0-1.5ºC for 1.5ºC compatible scenarios.

We apply GCAM to run multiple incremental scenarios for each of 5 Shared Socioeconomic Pathways (SSPs) up to 2050. We transform emissions pathways into cumulative emission potentials by sector and derive a specific potential "budget" by sector and a number of incremental scenarios, depending on the sector. The total budget is matched to the climate targets: to reach 2ºC compatible pathways, ~300 Gt has to be saved relative to the current policies baseline scenario. For 1.7ºC compatible scenarios, this is ~415 Gt, and for 1.5ºC compatible scenarios, this would be ~560 Gt. We then model scenarios with increasing mitigation in one sector in steps of 5 Gt up to their maximum mitigation, while keeping CO2 emissions in all other sectors on their NPi baseline level. At each level, we identify the relative impacts on the PSL indicator. PSL is derived for all the incremental scenarios from the LUC projections.

In the final step, we assess the biodiversity impact of optimised or "Pareto-optimal" mitigation scenarios using a robust portfolio analysis approach (Van De Ven et al., 2019). We identify one portfolio for each SSP and for 3 climate targets (1.5C, 1.7C, and 2C) that performs equally well on different environmental and socio-economic dimensions. In addition to the biodiversity metric, we include in the optimisation function an economic indicator (GDP per capita) and a poverty indicator (household expenditures on residential energy and food relative to their average income). Then, we take the sectoral mitigation portfolio and re-run GCAM with this combination of sectoral targets to illustrate the final biodiversity impacts of these balanced and optimised mitigation scenarios. For comparative purposes, we run least-cost scenarios for each combination of SSP and climate targets to assess the potential biodiversity gains derived from the optimised mitigation scenarios compared to the standard least-cost approach which focuses exclusively on reducing mitigation costs.

2.3 Results

The results indicate that there is considerable difference in biodiversity impacts depending on the different distributions of sectoral mitigation efforts. In these pathways, mitigation from the AFOLU sector is achieved through land conservation and the expansion of unmanaged land. Allocating a higher share of overall mitigation to the AFOLU has significant biodiversity benefits in our analysis, as shown in Figure 2-1. Incremental efforts in the AFOLU sector could reduce the global average PSL to up to -250 compared to the NPi baseline scenario, which has no equivalent across other sectors.

On the opposite, mitigation efforts in the transportation sector could be detrimental to biodiversity (up to +35 PSL) through increased land conversion driven by higher demands for biofuels for road, air and water transport. Increased efforts in other GHG emitting sectors (industry, energy supply, buildings and DAC) show relatively modest biodiversity impacts. Simultaneously, ramping up efforts for AFOLU mitigation does not significantly affect GDP while it significantly increases poverty through higher food prices.

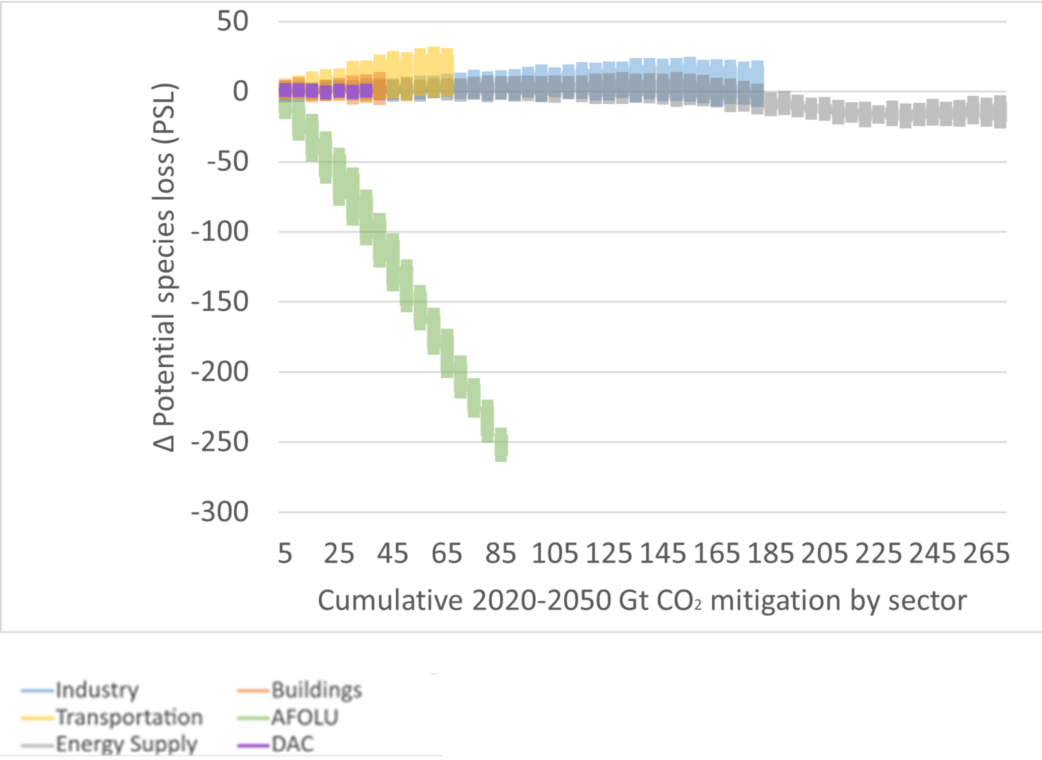


Figure 2- 1: Marginal impacts in the Potential Species Loss (PSL) indicators from incremental mitigation efforts in each sector. Ranges represent the range of outcomes under 5 different SSPs.

Then, we selected one portfolio for the 3 climate targets that performs reasonably well on each on the three indicators covered in the optimisation (economics, poverty and biodiversity). By simulating these balanced mitigation portfolios in a model, we illustrate how these mitigation scenarios look like in terms of biodiversity performance (Figure 2-2). Results suggest that under Paris-compatible mitigation pathways, an optimal share of AFOLU mitigation across the dimensions covered result in net gains in biodiversity compared to the baseline scenario. The optimal biodiversity impact across the SSPs scenarios is on average -173.84 PSL in a 2C degree scenario, -222.87 PSL in a 1.7C scenario and -281.89 PSL in a 1.5C scenario (Figure 2-2). Hence, ramping up climate ambitions is synergistic with a reduction of biodiversity loss under these conditions.

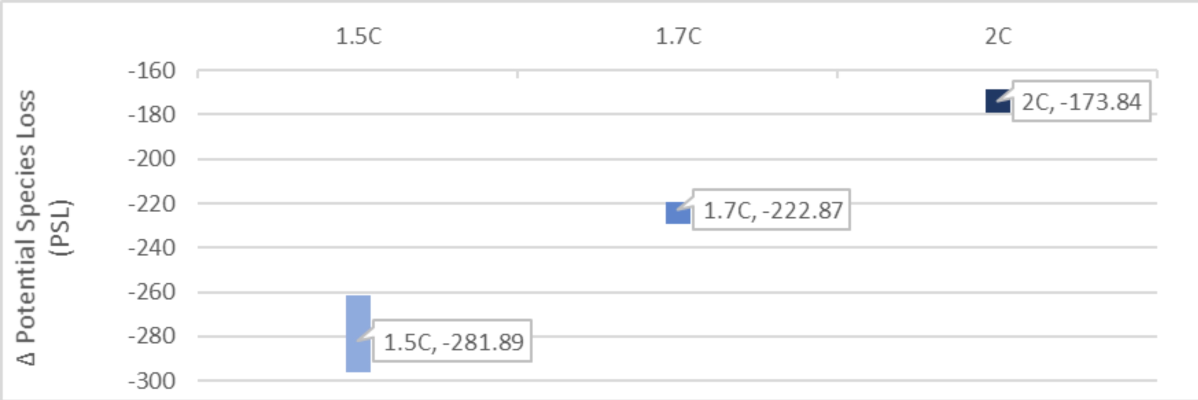
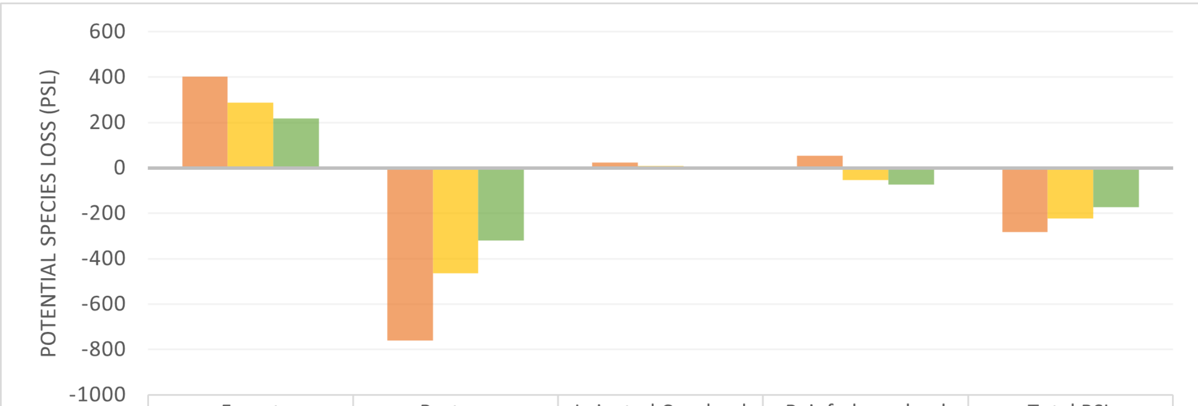


Figure 2- 2: Illustration PSL impacts of scenarios applying 2C, 1.7C and 1.5C compatible optimal mitigation portfolios compared to baseline scenarios. Ranges represent the range of outcomes under 5 different SSPs.

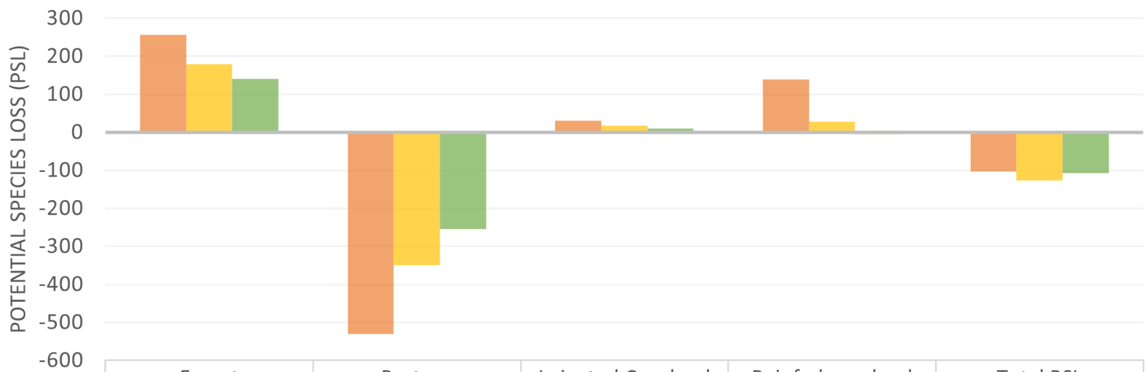
The PSL results of these optimal scenarios compared to the NPi baseline scenarios for each of the SSPs can be disaggregated per land use to provide additional insights on the gross biodiversity gains and losses. PSL inherently captures the extent to which biodiversity is affected by a transition from a pristine land cover to various human-modified land uses which in this analysis include forest, pasture, irrigated cropland and rainfed cropland. The disaggregated results shown in Figure 2-3 demonstrate that pasture conversion is the main determinant of net PSL in the mitigation scenarios. The single best biodiversity outcome across land uses is indeed achieved in the 1.5C scenario where either large conversion of pasture to unmanaged land or the avoided conversion of land to pasture, depending on the region, lead to up to -760 PSL compared to the NPi reference, a benefit that is sharply reduced (-319) in a 2.0C scenario. However, the increases in area of managed forests compared to NPi baseline negatively impacts biodiversity, with a positive PSL compared to NPi that ranges between 216 and 401 from the 2.0C to the 1.5C scenario.



	Forest	Pasture	Irrigated Cropland	Rainfed cropland	Total PSL
1.5C	401.9521639	-760.1772511	23.82384281	52.51152544	-281.889719
1.7C	287.1300377	-465.0247305	9.728121862	-54.69961318	-222.8661842
2C	216.8118548	-319.2374034	1.738376446	-73.14877307	-173.8359453

Figure 2- 3: Illustration of average PSL impacts across the 5 SSPs of scenarios applying 2C, 1.7C and 1.5C compatible optimal mitigation portfolios compared to NPi reference scenarios for the main land uses covered in the modelling framework: managed forests, pasture, irrigated cropland and rainfed cropland.

The biodiversity impacts of the optimised scenario can be compared to the impacts of least-cost (LC) scenarios, which reach the same 3 climate targets without being constrained by an optimisation of environmental and socio-economic impacts (Figure 2-4). The final net PSL results across land uses are also suggesting benefits to biodiversity relative to the NPi baseline. However, these benefits are significantly lower compared to optimal scenarios: on average in the 1.5C scenario, the PSL is –103 against –282 in the optimised scenarios. This worst performance of the LC scenarios on the aggregate level is however nuanced when looking at the level of land uses. LC scenarios indeed reduce the biodiversity loss caused by managed forests compared to the optimised ones, while they simultaneously decrease the biodiversity benefits from avoided conversion to pasture and increase the biodiversity impacts on rainfed cropland. This suggests that a higher share of land-based mitigation is provided by bioenergy crop than by forestation and avoided conversion of unmanaged land in the least-cost approach. These findings illustrate the importance of assessing biodiversity impacts from climate mitigation measure at the land use level in order to identify which land use transitions remain detrimental despite broader global benefits. Such assessment is a prerequisite to designing targeted biodiversity conservation measures that can foster synergies rather than exacerbate trade-offs with climate mitigation from the AFOLU sector.



	Forest	Pasture	Irrigated Cropland	Rainfed cropland	Total PSL
1.5C	257.0340238	-530.5142758	30.59234032	139.2994023	-103.5885094
1.7C	179.3564722	-349.9167241	17.03609017	27.037321	-126.4868407
2.0C	140.8619799	-253.7374475	10.44639946	-5.461332036	-107.8904002

Figure 2- 4: Illustration of average PSL impacts across the 5 SSPs of scenarios applying 2C, 1.7C and 1.5C compatible least-cost (LC) mitigation portfolios compared to baseline scenarios for the main land uses covered in the modelling framework: managed forests, pasture, irrigated cropland and rainfed cropland.

2.4 Discussion

While targeted conservation initiatives have the potential to reduce extinction rates of vertebrates by three to four times (Bolam et al., 2021), there is limited evidence to suggest that climate mitigation strategies and biodiversity conservation efforts inherently support each other (Jantz et al., 2015). Yet, previous work including a joint IPCC-IPBES workshop have concluded that the deep interconnection between climate and biodiversity challenges requires integrated, science-driven policies capable of addressing both crises simultaneously (Leclère et al., 2020; Pörtner et al., 2021).

As exemplified in this analysis, in the current GCAM modelling framework, the modelled mitigation scenarios, averaged across the five SSPs, have net biodiversity benefits compared to baseline scenario following national policies, both due to the large areas of unmanaged land whose conversion is avoided, and to the conversion of managed land such as pasture to unmanaged land. However, results also demonstrate that behind positive net impacts, impacts per land uses vary significantly across scenarios. Indeed, ambitious mitigation efforts in the AFOLU sector can benefit biodiversity under certain conditions and be detrimental in others, depending on the mitigation measure itself and the concerned land use. As exemplified in the optimised scenario, where AFOLU mitigation is achieved through land conservation, the expansion of unmanaged land and afforestation/reforestation, the PSL remains high in forests.

Yet, when climate targets are achieved through an economy-wide cost-minimising principle, AFOLU mitigation remains positive for biodiversity but to a lesser extent compared to optimised scenario. This is mostly caused by a reduction of the benefit in pastural agroecosystems despite a reduced pressure on biodiversity by forests as the mitigation portfolio relies less on forests for carbon removal and bioenergy in these scenarios. We can therefore conclude that pathways with the lowest macroeconomic impact, —close to what a least-cost approach would find, —can be synergistic with other non-climate policy objectives but that their explicitly integration in the modelling framework can significantly enhance the magnitude of the synergy.

These important differences between optimised and least-cost pathways demonstrate the relevance of expanding and improving the integration of biodiversity dimensions within the IAM modelling framework rather than relying on ex-post analysis of impacts. That integration remains challenging given the complexity of biodiversity loss both spatially and temporally and considering the multiple stressors. Recent studies going in this direction include Azuero-Pedraza et al., (2024) which used the GLOBIOM-Forest model to endogenise biodiversity impacts in forest management decisions. The study confirms that forest managed for bioenergy use in RCP 1.9 scenario led to adverse biodiversity impacts compared to an RCP 7.0 scenario, although biodiversity-conscious management could alleviate these trade-offs. Similar efforts to endogenise biodiversity metrics in IAMs like GCAM with full-economy coverage could provide further insights on policies and measures able to successfully navigate these complex interactions between land-based mitigation and biodiversity conservation.

Beyond an endogenous representation, future work could respond to several limitations of the current work. First, we have only modelled the biodiversity impacts of LUC while other drivers have not been explicitly considered, included but not limited to pollution, invasive species or climate change. Unlike LUC, climate change could also affect biodiversity in protected and unmanaged areas and hence our results, assuming zero impacts in pristine land, could be overly optimistic. In addition, we have only used one biodiversity metric (PSL) which limits the robustness of our results. Other established metrics of biodiversity include for instance Mean Species Abundance (MSA), Biodiversity Intactness Index (BII) or the Extent of Suitable Habitat (ESH). In addition, IAMs can be coupled with innovative biodiversity models to assess impacts on ecosystem services, such as the InVEST (Mukhopadhyay et al., 2025) or the GLOBIO (Schipper et al., 2020) models. Other models such as AIM-BIO (Ohashi et al., 2019) could capture the impacts of climate change on biodiversity, enabling multi-stressor analyses. Additional metrics as well as IAM-coupling with other models could greatly enhance these biodiversity analyses and refine their main conclusions.

Our work has quantified the biodiversity impacts of a range of mitigation scenarios optimised across environmental and socio-economic dimensions showing that climate action presents significant co-benefits with biodiversity conservation when land-based mitigation is performed through land conservation/avoided conversion and expansion of unmanaged areas. Although net biodiversity impacts are consistently positive compared to baseline scenarios, they are lower when mitigation is achieved through the cost-optimisation approach. This approach remains the standard across IAMs which suggests that modelling should advance in the direction of multi-dimensional assessments if synergies across policy portfolios are to be fostered. While previous policies have largely tackled the problems of climate change and biodiversity loss independently, addressing synergies across these challenges while accounting for societal impacts offers the opportunity to both maximise co-benefits and avoid trade-offs. This integration can materialise at different scales. Globally, greater collaboration across multilateral international agreements could facilitate the development of intersectoral policies and innovative regulatory frameworks. This becomes particularly relevant when considering telecoupling properties where one intervention can have off-stage impacts in far-away regions through indirect land use change, for instance. Tackling climate, biodiversity and human society as coupled systems and moving beyond siloed approaches is crucial when designing large-scale policy interventions and frameworks. Nationally, these cross-sectoral integration, when aligned with context-specific information, should be routinary rather than exceptional when making policy decisions so that biodiversity can be progressively mainstreamed into climate policy and vice versa, across sectors. As emphasised by the IPCC-IPBES workshop, managing adequately such complexity calls for robust and transparent deliberative and negotiation mechanisms including all relevant stakeholders that can address unequal power relations. To conclude, the findings of this study illustrate the importance of tackling in an integrated manner the climate and biodiversity crisis and call for enhancing the biophysical and ecological capacities of IAMs in order to increase the range of trade-offs and synergies that future modelling frameworks can cover. These are key priorities to efficiently optimise the mitigation co-benefits in the AFOLU sector.

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3. Uncertainty analysis against multiple SDG indicators: update

3.1 Introduction

In 2015, all United Nations Member States adopted the 2030 Agenda for Sustainable Development and the related 17 specific goals[1] as a shared policy framework seeking to guide towards prosperity, enabling human well-being and peace while harmony with nature[2]. Meetings have been played out since then such as the consecutive "Conference of Parties" (COP[3]) or the Summit of the Future[4] in 2024, and thousands of papers have been published to further analyze the framework and its application at different geographical and temporal scales[5]. However, the Agenda was agreed without a clear knowledge of how to achieve them[6]. Moreover, most studies find that focusing on a single goal often causes unintended negative impacts on others, resulting in a clearly negative-skewed imbalance[7]. For example, Weitz et al. (2018)[8] captured interactions among SDG targets through a typological classification and inference methods to identify directional relationships between targets in first- and second-order networks. They concluded that SDG interactions are asymmetrical, and policies should prioritise specific synergies to enhance the effectiveness of strategies. Consequently, the isolation, or silo, perspective for SDGs is the perhaps strongest problem that policy implementation must face. In this sense, it is essential to work in an integrated manner to ensure an efficient and feasible Sustainable Path[9]. A review of methodological approaches on SDG synergies and trade-offs can be found in Aliya et al. (2024)[10], Griggs et al. (2017)[11] reported a widely used SDG interaction guide and Pradhan et al. (2017)[12] proposed a ranking of global synergies and trade-offs. More specifically, some studies looked at the interactions between specific SDGs (e.g., environment-poverty-energy[13]) and located the research in precise country or region[14,15]. Nevertheless, previous studies are limited to analysing historical data, which prevents them from capturing major future change across dynamic conditions (such as economy, demography, or climate). As a result, the weights and directionality resulted from historical validation may become constrained or biased.

To address the SDGs in long-term decision making, integrated assessment models (IAMs) are central tools to mathematise key processes from the real world and provide quantifications for long-term storylines. The strong presence of IAMs in IPCC reports and climate policy assessments proves the value and relevance of these models in the decision making of international climate and sustainability agendas[16]. Modelling teams are working to integrate UN indicators to represent sustainable pathways through 2030 and beyond, providing insights into the acceptability of long-term impacts from SDG-aligned policies[17]. The first step on this direction has been the integration of the indicators into the IAMs. The second step, evaluate the most acceptable or optimal policy scenario to propose changes.

3.1.1 First step: Integrability of SDGs in IAMs

The work requires a quantitative analysis of storylines with SDGs as decision indicators. So, we first introduce recent contribution done in this task. Two studies[18] have recently discussed the quantification of SDGs in simulations and numerical approaches to correlate SDGs with proxy variables in IAMs. Although the harmonisation of SDG implementation in IAMs is still under development, most of the studies have proposed a similar solution based on the establishment of an own "target space", i.e., "*a limited set of targets formulated unambiguously and providing comprehensive coverage of the ambition of the SDGs"* , according to Van Vuuren et al. (2022)[19]. The objective of a target space is to help the scientific community in evaluating the achievement of SDGs in future scenarios, thus helping to identify potential synergies and trade-offs among policies.

The complex situation IAMs face when representing SDGs has led to diverse alternative lists of indicators. Van Vuuren et al. (2022)[19] established a *target space* where IAM variables were used as proxies. The selection criteria followed seven principles : indicators should be (1) relevant for society; (2) based on science; (3) valid until 2030 and beyond; (4) robustly quantifiable to enable quantitative analysis; (5) ensure operational simplicity, transparency and usability for policy makers; (6) sensitive to human decision making and achievability; and (7) comparable with data and knowledge. The result consisted of 36 proxy variables for targets covering the 17 SDGs. The authors selected articles where the SSP2[20] was exogenously assumed to identify proxies for the target space (except Riahi et al. (2017)[21], the reference where the modellers of the IPCC's IAMs explain the SSPs). Although all referenced studies used the same scenario data (MESSAGE-GLOBIOM, developed and maintained by IIASA), the methodological extensions applied to estimate inequality, hunger risk, population dynamics, impact indicators, and water stress were developed independently. This implies an underlying assumption that these extensions are not interdependent; otherwise, the results would not be directly comparable, and the scenario would need to be re-run with all methods fully integrated within the IAM framework. As a result, potential cross-model interactions – such as the influence of hunger risk in the population dynamics – may be missing from the IPCC scenario context.

Soergel et al. (2021b)[22] was the only study reporting results for all SDGs through 56 indicators. However, the authors faced similar limitations in their IAM (REMIND-MAgPIE). First, 12 indicators were exogenously assumed via scenario (SSPs) such as educational attainment, GDP, population and end-use energy demands in buildings and mobility. Similarly, 15 indicators were post-processed to extend the analysis with other tools. Specifically, SDG 3 (Good Health and Well-Being), SDG 4 (Quality Education), SDG 5 (Gender Equality), SDG 8 (Decent Work and Economic Growth), SDG 10 (Reduced Inequalities), SDG 11 (Sustainable Cities and Communities), SDG 14 (Life Below Water), SDG 16 (Peace, Justice and Strong Institutions), and SDG 17 (Partnerships for the Goals) were calculated out from the IAM. Later, Soergel et al. (2024)[23] proposed three sustainable development pathways based on 38 proxies to cover all the Goals, from which 22 were endogenous, 13 were scenario assumptions, and 3 post-processing assumptions.

Moreno et al. (2023)[61] analysed the implications of long-term mitigation strategies on SDG Agenda. The authors combined the IAM GCAM with two tools to extend the SDG coverage. On the side of the IAM, seven endogenous indicators were captured to assess on SDG 2, 6, 7, 11, 13, 14, and 15. In China, SDGs have been integrated in two models to assess the interplay of mitigation pathways with sustainable development. He et al. (2025)[24] used variables of the IPAC model as proxies of 32 SDG indicators, also requiring simplification hypothesis to quantify the indicators. For example, SDG 6.3.1 (Proportion of wastewater safely treated) was proxied by the industrial water demand, and material footprint (8.4.1) by GDP and population. Among them, 10 SDG indicators were directly quantified focusing on SDGs 7, 8, 9 and 12, while the rest were determined with the help of post-processing, independent analysis. However, we cannot clearly conclude which variables are exogenously assumed (scenario) and which others are endogenously calculated. Finally, Wang et al. (2025)[25] employed GCAM 6.0 to evaluate the effects of coal phase-down in SDGs. In this case, 16 indicators covered 9 SDGs. The level of detail remains similar than previous works, for example, GPD per capita to proxy SDG 1 (No Poverty), and municipal water per capita, water use efficiency and water consumption per GDP as proxies of SDG 6 (Clean Water and Sanitation). Furthermore, some proxies were exogenously assumed via scenario parametrisation (SSPs).

3.1.2 Second step: Scenario selection

About the second step, to date, only one study has proposed methods for selecting scenarios within IAMs. Forouli et al. (2020)[26] used the GCAM model to project the progress of three SDGs. Specifically, they used a multi-objective integer optimisation program targeting SDGs, and augmented ϵ-constraint method to identified "pareto-optimal" solutions to the mathematical optimisation. The uncertainty framework in this study addresses both deterministic and stochastic uncertainties to evaluate the robustness of optimal mitigation portfolios. Deterministic uncertainty is tackled through scenario analysis by exploring different technology performance levels across timeframes and socioeconomic contexts (SSP1, SSP2, SSP3), effectively stress-testing solutions under varying conditions. Stochastic uncertainty, inherent in model parameters like emission reduction potential, energy access, and health benefits of technologies, is incorporated using Monte Carlo simulation. These parameters are treated as random variables sampled from uniform distributions (±5% around GCAM-derived estimates). The model is first run deterministically to establish a baseline Pareto front, followed by 1000 Monte Carlo iterations that generate multiple Pareto fronts under stochastic variability. Comparing these fronts enables assessment of the robustness of "optimal" solutions under uncertainty.

3.1.3 Contribution of this work

The present work contributes to merge SDG analysis and IAMs. Specifically, we propose a space target based exclusively on endogenous variables to keep uncertainty in decision making and validate its robustness using Stochastic Multicriteria Acceptability Analysis (SMAA), which confirms that the proposed target maintains high acceptability across a wide range of preference scenarios, thus supporting reliable and resilient decision-making under uncertainty. Therefore, the current study addressed two research questions. First, what is the state-of-the-art in modelling SDGs in IAMs? Second, how robust is the IAM WILIAM supporting decision makers with an accepted scenario for sustainable development policy under uncertain preferences?

To address the research questions, we have started with a review of sustainable development goals in IAMs, along with methods that provide a top-level perspective for selecting the most accepted scenario. In methods, we present a nascent integrated assessment model, WILIAM, designed to support the scenario projections by 2050, and Stochastic Multiobjective Acceptability Analysis (SMAA) to address the uncertainty inherent in selecting among 72 long-term pathways. The study also includes a critical assessment of synergies and trade-offs to evaluate the coherence of WILIAM results with previous studies on SDG databases. In conclusion, we aim to facilitate the scenario selection of mitigation pathways in integrated assessment models under the lens of the UN Goals.

3.2 Methods

The approach presented in this work has been summarised in Figure 3-1. First, a target space has been modelled in the IAM called WILIAM. Second, we have developed three global scenarios as alternatives to the continuation of past trends. Third, we simulate the scenarios in WILIAM, including variations in key hypothesis, to provide quantitative results about SDGs. Fourth, these results feed the Stochastic Multicriteria Acceptability Analysis (SMAA) to elucidate an understanding of how the scenarios rank in terms of being likely to be acceptable to the stakeholders.

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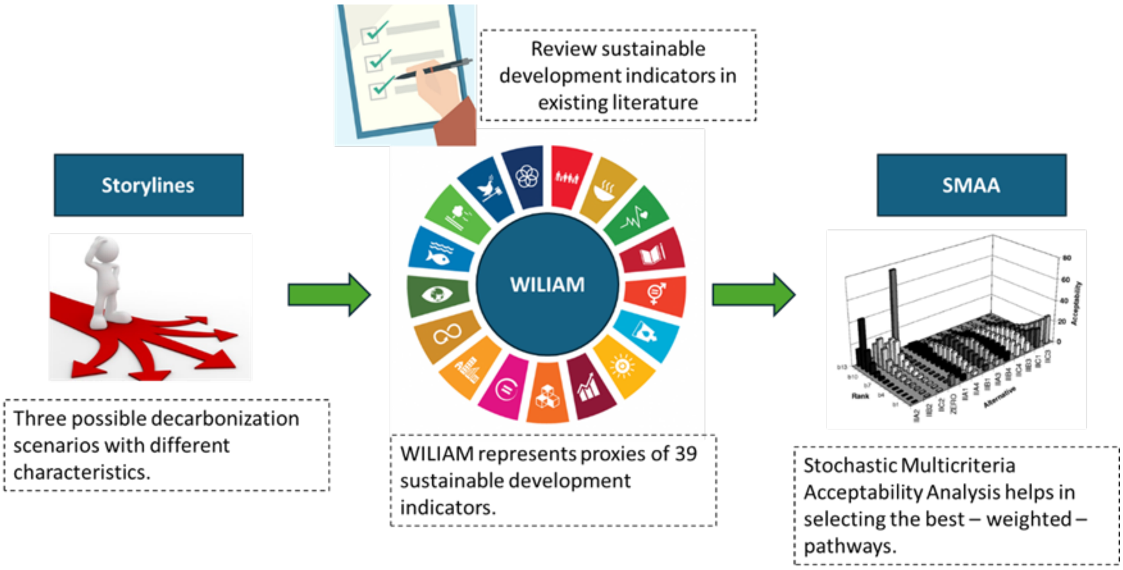

Figure 3- 1: Overview of the study about SDGs employing the IAM WILIAM and the SMAA method.

3.2.1 SDG space in WILIAM

The Within Limits Integrated Assessment Model (WILIAM) was developed under the H2020 Locomotion project (Grant Agreement No 821105). Details can be found in project deliverables[27,28], and an up-to-date wiki hosted in Github[29]. WILIAM is a model descendent from MEDEAS[30], and WoLiM[31]. The latest public version of the model can be downloaded from the same Github repository as the wiki.

WILIAM is developed under two integrated methodologies. On the one hand, system dynamics has been the general theory behind the modelling of most dimensions of our reality such as energy, materials, population, land uses[32] or climate. On the other hand, a detailed representation of economic processes using a dynamic econometric Input-Output approach, consistently linking the economic and biophysical spheres in line with the principles of ecological macroeconomics. The overall objective of WILIAM is to provide global and regional policies on climate change mitigation and energy transition. It incorporates nine global regions, with specific disaggregation for the European Union (27 countries).

This work acknowledges the limitations faced in previous studies (see introduction section). To our understanding, the best practices to carry out the modelling of SDGs in IAMs may be summarised in two points. First, the exclusive selection of endogenous variables as in Moreno et al. (2023)[61], avoiding scenario assumptions and post-processing tools to keep uncertainty within the whole exercise. Second, the qualitative relationship between SDG indicators and IAM proxies as in Soergel et al (2021)[22].

The information of SDGs has come from three sources: a) the original UN indicators, which are directly implemented where possible; b) indicators proposed by van Vuuren et al. (2022)[19], c) other literature. Yet, in this context "Partnerships" is excluded due to the lack of representation of institutional relationships in IAMs, and "Planet" is split into Planetary Integrity and Sustainable Resource (Management), resulting in five categories; and c) other indicators selected directly form the model to cover more aspects of the SDGs. Consequently, our SDG target space is concluded in table 3-1. We could not cover all the 230 indicators but analysed the percentages in Figure 3-2 to show the disbalanced representation of SDGs according to the information available in the model.

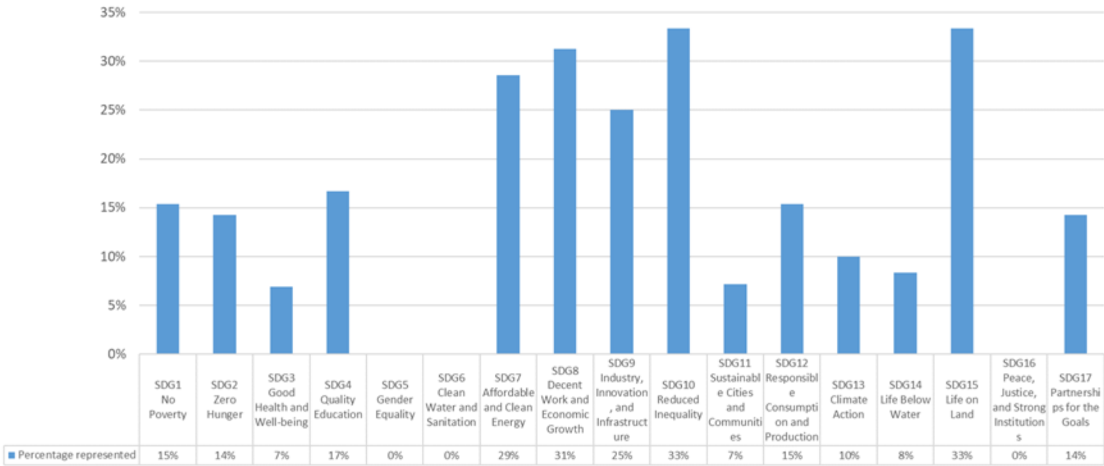

Figure 3- 2: Percentage of the SDG represented (number of indicators) in the integrated assessment model, WILIAM.

Table 3-1. Indicators to represent sustainable development goals in WILIAM.

OUTPUTS				
SDG indicator number	**SDG indicator**	**Variable in WILIAM**	**Description of the variable. Source & Comment**	**Units**
1	1.A.2	global_share_government_expenditure_in_social_benefits	World share of government expenditure in social benefits	share
2	2.4.1	global_ratio_of_sustainable_agriculture_area	Average share of the global agricultural area under sustainable agricultural methods	share
3	2.4.1	global_ratio_of_productive_agriculture_area	Average share of the global agricultural area under high-input agricultural industrial production	share
4	2.c.1	global_availability_of_crops_for_food	Global availability of crops for food	share
5	2.c.1	global_daily_nutritional_energy_intake	Daily nutritional energy intake worldwide	kcal/(person*day)
6	3.2.1	under_5_mortality_rate_1R	Average mortality rate under 5 years old in the World. Deaths during the first five years divided by the births in the year (probability of child survival in the first 5 years of live). Meaning of units: (deaths in first 5 years of life) / (1000 surviving births)	person/kpeople
7	6	global_effective_blue_water_demanded_for_agriculture	Effective blue water demanded for agriculture in the World	hm3
8	6	global_fertilizers_demanded	Demand of fertilizers in the industrial agriculture	tonnes
9	6	global_water_stress	Stress of water in the World	%
10	7.2.1	world_share_RES_in	Global share of renewable at the final energy	Dmnl

		_FE	level	
11	7.3.1	world_PE_GDP_intensity	Primary energy consumption vs gross domestic product, worldwide	TJ/Mdollars_2015
12	7	PROTRA_RES_capacity_stock_per_capita_1R	Installed capacity to exploit renewable energy sources in the World	w/person
13	8.1.1	world_annual_growth_rate_GDPpc_real	Annual growth rate of the global gross domestic product per capita, in real terms	Dmnl
14	8.2.1	world_annual_growth_rate_GDPpw_real	Annual growth rate of the global gross domestic product per worker, in real terms	Dmnl
15	8.4.1	cumulated_total_materials_required	Cumulated total materials required in the World since 2015	Mt
16	8.5.1	world_average_wage_hour	Average hourly wage worldwide	$/h
17	8.5.2	world_unemployment_rate	Average unemployment rate worldwide	Dmnl
18	8.9.1	GDP_pc_1R_vs_GDP_pc_OECD	Percentage of OECD countries contributing to the global gross domestic product	%
19	9.1.2	global_volume_passenger_transport	Volume of passenger transport demand in the World	person*km
20	9.2.1	global_share_manufacturing_value_added_per_GDP	Share of manufacture industries contributing to the global gross domestic product	Dmnl
21	9.2.1	global_manufacturing_value_added_per_capita	Global value of manufacturing industries per capita	Mdollars_2015/(Year*person)
22	9.2.2	global_manufacturing_employment_ratio	Global share of manufacturing employment related to total employment	Dmnl
23	9	CO2_industry_direct_emissions_1R	Direct carbon emissions of industry in the World	Gt/Year
24	10.4.1	global_labour_compensation_share	Global share of labour compensation related to gross domestic product	Mdollars/Mdollars_2015
25	10	Gini_GDPpc_regions	The Gini GDPpc index measures the extent to which the distribution of GDP between WILIAM regions deviates from a perfectly equal distribution. A Gini index of 0 represents perfect equality, while an index of 1 implies perfect inequality.	Dmnl
26	11.3.1	global_ratio_land_consumption_rate_to_population_growth_rate	Global ratio of land consumption for population growth	km^2

27	12.5.1	global_rate_minerals_recycled	Global rate of recycled material	Dmnl
28	12.a.1	global_capacity_renewables_installations_per_capita	Global capacity of renewable energy-supply infrastructure in "developing countries". We consider EASOC (East of Asia and Oceania), LATAM (Latin America), LROW (Rest of the World) as "developing regions"	w/person
29	13.2.2	total_CO2e_emissions_per_capita_1R	Total global emissions, in carbon dioxide equivalent units, i.e., after applying the global warming potentials.	t/(Year*person)
30	13	temperature_change	Temperature of the Atmosphere and Upper Ocean, relative to preindustrial reference period (1850)	°C
31	13	total_cumulative_CO2_emissions_from_2020	Total cumulative CO2 emissions from simulation since 2023 to calculate remaining carbon budget.Historical emissions in 2020, 2021, 2022 comes from GCB data.	Gt
32	13	C_emissions_LUC_and_cropland_management_region_1R	Global carbon emissions from land-use changes and associated to cropland management (LULU).	Gt/Year
33	14.3.1	pH_ocean	pH of the ocean, acidification.	pH
34	15.1.1	forest_area_vs_total_area_1R	Sustainable Development Indicator 15.1.1 - Forest area as a percentage of total land area	Dmnl
35	15.2.1	global_index_of_forest_stock_per_area	Global index of forest stock per area	Dmnl
36	15.2.2	global_index_of_forest_area	Global index of forest area	Dmnl
37	15.3.1	global_degraded_land_over_total_land	Degradation is more general and it should be thouroughly studied. This is a proxy based on the category "other land" (deserts, shrubland, snow, ice, waterbodies) and "loss of primary forest"	Dmnl
38	17.1.1	governmental_revenue_1R	Global government revenue.	Mdollars/Year
39	17.11.1	global_share_exports_in_GDP	Share of exports in the global gross domestic product	Dmnl

3.2.2 Storylines, scenarios and pathways

In this work, we use the word *scenario* to represent an exploration of potential future developments, built upon a set of qualitative and quantitative assumptions and reflecting un underlying *storyline*. A scenario provides insights into strategic decision making by envisioning a future and evaluating its consequences under different actions[33,34]. The quantification of a scenario is thus preceded by the development of a qualitative *storyline,* to provide the narrative of which the quantitative scenario elements follow. Thus, a storyline is essential to provide a general and common context for questioning[35]. Finally, a *pathway* is a specific simulation or trajectory (time series) showing how the quantitative model variables evolve over time. We considered four storylines, which are quantitatively parametrised as four scenarios. When including the simulations varying uncertain parameters, we reach 72 distinct pathways.

We selected three mitigation scenarios that projects a reality aimed at reducing greenhouse gas emissions and avoiding, as far as possible, an increase in the global average temperature change. We have reviewed literature, mainly related to the IPCC SSPs, to identify common characteristics of mitigation based on technological changes for an energy transition, mitigation based on lifestyle change, and mitigation based on environmental policy. Common characteristics across them are listed below from Nakicenovic et al.[33]:

1. Span a range of potential futures addressing socio-economic challenges.
2. Incorporate various scenario assumptions related to key systems: energy (both demand and supply), technological advancements, land-use changes (as seen in[31,36]), and behavioural shifts (e.g., lifestyle).
3. Demonstrate significance in terms of mitigation, sharing a common goal of decarbonisation scenarios.
4. Consider a sustainable perspective aligned with global sustainable development in the storyline, offering "more truly" sustainable goals beyond the reference scenario.
5. Promotion of an energy transition towards energy efficiency and dominant presence of renewable energies.

For the present study, Table 3-2 covers all the attributes implemented in WILIAM for representing the scenarios. All the mitigation storylines imply a higher ambition than the reference business-as-usual, so they share the same climate target, equal to 1.84ºC in 2050 (continues to increase after that year).

Business-As-Usual (BAU, reference scenario)

The world continues with historical and current trends in social, economic, policy, and technological developments, reflecting patterns from the past. This encompasses existing policies, along with their level of implementation, without the explicit climate policies described in Van Vuuren et al.[35]. We assumed historical trends to project exogenous variables.

Scenario 1. Energy transition with high technology development (ET)

In this storyline, the world transitions towards decarbonisation of the energy system centred on technological advancements, accelerated energy efficiency, and extensive integration of renewables in the energy sector. This storyline places less emphasis on social aspects or environmental considerations beyond climate change. The primary goal is the decarbonisation of the energy system.

Scenario 2. Energy transition combined with promotion of Lifestyle Changes (LC)

To significantly limit global warming, there is a need to not only transform how energy is produced but also how resources are consumed. This entails instigating social change in the climate scenarios. In this storyline, mitigation efforts are divided between an energy transition coupled with assumptions of lifestyle and behavioural change that curtail energy demand and consequently reduce resource consumption. The focus and investment are directed towards promoting lifestyle modifications and structural alterations that facilitates these environmentally sustainable shifts on both individual and collective scale. This approach will help assess the positive and/or negative impacts of these combined policies (related to energy and social aspects) on specific SDGs in comparison to the technology focused storyline (scenario 1).

Scenario 3. Energy transition with Environmental Considerations promoting policies in the land-use sector (EC)

This scenario recognises environmental policy beyond climate, defining a more ambitious land regulation. In particular, the management of wood, forest protection for autochthonous habitats, and the promotion of regenerative agriculture are dominant when unfolding this scenario. So, the efforts for mitigation are not only considered in the energy system or demand side, but also in the land use sector.

Table 3-2. Qualitative attribute table for the storylines implemented in this study.

Attributes	Business-as-Usual (BAU)	Storyline 1 - ET	Storyline 2- LC	Storyline 3- EC
Demography (SSP2, 8869 million people worldwide in 2050)				
Fertility	Medium			
Mortality	Medium			
Migration	Bilateral migration rates are constant values of 2020			
Economy				
Carbon tax in 2050	No	Low	High	No
Basic income	No	No	Yes	No
Carbon revenues recycling	No	Yes	Social benefits & Debt reduction	No
Government consumption & investment	Past Trends	Past Trends	Higher for education	Past Trends
Energy/Technology				
Renewables	Medium	High	Medium	Medium
Energy Efficiency Improvement	Past Trends	High	Past Trends	Past Trends
Unmature technologies (CCS, offshore floating wind)	No	Yes	No	No
Rooftop solar	Medium	High	Medium	Medium
Capacity investment costs	Past Trends	Low	Past Trends	Past Trends
LAND				
Afforestation/New plantations	No	Moderate	Low	Yes (high)
Protection of managed and primary forest	No	No	No	Yes
Technology Improvement Agriculture	Past Trends	Yes	Past Trends	Past Trends
Regenerative agriculture	Past Trends	Past Trends	Past Trends	Yes (40 % approx.)
Urban land density (person/m2)	Past Trends	Past Trends	Past Trends	Increase nº of people inhabiting a given area
SOCIETY/LYFESTYLE CHANGES				
Diet	Past Trends	Transitions to 50% flexitarian	Transitions to 50% plant-based	Past Trends
Passenger demand	Past Trends	Past Trends	Lower	Past Trends
Transport mode	Past Trends	Past Trends	Electrification & biking	Past Trends

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Hypothesis for the uncertainty analysis (SMAA exercise)		
Population	Medium	Low (minimum historical values in the period 2005-2020) Medium (mean historical values in the period 2005-2020) High (maximum historical values in the period 2005-2020)
Minimum EROI solar and wind technologies	Medium	Low = 5 Medium = 8 High = 10
Government budget balance	Negative (past trends by 2050)	Negative (past trends by 2050) Positive (1% by 2050)

For the stochastic multicriteria acceptability analysis (SMAA, see below) uncertainty ranges need to be produced for mapping decisions to outcomes. The next hypotheses have been used to generate these uncertainties in the three mitigation scenarios:

6. Energy Returned on Energy Invested (**EROI**). The minimum EROI (EROImin) is the minimum ratio of the energy delivered from a process divided by the energy required to get it over its lifetime, indicating the net energy available for the society. The uncertainties around the estimation of the EROImin is very big, as the reduced availability of discretionary energy, as intermediary operations become less efficient, is a gradual non-linear process with increasing and cascade consequences over time.
7. **Population**. Given the United Nations statistics from 2005 to 2020, the minimum and maximum population size is determined by the minimum and maximum fertility rates and life expectancies at birth by region, respectively.
8. **Government budget balance**. The effort to avoid deficit in the national accounts is set from negative (according to past trends) to a positive 1% to show the impact of economic restrictions imposed by the government in the economies.

Acceptance in preference uncertainty

The conventional multicriteria decision analysis (MCDA) approaches usually consider the preference information by selecting importance weights for criteria. The stochastic multicriteria acceptability analysis (SMAA) methods, however, examine the weight space to show the preferences that would make an alternative the best choice (or any given rank) for the decision makers. In addition, the SMAA methods allow for assessing uncertainties in both preference information and criteria measurements. Therefore, SMAA applies to many real-life problems where the decision makers are unable or unwilling to provide their preference, or it is difficult to reach consensus over the preferences. In these situations, the weight information can be provided as intervals that represent all decision makers' preferences, or with some other weight distribution accepted by all decision makers[37].

A multicriteria decision problem is considered as a set of alternatives evaluated based on several criteria. SMAA methods are developed for cases where the weight and criteria values are not precisely known to deal with multiple sources of uncertainties. As a result of SMAA, three measures are computed for the alternatives: rank acceptability indices, central weight vectors, and confidence factors.

The rank acceptability indices are the share of all feasible weights that make the alternatives acceptable for a particular rank. This is computed as a multidimensional integral over the criteria distributions and favourable rank weights. The most acceptable (best) alternatives are those with high acceptability for the best ranks. The rank acceptability indices are within the range [0, 1], where 0 shows the alternative will not obtain a given rank in any circumstances, and 1 indicates that it will always obtain the given rank no matter how uncertain the weights are.

The central weight vectors represent the preferences of a typical decision maker supporting a specific alternative. It is also computed as a multidimensional integral over the criteria and weight distributions. By presenting the central weight vectors to the decision makers, an inverse approach for decision support can be applied, in the sense that instead of eliciting preferences and building a solution to the problem, the decision makers can learn what kind of preferences lead to which alternatives without providing any preference information.

Finally, the confidence factors are the probability for an alternative to obtain the first rank when the central weight vector is chosen. Such factors could be computed as a multidimensional integral over the criteria distribution. For every given weight vector, the confidence factors can be calculated similarly. The confidence factors measure the accuracy of the criteria measurements in determining the most efficient alternatives. If the problem formulation is to choose an alternative to implement, the ones with low confidence factors should not be selected. More accurate criteria data should be collected to make a robust decision if they are deemed attractive.

As described above, to implement the SMAA method, one needs to compute a few multidimensional integrals that are practically impossible to calculate analytically. Therefore, Tervonen et. al.[37] suggest Monte Carlo simulation as a solution to this problem and discuss their algorithm for this purpose. In this study, we use follow-up versions, the SMAA-2 method[38], and SMAA-O methods[39], and specifically, the software named JSMAA, which is an open-source software for SMAA computations[40] as a multicriteria assessment tool to address the uncertainty analysis. The SMAA-2 handles the uncertain intervals of weights, and the SMAA-O method considers the ordinal preference information of weights.

Apart from the uncertainties in the criteria measures, the preferences of decision makers are uncertain, as there are many stakeholders, some of whom are unable or even unwilling to reveal their preferences. Also, it isn't easy to reach a consensus over the preferences. To address this issue, two uncertain preference schemes have been evaluated in this study. In the first scheme, we assume that there is no information on the preferences of decision makers regarding the SDG indicators, thus, the uniform range [0, 1] is considered for the weight of each SDG criterion. However, for the second scheme, we used the information from Koasidis et al.[41] to extract an ordinal relationship between the SDGs from the perspective of various stakeholders. In this scheme, the weights of the criteria are uncertain as they maintain the following order: SDG15 ≥ SDG14 ≥ SDG10 ≥ SDG12 ≥ SDG2 ≥ SDG7 ≥ SDG6 ≥ SDG1 ≥ SDG11 ≥ SDG3 ≥ SDG9 ≥ SDG8. It should be noted that SDG 13 and SDG 17 are not considered in the second scheme, as Koasidis et al.[41] does not provide any information on the preferences of stakeholders about them.

To apply the SMAA to our case, WILIAM is run multiple times for each mitigation scenario, considering the uncertainties in EROI, population and government budget balance, creating 18 pathways (S) for each scenario (a total of 72 pathways). Subsequently, the results of each pathway (s) are used to derive the SDG criteria.

3.3 Results

3.3.1 SDG analysis

This section discusses a comparative assessment of the performance of SDGs across the four aforementioned scenarios. The analysis encompasses 39 indicators from the WILIAM IAM (presented in the next tables 3-4, 3-4, 3-5, and 3-6), covering most of the SDGs and spanning the period 2015-2050. This study, proceeding SDG by SDG, allows to evaluate how the different policy packages impact on the sustainable areas by quantifying the outcomes and identifying which scenario delivers the most significant improvements. The BAU scenario is used as reference baseline for comparison.

The results shown in these tables represent the percentage of change related to the absolute in the BAU scenario. Green shades with different intensities are used to show indicator improvements (I > 1%), red shades for worse performances (I ≤ -1%) and orange shades for similar performances (-1% ≤ 1%).

Figure 3-3 illustrates the evolution of these 39 indicators over time by comparing the results of each scenario with BAU in 2030 and 2050 (for ease of visualisation, all values are percentage changes).

SDG1 – No Poverty

All scenarios improve over BAU. LC shows the strongest early boost in social spending (until 2030), followed by a drop due to GDP decline or budget shifts. EC and ET show steady increases in public investment.

SDG2 – Zero Hunger

EC performs best in sustainable agriculture (+50% vs BAU), though it reduces crop availability and nutrition due to land reallocation (e.g., for renewables, afforestation). LC and ET yield modest gains; LC shows some decline in productive agriculture, likely due to dietary shifts. BAU remains optimal for food availability and intake.

SDG3 – Good Health & Well-Being

LC shows the greatest improvement in air pollution-related health outcomes due to lower consumption and energy demand. ET also performs well through clean energy deployment.

SDG6 – Clean Water and Sanitation

Water use drops in all scenarios: ET through efficiency and renewable energy uptake (-33.2% vs BAU by 2050), LC through reduced energy demand (-15.4%). Fertiliser use also falls, with EC showing the strongest reduction thanks to regenerative agriculture.

SDG 7 – Affordable & Clean Energy

ET leads with a rapid renewable deployment since LC does not shift the supply side of the energy sector while EC foresees slower renewable expansion.

SDG8 – Decent Work & Economic Growth

ET supports decent work through tech-led productivity gains, while LC's equity focus and work-sharing reduce indicators like wages. ET struggles with GDP growth due to modelling limits, i.e., energy investment is not fully linked to input-output tables. LC's less-intensive economic development requires lower materials consumption, consistent with a circular economy, whereas the deployment of renewables has resource needs as one of its main challenges. No scenario narrows the global North-South divide.

SDG9 – Industry, Innovation and Infrastructure

ET shows the strongest growth in manufacturing and industrial employment, and the greatest emissions cuts (-67% CO_2 vs BAU by 2050). The demand reduction assumed in LC limits the industrial relevance through the I-O method. EC aligns closely with BAU.

SDG10 – Reduced Inequalities

LC surprisingly shows the least improvement in economic equality (GINI index, labour compensation), with minimal differences across scenarios. This suggests that some beneficial socio-economic measures don't always lead to favourable outcomes, so global uniform policy intensity may preserve current inequality patterns.

SDG 11 – Sustainable Cities and Communities

EC reduces land consumption by increasing household sharing, which not only responds to socioeconomic drivers such as affordability and income constraints but also reflects a shift in **urban**

form and land use patterns. Increased household sharing can lead to denser living arrangements and a transformation in architectural typologies, contributing to more efficient land use and reduced urban sprawl. As a result, the corresponding indicator improves markedly by **+33.9%** compared to BAU in 2050, in contrast with the ET scenario and LC's deterioration of **-31.4%**.

SDG12 – Responsible Consumption and Production

ET performs synergetic between renewable deployment and improved recycling (e.g., Fe, Al), supporting cleaner economic growth.

SDG13 – Climate Action

All scenarios cut emissions vs BAU. EC reduces emissions earlier via land-use change and afforestation. ET and LC present steadier and more ambitious reductions of emissions, but a lower final value per capita in 2050, related to EC.

SDG14 – Life Below Water

All alternative scenarios show slight pH increases (+0,5%) from reduced CO2 atmospheric concentration, with minimal ecological impact expected (biodiversity).

SDG15 – Life on Land

Looking at the indicators that target net forest area, EC excels due to afforestation and protection policies. LC and ET also outperform BAU. However, the forest stock per area index is lower in EC than in BAU and LC because, although the net forest stock is higher across all regions, some of those with the largest forested area present lower stock density. This situation reflects the existing delay between the growth of forest stocks and the area afforested, with the latter growing much faster and leading to lower stock per area unit.

SDG 17 – Partnerships for the Goals

Governmental Revenue mostly depends on taxes on income, wealth, GHG emissions, as well as on the gross value added of different productive sectors. Therefore, this goal drops in LC (−77.5%) due to lower demand and rises in ET (+98.8%) from strong economic activity. Export shares remain stable (21–22%) across all scenarios.

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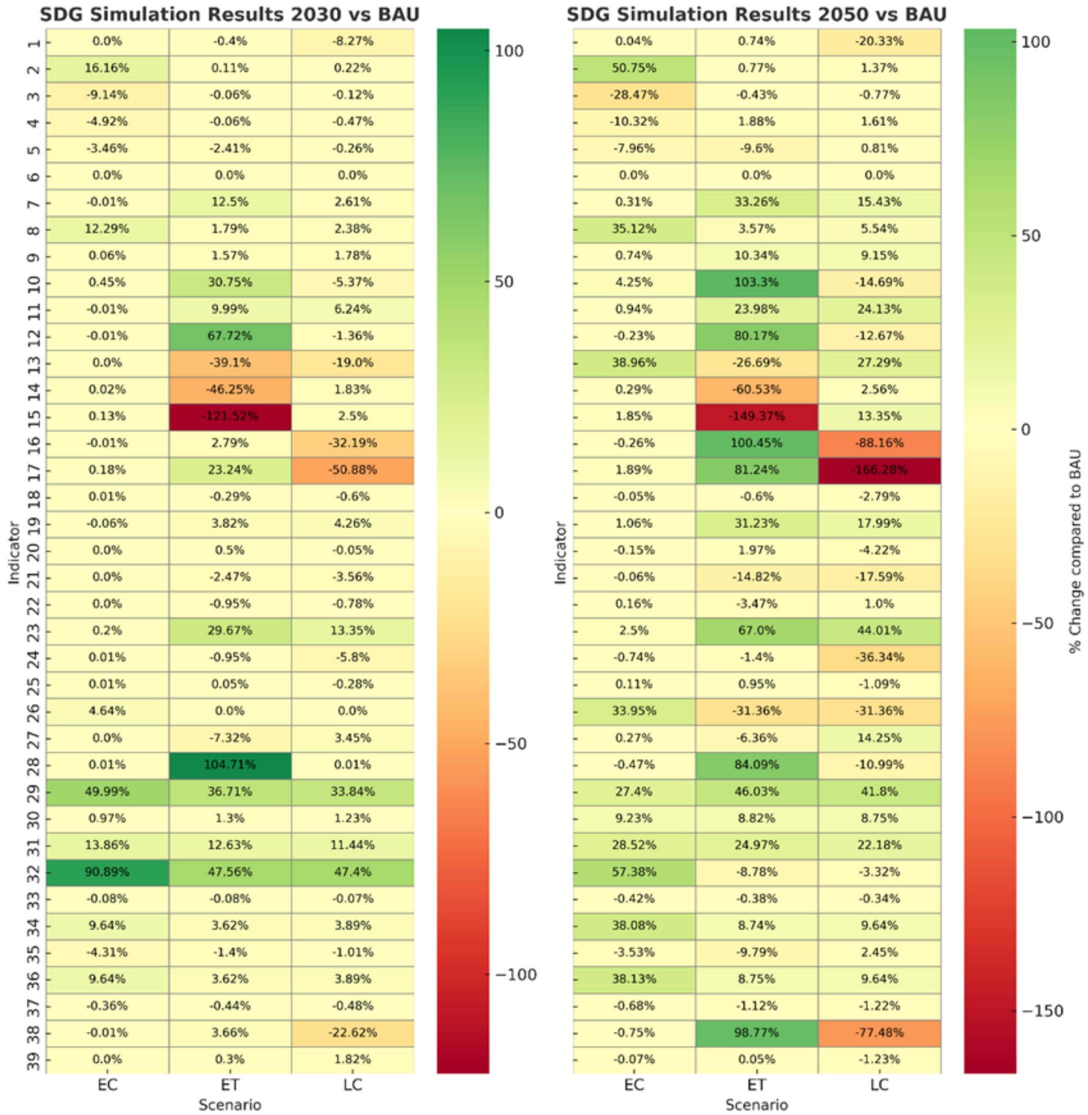

Figure 3- 3: Evolution of the 39 WILIAM indicators for SDGs over time, related to the BAU reference scenario.

The four storylines trigger different synergies and trade-offs among SDGs that are here discussed.

In the ET scenario, the massive clean electrification of industrial and domestic systems (Goal 7) generates simultaneous synergies in reducing emissions (Goal 13) and enhancing industrial efficiency (Goal 9), as reported by McCollum et al.[42]. This improved efficiency translates into higher productivity, which results in more decent jobs (higher hourly wages and lower unemployment rate, Goal 8). Table 3-3 shows the aforementioned synergies between SDG13 and SDG7 by comparing their main indicators for the BAU and ET narratives.

Table 3-3. Quantitative SDG interactions for the ET scenario.

SDGs 13-7 interactions					
SDG	SDG 13				SDG 7
Indicator	GHG emissions	Global Mean Temperature increase	Cumulative carbon emissions from 2020	Cumulative land-use change emissions since 2005	Final energy intensity
Units	$GtCO_{2eq}$/Year	ºC	$GtCO_2$	$GtCO_2$	TJ/M$
BAU	68	2,0	1278	35	5480
ET	50	1,823	958,88	15	4630,6
% Change	-26,5%	-8,82%	-24,97%	-60,0%	-15,5%

Beyond these benefits, the intensive development of energy infrastructure might pose a significant challenge in terms of material requirements (Goals 7 and 12) and forest degradation (Goal 15), which could be diverted to other uses, such as the installation of solar photovoltaic panels or wind turbines. This collateral environmental degradation caused by decarbonisation was already noted by van Vuuren et al.[43] and Nilsson et al.[44] Moreover, a more subtle trade-off emerges when examining the GINI index (SDG 10): although substantial economic growth is achieved, the benefits are not equally distributed at the global level.

In the LC scenario, the overall decline in energy demand and consumption has a significant positive impact on all SDGs related to consumption and health. Thus, material needs are less intensive (Goals 7 and 12), water stress decreases (Goal 6) and climate change mitigation ameliorates in the long term (Goal 13, shown in Table 3-4), aligned with Soergel et al.'s forecasts[45]. Health conditions also improve (Goal 3), probably due to reduced air pollution through cuts in emissions from industry and transport (Goal 9), in line with results obtained by Fuso Nerini et al.[46].

The classic trade-off between equity and economic growth[47] can be assessed by this research, showing reductions in key economic indicators (Goal 8) compared to the BAU[48] and, potentially even more damaging, neither the GINI index nor the labour compensation share do not outperform BAU. In addition, other SDGs laterally associated with economic factors worsen, e.g., public revenue due to less tax income (Goal 17, shown in Table 3-4), which consequently impacts on the share of government expenditure on social benefits (Goal 1).

Table 3-4. SDG interactions for the LC scenario.

SDGs 13-17 interactions					
SDG	SDG 13				SDG 17
Indicator	GHG emissions	Global Mean Temperature increase	Cumulative carbon emissions from 2020	Cumulative land-use change emissions since 2005	Total government revenue
Units	$GtCO_{2eq}$/Year	ºC	$GtCO_2$	$GtCO_2$	M$/Year
BAU	68	2,0	1278	35	104043000
LC	49,84	1,825	994,54	19,15	23430484
% Change	-26,7%	-8,75%	-22,18%	-45,3%	-77,48%

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In the EC scenario, there is an evident interconnection between afforestation and sustainable agriculture policies[49], as both aim to improve forestry indicators, preserve biodiversity (Goal 15) and reduce intensive agriculture (Goal 2). Ecological agriculture, although not in terms of water demand, does have a positive effect on Goal 6 by strongly limiting fertilisers consumption. In this case, the reason behind the emission cut (Goal 13) is the expansion of forest extension, which makes land-use change emissions even negative since forests behave as carbon sinks. All these synergies, shown in Table 3-5, are also well documented by Fuso Nerini et al.[50].

Table 3-5. SDG interactions for the EC scenario

SDGs 13-15-2 interactions										
SDG	SDG 13				SDG 15					SDG2
Indicator	GHG emissions	Global Mean Temperature increase	Cumulative carbon emissions from 2020	Cumulative land-use change emissions since 2005	Forest area as proportion of total land	Primary forest as share of total terrestrial land area	Global area of forested land as % of original forest cover	Other natural land as share of total land area	Non-agricultural land	Food availability
Units	$GtCO_{2eq}$/Year	ºC	$GtCO_2$	$GtCO_2$	%	%	%	%	%	kg/(person*day)
BAU	68	2,0	1278	35	0,4	0,1019	91	0,3	86	1,9
EC	50	1,815	913,51	15	0,55	0,1068	108	0,24	86,43	1,9
% Change	-26,5%	-9,23%	-28,52%	-60,0%	+38,08 %	+4,9%	+18,7 %	-18,7 %	+0,5%	-7,96%

The remarkable shift in the type of agriculture favours multiple indicators, but it drags has a serious drawback in terms of food availability and nutrition (Goal 2), because crop production declines and needs to be overcome with some dietary pattern changes.

3.3.2 SMAA results

The results of the SMAA, including the rank acceptability indices and central weight vectors, are presented in Figure 3-4. In the first weight scheme, where there is no information on stakeholder preferences and a uniform distribution is thus used across the SDGs, BAU and LC scenarios are rarely chosen as the most acceptable alternatives (13% and 1%, respectively) and less than 20% (BAU) or 10% (LC) of the time do they reach the top two. Interestingly, of the two scenarios especially LC performs badly against the range of SDG indicators. On the other hand, the results indicate that 72% of all the feasible weights make the ET scenario the most acceptable option, with the EC pathways having a 23% chance of being ranked first and a 58% chance of ending up in second place.

The central weight vectors reflect the preferences – in our case weights over the SDG indicators – of a typical decision maker who chooses the alternatives as the first rank. In the first scheme, the decision maker in favour of the BAU scenario generally value SDG 2, 8, 10 and 11 more than the extent to which the decision makers who choose the other scenarios do. On the contrary, they do not deem SDGs 6, 12, 13, and 14 as important as the others. It is also notable how highly this type of decision maker regards SDG2 in comparison to the other SDGs. The ET-oriented decision makers surprisingly value all the SDGs fairly similarly, with small differences. This suggests that they take a more balanced approach to make their choice. The differences, however, relate to SDG15 and, to a lesser extent, to SDGs 8 and 11, where they are considered less important compared to the others. Besides, they weigh SDGs 7, 9, and 17 more, and SDGs 11 and 15 less in comparison to the other decision makers. As for the EC scenario, the corresponding type of decision maker prefers to value SDGs 12, 14, and 15 more, and SDG2 less strongly, compared to the other stakeholders. SDG15 plays a prominent role in the preferences of this group, being weighted as the most important criterion. It is also clear that this type allocates relatively lower weights to SDGs 7 and 12. And, the last group of decision makers, who prefer the LC scenario as the best, weigh the criteria disproportionately. For instance, while SDGs 2 and 3 are highly valued, SDGs 1, 7, 8, 9, 10, and 17 are almost neglected. Actually, the latter set of SDGs is never considered less important by any other decision maker type. It should also be noted that the confidence factors for the central weight vectors of the BAU, ET, EC, and LC scenarios are 0.84, 1, 0.8, and 0.13, respectively. While the high factors for the BAU, ET, and EC scenarios suggest that if the corresponding weight vector is chosen, the uncertainties in the criteria do not significantly impact the choices, especially for the ET case. Conversely, the low confidence factor for the LC scenario indicates the deciding role of the criteria uncertainties.

In the second weight scheme, where the order of stakeholders' preferences is known, the results show that, like the first weight scheme, the BAU was rarely chosen as the most favourable option, which suggests that the continuation of current trends is not acceptable under any circumstances from the stakeholders' perspective. Like the previous weighing scheme, the LC scenario has also never been selected as the best alternative and there are few weigh combinations with which either of the two would reach even the position of second most preferred scenario (2% for BAU, 6% for LC). In contrast to the first scheme, however, the EC scenario emerges as the most favourable alternative, with a likelihood of 73% to be the most preferred option, leaving 27% for the ET scenario. Completing the reversal from the first weighing scheme, the ET scenario is most frequently chosen as the second-best, with a 65% probability, followed by the EC scenario at 26%. In this scheme, the weakest positions are even more pronounced: the LC scenario lands in third place 84% of the time, and the BAU scenario falls to fourth place 87% of the time. Comparing the results of the two schemes suggests that incorporating the existing information on stakeholders' preferences not only shifts the most acceptable scenario but also amplifies the differences in acceptability of the alternatives.

Regarding the central weight vectors of the second scheme, since the order of the preferences is introduced, the vectors follow a rather similar pattern. It is noteworthy that because the BAU scenario is never chosen as the most acceptable scenario, it does not have a central weight vector. While SDGs 2, 10, 12, 14, and 15 are the ones that are weighted more than the others, SDGs 1, 3, 8, 9, and 11 are less valued by the typical decision makers who choose either of the scenarios as the best one. Compared to EC-oriented decision makers, ET-oriented decision makers assign greater weight to all SDGs except for SDGs 14 and 15. These two SDGs have higher weights in the EC vector than they do in others. Except for SDGs 2, 10, 12, and 14, the LC central weight vector is consistently lower than the EC vector. Additionally, compared to the other decision makers, the typical LC chooser places greater emphasis on SDGs 2, 10, and 12. Nevertheless, the criteria weights across the vectors are generally very similar, indicating that even slight shifts in preferences can lead to markedly different choices. Furthermore, the confidence factors for the central weight vectors of the ET, EC, and LC scenarios are 0.7, 1, and 0.02, respectively. The high factors for the ET and EC scenarios and the low factor for the LC scenario mirror the first scheme's results, indicating that criteria uncertainties have a significant impact on the LC scenario but are negligible when choosing ET or EC.

Comparing the two schemes reveals that incorporating stakeholder preferences not only changes which scenario wins (from ET to EC) but also increases the gaps in acceptability, making the best and worst options even more distinct. Regardless of whether stakeholder preferences are specified, BAU and LC consistently rank as the least favoured scenarios, highlighting how poorly they perform. In contrast, ET and EC remain the most desirable options, even when preferences are unknown. In the second scheme, the central weight vectors for each scenario are remarkably similar, unlike in the first scheme. This highlights that, despite having nearly identical preferences, typical supporters of each scenario still end up making different choices. Lastly, the confidence factors in both schemes highlight that the ET and EC scenario's top ranks remain robust to uncertainty in the criteria.

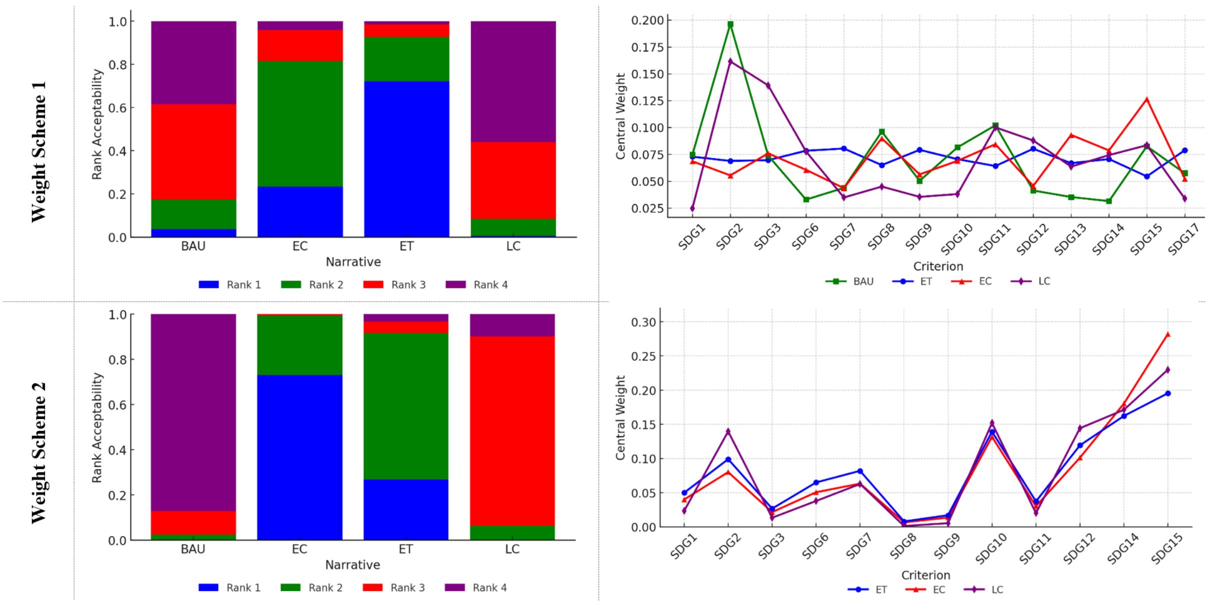

Figure 3- 4: Rank acceptability indices and central weight vectors of different pathways in the two weight schemes (uniform distribution above, ordinal information from Koasidis et al.[41] used in the latter figure).

3.4 Discussion

The integration of Sustainable Development Goals into integrated assessment models is a current ask under development, with discussion and ideas on how to implement them to best reproduce the UN 2030 agenda. Models can capture synergies and trade-offs through tailored representations, according to the dimensions and variables they offer for relevant indicators.

The use of SDGs as criteria for policymaking remains a topic of the debate. The literature stress, on the one hand, for extensive assistance from experts and scientists to operationalise several hundred of specific and technically advanced indicators[51]. Specifically, the authors concluded that *"out of 169 targets, 49 (29%) were considered well developed, 91 targets (54%) could be strengthened by being more specific, and 29 (17%) required significant work"*, as a consequence of the *"poor alignment of targets and goals with existing international agreements and political processes; lack of effective implementation; conflicts between Goals and targets, and non-quantified targets"*. On the other hand, Spaiser et al. (2017)[52] notified an inherent tension in existing targets between socio-economic development and ecological sustainability. In this sense, SDGs may inadvertently steer initiatives –such as corporate social responsibility– towards misguided outcomes like *greenwashing*[53], depending on how the goals are selected and weighted in the analysis. A key weakness lies in the vague definition of the SDGs themselves, which makes it difficult to measure impacts reliably and validate assessment models[54]. Finally, the large number of targets and indicators involved in tracking SDG progress complicates obtaining a holistic view of their interconnections, as well as the potential benefits and trade-offs created among them. When applying SDGs to simulation models and future scenarios, some indicators from different goals may overlap, while others can be difficult or even impossible to measure[55].

In line with previous studies, we must acknowledge the complexity of modelling goal 5 (gender equality) in IAMs, which remains as a pending task in the field (Table 3-1). WILIAM already differentiates population by sex; however, sex division in the labour market and education should be the next work to further improve gender modelling. Another goal clearly underrepresented is goal 6, given the lack of water module in WILIAM, which keeps open the research to further contribute and cover the goal.

As shown in Figure 3-4, the goals already accounted in the model are not fully represented. This is the case of, for example, goal 8, which does not include the indicator 8.3.1, 8.4.1 and 8.4.2. due to the lack of good variables to approach them. Looking more closely, proxies are intended to reflect the original indicators, but some fail to fully align with the official definitions. For example, the indicator 15.3.1: (proportion of land that is degraded over total land area[56]) assumes land cover and land cover changes comes from two different geographical models of 300 meters and 500 meters of spatial resolution (grid cell). Land productivity uses another two different models averaged at 250 meters and 1 km pixel resolution. Soil organic carbon stock data is determined with another three models with a spatial resolution of between 250 meters and 1 km, covering a depth of 0-30 cm. Additionally, the text offers open field for modelling, conditioned to later validation: *"In the absence of, to enhance, or as a complement to national data sources, good practice suggests that the data and information derived from global and regional data sets should be interpreted and validated by national authorities"*.

Compared to van Vuuren et al. (2022)[19] our target space differs significantly, as our objective was to focus on covering specific SDG indicators rather than assume proxies for the broader Goals. Regarding Soergel et al (2021b)[27], they followed a similar idea by linking indicators to IAM variables. For instance, Goal 5 was addressed through the education module, focusing on gender gaps in primary and secondary education, while Goal 6 excluded supply-side water variables (e.g., rainfall, water availability). A key difference between their study and ours is that we do not include exogenous variables as indicators, to avoid introducing bias in the subsequent SMAA step.

The SMAA results underscore the critical role that stakeholder engagement plays in shaping decision outcomes: incorporating stakeholder input and preferences not only changes which option emerges as preferred but also sharpens the distinctions among all alternatives, clarifying the most and least acceptable pathways. It was shown that "business as usual" is not the way forward, and the LC scenario, which couples energy transition with lifestyle changes, consistently ranks among the weakest options. When stakeholder preferences are explicitly accounted for, the EC scenario (combining energy transition with ambitious environmental and land-use policies) becomes the clear frontrunner, with the ET storylines (emphasising technological advances over social and environmental considerations) as its nearest competitor. In this situation, the analysis also revealed that the typical supporters of each alternative are relatively similar in terms of their preferences, indicating the importance of details in decision making and accurate elicitation of stakeholders' preferences. Finally, EC's high confidence factor demonstrates that its top ranking is notably more robust to uncertainties than those of the other scenarios.

As further work, we have noted the next lines. First, other frameworks have been proposed in the literature and can be applied to the methods here proposed. For example, the safe and just space framework proposed by Raworth[57] described in her book Doughnuts Economics[58]. Second, future research should consider a broader range of uncertainties and explore additional scenarios to reflect a wider range of potential transition strategies. Moreover, eliciting stakeholder preferences in greater detail will help capture the nuances of the SDGs more accurately.

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Efforts are spent in collecting data. For example, the SDG Index platform[59] incorporates 125 indicators, including 98 global indicators and 27 additional indicators used for the OECD countries' dashboard supported by the Sustainable Development Solutions Network and United States[60]. However, major data gaps are still pending such as food loss and food waste, global yield gap statistics, or measurement of decent work, inequality and climate adaptation (table A.2 in [49]). Monitoring 230 indicators is of interest for IAMs as they require data to initialise and represent relationships between the exiting mathematical equations and the indicators. The presence of expert surveys[61] to create a parallel target space is indicative of the limitations in representing SDG indicators in IAMs.

Finally, improvements to WILIAM would enhance the robustness of results. Additional work should be dedicated to assigning an economic budget to each policy, ensuring that all scenarios reflect comparable levels of economic effort – an uncertain aspect in the current study. This approach would enable an assessment of which allocation of resources offers the best performance in terms of SDGs, thereby guiding investment and governmental expenditure.

Despite the limitations, and the complexity that the SDG framework introduces, this work contributes with methods to select the scenario for policy decision under uncertain hypothesis. Efforts to support a way of common thinking for a common fair and sustainable future.

3.5 Overall conclusions

The 2030 Agenda is gradually being embedded in the integrated assessment models of IPCC to align them with specific goals in the narratives conceptualised for international decision makers. Although all modellers are aiming the representation of the 17 SDGs, epistemic barriers need to be overcome if IAMs want to fairly represent the social dimensions of gender, peace, international partnership implications in the system.

The literature review also put in the table the substantial differences in the selection of variables used to represent the same sustainable development goals– and even the same targets – making model comparisons difficult or even unjustifiable. This gap can only be solved with workshops and project tasks focused on harmonisation and standardisation accountability, like the IPCC in regards on emissions, to solve the question of whether the modeller adopts strict definitions with standardised variables or allows flexible variable selection tailored to the specific topic being addressed.

The three alternative scenarios positively reacted to past trends, reaching 1.84ºC in 2050 while improving Goals 1, 2, 3, 6, 7, 9, 13, and 14. However, Goal 8 (decent work and economic growth) and 17 (proxied by the governmental revenue) would be more promoted if past trends are assumed for the future. Nevertheless, the temperature increase in all scenarios continues after 2050, highlighting the need of representing bottom-up policies in industries and waste. Regarding SDG interactions, results show alignment of WILIAM with existing literature.

The inclusion of stakeholders in scenario-based decision making not only influences which option is preferred but also clarifies the distinctions among all alternatives. The SMAA analysis revealed that the EC scenario –which combines energy transition with environmental and land-use policies– emerges as the clear frontrunner over the others.

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4. Land use, renewable energy and impacts (Study 15)

4.1 Workshop with stakeholders

4.1.1. Context

Project partners met with stakeholders from DG AGRI, the European Environment Agency, CAN, IDDRI, and WWF European Policy, among others, to explore the impacts of decarbonisation pathways on land use. The workshop aimed to obtain feedback about **land requirements and potential land use competition** conflicts in scenarios with high renewable energy penetration, and to co-design modelling pathways that could minimise environmental impacts and maximise benefits for local communities.

Towards this goal, partners briefly explained the modelling capabilities of IAM COMPACT in terms of land use representation and discussed social and economic barriers related to the energy transition, with a focus on key areas such as PV deployment, bioenergy, and sustainable land use management. The session sought guidance on the balance between the energy transition, the ecological transition of the agriculture, and the preservation of nature and biodiversity in a world of growing population and climate change with biophysical constraints.

The workshop was structured into four questions, each soliciting stakeholders' feedback on different research and policy aspects of the study.

9. The first question focused on <u>impacts on the environment / natural resources</u>: What are the current and potential future environmental and climate impacts? (e.g. on biodiversity, land use change emissions, competition with nature conservation and carbon/ecological rich land uses, etc.).

10. The second question focused on <u>socio-economic impacts</u>: Are social and economic barriers to renewable energy deployed or dependent on land-based products already taking place? (e.g. effects on local economies, economic sectors competition, problems for public acceptance, etc).

11. The third question focused on the <u>design of policies</u>: Could the environmental and socio-economic negative impacts with specific policy instruments be alleviated? (e.g. land use planning, agrivoltaics, etc.) Is there room for synergies with other objectives (e.g., with mitigation or adaptation objectives)?

12. The fourth question focused on <u>indicators to measure</u> a sustainable energy and land-use transition, including three sub questions:
    - Q4.1: How can we design and measure a sustainable energy and land-use transition that ensures food security, biodiversity preservation, and water sustainability, while considering the biophysical limits and the impacts of climate change?
    - Q4.2: What key indicators can be used to quantify the interconnections between climate change, land use, water resources, and food security, including the impact of irrigation, biodiversity preservation, and sustainable energy transitions?
    - Q4.3: Which indicators of environmental performance are of interest in the European context? At what level of detail?

Finally, for this objective three modelling tools have been presented in the workshop with their own particularities in relation to the issue covered, as shown in Table 1:

Table 1: List of models used across this deliverable

Model	Organisation	Scale options of the analysis
WILIAM (global IAM)	UVa, CARTIF	Global, Europe-27, UK, China, India, Russia, USCMA (USA, Mexico and Canada), Latin America, East of Asia and Oceania, Rest of the World
CLEWs (nexus model)	KTH	Global, National, Regional, Urban, Basin
GCAM (global IAM)	BC3	Global, Regional, Water basins. Disaggregated versions for some regions (USA, China, Europe, South Korea)

4.1.2. Workshop feedback

4.1.2.1 Impacts on environment of renewable energy deployed on land

The objective is to collect information about potential future (and current) environmental impacts of renewable energy deployed on land or fed by land-based products. This includes the analysis of the competition between land uses for energy purposes versus the conservation or creation of ecological rich areas.

For this, some preliminary examples have been given (based on literature) in order to clarify better the question. In particular, the specific question made in the workshop has been the following: *What are the current and potential future environmental and climate impacts? (e.g. on biodiversity, land use change emissions, competition with nature conservation and carbon/ecological rich land uses, etc.).*

The answers obtained by type of energy are the following:

- Solar energy: the impacts collected are associated to the land use change that implies the deployment of solar PV energy on land. In particular:
    - Vegetation clearing: impacts on land use changes that implies vegetation clearing like deforestation.
    - Impacts due also to the ancillary infrastructure and modifications needed (e.g. access roads, lighting systems, built perimeters leading to fragmentation of habitats).
    - Impacts on GHG emissions associated to the land use change.
    - Potential impacts on biodiversity (e.g. fragmentation of habitats due the land use change).
- Wind energy: impacts are similar to those related with solar energy, and due to the land use change when deploying this energy type on land. Specifically:
    - As in the case of solar energy, also impacts due to the ancillary infrastructure and modifications needed (e.g. access roads, etc.).
    - Impacts on biodiversity.
- Bioenergy: energy derived from biomass. This is specially framed not only in the EU but also abroad.
    - Biomass use competition and impacts on ecosystems including biodiversity: biomass is a scarce resource with different potential uses and roles in the energy transition. This competition could lead to several negative impacts on the environment, food system, and biodiversity due to the potential unsustainable extraction.

  - Land use change associated that reduces carbon stock, as the source origin (biomass) of this type of energy is precisely from carbon rich ecosystems (including the reduction of forest carbon sink).
  - Land use competition: specially in the case of energy crops competing with crops for food (displacement of food crops), but also potentially replacing (competing) with natural land.
  - Impacts on environment of tele-coupling: exporting the environmental impact of the European food consumption to other regions of the world (global impacts). These are related to global trade.
  - Impacts on water use and water pollution due to increased land used for harvesting biomass to feed bioenergy.
- Green hydrogen:
  - Additional land use required for hydrogen related infrastructure which require high consumption of land (e.g. solar and wind energy capacity deployment for feeding the electrolysers, plants, H2 pipelines, storage processes, etc.).
  - Land use required for an excessive new hydrogen capacity currently planned. In addition, the ambitious capacity projected could be not aligned with the future hydrogen demand.
  - Associated impacts on land use due to this land use change required (e.g. impacts on emissions due to land us change, competition with other economic uses of the land, etc.).
  - Synthetic fuels based on green hydrogen and carbon would require not only hydrogen related infrastructure (e.g. solar energy mentioned before), but also carbon capture and storage infrastructure. This carbon can have its origin in different sources, being one of them the "harvesting of biomass". This biomass demanded can be summed to the already potential high future biomass demanded fostering biomass use competition, and related land use impacts: land use competition, reduction of stock of carbon, etc.

Conclusions

The previous feedback collected is focused on the following energy types: solar PV, wind energy, bioenergy and green hydrogen production. For these four RES types, the impacts can be listed as follows:

- Scale: Impacts are mainly focused on the European level, but also indirect impacts requires a global perspective (global renewable energy transition, land use requirements very close to "tele-coupling" conflicts, global energy and food trade, biomass imports to the EU etc.).
- Impacts on the carbon sink of the area occupied (direct or indirectly) for the related infrastructure (impacts on LULUCF GHG emissions).
- Impact on ecosystems services: biomass use competition, land use competition, water use and pollution.
- Impacts on biodiversity.
- Effects of tele-coupling (impacts exchanged over distances)

This guide us in the selection of modelling tools that could answer to each of the above points, from IAM COMPACT presented models, considering not only type of RES and systems where impacts need

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to be analysed, but also the scale.

4.1.2.2 Socio-economic impacts of renewable energy deployed on land

In this case, the objective is to collect information about the socio-economic impacts of renewable energy deployed on land or fed by land-based products. This includes the analysis of social and economic barriers: e.g. effects on local economies, land-based economic sectors competition, territorial inequalities, public acceptance, etc.

For this, some preliminary examples have been given (based on literature) in order to clarify better the question. In particular the specific question made in the workshop has been the following: *Are social and economic barriers to renewable energy deployed or dependent on land-based products already taking place? (e.g. effects on local economies, economic sectors competition, problems for public acceptance, etc).*

The answers obtained by type of energy are the following:

- Solar energy: the impacts collected are associated to the land use change associated that increase land use competition and degrading of natural/productive areas. In addition, social barriers are already happening, not being assured the public acceptance. In particular:
    - Competition with other economic sectors: potential jobs displacement of other economic sectors such as agriculture due to land use competition.
    - Less public acceptance of land-based renewables due to inadequate land use planning: Inadequate use of productive land: Change of land use to "artificial areas" and "degraded land" which can be used to other uses.
- Wind energy: social barriers are already taking place. Specifically:
    - Anti-wind movements rising in EU (Member States): this is related to different profiles (or groups´ rationale). In particular, these two profiles examples are given in the meeting:
        - Antagonistic voices: these groups are often based on disinformation, hoaxes, or influenced by those in power seeking to maintain the status quo (e.g., politics, nuclear, and fossil fuel industries).
        - Legitimate local concerns: based on real issues with the permitting process and community engagement (e.g., NIMBY, lack of trust, and not being heard/invited to engage in the process).
- Bioenergy: energy derived from biomass.
    - Biomass use competition: competition among different economic sectors for the use of biomass.
    - Also, technology-based barriers are mentioned. In particular: technology-based barriers for the scaling up new technologies relying on less land use (i.e. secondary woody biomass).
    - Negative impact on food security: due to the competition with the agriculture sector (impact of increased land use for bioenergy), which indirectly affects also food prices.
    - Local pollution as a barrier for bioenergy plants.
    - Impacts on human rights also (e.g. land access, jobs conditions, etc.) in low- income countries when biomass is imported without strong regulation in place.

These additional socio-economic impacts are also mentioned, which are in general common to all the type of RES mentioned before, i.e., solar, wind, bioenergy and green hydrogen:

13. Low levels of trust in government policies and corporate actors:
14. Low trust in large energy companies not focusing on local people needs or interests
15. Low trust in government: health concerns/misinformation about impacts of e.g. wind infrasound
16. Territorial inequalities: Unbalance of generation and consumption areas. Project from non-local companies.
17. Threat to local cultural and natural areas (e.g. impacts on tourism): Perceived threat of substantial transformation (industrialisation) of historically natural landscape
18. Benefits not equally distributed in the areas affected: Project revenues normally only benefitting few rich landowners.
19. Limited potential for local job creation (technology manufacturing takes place in other countries with strong industrial base, most of constructions carried out by large, non-local companies).
20. Lack of social participation: Lack of local ownership because lack of public engagement / consultation during the RES projects deployment
21. Higher electricity prices mainly impacting on low-income population

Conclusions

In general, the socioeconomic impacts of RES deployed on land are focused on territorial inequalities, lack of acceptance, local benefits and trust.

- Scale: Socio-economic impacts (barriers) occur mainly at local scale.
- Competition with other economic sectors (land use competition) and potential job (of other sectors) displacement, whereas the jobs created are more limited (or temporal).
- Lack of public acceptance due to 1) inadequate land use planning, 2) lack of trust (government, large energy companies), 3) lack of engagement and participation in the processes, 3) territorial inequalities (regarding negative impacts, resources consumption, and also allocation of economic benefits), 4) threat to local cultural and natural areas (landscape) and 5) antagonistic voices pro-fossil fuels interests.
- Bioenergy, in addition, has specific impacts on food security (this could be expanded also to the rest of RES requiring/competing for land) and regarding social barriers due to the local pollution from bioenergy plants.

As in the previous case, this can guide us in the selection of modelling tools that could answer to each of the above points, from IAM COMPACT presented models. However, is worth saying that the social impacts are the ones more difficult to assess in general in IAMs tools, not being an exception the models from IAM COMPACT presented. In addition, the local scale of these particular impacts makes more difficult the analysis in the models.

4.1.2.3 Co-design of land-based policies for addressing the impacts

In this question, the objective has been to collect information about land-based policies (such as land use planning, zoning, forest management, and afforestation) that can support or challenge decarbonisation goals, also alleviating the negative environmental or socio-economic impacts mentioned before in the past two questions.

For this, some preliminary examples have been also given (based on literature), as in the previous questions, in order to clarify better the exercise to the stakeholders. The specific question made in the workshop has been the following: *Could the environmental and socio-economic negative impacts with specific policy instruments be alleviated? (e.g. land use planning, agrivoltaics, etc.) Is there room for synergies with other objectives (e.g. with mitigation or adaptation objectives)?*

The answers obtained by type of energy are the following, although most of them are not just applied or related to specific types of energy:

- Solar and wind energy. For alleviating its negative impacts when deployed in land, which are focused on the multi-use perspective of the land. In particular:
  - More research on multi-use benefits/negative impacts (e.g., agrivoltaics).
  - Encourage the use of dual-land use for wind and solar (agrivoltaics, solar PV, etc.)
  - Land policies incentives not just based on economic and mitigation criteria but also in "nature protection" consideration: Non-price auction criteria for solar and wind to reward restoration measures (not only mitigation).
  - Agrivoltaics with funding premiums for farmers and compensation in case reduced crop yield.
- Bioenergy: energy derived from biomass. This is specially framed not only in EU but also abroad.
  - Stop/ minimise subsidies to bioenergy, as it is a very inefficient use of land (very low energy output per ha compared to solar and wind)
  - Land use planning is clearly needed especially considering that we will also see additional pressure on the land access with biomass-based CDR (BECCS, biochar, etc)
  - There is a need to change current bioenergy policies - "we need to stop rewarding destruction"

- Mentioned in the workshop the following study: EEA study à https://www.eea.europa.eu/en/analysis/publications/the-european-biomass-puzzle

In general, the following land-based policy recommendations, common to all the type of RES listed in the previous sections, i.e., solar, wind, bioenergy and green hydrogen, are mentioned:

- Inclusive land-use planning (involving all local stakeholders and scientific experts).
- Locational pricing - lowering electricity prices in area with high RE penetration.
- More funds and administration assistance to Renewable Energy Communities.
- Projects with high standards to avoid impacts on biodiversity: especially no unnecessary ancillary works, lights, nets...
- Enforce current existing targets and measures (LULUCF for enforcement and NRL (National Reference Level) for implementation).
- Reconcile current climate policies which are acting with opposing force: LULUCF and NRL vs bioenergy policies, (for example).
- Pricing agricultural emissions / set a sectorial target on the agricultural sector (both demand side and supply side measures are needed).

Multiple objectives in mind when designing policies:

- Pair emission pricing with restoration commitments. Broader focus than just emissions (biodiversity indicators)
- RES directive versus land use targets needs to be avoided.

22. Some links shared with additional information from the stakeholders presentation:

- Document covering "Biofuels and its relationship with food insecurity (2024) and EU policies that have promoted it". This also promotes recommendations to changes in "EU biofuel policies" for sustainability: https://policy-practice.oxfam.org/resources/biofuel-blunders-time-to-fix-two-decades-of-eu-policies-driving-food-insecurity-621622/
- Report "Biofuels: An obstacle to real climate solutions". That explains the cons of biofuels as mitigation policies https://www.transportenvironment.org/articles/biofuels-an-obstacle-to-real-climate-solutions

Conclusions

The previous feedback collected cover different type of policies that could support the sustainable deployment of RES in land. In resume: land use planning, local lower prices, more funds, reconcile climate policies (emissions) with energy policies (e.g. bioenergy), multiple objectives when designing policies, broader focus (integrated).

4.1.2.4 Indicators to measure a sustainable energy and land-use transition

In the context of developing "Truly sustainable decarbonisation pathways, including biodiversity, materials and biophysical limits", the fourth question focused on indicators able to quantify the modelling results for enabling model comparisons, and increasing transparency. When dealing with indicators, and more in general, quantification of the modelling results, it is also crucial to understand the assumptions made by the modellers and their implications on the modelling results. Because of that, the feedback highlighted also a strong interest into carbon accounting especially in the context of biomass use and production. On the other hand, biodiversity indicators remain the priority into the EU context. Breaking again the response according to the three leading questions described in the section above, the PRM returned the following response:

R4.1:

23. Proper carbon accounting for biomass. This resource is indeed often considered as carbon neutral. However, this assumption is true only when the carbon released during the combustion is the same absorbed by the plant during its growth - if sustainably produced. Carbon emissions are indeed related to the fraction of non-renewable biomass, which increases if the demand for fuel exceeds the regrowth: the higher the difference, the lower the biomass can be considered carbon neutral.

24. Most analysis are often designed under the assumption of a continuous economic growth, measured as GDP annual increase. However, the studies could be shaped also under the assumption that there won't be a continuous economic growth, understanding its impact on the transition.

R4.2:

25. Proper carbon accounting for bioenergy production with a carbon opportunity cost indicator. Deliverable D5.8, showed the importance of understanding the relationship between land use change and economic activities. In the European context, land use change is primarily caused by human activities that are contributing to biodiversity degradation and carbon sequestration capacity. The carbon opportunity cost can be seen as indirect measurement of the impact of land use change on environment.

26. The roll out of the renewable resources, calls for a quantification of their energy density which can be quantified as the ratio between the energy output per ha of land used.

27. Nature restoration law (European Commission, 2025). Around 81% of the EU habitats are in poor conditions. The Nature Restoration Law plays a crucial role in the EU Biodiversity Strategy for establishing mandatory goals to revive damaged ecosystems. To track the accomplishments of the targets, the European Commission has identified suitable indicators relevant for the restoration of the agro-ecosystem. The main areas of interest can be summarised as follows (European Commission. Joint Research Centre., 2024): pollinators population, agricultural indicators, forest indicators, urban green space, and urban tree canopy by 2030.

RQ4.3:

28. Carbon accounting enhancement for biofuels and biomass The European Climate Law, sets the targets for achieving climate neutrality by 2050 (European Commission, n.d.). It is therefore needed to have progress assessments and indicators at a National level for ensuring that all member States and sector of the economy contribute to the decarbonisation.

4.1.3 Key takeaways

Environmental Impacts of Land-Based Renewables

- **Land use change impacts**: Renewable energy projects (solar, wind, bioenergy, hydrogen infrastructure) contribute to land clearing, habitat fragmentation, and potential biodiversity loss.
- **GHG emissions from land use change**: Bioenergy raises concerns regarding carbon neutrality due to carbon stock depletion and indirect land use change (ILUC) emissions.
- **Competition with nature conservation**: Renewables may compete with land uses that serve as carbon sinks or ecological reserves.

- **Tele-coupling of environmental impacts**: European demand for bioenergy and green hydrogen may shift environmental pressures to other global regions

Socio-Economic Barriers & Impacts

- **Land use conflicts**: RES projects compete with agricultural land, forestry, and conservation areas, potentially displacing food production or other land-based activities.
- **Public acceptance issues**: Mistrust in government policies and corporate actors, lack of public engagement, and perceived threats to local landscapes drive opposition to wind and solar projects.
- **Territorial inequalities**: RES deployment benefits (jobs, revenues) are often concentrated among a few landowners, exacerbating regional disparities.
- **Economic sector competition**: Bioenergy and solar farms may displace agricultural jobs while creating fewer permanent local employment opportunities.
- **Bioenergy-specific concerns**: Local pollution from bioenergy plants, risks to food security, and human rights issues (e.g., land access for biomass sourcing) were flagged as significant barriers.

Policy Considerations for Sustainable Deployment

- **Land-use planning and multi-use strategies**: Encouraging dual land use (e.g., agrivoltaics, wind and livestock farming) could mitigate land competition.
- **Stronger biodiversity safeguards**: Renewable energy projects should integrate restoration measures and avoid unnecessary infrastructure impacts.
- **Reevaluating bioenergy policies**: There is growing support for reducing subsidies for bioenergy due to its inefficiencies and ecological impacts.
- **More inclusive governance**: Ensuring local stakeholder participation and ownership in energy projects could improve public trust and equity.
- **Carbon pricing and opportunity cost accounting**: The impact of land use change on carbon sequestration should be integrated into policy frameworks.

Indicators

The feedback highlighted a strong interest into carbon accounting especially in the context of biomass use and production. Its neutrality indeed depends on whether the carbon released during the combustion is the same absorbed by the plant during its growth. Additionally, biodiversity indicators remain the priority into the EU context since land use change, driven by human activity, is a key factor in both carbon emissions and biodiversity loss.

The need of combining proper carbon accounting, biodiversity impact and land use trade-offs calls for adopting integrated modelling approaches. The feedback has been used for shaping the CLEWs exercise presented in Section 4.5. Table 6 describes the stakeholder feedback integration into the CLEWs analysis for enhancing comparability, transparency, and policy relevance.

4.2 Introduction

The feedback provided by the workshop supported the development of two modelling exercises conducted with the IAM WILLIAM and optimisation system model CLEWs. The objectives of both studies were based on the priorities of intervention identified during the workshop and in line with the IAM compact policy response mechanism. Both exercises attempt to understand the impact of the stated national determined contribution policies and long term strategies on afforestation, carbon emissions, cropland availability and resource stress. However, the exercises are also an example of different approaches and modelling techniques that can be adopted for an integrated assessment of resource use and trade-offs.

CLEWs is the Climate, Land, Energy, Water systems management framework designed for the integrated assessment of resource systems. It is highly flexible due to its customizable system boundaries, geographical coverage, level of detail and techno-economic input data. It uses the Open-Source Energy Modelling System (OSeMOSYS) tool suitable for dynamic long-term planning. It is an optimisation model which minimises the system's costs assessing the role of technology choice and technology change.

WILIAM is the "WIthin Limits" Integrated Assessment Model, a multi-regional IAM that covers nine global regions, one of them (EU27) at country level. WILIAM is based on the pre-existing MEDEAS model and focuses on addressing the complex interrelationships between natural resources and human behaviours, thus consisting of modules specifically dedicated to economics, demographics, land, emissions, etc. The model relies on the System Dynamics technique to represent dynamic evolution of variables over time using the Vensim software.

Despite both models are suitable for an integrated assessment of resource systems, they present some differences. First, the geographical scope varies greatly, as CLEWs is country-specific (in this case Ethiopia) and WILLIAM is global, broken down by different regions (the study only analyses EU27). However, the main difference lies in their mathematical algorithm being CLEWs an optimisation tool and WILLIAM a policy simulation model based on System Dynamics. As previously mentioned, CLEWs minimise the total system's costs analysing the current and future energy-land-water-waste system through linear optimisation. WILIAM on the other hand, relies on scenarios not to make predictions about the future, but to apply different policies to assess their impacts as exercises "what if" . For these exercises both models will investigate the same scenarios: a baseline and a stated policy (based on the updated national determined contributions and long-term strategies). However, the way through which these scenarios are designed vary.

In a CLEWs model, we refer to the baseline scenario as Business-as-Usual. This type of scenario refers indeed to the "optimal" future pathway if the country keeps pursuing the same current policy. In this case the optimisation is not constrained with environmental limitations (e.g. emissions) or renewable energy share or sustainable use of resources: the model is free to seek the least-cost optimal solution. For the second scenario, it is possible to set specific constraints according to the scenario design. For instance, in the NDC - long term scenario, we constrained primary energy uses, thermal energy production, forest share and transmission system losses. Another difference consists in the model calibration. In a system optimisation model, *we refer to calibration* as the accuracy of representing historical years (happened in the past). This depends on data availability and means to add constraints to the first years of the modelled time horizon. It is important to note that this calibration does not have any impact on the future optimisation, but it is rather necessary for ensuring consistency with real-world context.

In the case of WILIAM, we refer also to the baseline scenario as the Business-As-Usual (BAU), but in this case it refers to the scenarios where historic trends continue (including current policies already applied). In this case the historic trends are projected into the future. On the other hand, the second scenario is also the NDC - long term scenario (NDC-LTT) that allows to analyse the impacts of introducing current EU energy and environmental policies. In this scenario current EU policies are parametrised based on WILIAM capabilities, which depend on the policies modelled: e.g. energy types penetration, EU afforestation objectives, energy efficiency improvement etc.). The objective then, is not optimisation, but comparison among different scenarios or pathways simulating their effects and therefore being able to prioritise one over another. In this way the model allow to explore the impacts of different scenarios under various conditions and policies. The objective is not to find the "optimal" solution but to understand "what if" scenarios, so that we can choose the most appropriate policies (e.g. those producing synergies).

4.3 WILIAM exercise

This exercise focuses on the European Union (EU27 at regional, not country, level), which is undergoing a profound energy transition to meet climate neutrality goals. Although the EU is already a highly developed region in terms of technology, the more ambitious targets call for a further expansion of renewables, particularly bioenergy and solar systems. This scenario might therefore lead to new land-related challenges such as competition for land-based resources and land use (Ferreras-Alonso et al., 2024).

The research attempts to understand the impacts of large-scale bioenergy and solar PV adoption on forest stock, carbon emissions, cropland availability, etc. by running several alternative policy and non-policy scenarios.

4.3.1 Research questions

The aim of this study is to evaluate the impacts of expanding solar PV and bioenergy from forests on EU's environment and land. The leading research questions are the following:

- What are the land-use implications of large-scale solar PV deployment in the EU?
- How does an ambitious renewable energy scenario based on bioenergy (in particular, from biomass from forests) affect land demand (including impacts outside the EU), and put pressure on forest biomass and ecological boundaries?
- Which policy mechanisms can mitigate the adverse impacts of land-intensive renewable energy expansion while aligning with climate and energy objectives?

4.3.2 Scenario design and methods

4.3.2.1 Methods: WILIAM IAM

This study adopts a scenario-based approach using the WILIAM IAM, so it is first necessary to introduce the model appropriately: WILIAM is capable to simulate the interplay between energy, land, and climate systems on a global scale, with regional detail for areas such as the EU, CHINA, RUSSIA, etc. By integrating these domains within a unified framework, the model allows for a comprehensive assessment of how land and energy policies interact, including their effects on emissions (Mediavilla et al., 2025). It incorporates a range of land-based policy measures, such as forest conservation, sustainable forest management, and afforestation initiatives. Figure 4-1 depicts the general structure of WILIAM as well as the main interlinks between modules, highlighting those of relevance to this research.

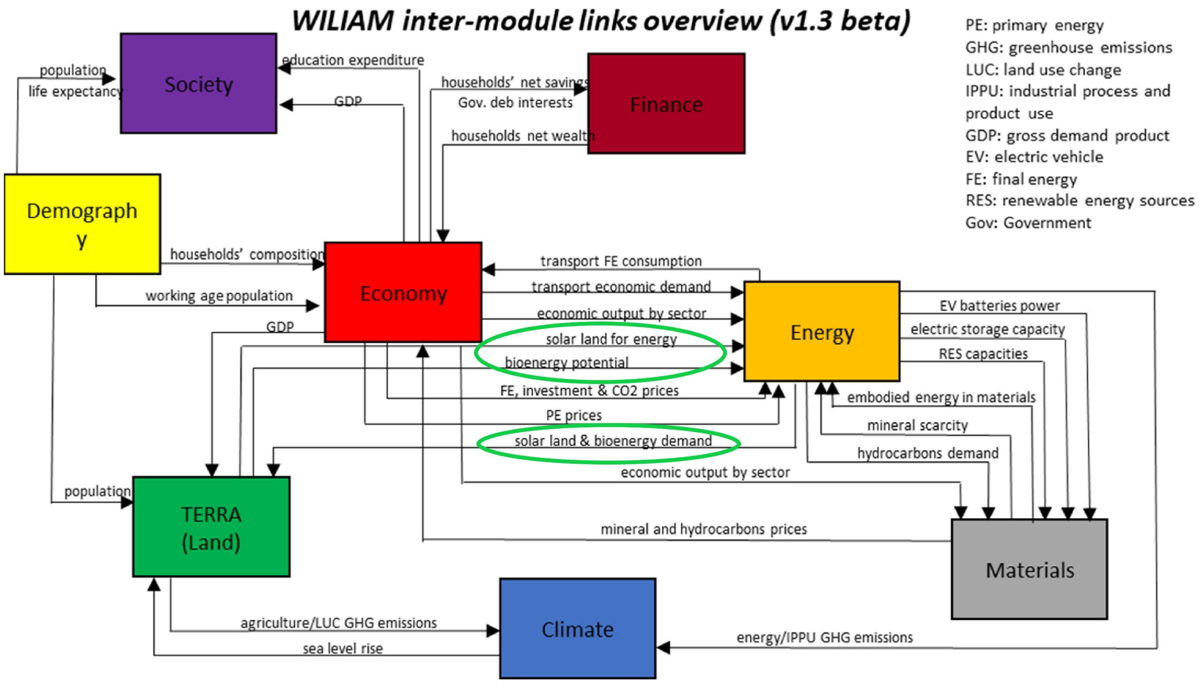

Figure 4- 1: WILIAM's multi-modular structure and interlinks. Source: (Mediavilla et al., 2025).

In particular, as can be seen in the figure, the exercise evaluates the impacts of renewables on land use and the environment, putting a special emphasis on solar PV and forest-based bioenergy. Its main objective is to assess the impacts of deploying these energy sources within the EU under existing policy frameworks, with a focus on identifying trade-offs related to land competition, biophysical limitations, and resulting carbon emissions. Additionally, it seeks to evaluate land-based policy options that could help mitigate these negative outcomes.

Specifically, the links highlighted work in this way: the ENERGY module estimates the new energy capacity to be deployed in land, including the land required and the amount of land products (e.g. wood) needed. This demand is sent to the LAND module which allocates the different land-products and also the land use types depending on the demand received and availability of land. If any type of land constraints happens, the LAND module send a "shortage" signal to the ENERGY module.

4.3.2.2 Scenario design

Since two different technologies are covered, the study is divided into two analyses. The first analysis investigates the consequences of high biomass penetration as a central element of the energy transition, focusing on the potential biophysical constraints affecting energy production, food security, and ecosystem conservation. The second evaluates the effects of large-scale solar PV deployment on land use across the EU. Both sub-studies share two reference scenarios that are used to assess the effects of current trends ("baseline"), and the impacts of introducing current EU energy policies ("NDC-LTT"). In addition to these two, specific scenarios to each analysis are created by applying land-based policies. All scenarios developed for each analysis are explained below:

A. <u>Analysis of bioenergy penetration in EU</u>:

1. Baseline: Business-As-Usual (BAU) scenario, where historic trends continue.

29. NDC-LTT scenario: it includes short and long-term policy ambition set by EU countries, encompassing ambitious policies for the penetration of renewable energy such as solar PV and bioenergy. Also, the NDC-LTT already envisages the protection of primary and

managed forests as well as certain reforestation. All these policies set by EU countries have the objective of 55% (2030) and 100% (2050) reduction of GHG emissions.

2. NDC-LTT-Self-Sufficiency: land-based policies are applied focused on EU forest preservation, including limits on forest biomass extraction and relocating roundwood production to ensure total autonomy.

3. NDC-LTT-Afforestation: a more ambitious afforestation policy is applied with respect to NDC-LTT scenario in order to offset the impacts of increased demand for biomass.

B. Analysis of the impacts of solar PV penetration in EU[5]:

1. Baseline: BAU scenario; same as described in the previous analysis.

2. NDC-LTT scenario: short and long-term policy ambition set by EU countries; same as described in the previous analysis.

3. Baseline-land-based policies: in this scenario land-based policies associated to the deployment of solar PV on land are applied. In particular: 1) siting of solar PV panels prioritising those areas with lower carbon stocks and less ecological value, and 2) protecting specific land use types from solar PV deployment that could increase land competition (e.g. cropland or forestland).

4. NDC-LTT-land-based policies: as in the previous scenario, land-based policies associated to the deployment of solar PV on land are applied over an NDC-LTT scenario.

All the characteristics of the presented scenarios are summarised in Table 2.

[5] Assumption/hypothesis made for the analysis of solar PV on land: The installation of solar panels has been restricted to areas with a net energy ratio of 8:1 or higher. This implies that solar-PV installations supply 8 times more energy over their lifetime than is needed to produce it.

Table 2: Scenario design characteristics: Concept and land-based sustainability policies

Scenario	Concept	Afforest.	Primary Forest Protect.	Managed Forest Protect.	Biomass Extract. Limit	Forestry Self-Suff.	Solar PV siting policies	Land protected from solar PV
Baseline	Continue historic Trends	None	None	None	None	None	None	None
NDC- LTT	High bioenergy and solar PV penetration	Medium	High	Medium	Low	None	None	None
ANALYSIS OF BIOENERGY PENETRATION IN EU								
NDC-LTT-Self-Suff.	High bioenergy use with biomass only from EU forests, and solar PV penetration	Medium	High	Medium	High	High	None	None
NDC-LTT-Afforest.	High bioenergy use with biomass only from EU forests, reforestation, and solar PV penetration	High	High	Medium	High	High	None	None
ANALYSIS OF SOLAR PV PENETRATION IN EU								
Baseline-land-based policies	Continue historic Trends and apply land-based policies	None	Just from solar PV	None	None	None	Yes. Prioritising less carbon rich areas	Yes. Protecting forest and cropland
NDC-LTT-land-based policies	High bioenergy and solar PV penetration and apply land-based policies	Medium	High	High	Low	None	Yes. Prioritising less carbon rich areas	Yes. Protecting forests and cropland

4.3.3. Results

In both analyses, the model projects a significant expansion of bioenergy and solar PV under the NDC-LTT scenario by simulating current EU policies in order to achieve the EU's net zero emissions goal by 2050. This is illustrated in the following plots (Figure 4-2), where bioenergy growth is represented in green and the increase in solar PV deployment is shown in light yellow:

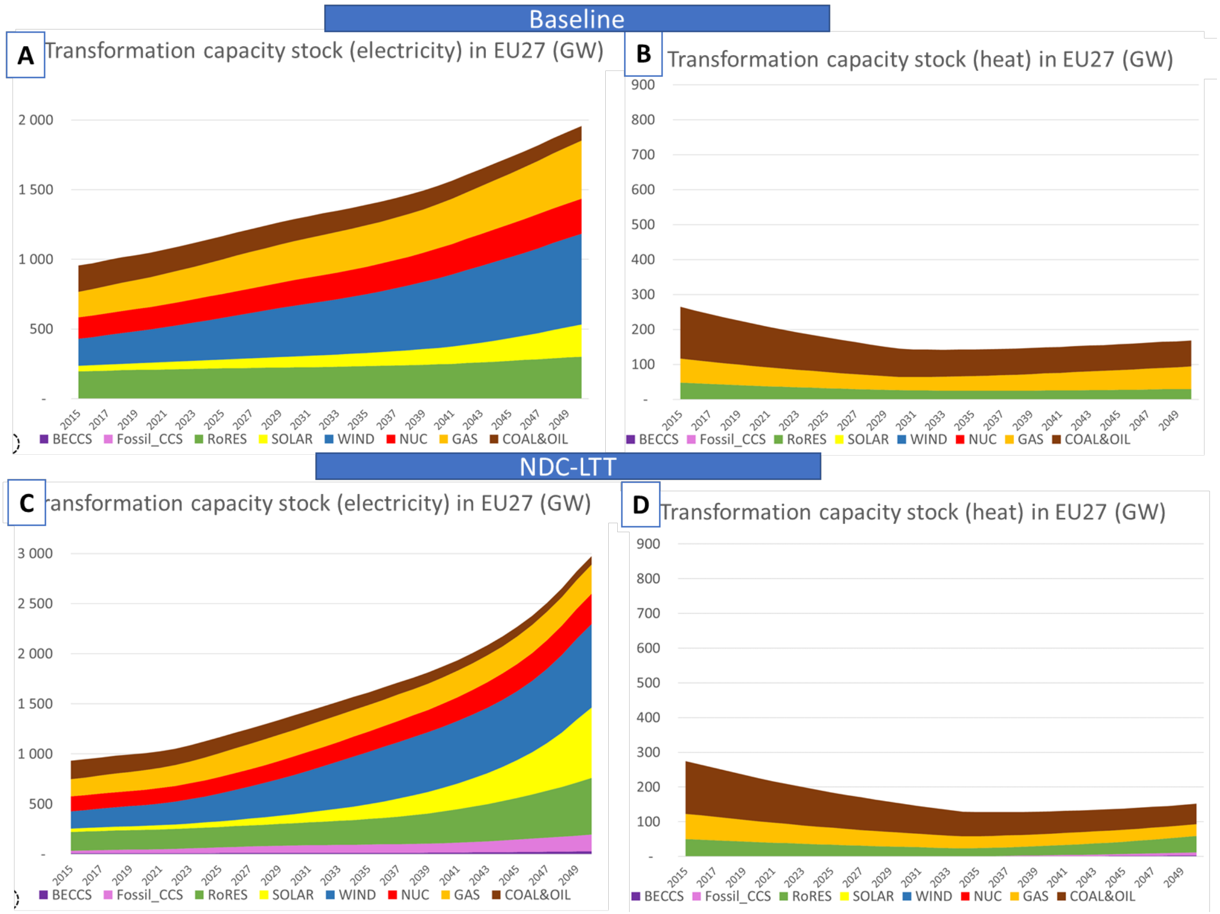

Figure 4- 2: Higher penetration of solar PV energy (light yellow) and bioenergy (green) in the NDC-LTT scenario (4C and 4D) than in the baseline (4a and 4B).

In terms of emissions, Figure 4-3 illustrates that the NDC-LTT scenario leads to a reduction in emissions within the EU compared to the baseline, although overall emissions tend to stabilise rather than decline sharply, so the EU targets related to GHG emissions reduction (output of WILIAM) are not reached in WILIAM simulation due to the pace of change in the system It is worth to mention that WILIAM simulations set as hypothesis in the NDC-LTT scenario the current EU policies that can be simulated in the model (not the objetives, such as reduction in terms of GHG emissions). This is the reason why climate neutrality is not reached in these simulations, although overall emissions are stabilised. On the other hand, the global effects of current EU policies are uneven: emissions increase in other regions, with CHINA showing a 0.91% rise, EASOC (East Asia and Oceania) increasing by 1.1%, and LATAM (Latin America) region experiencing a 2.64% growth under the same scenario.

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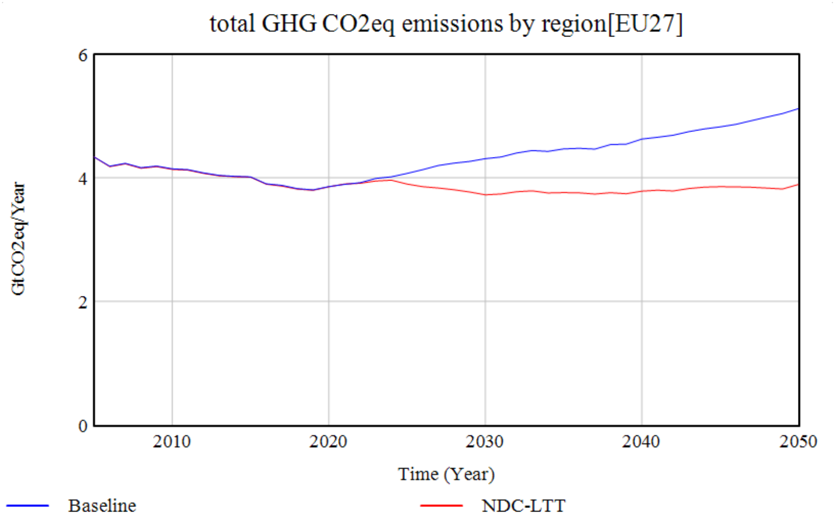

Figure 4- 3: Comparison in terms of total emissions in CO2 equivalent between the baseline and the NCD-LTT scenarios in EU

4.3.3.1 ANALYSIS OF BIOENERGY PENETRATION IN EU

Figure 4-4 shows the rise in bioenergy demand within the EU under the NDC-LTT scenario compared to the Baseline. This increase is particularly notable in the energy sector, with a smaller growth observed in industrial wood use, as depicted in Figure 4-4.

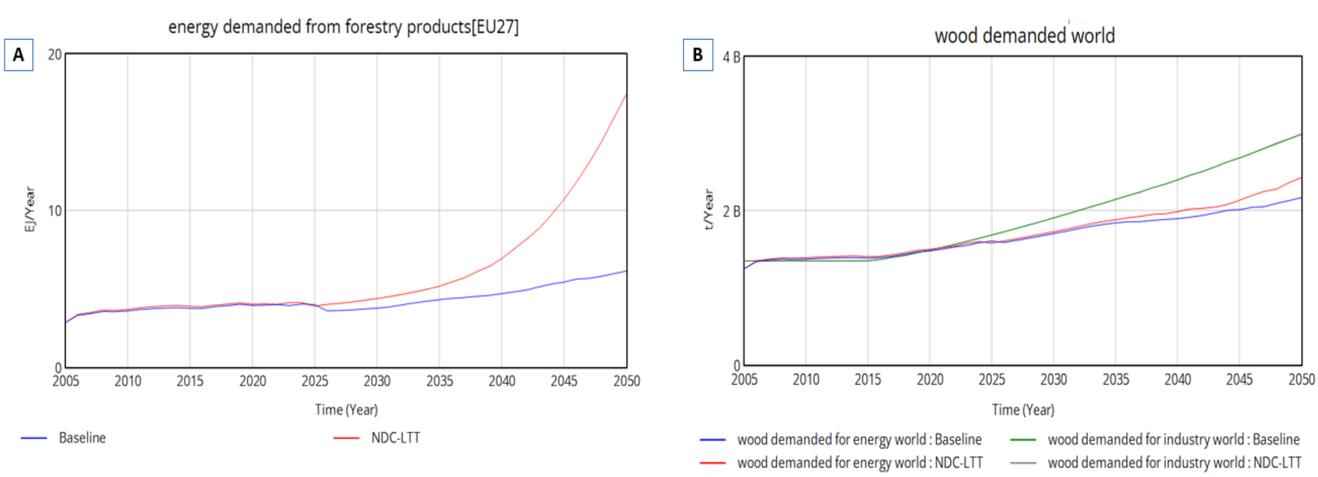

Figure 4- 4: Demand for (A) energy from forestry product in EU27; and (B) wood for energy and industry globally

While the moderate afforestation efforts in the NDC-LTT scenario (targeting a 7% increase in planted forests by 2050 relative to the managed area in 2005) help improve the condition of the EU's forest stock, concerns persist due to a decline observed from 2035 onwards, which is even more pronounced in the Baseline scenario (Figure 4-5). Additionally, since global demand for bioenergy? remains steady and supply distribution is not adjusted, forest stocks deteriorate in other regions under the NDC-LTT scenario, as shown in Figure 4-5.

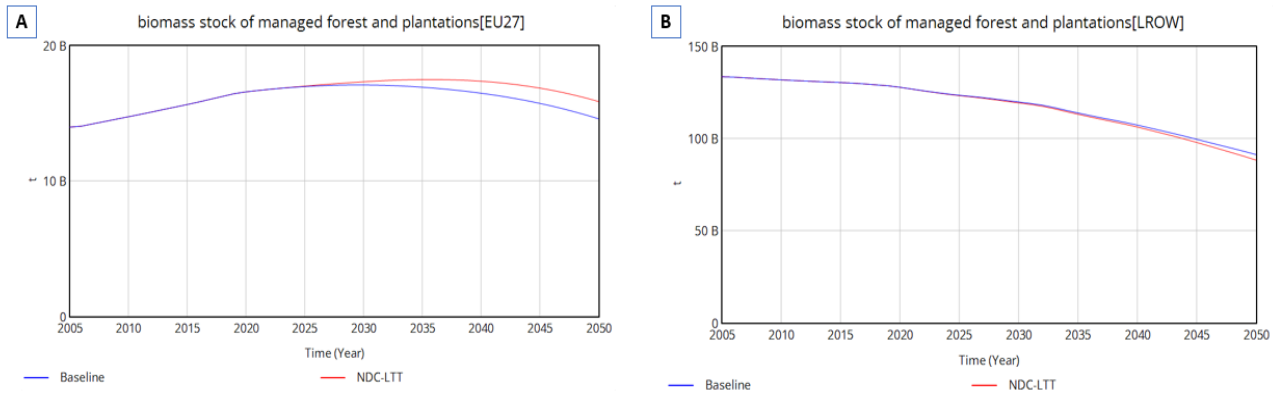

Figure 4- 5: Biomass stock of managed forest and plantations in (A) EU27; and (B) LROW

These initial simulations underscore the necessity for more ambitious afforestation policies combined with restrictions on forest stock removals, aiming to prevent reliance on developing regions to meet the EU's growing biomass demand.

The NDC-LTT-Self-Sufficiency scenario addresses this by gradually tightening protection measures, leading to full protection by 2050, and limiting biomass extraction exclusively to regional forests to minimise global spread effects. As shown in Figure 4-6A, these measures result in a recovery of forest stock toward the end of the simulation period. However, Figure 4-6B reveals a trade-off: the restrictions significantly reduce harvested roundwood, making it impossible to fully meet European biomass demand under this scenario.

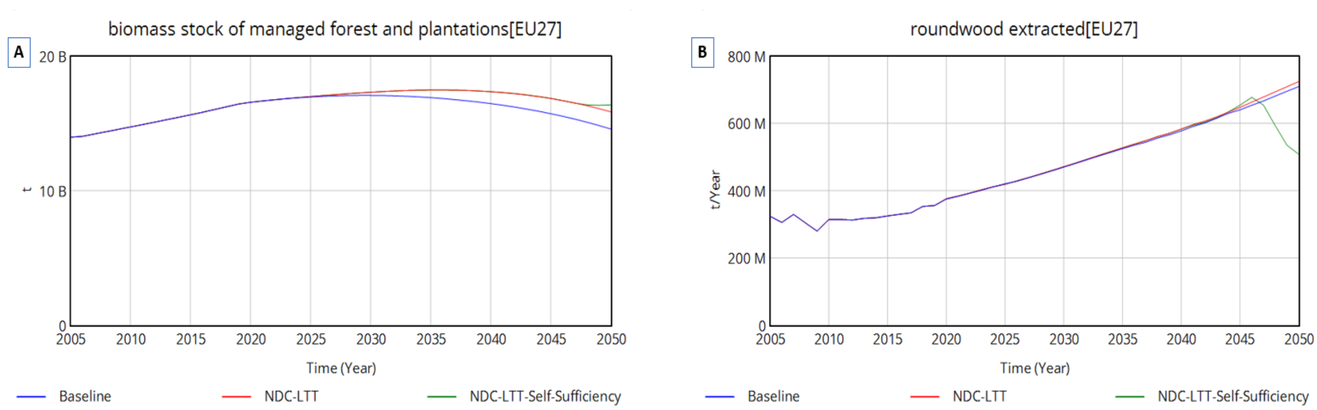

Figure 4- 6: Comparison in EU27 of (A) biomass stock of managed forest and plantations; and (B) roundwood extracted, under three scenarios.

To address the unmet biomass demand while maintaining constraints on forest removals, the NDC-LTT-Afforestation scenario emphasises a substantial increase in reforestation, aiming for new planted forests equivalent to 24% of the managed forest area in 2005. This approach results in the highest forest stock levels across all scenarios, successfully preventing its decline until 2045 and enabling the biomass demand to be fulfilled (Figure 4-7A). However, as illustrated in Figure 4-7B, a key drawback emerges: forest expansion begins to encroach on cropland, leading to a slight reduction in agricultural area, a trade-off that could become more pronounced over the long term.

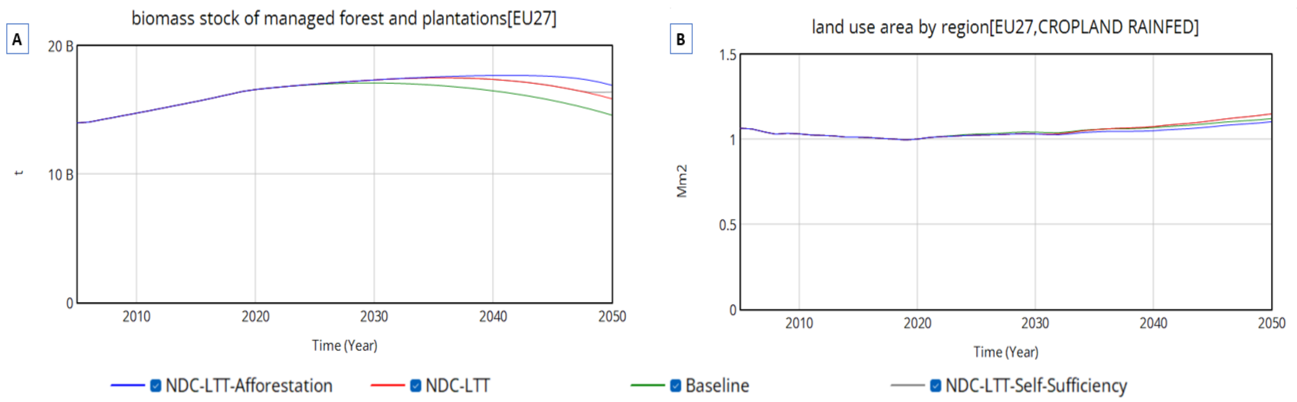

Figure 4- 7: (A) Comparison of biomass stock of managed forests and plantations in EU27 under all scenarios. (B) Rainfed cropland extension in EU27 under all scenarios.

4.3.3.2 ANALYSIS OF SOLAR PV PENETRATION IN EU

Figure 4-8 reflects the remarkable growth of area devoted to solar uses in the NDC-LTT compared to the Baseline. The impacts are very evident in the land area directly occupied by solar PV installations, which are distributed across various land use types. Notably, around 55% of these installations are located on rainfed cropland, reflecting historical patterns of solar deployment observed across the EU (Ferreras-Alonso et al., 2024).

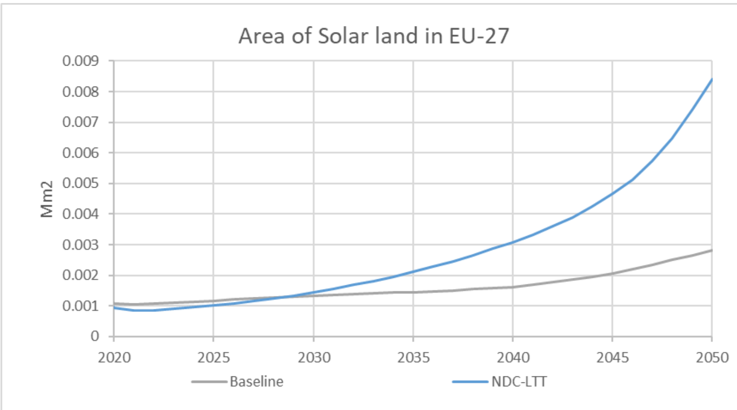

Figure 4- 8: Area occupied by solar PV infrastructure in the baseline and the NDC-LTT scenarios.

To mitigate the negative impacts of high solar PV deployment, the scenarios described in Section 3.4.1 incorporate land-based policies, including solar siting guidelines and the protection of specific land use types from PV installations. As shown in Figure 4-9, these measures effectively reduce the area occupied by solar panels on productive land types such as cropland and forest land, thereby limiting potential adverse effects such as land-use competition for food, timber, and other resources. Additionally, preserving forest land is vital, as it contributes to ecological stability and functions as a major carbon sink

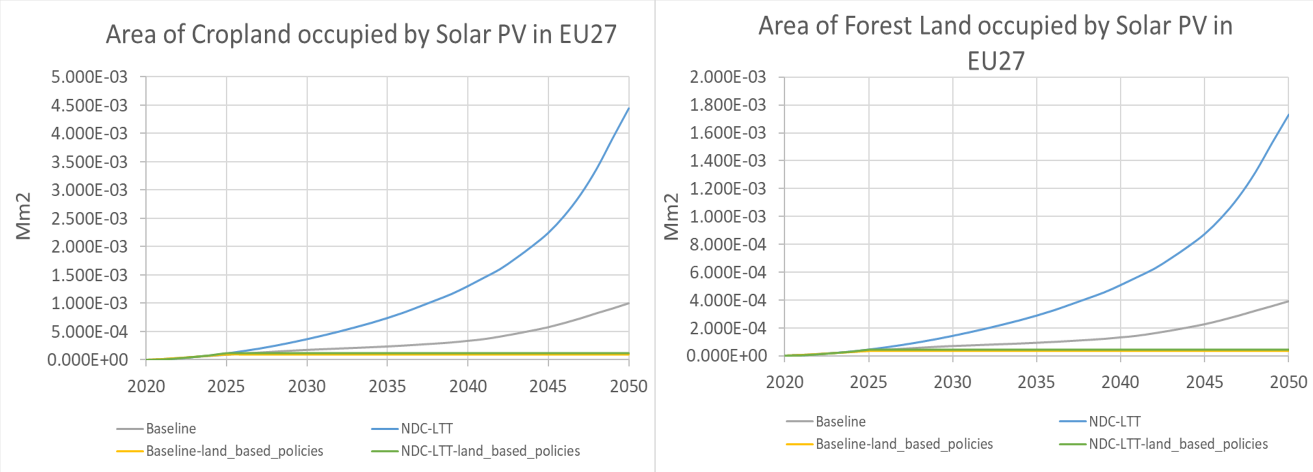

Figure 4- 9: Evolution of other productive land use types occupied by solar PV for the different scenarios in EU-27.

Moreover, carbon emissions associated with Land Use Changes (LUC) resulting from solar PV deployment are significantly lower in scenarios where land-based policies are implemented, compared to the Baseline and NDC-LTT scenarios without such measures (see Table 3). The Baseline shows lower LUC-related emissions than the NDC-LTT primarily because it involves a less aggressive expansion of solar PV, and thus a smaller land footprint.

Table 3: Land Use Change emissions associated to the deployment of solar PV on land.

	Cumulated carbon emissions (GtC) 2020–2050 (associated to the deployment of solar PV on land)	**% of carbon emissions with respect to Baseline and NDC-LTT scenario**
Baseline	0.02	100%
Baseline-land-based policies	0.009	59%
NDC-LTT	0.06	100%
NDC-LTT-land-based policies	0.035	55%

4.3.4 Discussion

The WILIAM exercise contributed to addressing the three key research questions of this task/deliverable by evaluating the impacts of bioenergy and solar PV deployment on land use, emissions, and natural resource competition in the EU. The selected indicators and modelling results helped assess policy coherence and the trade-offs associated with different land-based strategies under various energy transition scenarios.

For bioenergy, both the NDC-LTT and land-focused policy scenarios show that ambitious biomass deployment can increase pressure on forest ecosystems, especially beyond 2035. Afforestation policies improve net emissions and forest stock levels but are not sufficient alone to offset the growing demand for biomass, particularly in the residential sector. Scenarios that impose stricter limits on forest removals, such as the NDC-LTT-Self-Sufficiency, succeed in protecting forest stocks but lead to unmet biomass demand unless combined with large-scale afforestation, as seen in the NDC-LTT-Afforestation scenario. However, this latter approach comes with the trade-off of increased land competition, particularly affecting cropland availability.

Regarding solar PV, results show that high deployment aligned with current EU policies significantly increases land occupation, mostly on rainfed cropland, which raises concerns on food production and LUC emissions. When land-based policies are applied, the model indicates a reduction in land competition and lower carbon emissions, proving their effectiveness in balancing renewable energy targets with sustainability goals.

Overall, both renewable energy strategies offer clear benefits but also generate considerable trade-offs that should be tackled by integrating surgical land-related policies that ensure a more balanced path.

4.4 CLEWS exercise

The CLEWs exercise focuses on the case study of Ethiopia. Ethiopia is a landlock country and is the second most populated country in the African continent expected to reach around 200 million people by 2050 (World Bank, 2022). The country still faces great challenges such as limited access to energy, water, and sanitation services, particularly in rural areas (World Bank, 2022). Additionally, food insecurity is also significant, with 15.8 million people facing hunger in 2024 (United Nations, 2024).

According to the African Development Bank Group (2024) 62.8% of employment comes from the agricultural sector (32% of the GDP) mostly characterised by rainfed crops with low levels of mechanisation (GIZ, 2018) making it vulnerable to climate change. Because of this Ethiopia embedded adaptation strategies into its national framework, seeing irrigation and one of the key strategies for tackling climate impact (Ministry of Planning and Development, 2022).

This exercise focuses on understanding the impact of land use change and irrigation increase on biodiversity, food production and water stress. The stakeholder engagement workshop supported the selection of indicators able to quantify the modelling results for enabling model comparisons and increase transparency. The selected indicators for this case study are water stress, biodiversity index, net emissions, harvested area, area under irrigation and dependency ratio on food imports.

4.4.1 Scenario design

We designed two scenarios: BAU (Business as usual) and NDC-LTLEDS (National determined contribution and long-term strategy). The first one corresponds to the baseline scenario, and it is called business as usual since it is an unconstrained optimisation that seeks the optimal solution based on the current policies. The only constraints are the ones needed for calibrating the model according to historical trends and technology roll-out feasibility. On the other hand, the second scenario is designed for reaching the goals stated in the NDC plan by 2030 and LTLED strategy by 2050 (Ministry of Planning and Development, 2022), where the optimal solution is constrained to reach the stated targets.

Table 4: Scenario description for CLEWs Ethiopia

Scenario	Description
BAU – Business as usual	This scenario can be considered as a baseline needed for the comparison with the NDC-LTLEDS scenario. It represents the optimal least cost solution if the current policies are in place.
NDC-LTLEDS	This scenario is based on the implementation of the current stated policies and targets presented

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	in the updated national determined contribution and Ethiopia's long-term low-emission and climate resilient development strategy (2020-2050). See the table below for the targets.

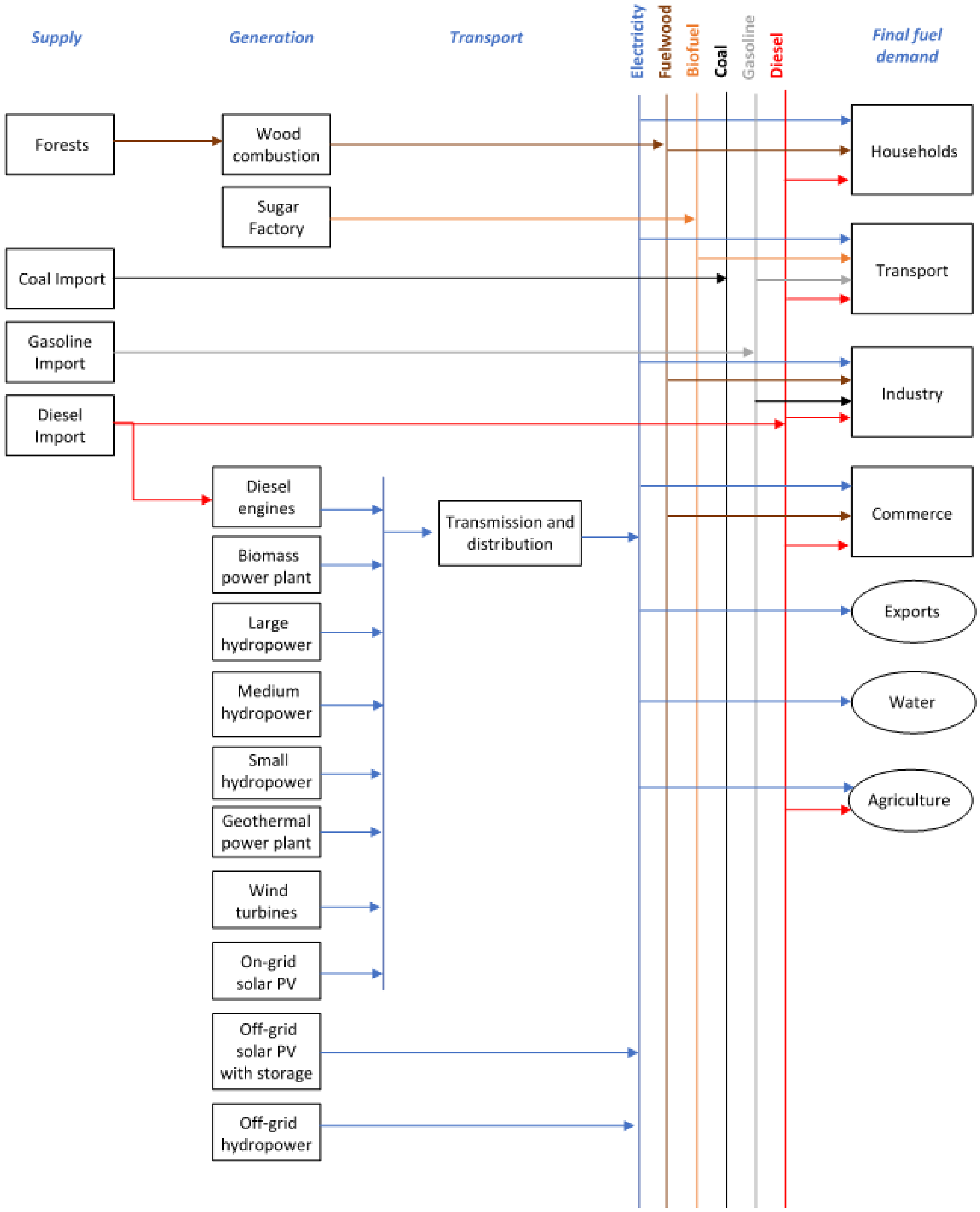

Figure 4- 10: Ethiopia Reference System - CLEWs model

Figure 4-10 represents a simplified reference system for the Ethiopian CLEWs model. The energy mix, resource, technology options and final demands, are the same for both models. The agricultural sector is characterised by 4 different options for each crop type: rainfed with low level of mechanisation, rainfed with high level of mechanisation, irrigated with low level of mechanisation and irrigated with high level of mechanisation. The mode switch from low to high mechanised is constrained to 1% per year consistent with the current and stated policies. The NDC-LTLEDS scenario spans from the BAU with the addition of specific constraints on the land use and forestry, and energy sectors. With the aim of an average annual emission reduction of 28 MtonCO2 equivalent per year, the following table summarised the main targets presented in the national strategy and implemented in the second scenario:

Table 5: NDC-LTLEDS scenario targets - CLEWs model

Type	2030 target	2050 target	Policy
Forestry	Afforestation of +3 million ha	Afforestation + 8.2 million ha	LT-LEDS, NDC aligned scenario
Reduction of residential biomass use	-14.5%	- 60%	LT-LEDS, NDC aligned scenario
Food security: crop production through irrigation	Production of 30 million quintals		
Transmission losses	-	10%	LT-LEDS, NDC aligned scenario
Increase in renewable energy contribution	100%	100%	
Transport electrification	10%	75%	LT-LEDS, NDC aligned scenario

The following table shows how the results of the feedback, presented in **Section 3.1.2.4**, were integrated into the CLEWs analysis. The scenario comparison was conducted using selected indicators available at the *Indicators4CLEWs* GitHub[6] repository.

Table 6: Stakeholder feedback integration into the CLEWs analysis

Feedback	Context-specific indicator	Model variable / data post-processing
Proper carbon accounting for biomass	According to (IEA, 2025) the residential sector still heavily relies on biomass.	Emission factor for the biomass residential use.
Track restoration of ecosystems	Biodiversity Habitat Index	Indicators4CLEWs
Consider agricultural indicators	Harvested area, Irrigated area, crop yields.	Indicators4CLEWs

[6] https://github.com/IAM-COMPACT/Indicators4CLEWs

Consider forest indicator	Forest cover	Indicators4CLEWs
Targets and indicators for achieving climate neutrality	Net emissions, emissions by sector	Indicators4CLEWs and direct model outputs

Additionally to these indicators, the repository includes also the crop import dependency ratio and the annual average water stress score needed for addressing the scope of the study. The formulas adopted for each indicator are documented in the online *Indicators4CLEWs* GitHub repository. The data used, assumptions and references are available on the Zenodo online repository[7].

4.4.2. Research questions

The aim of this study is to understand the impact of land use change on biodiversity, food production and water stress. The leading research questions are the following:

- How will land use change if NDC-LTT policies are put in place?
- How will this affect food production, crop yield and water stress?
- What will be the impact of the use of resources on climate?

4.4.3. Results

Both scenarios show similar results in land use change. The gradual reduction of grassland and other land (which encompasses shrubland, sparse vegetation and bare area) is replaced by agricultural land to meet the growing annual demand.

[7] https://zenodo.org/records/15684542

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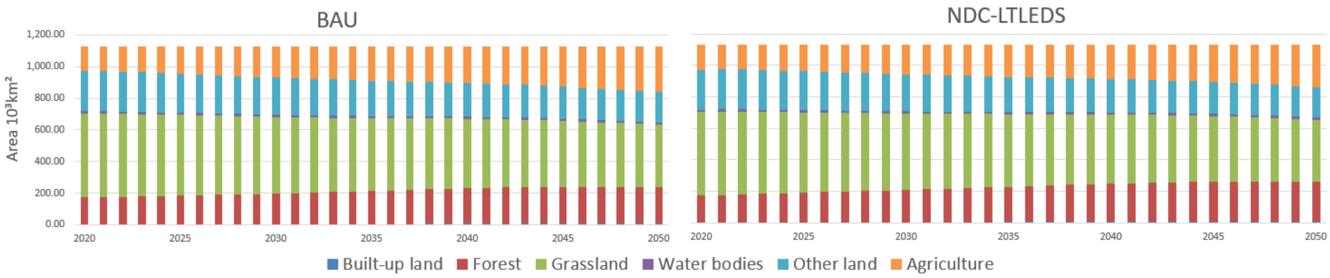

Figure 4- 11: Land use change - CLEWs Ethiopia

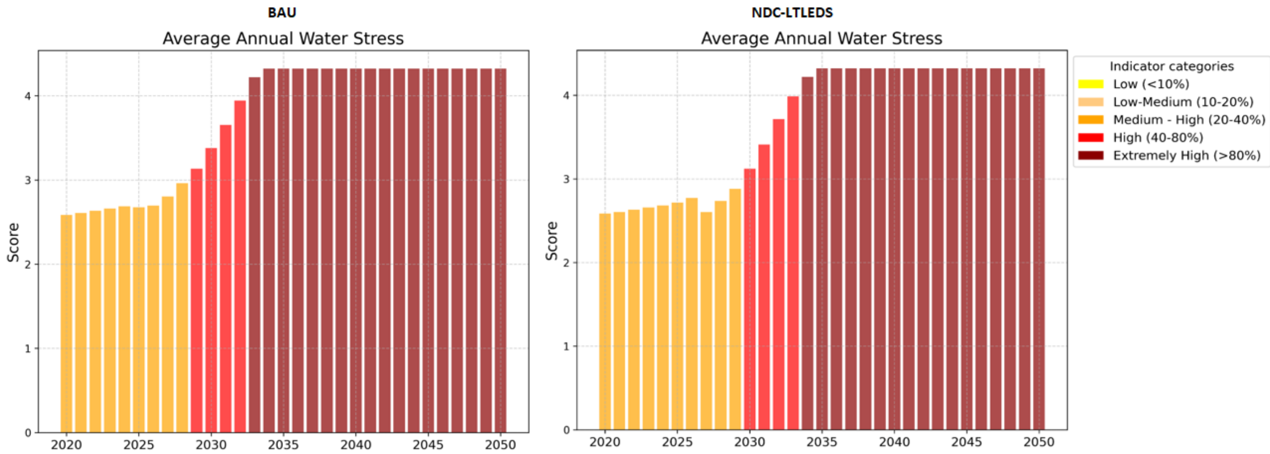

Figure 4- 12: Average annual water stress - CLEWs Ethiopia

Both scenarios see an increase in the water stress. As we can see in the Annex II, the stress is caused by the irrigated land, which reaches in both cases 74% of the total harvested land.

When afforestation targets are put in place, the overall harvested area reaches only 23.6% of the total area compared to the 25.7% of the BAU (see **ANNEX II**). This leads to an increased dependency ratio of crop imports, which is minimised in the BAU, and a slight decrease in the overall crop yields. The following figure has indeed two peaks which correspond to the afforestation targets that are put in place.

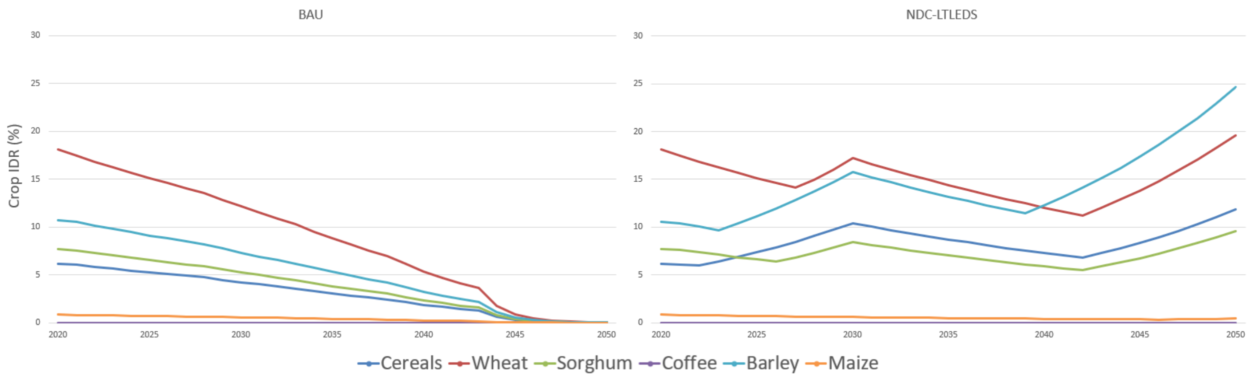

Figure 4- 13: Dependency ratio on crop imports

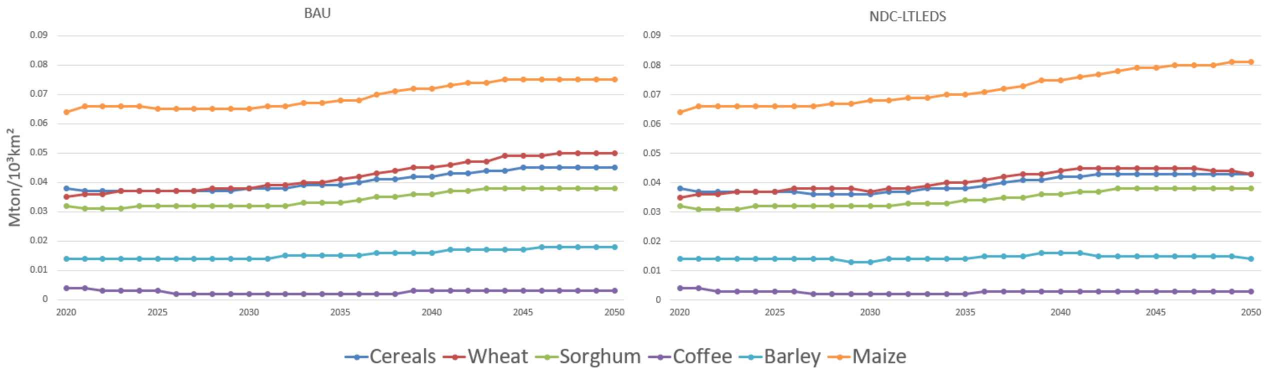

Figure 4- 14: Crop yields

However, despite becoming more reliant on imports, the positive effect of afforestation targets is shown by the biodiversity habitat index (BHI).

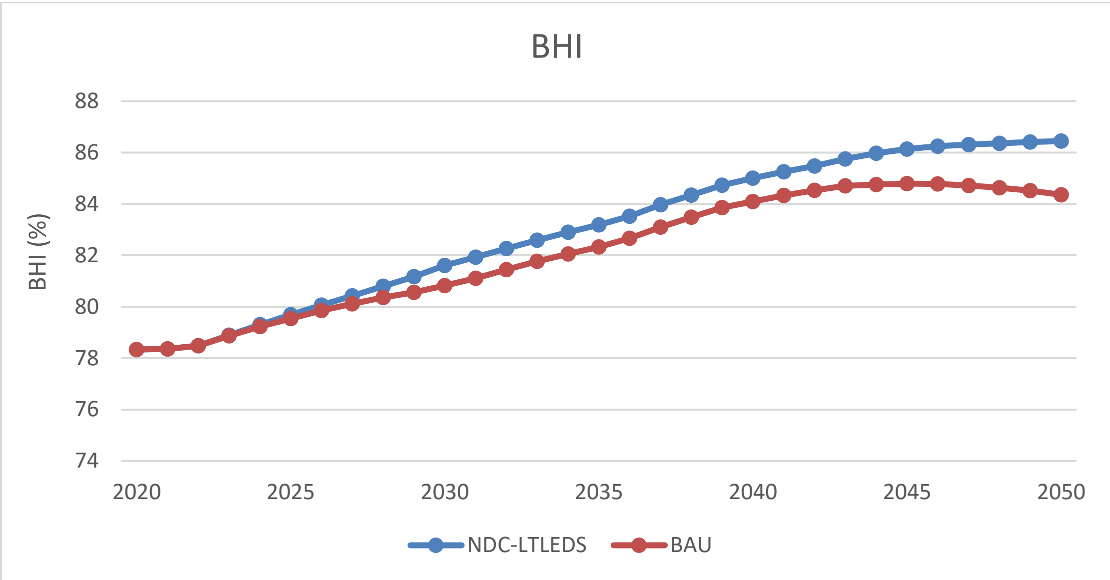

Figure 4- 15: Biodiversity habitat index - CLEWs Ethiopia

In both cases the ecosystems have a positive trend, with the BHI index of the NDC-LTLEDS scenario reaching 86.44%. Habitat recovery is indeed driven by the afforestation targets since we followed the same methodology adopted in D5.8.

Finally, if all the selected NDC-LTLEDS targets are put in place, we can see a reduction in the net CO_2 equivalent emissions of 30% and 55% by respectively 2030 and 2050.

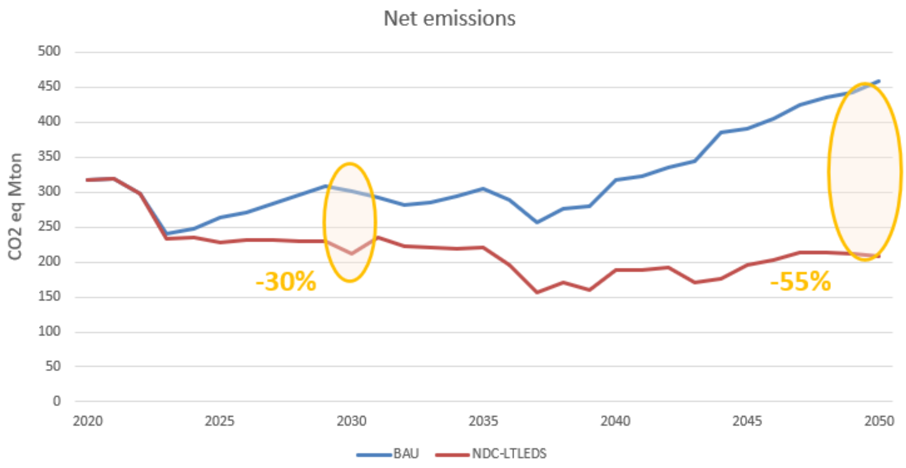

Figure 4- 16: Net emissions - CLEWs Ethiopia

As shown in **ANNEX II**, the main sectors contributing to the emissions are the residential sector, followed by agriculture and transport. The residential sector is indeed still reliant on biomass with a consumption of 1370 PJ in 2022 (IEA, 2025), while the transport sector uses oil products as a fuel. In both scenarios the energy sector does not contribute significantly to the net balance, being the only source of emissions the diesel power plant which is phased out in the NDC-LTLEDS scenario for reaching the 100% renewable share target. The great decrease in the emissions can therefore be attributed to the electrification targets of the transport and residential sectors combined with the increase in afforestation which has a positive effect on land use change emissions.

4.4.4. Discussion

The CLEWs exercise supported answering the three main research questions. The selected indicators and modelling results were useful for analysing policy coherence and the causal-effect of the stated policies. Both scenarios show an increase in the water stress, reaching by 2050 the highest score. This is due to the high increase in irrigated land which allows to meet the growing food demand due to higher yields. However, this is caused also by the 1% increase constraint in the mechanisation level. Higher levels of mechanisation and thus an increased share of this technology option, would allow to reach both lower water stress and reliance on crop imports (in the NDC-LTLEDS scenario) because of higher crop yields.

The afforestation targets proved to have a beneficial effect on both biodiversity and net emissions. However, this is not enough for reaching the climate neutrality by 2050 due to the high impact of biomass use in the residential sector.

Finally, both scenarios bring benefits and drawbacks. If the priority is to restore and preserve biodiversity while decreasing the emissions, the NDC-LTLEDS targets proved to be the best pathway to follow. However, a more careful planning is needed for ensuring also a sustainable use of resources and lower water stress.

4.5 Conclusions

The WILIAM exercise shows the need and benefits of applying integrated energy and land planning responses, i.e., land-based strategies under various energy transition scenarios. On one side, without appropriate land planning, pressure can be increased on forest ecosystems (biomass deployment) and also on land competition (solar PV mostly deployed on rainfed cropland following past trends). However, the land planning measures have to be designed carefully to ensure balance between conflicting priorities to avoid unexpected consequences, such as shifting the problem to others parts of the world, increasing land competition due to large-scale afforestation, or unmet biomass demand due to the protection of forests.

The CLEWs exercise also highlights the need of integrated analysis for ensuring policy coherence and sustainable use of resources. Depending on what the priorities of interventions are, it is important to consider all the systems belonging to the nexus, understanding their synergies and trade-offs. For instance, a boost in irrigation for the case study of Ethiopia, showed to lower competing land uses, support afforestation targets and decrease emissions, but with high water stress associated.

Finally, despite having different algorithms, modelling techniques and scales, both exercises show the importance of planning integrated responses for avoiding mitigation negative impacts on other sectors, such as land use and land-based related resources. This means that to achieve mitigation goals not only the energy transition has to be planned, but also solutions regarding land planning, water management and their interconnection.

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5. Environmental and societal implications of transitioning to sustainable diets

The study is under review in the journal *Nature Food*. Rodés-Bachs, C., Sampedro, J., Van de Ven, D., Horowitz, R., Pardo, G., and Zhao, X. (2025) Environmental and societal implications of transitioning to sustainable diets. https://doi.org/10.21203/rs.3.rs-5346673/v1

Abstract

The global food system plays a crucial role in shaping societal and environmental futures, with dietary shifts having broad implications across multiple sectors. While plant-based and non-ruminant proteins are gaining popularity in wealthier nations, regional adoption of sustainable diets remains uncertain and highly variable. Here, we explore the benefits of increasing plant-based protein intake or reducing ruminant livestock consumption across global and regional scenarios.

Using an Integrated Assessment Model, we find that sustainable diet transitions enhance regional protein and fat intake, improve dietary energy adequacy, and reduce greenhouse gas emissions, air pollution-related mortality, water scarcity, and food costs. These changes also support re/afforestation and biodiversity gains, though some regions may face trade-offs. Notably, regional efforts yield faster benefits compared to uniform global targets. Our results emphasise the need for effective social policies to promote a shift toward plant-based and low-ruminant diets, demonstrating their nutritional and environmental advantages.

5.1 Introduction

The global food system is a key element in achieving several objectives of the Sustainable Development Goals (SDGs) [1] and the Paris Agreement [2], which are the main global priorities for transitioning to a sustainable and equitable future [3]. Dietary patterns have a significant influence on malnutrition and subsequent non-communicable diseases [4], which cause 11 million deaths each year [5, 6]. According to the Food and Agriculture Organization (FAO), one in three of the world's population suffered from food insecurity in 2020 and between 702 and 828 million people faced hunger, with recent trends indicating that this issue is on the rise [7]. Moreover, food-related problems exhibit significant geographical and gender inequalities. Women are 10% more likely than men to suffer from food insecurity and half of the people who lack regular access to sufficient, safe, and nutritious food live in Asia and a quarter in Africa [7]. Additionally, the food system, encompassing the entire supply chain from food production to processing and transport, is responsible for about one-third of all greenhouse gas (GHG) emissions. These emissions primarily stem from methane (CH_4) produced during enteric fermentation, carbon dioxide (CO_2) released through land-use change, and nitrogen (N_2O) from managed soils and animal waste [8], which directly affect human health [9, 10]. Besides, agricultural production accounts for 80% of the total water consumption [11, 12] and irrigation practices are expected to exacerbate water scarcity pressures in some basins [13]. The food sector is also the main driver of soil degradation, freshwater consumption, nitrogen pollution [14, 15], and has a major impact on biodiversity loss [13].

This evidence highlights the need for a drastic change of the global food systems and dietary patterns [16]. Currently, livestock is responsible for providing one-third of the protein in human diets [11, 17, 18]. Shifting to plant-protein-based diets is gaining popularity in developed economies due to ethical issues related to animal treatment and concerns regarding environmental, land-use change, and nutritional impacts of red meat consumption [11, 18, 19]. Indeed, within the agricultural sector, livestock management is estimated to be responsible for 45% of the GHG agricultural emissions [17] and 80% of non-CO_2 agricultural emissions, such as CH_4 and N_2O [20]. There are also large differences in environmental implications within the livestock sector. Ruminant species—such as sheep, cattle, and

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goats—rely more on grasses and forages that are inedible to humans, require larger pasture areas, and produce higher reactive nitrogen and CH_4 emissions than monogastric species—such as poultry and pigs—which are more reliant on grains and pulses that compete for arable land that could grow human food [21, 22, 23]. Beyond the environmental aspects, the nutritional quality of plant proteins may be inferior relative to animal proteins [21, 24], which influences the adoption of diets like veganism, vegetarianism, or flexitarianism [24, 25, 26, 27, 28]. In some cases, only certain types of animal protein are removed, resulting in a global decrease in beef consumption and a global increase in poultry consumption [29, 30, 31].

Literature has analysed the implications of these dietary changes focusing on isolated sectors like food prices [22], land use management [24], or air quality [32]. Other studies examined the system-wide impacts of the dietary change combined with a larger portfolio of mitigation options and/or alternative socio-economic pathways [33–42], blurring the individual impact of dietary changes. Recently, a one-off impact of dietary shifts was given by Humpenöder et al. [43], focusing on the feasibility of 1.5°C pathways under this behavioural change. However, all these studies focused on "stylised" transition diets, quantifying calorie intake and shifting to a determined food consumption mix in specific years with no transition barriers, such as the Flexitarian EAT-Lancet diet [4]. This type of diet has received criticism regarding its nutritional value, its lack of regional considerations under the global convergence assumption, and its similarity to a "fully-vegan" choice [44]. Moreover, little analysis was paid to the differences between regions and the generated inequalities.

In this study, we address these limitations by evaluating the impact of dietary shifts across a wide range of dimensions aligned with various SDGs, including poverty (SDG1), nutrition/hunger (SDG2), health (SDG3), water resources (SDG6), land use (SDG15), and climate policies (SDG13). We also assess the nutritional aspects of the proposed diets, examining regional protein, fat, and micronutrient intake. Furthermore, we incorporate regional diversity and disparities into the study design.

We explore three scenario axes: (a) promoting plant-based protein sources (SPP), (b) reducing reliance on ruminant livestock (SNR), and (c) a combination of these behavioural shifts (SPPNR). Additionally, we examine two pathways to capture regional dietary transitions: (a) the Global Target (GlobT), where all regions aim for a universal protein target by source, and (b) the Regional Growth (RegG), where regions increase their protein intake from a specific source by a targeted percentage. These scenarios are based on the SSP2 reference storyline [45], which serves as the benchmark for comparing SDG indicators. For mitigation impacts, the Reference scenario, along with the other scenarios, incorporates the Nationally Determined Contributions (NDCs) and Long-Term Targets (LTTs) policy portfolio.

Overall, we consider nearly 1,300 runs implemented into a multisector integrated assessment model (the Global Change Analysis Model [46]). We also account for additional sensitivity dimensions, including the targeted protein share, the transition speed, and peak year, further detailed in the Methods section.

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	Acronym	Full name	Description
Scenarios	REF	Reference Scenario	SSP2 scenario.
	SPP	Plant Protein Scenario	Increase of plant protein sources to the detriment of animal protein sources.
	SNR	Non-Ruminant Scenario	Reduction of ruminant protein sources but maintenance of the total meat consumption preference.
	SPPNR	Plant Protein & Non-Ruminant Scenario	Conjunction of the SPP & SNR scenarios, i.e., increase of plant protein sources and reduction of ruminant protein among animal protein sources.
Pathways	GlobT	Global Target Patwhay	All regions reach the targeted plant or non-ruminant protein share by 2050. No region can reduce its initial share.
	RegG	Regional Growth Pathway	All regions increase the plant-protein share or decrease the ruminant protein share by a target of X percentage points by 2050.

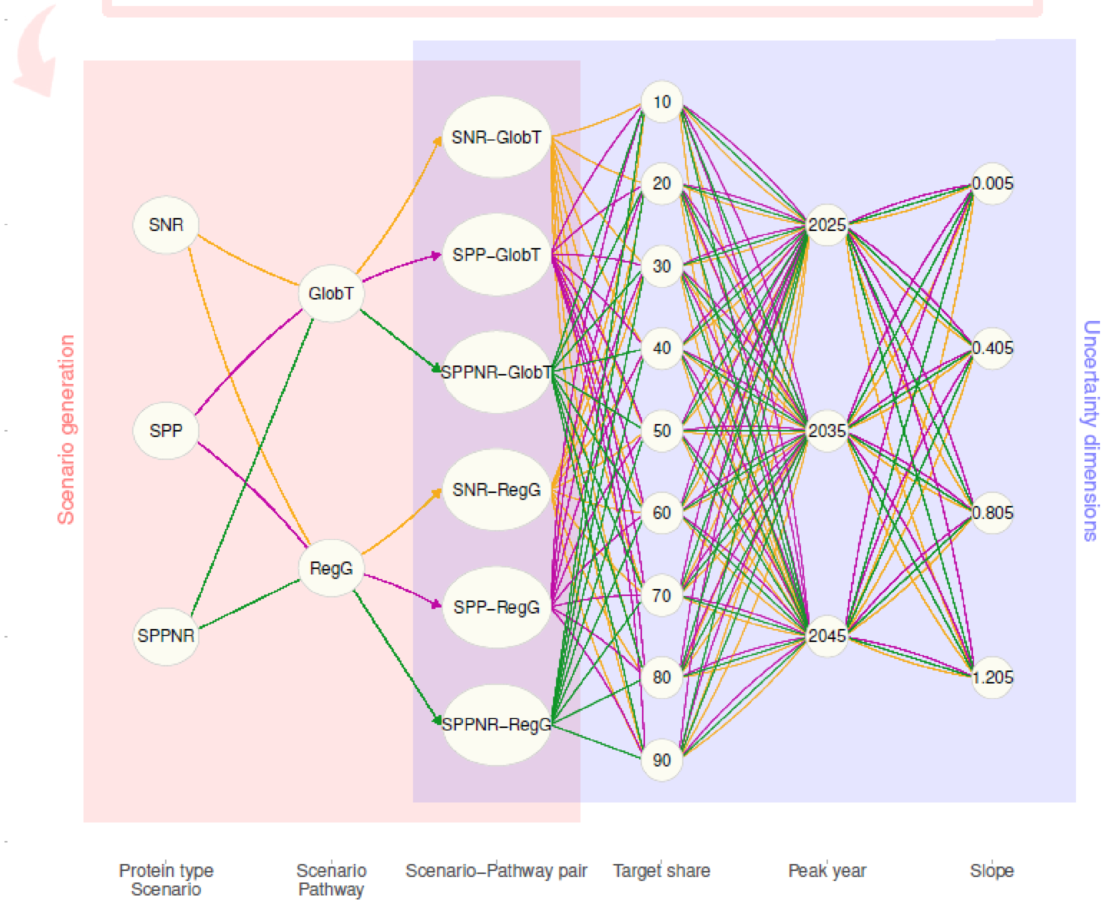

Figure 5- 1: Overview of scenario generation and uncertainty dimensions included in the study. The top table outlines the *scenario-pathway* generation pairs, while the lower graph illustrates both the *scenario-pathway* generation pairs and the uncertainty sources considered.

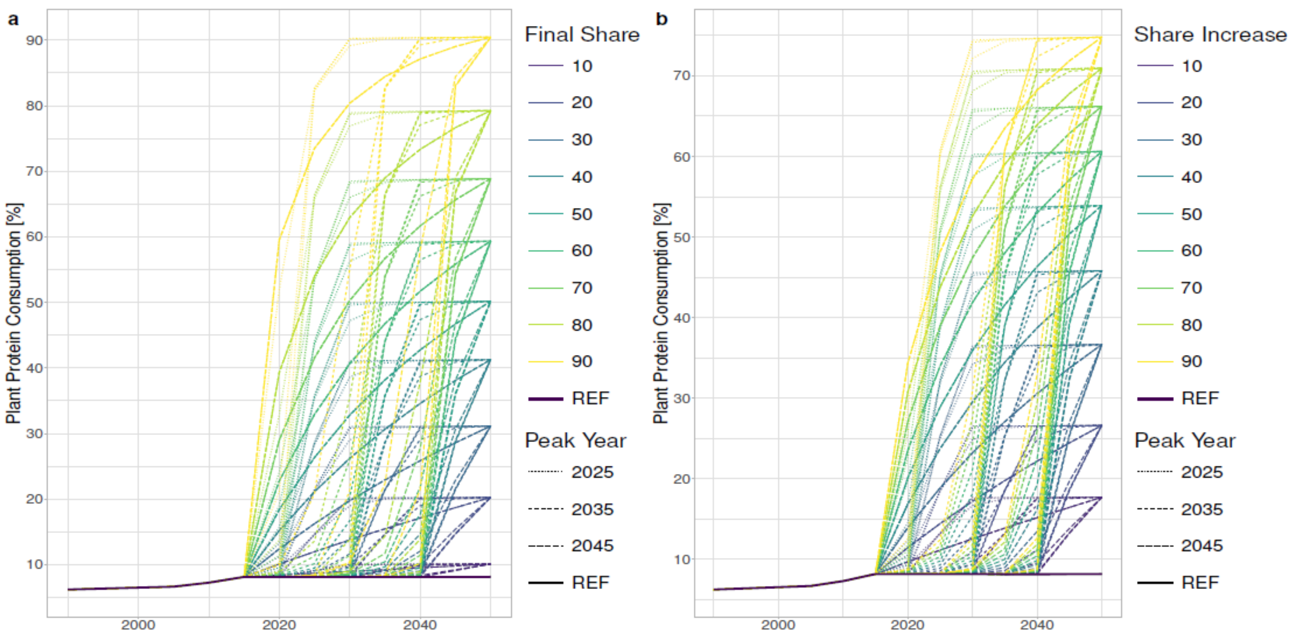

Figure 5- 2: Exemplification of the scenario design for EU-15 accounting for all uncertainty dimensions present in the study. See S1 for regional details. a) Scenario runs under the Global Target pathway. b) Scenario runs under the Regional Growth pathway.

5.2 Methods

4 Global Change Analysis Model

The Global Change Analysis Model (GCAM) is a multisector integrated assessment model designed to quantify human and physical Earth-system dynamics by exploring the interdependencies between economy, energy, water, climate, and agriculture, forestry, and land use (AFOLU) systems [46, 76, 77]. GCAM allows quantification and exploration of the implications of alternative uncertain "what-if" type scenarios from 2015 to 2100 in 5-year time steps within a single computational platform. The model outcomes can be used to explore the implications of alternate futures, so they can inform stakeholders in the design or implementation of different climate policies or transformational strategies. Therefore, the model has been widely applied for both national and international assessments. These include the Intergovernmental Panel on Climate Change (IPCC) scenarios [3], the Shared Socioeconomic Pathways (SSPs) [45], the Network for Greening the Financial System (NGFS) scenarios [78], or the U.S. decarbonisation strategy [79]. More information can be found in the online documentation: https://github.com/JGCRI/gcam-doc.

Economic systems, represented by population and gross domestic product (GDP), are the exogenous drivers for the system's activities. The energy system in GCAM covers primary energy resource production, energy transformation, and final energy demands, and includes international trade in energy commodities. It distinguishes between fossil fuel (oil, gas, and coal), uranium, and renewable sources (biomass, wind, geothermal, hydropower, rooftop solar photovoltaic, and non-rooftop solar). In the land use module, land is categorised and modelled based on the vegetation cover type across 32 geopolitical regions and 235 water basins. Land uses can be for commercial (crops, forestry, and grazed pasture) or non-commercial (natural forest, grassland, scrubs, and other pasture) purposes. The water module balances water supply (renewable surface and groundwater, non-renewable groundwater, and desalinated water) in the 235 water basins with water demand in the energy and agricultural systems.

Technology choice is determined by market competition. The market share captured by technology increases as its costs decline, but GCAM uses an implicit probabilistic (logit) model of market competition and not a "winner take all" model of cost competition. This formulation is designed to represent decision-making among competing options when only some characteristics of the options can be observed [80]. Apart from costs, stated preferences for specific technologies are taken into account through calibrated historical technology shares.

More information on the methodology of economic choices can be found at: https://github.com/JGCRI/gcam-doc/blob/gh-pages/choice.md.

Relevant to this study, food consumption choices in GCAM are based on a modified logit model of sharing [80]. This modified logit model estimates the probability of selecting a particular choice among a set of alternatives by incorporating various factors and modifying standard assumptions to better capture real-world behaviours. In particular, the share *si* of an alternative choice *i* is given by:

$$s_i = \frac{\alpha_i p_i^{\gamma}}{\sum_{j=1}^{N} \alpha_j p_j^{\gamma}}, \qquad [1]$$

Where *a* is the share weight, γ is the logit exponent, p_i is the cost, and *N* the number of alternative choices. The food alternative choices are ordered through a nesting structure (Figure S8) divided into staple and non-staple food demand. Each branch contains different nesting levels. In particular, under the non-staple products, we can distinguish the Protein layer, divided into Plant and Animal. At this point, in our GCAM version based on the GCAM 7.1 release [81], we have added an extra nesting level to differentiate between Ruminants, Monogastrics, and Fish animal proteins. The nesting structure ends with Beef, Dairy, Pork, Poultry, Sheep and Goat, Fish, Legumes, and Nuts and Seeds leaves [82, 83] (Figure S8).

For every period, markets are cleared based on price information available at that specific time step, so the price evolution in future time periods is not taken into account in the modelling decision-making process. The production outputs of the modules in GCAM are then converted not only to GHG and F-gases emissions (e.g., CO_2, CH_4, and N_2O) and air pollutants (e.g., OC, BC, SO_2, NO_x, CO, NMVOC) but also to other non-CO_2 gases including HFCs which will have a significant role in the decarbonisation pathways [84].

To represent climate, GCAM considers a hard-linked module named Hector, a simple climate model frequently used to run together with IAMs [85]. GCAM is able to incorporate SSP narratives and uses a carbon-cycle model to replicate historical emissions, radiative forcing, and surface temperatures while simulating IPCC GHG concentration trajectories or the Representative Concentration Pathways (RCPs) [86]. Hector translates emission outputs from energy, land, and water modules from GCAM into climate outcomes. Its hard link with GCAM allows defining global temperature targets with a backcasting approach, which readjusts resource allocation in GCAM's modules.

In this study, each run combines a protein-type scenario, a pathway, and uncertainty dimensions. The first two components define the scenario itself, while the uncertainty dimensions introduce plausible perturbations (Figure 1). To streamline the analysis, we assume that once a region reaches a specified share of plant and/or non-ruminant protein, it does not decrease. A total of 1,298 runs were conducted: 649 with mitigation and 649 without. The reference scenario follows the SSP2 storyline [45], applied with and without the NDC-LTT mitigation portfolio. This policy portfolio is consistently used across all mitigation scenarios.

In particular, we consider three protein-type scenarios and two scenario pathways, which create a total of six scenario pairs as detailed in the subtable of Figure 5-1. In particular, we model a plant-based protein scenario (SPP), which reduces the dependency on animal protein; a low-ruminant protein scenario (SNR), which reduces the ruminant protein consumption but maintains the animal protein intake preference; and a conjunction scenario (SPPNR), where the previous scenarios are both implemented at the same time. In this last case, the efforts to increase plant proteins and reduce ruminant proteins are symmetric, i.e., either the percentage increase of plant proteins corresponds to the percentage decrease of ruminant proteins, or the target share of plant and non-ruminant proteins is the same.

We consider two pathways: the Global Target (GlobT) pathway, where all regions must reach a specified percentage of plant and/or non-ruminant protein by 2050, and the Regional Growth (RegG) pathway, where all regions increase their plant protein share and/or decrease their ruminant protein share by a set number of percentage points by 2050. For example, a region starting with 10% plant protein may be required to increase to 20%, while a region starting at 60% could need to reach 70%, ensuring that all regions make efforts toward their targets. Notice that no share can be below 0 or above 100, and no region can decrease the share of plant protein in the SPP and SPPNR scenarios or increase the ruminant share in the SNR and SPPNR scenarios with respect to Reference. Thus, for instance, regions with a high plant protein share in the Reference scenario will reach the full intake of plant protein when increasing X percentage points in the RegG pathway, and the subsequent increases will keep this value. Conversely, these regions will not be affected by runs with the GlobT pathway whose protein target share is already met by its Reference scenario.

As indicated by the literature, dietary choices are influenced by culture, sex, level of education, social framework, perception of consumption of animal products, food cost and monthly income, religion, and beliefs among other factors [87].

To capture all these elements, we have designed raw adoption curves for the new diets. They are modelled through three axes: (a)The average regional share of plant and/or non-ruminant intake by 2050 (the target share); (b) The speed at which the dietary shift is adopted (the slope); and (c) The year when more people shift to the new diet (the peak year).

(a) The target share ranges from 10% to 90% in increments of 10%, specifying the 2050 regional share of plant or non-ruminant protein. This approach allows us to account for varying degrees of diet adoption while maintaining regional heterogeneity. For instance, when we indicate that a region has a 70% share of plant-based protein, it reflects a future where some segments of the population consume a 100% plant-based diet, while others may follow omnivorous, flexitarian, or vegetarian diets. However, the regional average indicates a strong overall preference for plant-based products.
(b) The slope can be 0.005, 0.405, 0.805, or 1.205. A higher slope indicates a higher adoption rate. Through this parameter, we can model the speed of the diffusion of the new diet, considered here as a spreading trend [88, 89].
(c) The peak year can be 2025, 2035, or 2045. It represents the year when the highest number of people will switch to the new diet, indicating the point at which the majority of those who will make the dietary shift do so. If the adoption of the new diet over time was represented by a bell curve, the peak year will correspond to the top vertex.

To implement the 1,298 dietary change scenarios, we increased the share weights of the Protein-Plant nesting subsector to push plant protein good consumption and reduced the share weights of the Protein-Animal-Ruminant nesting subsector to reduce the consumption of ruminant goods. To calibrate the share weights, we considered the plant and non-ruminant regional protein in the SSP2 scenario. For each run (with a defined protein type, pathway, target share, peak year, and slope), we computed the targeted protein by 2050. In the SPP scenario, if this target value was lower than the Reference value, we did not modify anything. However, if the target value was higher than the Reference scenario, we updated the share weight by re-calibrating its value in 2050 to meet the final target share. Then, we interpolated the values from 2015 to 2050 with the determined peak year and slope through a logit simplification of a diffusion model (Equation 2) [90], as in previous behavioural change studies [89]. Conversely, in the SNR scenario, we reduced the share weight when the target value was lower than the Reference value and did not modify it when the target value was higher.

The new share weight for a given year y was interpolated through:

$$\alpha_i = A + B \cdot \frac{\hat{\alpha}_{2050} - \alpha_{2015}}{1 + e^{-k\cdot(y - pYear)}}, \quad [2]$$

Where:

$$A = \hat{\alpha}_{2050} - (1 + e^{(-k\cdot(2015 - pYear))}) \cdot \frac{\alpha_{2050} - \alpha_{2015}}{e^{(-k\cdot(2015-pYear))} - e^{(-k\cdot(2050-pYear))}},$$

$$B = (1 + e^{(-k\cdot(2015 - pYear))}) \cdot \frac{1 + e^{(-k\cdot(2050-pYear))}}{e^{(-k\cdot(2015-pYear))} - e^{(-k\cdot(2050-pYear))}},$$

k refers to the slope, *pYear* refers to the peak year, and *a ˆ2050* refers to the target share weight by 2050. Plant and non-ruminant regional protein intakes of the different runs are presented in Figures S4, S5, S6, and S7.

To estimate the macronutrient intakes, i.e., fat and protein, we multiply the consumption of each food item (e.g., beef, dairy, oil...) by the FAO's regional nutritional value in the base year 2015.

To estimate the micronutrient intakes, we multiply the consumption of each food item (e.g., beef, dairy, oil...) by the USDA's nutritional value in the base year 2015. We consider the mean among all the USDA items mapped to the same GCAM item. For instance, the quantity of vitamin B12 (in g) found in the beef GCAM technology is the average over the quantity of vitamin B12 in beef steak chucks, beef steak cubes, beef steak flanks, beef steak rib-eyes, beef steak rounds, beef steak T-bones, beef short-ribs, beef roasts, beef bacons, among other beef descriptions provided in the USDA database.

The FAO estimates the Average Dietary Energy Supply Adequacy (ADESA), which is the ratio of dietary energy consumed to the Average Dietary Energy Requirement (ADER) for a country [55]. This metric, part of the FAO's food security indicators, varies by country due to differences in demographic factors such as sex, age, and height. While the ADER is calculated assuming uniform energy requirements for individuals of the same sex, age, and height, countries with a higher proportion of children, elderly individuals, or shorter populations will have a lower population-level ADER. To calculate the ADESA, the Food Balance Sheet's [91] estimate of dietary energy supply is divided by the ADER estimate of dietary energy requirements and then multiplied by 100. Ratios above 100 suggest that the food supply exceeds the requirements, whereas ratios below 100 indicate that the food supply is insufficient [55].

To compute the ADESA index, we divide the dietary energy supply from the food goods consumed in our GCAM scenario runs into the estimated annual regional energy requirements according to the SSP2 demographic projections [92, 93].

To compute the re/afforestation percentage we aggregate all the total non-urban land into Forest (including softwood, hardwood, unmanaged softwood, unmanaged hardwood, protected unmanaged softwood, and protected unmanaged hardwood forest) and NonForest land types. Then, we compute the percentage of forest area as:

$$PercentageOfForest_{i,t} = \frac{F_{i,t}}{\sum_{l \in LandTypes} A_{i,t,l}}, \quad [3]$$

where *F* is the total forest area in Mha in year *t* and scenario run *i*, and *A* is the non-urban land type area of type *l* in Mha.

As employed in existing literature [41], we use the percentage of unmanaged land as an indicator of biodiversity. To compute it, we aggregate the total non-urban land into Unmanaged (including unmanaged forests, protected unmanaged forests, shrubland, grassland, protected grassland, unmanaged pasture, protected unmanaged pasture, tundra, rock, ice, and desert) and Managed land types. Then, we compute the percentage of unmanaged land type as:

$$PercentageOfUnmanagedLand_{i,t} = \frac{U_{i,t}}{\sum_{l \in LandTypes} A_{i,t,l}}, \qquad [4]$$

where U is the total unmanaged area in Mha in year t and scenario run i, and A is the non-urban land type area of type l in Mha.

To understand the changes in land use management, we compute the total amount of Forest (including softwood, hardwood, unmanaged softwood, unmanaged hardwood, protected unmanaged softwood, and protected unmanaged hardwood forest), Cropland (including food and feed crops, biomass, and other arable land), Pasture (including grazed and other pasture lands), and Other Natural (including shrubs, grasslands, and any other non-urban land) land types.

Water withdrawals refer to the total amount of water taken from a natural source (like rivers, lakes, groundwater, or reservoirs) for use in various activities such as agriculture, industry, domestic use, electricity production etc. It might be returned to the source after use, either treated or untreated. In this study, we compute the total water withdrawals by region.

Land types can be distinguished by the water type: irrigated or rainfed water. To quantify the rainfed water land type share we considered the following ratio:

$$RainfedWaterLandTypeShare_{i,t} = \frac{R_{i,t}}{I_{i,t} + R_{i,t}}, \qquad [5]$$

where R represents the land type using rainfed water, I is the land type using irrigated water in thousand km², t is the year, and i the scenario run.

The water scarcity index stems from the different water sources and water withdrawals of each region. There are three distinct sources of fresh water: renewable water, non-renewable groundwater, and desalinated water. Renewable water is water that is replenished naturally by surface runoff and subsurface infiltration and release. It is determined by the natural streamflow, baseflow, the total reservoir storage and the environmental flow requirement for each basin [94].

We quantify physical water scarcity as the ratio of water withdrawals to renewable water supply for each basin [95]. The fraction of water demand relative to available renewable surface water supply has also been labelled as the "water stress index" in previous studies [96]. To derive a single estimate per scenario, we compute the average of the water stress index weighted by the volume of renewable water withdrawal of each basin at base year (2015). The index is estimated with the following equation:

$$I_{i,t} = \sum_{b \in B} \frac{I_{i,t,b} \cdot W_{i,2015,b}}{\sum_{k \in B} W_{i,2015,k}}, \qquad [6]$$

Where

$$I_{i,t,b} = \frac{W_{i,t,b}}{S_{i,t,b}}.$$

I represents the water scarcity index per basin (dimensionless), W is the water withdrawal in km³, S is the renewable water supply in km³, B are the available basins, t the year, and i the scenario run.

To estimate the total Greenhouse Gas (GHG) emissions we converted all pollutants' emissions into global warming potentials (GWP) relative to CO_2 using the AR5 100-year time horizon values [97].

To estimate the outdoor air pollution premature deaths, we used **rfasst** [98], a global source-receptor air pollution model based on the chemical air quality model TM5-FASST [99]. This model provides fine particulate matter (PM2.5) and ozone (O_3) premature deaths from GCAM greenhouse gas and air pollutants concentrations.

GCAM associates a price to technologies. In the food sector, only staple and non-staple food goods have an associated price. Thus, we estimate the annual regional food expenditure of a median consumer by multiplying the total consumption by the cost for each year *t* and scenario run *i*:

$$FoodExpenditurePC_{i,t} = \sum_{fs \in foodStapleItems} ConsumptionPC_{fs,i,t} \cdot PricePCStaples_{i,t} + \sum_{fn \in foodNonStapleItems} ConsumptionPC_{fn,i,t} \cdot PricePCNonStaples_{i,t} \quad [7]$$

To meet the NDC-LTT mitigation policy we impose a carbon price on the energy system. This price is set to minimise the cost of mitigation. Consequently, it will increase the interest rate until the climate target is achieved. Once the target is met, the price adjusts to maintain the target and may fluctuate significantly [100].

In GCAM we denote **policy cost** [101] the sum of the price of carbon (needed to achieve the desired emissions mitigation goal) and the **deadweight loss** (which measures the welfare loss from emission mitigation efforts) [102].

5.3 Results

This section details the main results by protein-type scenario—SPP, SNR, and SPPNR—scenario pathway (GlobT and RegG), and region. The figures and values in the main manuscript show the median and the min-max interval of the total scenario ensemble unless specified otherwise. Detailed figures incorporating all the uncertainty dimensions are provided in the Supplementary Information (SI).

Nutritional impacts of shifting diets

A healthy diet ensures adequacy of health-promoting nutrients while avoiding harmful substances and nutrient excess [47]. To verify that the proposed dietary shifts meet this definition, we analyze the macronutrient and micronutrient consumption. The introduction of plant proteins (SPP and SPPNR) increases the global levels of fat, and especially protein, in the daily energy consumption (Figure 5-3.a). This rise in protein content results from a reduction in the cost of the food basket (Figure 5-6.a). When reducing the share of ruminants (SNR scenario), fat intake rises significantly more than protein intake due to the increased availability of high-fat protein sources (e.g., pork).

Protein and fat consumption are higher when shares are increased on a region-specific basis (RegG pathway) compared to a globally targeted common share (GlobT pathway) (Figure S9). As shown in Figure S10, the cumulative distribution functions for the GlobT pathway are consistently left-shifted and closer to the Reference. This is because regional efforts under the GlobT pathway are systematically lower since no dietary shift scenario can reduce the proportion of plant or non-ruminant protein suggested by the Reference scenario. Thus, some regions maintain constant diets in the GlobT pathway when already meeting the target values, reducing the diet shift median impact. For instance, Western Africa, with 64.1% plant protein intake in 2050 according to the Reference, sees no change in the spp-gt-10, spp-gt-20, ..., spp-gt-60 scenarios.

Regardless of the scenario pathway, all regions increase the protein intake under the three alternative scenarios (Figure S9), reflecting greater access to protein sources. However, under the SPP or SPPNR scenarios, some regions reduce the percentage of fat in the diet, such as Argentina or Brazil, as they shift away from pork-based diets, which have a high fat content.

Micronutrient intake remains globally largely unchanged (Figure 5-3.b, S13). As indicated in the literature, shifting to plant proteins lowers vitamin B12 [48, 49], folate [50], and zinc [51], while monogastric sources (SNR and SPPNR) reduce vitamin A due to the lower presence of ruminant products [52, 53] (Figure 3.b, S13). Increased legume intake boosts folate absorption. Calcium, vitamin D, and zinc intake remain below the reference nutrient intake [54] across all scenarios (Figure S13).

Reaching region-specific share increments (RegG pathway) impacts nutritional intake more than reaching a common share (GlobT pathway). In addition, the SNR scenario aligns most closely with Reference values, reflecting consistent animal protein consumption preferences and lower uncertainty (Figure S12).

Besides the nutritional quality of the food supply, it is important to verify the adequacy of the average dietary energy supply (ADESA) in relation to the average dietary energy requirement of the population. Ratios above 100 indicate a food supply surplus, while ratios below 100 indicate a deficit [55]. Our analysis reveals that the ADESA is directly influenced by food accessibility (Figure 5-6.a). Specifically, in the SPP and SPPNR scenarios, the cost of the food basket decreases, thereby increasing food availability and boosting the ADESA. However, under the SNR scenario, some regions face food expenditure challenges, reducing the ADESA (Figure 5-3.c). Notably, Pakistan's median ADESA falls below the energy minimum in the Reference scenario and declines further under the SNR. In this region, the low intake of monogastric proteins in the Reference scenario coupled with a sudden shift of preference for these proteins results in an increased cost of the food basket (Figure 5-6).

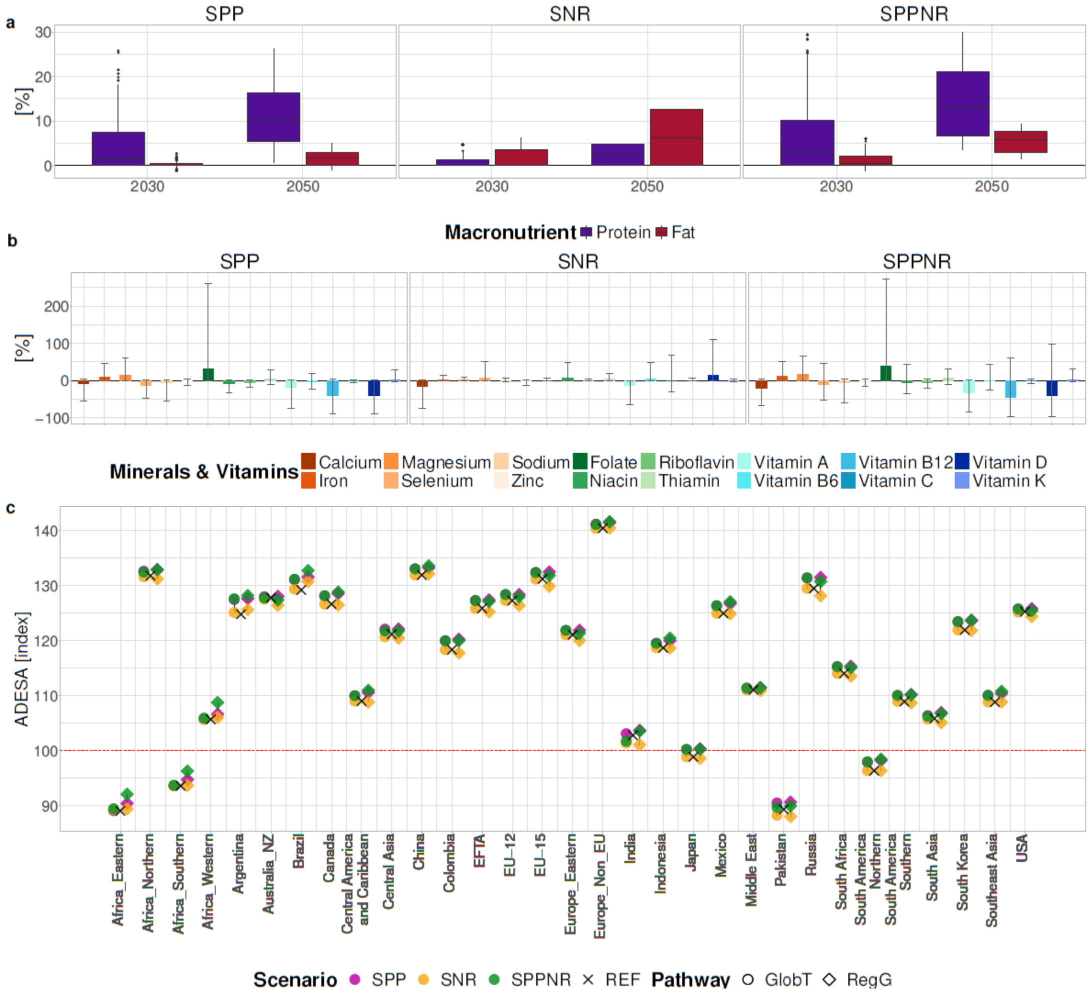

Figure 5- 3: a) Boxplot showing the percentage difference in macronutrient intake proportion of the diet by scenario compared to the Reference scenario globally (aggregated, population-weighted regional values) by year. b) Percentage difference to Reference for micronutrient global median consumptions in 2050 (aggregated population-weighted regional values) by scenario in 2050. Gray bars indicate the minimum and maximum intervals. Since values are very small, the percentual difference is very high. c) Median ADESA index by region, scenario type, and scenario pathway in 2050. The dashed red line represents the minimum energy requirement.

Implications of dietary shifts for biophysical systems

The food sector directly impacts land use management, water use, and GHG emissions. Focusing

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on the land-use system, under the SPP diets, there is a global reduction in cropland for feed and pasture for livestock, while natural lands such as forest, shrub, and grass areas increase (Figure 5-4.b). Cropland needed for age is larger 162 than that required for plant-based protein sources (i.e., nuts and legumes) [56]. The SNR scenario decreases pasture while increasing forest, cropland, shrub, and grass areas, due to the monogastric diet preferences (Figure 4.b). Ruminants require more grazing land, making them more reliant on grasses, forages, and other fibrous plants that grow on non-arable land [57]. In contrast, monogastric species depend more on grains and legumes, typically grown on arable land [58, 59]. Therefore, as monogastric meat production increases and ruminant meat production decreases, cropland use slightly rises, and pasture areas decrease rapidly (Figure 4.b). The combination of these scenarios (SPPNR) results in the most significant reforestation, especially in Eastern Africa (23.8%). In this area, the grazing pastures are percent-wise deeply reduced due to one of the heavier reductions in ruminant production. In contrast, the Middle East (-0.70%), Taiwan (-0.66%), South Africa (-0.30%), and South Korea (-0.28%) experience some forest area decline (Figure 4.a). In these regions, scarce water resources make unmanaged pastures more adaptable than forests.

Unmanaged land is also impacted by dietary changes, which has been traditionally used as an indicator of biodiversity [41]. As further analysed in Figure S15, all scenarios generally increase unmanaged land, except in regions with rising cropland for exports (e.g., Taiwan).

The SNR scenario is more susceptible to the scenario pathway (GlobT and RegG) (Figure S16, Figure S17). Indeed, pasture reduces globally to 1.2% under the GlobT pathway and to 9.8% under the RegG pathway, which leads to a 14% median difference in the global forest area (Figure S14). The reason for this is that the regional non-ruminant protein intake of the Reference scenario has a median of 49.3%, whereas the plant protein intake has a median of 12.2% (Figure S1). Therefore, the SPP scenario has more room than the SNR scenario to increase the target share and both pathways (GlobT and RegG) require regional efforts to meet the target plant-protein shares. On the contrary, under the SNR scenario, some regions will not modify their diet when following the GlobT pathway since their non-ruminant intake share already matches the target share. Thus, the RegG pathway has much more impact.

Water withdrawals decrease globally under all scenarios by 2050, with SPPNR showing the largest reduction (3.2%) compared to Reference (Figure S18). Monogastric and plant-based diets use water more efficiently than ruminants, resulting in reduced cropland and water demand [21, 60, 61]. This metric shows minimal uncertainty, as indicated by the linear cumulative functions across regions (Figure S19). Once more, the region-specific share modifications (RegG pathway) result in the highest water savings achievable (Figure S19), with its cumulative function surpassing that of the GlobT pathway.

While the SPP scenario increases the share of land types utilising rainfed water demand, the SNR scenario diminishes it and the SPPNR scenario barely changes the irrigated-rainfed land type ratio, as further discussed in Figure S20.

Water scarcity decreases everywhere under the SPPNR scenario (Figure 5-4.c). Similarly, the SPP scenario eases water scarcity everywhere except the Middle East, which significantly boosts its exports of legumes and nuts—two crops requiring irrigation in this region (Figure S21). Conversely, Argentina faces increased water pressure under the SNR scenario, driven by livestock exports (Figure 5-4.c). The African regions benefit the most from the RegG pathway (Figure S22) since they have some of the highest plant protein intake shares in the Reference scenario (Figures S4–S7).

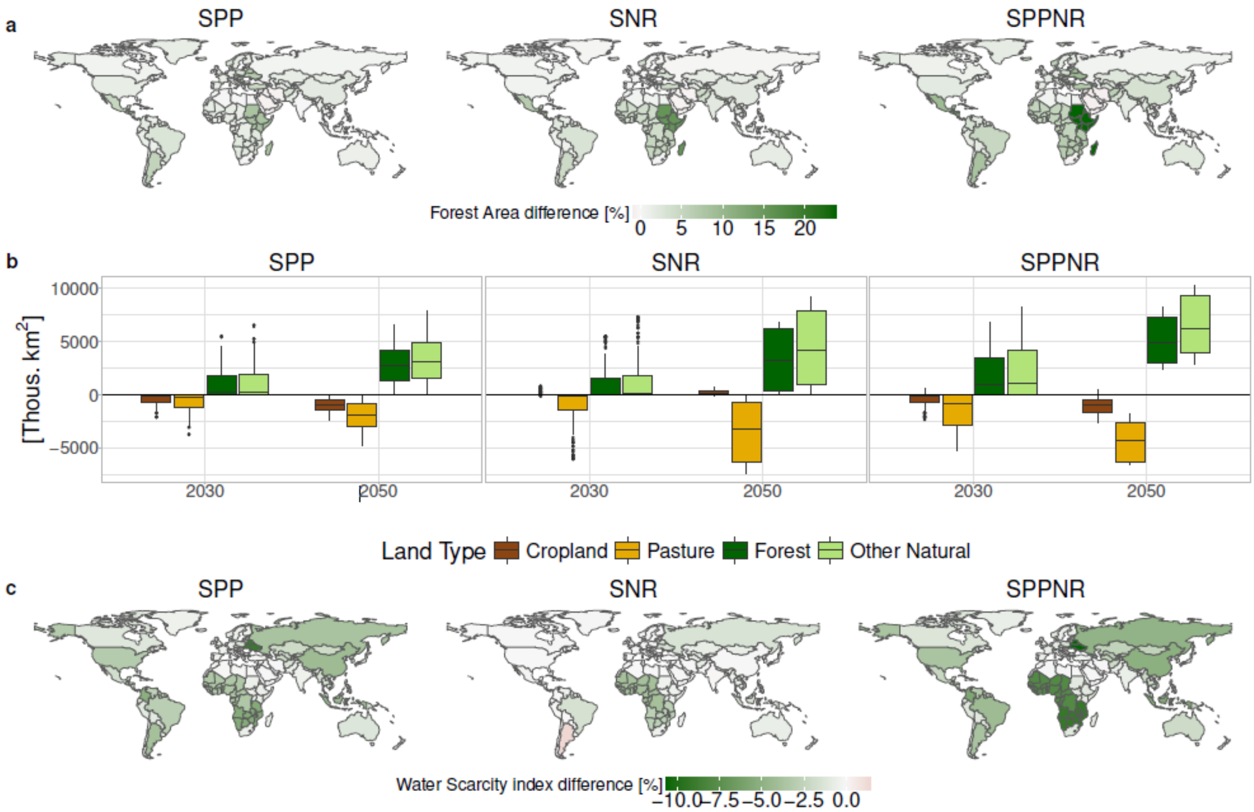

Figure 5- 4: Direct impact on SDG15 and SDG6. The maps represent the 32 GCAM geopolitical regions. a) Median percentage of forest area changes relative to Reference in 2050 by scenario. b) Boxplot showing the absolute difference in land type area by scenario compared to Reference globally by year in Thous. km2. c) Median percentage water scarcity index changes relative to Reference in 2050 by scenario.

All three scenarios reduce global GHG emissions (Figure S23). SPPNR reduces emissions especially in South America and Africa due to CH_4 and LUC CO_2 decreases from livestock and pasture reductions. N_2O emissions also drop as cropland shrinks (Figure 5.a, b, S25). Importantly, the LUC CO_2 reduction is more pronounced under the scenarios where ruminants are specifically lowered—SNR and SPPNR (Figure 5.b). In regional terms, India and Pakistan heavily reduce dairy production, which heavily diminishes their CH_4 emissions (Figure S25). The scenario pathway plays a crucial role in GHG reduction, leading to 89.6 $MtCO_2$ global differences in 2050 under the SNR scenario (Figure S25).

Beyond GHGs, pollutant emissions can increase the concentrations of fine particulate matter (PM2.5) and ozone (O_3), two of the main harmful air pollutants for human health [62, 63]. For the three scenarios considered, deaths are averted in all regions, especially in Argentina and countries of Europe, North America, and Oceania due to the reduction of nitrogen oxides (NO_x) (Figure 5.c), which is aligned with existing studies [32, 64]. O_3-induced mortalities are more responsive to the dietary scenarios than PM2.5-induced fatalities. Globally, O_3-related premature deaths are reduced by 5.6%, whereas PM2.5-related premature deaths are reduced by 1.56%. Thus, the regions where O_3 premature deaths represent a high percentage of the total premature deaths are more affected by the scenario pathway. For instance, Argentina and EU-12 reduce 38.4% and 34.9% of total premature deaths respectively when considering the RegG pathway instead of the GlobT one (Figure S26).

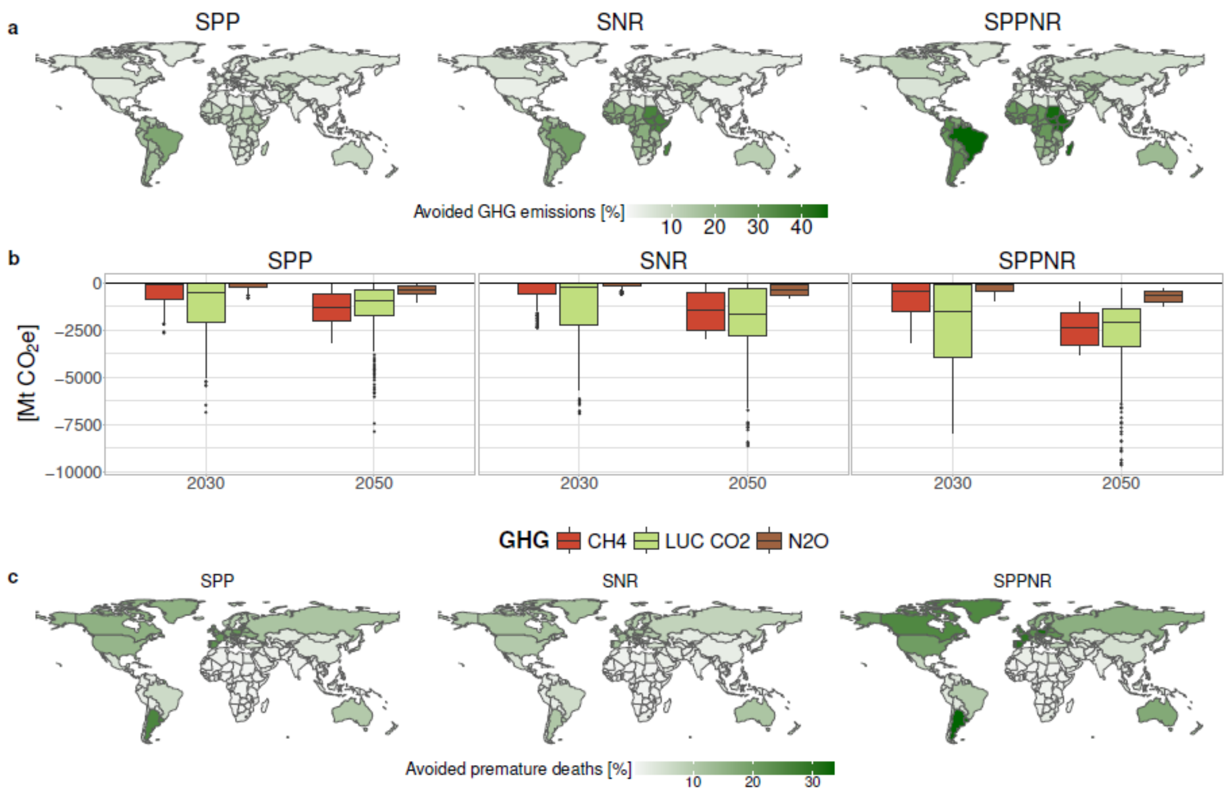

Figure 5- 5: Direct impact on SDG13 and indirect impact on SDG3. The maps represent the 32 GCAM geopolitical regions. a) Median percentage of GHG emissions avoided by scenario relative to the Reference in 2050, including CO2, non-CO2, and LUC emissions, expressed in Mt CO2 equivalent. b) Boxplot showing the absolute difference in GHG emissions by scenario compared to Reference globally by year in MtCO2 equivalent. c) Median percentage of premature deaths avoided by scenario relative to the Reference in 2050.

Implications of dietary shifts for the economy

Alternative dietary patterns influence land use and food prices [22]. Shifting to plant-based diets significantly lowers per capita food expenditure (Figure 5-6.a). However, reducing ruminant intake generally raises food prices (Figure 5-6.a), especially in regions like India and Pakistan, where ruminant protein intake is already low. These regions increase monogastric protein consumption (e.g., pork, poultry, fish), raising food basket costs. Regions like Russia and Australia-New Zealand face higher expenditures due to importing monogastric proteins. Under the SPPNR scenario, the reduction of the food expenditure of an average consumer comes with high uncertainty. In this scenario, all regions see reduced costs except for Australia-New Zealand, which needs significant nut imports. Since the RegG pathway shows a larger deviation in land use management compared to the Reference, positioning its cumulative function leftward, it also holds a greater difference in food costs than the GlobT pathway (Figure S27).

Beyond food costs, dietary shifts impact the total mitigation cost of achieving NDC-LTT climate goals. Since dietary changes reduce GHG emissions (Figure S24), they can be a valuable instrument for reducing abatement costs. Therefore, we evaluated all the 649 scenarios simulated in this study under the NDC-LTT mitigation policy to quantify the differences in policy costs (Table S2). Our findings indicate that all regions reduce the abatement costs across all scenarios and pathways, especially under RegG pathway, with extreme reductions of around 30% in Northern South America, Argentina, and Mexico under the SPPNR scenario (Figure 6.b, Figure S28). The SPPNR scenario, achieving the most GHG reductions, offers the greatest abatement cost savings. Moreover, the abatement cost probability distribution functions feature long left tails, indicating high potential for cost reductions (Figure S29). Notably, all scenarios under the RegG pathway consistently have greater median cost reductions than

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those under GlobT pathway (Figure S29), indicating that mitigation costs are lower in any RegG pathway scenario compared to any GlobT pathway scenario.

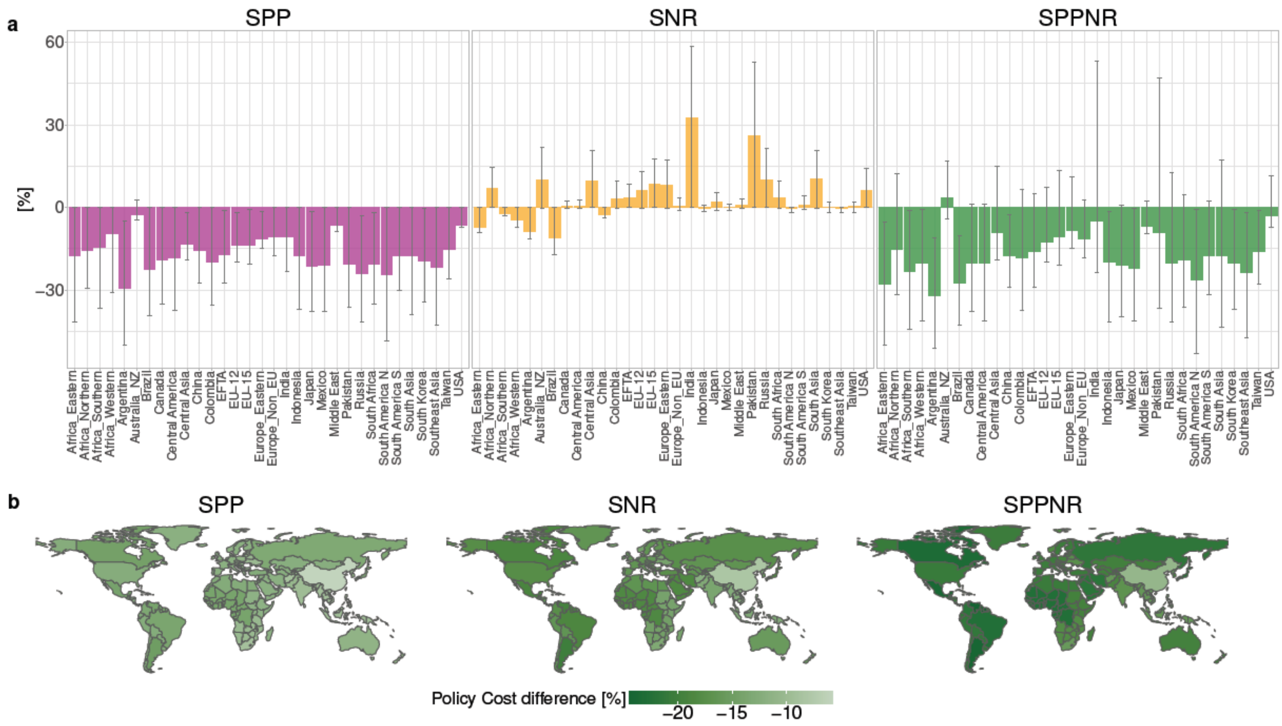

Figure 5- 6: Indirect impact on SDG2 and SDG13. The maps represent the 32 GCAM geopolitical regions. a) Percentage difference of per capita food daily expenditure relative to Reference in 2050 by scenario. Gray bars represent min-max intervals. b) Percentage policy cost difference relative to Reference in 2050 by scenario.

5.4 Discussion

This analysis has examined the system-wide impacts of dietary shifts under regional uncertainties, demonstrating that transitioning to sustainable diets delivers both environmental and socioeconomic benefits while reducing the mitigation costs of achieving the existing portfolio of climate policies and pledges, namely the NDCs and longer-term decarbonisation strategies. This aligns with existing studies that show the benefits of transitioning to more sustainable diets across various systems [15, 43, 65, 66, 67].

While several studies have explored the effects of dietary shifts, most have not considered the regional dietary specifications and the high uncertainty in the transition. In this work, we incorporate a wide range of uncertainties surrounding behavioural shifts and future scenario pathways, underscoring the critical role of regional efforts in maximising the environmental, social, and mitigation benefits of dietary changes. Expecting all regions to achieve identical protein shares is unrealistic due to diverse economic and cultural contexts. Instead, reflecting individualised regional efforts presents a more practical and regionally adapted solution. In particular, dietary change scenarios that consider individualised regional efforts led to a more significant reduction in mitigation costs compared to those under the global pathways. In addition, the large scenario ensemble modelled in this work improves the robustness of the results across various uncertainty factors, demonstrating that the benefits of behavioural changes hold steady regardless of the extent of the dietary shift, the timing of the transition peak, or the speed at which populations adopt new diets.

In addition, the integrated assessment modelling approach utilised in this study allows quantifying the multisector and multiscale implications of alternative dietary shifts on a wide range of dimensions that represent alternative SDGs [68]. We find that sustainable dietary patterns are nutritionally beneficial. In line with earlier findings, these patterns increase global protein and fat intake while diversifying micronutrient absorption and reducing the food basket bill, easing inner regional inequalities [49, 50, 67, 69, 70, 71, 72]. In terms of environmental co-benefits, our analysis also shows a global increase in forest areas and unmanaged lands, with the latter serving as a proxy for biodiversity improvement. Expanding natural lands and reducing crop areas lead to lower overall water consumption, while shifting to plant-based proteins enhances the rainfed-to-irrigated water ratio, alleviating water scarcity. These findings align with previous research [41, 43, 61, 73, 74, 75]. Moreover, the land-use changes resulting from dietary shifts contribute to widespread reductions in GHG emissions, as noted by recent studies [32]. This, in turn, improves human health by reducing premature deaths caused by outdoor air pollution, particularly those linked to O_3 emissions.

The modelling framework used has some limitations, which are outlined in the SI (Section S1.1). For example, using multiple consumers instead of a single representative consumer could offer a more nuanced understanding of within-country disparities. By capturing these differences, the model could provide a clearer picture of how dietary shifts impact vulnerable populations. Likewise, considering the upstream emissions in food processing and transport will produce more accurate estimates of CO_2 emissions, capturing more precise estimations of the environmental impacts of dietary changes.

Despite the limitations, this study offers timely and valuable insights for both the scientific community and different global and regional stakeholders. While the evolution of dietary patterns is not systemically considered in IAM-based studies, this study demonstrates that their inclusion can considerably influence results. Indeed, considering potential dietary changes could have influenced the outcomes of previously published research. Likewise, behavioural or demand-side measures have been identified as key mitigation measures for IPCC and global change analysis [3, 43]. Our results add to this literature, underscoring the need for effective social policies to promote dietary transitions toward plant-based and low-ruminant diets, which is at the heart of the political debate. This study demonstrates that in order to craft effective dietary strategies that produce environmental and socioeconomic co-benefits within the region, the policies must account for their unique circumstances, developing strategic plans to mitigate water scarcity and alleviate food price increases.

5.5 Code and data availability

The analysis has been developed using an enhanced version of the Global Change Analysis Model, which is an open-source model available in an online repository: https://github.com/JGCRI/gcam-core. The repository includes all the data, assumptions, and parameters that are read in by the model.

A detailed documentation for all these input assumptions can be found in the following open-access repository: https://github.com/JGCRI/gcam-doc. The version of the model used for the analysis is accessible in the following repository: https://github.com/klau506/gcam-core/tree/gcam_v7.0p_diets.

The code for reproducing the results and generating the figures has been stored in an open-access repository: https://github.com/klau506/implications_sustainable_diets, whose data is available in Zenodo: https://zenodo.org/records/13993989.

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6. Projecting progress in Sustainable Development Goals vis-à-vis climate action in climate-economy models

Nikas A (2024) Projecting progress in sustainable development goals vis-à-vis climate action in climate-economy models[8]. PLOS Clim 3(7): e0000449. https://doi.org/10.1371/journal.pclm.0000449

6.1 Introductory comments

The year 2015 was an important milestone in the world's struggle for sustainability. Although mostly remembered for the landmark Paris Agreement, which formalised and operationalised a mechanism for globally coordinated and cooperative efforts to address the climate crisis, it also featured the UN-wide adoption of the 2030 Agenda for Sustainable Development, embodied in seventeen distinct yet highly intertwined dimensions—the Sustainable Development Goals (SDGs). These *inter alia* include poverty and hunger elimination, alleviating social and gender inequalities, fostering peace and the development of strong institutions, making production responsible, environmental and biodiversity protection, and achieving good health and well-being.

The scientific community has since attempted to actively support the assessment of progress and prospects/trends towards sustainability using an array of tools as interdisciplinary and diverse as the SDG agenda itself. When it comes to quantitatively assessing progress per SDG indicator by country and/or globally, scientists have drawn on the latest available data to estimate the gap in achieving each SDG indicator (e.g., [1]). However, such studies are mostly static and capture an overview of how far we still need to go; in other words, they are not forward looking in that they cannot project where each country (or the world) is headed along each SDG towards 2030 or later, or what needs to be done to bridge the identified gaps.

To address this need, climate-economy models—i.e., the quantitative systems models typically used to evaluate or support the design of climate policies, also called Integrated Assessment Models (IAMs)—have increasingly been used to offer quantified projections of SDG progress into the future, in tandem with mitigation effort [2]. This is largely for two reasons: (a) climate action (SDG13) has long been documented to interact vividly with all other SDGs [3], and (b) these models have been found well-equipped to extract insights into SDG-related metrics among their numerous quantitative outputs [4] as well as into the interactions of climate action and other SDGs [5].

6.2 Getting the most of climate-economic models in projecting SDG progress

This piece discusses six ways, in which the capacity to evaluate progress in SDGs vis-à-vis efforts to mitigate climate change using IAMs is currently being enhanced to offer robust and actionable policy prescriptions that may place climate policy in a holistic sustainable development context.

First, considerable efforts have been made to facilitate the extraction of insights from IAM exercises, by mapping SDG indicators onto typical IAM variables [6]. Modellers can thus employ, build on, and even expand on this formalised target space to provide standardised outputs that can be inter-compared in the literature. However, the coverage of the established SDG target space in IAMs remains limited, while many of the identified indicators are only proxies of a subset of the official SDG spectrum, and issues of scalability, inter-dependencies, or underdeveloped modelling capacity may pose challenges.

[8] https://zenodo.org/records/12760230

Especially regarding the latter, a second line of research lies in developments and instrumental upgrades in IAMs themselves. There currently exists a large ecosystem of IAM development research and innovation projects (such as DIAMOND, PRISMA, WorldTrans, TRANSIENCE, etc.), all tasked with creating new and mostly open-source capacities in existing or new IAMs, with explicit considerations for assessment of SDG-related progress. Despite the promise lying within this ecosystem of research initiatives, the envisaged updates do not markedly stray from the state-of-the-art modelling practice in that they are mostly incremental; the need to achieve SDGs already by 2030 is not well aligned with the lifecycle of these projects (most of which span until the latter half of this decade) and thus the timeline of the expected IAM upgrades; while IAM developers' perceptions of the need to expand SDG coverage capacity appears anchored to the existing capabilities of their models [7].

A third prospect lies in developing customised IAM frameworks, based on soft links between IAMs and other modelling tools, to enhance the representation of SDG indicators beyond IAMs' typical output variables. Even though such efforts enable scientists to cover an impressive diversity of the SDG spectrum (e.g., [8]), the coverage of (sub-)indicators within each SDG remains limited.

Similarly, a fourth line of research employs integrated modelling frameworks, either in model inter-comparison settings where different IAMs are employed in parallel to increase the robustness of and confidence in resulting model insights (e.g., [9]), or in multi-model settings in which several IAMs, sectoral models, and/or other modelling tools are soft-linked with one another to expand the aggregate capability to represent different SDGs (e.g., [10]). However substantial, the benefit of this approach in terms of larger coverage of SDG indicators does not expand the SDG coverage by orders of magnitude and comes at the price of extensive harmonisation efforts across the employed models to reduce response heterogeneity—which is in itself challenging [11].

Critically, none of these routes escape the limitations of the 'job description' of an IAM, which usually is to quantify the cost-optimal way of achieving a climate (policy) objective. To move from the decarbonisation-oriented accounting of SDG progress in IAMs onto the optimisation of progress in SDGs, a fifth avenue lies in economically integrating (internalising) SDG progress within the least-cost, environmentally constrained IAM solution process, by means of hard links between IAMs with other modelling tools (e.g., [12]). This practical way of optimising SDG performance also comes at a high price in terms of development efforts and resources; most importantly, it also implies a focus on a particular SDG.

Along these lines, a final approach to identifying optimal portfolios that optimise climate action in parallel with performance in other SDGs includes establishing soft links between IAMs and multi-objective optimisation algorithms [13]. Although such approaches help to identify policy portfolios that achieve simultaneous progress in the SDG agenda, by maximising co-benefits and minimising trade-offs of mitigation with other SDGs (e.g., [14]), its potential in building on all above ways to boost the internal capabilities of IAMs to represent SDG indicators is severely constrained by the number of indicators that can be meaningfully selected to avoid computational challenges associated with multi-objective optimisation.

6.3 Concluding remarks

Linkages between mitigation pathways and progress in SDGs permeate—and are systematically assessed in a dedicated chapter of—the entire 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) on climate change mitigation [15]. There is no doubt that the trend of projecting SDG progress in tandem, and/or quantifying SDG interactions, with climate action will consume increasing chunks of the IAM community's research efforts onwards. This will also be reflected in the scenario literature underpinning the IPCC's upcoming 7th Assessment Report that is expected by the end of this decade—just in time to stocktake SDG progress against the original timeline of the UN's Agenda for Sustainable Development and inform the way forward. The IAM community should collaborate on progressing along—and combining efforts in—all six avenues discussed.

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ANNEX I: Section 1 – SDG coverage in IAM COMPACT models

Table AI- 1: List of indicators included in the IAM COMPACT-SDG-Coverage template

Cluster	SDG	Indicator	Units
People	SDG1	1.2.1. Number of people living under extreme poverty conditions	%
		Food expenditure share	%
		1.5.2. Climate Change damage on capital stock	**M$**
		1.A.2. Proportion of total government spending on social services	**%**
	SDG3	Healthy life expectancy	yr
		3.2.1. Under-5 mortality rate	%
		3.9.1. Disability adjusted life years lost from PM 2.5	DALYs/yr
		3.7.2. Adolescent birth rate	**%**
	SDG4	4.6.1. Share of people >15 w/o education	%
		4.1.2 Completion rate (primary education, lower secondary education, upper secondary education)	%
		4.5.1. Global Gender Parity Index	**dmnl**
	SDG5	Education gender gap in (a) secondary education; and (b) primary education	%
		Female estimated earned income over male	%
Prosperity	SDG8	GDP/capita compared to average OECD GDP/capita	%
		8.1.1: Annual growth rate of real GDP per capita	%
		8.5.2. Unemployment rate	%
		8.2.1. Annual growth rate of real GDP per worker	**%/worker**
		8.4.1. Material footprint per capita and/or per GDP	**kg/cap & kg/$**
		8.5.1. Average wage hour	**$/h**
		8.9.1. Share of tourism in GDP	**%**
		Employed people by skill level	**People**
	SDG9	Industry Clean Energy (Share od FE provided by hydrogen/electricity in industry)	%

		Direct CO_2 emissions from industry	Gt CO2/yr
		9.4.1. Private and government-financed gross domestic R&D expenditure (GERD) in per cent GDP	%
		Proportion of people using the internet	%
		Proportion of adult people with access to financial services	%
		Travel time to the nearest city	h
		9.1.2. Volume of passenger in transport	**%**
		9.2.1. Manufacturing value added as a proportion of GDP and per capita	**% & $/cap**
		9.2.2. Manufacturing employment as a proportion of total employment	**%**
	SDG10	Average income of bottom 40% relative to national average	%
		10.1.1. Proportion of income received by the 20% of the population living in the richest households	**%**
		10.4.1. Labour compensation share	**%**
		GINI GDP per capita Index	**dmnl**
	SDG11	11.6.2. Share of people exposed to annual average PM2.5>25 µg/m3	%
		11.1.1. Number of people living in slums	%
		11.3.1. Ratio of land consumption rate to population growth rate	**%**
Planet Integrity	SDG13	13.2.2. GHG emissions	Gt CO_2-eq/yr
		Global Mean Temperature increase according to Paris Goals	ºC
		Cumulative CO_2 emissions	$GtCO_2$/yr
		Cumulative CO_2 removal by means of bioenergy with carbon capture and storage	Gt CO_2/yr
		Cumulative land-use change emissions	Gt CO_2/yr
	SDG14	Aragonite saturation state	dmnl
		Saturation state of calcite	dmnl
		Phosphorous flow from freshwater systems into the ocean	Mt/yr
		14.2.1. Proportion of fish stocks within biologically sustainable levels	%

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Sustainable Resources		14.3.1: Average marine acidity (pH) measured at the surface	dmnl
		Net primary production of biomass in oceans	Gt/yr
		New production of biomass in oceans	Gt/yr
	SDG15	Industrial and intentional biological fixation of N	Mt/yr
		Biodiversity Intactness Index	ha
		15.1.1: Forest area as a proportion of total land area	%
		Primary forests as share of total terrestrial land area	%
		Land area afforested	km^2/year
		Global area of forested land as % of original forest cover	km^2/year
		15.2.1. Index of forest stock per area	**dmnl**
		15.2.2 Index of forest area	**dmnl**
		15.3.1. Proportion of land that is degraded over total land area	**%**
	SDG2	2.2.2. Prevalence of underweight in (a) total population; and (b) children	%
		2.2.2. Prevalence of overweight in (a) total population; and (b) children	%
		2.2.2. Prevalence of obesity in children	%
		Food availability	kg/cap·day
		Agricultural commodity price index	dmnl
		2.4.1. Proportion of agricultural area under productive and sustainable agriculture	**%**
		2.c.1. Indicator of food price anomalies	**dmnl**
		Food production by commodity\country	**Mt/yr**
	SDG6	Agricultural water use	km^3/yr
		Fertiliser use	Mt/yr
		Nitrogen surplus on cropland	Mt/yr
		Water consumption for electricity	km^3/yr
		6.1.1. Population without access to improved water source piped	%
		6.2.1. Population without access to improved sanitation facility	%

		Area under water stress	%
	SDG7	Useful energy buildings & mobility	GJ/cap·yr
		Useful energy per capita for passenger transport.	GJ/cap·yr
		Useful energy per capita for buildings	GJ/cap·yr
		7.1.1. Population without basic electricity access	%
		7.1.2. Energy obtained from traditional biomass combustion in buildings	%
		7.2.1. Share of electrified Final Energy	%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	%
		Final energy intensity	MJ/$
		Projections on new solar PV capacity additions by households/citizens in a monthly resolution	**W/cap**
	SDG12	Food waste per capita & day	kcal/cap·day
		12.2.1. Agricultural material footprint (biomass usage per capita)	t/cap
		Municipal material recovery	t/yr
		12.5.1. Recycling rate	**%**
		12.a.1. Installed renewable energy-generating capacity per capita	**W/cap**
Peace, Institutions & Implementation	SDG16	16.1.2. Share of battle-related deaths and fatalities from violence	%
		Equality before the law and individual liberty index	dmnl
	SDG17	Net international climate finance	$/yr
		17.1.1. Total Government Revenue	M$
		Member of international NGOs	People
		17.11.1. Share of exports in GDP	**%**

ANNEX II: Section 4.4 – CLEWs supplementary results

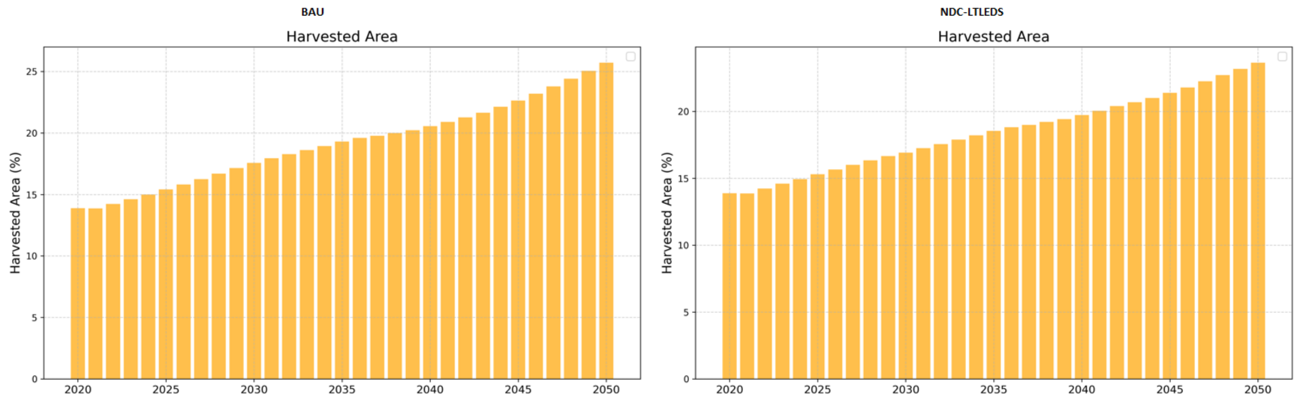

Figure AII 1: Harvested area - CLEWs Ethiopia

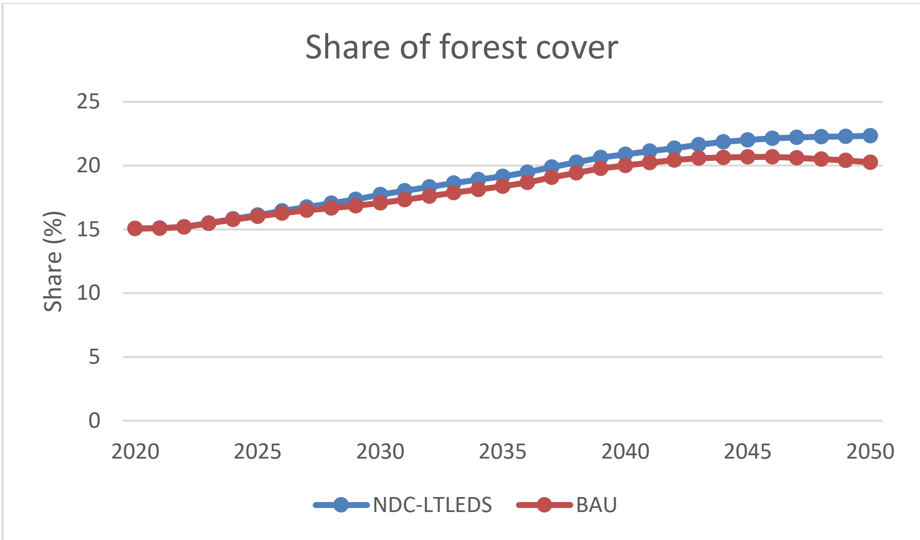

Figure AII 2: Share of forest cover - CLEWs Ethiopia

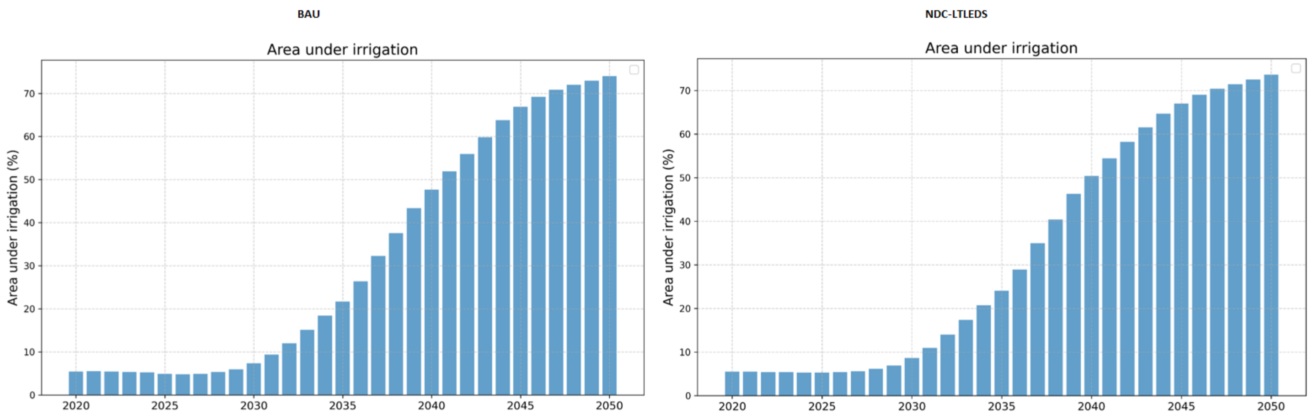

Figure AII 3: Share of irrigated land with respect to all harvested area - CLEWs Ethiopia

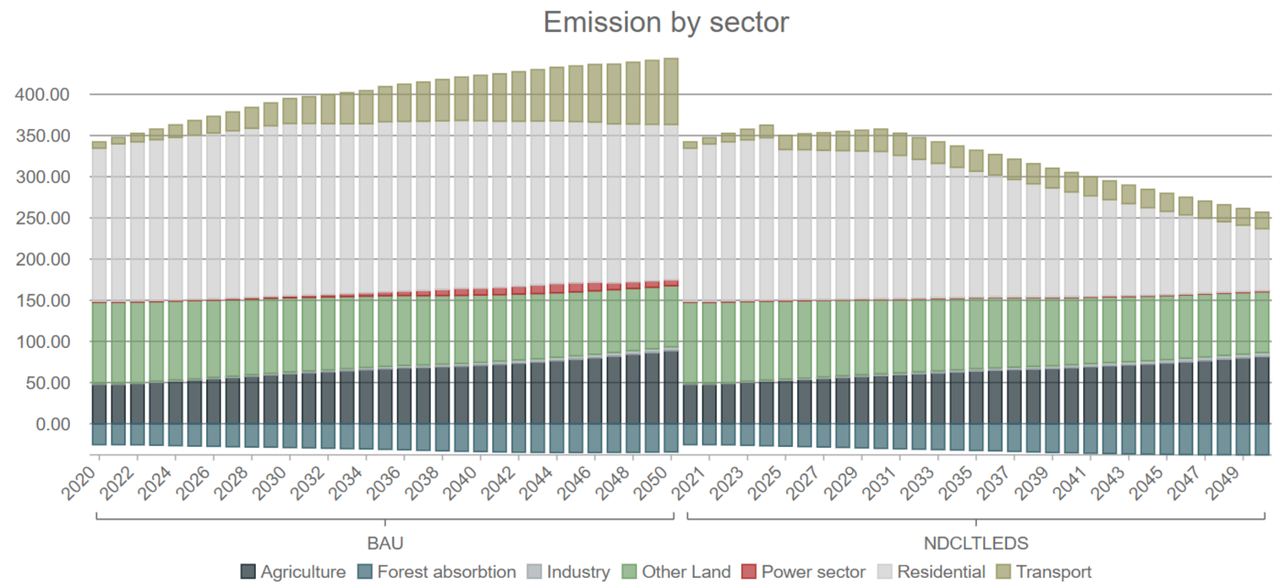

Figure AII 4: Mton of CO2 equivalent emissions by sector - CLEWs Ethiopia

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Annex III: Section 5 – Supplementary information

DietspapersianonymSUBMITTED.pdf

Methodology

Source: https://jgcri.github.io/gcam-doc/common_assumptions.html

Table AIII- 1: Mapping from GCAM region to countries.

GCAM Region	Countries
Africa_Eastern	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Sudan, Somalia, Uganda
Africa_Northern	Algeria, Egypt, Western Sahara, Libya, Morocco, Tunisia
Africa_Southern	Angola, Botswana, Lesotho, Mozambique, Malawi, Namibia, Swaziland, Tanzania, Zambia, Zimbabwe
Africa_Western	Benin, Burkina Faso, Central African Republic, Cote d'Ivoire, Cameroon, Democratic Republic of the Congo, Congo, Cape Verde, Gabon, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Sao Tome and Principe, Chad, Togo
Argentina	Argentina
Australia_NZ	Australia, New Zealand
Brazil	Brazil
Canada	Canada
Central America and the Caribbean	Aruba, Anguilla, Netherlands Antilles, Antigua & Barbuda, Bahamas, Belize, Bermuda, Barbados, Costa Rica, Cuba, Cayman Islands, Dominica, Dominican Republic, Guadeloupe, Grenada, Guatemala, Honduras, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Montserrat, Martinique, Nicaragua, Panama, El Salvador, Trinidad and Tobago, Saint Vincent and the Grenadines
Central Asia	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan, Uzbekistan
China	China
Colombia	Colombia
EU-12	Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Slovakia, Slovenia
EU-15	Andorra, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Greenland, Ireland, Italy, Luxembourg, Monaco, Netherlands, Portugal, Sweden, Spain, United Kingdom
Europe_Eastern	Belarus, Moldova, Ukraine
European Free Trade Association	Iceland, Norway, Switzerland
Europe_Non_EU	Albania, Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, Serbia, Turkey
India	India
Indonesia	Indonesia
Japan	Japan
Mexico	Mexico
Middle East	United Arab Emirates, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Yemen
Pakistan	Pakistan
Russia	Russia

GCAM Region	Countries
South Africa	South Africa
South America_Northern	French Guiana, Guyana, Suriname, Venezuela
South America_Southern	Bolivia, Chile, Ecuador, Peru, Paraguay, Uruguay
South Asia	Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives,
Southeast Asia	American Samoa, Brunei Darussalam, Cocos (Keeling) Islands, Cook Islands, Christmas Island, Fiji, Federated States of Micronesia, Guam, Cambodia, Kiribati, Lao Peoples Democratic Republic, Marshall Islands, Myanmar, Northern Mariana Islands, Malaysia, Mayotte, New Caledonia, Norfolk Island, Niue, Nauru, Pacific Islands Trust Territory, Pitcairn Islands, Philippines, Palau, Papua New Guinea, Democratic People's Republic of Korea, French Polynesia, Singapore, Solomon Islands, Seychelles, Thailand, Tokelau, Timor Leste, Tonga, Tuvalu, Viet Nam, Vanuatu, Samoa
South Korea	South Korea
Taiwan	Taiwan
USA	United States

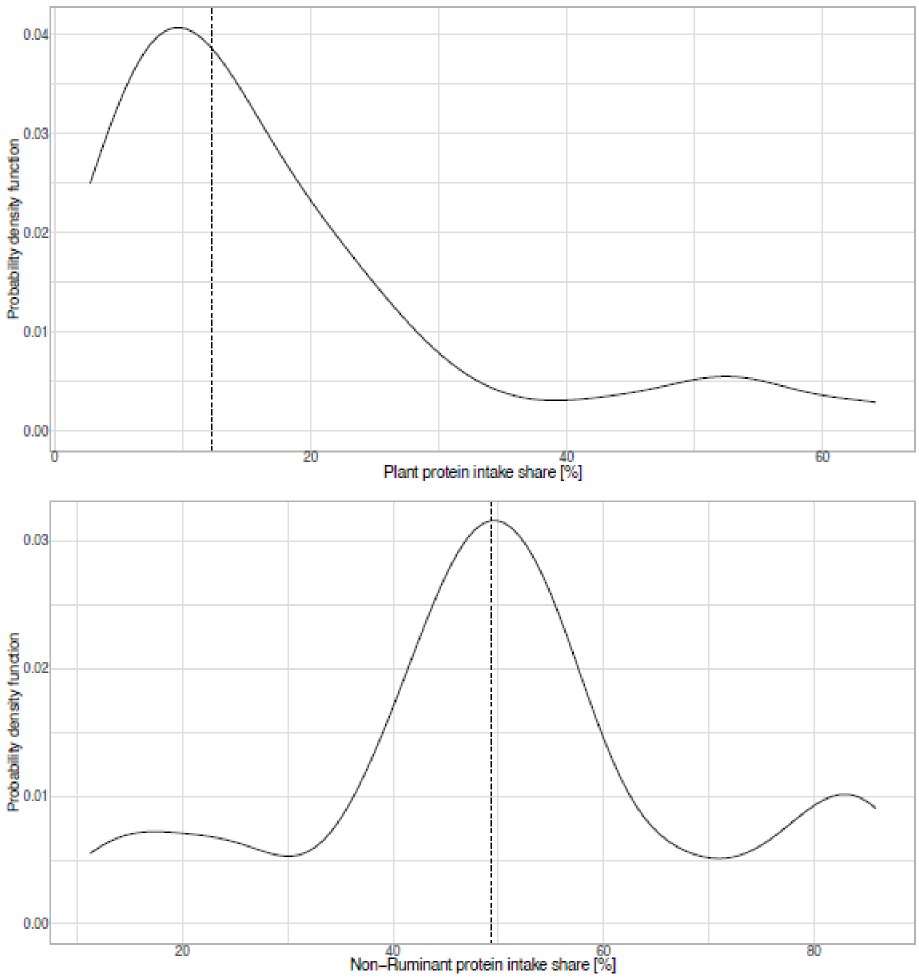


Figure S- 1: Probability density plots of regional plant protein shares (from the total protein intake) and ruminant protein shares (from the animal protein intake) in 2050 following the Reference scenario. The dashed line indicates the median.

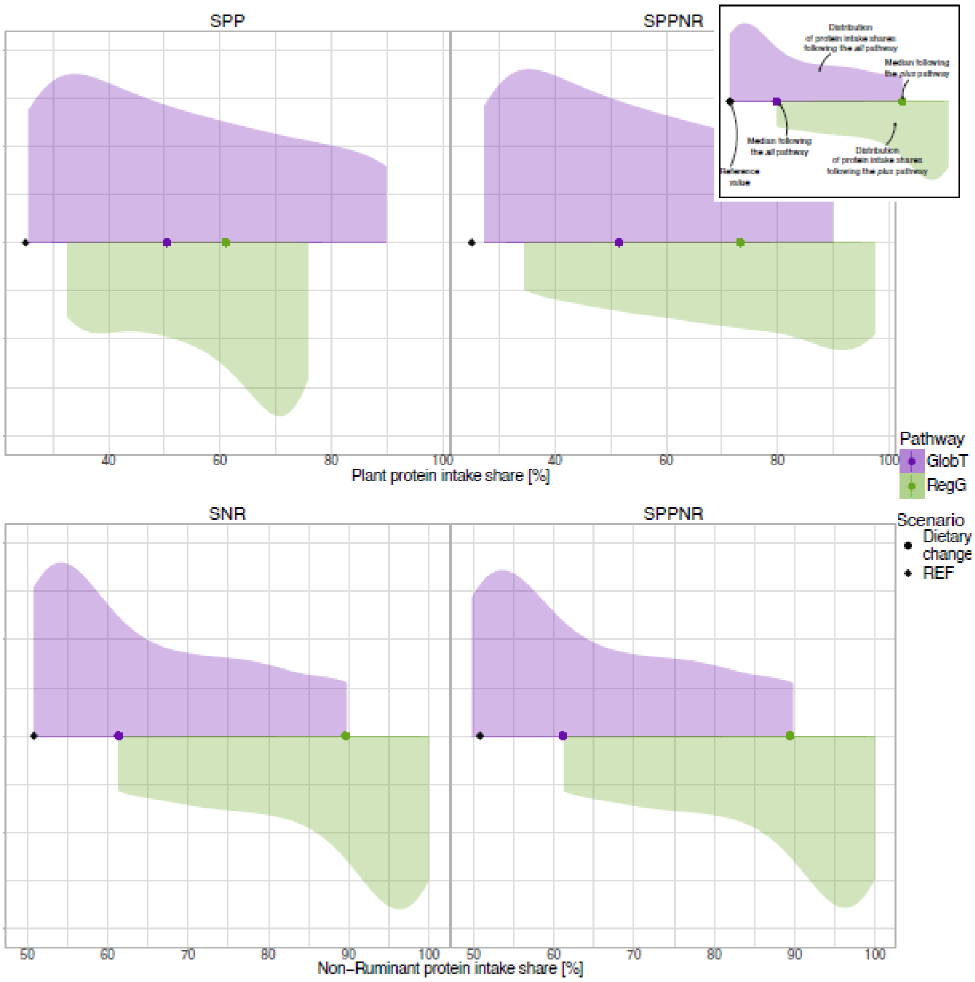
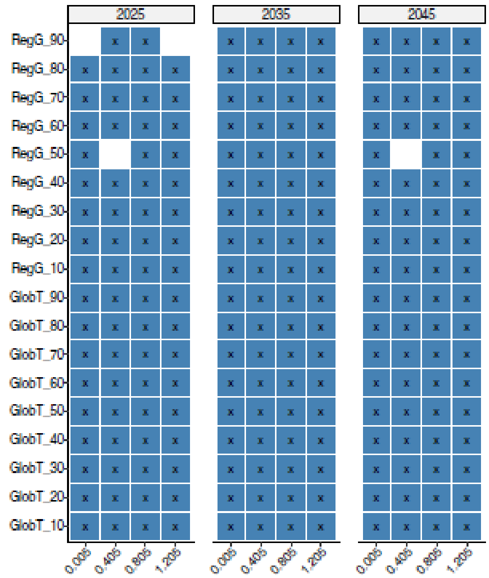
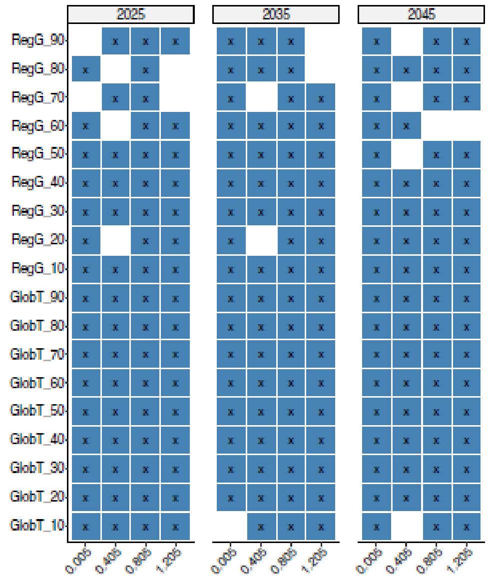


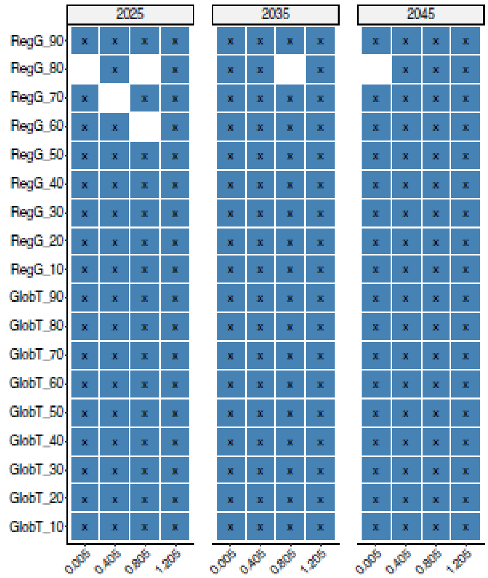
Figure S- 2: Distribution-density plots of global plant and ruminant protein intake share plant protein shares (from the total protein intake) and ruminant protein shares (from the animal protein intake) in 2050 by scenario and pathway.



(a) Runs under the SPP protein type scenario.



(b) Runs under the SNR protein type scenario.



(c) Runs under the SPPNR protein type scenario.

Table AIII- 2: Overview of the scenarios under the NDC-LTT mitigation policy by peak year (top), slope (bottom), pathway-target share (right), and scenario protein type: a) SPP, b) SNR, and c) SPPNR. 'x' indicates that the scenario was run successfully and an empty cell indicates that the scenario was not attainable7 by GCAM.

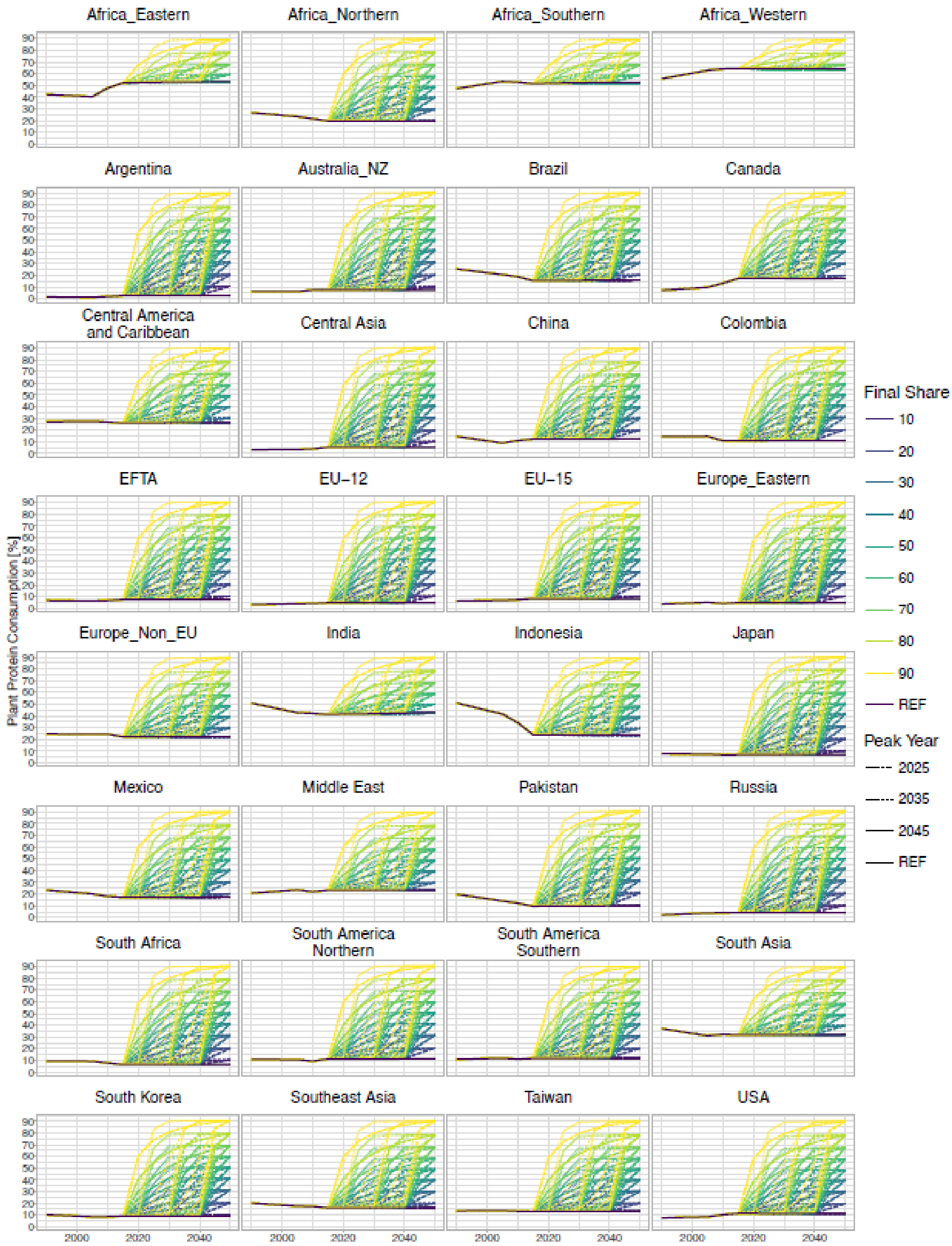


Figure S- 3: Regional annual plant protein consumption under the SPP scenario and the *all* pathway.

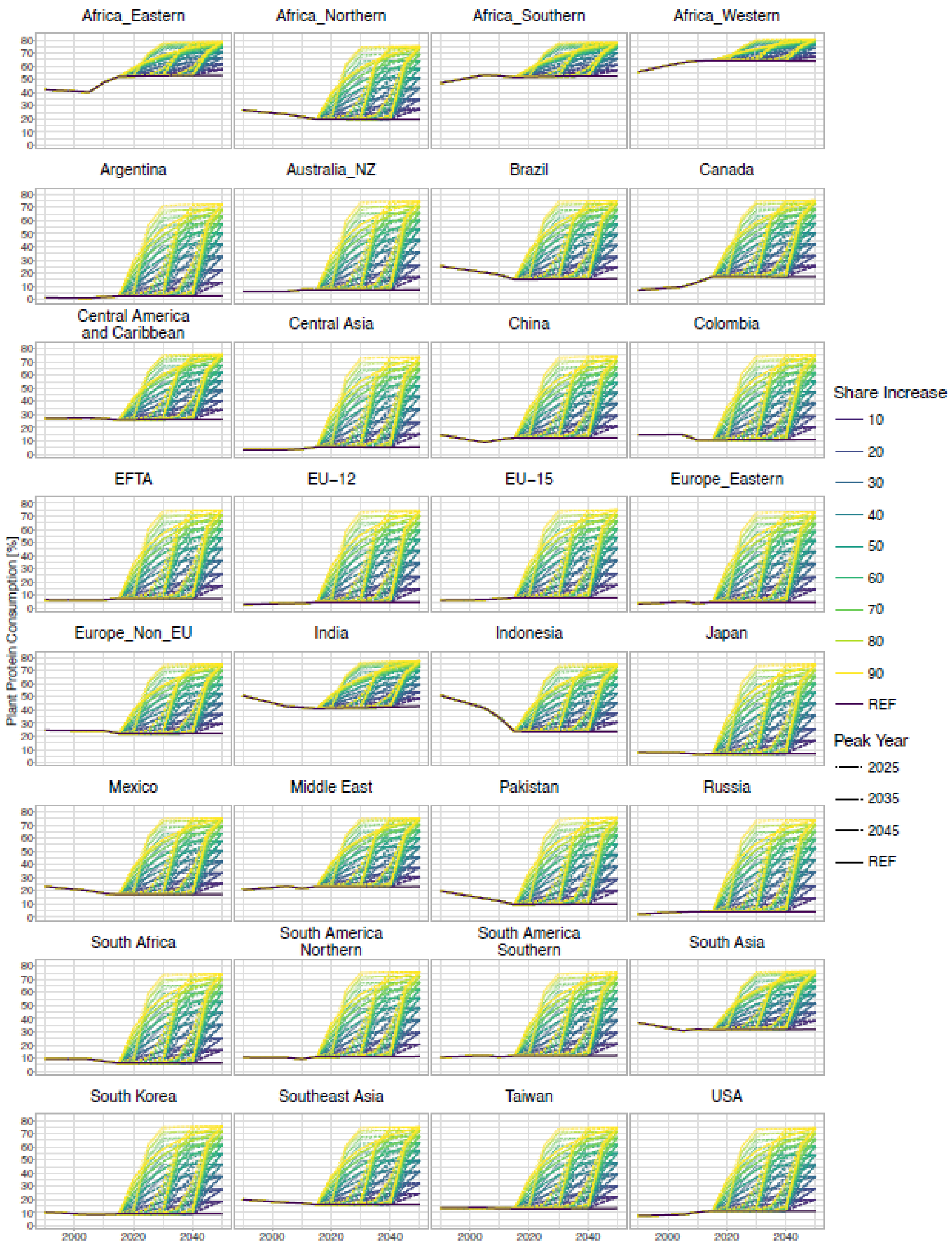


Figure S- 4: Regional annual plant protein consumption under the SPP scenario and the *plus* pathway.

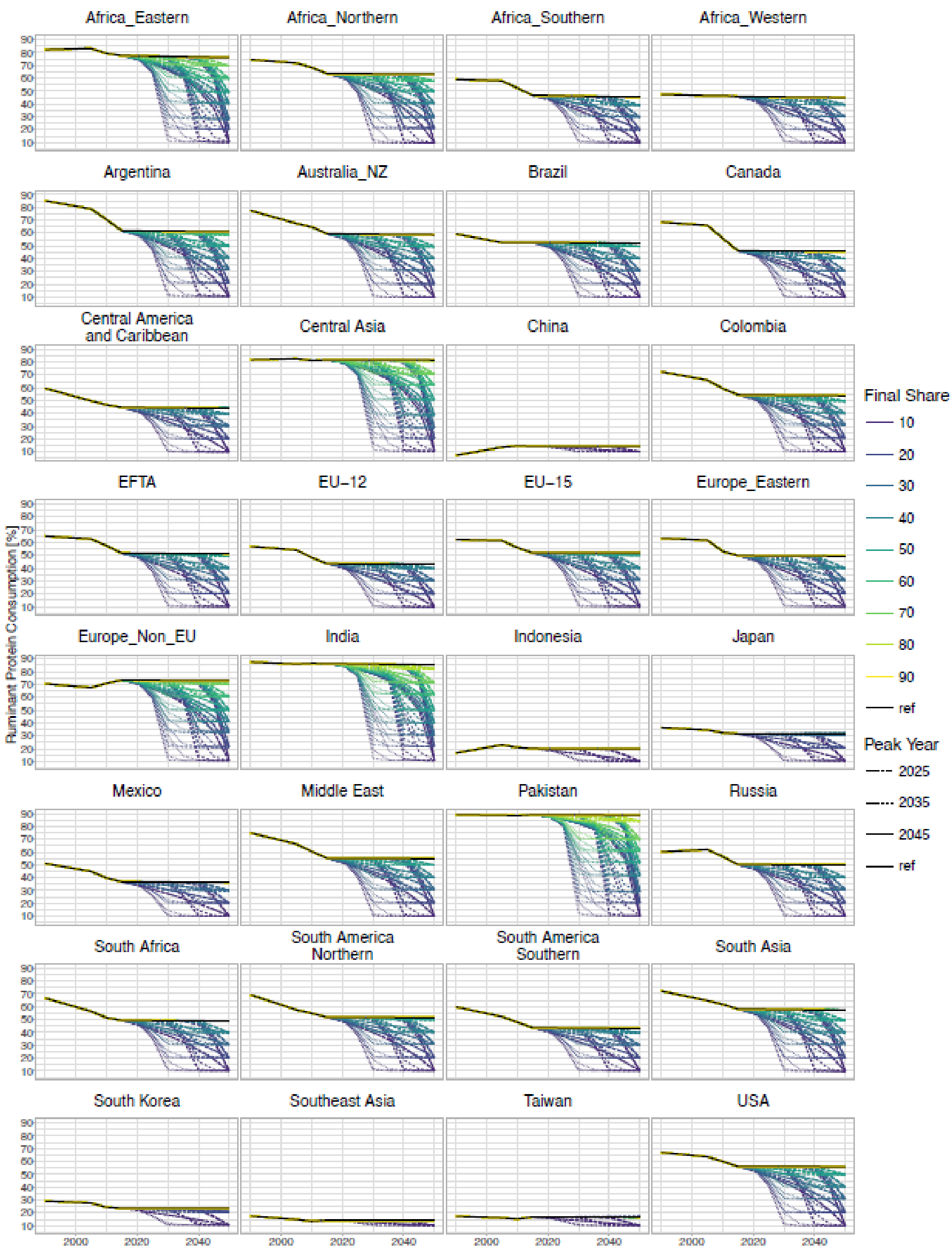


Figure S- 5: Regional annual ruminant protein consumption under the SNR scenario and the *all* pathway.

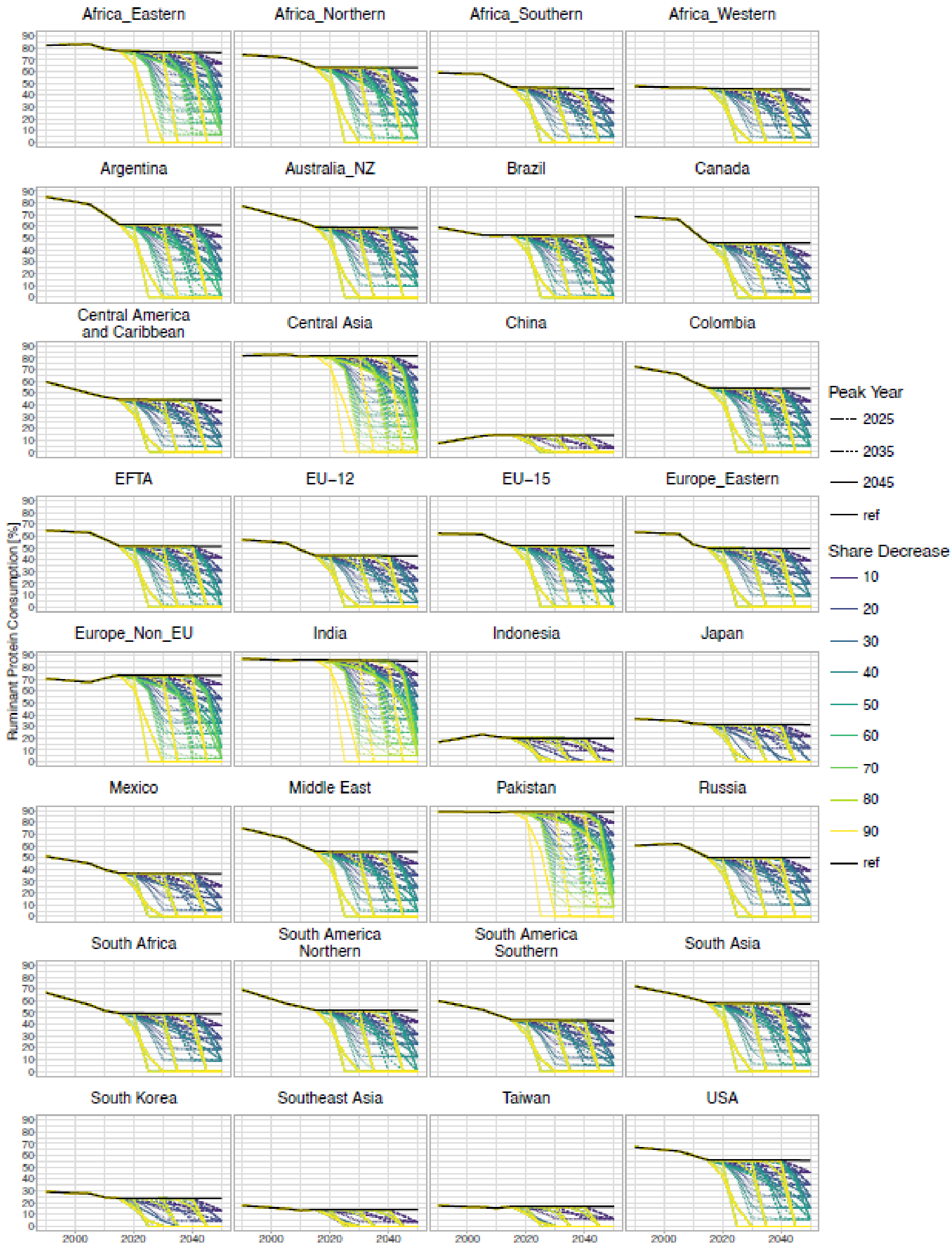


Figure S- 6: Regional annual ruminant protein consumption under the SNR scenario and the *plus* pathway.

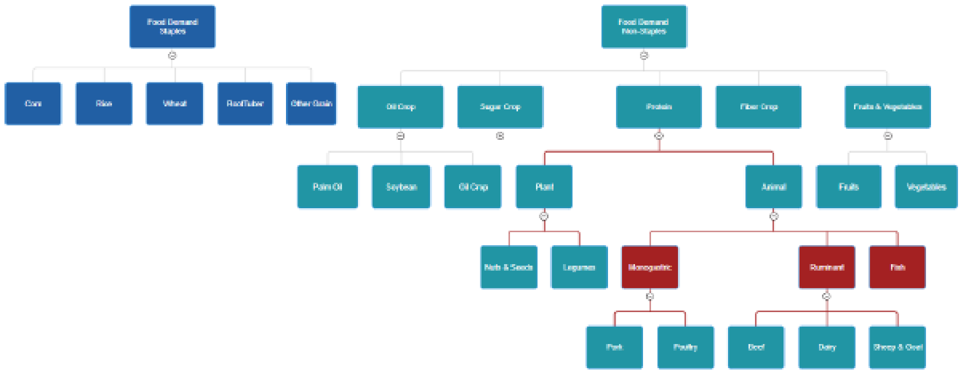


Figure S- 7: Staple & Non-staple food nesting structure. Red items emphasise the new nesting level added in our GCAM version.

Study limitations

There are several limitations to the current modelling framework that future re-search should address to improve the accuracy and scope of its projections. First, the treatment of uncertainty within the model could be significantly expanded. At present, the analysis may not fully capture the range of possible outcomes or the sensitivity of the model to various assumptions. A more robust exploration of uncertainty could help identify the key drivers of dietary changes across different regions, revealing how these factors may evolve under various future scenarios. Such an approach would also allow for a more detailed understanding of how shifts in diets are influenced by factors like policy interventions, economic changes, and consumer preferences, offering a more comprehensive risk assessment of different pathways.

Moreover, one important limitation is the reliance on regional averages for understanding consumption patterns. While these averages provide useful insights at a broad scale, they may obscure significant internal dynamics and inequalities. Incorporating multiple consumer profiles into the model would offer a more nuanced understanding of within-country disparities. This is particularly relevant in regions with high levels of inequality, where food access, affordability, and preferences can vary widely between different socio-economic groups. By capturing these differences, the model could provide a clearer picture of how dietary shifts impact vulnerable populations, helping policymakers design more targeted and equitable interventions.

Another significant limitation is that the current version of the GCAM model does not account for emissions from food processing or transportation. This omission likely explains why the model shows only minimal impacts of dietary changes on CO_2 emissions. Given the importance of the entire food supply chain in contributing to greenhouse gas emissions, future versions of the model should incorporate these additional sources of emissions to provide a more accurate estimate of the environmental impacts of dietary changes.

Additionally, GCAM's representation of food prices is limited to primary crop prices, which excludes the pricing of processed foods or secondary products. This simplification could lead to an underestimation of ADESA values. Expanding the model to include a broader range of food prices would yield more accurate insights into how economic factors influence dietary choices and food security.

Finally, the structure of GCAM itself presents certain constraints. Its nested structure may limit its ability to capture emerging trends in food consumption, such as the increasing preference for fruits and vegetables in wealthier countries. As dietary patterns evolve and consumer preferences shift in response to factors like health trends or environmental awareness, the model must be adapted to account for these changes. Addressing these limitations in future iterations of the model will be crucial to providing more accurate, comprehensive, and policy-relevant insights into global food systems and their environmental impacts.

SDG3 – Nutrition

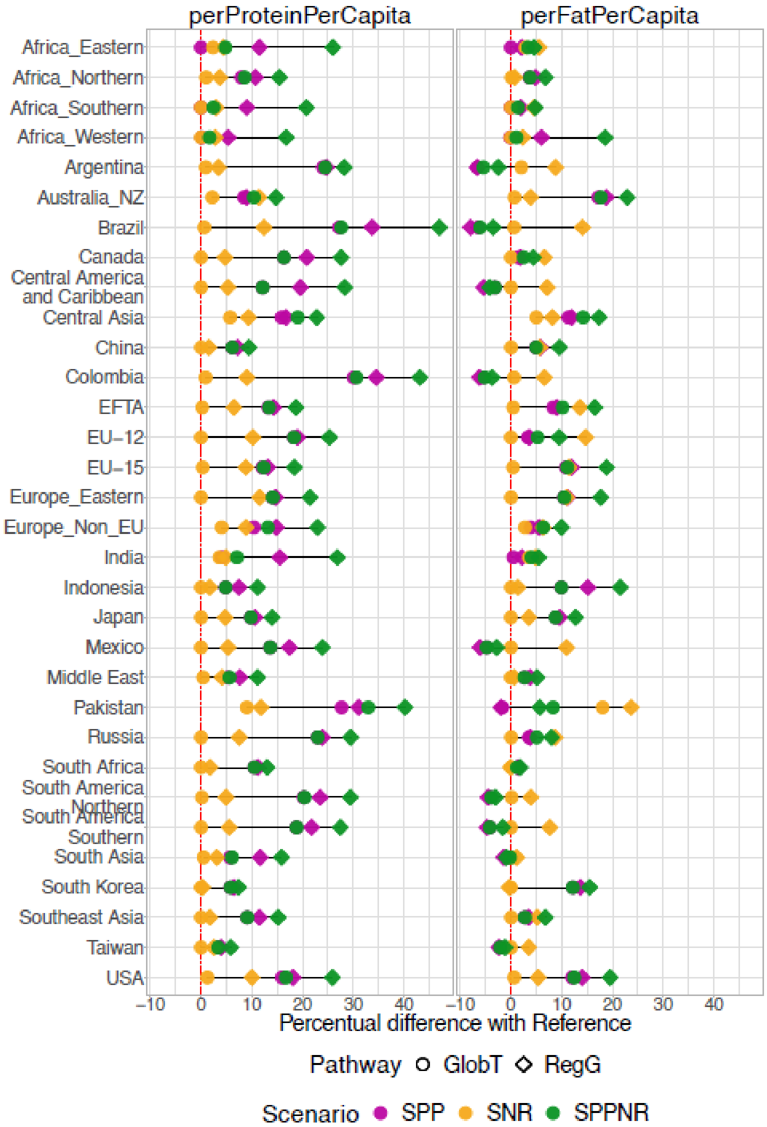


Figure S- 8: Regional percentage difference to Reference of protein and fat consumption as a percentage of energy intake [capita/day] of an average consumer by region in 2050. Dashed red line indicates a 0% difference.

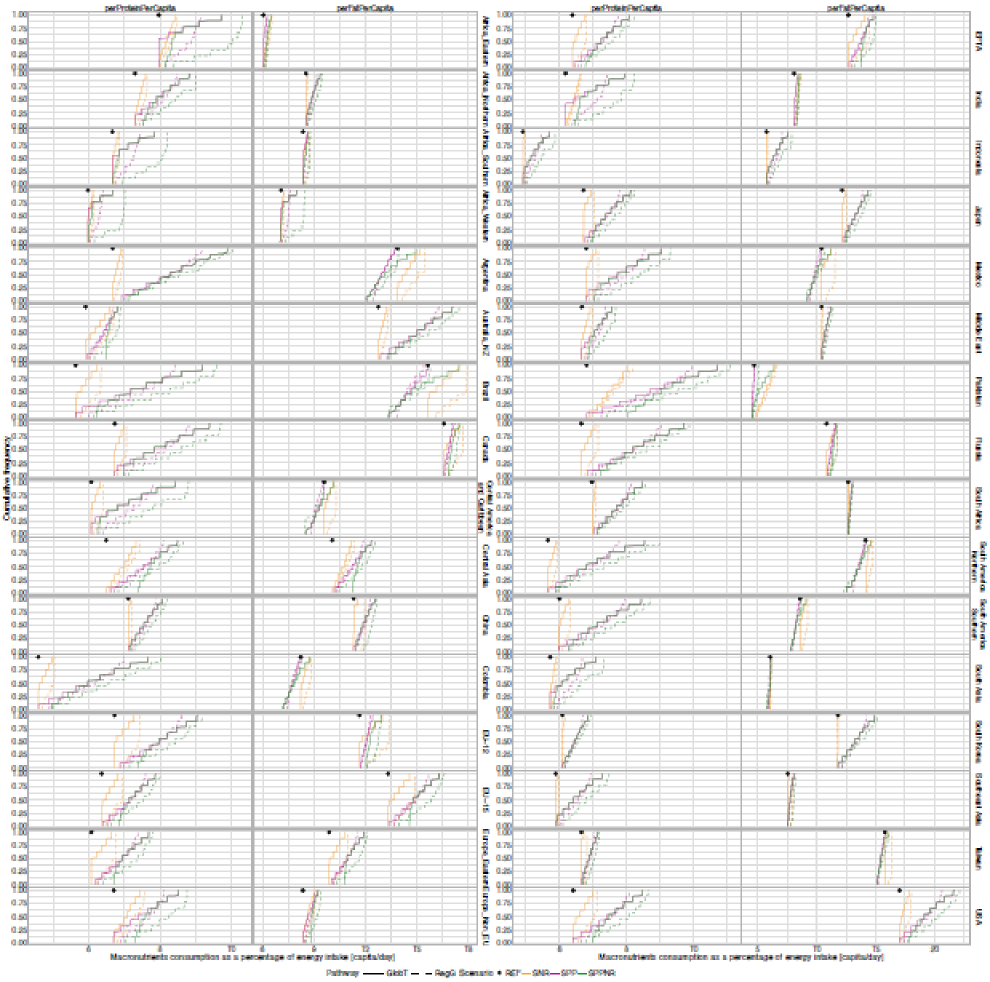
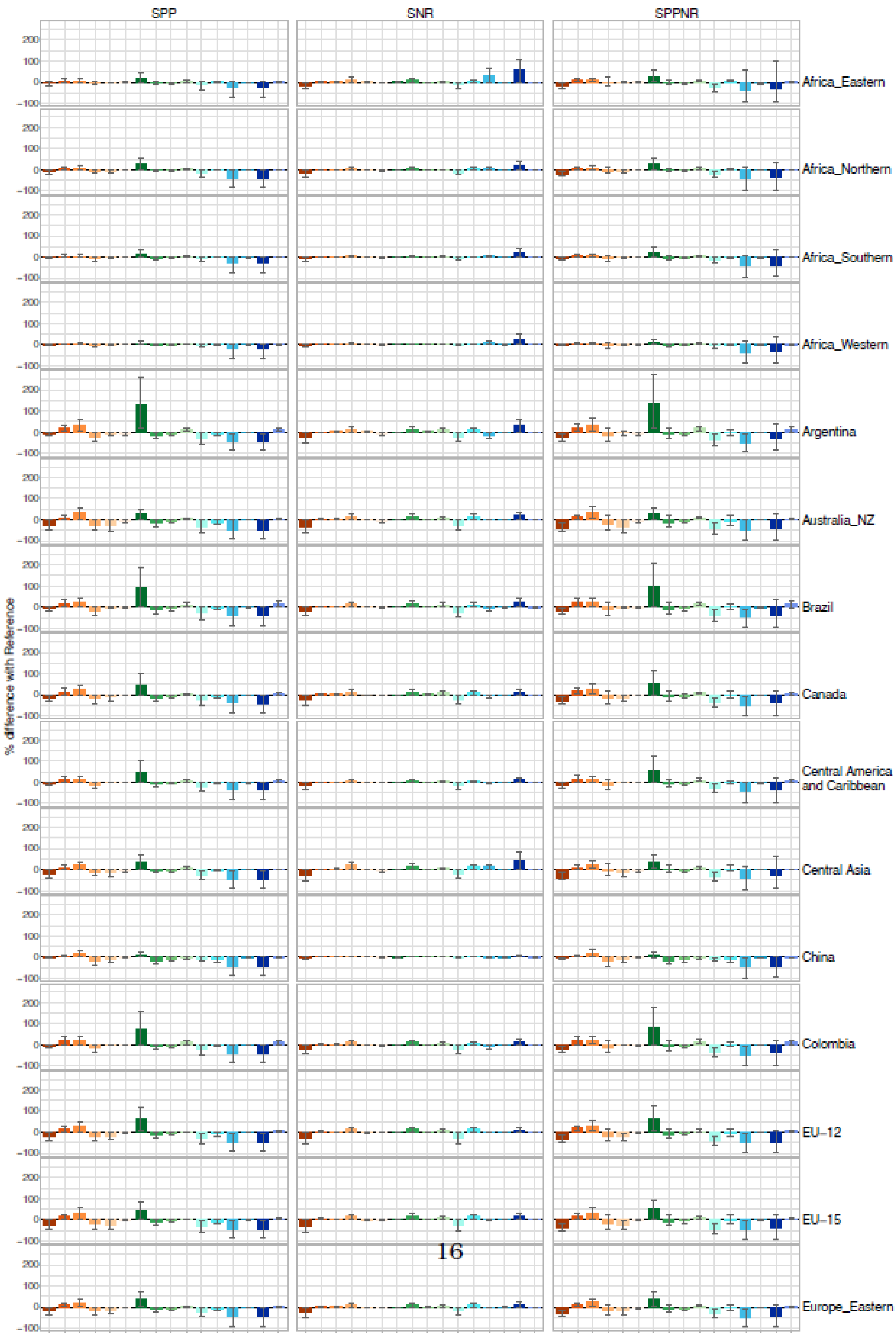


Figure S- 9: Cumulative functions of macronutrient consumption as a percentage of en-ergy intake by region, scenario protein type (colour), and scenario pathway (linetype) in 2050. The diamond bullets represent the Reference values.


SPP
SNR
SPPNR
200
100
0
−100
% difference with Reference
Africa_Eastern
Africa_Northern
Africa_Southern
Africa_Western
Argentina
Australia_NZ
Brazil
Canada
Central America and Caribbean
Central Asia
China
Colombia
EU−12
EU−15
Europe_Eastern
16

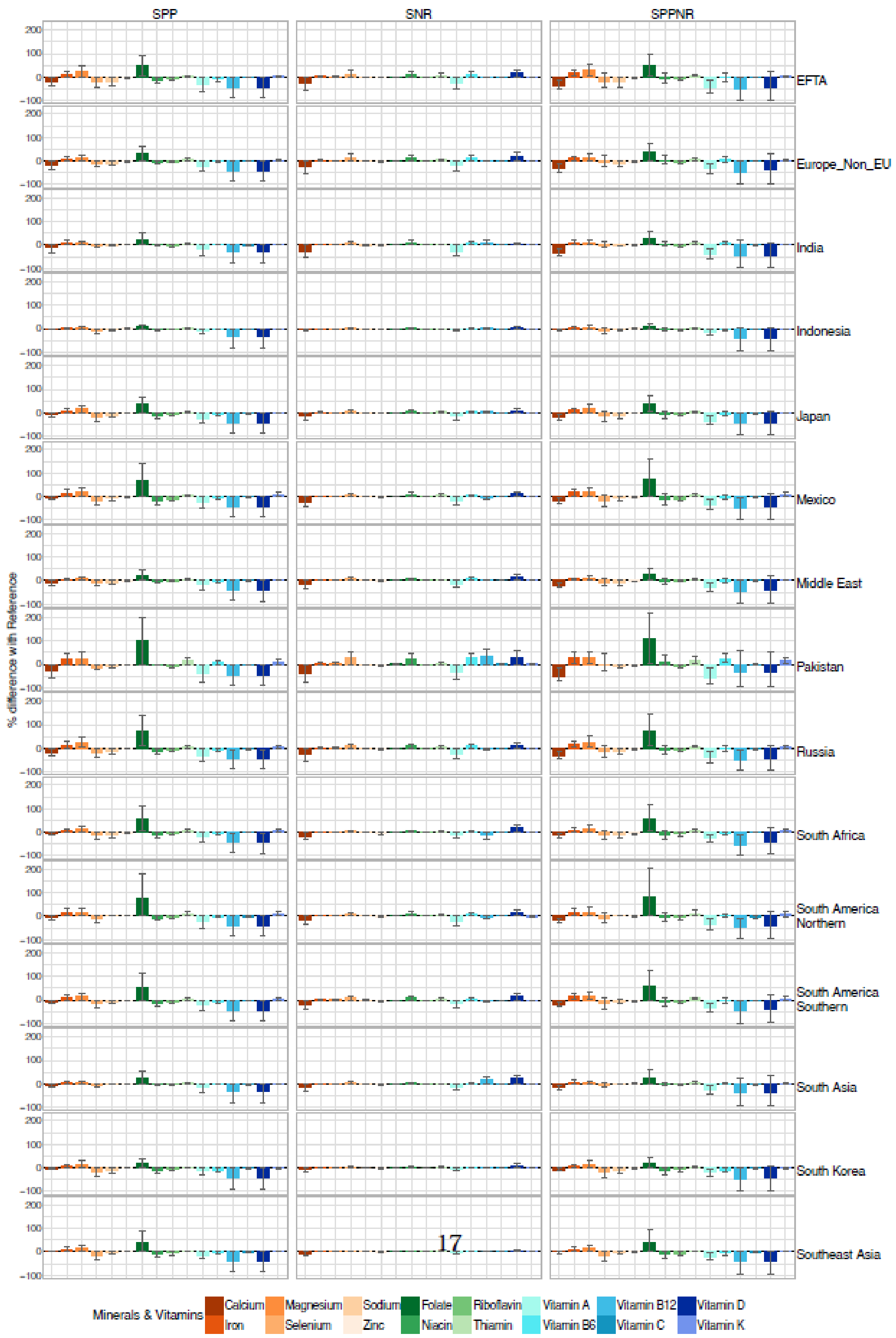


Figure S- 10: Regional percentage difference to Reference of micronutrient intake [capita/day] of an average consumer by region in 2050. Gray bars represent min-max intervals. The diamond bullets indicate the Reference values.

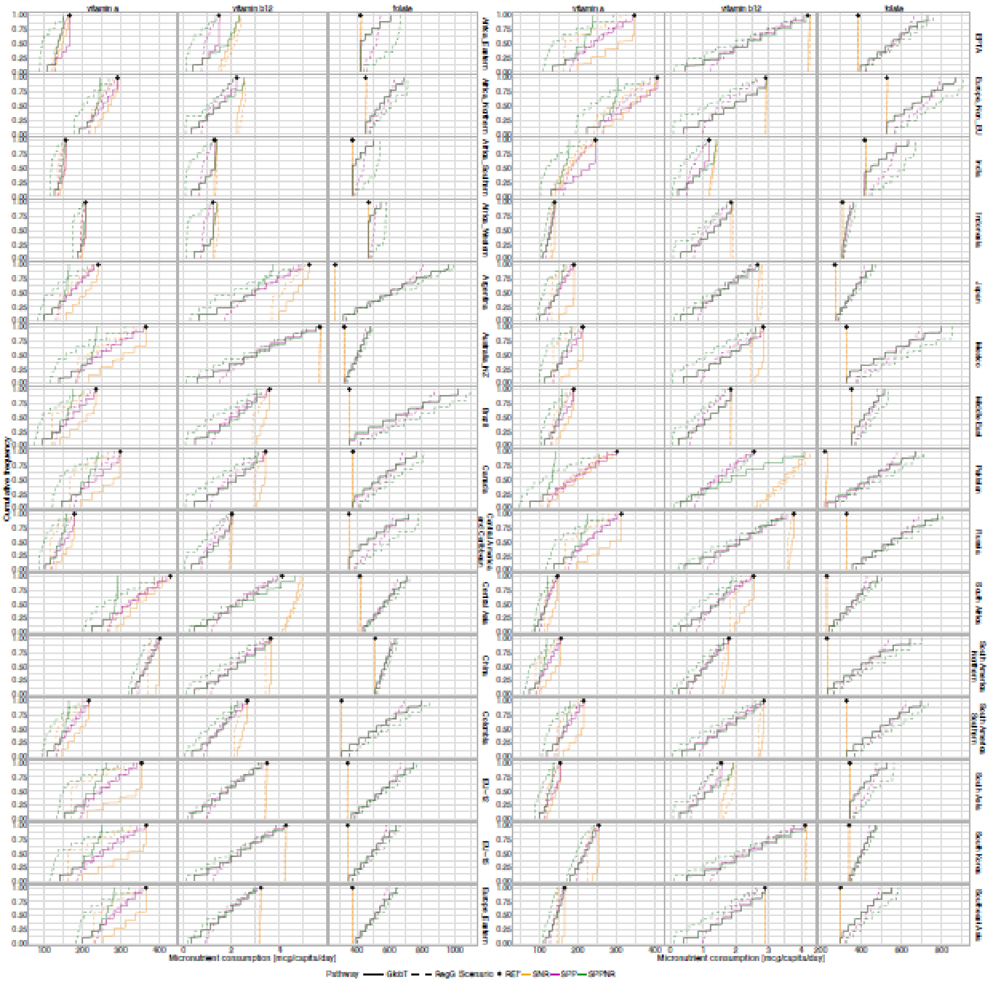


Figure S- 11: Cumulative functions of micronutrient consumption by region, scenario protein type (colour), and scenario pathway (linetype) in 2050. The diamond bullets represent the Reference values.

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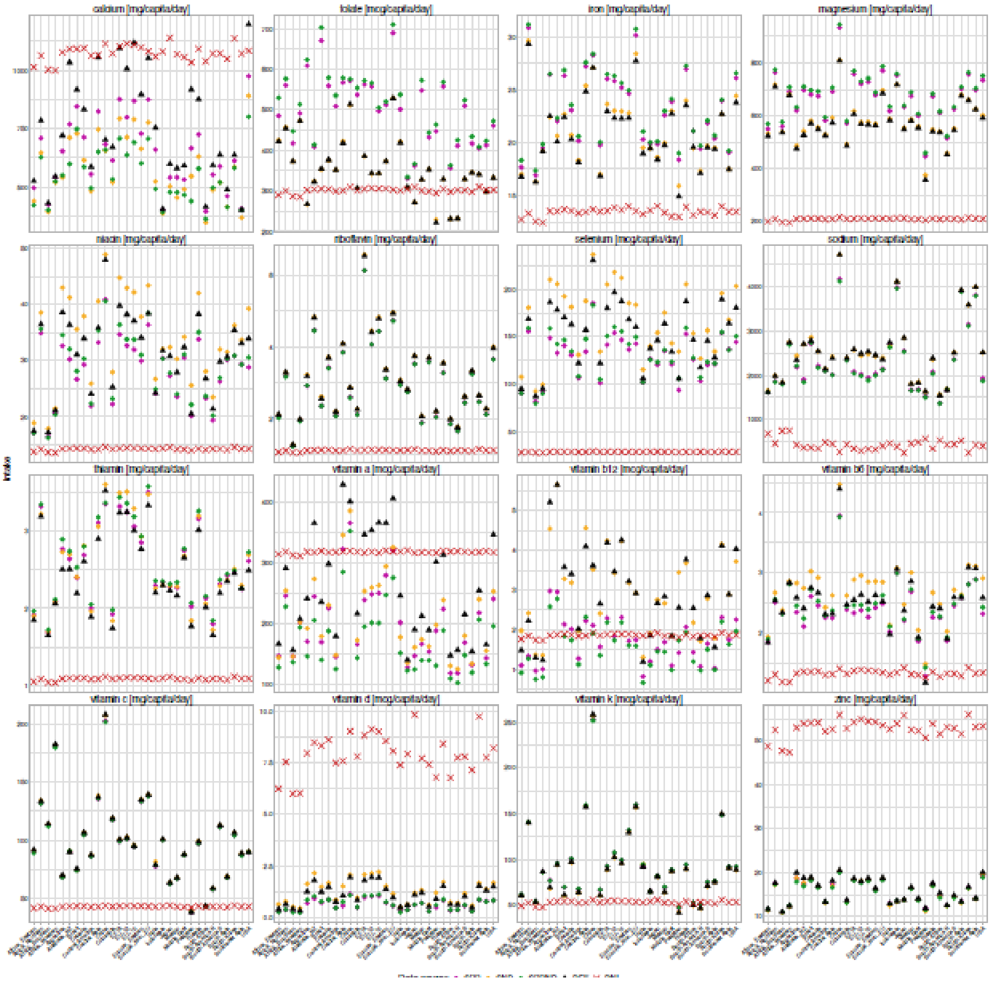


Figure S- 12: Micronutrient intakes by scenario and the Reference Nutrient Intake (RNI) [1] by region in 2050.

SDG 15 – Land

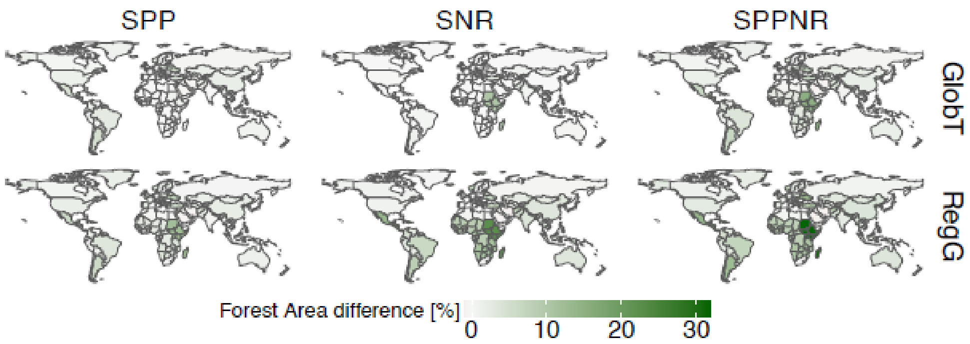


Figure S- 13: Percentage of forest area compared to Reference scenario in 2050.

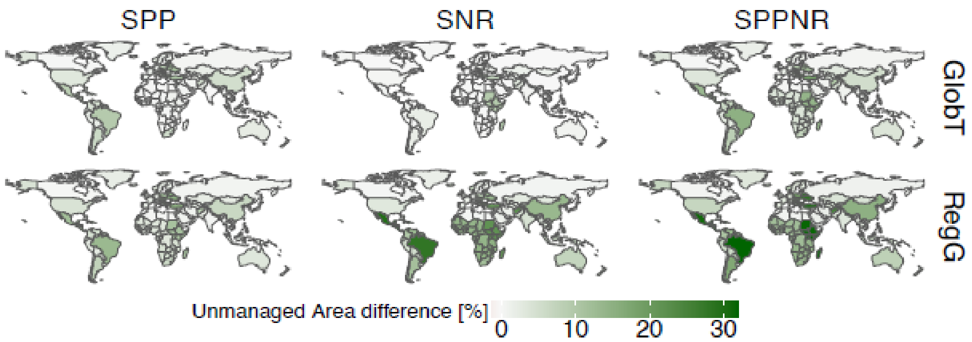


Figure S- 14: Percentage of unmanaged land compared to Reference scenario in 2050.

Unmanaged land is also impacted by dietary changes, which has been traditionally used as an indicator of biodiversity [2]. We observe that all scenarios improve the share of unmanaged land globally, except in a few regions where the cropland area heavily increases due to large legumes and nuts exports (e.g., Tai-wan) (Figure S14). Regions with initially low plant protein intake but moderate non-ruminant intake, such as Eastern Europe and non-EU Europe, raise their rates of unmanaged land in the SPP scenario. In contrast, regions with high non-ruminant and plant protein intake, like Africa Eastern and Central America and the Caribbean, have larger shares in the SNR scenario. When ruminant protein intake is reduced, the pasture and grazing lands that are no longer in use might revert to unmanaged states if they are not repurposed or managed for other agricultural activities. On the other hand, croplands currently used for feed are high-quality arable lands that can be more easily and cost-effectively converted to food production [3].

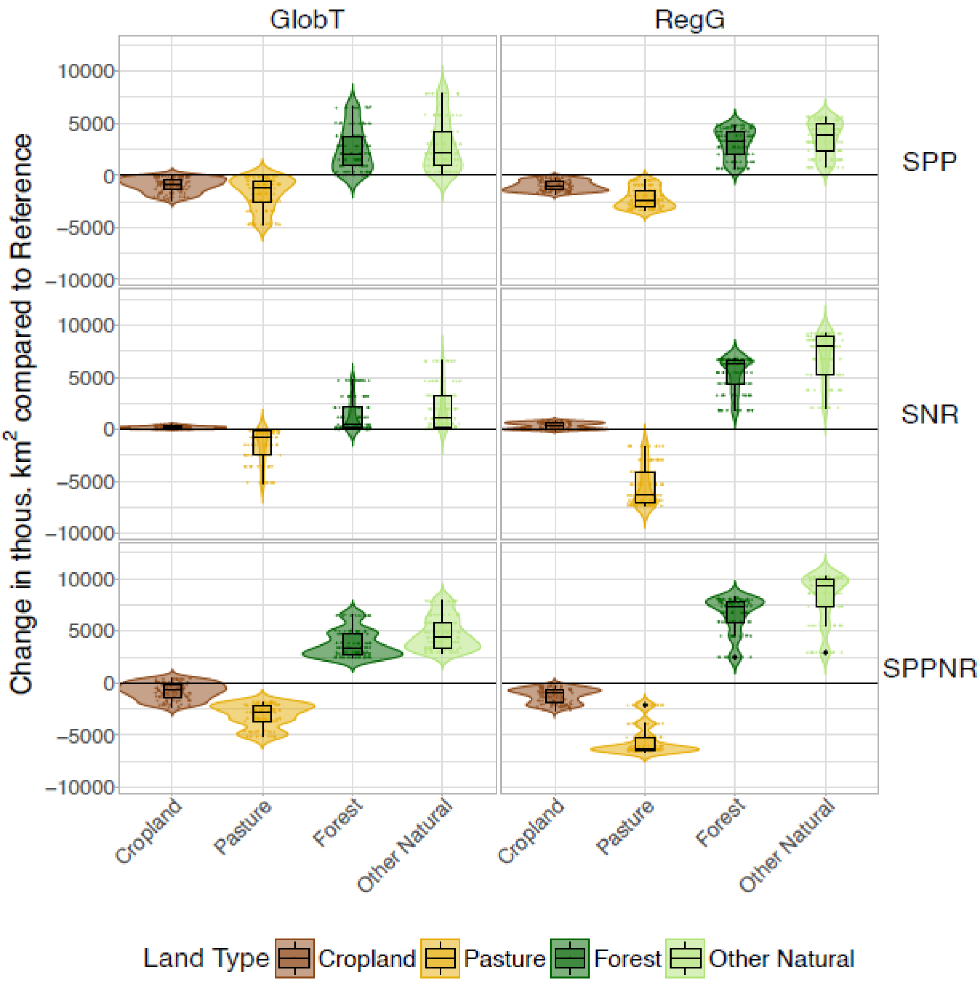
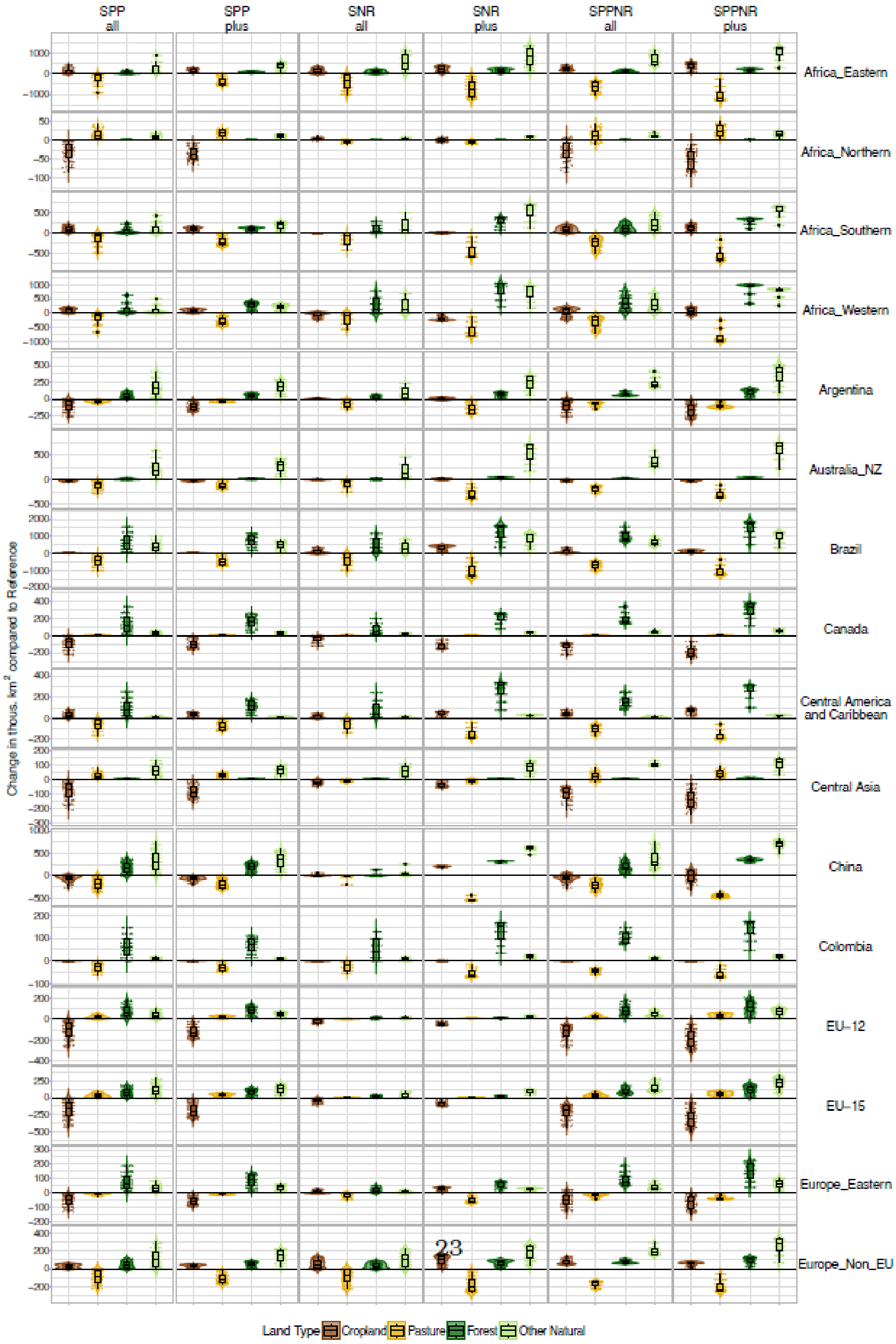


Figure S- 15: Global violin diagram for 2050 of the land area difference compared to Reference [thous. km^2] by scenario protein type and scenario pathway. The colour indicates the land type. The box plot indicates the median, the 0.25 and 0.75 percentile, and the minimum and maximum values. Jittered points show all the data values.


SPP all
SPP plus
SNR all
SNR plus
SPPNR all
SPPNR plus
Africa_Eastern
Africa_Northern
Africa_Southern
Africa_Western
Argentina
Australia_NZ
Brazil
Canada
Central America and Caribbean
Central Asia
China
Colombia
EU-12
EU-15
Europe_Eastern
Europe_Non_EU
Change in thous. km² compared to Reference
Land Type
Cropland
Pasture
Forest
Other Natural

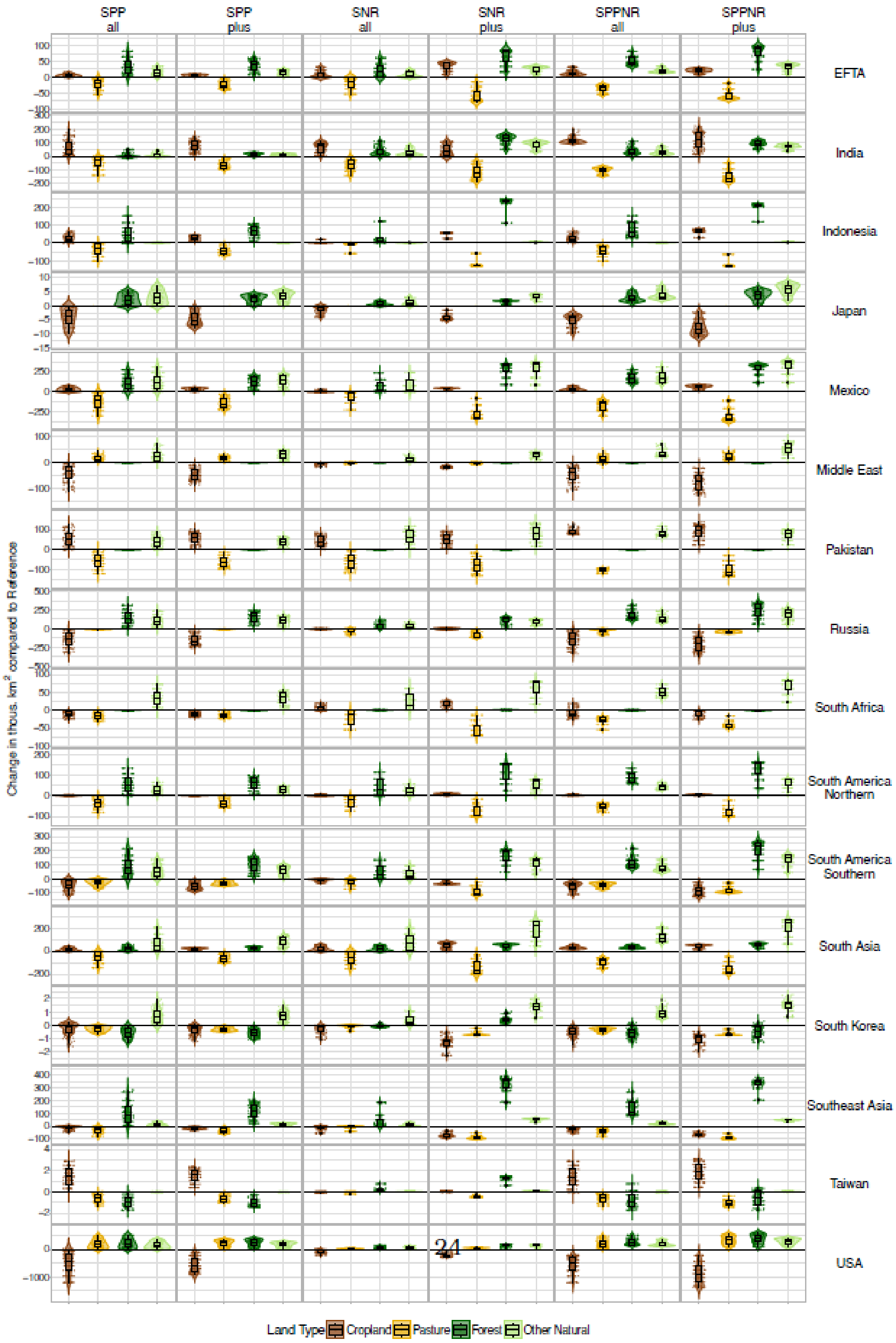


Figure S- 16: Violin diagram for 2050 of the land area difference compared to Reference [thous. km^2] by scenario protein type, scenario pathway, and region. The colour indicates the land type. The box plot indicates the median, the 0.25 and 0.75 percentile, and the minimum and maximum values. Jittered points show all the data values

SDG6 – Water

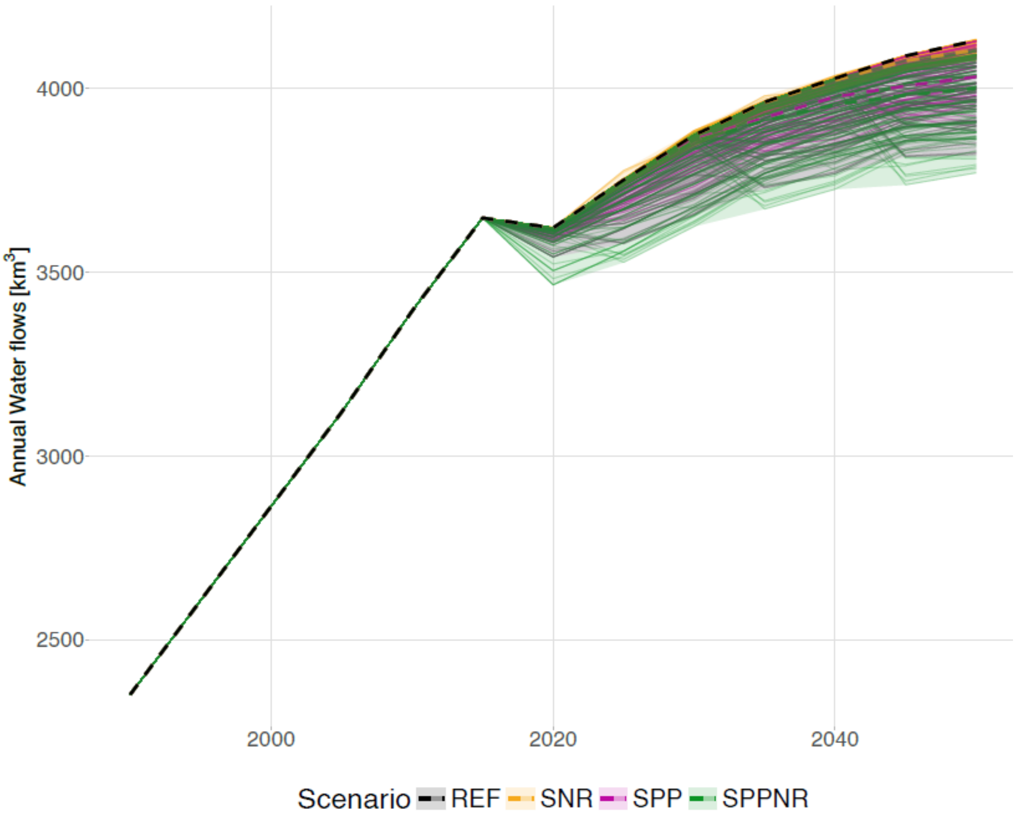


Figure S- 17: Global annual water withdrawals (km^3) by scenario protein type. The dashed line indicates the median.

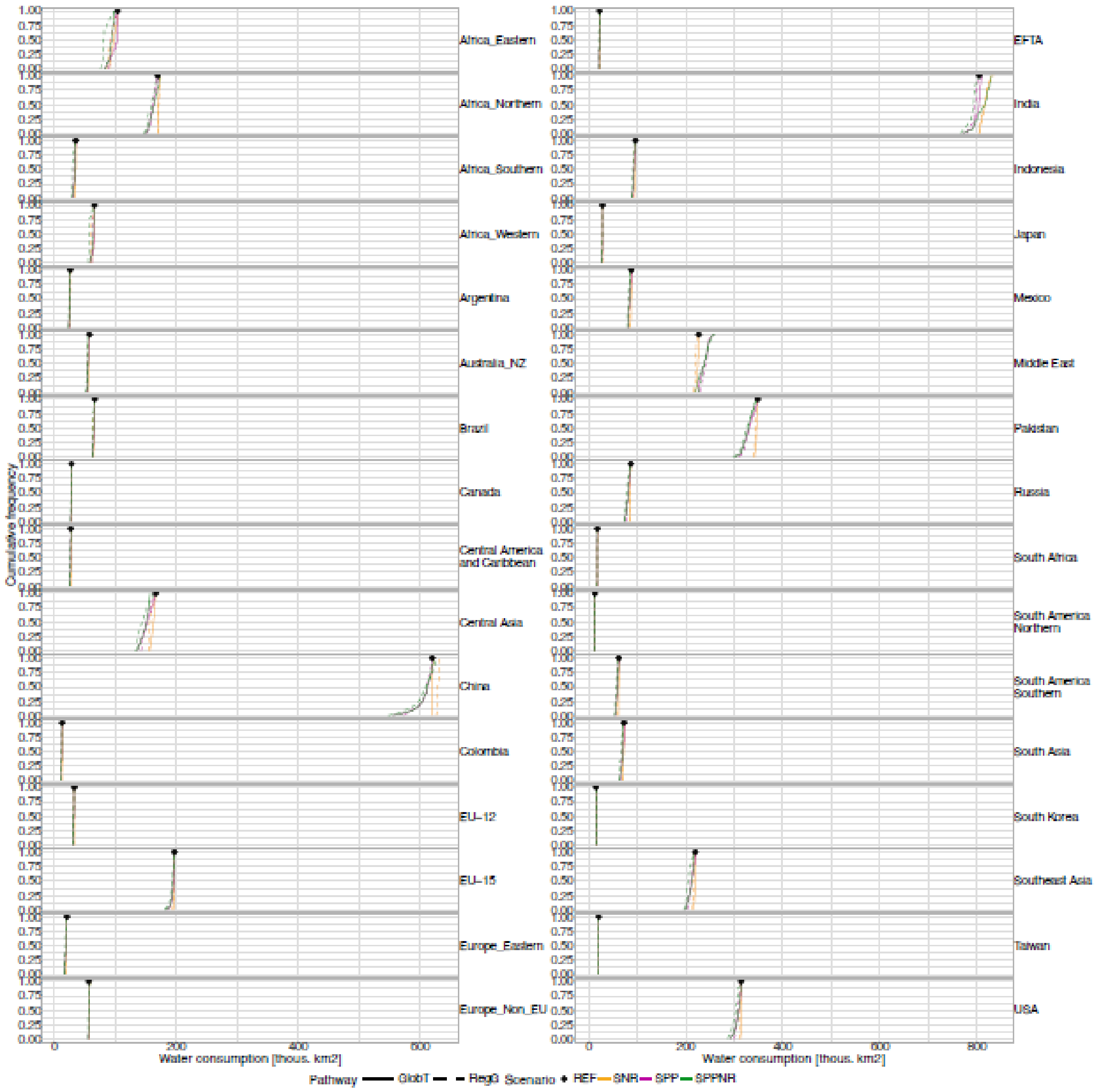


Figure S- 18: Cumulative functions of water withdrawals by region, scenario protein type (color), and scenario pathway (linetype) in 2050. The diamond bullets represent the Reference values.

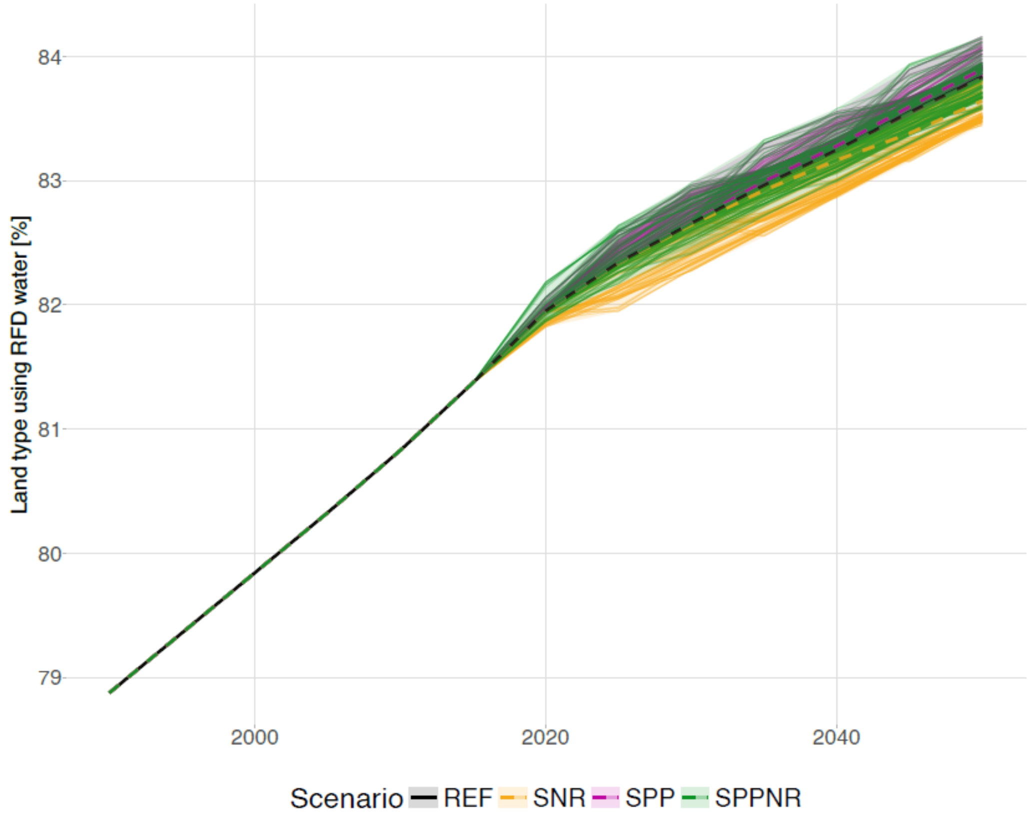


Figure S- 19: Global land types using rainfed water as a percentage of the overall (irrigated + rainfed) water land types by scenario.

The SPP scenario increases the share of land types utilising rainfed water demand since legumes and nuts are more likely to be grown under rainfed conditions (depending on species and climate [4]). On the other hand, although ruminants are low water productive [5], the SNR scenario increases the cultivated area, which increases the share of land types demanding irrigated water. Finally, the SPPNR scenario barely changes the irrigated-rainfed land type ratio (Figure S19). All these trends are magnified under the *plus* pathway, further reducing the dependence on irrigated water (Figure S20).

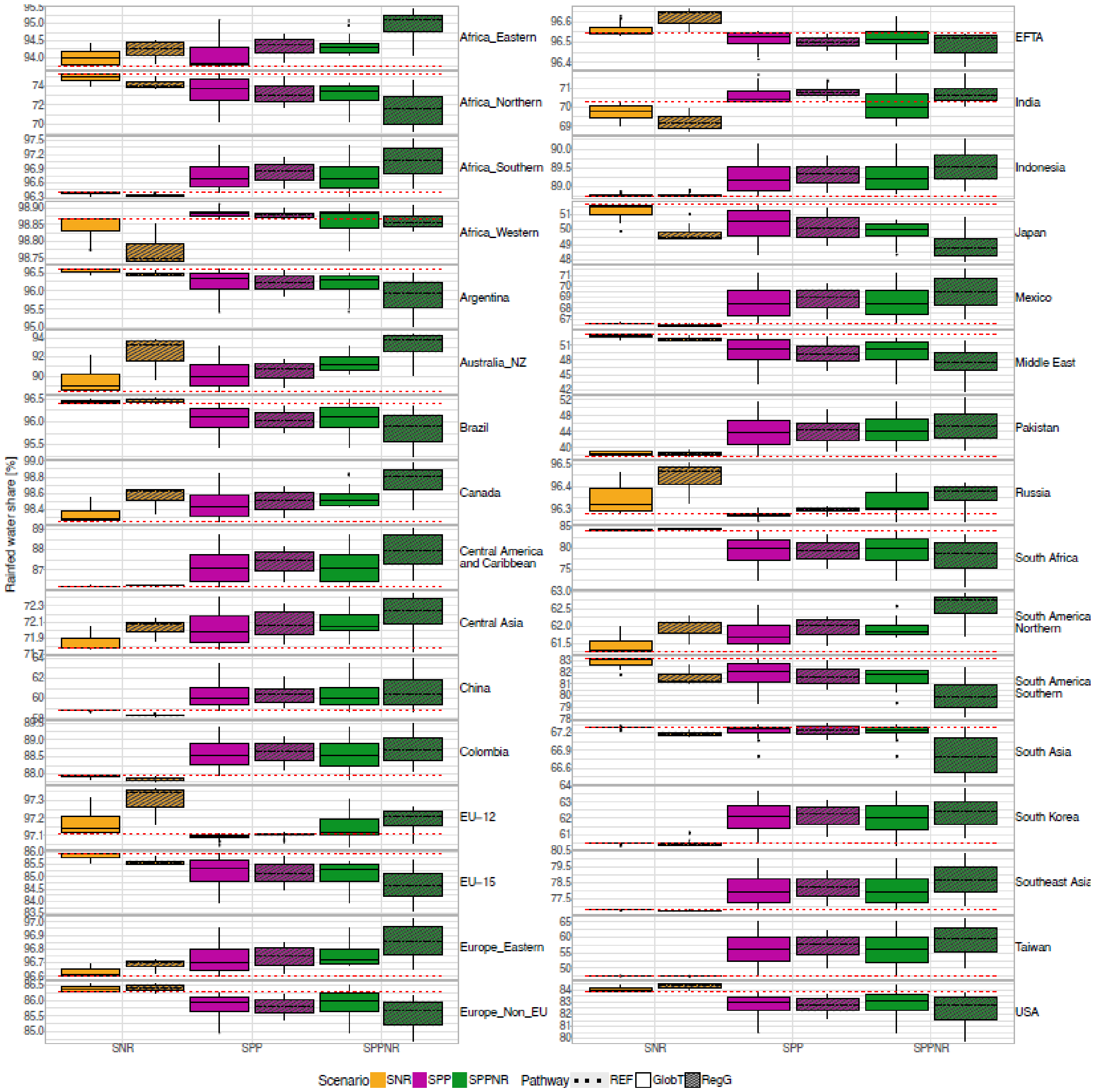


Figure S- 20: Box plots of rainfed water land types share by region, scenario protein type (colour), and scenario pathway (linetype/pattern) in 2050. The red dashed lines represent the Reference values.

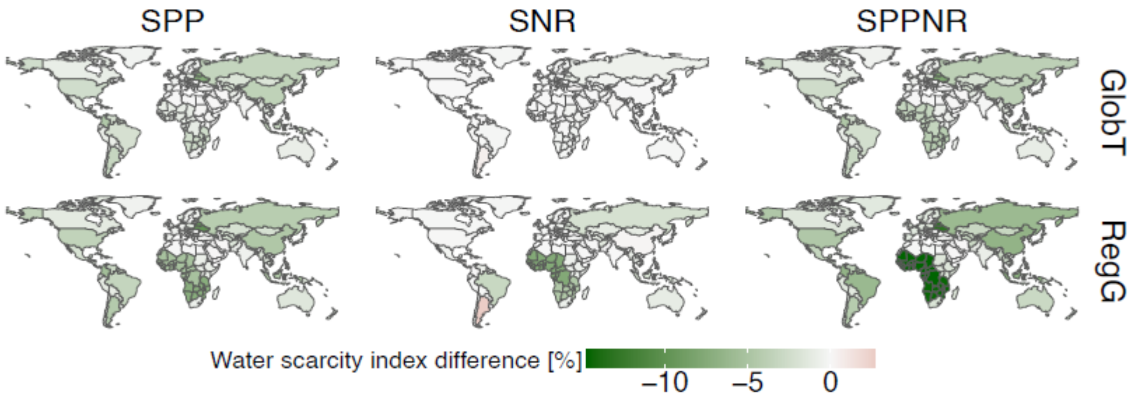


Figure S- 21: Reginal percentage water scarcity pressure in 2050 by scenario protein type and scenario pathway compared to Reference.

SDG13 – Emissions

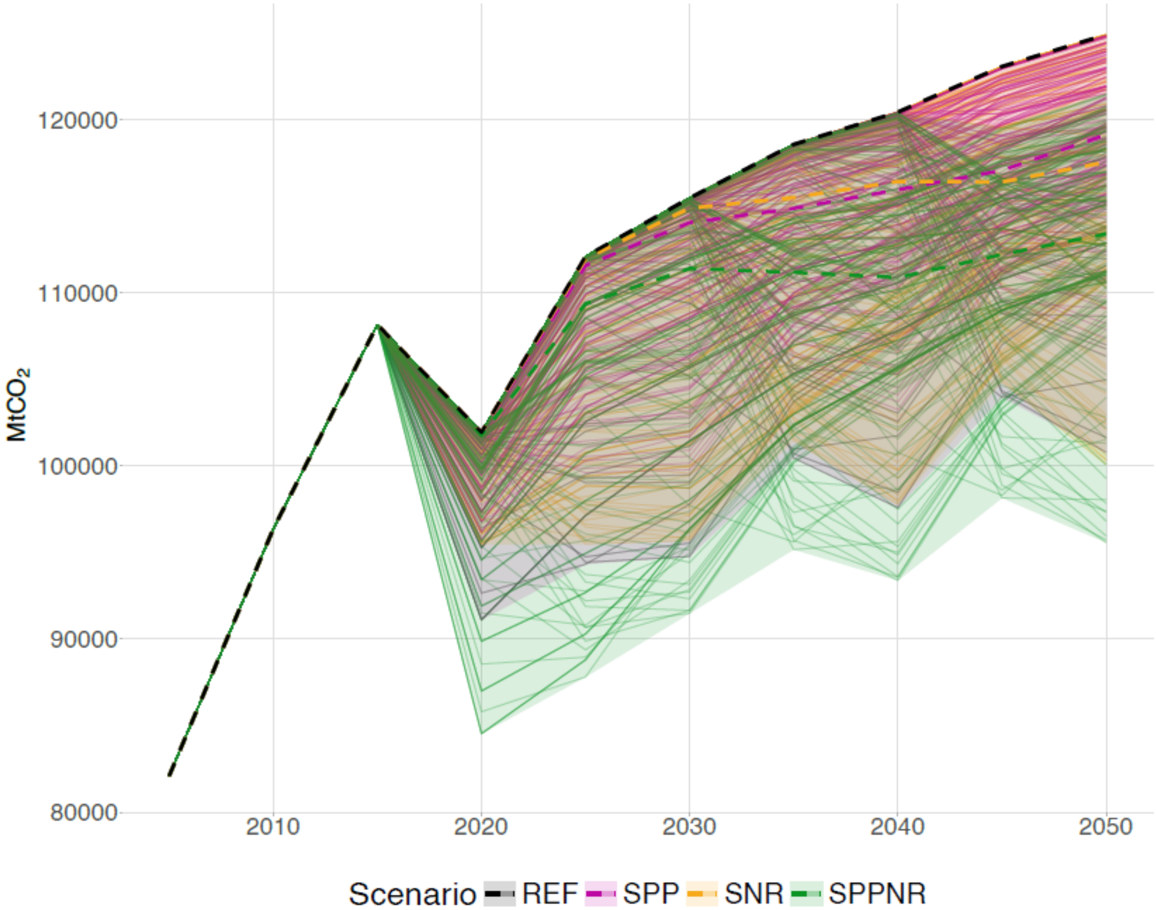


Figure S- 22: Global total GHG emissions (Mt CO_2) by scenario. The dashed line indicates the median

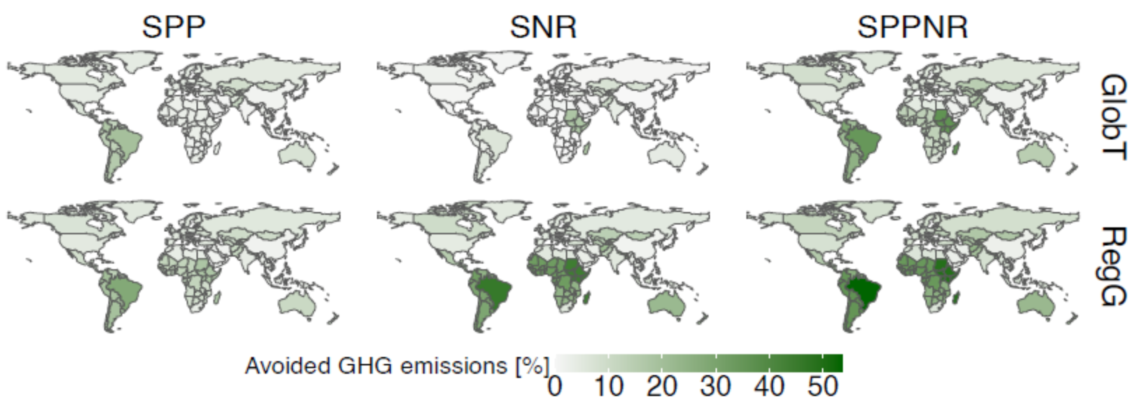


Figure S- 23: Regional percentage avoided GHG emissions by scenario protein type and scenario pathway in 2050.

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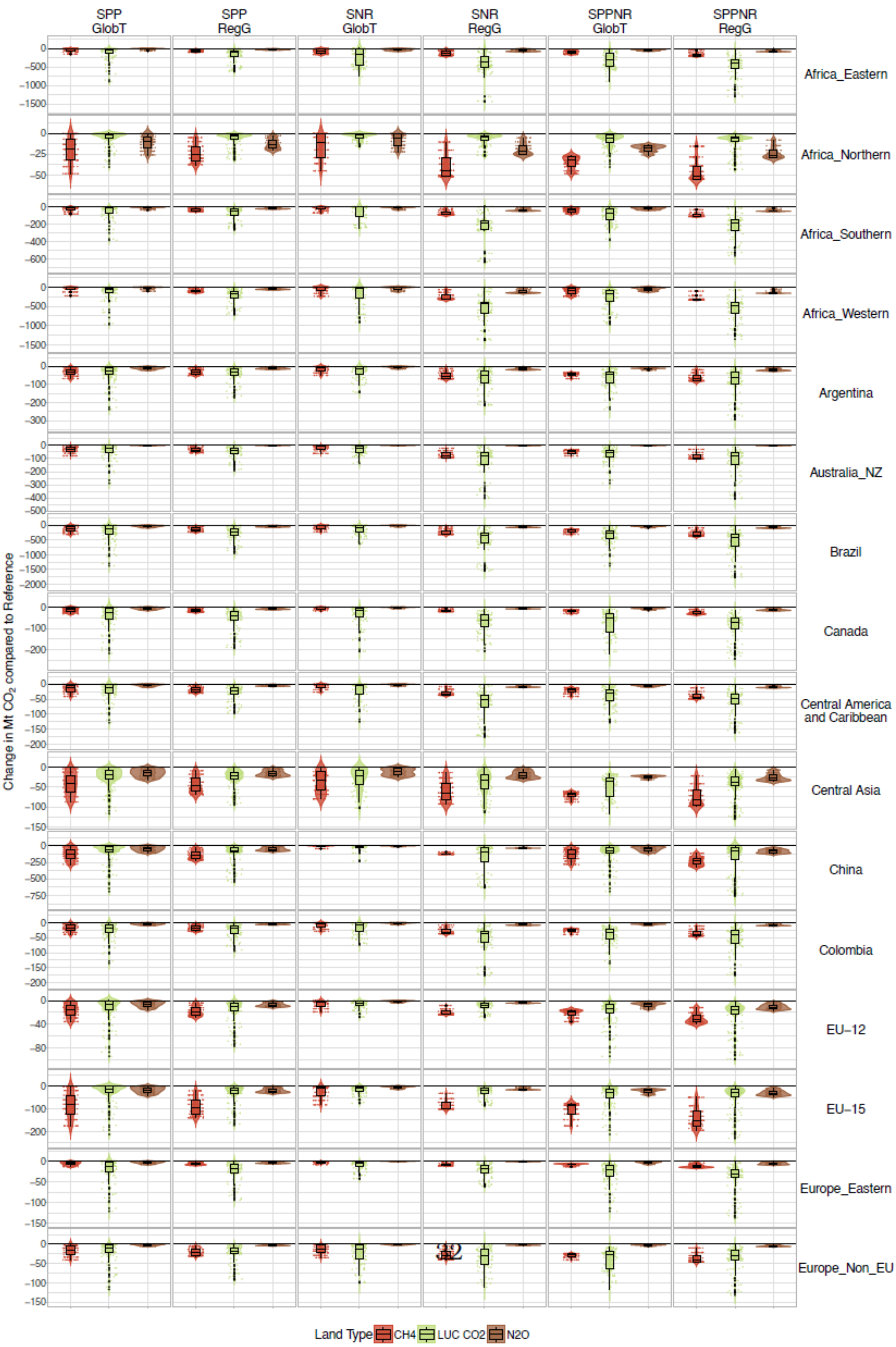
SPP
GlobT
SPP
RegG
SNR
GlobT
SNR
RegG
SPPNR
GlobT
SPPNR
RegG
Africa_Eastern
Africa_Northern
Africa_Southern
Africa_Western
Argentina
Australia_NZ
Brazil
Canada
Central America
and Caribbean
Central Asia
China
Colombia
EU−12
EU−15
Europe_Eastern
Europe_Non_EU
Change in Mt CO2 compared to Reference
Land Type
CH4
LUC CO2
N2O

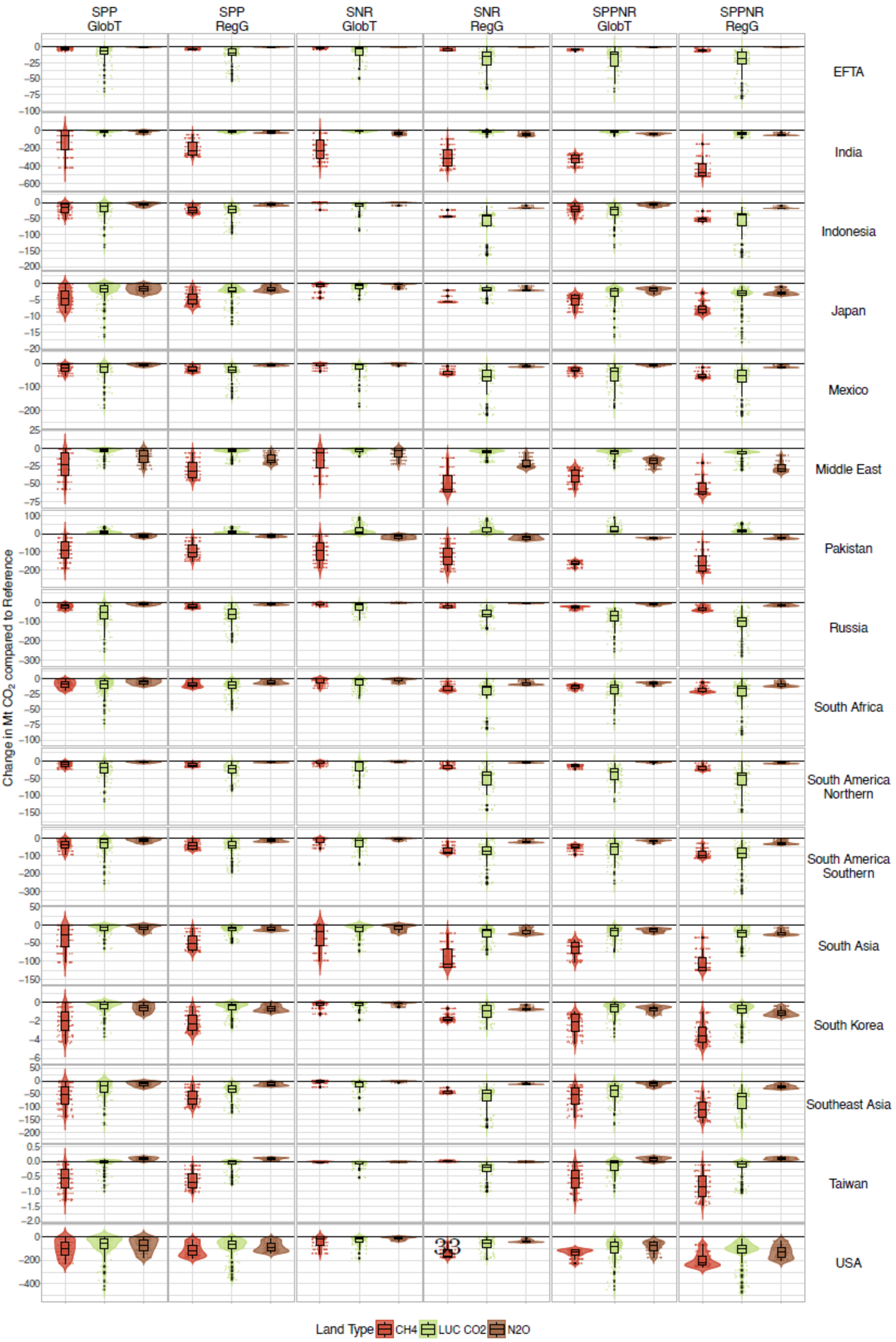

Figure S- 24: Violin diagram for 2050 of the emissions difference compared to Reference [Mt CO_2] by scenario protein type, scenario pathway, and region. The colour indicates the GHG type. The box plot indicates the median, the 0.25 and 0.75 percentile, and the minimum and maximum values. Jittered points show all the data values.
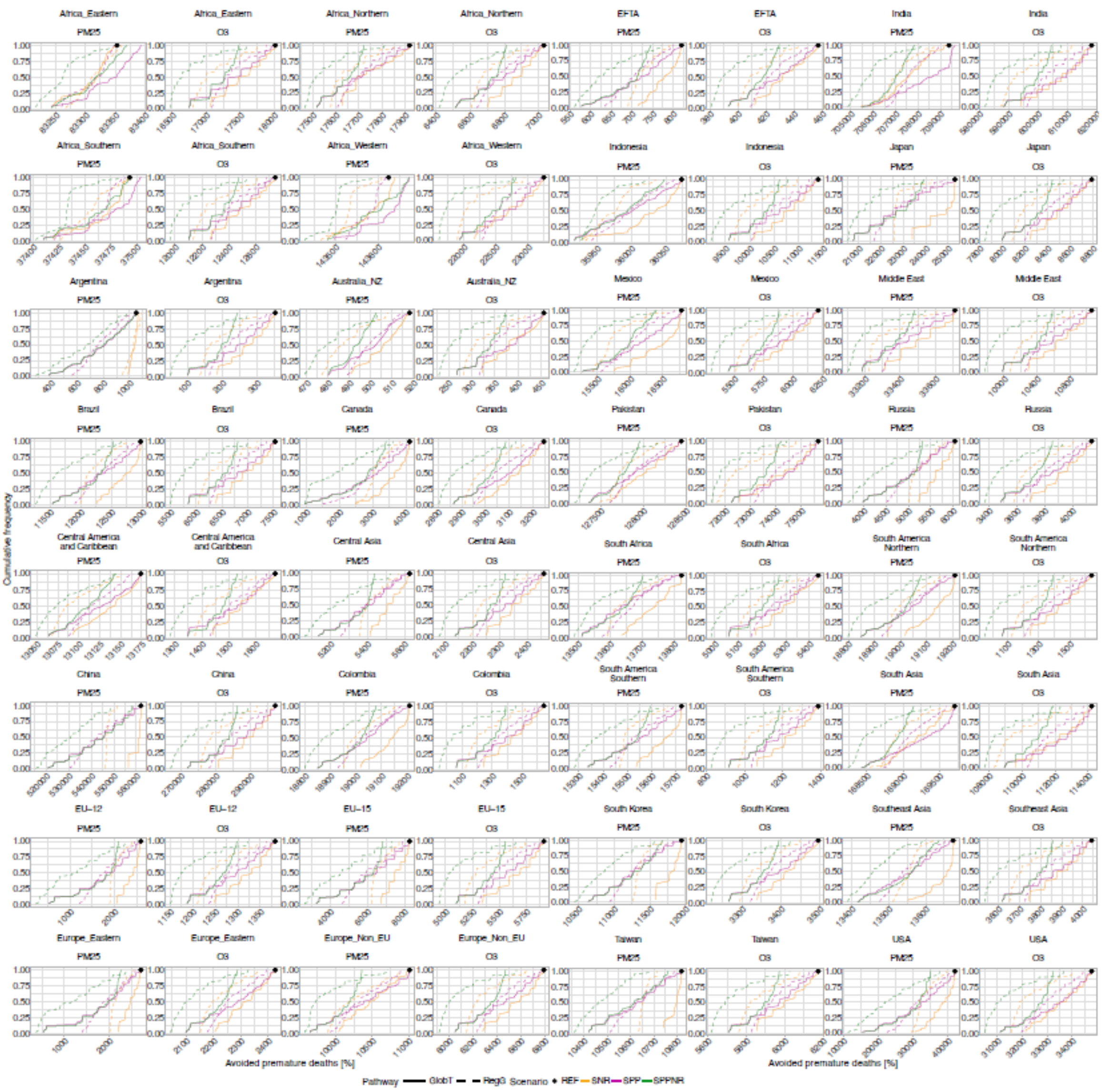
Figure S- 25: Cumulative functions of premature deaths due to outdoor air pollution by region, scenario protein type (colour), and scenario pathway (linetype) in 2050. The diamond bullets represent the Reference values.

SDG2 – Food basket bill

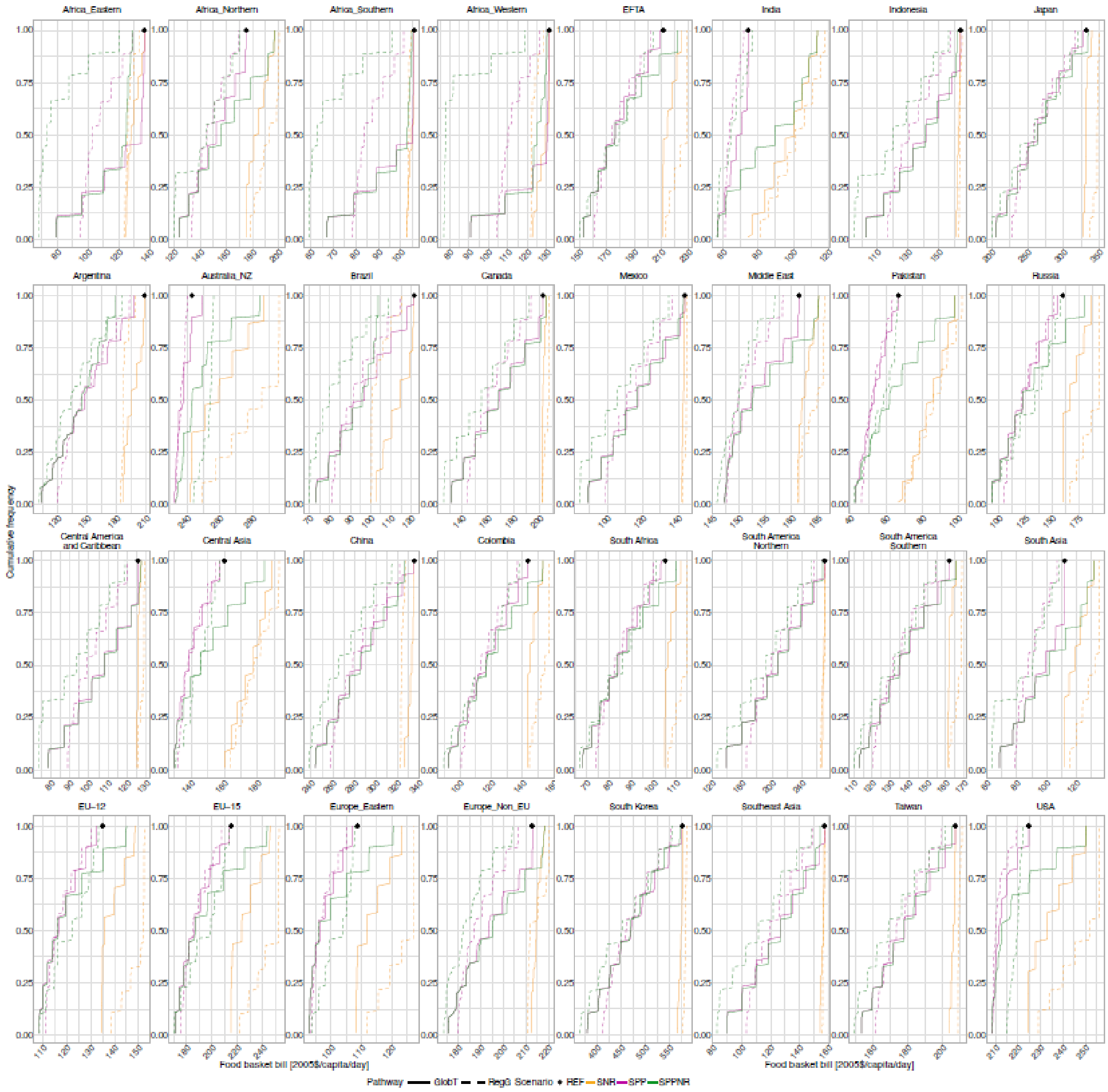

Figure S- 26: Cumulative functions of food basket bill by region, scenario protein type (colour), and scenario pathway (linetype) in 2050. The diamond bullets represent the Reference values

SDG13 – Policy cost

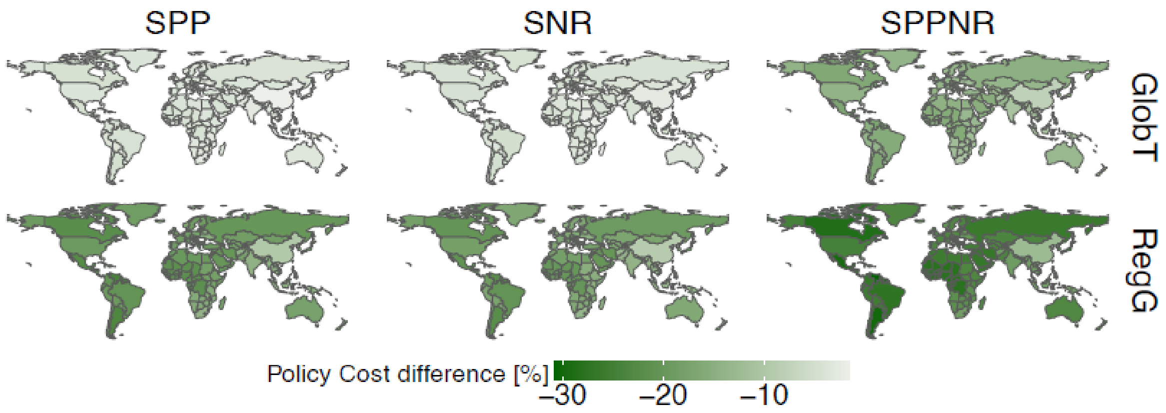

Figure S- 27: Policy cost regional percentage difference compared to Reference scenario in 2050

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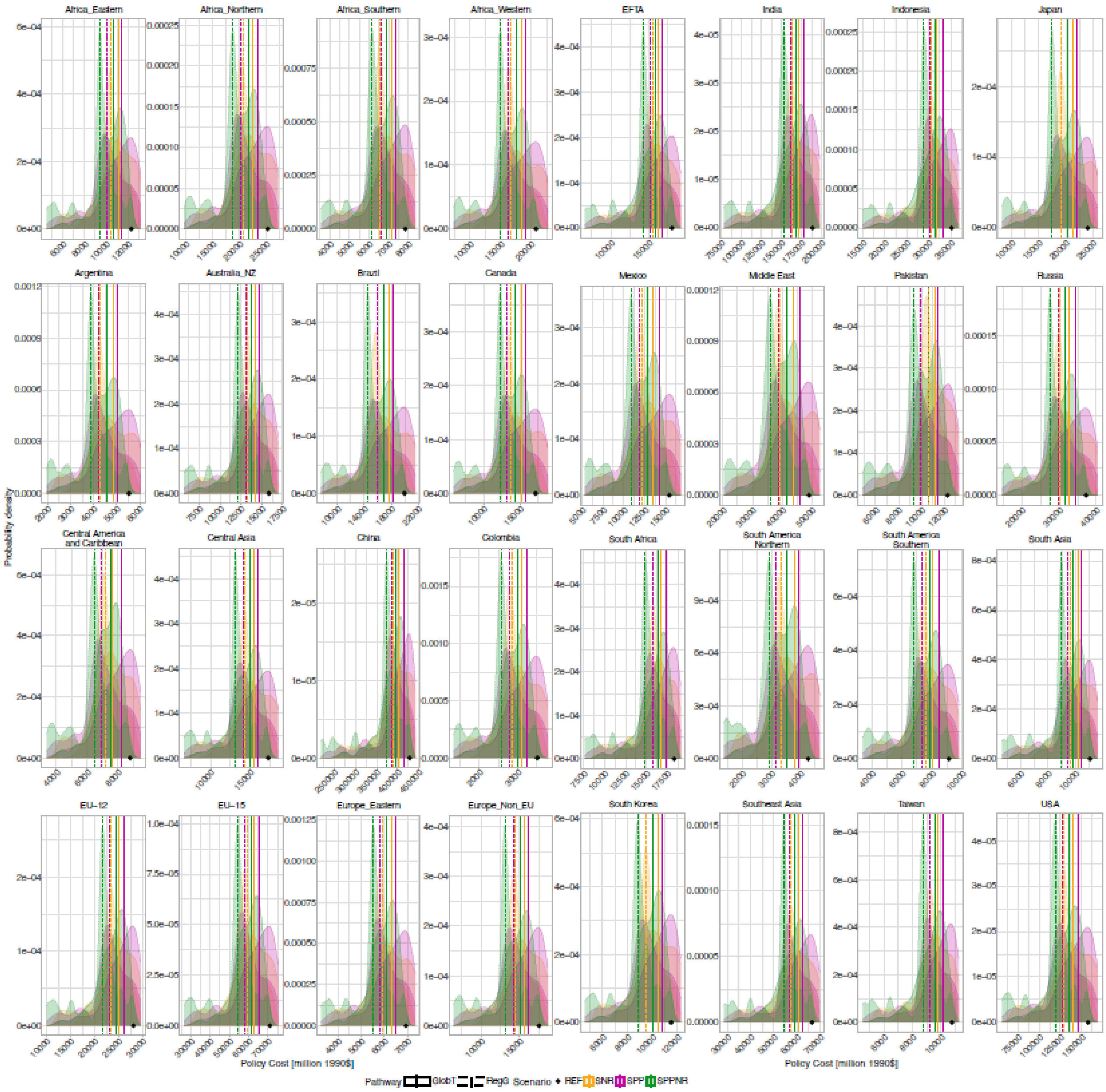

Figure S- 28: Probability density plots of regional policy costs in 2050 by scenario protein type and scenario pathway. The vertical lines indicate the median and the bullet point the Reference value.

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