Supplementary Information: Environmental and societal implications of transitioning to sustainable diets

October 28, 2024

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S1 Methodology

Table S1: Mapping from GCAM region to countries.
Source: `https://jgcri.github.io/gcam-doc/common_assumptions.html`

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

Continued on next page

Table S1: Mapping from GCAM region to countries (continued)

GCAM Region	Countries
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
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, Nepal
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 Peoples 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

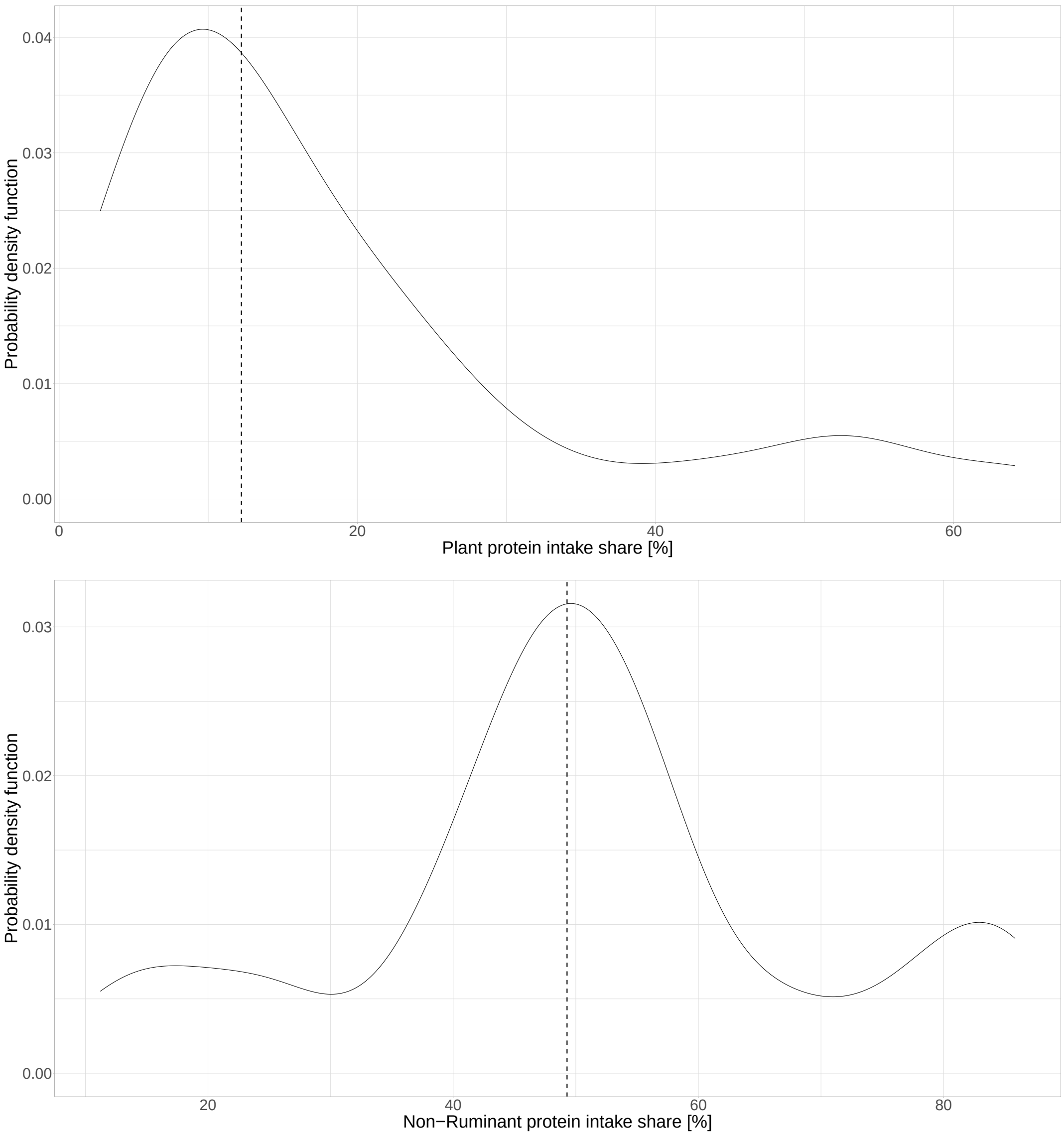


Figure S1: Probability density plots of regional plant protein shares (from the total protein intake) and ruminant protein shares (from the animal protein intake) in 2050 following the Reference scenario. The dashed line indicates the median.

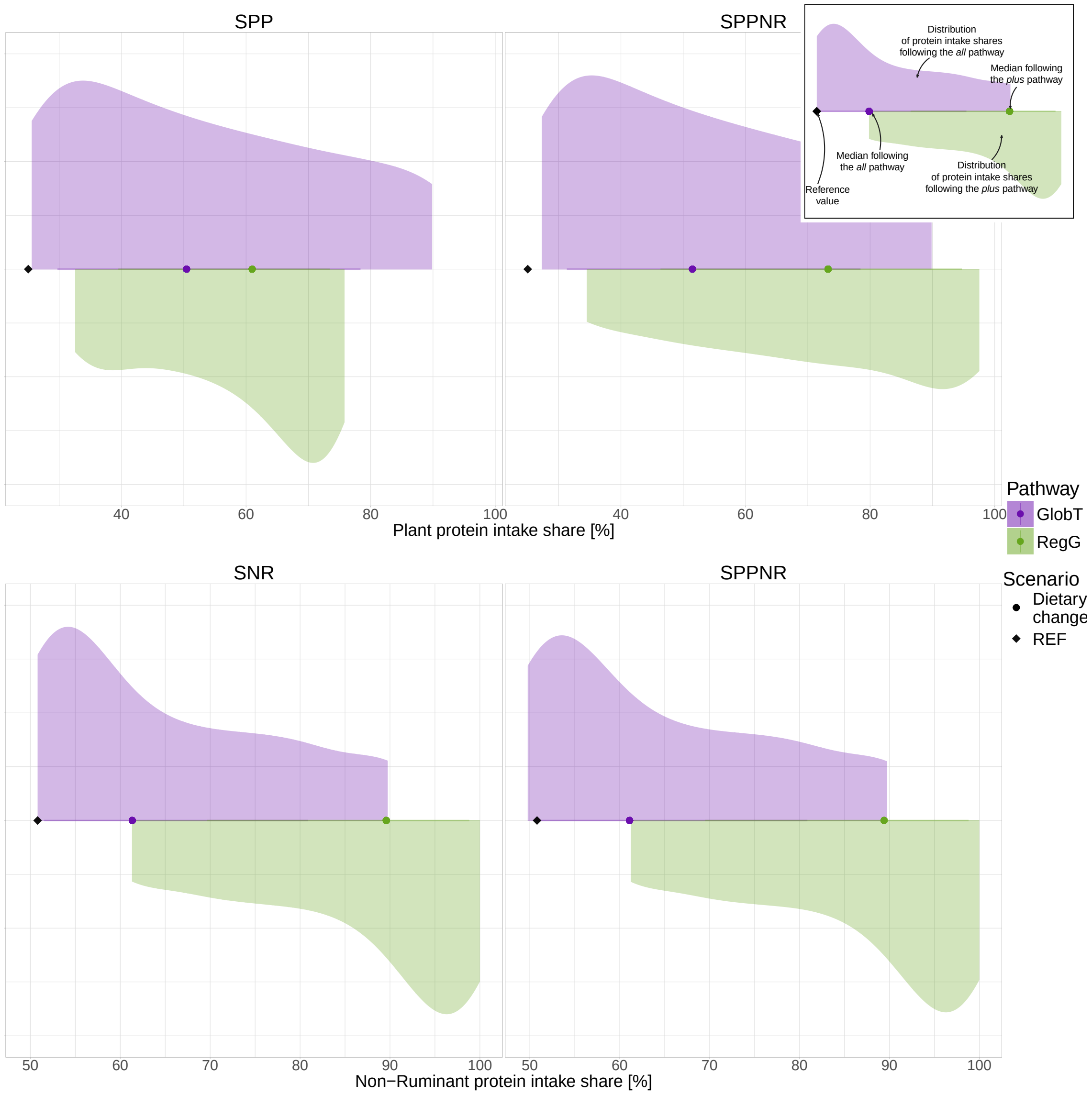
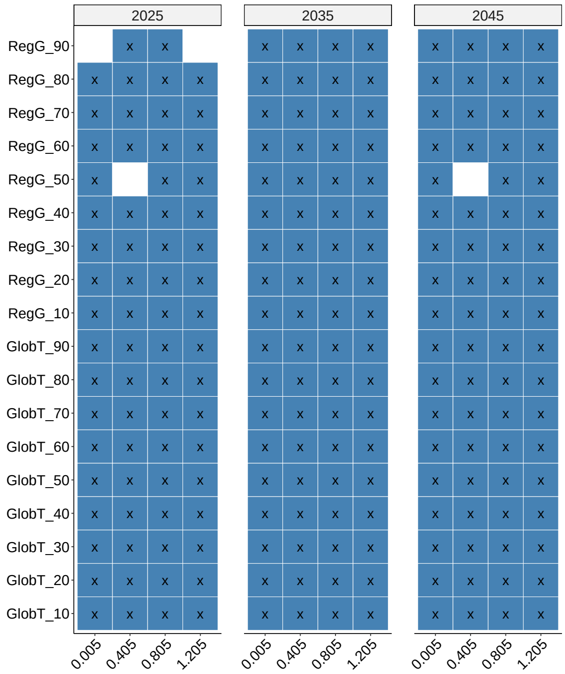
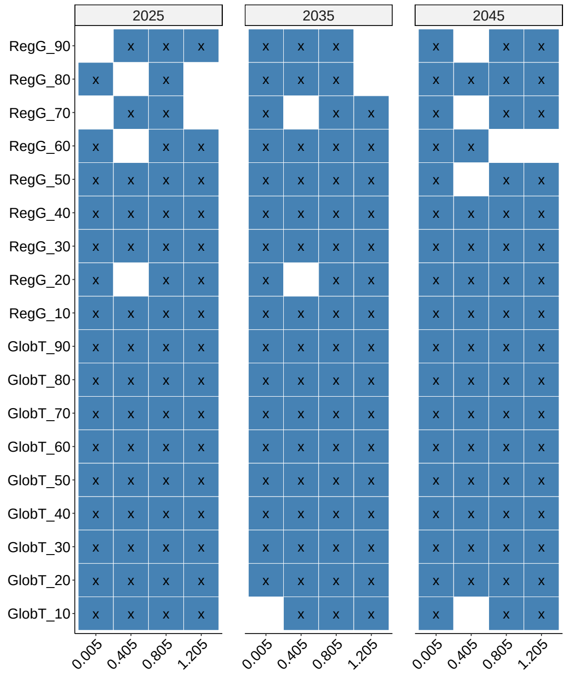


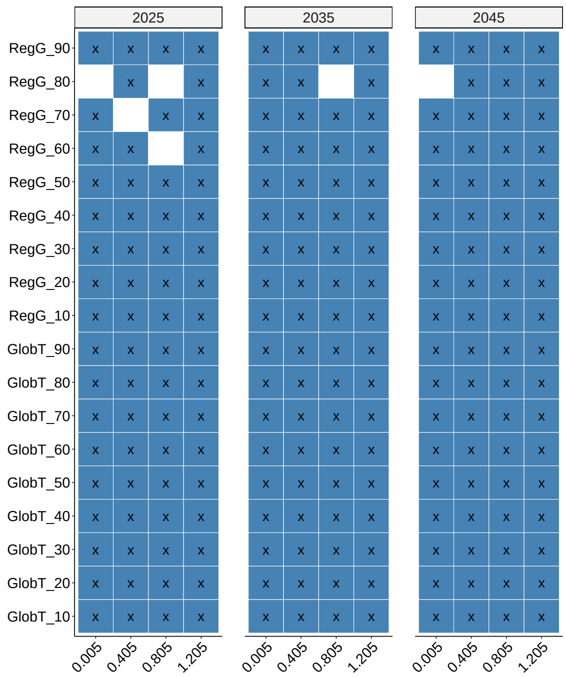
Figure S2: Distribution-density plots of global plant and ruminant protein intake share plant protein shares (from the total protein intake) and ruminant protein shares (from the animal protein intake) in 2050 by scenario and pathway.



(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 S2: 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 attainable by GCAM.

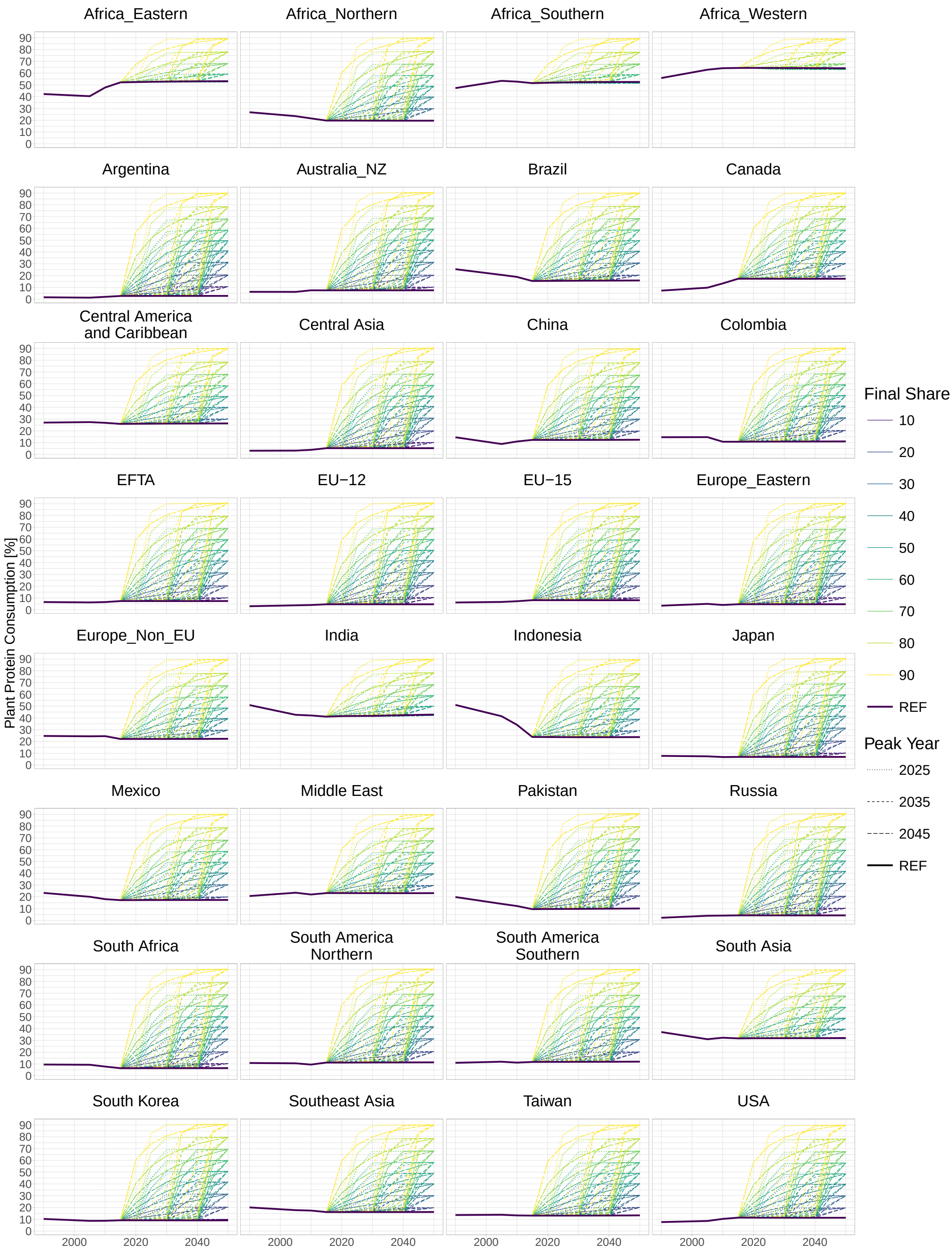


Figure S4: Regional annual plant protein consumption under the SPP scenario and the *all* pathway.

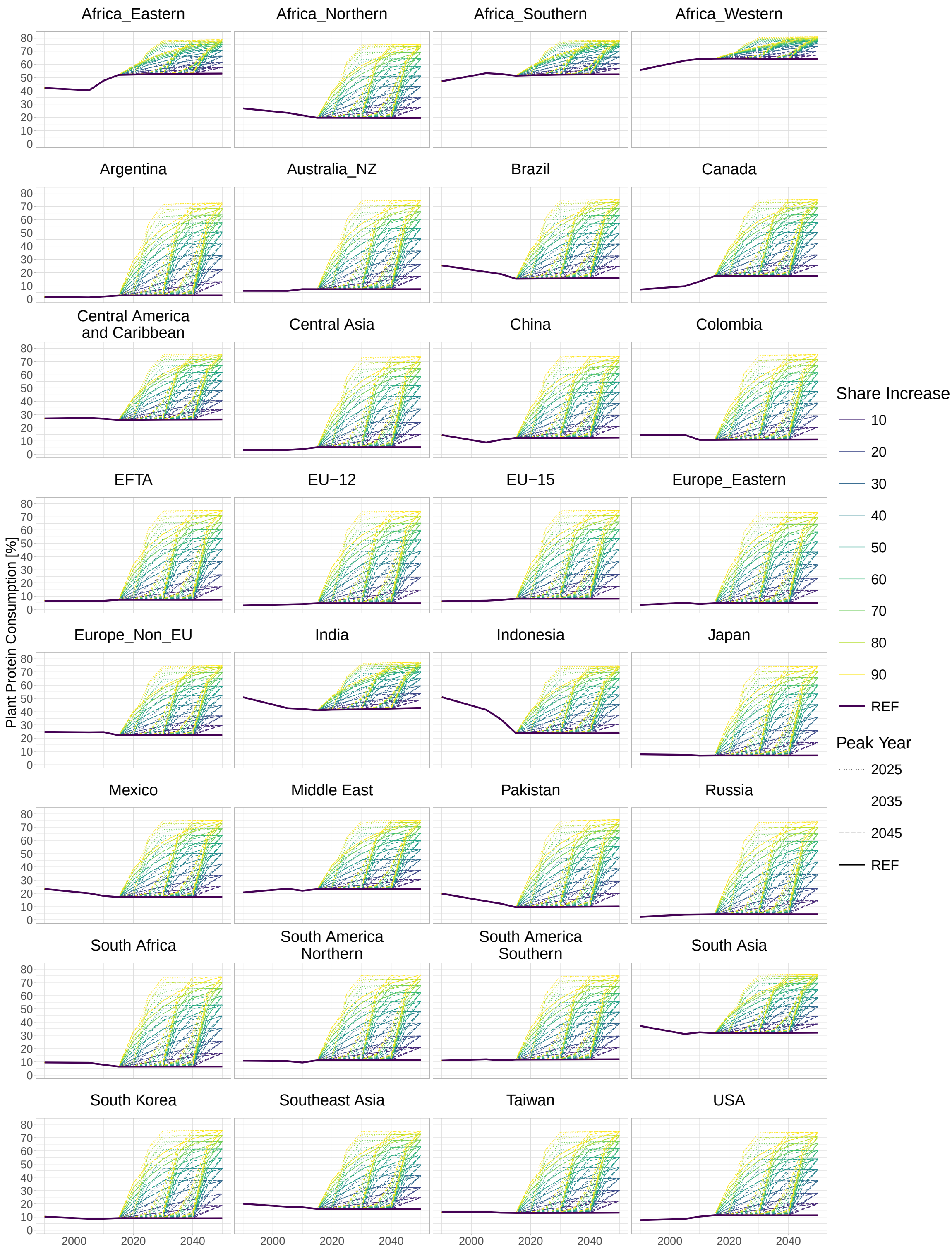


Figure S5: Regional annual plant protein consumption under the SPP scenario and the *plus* pathway.

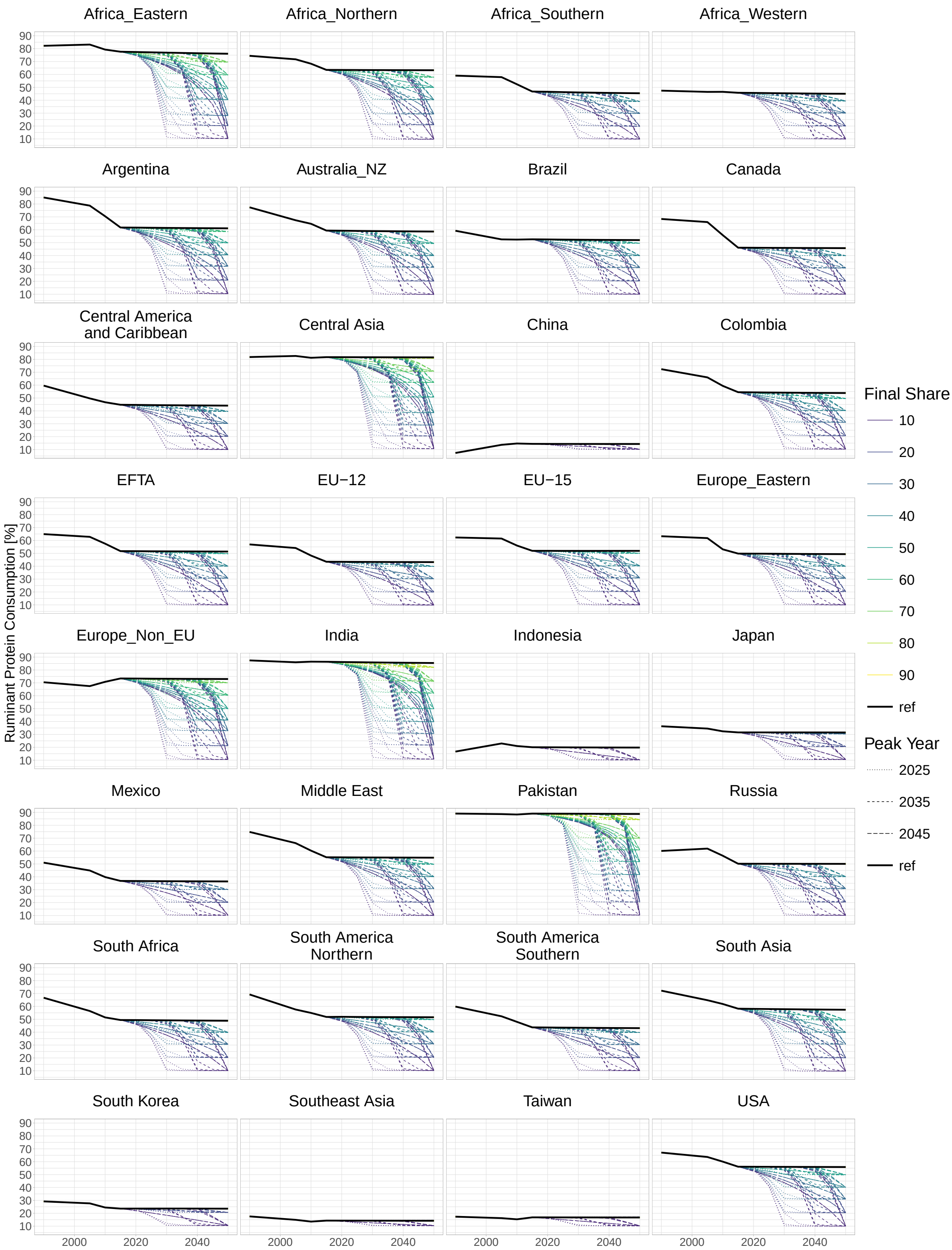


Figure S6: Regional annual ruminant protein consumption under the SNR scenario and the *all* pathway.

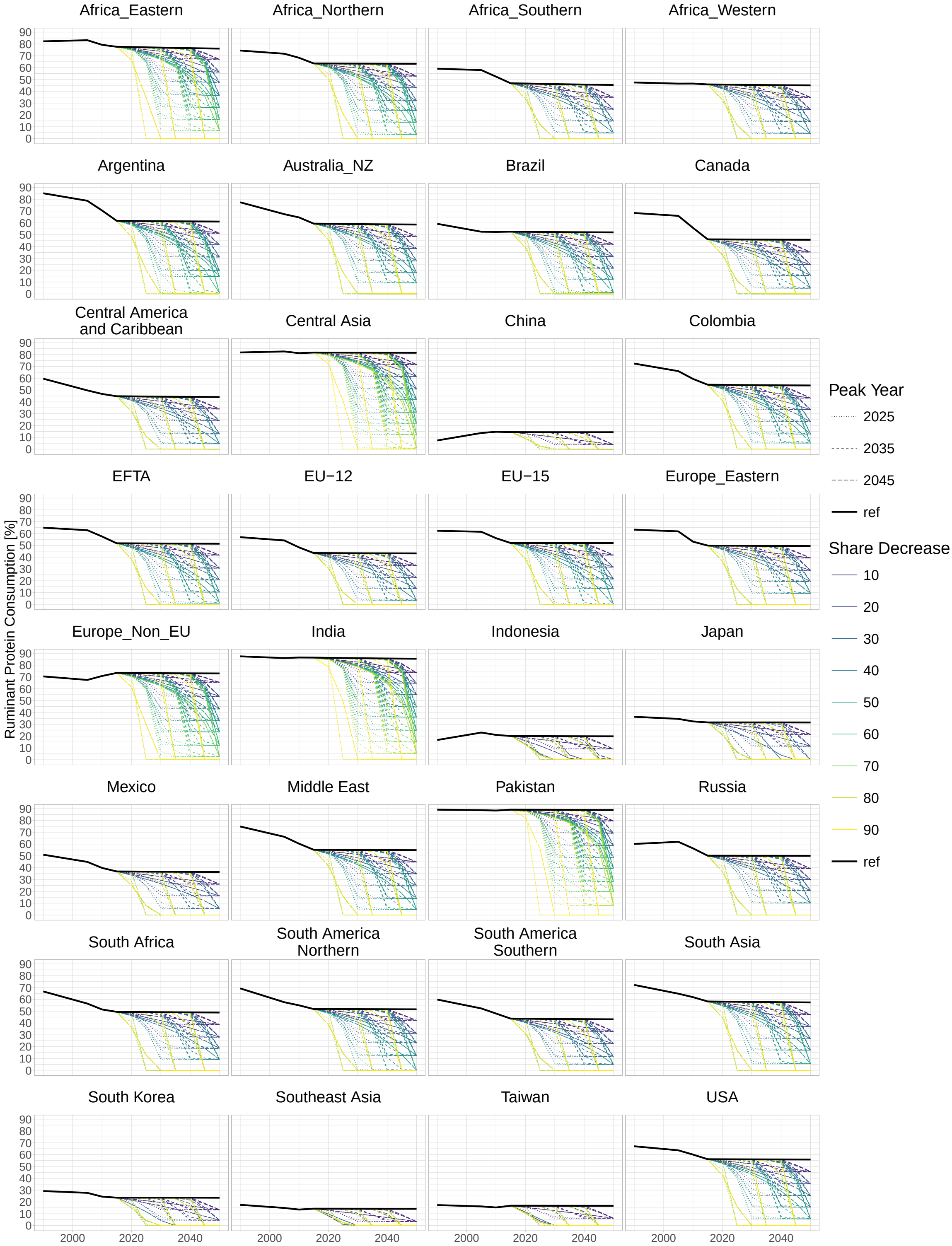


Figure S7: Regional annual ruminant protein consumption under the SNR scenario and the *plus* pathway.

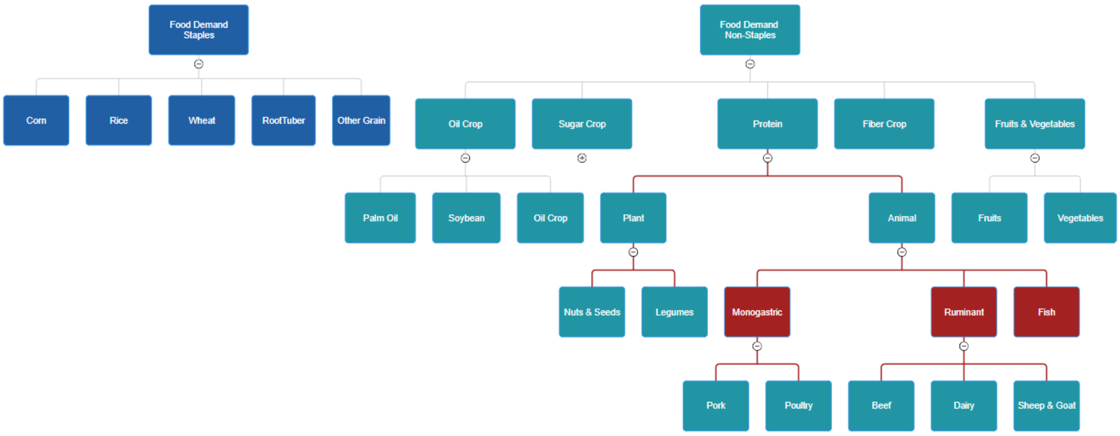


Figure S8: Staple & Non-staple food nesting structure. Red items emphasize the new nesting level added in our GCAM version.

S1.1 Study limitations

There are several limitations to the current modeling framework that future research 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.

S2 SDG3 - Nutrition

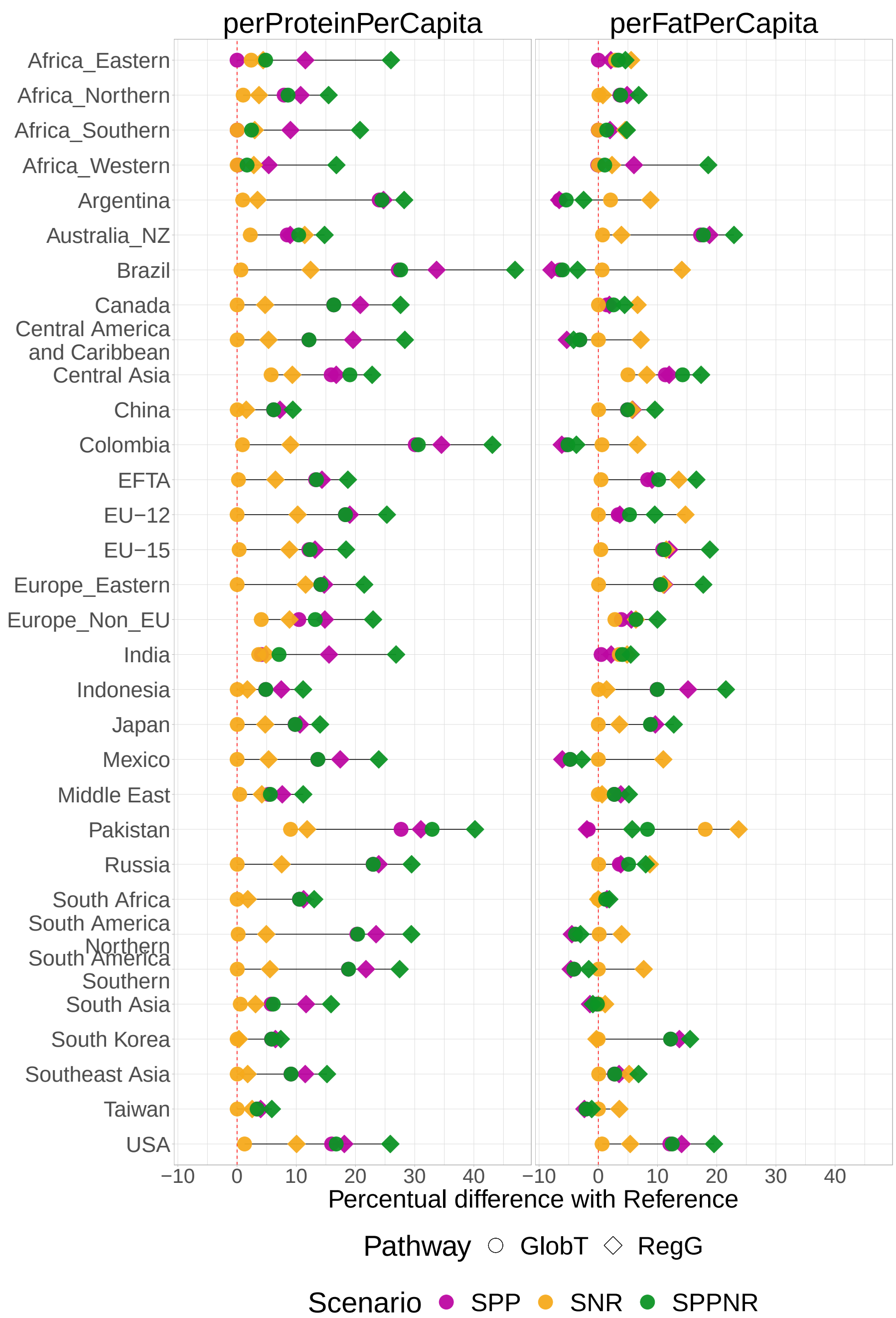


Figure S9: Regional percentage difference to Reference of protein and fat consumption as a percentage of energy intake [capita/day] of an average consumer by region in 2050. Dashed red line indicates a 0% difference.

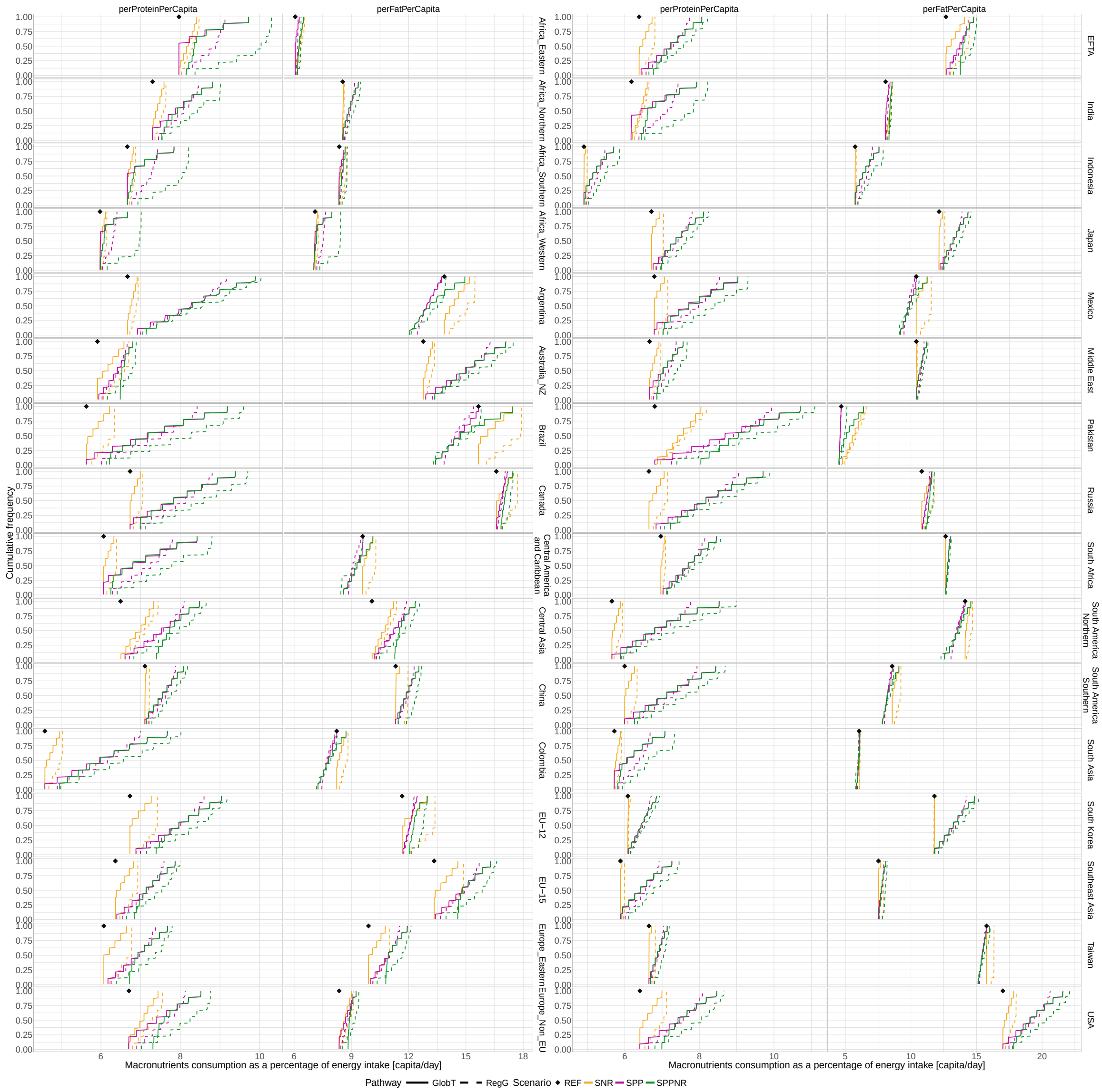
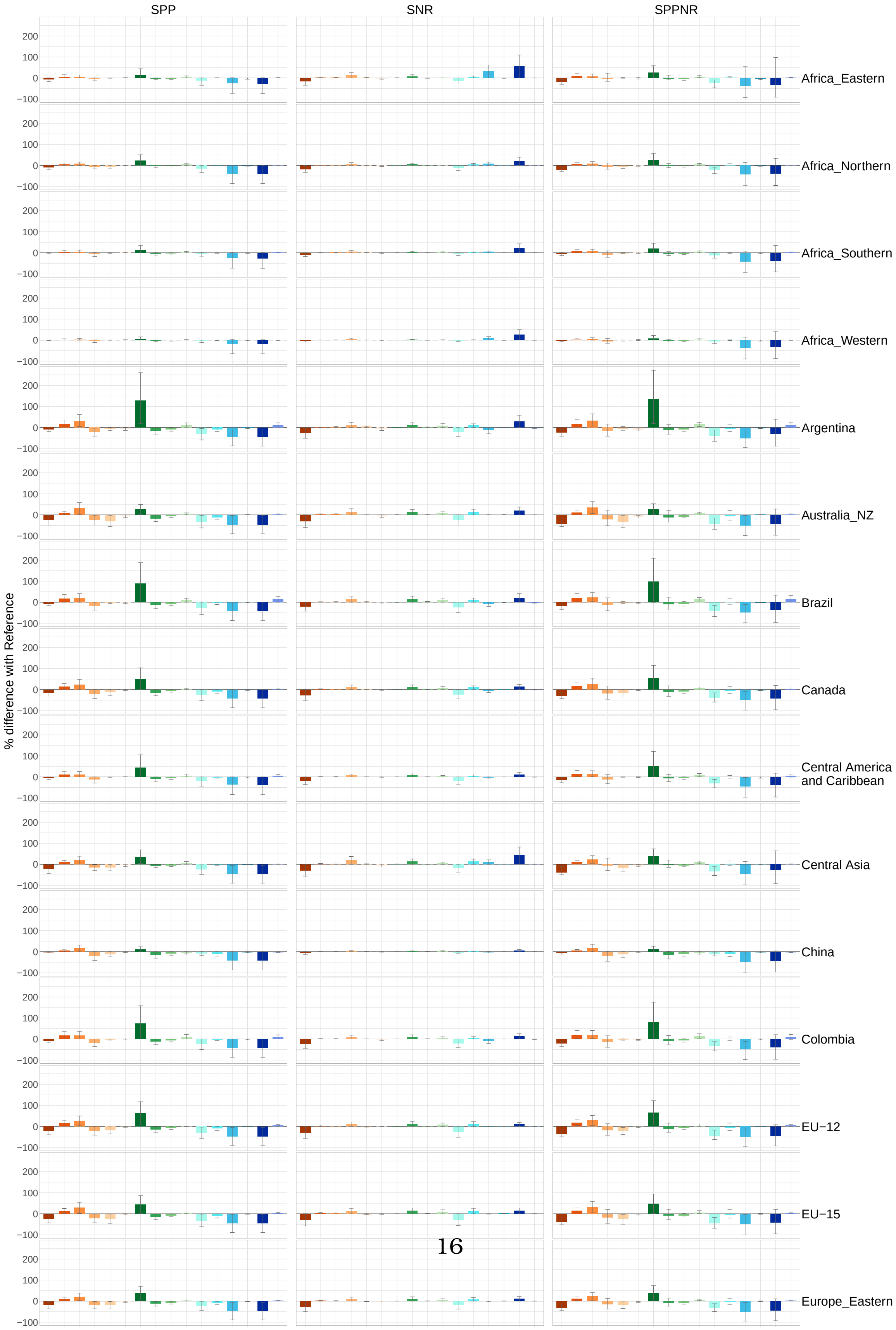


Figure S10: Cumulative functions of macronutrient consumption as a percentage of energy intake by region, scenario protein type (color), and scenario pathway (linetype) in 2050. The diamond bullets represent the Reference values.


SPP
SNR
SPPNR
% difference with Reference
200
100
0
−100
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

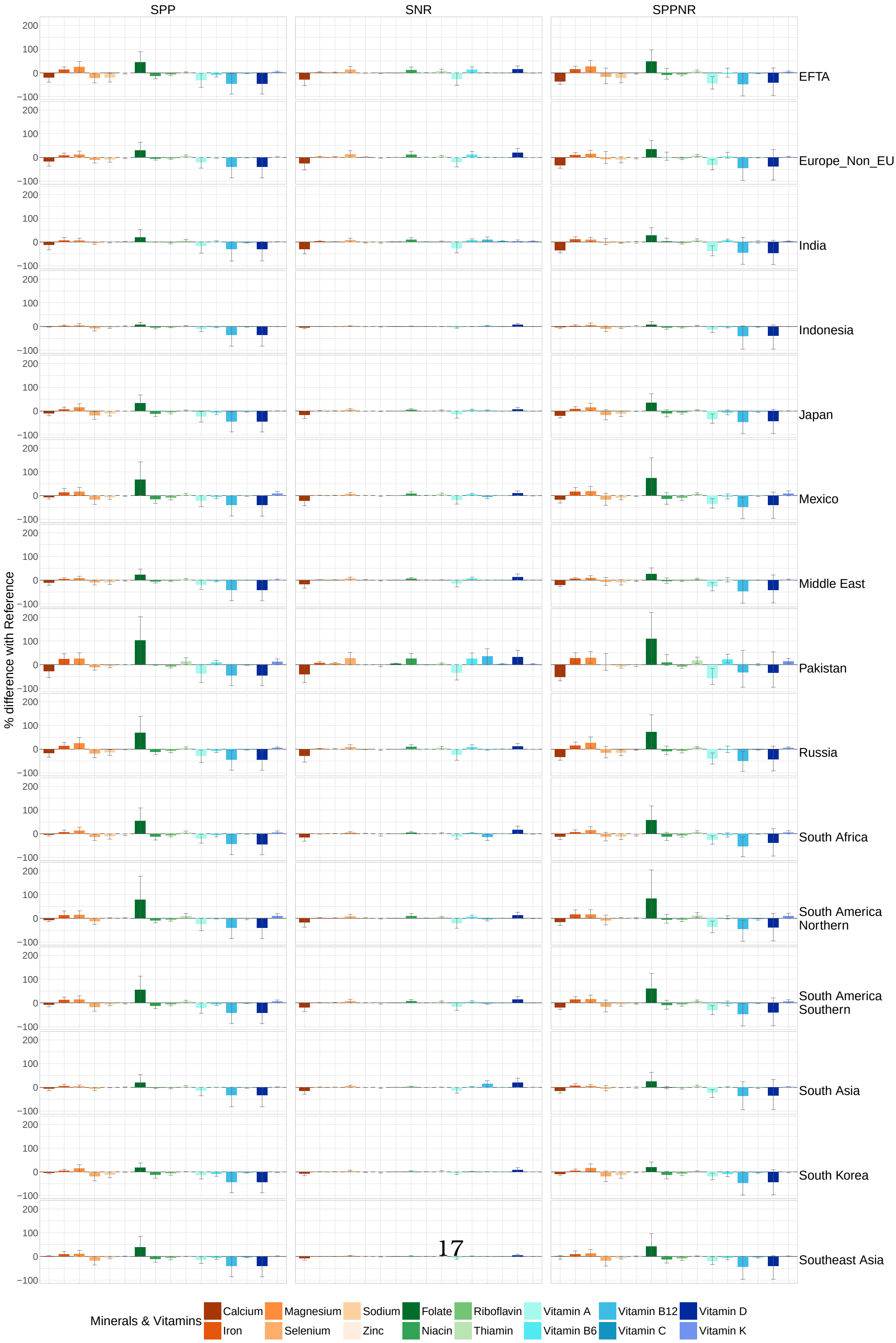


Figure S11: Regional percentage difference to Reference of micronutrient intake [capita/day] of an average consumer by region in 2050. Gray bars represent min-max intervals. The diamond bullets indicate the Reference values.

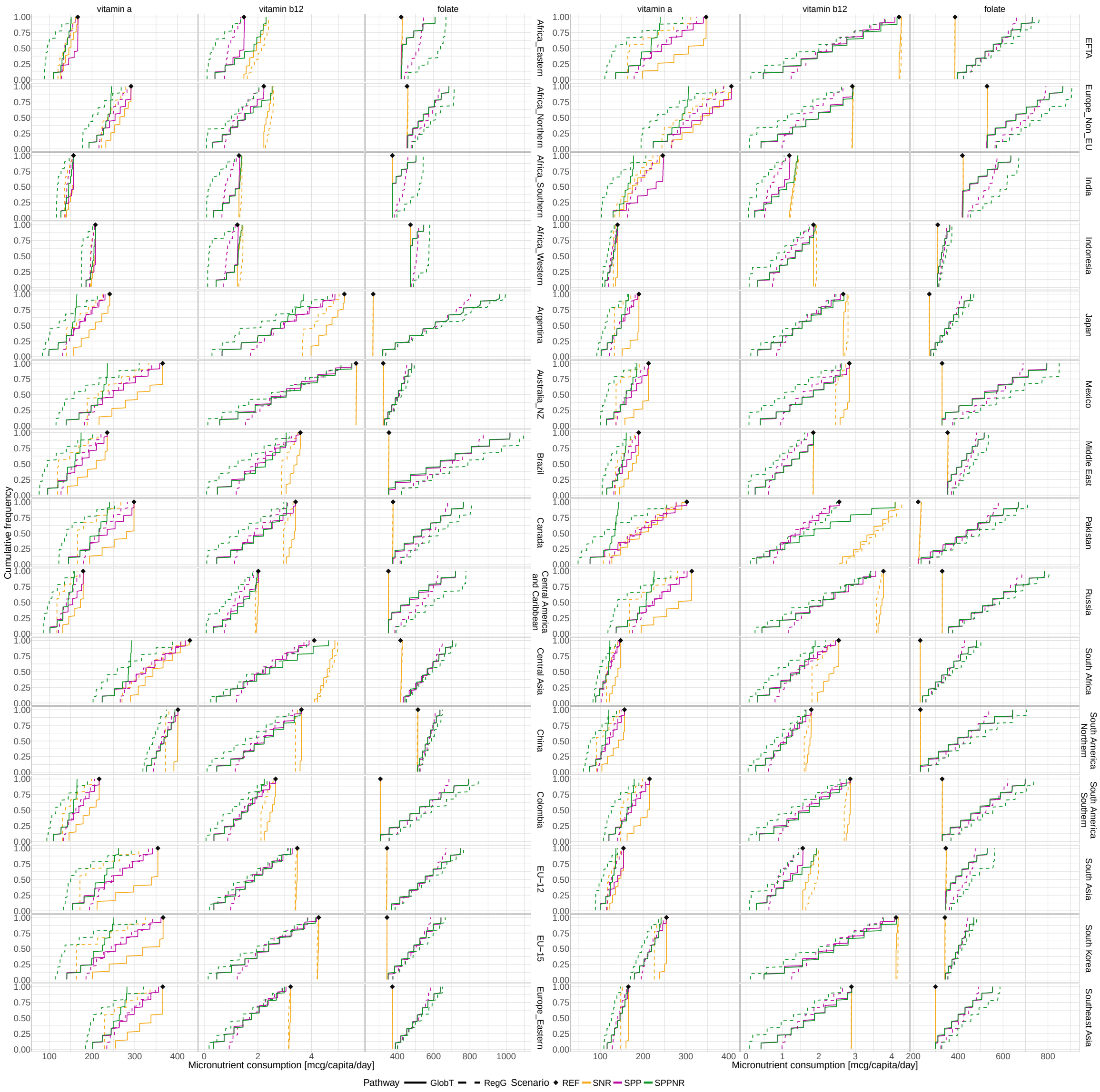


Figure S12: Cumulative functions of micronutrient consumption by region, scenario protein type (color), and scenario pathway (linetype) in 2050. The diamond bullets represent the Reference values.

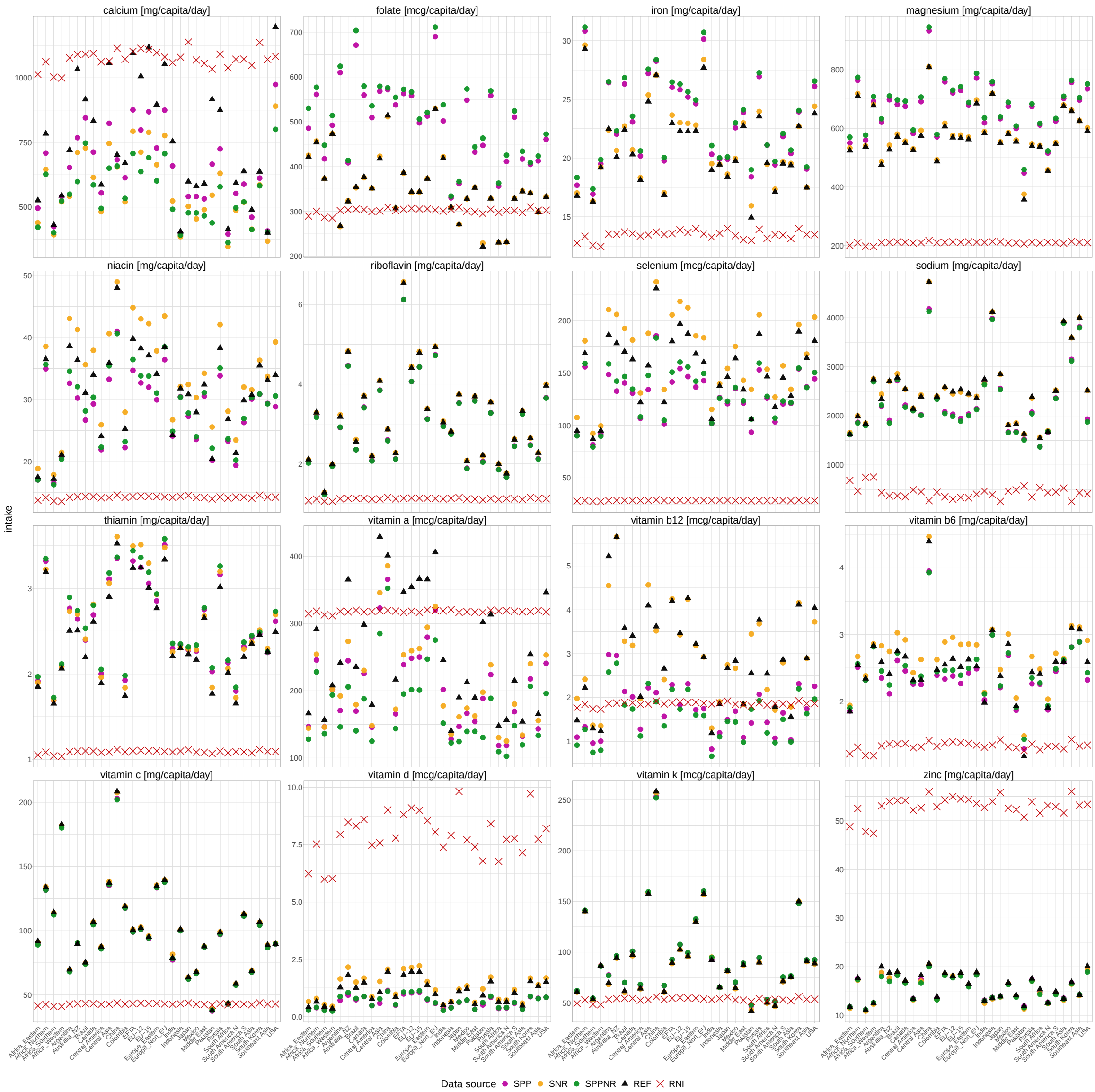


Figure S13: Micronutrient intakes by scenario and the Reference Nutrient Intake (RNI) [1] by region in 2050.

S3 SDG15 - Land

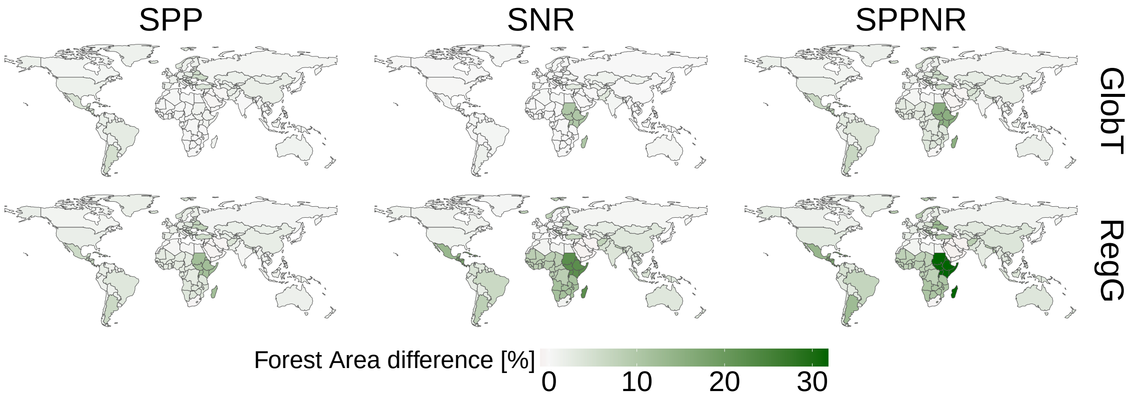


Figure S14: Percentage of forest area compared to Reference scenario in 2050.

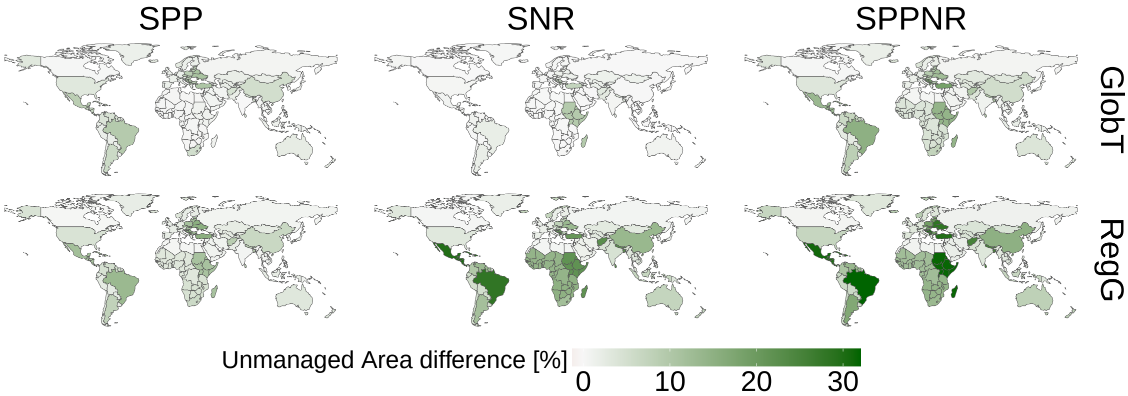


Figure S15: Percentage of unmanaged land compared to Reference scenario in 2050.

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., Taiwan) (Figure S15). 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].

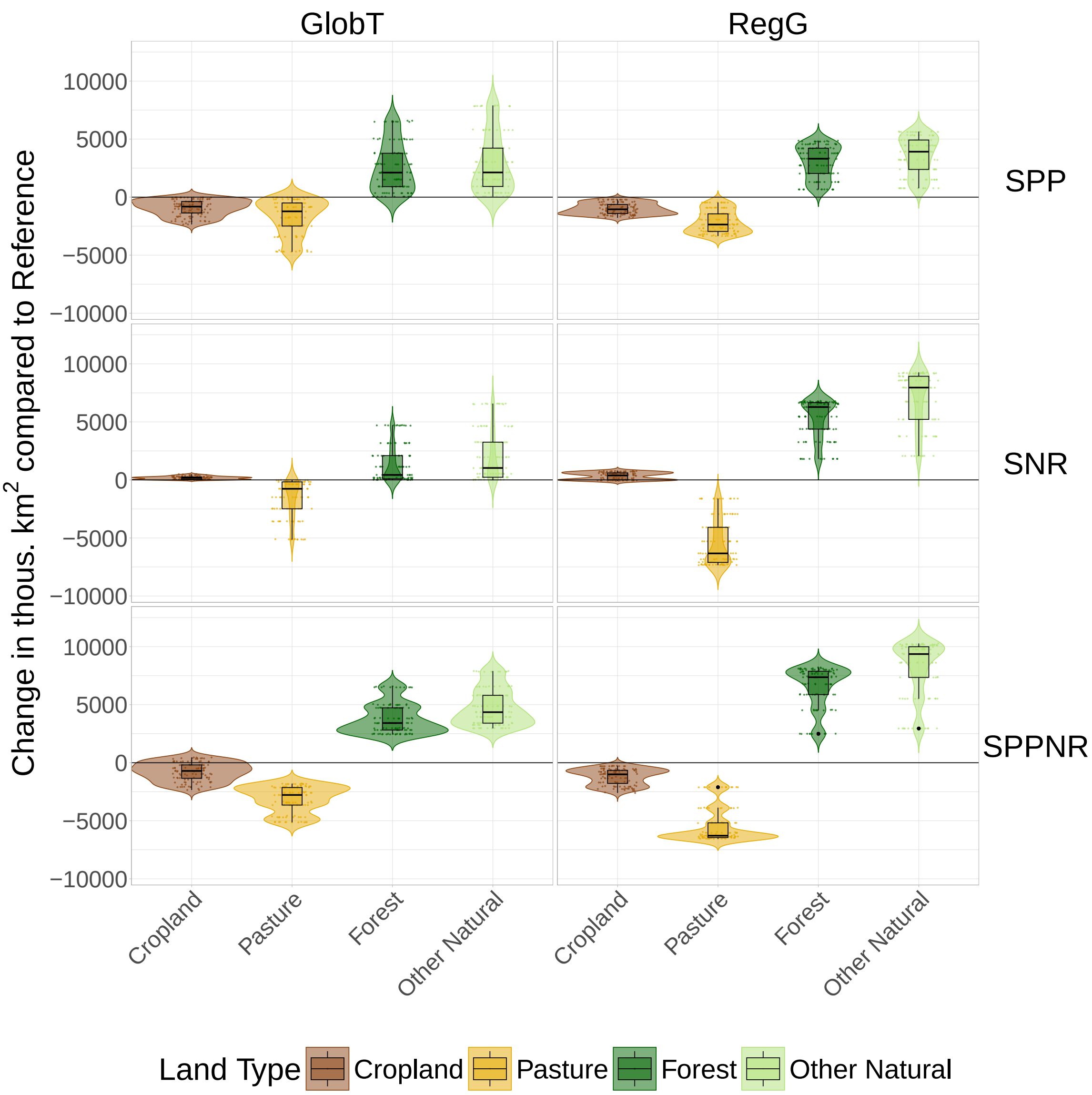
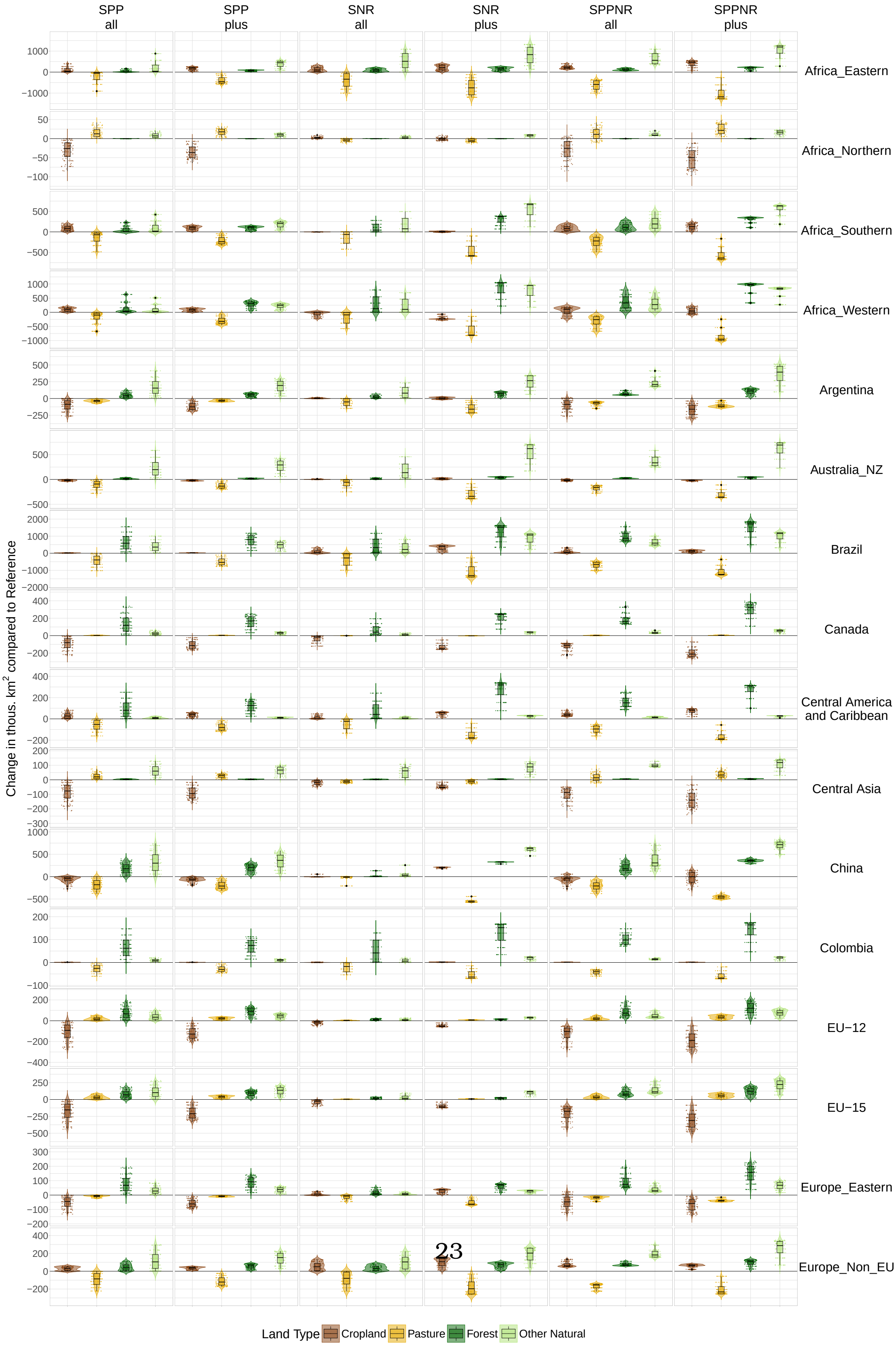


Figure S16: Global violin diagram for 2050 of the land area difference compared to Reference [thous. km^2] by scenario protein type and scenario pathway. The color indicates the land type. The box plot indicates the median, the 0.25 and 0.75 percentile, and the minimum and maximum values. Jittered points 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

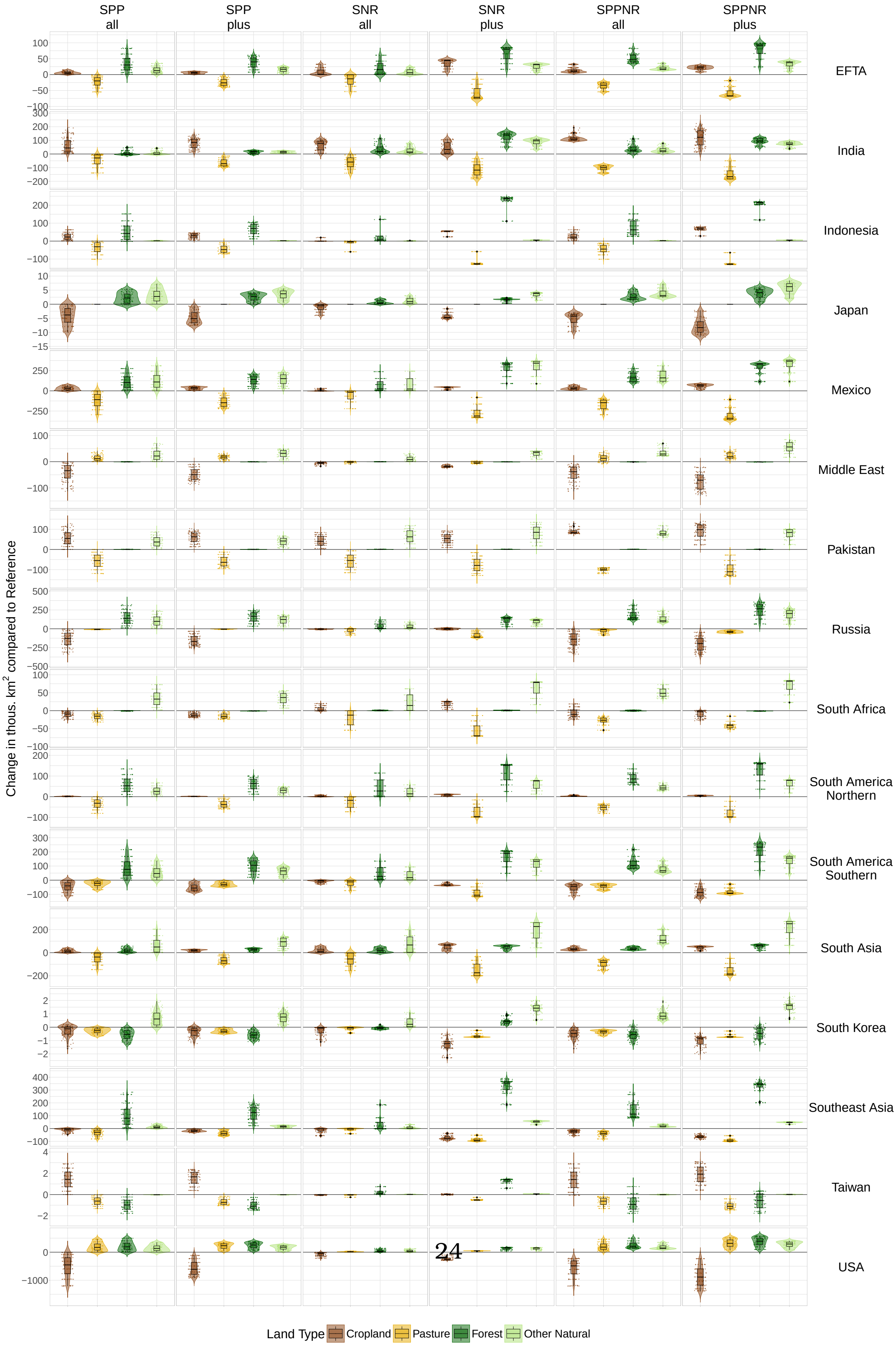


Figure S17: Violin diagram for 2050 of the land area difference compared to Reference [thous. km^2] by scenario protein type, scenario pathway, and region. The color indicates the land type. The box plot indicates the median, the 0.25 and 0.75 percentile, and the minimum and maximum values. Jittered points show all the data values.

S4 SDG6 - Water

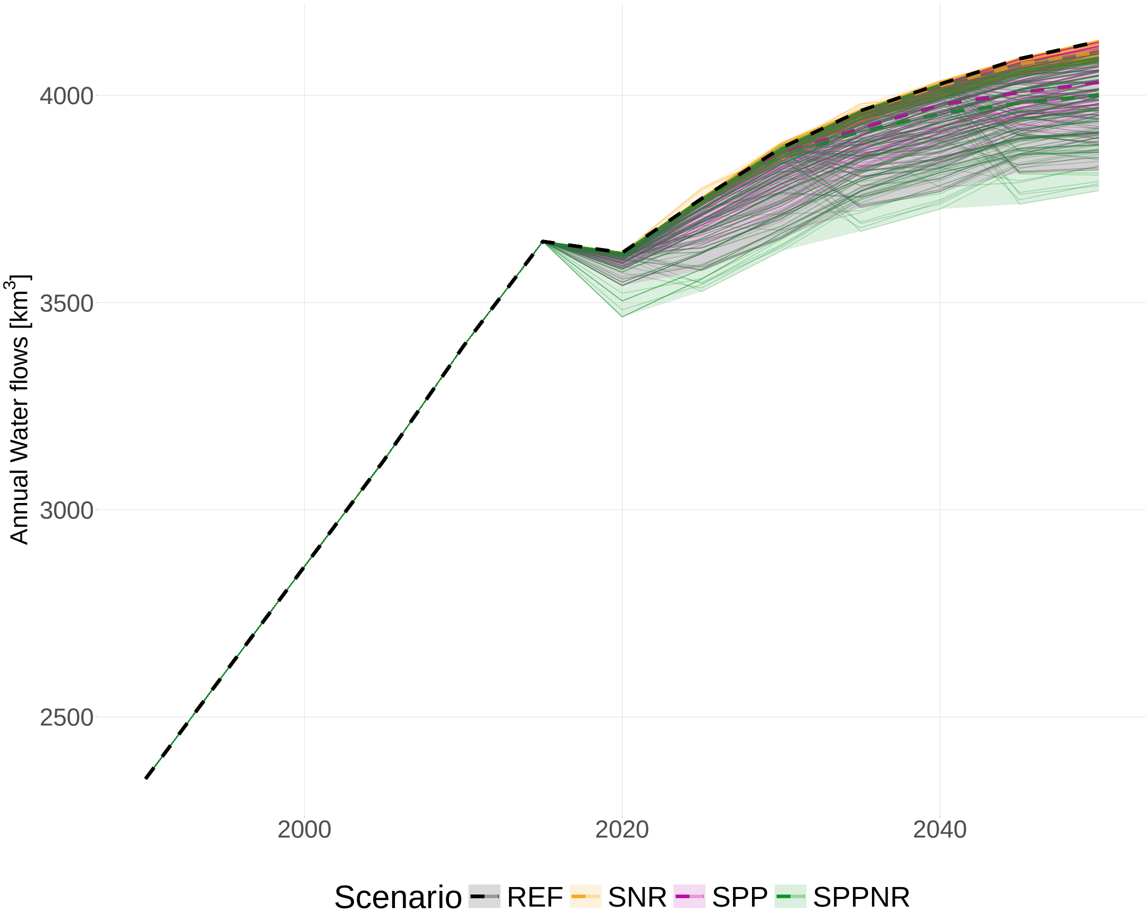


Figure S18: Global annual water withdrawals (km^3) by scenario protein type. The dashed line indicates the median.

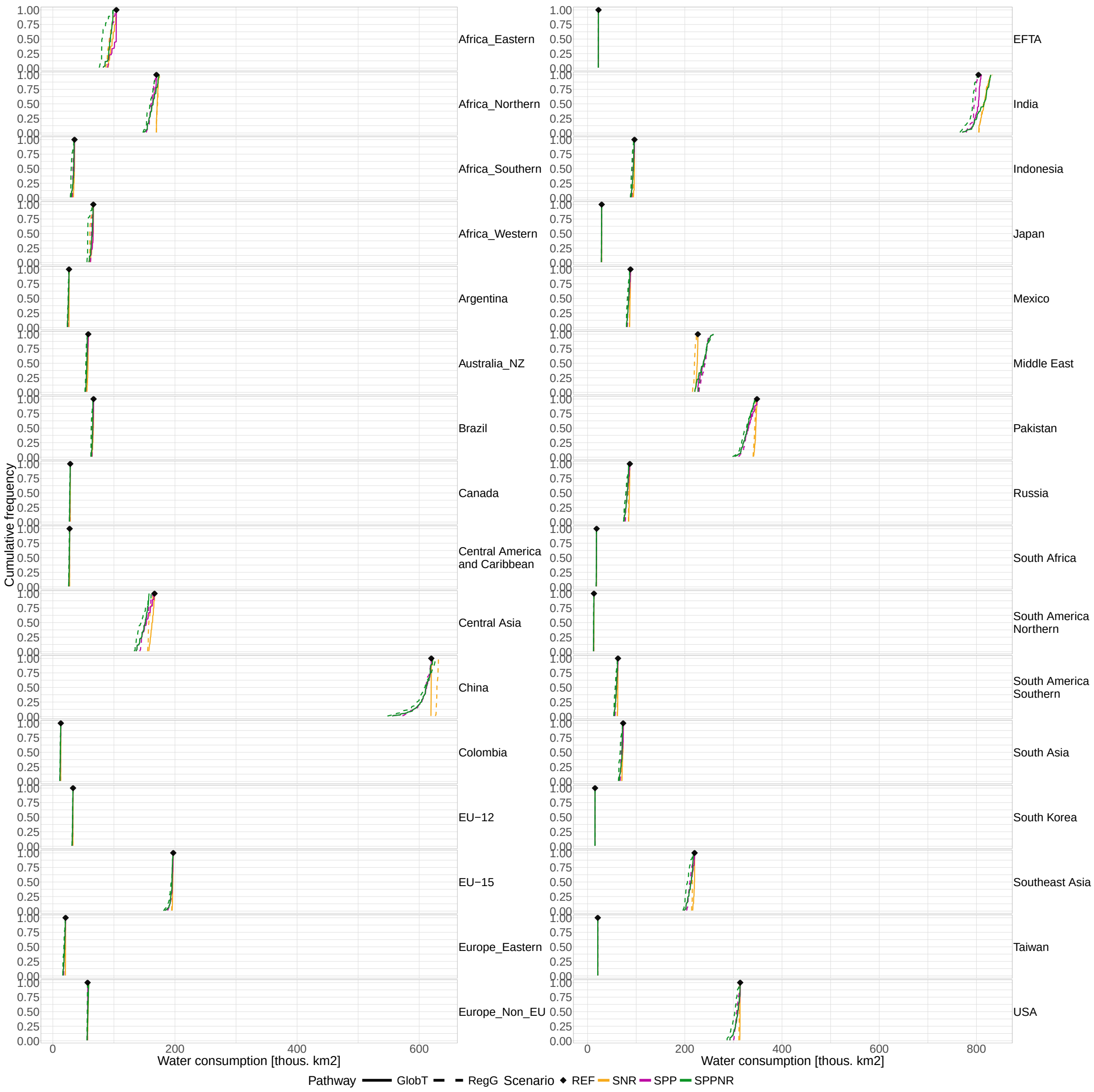


Figure S19: Cumulative functions of water withdrawals by region, scenario protein type (color), and scenario pathway (linetype) in 2050. The diamond bullets represent the Reference values.

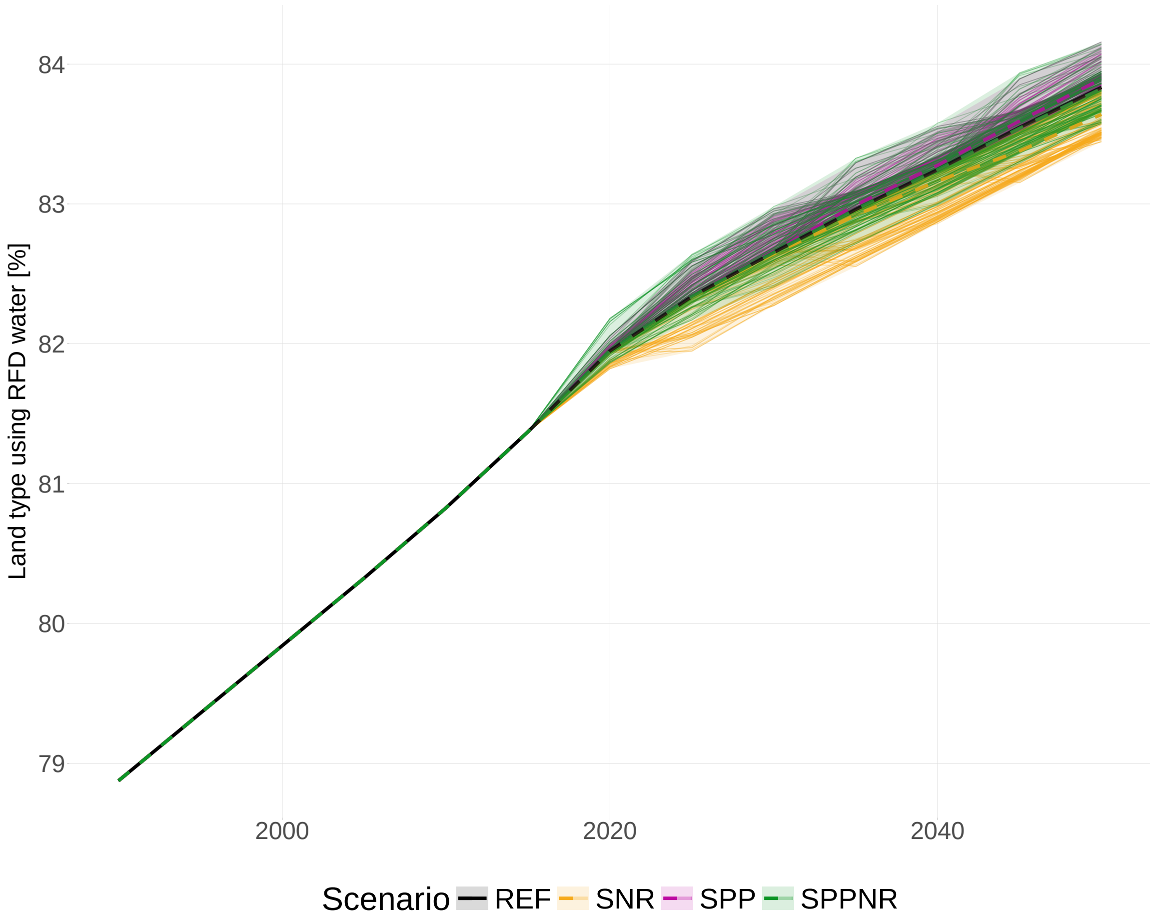


Figure S20: Global land types using rainfed water as a percentage of the overall (irrigated + rainfed) water land types by scenario.

The SPP scenario increases the share of land types utilizing 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 S20). All these trends are magnified under the *plus* pathway, further reducing the dependence on irrigated water (Figure S21).

Figure S21: Box plots of rainfed water land types share by region, scenario protein type (color), and scenario pathway (linetype/pattern) in 2050. The red dashed lines represent the Reference values.

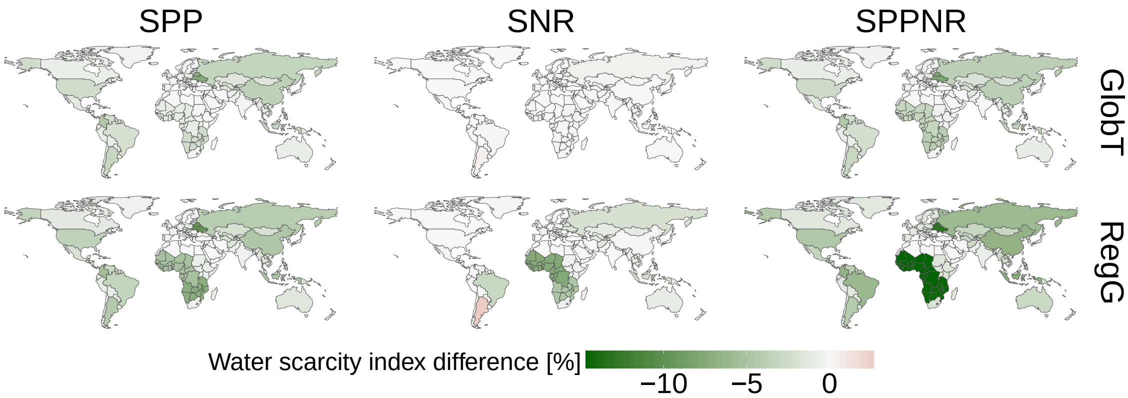


Figure S22: Reginal percentage water scarcity pressure in 2050 by scenario protein type and scenario pathway compared to Reference.

S5 SDG13 - Emissions

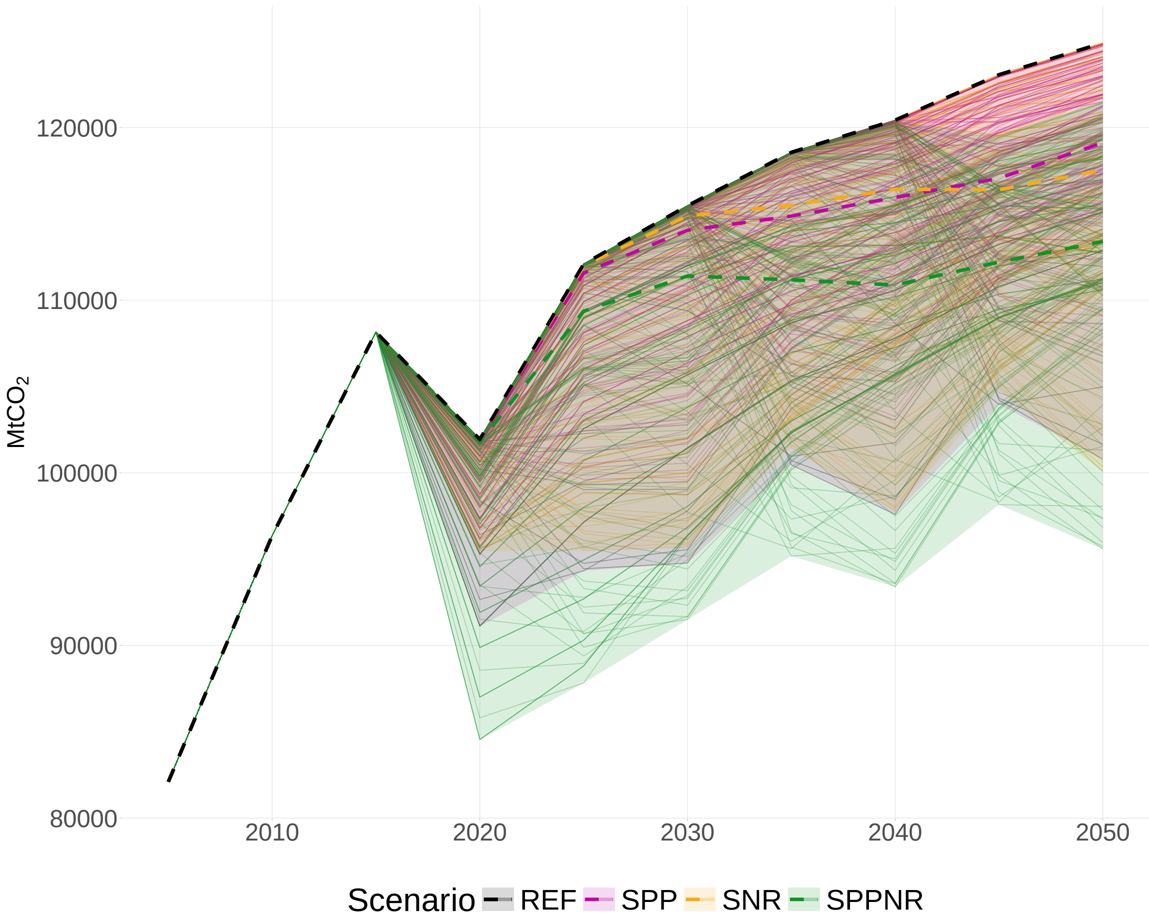


Figure S23: Global total GHG emissions (Mt CO_2) by scenario. The dashed line indicates the median.

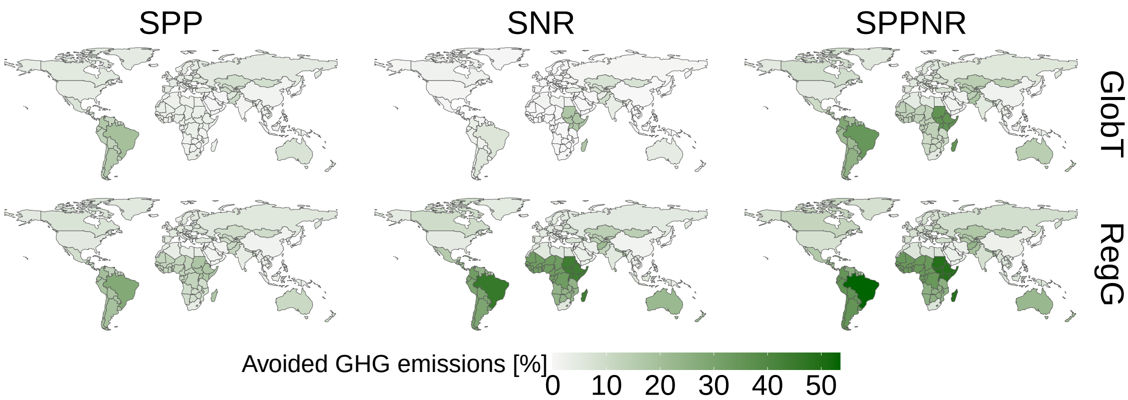
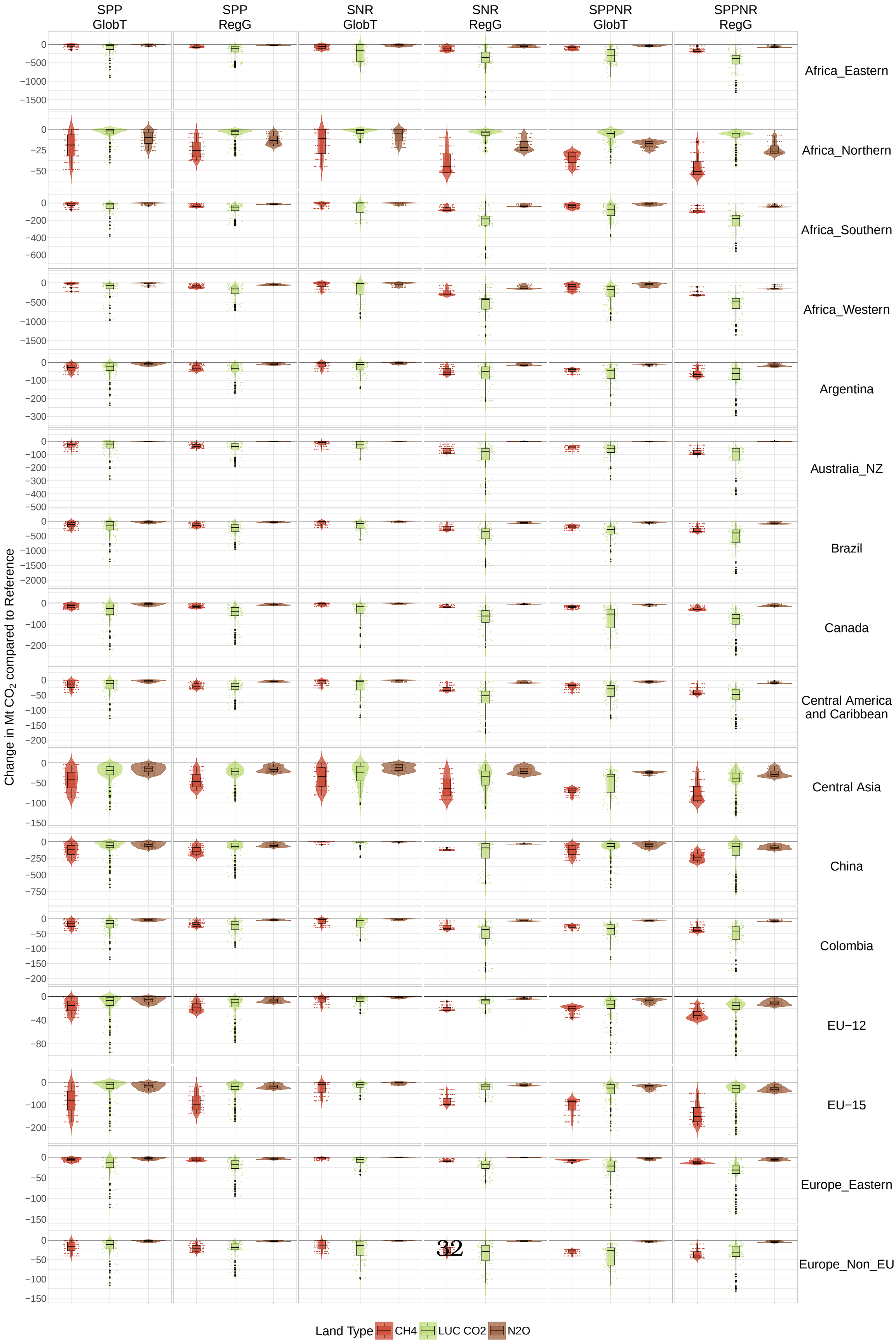


Figure S24: Regional percentage avoided GHG emissions by scenario protein type and scenario pathway in 2050.


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 CO_2 compared to Reference
Land Type
CH4
LUC CO2
N2O

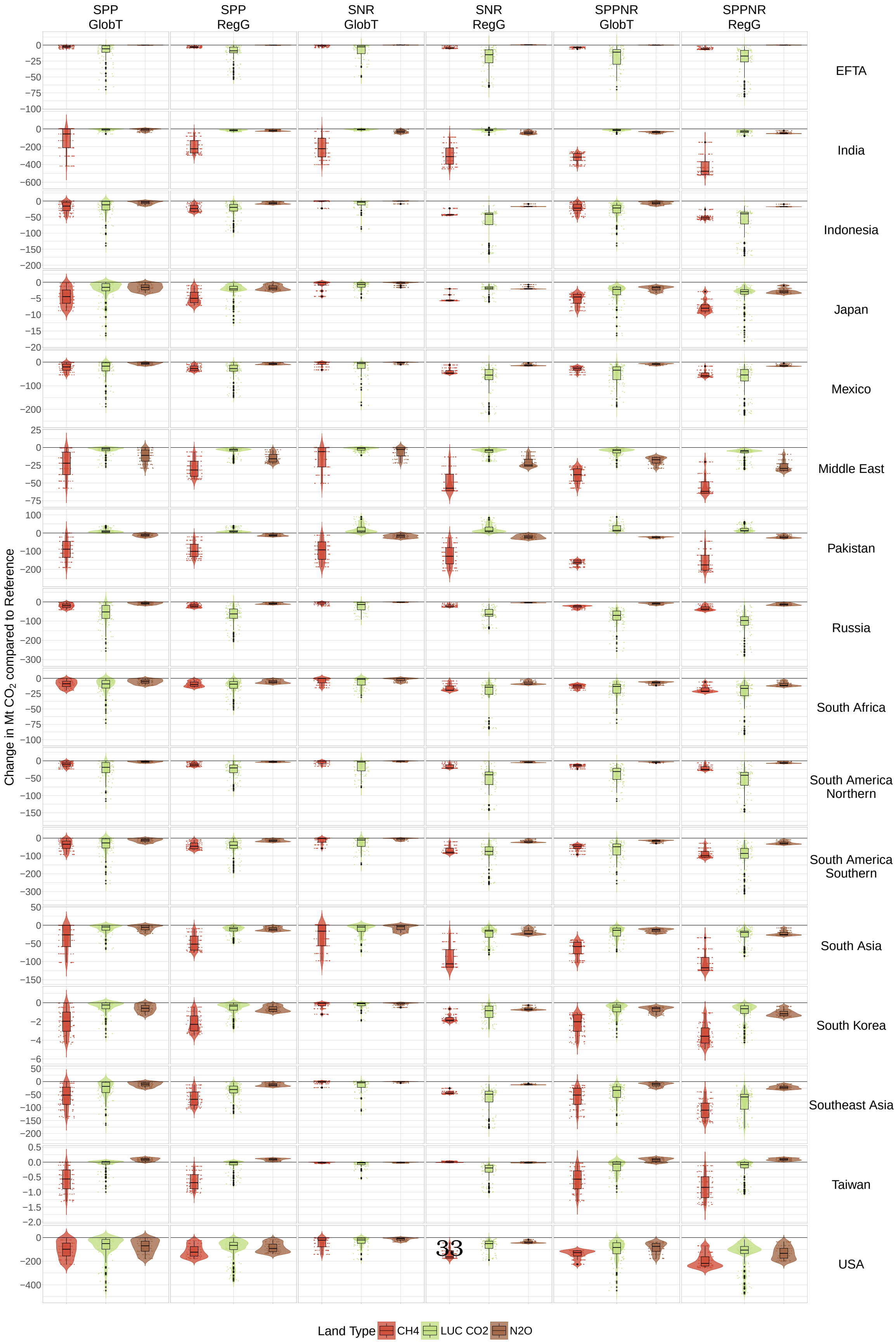


Figure S25: Violin diagram for 2050 of the emissions difference compared to Reference [Mt CO_2] by scenario protein type, scenario pathway, and region. The color indicates the GHG type. The box plot indicates the median, the 0.25 and 0.75 percentile, and the minimum and maximum values. Jittered points show all the data values.

Figure S26: Cumulative functions of premature deaths due to outdoor air pollution by region, scenario protein type (color), and scenario pathway (linetype) in 2050. The diamond bullets represent the Reference values.

S6 SDG2 - Food basket bill

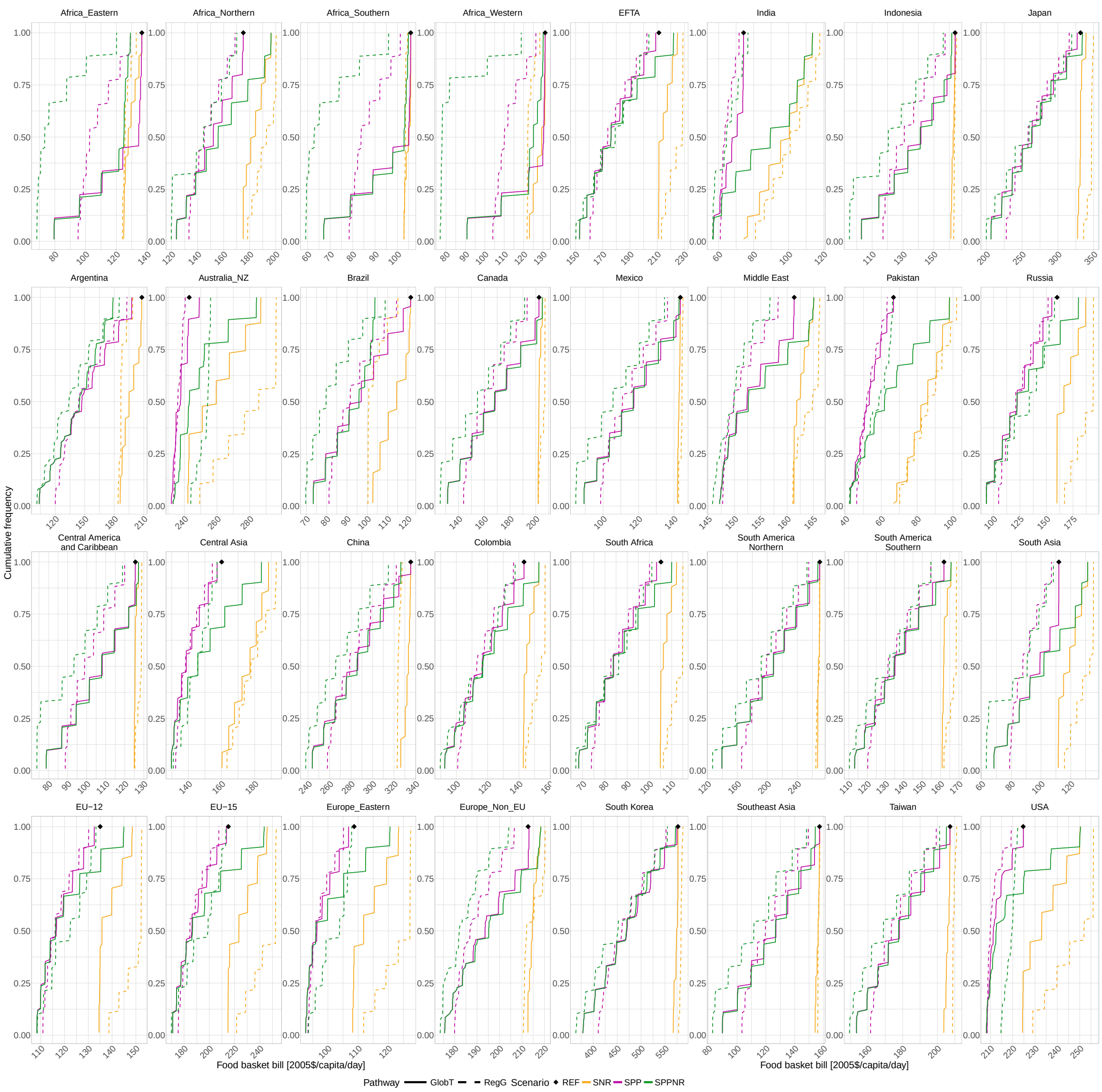


Figure S27: Cumulative functions of food basket bill by region, scenario protein type (color), and scenario pathway (linetype) in 2050. The diamond bullets represent the Reference values.

S7 SDG13 - Policy cost

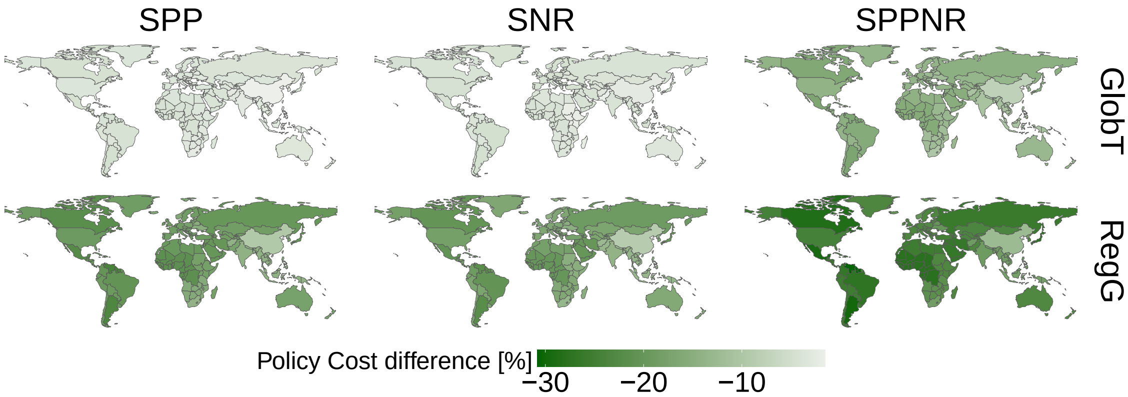


Figure S28: Policy cost regional percentage difference compared to Reference scenario in 2050.

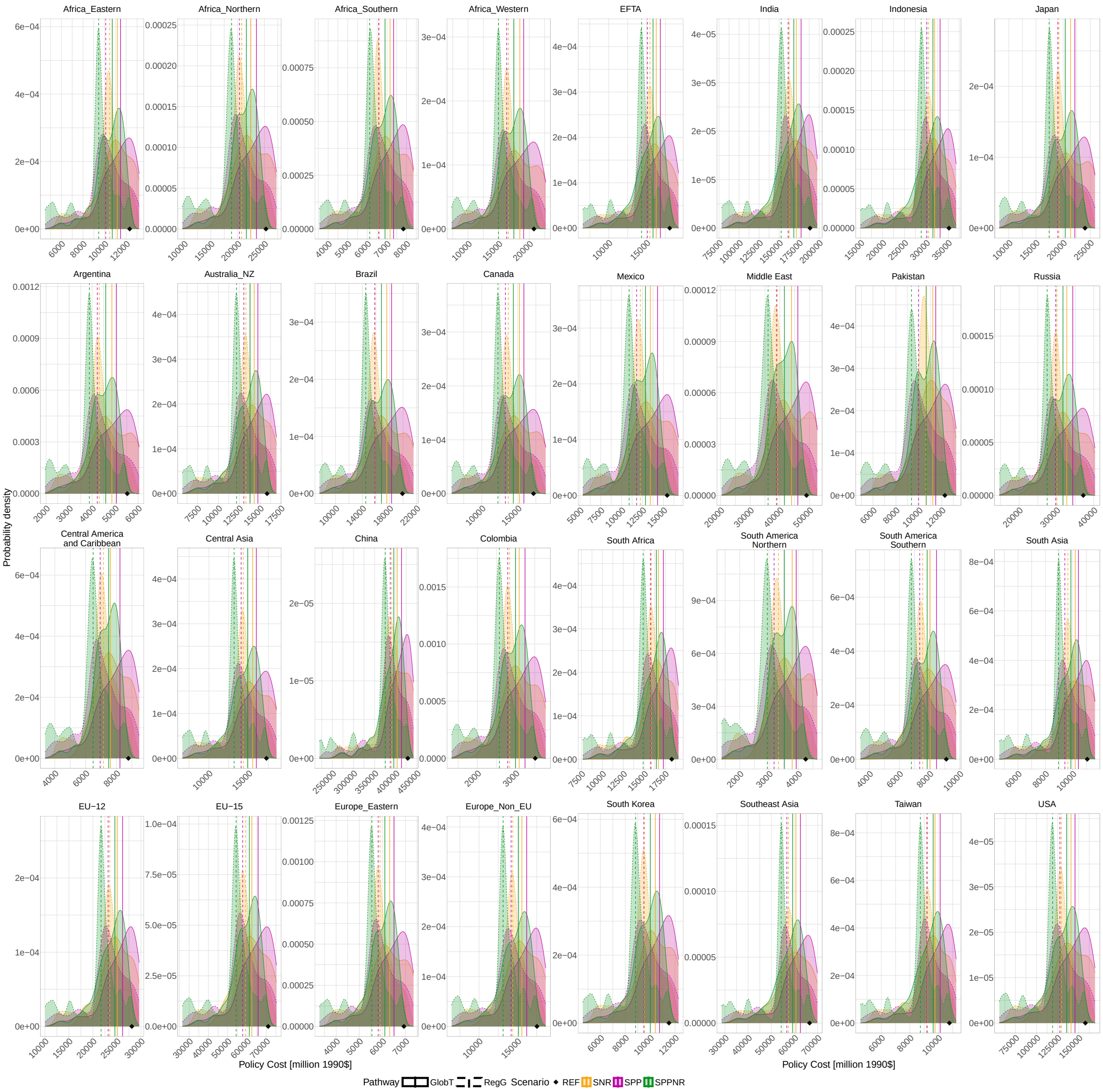


Figure S29: Probability density plots of regional policy costs in 2050 by scenario protein type and scenario pathway. The vertical lines indicate the median and the bullet point the Reference value.

References

[1] Joint FAO/WHO Expert Consultation on Human Vitamin and Mineral Requirements (1998 : Bangkok, Thailand). *Vitamin and Mineral Requirements in Human Nutrition: Report of a Joint FAO/WHO Expert Consultation, Bangkok, Thailand, 21–30 September 1998*. World Health Organization, Geneva, 1998.

[2] Isabela Schmidt Tagomori, Mathijs Harmsen, Muhammad Awais, Edward Byers, Vassilis Daioglou, Jonathan Doelman, Adriano Vinca, Keywan Riahi, and Detlef P Van Vuuren. Climate policy and the SDGs agenda: how does near-term action on nexus SDGs influence the achievement of long-term climate goals? *Environmental Research Letters*, 19(5):054001, May 2024.

[3] Richard D Bardgett, James M Bullock, Sandra Lavorel, Peter Manning, Urs Schaffner, Nicholas Ostle, Mathilde Chomel, Giselda Durigan, Ellen L Fry, David Johnson, et al. Combatting global grassland degradation. *Nature Reviews Earth & Environment*, 2(10):720–735, 2021.

[4] Mark Rosegrant, Ximing Cai, Sarah Cline, and Naoko Nakagawa. The role of rainfed agriculture in the future of global food production. 02 2002.

[5] Jens Heinke, Mats Lannerstad, Dieter Gerten, Petr Havlík, Mario Herrero, An Maria Omer Notenbaert, Holger Hoff, and Christoph Müller. Water Use in Global Livestock Production—Opportunities and Constraints for Increasing Water Productivity. *Water Resources Research*, 56(12):e2019WR026995, December 2020.