

Core Model Proposal #411:

GCAM Macro-Economic Module
KLEAM and Related Agriculture Sector
Updates

September 2026

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U.S. DEPARTMENT
of **ENERGY**

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Core Model Proposal #411: GCAM Macro-Economic Module KLEAM and Related Agriculture Sector Updates

Product: Global Change Analysis Model (GCAM)

Institution: Joint Global Change Research Institute (JGCRI)

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Purpose: This Core Model Proposal (CMP-411) introduces the GCAM **Macro-Economic Module KLEAM** (Capital-Labor-Energy-Agriculture-Materials), an extension of the existing GCAM-Macro (KLEM) framework that explicitly integrates primary agriculture, energy systems, and materials production within a unified macroeconomic accounting and market-clearing structure. Building on prior macroeconomic and socioeconomic updates in GCAM (CMP-332, CMP-399, CMP-410), this proposal advances the representation of labor, capital, savings, and investment across agriculture, energy, and materials sectors, enabling more consistent feedback between sectoral production decisions and aggregate economic outcomes (e.g., GDP, capital rental prices, and wage rates). In addition essential data updates in agriculture (crops, livestock, and forestry) and socioeconomic modules, key advancements include: (i) explicit representation of labor and capital inputs in primary agricultural sectors with technology- and region-level value tracing; (ii) updated capital cost and investment tracking for primary agriculture, energy supply and energy service sectors; (iii) extensions to the materials nested CES production function to incorporate agricultural nonfood services and revised energy service value assumptions; (iv) improved treatment of final consumption (including agricultural food services), trade balance, and national accounting consistency; and (v) new mechanisms for labor mobility, savings–investment market clearing, capital price feedbacks, and aggregate GDP responses. These advances establish a more internally consistent macroeconomic structure for GCAM and lay the foundation for deeper integration of human-Earth systems.

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1. Introduction

Global economic multisector dynamic models increasingly rely on internally consistent macroeconomic representations to capture feedbacks between economic growth, sectoral production, and resource supply (Bauer et al., 2008; Fernández-Villaverde et al., 2025; Harmsen et al., 2021). Capturing interactions between macroeconomic responses and sectoral drivers (e.g., biophysical, technological, or policy shocks) is essential for evaluating economy-wide impacts of energy transitions, agricultural change, and land-use change, as sector-specific dynamics can propagate through factor markets, prices, and investment decisions (Edmonds et al., 2025; Lima et al., 2021; McFarland et al., 2018).

Historically, GCAM relied on exogenous trajectories of GDP to drive final demand and sectoral activity, which provided a transparent linkage between socioeconomic pathways and sectoral activity but limited the model's ability to represent feedbacks between sectoral dynamics and aggregate economic outcomes. As the representation of energy systems, agriculture, and land use in GCAM became more detailed (and increasingly policy-relevant in many applications), the absence of endogenous macroeconomic adjustment increasingly constrained the model's analytical scope.

To address this limitation, the GCAM-Macro KLEM framework was introduced as an optional model feature (CMP-332) (Patel et al., 2023), establishing a parsimonious yet flexible macroeconomic structure that links GCAM energy systems to an aggregated materials sector representing the rest of the economy through materials production and capital investment constraints. This framework enabled endogenous GDP responses through energy–materials interactions and factor market clearing for labor and capital.

At the same time, agriculture plays a central role in economic development, labor market evolution, and land and water use, while interacting closely with energy and food systems (Edmonds et al., 2017; Hertel, 2011). Structural transformation associated with agricultural productivity growth has long been recognized as a key driver of labor reallocation and income growth, particularly in developing economies, while agricultural production and consumption remain closely linked to energy use and materials demand across the broader economy (Fuglie, 2018; Sheng et al., 2025).

The gap between primary agriculture and the macroeconomic framework is therefore particularly notable given that GCAM already includes a sophisticated and data-rich representation of primary agriculture, including land-use allocation, crop and livestock production, forestry, and associated biophysical processes (Zhao et al., 2024a; Zhao and Wise, 2023). Bridging this detailed agricultural system with the macroeconomic framework is therefore important to ensure internal consistency between sectoral production decisions, factor markets, final demand, and aggregate economic outcomes.

Building on the KLEM foundation (CMP-332) (Patel et al., 2023) and recent socioeconomic and macro data updates (CMP-399 and CMP-410) (Zhao et al., 2025, 2024b), the KLEAM extension further expands the macroeconomic representation by explicitly integrating primary agriculture into the materials production, final consumption, investment, and factor market structure. In doing so, KLEAM strengthens the endogenous determination of capital rental prices (gross capital rates of return) and wage rates, allowing changes in economy-wide factors, such as savings, labor force supply, and productivity growth, to feed back consistently into agriculture and energy system decision-making.

This Core Model Proposal (CMP-411) documents the conceptual design, data foundations, and technical implementation of the KLEAM framework, along with initial diagnostic results and model validation runs. In addition, the CMP documents several updates to GCAM agricultural sector parameterization and assumptions that were required for compatibility and generating useful scenarios with the KLEAM framework.

2. Conceptual and Technical Advancements in GCAM-Macro KLEAM

The GCAM-Macro KLEAM framework introduces several structural extensions to the GCAM modeling system, expanding the macroeconomic representation and strengthening integration between macroeconomic dynamics and sectoral modules. Key advances include the explicit representation of labor and capital in primary agriculture, the introduction of a unified regional capital market with endogenous capital rental price feedback, revised materials production structure, and updated representations of productivity and biomass supply calibration. An overview of the accounting framework is presented in **Fig 1**.

Because several components of the KLEAM framework involve substantial structural modifications and extensive data development, the full methodological descriptions are documented in the accompanying GCAM-Macro KLEAM Research Memoranda, which are included as appendices to this CMP. These memorandums provide detailed descriptions of the model architecture, data construction, and implementation procedures that underpin the changes summarized in this proposal. Accordingly, the main CMP document focuses on the overarching conceptual advances and their implications for model behavior, while the technical memorandums provide more comprehensive documentation of individual model components. In many cases, figures presented in the main CMP are extracted from the appendices, where they are accompanied by additional technical explanations and supporting details. Each memorandum is designed to function as a standalone reference document; however, all appendices are attached to and released together with this CMP. The following memorandums/appendices are included:

- **Appendix A:** Architecture of the GCAM-Macro KLEAM Framework, Accounting Structure, Materials Production Function, and Agricultural and Energy Service Inputs
 - See **Fig. 1** and additional details in Appendix A.
- **Appendix B:** Value-Added (Land, Labor, Capital) Representation in Primary Agriculture, Labor Supply, and Labor Market Clearing
 - In the KLEAM implementation, we updated the source datasets to more recent versions, improved several underlying data assumptions (e.g., land rental profit, feed prices, forest production costs) and associated data processing procedures, and conducted additional cross-verification using an agricultural value-added dataset from FAO.
 - Labor supply is now represented at the regional level using a logit-based sharing function that allocates total regional employment (derived from working-age population estimates and corresponding labor participation and employment assumptions) between the agriculture and materials sectors. A common wage rate is assumed across primary agricultural sectors, reflecting the assumption that labor is perfectly mobile within agriculture. Thus, the Materials and Agriculture sectors are connected through regional labor supply while their sectoral labor markets clear separately.

- **Appendix C: Capital Costs, Capital Accumulation, Investment Allocation, Savings–Investment Closure, and Capital Rental Price Feedback**
 - Introduces a unified regional capital market with an endogenous capital rental price that links macroeconomic conditions with investment costs in the Materials, Energy, and Agriculture sectors.
 - Documents the treatment of sectoral investment demand, capital accumulation, and savings–investment market clearing within GCAM-Macro’s recursive dynamic framework, including capital price feedbacks through fixed charge rate (FCR) calculations.
- **Appendix D: Agricultural Factor Productivity Growth Representation**
 - Generalizes agricultural productivity representation by explicitly modeling factor-augmenting productivity growth for land, labor, capital, water, and fertilizer inputs within the KLEAM production structure.
 - Develops agricultural labor productivity trajectories anchored to land productivity growth while maintaining consistency with structural transformation dynamics and economy-wide productivity trends.
- **Appendix E: Purpose-grown Energy Crop Introduction: Ghost Share Recalibration and Assumption Updates**
 - Delays the introduction year for purpose-grown energy crops from 2025 to 2030 and recalibrates biomass share-weight parameters to reflect updated agricultural and forest land rental profit assumptions.
 - Introduces regional differentiation in biomass share-weight assumptions.
 - Change is required because the "ghost-share" is based on the profit of biomass, which in early years at least will be set by its price in the energy sector - so the profit of biomass will not automatically change proportionally with other crops when they are re-baselined. For example, a decrease in the computed profit rates of food crops will result in a higher share of biomass, all else equal. Therefore, the change in profits from KLEAM lowered food crops, resulting in a need for reduced ghost shares for biomass.
- **Appendix F: Visualization Document: Key Supplementary Figures for Macroeconomic Data and Parameter Visualization**
 - See **Table 3** for table of contents

GCAM-Macro-KLEAM Input-Output Framework and Accounting Structure

	Ag	En	Ma	Final Cons.	Trade	Sum
Land	land					
L	labor		labor			GDP: Income
K	capital /Inv	capital /Inv	capital /Inv			
Ag			ag non- food- service	ag food- service	ag-net- export	
En			energy service		energy- net- export	
Ma				cons. & capital goods	material- net- export	gross- demand
Sum			gross- output	GDP: Expenditure C & G + Inv + NX		

GDP decomposition by income:

GDP = sum of the compensation (factor rewards) from land, labor (L), & capital (K) across all sectors

GDP decomposition by expenditure:

GDP = household & government (GOV) consumption (C & G) + investment (INV) + net export (NX)

→ GDP = materials gross-output + ag food-service + gcam-net-export (ag & energy)

- Ma gross-output (supply) = nested CES production function (K, L, En, Ag; productivities; elasticities)
- Ma gross-output (demand) = consumption goods (HHD & Gov) + capital goods + material-net-export

Materials production function

Nested constant elasticity of substitution (CES) (En, Ag, (K, L))

- Ag nonfood services are collected and aggregated from GCAM sectors, with initial prices used as weights
- En is an energy service index, linked to GCAM energy service inputs in final demand
- En is endogenous, aggregating energy services using initial prices as weights (with value rescaled in calibration)

Clearing capital/investment market

sum of investment from Ag, En (incl. CD), and Ma = savings + capital-net-export

- ag-investment: derived based on Ag capital return and related assumptions
- energy-investment: derived based on GCAM energy sectoral assumptions at technology levels
- material-investment = depreciation-rate x capital stock (beginning) + capital stock increase
- savings = function(lagged savings-rate, per-capita GDP growth rate) x GDP, adjusted by CD in initial calibration
- capital-net-export: initially calibrated to -NX but being phased out to zero regionally (trade balance)

Clearing labor market

Labor supply (employment linked to population) = Labor demand from Ag and Materials

Fig. 1 Overview of the GCAM-Macro-KLEAM input-output and accounting framework. Agriculture (Ag), Energy (En), and Materials (Ma) use primary factors of production and supply services and goods to final demand. GDP is defined consistently by income and expenditure.

3. Overview of key changes in GCAM and gcamdata

The implementation of the KLEAM framework required coordinated updates across the GCAM core model and the associated gcamdata preprocessing pipeline to ensure internal consistency between macroeconomic accounting, sectoral production structures, and socioeconomic inputs. **Table 1** provides a structured summary of the major code and data changes introduced in the present CMP, focusing on updates that directly support the KLEAM architecture. Relevant minor bug fixes and housekeeping changes are also included for completeness.

Key updates include:

- **Updated macroeconomic data inputs:** Transition from Penn World Table (PWT) v10 to v11 (Feenstra et al., 2015), extending historical coverage from 2019 to 2023.
- **Expanded agricultural and labor data sources:** Integration of new USDA and ILO datasets, with harmonized preprocessing of agricultural labor and capital inputs across FAO, USDA, ILO, and GTAP-based sources.
- **Improved agricultural labor and capital downscaling and cost tracing:** Downscaling of labor and capital inputs to agricultural technologies and enhanced tracing of labor costs, wages, and capital returns (e.g., `zaglu_L2082.ag_an_for_laborcapital.R`).
- **Introduced parameters to differentiate labor- and capital-intensive technologies:** Leverage the existing technology structure to assign capital-intensive assumptions to high-input technologies and labor-intensive assumptions to low-input technologies using a cost-consistent technology downscaling approach.
- **Restructured agricultural productivity processing:** Consolidation of water, fertilizer, labor, capital, and land productivity inputs into a coherent and extensible framework.
- **Enhanced capital and investment transparency with factor price feedbacks:** Improved tracking of sectoral capital stocks and investment flows, enabling endogenous capital rental prices (gross rates of return) and consistent propagation of capital cost signals across agriculture, energy, and materials sectors.
- **Refined use of GTAP-derived data:** Removal of legacy GTAP-based land value processing and using land cost shares to improve agricultural land valuation and improve transparency.
- **Updated assumption of biomass introduction:** Purpose-grown energy crop introduction is pushed to 2030 (from 2025) with recalibrated (regionally) differentiated parameters.
- **National account consistency improvements:** Updates to national accounting variables to better align production, final consumption, trade balance, and factor income across sectors.
- **Agricultural nonfood demand parameter:** Updated price and income elasticity for nonfood agriculture demand of crops and livestock, and increase the income elasticity for forestry products.
- **Harmonization of near-term drivers and parameters:** Adoption of a unified scenario alignment year (`MODEL_SCENARIO_ALIGN_YEAR = 2025`) for consistent calibration across scenarios.
- **Greater regional parameter flexibility:** Expanded support for region-specific labor allocation parameters and materials-sector CES coefficients.
- **Targeted bug fixes and data consistency improvements:** Fixes to base-year forest yield processing and improved handling of woodpulp demand.

Table 1 Key data and code changes implemented in GCAM and gcamdata

Data file/R chunk/CPP	Changes made
National accounts (GCAM core) containers/source/national_account_container.cpp containers/source/national_account.cpp	Updated national accounting variables to include agricultural food and nonfood services; Set up labor and capital markets; Improved consistency of using tracking accounts.
Macro production functions/source/nested_ces_production_function_macro.cpp	Extended the nested CES production structure to explicitly incorporate agriculture alongside capital, labor, energy services, and materials.
Capital tracking and investment (GCAM core) functions/source/non_energy_input.cpp functions/source/input_capital.cpp	Updated approaches for sectoral capital tracking and investment calculation, supporting endogenous capital accumulation and rental price feedbacks.
gcamdata key constants update constants.R	Updated years and scenario constants (e.g., PWT and GMD database constants; scenario alignment year; trade balance year updated to 2050), along with minor code cleanup. socioeconomics. TRADE_BALANCE_YEAR <- 2050 (changed from 2035) MODEL_SCENARIO_ALIGN_YEAR <- 2025
Agricultural capital stock and depreciation zaglu_L100.FAO_preprocessing_OtherData.R aglu/FAO/GCAMFAOSTAT_CapitalStock.csv	Added FAO-based agricultural capital stock data and integrated processing into the L100 module.
Agricultural labor and capital zaglu_L103.ag_labor_capital.R aglu/USDA/USDA_InternationAgProductivity_LaborCapital.csv	Added and processed USDA agricultural labor and capital data; harmonized labor inputs across FAO, USDA, and GTAP sources to derive sectoral employment shares.
Removal of legacy GTAP land value processing zaglu_L100.GTAP_downscale_etry.R (removed) zaglu_L131.LV_R_GLU.R (removed) aglu/LDS/LDS_value_milUSD.csv (removed) zaglu_L221.land_input_1.R	Removed optional GTAP-based land value processing and associated data to simplify agricultural land valuation workflows.
Bugfix: Forest yield processing zaglu_L123.LC_R_MgdPastFor_Yh_GLU.R	Bug fix to improve base-year forest yield processing.
Woodpulp balance improvement and demand cleanup zaglu_L110.For_FAO_R_Y.R zaglu_L203.ag_an_demand_input.R zaglu_L240.ag_trade.R zaglu_L2042.resbio_input_irr_mgmt.R zaglu_xml_paper_delete_ag_demand.R (removed) emissions/A_PrimaryFuelCCcoef.csv aglu/A_demand_nesting_subsector.csv aglu/A_demand_subsector.csv aglu/A_demand_supplysector.csv aglu/A_demand_technology.csv	Removed nonfood woodpulp demand to avoid double counting and processing complexity. Improved processing of the related agricultural demand and trade flows. Remove NonFoodDemand_woodpulp in parameter files. The following is deleted from configuration files: <Value name = "demand_paper">./input/gcamdata/xml/paper_delete_ag_demand.xml</Value>
Biomass introduction assumption updates aglu/A_bio_ghost_share.csv aglu/A_biomassSupplyShare_R.csv energy/A22.globaltech_shrwt.csv	Recalibrate ghost shares for purpose-grown energy crop introduction (pushed to 2030 and differentiated by region).
Crop production cost restructuring zaglu_L2052.ag_prodchange_cost_irr_mgmt.R (removed) zaglu_L2052.ag_nonlandcost_irr_mgmt.R (new) zaglu_L2053.ag_land_prodchange.R (new)	Split module_aglu_L2052.ag_prodchange_cost_irr_mgmt into module_aglu_L2052.ag_nonlandcost_irr_mgmt and module_aglu_L2053.ag_land_prodchange. Improve cost data flow and update cost shares in crop production.
Agricultural labor and capital coefficients zaglu_L2082.ag_an_for_laborcapital.R (new) zaglu_L2083.ag_factor_productivity_scen.R (new)	Downscale labor and capital to agricultural technologies; added downscaling of labor and capital inputs to agricultural technologies; derived labor wage rates and capital rental prices.

Data file/R chunk/CPP	Changes made
aglu/gcam_ag_labor_productivity.csv	Update cost flows. Define parameters to differentiate between labor-intensive and capital-intensive technologies in the crop sectors. Introduced a structure for scenario-specific labor and capital productivity projections for agriculture; added regional agricultural labor productivity projections in CSV inputs (currently not differentiated by SSP). Derive labor productivity growth bases on land productivity assumptions.
Agricultural productivity zaglu_xml_ag_land_prodchange_Scen.R (new) zaglu_xml_ag_nonland_input_Scen.R (new) zaglu_xml_ag_Fert_IRR_MGMT.R (removed) zaglu_xml_ag_prodchange_ref_IRR_MGMT.R (removed) zaglu_xml_ag_prodchange_ssp1_IRR_MGMT.R (removed) zaglu_xml_ag_prodchange_ssp5_IRR_MGMT.R (removed) zaglu_xml_ag_water_input_IRR_MGMT.R (removed)	Restructure and simplify the agricultural productivity scenario generation (XMLs).
Livestock inputs zaglu_xml_an_input.R	Added livestock labor and capital productivity coefficients.
Energy and energy service capital tracking zenergy_L154.transportation_UCD.R zenergy_L210.resources.R zenergy_L222.en_transformation.R zenergy_L225.hydrogen.R zenergy_L226.en_distribution.R zenergy_L232.other_industry.R zenergy_L244.building_det.R zenergy_L2321.cement.R zenergy_L2323.iron_steel.R zenergy_L2324.Off_road.R zenergy_L2325.chemical.R zenergy_L2326.aluminum.R zenergy_L2327.paper.R zenergy_L2328.food_processing.R zwater_L2233.electricity_water.R	Updated capital tracking and parameters for deriving sectoral investment, including capital ratios, interest rates, payback periods, depreciation rates, and tracking markets across energy, industry, buildings, transport, and water sectors. The following variables were specified: capital.ratio, interest.rate, payback.years, invest.unit.conversion, tracking.market, and depreciation.rate
ILO employment data integration zsocio_L100.Employment.R (new) socioeconomics/ILO/ILO_country_iso_mapping.csv socioeconomics/ILO/ILO_Employment_by_sex_and_economic_activity_ILO_modelled_estimates.csv.gz socioeconomics/ILO/ILO_Employment_by_sex_and_economic_activity_ISIC_level2.csv.gz socioeconomics/ILO/ILO_ISIC_sector_mapping.csv	Added two ILO employment datasets with sectoral and regional mappings; processed employment data across ILO, USDA, and other sources to compile sectoral labor inputs.
GTAP preprocessing zsocio_L100.GTAP.R socioeconomics/GTAP/GTAP_sector_mapping.csv	Updated preprocessing of GTAP labor and capital data used in macro calibration (in prebuilt data); minor update in sector mapping.
National accounts (socioeconomics) zsocio_L100.NationalAccounts.R zsocio_L103.NationalAccounts.R socioeconomics/NationalAccounts/pwt110.csv (new) socioeconomics/NationalAccounts/NationalAccounts_variable_mapping.csv (updated) socioeconomics/NationalAccounts/pwt1001.csv (removed)	Updated Penn World Table data to v11.0 (from v10.01); removed legacy energy capital partitioning and improved national account consistency.

Data file/R chunk/CPP	Changes made
socioeconomics/NationalAccounts/pwt1001_legend.csv (removed)	
Labor supply and allocation zsocio_L201.Pop_GDP_scenarios.R socioeconomics/A_labor_supply_sector.csv zsocio_xml_socioeconomics_SSP.R	Updated scenario-based labor supply processing; specified region-specific logit exponents governing labor allocation across sectors (in CSV inputs).
Macro CES parameters and factor productivity zsocio_L203.NationalAccounts.R socioeconomics/gcam_macro_TFP_open.csv socioeconomics/gcam_macro_nested_CES_function.csv socioeconomics/A81.factor_productivity.csv zsocio_xml_socioeconomics_macro.R	Updated nested CES parameters; partitioned energy and agricultural labor and capital from materials. Updated materials total factor productivity, calibrated to reference socioeconomic drivers by SSP. Introduced a parameter to increase energy service capital share in the partition process (in order to increase energy service value input in Materials production). Added capital investment and consumer durable market linkers.
Income (and price) elasticity processing zsocio_L232.Inc_Elas_scenarios.R (new) zsocio_xml_socioeconomics_IncomeElasticity.R zenergy_L2321.cement.R (modified to move elasticity calculations) zsocio_L2323.iron_steel_Inc_Elas_scenarios.R (removed) zsocio_L2324.Off_road_Inc_Elas_scenarios.R (removed) zsocio_L2325.chemical_Inc_Elas_scenarios.R (removed) zsocio_L2326.aluminum_Inc_Elas_scenarios.R (removed) zsocio_L2327.paper_Inc_Elas_scenarios.R (removed) aglu/A_demand_supplysector.csv	Consolidated and improved processing of income elasticities for industrial and transport sectors; removed redundant sector-specific scripts. - zsocio_L232.Inc_Elas_scenarios.R now has a central processing of elasticities for industrial and transport sectors - Originally separated modules are consolidated and improved - Cement income elasticity related processing is also moved to the new module Add price and income elasticity for nonFoodDemand Crops and Meat. Update income elasticity for forestry (sawnwood) products
Macro account tracking zsocio_L281.macro_account_tracking.R zaglu_xml_ag_trade.R	Added explicit tracking of macroeconomic accounts from agriculture.
Configuration and linker updates exe/configuration_ref.xml exe/configuration_policy.xml and other configurations	Added information for deriving agricultural investment <Value name = "capital_Ag">../input/gcamdata/xml/ag_capital_tracking.xml</Value> Added agricultural labor and capital coefficients in crops <Value name = "aginput_VA">../input/gcamdata/xml/ag_input_laborcapital_IRR_MGMT.xml</Value> Restructured: Ag productivity drivers or other input coefficients <Value name = "ag_prodchange">../input/gcamdata/xml/ag_land_prodchange_ref_IRR_MGMT.xml</Value> <Value name = "fertilizer">../input/gcamdata/xml/ag_Fert_IRR_MGMT.xml</Value> <Value name = "animal_input">../input/gcamdata/xml/an_input.xml</Value> <Value name = "aginput_fert">../input/gcamdata/xml/ag_input_fert_MGMT.xml</Value> <Value name = "aginput_water">../input/gcamdata/xml/ag_input_water_IRR_MGMT.xml</Value>
Queries and interface headers Main_queries.xml ModelInterface_headers.txt	Added new queries and headers to support agricultural labor, capital, and investment diagnostics. Added new headers; added CO2 to agricultural storage technologies to suppress extended log warnings.

Data file/R chunk/CPP	Changes made
Other minor improvements zsocio_L100.SSP_database.R zaglu_L100.regional_ag_an_for_prices.R zenergy_xml_negative_emissions_budget.R zenergy_L254.transportation_UCD.R solution/cal_broyden_config.xml	Miscellaneous code cleanup and data flow improvements.

In this CMP, the structure of the socioeconomics modules in gcamdata was further refined to enhance the traceability and transparency of data flows. A schematic illustrating the main data flows across these modules, together with key processing notes, is provided in the Supplementary Figures. **Table 2** summarizes the key GCAM input XMLs generated by the socioeconomics modules, which serve as the primary inputs for constructing the macroeconomic accounting structure of GCAM-Macro.

More detailed labor market information, including sectoral labor supply and wage rates, is now incorporated into historical calibration, with total employment (Labor_Total) explicitly specified as a fixed final-demand by SSPs. In addition, energy-related investment in the materials sector is no longer required for historical calibration, as the savings–investment market is only cleared in future periods. Other macroeconomic variables are either derived endogenously from GCAM sectoral outputs or constructed using available external data sources.

Table 2 GCAM input data in key socioeconomics modules (XMLs)

XMLs	Variable/data	Period
socioeconomics_CORE[or by SSP].xml	National Account: GDP	1975-2100
	gdp-ppp-conversion	2021
	Demographics: population	1975-2100
	fixed-final-demand: Labor_Total	1975-2100
	National Account: labor-force-share	1975-2021
	supplysector: Labor_Total (Ag & Materials)	1975-2021
	resource: Labor_Ag prices	1975-2021
	resource: Labor_Materials prices	1975-2021
	National Account: total-factor-productivity	2025-2100
	National Account: capital-stock	1975-2021
socioeconomics_macro.xml	National Account: depreciation-rate	1975-2100
	National Account: labor-wages	1975-2021
	National Account: capital-value	1975-2021
	National Account: savings-rate	1975-2021
	National Account: capital-net-export	1975-2021
	Saving-rate-param	
	gdp-macro-function	
socioeconomics_incelas_[by SSP].xml	energy-final-demand: income-elasticity	2025-2100

Building on the macro data visualization framework established in CMP-410, we updated existing figures and added new diagnostics (KLEAM) in the Supplementary Figures, with detailed captions documenting

data sources and processing steps. Selected figures are highlighted here. **Fig. 3** presents key socioeconomic drivers; GDP and population are unchanged, while the employment-to-population ratio is rebased to more recent observations (2023). **Fig. 4** shows calibrated TFP by region and SSP, together with agricultural labor productivity. Agricultural labor productivity is currently derived based on an earlier version of calibrated TFP and may be further updated (e.g., iteratively using the revised TFP calibration or alternative external sources). Caution is warranted for regions such as Ukraine and South America_North, where large near-term variations in calibrated TFP should not be fully propagated into labor productivity assumptions. **Fig. 5** presents income elasticity assumptions for key GCAM sectors. These income elasticities, along with other related drivers and parameters (e.g., agricultural yield assumptionsⁱ), are harmonized across scenarios (Core and SSPs) in 2025. Further exploration and refinement of these assumptions are planned. A complete list of Supplementary Figures is provided in **Table 3**.

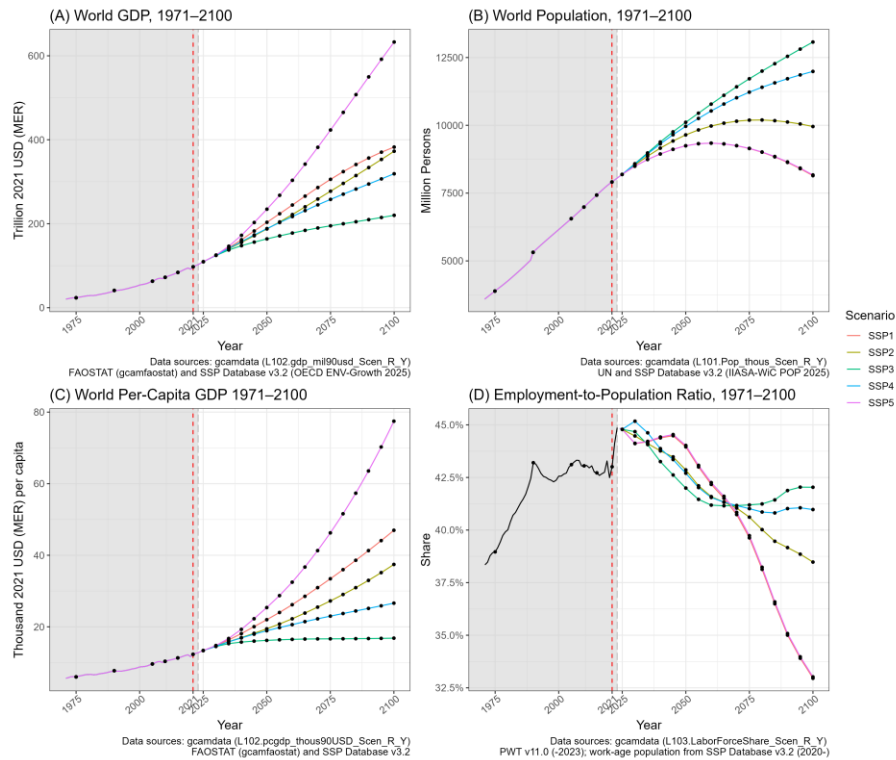


Fig. 2 Historical (1971–2023) and Reference Projection (2025 – 2100) of Socioeconomic Drivers of Population, GDP, Per-Capita GDP, and Employment-to-Population Ratio, by SSP at the World level

ⁱ There is an SSP1-specific parameter governing dietary change—food demand fuel preference elasticities (food_SSP1.xml)—that was applied across the entire historical period. As a result, model calibration was altered, and near-term projections (e.g., 2025) were affected, implying that a dietary shift had already occurred by 2025 in SSP1 but not in other SSPs. Simply changing the parameter introduction year from 1975 to 2030 would not resolve this issue, as it would instead introduce a substantial shock in 2030 due to the prior historical calibration change. This approach may remain viable if a lower parameter value is used, but further exploration is required. Thus, no change to this parameter was made in the CMP.

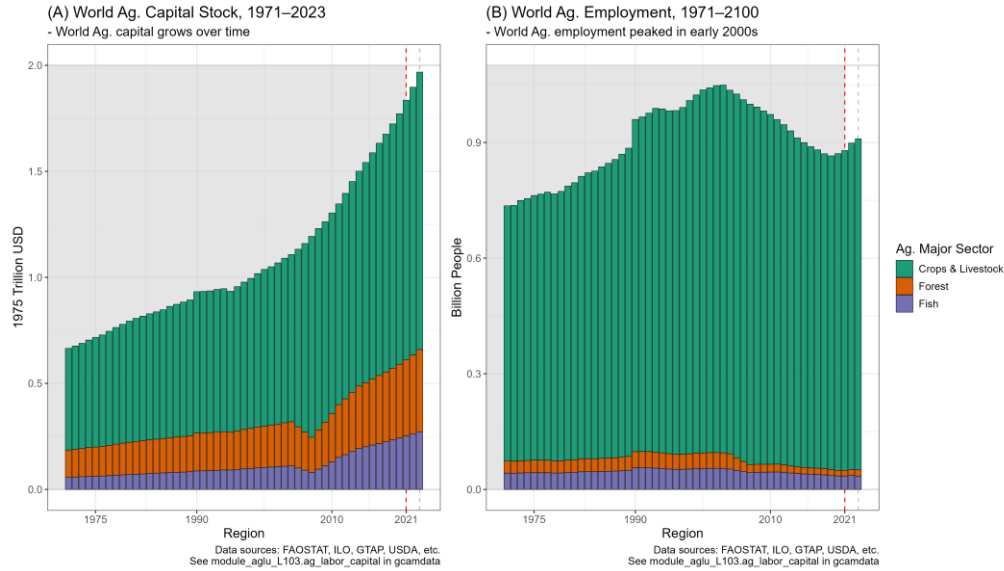


Fig. 3 Historical Agricultural Capital Stock and Employment, World, 1971–2023

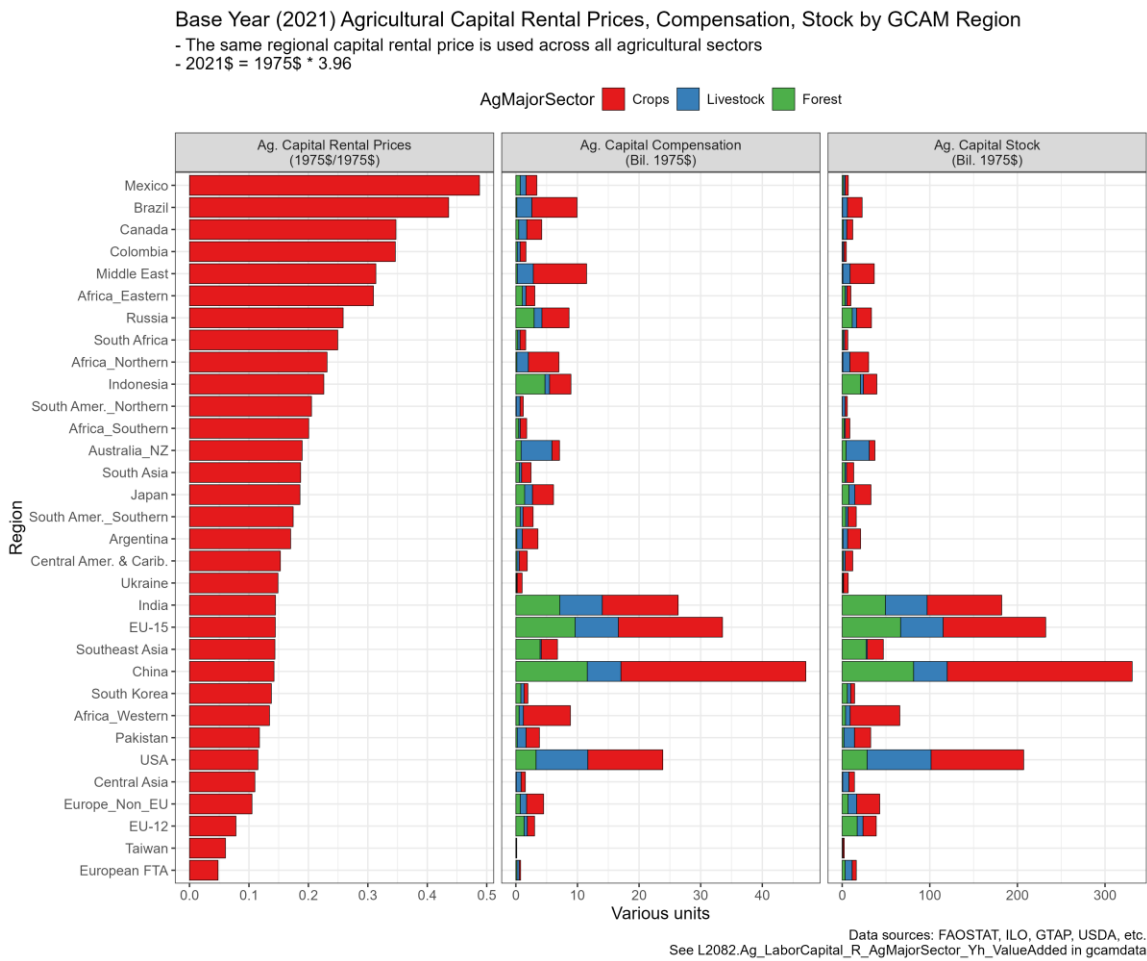
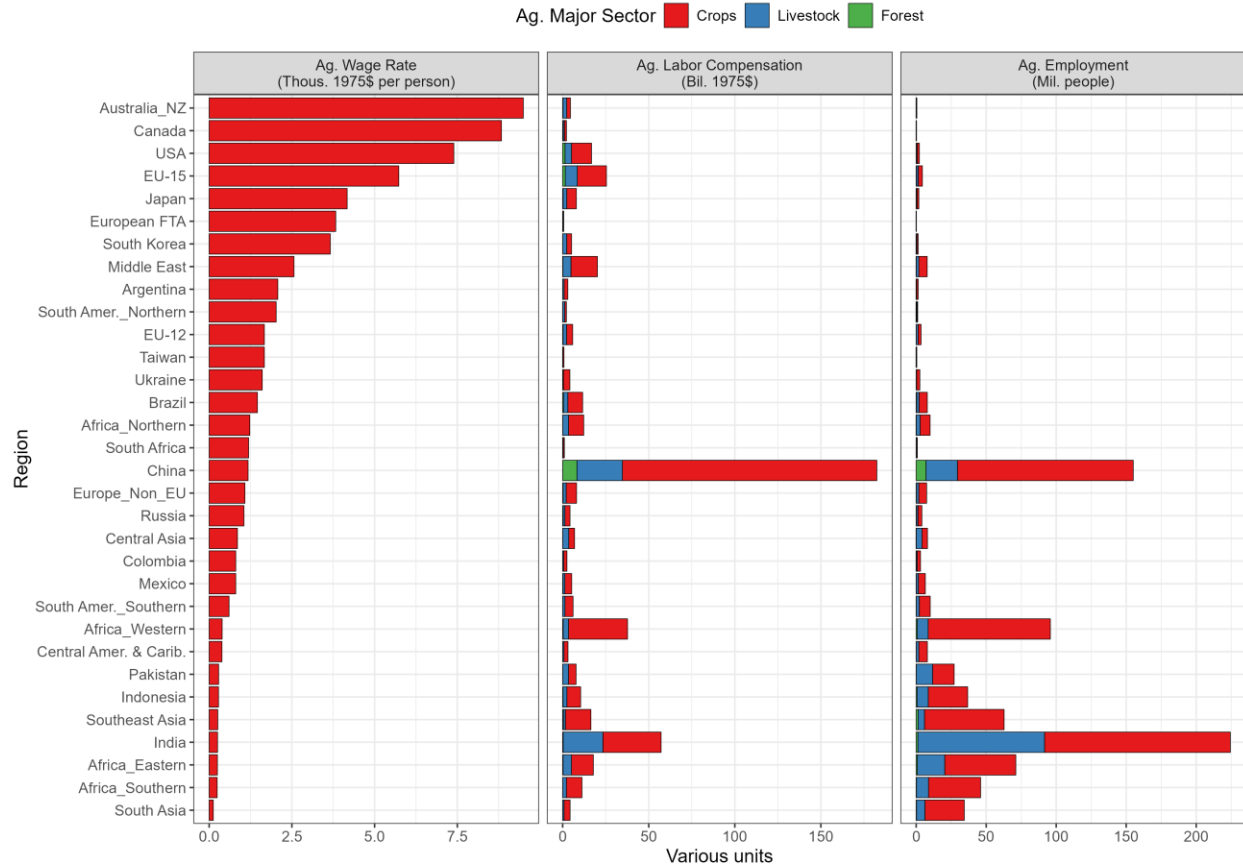


Fig. 4 Base Year (2021) Agricultural Capital Rental Prices, Compensation, Stock by GCAM Region

Base Year (2021) Agricultural Labor Wage Rate, Compensation, Employment by GCAM Region

- The same regional wage rate is used across all agricultural sectors
- The final base year prices for agricultural products and costs were improved based on observations
- Note that GCAM used 2021 Ag. prices for historical years
- $2021\$ = 1975\$ \cdot 3.96$



Data sources: FAOSTAT, ILO, GTAP, USDA, etc.
See L2082.Ag_LaborCapital_R_AgMajorSector_Yh_ValueAdded in gcamdata

Fig. 5 Base Year (2021) Agricultural Labor Wage Rate, Compensation, Employment by GCAM Region

Calibrated TFP in the Material Sector by GCAM Region and SSP, 2021–2100

- These calibrated TFP values enable GCAM-Macro to reproduce SSP GDP trajectories
- TFP values are applied to the CES production function for the Material sector in GCAM-Macro

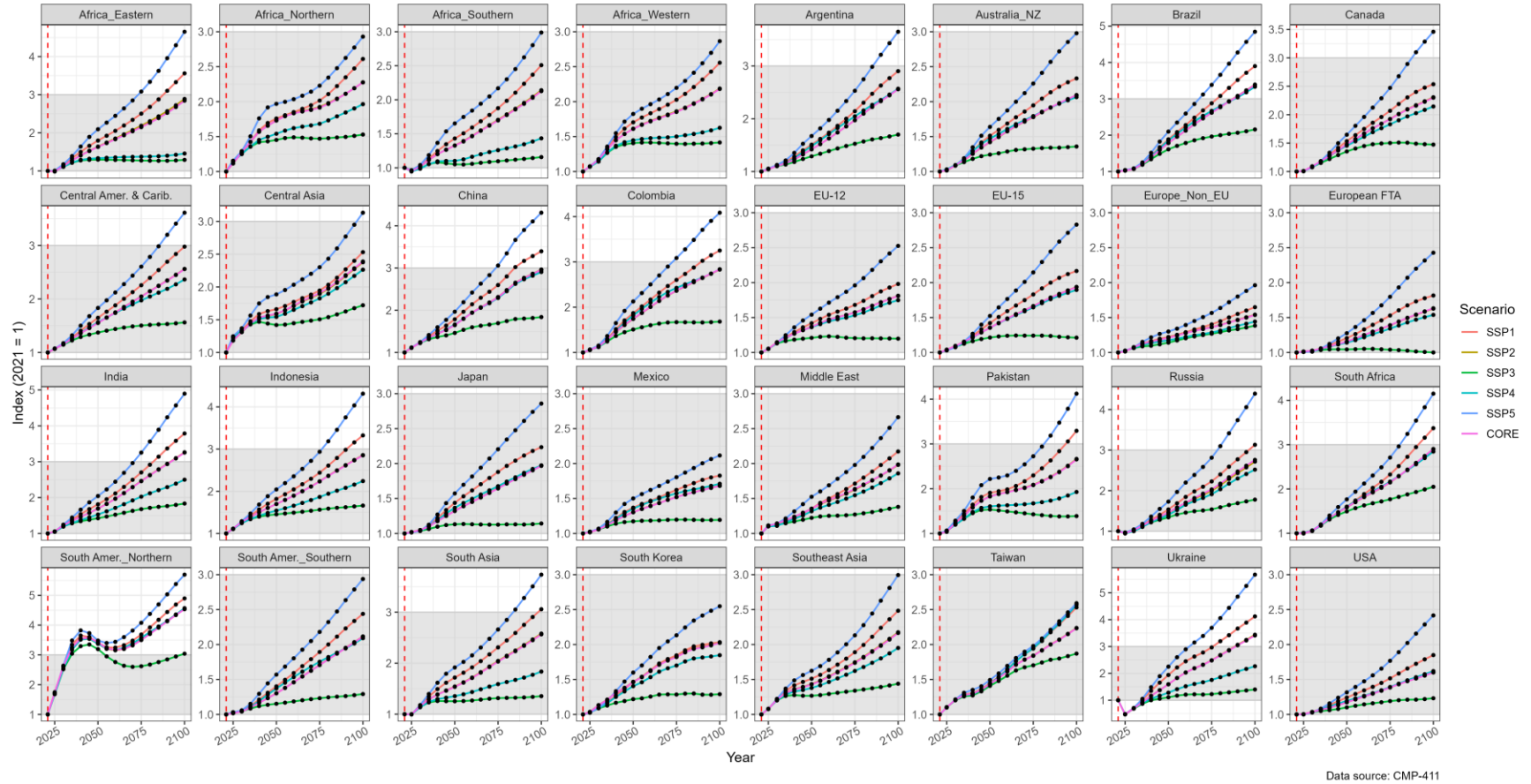


Fig. 6 Calibrated TFP in the Materials Sector by GCAM Region and SSP Scenarios, 2021 – 2100

Table 3 List of key supplementary figures for macroeconomic data and parameter visualization

Group	Figure Description	#
Accounting framework	GCAM-Macro-KLEM input–output and accounting framework	1
	GCAM-Macro-KLEAM input–output and accounting framework	2
Socioeconomic drivers	Historical (1971–2023) and Reference Projection (2025 – 2100) of Socioeconomic Drivers of Population, GDP, Per-Capita GDP, and Employment-to-Population Ratio, by SSP at the World level	3
	MER-to-PPP Conversion Factors by GCAM Region in 2021	4
	Reference GDP by GCAM Region and SSP, 1971–2100	5
	Reference Population by GCAM Region and SSP, 1971–2100	6
	Reference per-capita GDP by GCAM Region and SSP, 1971–2100	7
	Reference Employment-to-Population Ratio by GCAM Region and SSP, 1971–2100	8
Economy-wide accounts	Historical Economy-Wide Capital Stock by GCAM Region, 1971–2023	9
	Historical Economy-Wide Capital Compensation by GCAM Region, 1971–2023	10
	Historical Economy-Wide Depreciation Rates by GCAM Region, 1971–2023	11
	Historical Economy-Wide Capital Rental Prices (& Depreciation Rates) by GCAM Region, 1971–2023	12
	Historical Economy-Wide Labor Compensation by GCAM Region, 1971–2023	13
	Historical Economy-Wide Wage Rates by GCAM Region, 1971–2023	14
	Historical Saving Rates (Gross Domestic Savings, % of GDP) by GCAM Region, 1971–2023	15
	Historical Capital Net Exports by GCAM Region, 1971–2023	16
	Capital net export (net import) by GCAM region in 2021	17
Sectoral variables	Historical Agricultural Capital Stock and Employment, World, 1971–2023	18
	Historical Agricultural Capital Stock by GCAM Region, 1971–2023	19
	Historical Agricultural Employment by GCAM Region, 1971–2023	20
	Base Year (2021) Agricultural Capital Rental Prices, Compensation, Stock by GCAM Region	21
	Base Year (2021) Agricultural Labor Wage Rate, Compensation, Employment by GCAM Region	22
	Historical Agricultural Capital Depreciation Rates by GCAM Region, 1995–2021	23
Parameter	Calibrated Materials Total-Factor-Productivity and Ag Labor/Land Productivity by GCAM Region and SSP, Core (SSP2), 2021–2100	24
	Calibrated TFP in the Material Sector by GCAM Region and SSP, 2021–2100	25
	Income Elasticities by GCAM Sector, Region, and SSP	26
	SSP2: Income Elasticities by GCAM Sector and Region (32 lines per panel)	27
Raw input data (additional info)	GDP Decomposition by Expenditure Share by GCAM Region, 2021	28
	GDP Decomposition by Expenditure Share by GCAM Region, 1971 – 2023	29
	Capital–Output (GDP) Ratio and Factor (Labor & Capital) Reward Shares by GCAM Regions, 2021	30
	Capital–Output (GDP) Ratio by GCAM Region, 1971 – 2023	31
	Economy–Wide Labor Reward Share in GDP by GCAM Region, 1971 – 2023	32

Table 4 documents the definitions of key national account variables included in the GCAM model interface under the KLEAM framework. These variables constitute the core macroeconomic quantities used for accounting consistency, diagnostics, and interpretation of endogenous macroeconomic feedbacks in GCAM-Macro, including GDP, savings and investment, factor incomes, capital stocks, and sectoral value flows across agriculture, energy, and materials. The table clarifies variable meanings, accounting relationships, and updates relative to the legacy KLEM implementation, serving as a reference for both model users and developers.

All value-based national account variables reported in **Table 4** are expressed in million 1990 USD, consistent with the historical calibration and preprocessing conventions used in gcamdata. Values can be converted to 2021 USD using a GDP deflator (United States) of 1.868, which was applied during initial data processing and calibration. This unit convention ensures consistency with legacy GCAM macroeconomic datasets while allowing transparent conversion to more recent price bases where needed.

In addition, caution is warranted when interpreting historical price or value data from the GCAM model interface. In many cases, only final base-year prices were used for historical calibration, representing a limitation that should be improved in future work.

Table 4 Definitions of National Account Variables (Model Interface) in GCAM-Macro (KLEAM).

#	National Account	Definition	Unit	Update
1	GDP	Gross domestic product (GDP), converted to USD using Market Exchange Rate (MER). It sets the scale for all other value-based macroeconomic variables.	Million 1990\$	KLEM-consistent
2	population	Population with exogenous assumptions in future growth by SSP.	Thousand people	KLEM-consistent
3	gdp-per-capita	GDP divided by total population, measured in market exchange rate (MER) terms.	Thousand 1990\$ per capita	KLEM-consistent
4	gdp-per-capita-ppp	GDP per capita expressed in purchasing power parity (PPP) terms, used for cross-regional income comparisons. The variable is mainly used in food demand and is not currently used in macro or other demand systems in GCAM.	Thousand 1990\$ per capita	KLEM-consistent
5	investment	Aggregate gross investment demand, equal to the sum of sectoral investment across agriculture, energy, energy services (including consumer-durable), and materials sectors.	Million 1990\$	KLEM-consistent
6	savings-rate	Domestic savings as a share of income (GDP). Future changes in saving rates are dependent on the per-capita GDP growth rate.	Share	KLEM-consistent
7	savings	Aggregate regional savings, derived from savings-rate and GDP, with adjustment of consumer-durable in the initial calibration.	Million 1990\$	KLEM-consistent
8	capital-net-export	Net financial inflows (balance of financial account), calibrated to offset regional value net exports (current account balance) in the base period and representing net monetary inflows consistent with national accounting identities. It is phased out by 2050 with the trade balance assumptions.	Million 1990\$	KLEM-consistent

#	National Account	Definition	Unit	Update
9	ag-food-service-value	Value of agricultural food services entering final consumption, representing food demand within the macroeconomic accounting framework. It is consistent with the food demand model and valued using GCAM regional primary agricultural prices. Fisheries and aquaculture are not included.	Million 1990\$	Added
10	ag-nonfood-service	Quantity index of GCAM agricultural products used in nonfood (& nonenergy/nonfeed) sectors ('other demand' in GCAM), aggregated using initial prices and supplied to the materials production sector.	Million 1990\$ (index)	Added
11	ag-nonfood-service-value	Value of ag-nonfood-service.	Million 1990\$	Added
12	ag-investment	Investment demand generated endogenously within GCAM agricultural sectors	Million 1990\$	Added
13	energy-service	Quantity index of aggregate energy services (building, transport, and industries) produced by the GCAM energy system (aggregated using initial prices) and supplied to Materials production.	Million 1990\$ (index)	KLEM-consistent
14	energy-service-value	The value of energy service entering the Materials production function, with initial prices calibrated to initial energy service value share.	Million 1990\$	Updated (data uncertainty)
15	consumer-durable	Capital goods demand in GCAM "energy service" sectors (residential heating/cooling/other & passenger road transportation) that are categorized as consumer durables.	Million 1990\$	KLEM-consistent
16	energy-investment	Investment demand generated endogenously within GCAM energy & energy service sectors.	Million 1990\$	KLEM-consistent
17	gcam-net-export	Net exports of goods and services are generated within GCAM sectors (agriculture & energy).	Million 1990\$	Updated from "energy-net-export"
18	materials-gross-output	Total value output of the aggregated materials sector, representing the rest of the economy outside agriculture and energy systems. The price of Materials is 1 (numeraire).	Million 1990\$	Updated from "gross-output"
19	fac-share-labor	Share of Materials sector value output attributed to labor compensation.	Share (in materials-gross-output)	KLEM-consistent
20	fac-share-capital	Share of Materials sector value output attributed to capital compensation.		KLEM-consistent
21	fac-share-ag	Share of materials sector value output attributed to agricultural service inputs (nonfood-service).		Added
22	fac-share-energy	Share of materials sector value output attributed to energy service inputs.		Updated (data uncertainty)
23	materials-value-added	The value-added (labor & capital) in Materials production. It equals (fac-share-labor + fac-share-capital) x materials-gross-output. Value-added is at the bottom-level nest in the Materials CES production function.	Million 1990\$	Updated from "value-added"

#	National Account	Definition	Unit	Update
24	materials-labor-wages	Total labor compensation paid by the Materials sector.	Million 1990\$	Updated from "labor-wages"
25	materials-labor-force	Employment allocated to the Materials sector.	Million people	Updated from "labor-force"
26	materials-capital-stock	Productive capital stock employed in the materials sector at the end of the model period (after accounting for depreciation and new investment in a model timestep).	Million 1990\$	Updated from "capital-stock"
27	materials-capital-investment	Gross investment in the Materials sector capital; annual mean value in the model timestep.	Million 1990\$	Added
28	capital-price	Capital rental price (gross rate of return) in the Materials sector, defined as capital compensation divided by the value of the capital stock. Materials capital compensation = materials-capital stock x capital-price = fac-share-capital x materials-gross-output	1990\$/1990\$	Added
29	depreciation	Consumption of fixed capital. Average annual depreciation in the Materials sector, calculated as $[1 - (1 - \text{materials.depreciation.rate})^{(n \text{ years in a step})}] \times \text{lagged(materials-capital-stock)} / (n \text{ years in a step})$.	Million 1990\$	KLEM-consistent
30	materials-net-export	Value net export in the Materials sector, with initial values calibrated based on observed economy-wide net trade and gcam-net-export.	Million 1990\$	KLEM-consistent
31	total-factor-productivity	Exogenous productivity parameter governing efficiency improvements in Materials production. The total factor productivity (TFP) is calibrated based on reference GDP projections (i.e., such that endogenous (open GDP mode) GDP results match the reference GDP projections from the SSP database).	Base year = 1	KLEM-consistent (recalibrated)

4. GCAM validation runs

Fig. 7 summarizes the set of GCAM validation scenarios used to compare results from the Updated development branch (CMP-411) against a recent Master reference branch (CMP-400; PR-342, corresponding to GCAM v8.6), following standard GCAM CMP conventions. Both fixed-GDP and open-GDP (with endogenous macroeconomic feedbacks) configurations were included for RCP 2p6 scenarios. In the open-GDP scenarios, total factor productivity (TFP) trajectories are updated to match the corresponding Reference scenarios.

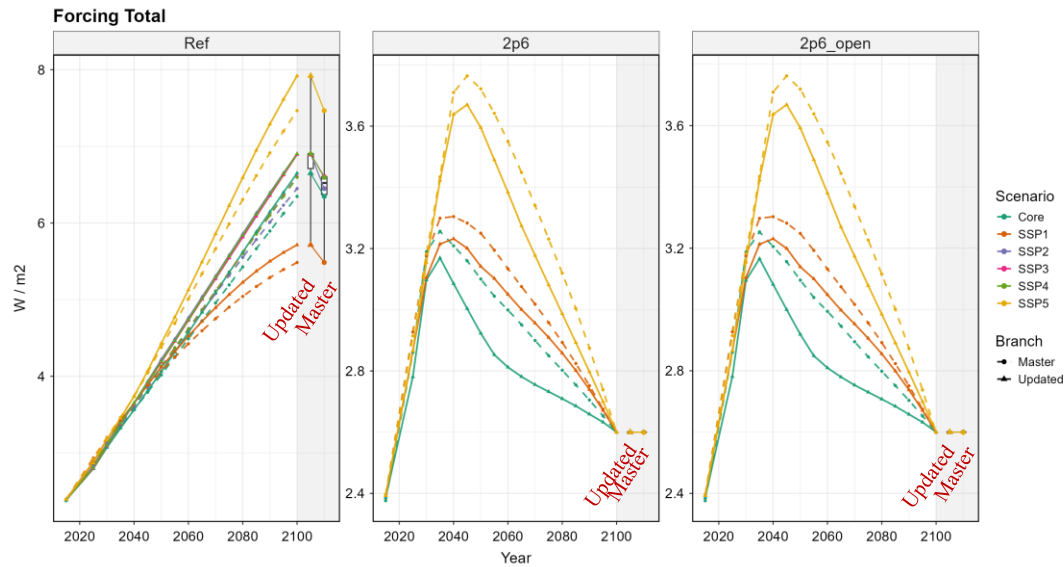
In total, the validation scenario set comprises 24 Shared Policy Assumption (SPA) scenarios, spanning GCAM Core and SSP assumptions, Reference versus RCP 2.6 policy cases (fixed & open), and two model branches. SSP2–SSP4 RCP 2.6 scenarios are excluded because they did not converge. All validation runs are archived in the corresponding internal pull-request directories (CI342 for the Reference Master branch and CI383 for the Updated branch).

		Core	SSP1	SSP2	SSP3	SSP4	SSP5
Master CMP-400	Ref.						
	2p6_fixed						
	2p6_open						
Updated CMP-411	Ref.						
	2p6_fixed						
	2p6_open						

Fig. 7 GCAM validation scenarios and model comparison framework. Grey cells denote unsolved scenarios.

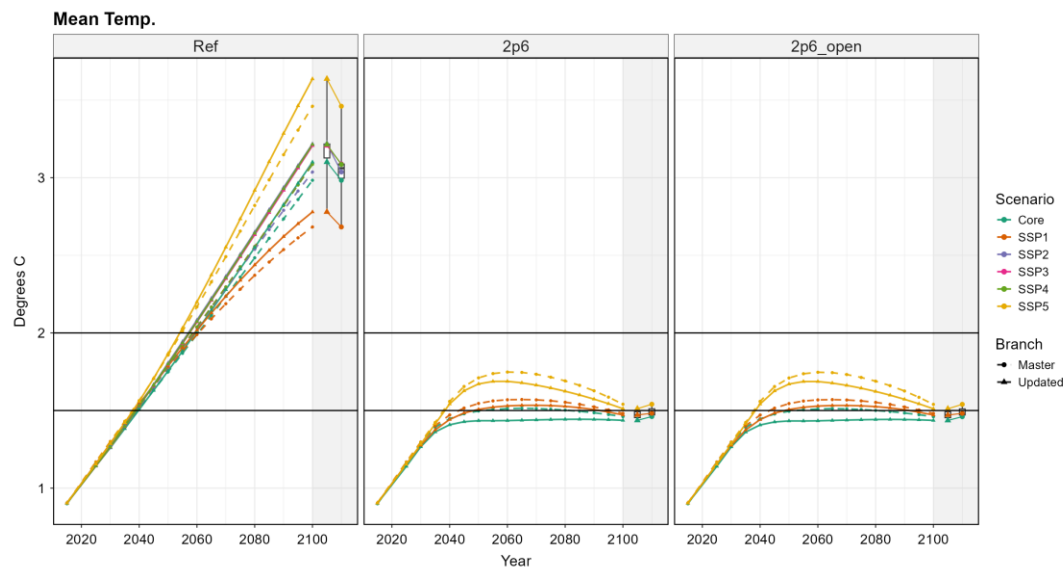
We update the key validation figures (in line with CMP-411), now highlighting revised results for national account variables—only key indicators are indexed (in the Table of Contents) here. The figures are designed to be self-explanatory, with explanatory notes included in the captions where applicable.

4.1. Radiative Forcing, Temperature, and Carbon Prices

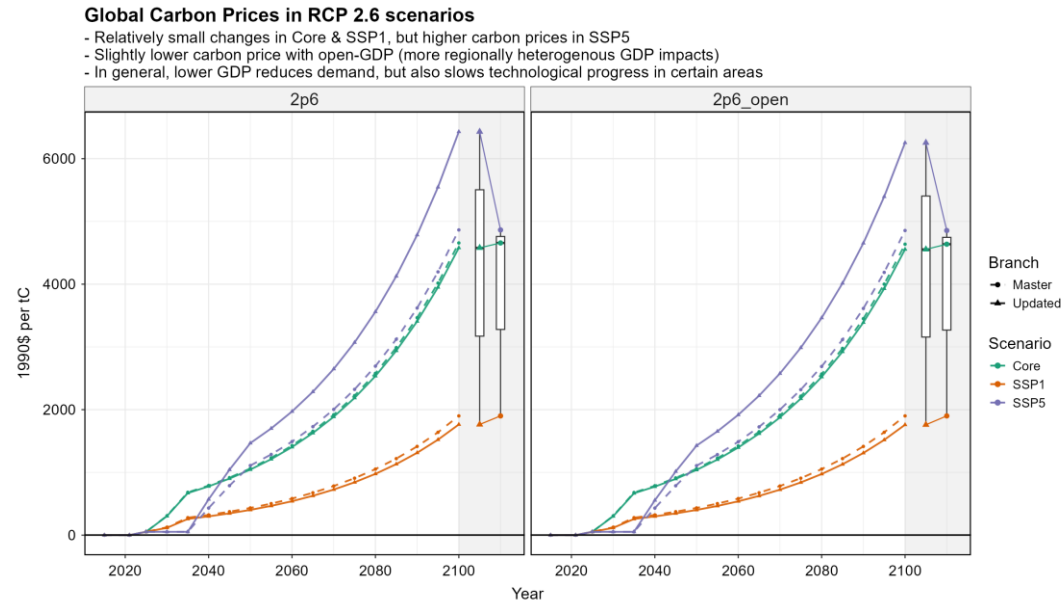


Total forcing across SPA and GDP-response (fixed vs. open) scenarios.

The lines present projections by 2100 by scenario (SSPs or GCAM core; GCAM-core is identical to SSP2 for population) across branches, Master (dotted lines) vs. Updated (solid lines). The boxplots show distributions of 2100 values across branches Master (left) vs. Updated (right), i.e., including the median values (line), the 1st and 3rd quartiles (boxes), and the 0-100 percentile ranges (whiskers) of the scenarios. Data of the boxplots are shown (points) and the lines connecting these points across branches show changes due to the updates. The same plot format (2100 scenario distribution, where applicable) is applied consistently across all validation figures.

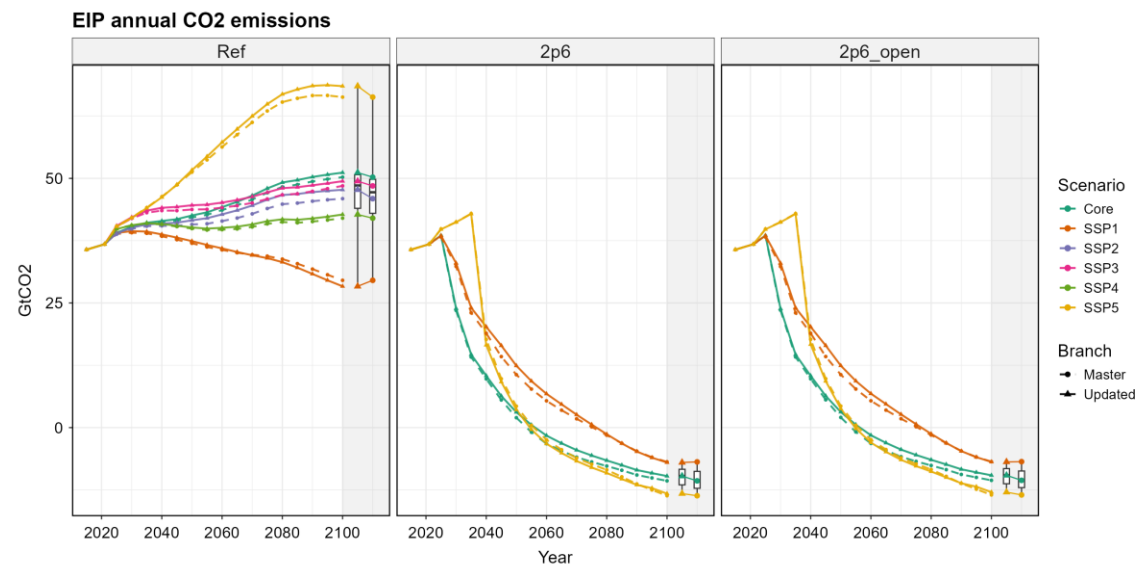


Mean temperature across SPA and GDP-response (fixed vs. open) scenarios.



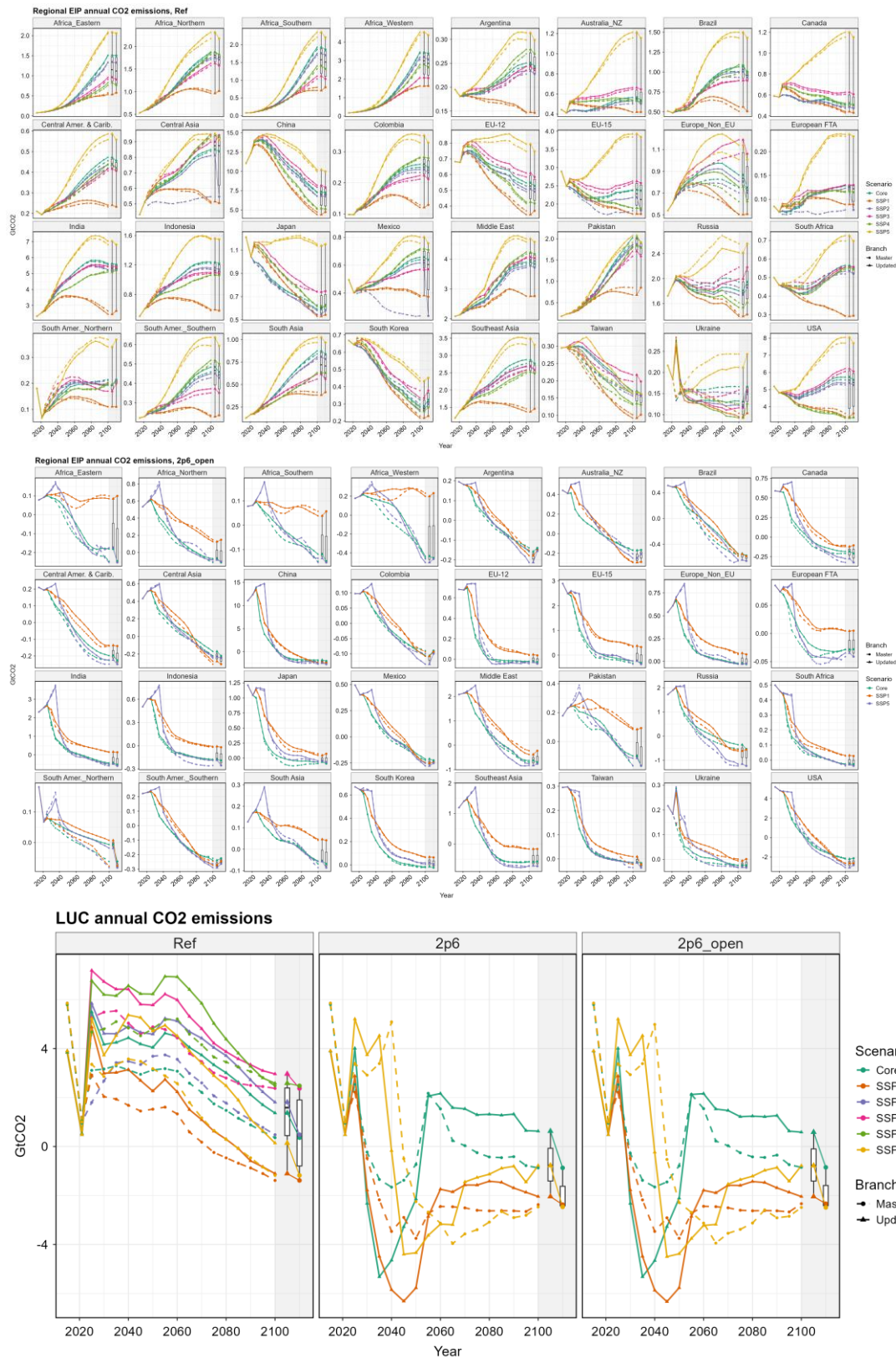
Global carbon prices across SPA and GDP-response (fixed vs. open) scenarios.

4.2. Emissions

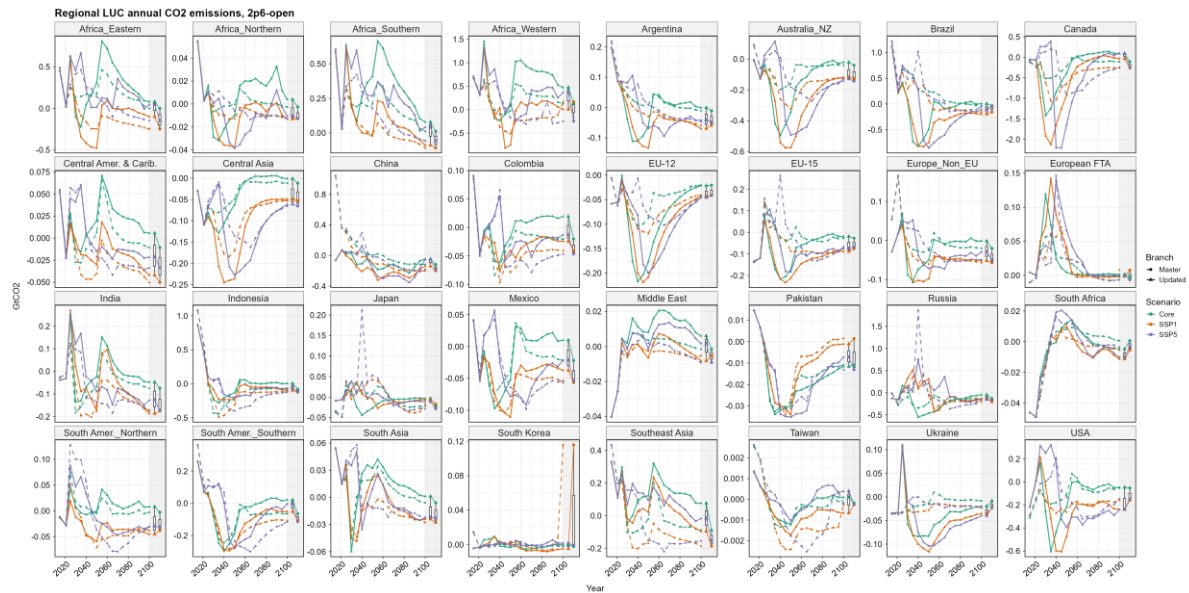
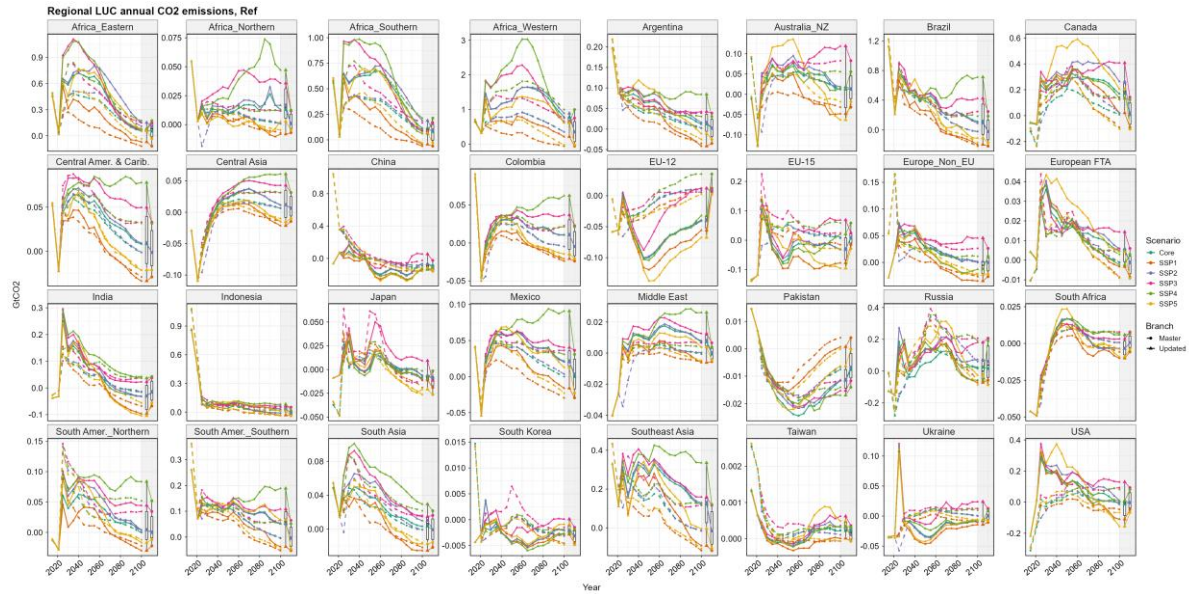


Global energy and industrial processes (EIP) carbon dioxide emissions across SPA and GDP-response (fixed vs. open) scenarios.

- Changes in EIP emissions are relatively small, even at the regional level.
- Regional results for the Ref and 2p6-open scenarios are presented below.
- The largest changes occur in Central Asia, EU-15, European FTA, and Mexico, in the Ref scenario under SSP2, where emissions were previously considerably lower (including relative to other scenarios).



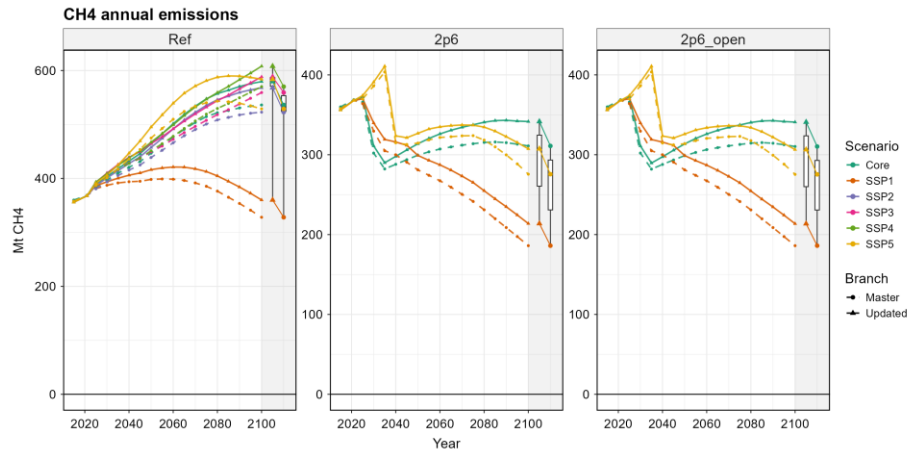
Global (& regional) land use change (LUC) carbon dioxide emissions across SPA and GDP-response (fixed vs. open) scenarios.



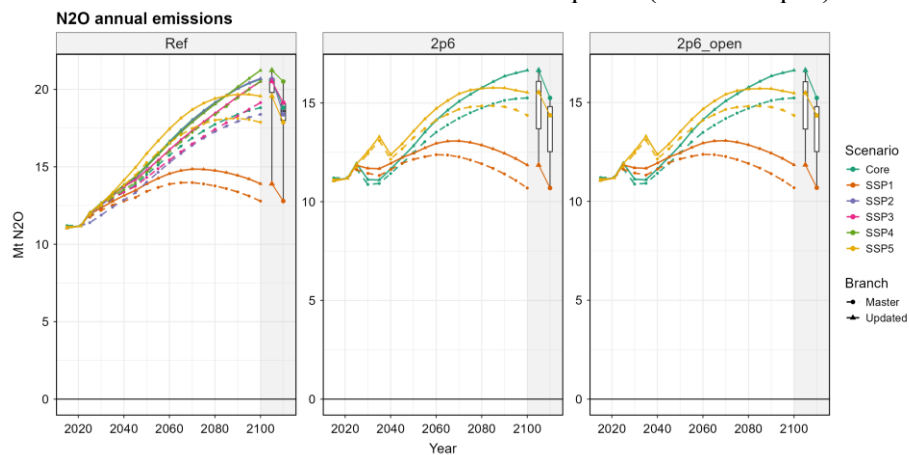
- Global LUC emissions are generally higher in Ref scenarios. However, there was a considerably larger reduction in LUC emissions in 2p6 scenarios due to higher afforestation/reforestation. With all the updates, the new AgLU under KLEAM is more responsive to land carbon pricing, mainly due to the relatively lower land competition from purpose-grown energy cropland and more price-responsive nonfood demand for agricultural products.
- Regional results for the Ref and 2p6-open scenarios are presented below.
- Historical processing of managed versus unmanaged forest area has been improved, resulting in better alignment in recent historical and near-term regional outcomes (e.g., China).
- Previously observed emission spikes in the 2p6 scenario have also been reduced (e.g., Russia, Japan, and South Korea).
- Overall, updated results show higher agricultural production in Ref scenarios, driven by the integration of agricultural nonfood services into the broader macroeconomic system. This leads to greater cropland demand under reference conditions, while the 2p6 scenarios exhibit stronger

market-mediated responses, such as greater demand reduction and substitution in response to higher prices.

- Note that previously, both the income and price elasticities for nonfood demand were set to zero. These values have now been updated to ensure consistency with the macroeconomic linkage through NonFood-Service.

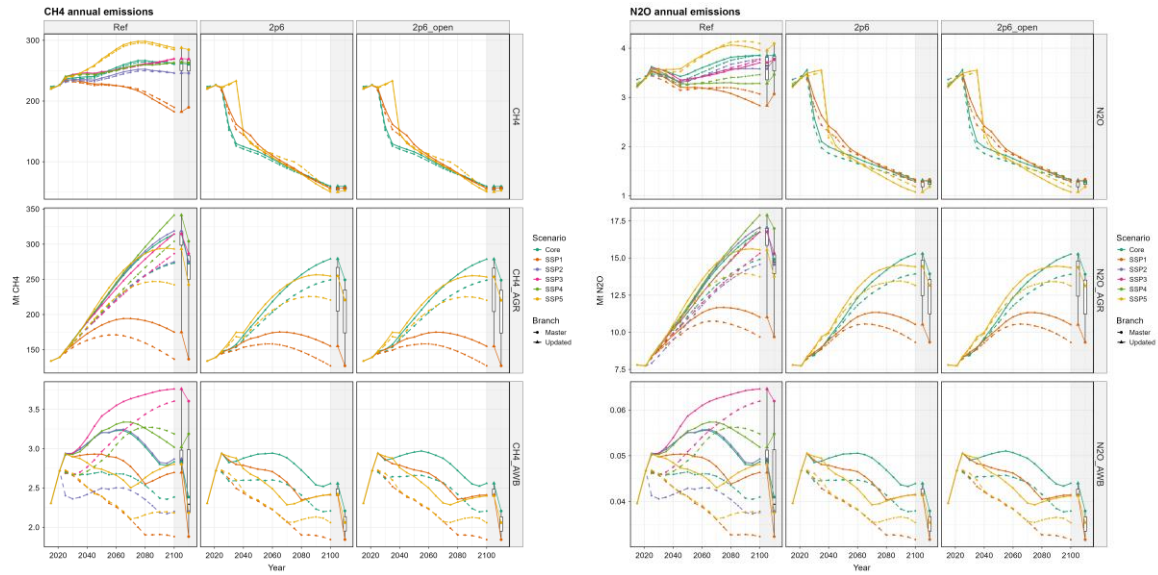


Global CH4 emissions across SPA and GDP-response (fixed vs. open) scenarios



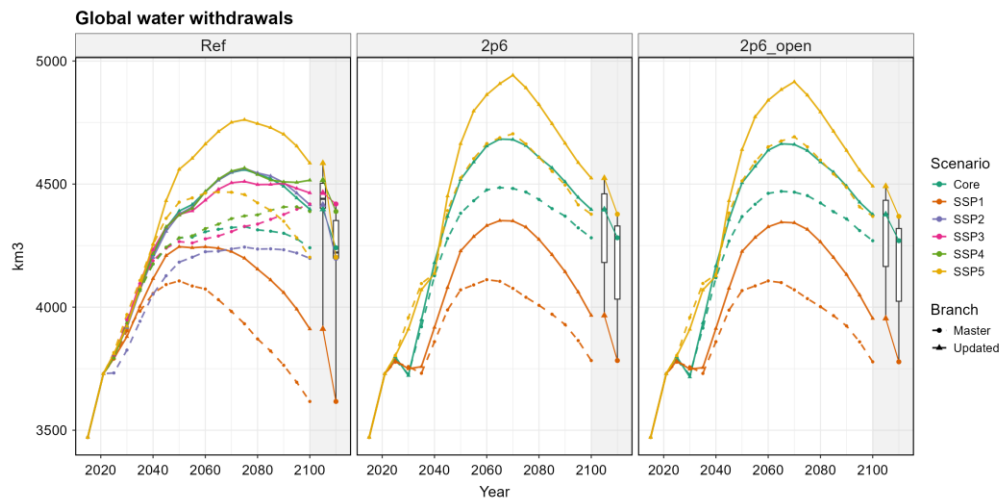
Global N2O emissions across SPA and GDP-response (fixed vs. open) scenarios

- Changes in CH4 and N2O emissions are mainly driven by changes in agricultural production

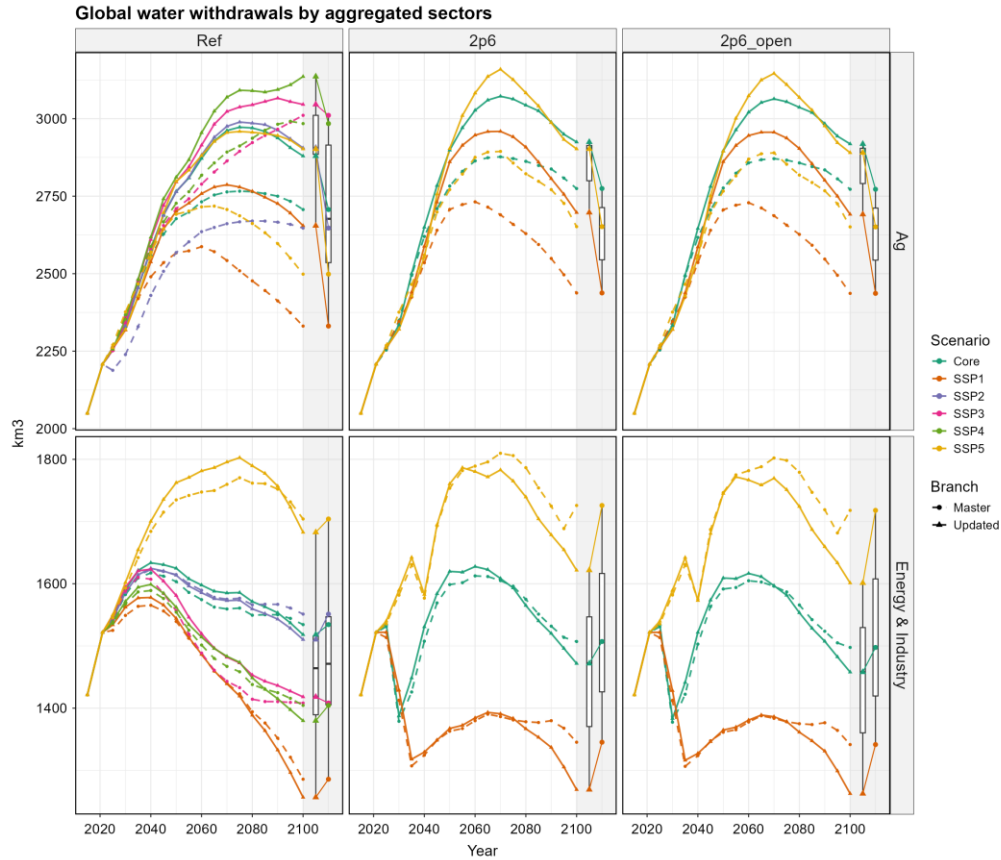


Global CH₄ and N₂O emissions across SPA and GDP-response (fixed vs. open) scenarios by sectors. Row panels indicate emissions by sector: non-Ag (CH₄/N₂O), agriculture (_AGR), and agricultural waste burning (_ABW).

4.3. Water withdrawal



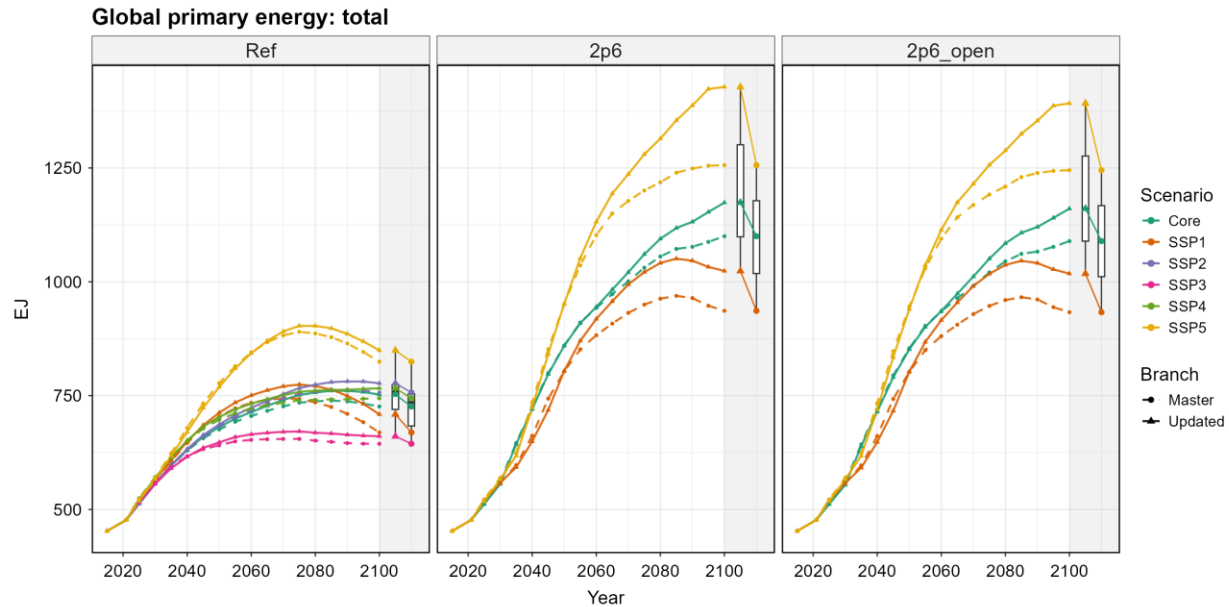
Global water withdrawal across SPA and GDP-response (fixed vs. open)



Global water withdrawal across SPA and GDP-response (fixed vs. open) scenarios by sectors.

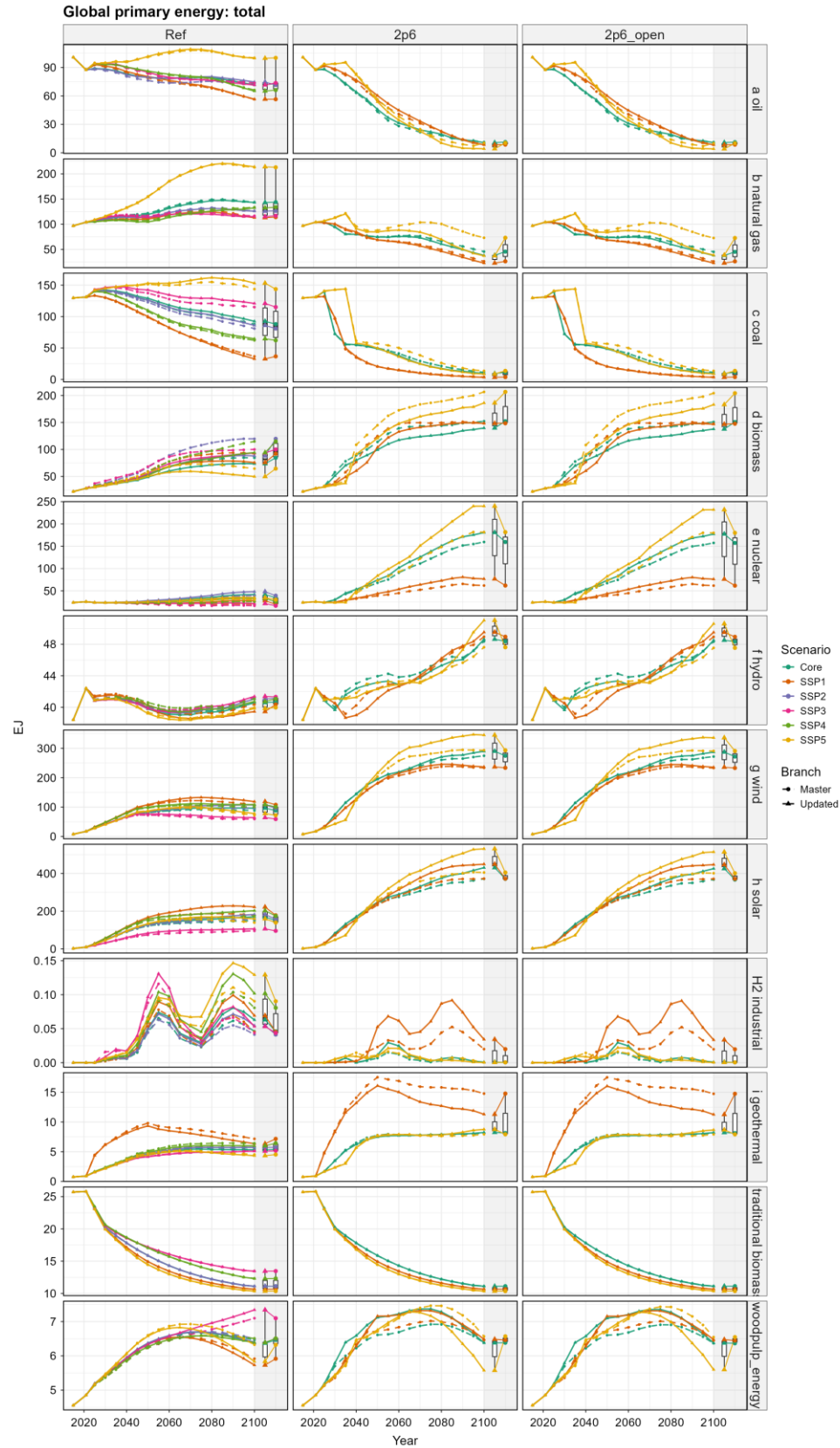
- Changes were mainly in agricultural sectors, driven by higher agricultural production, particularly in sectors with high other uses (e.g., fiber crops), since we include a positive income elasticity for those nonfood services (for macroeconomic consistency).

4.4. Energy

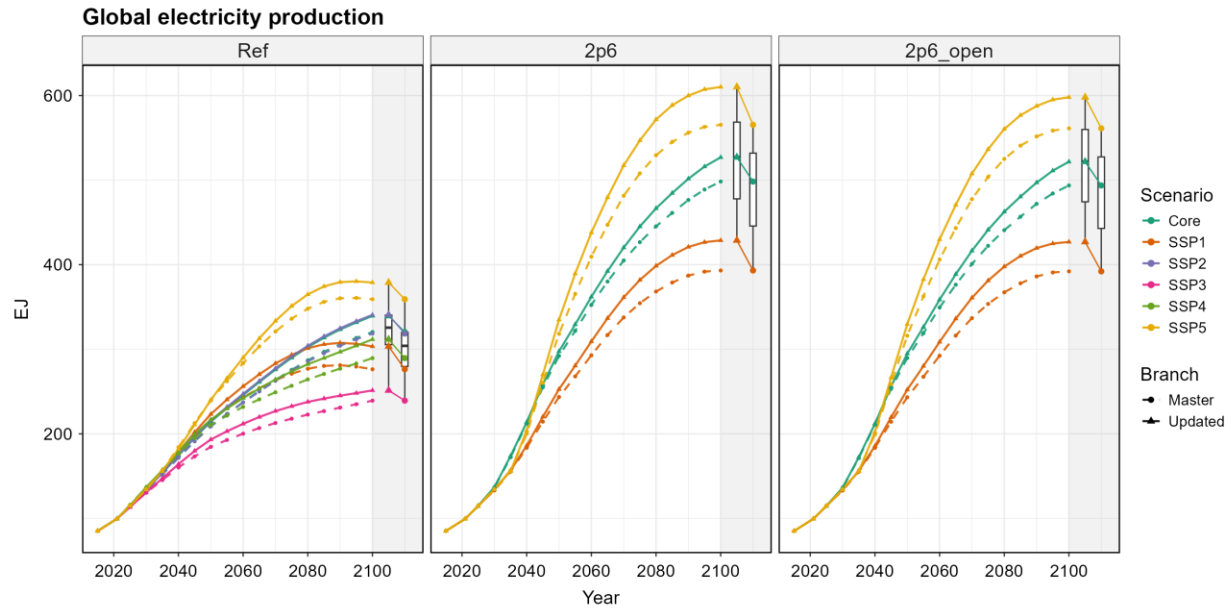


Global total primary energy across SPA and GDP-response (fixed vs. open) scenarios.

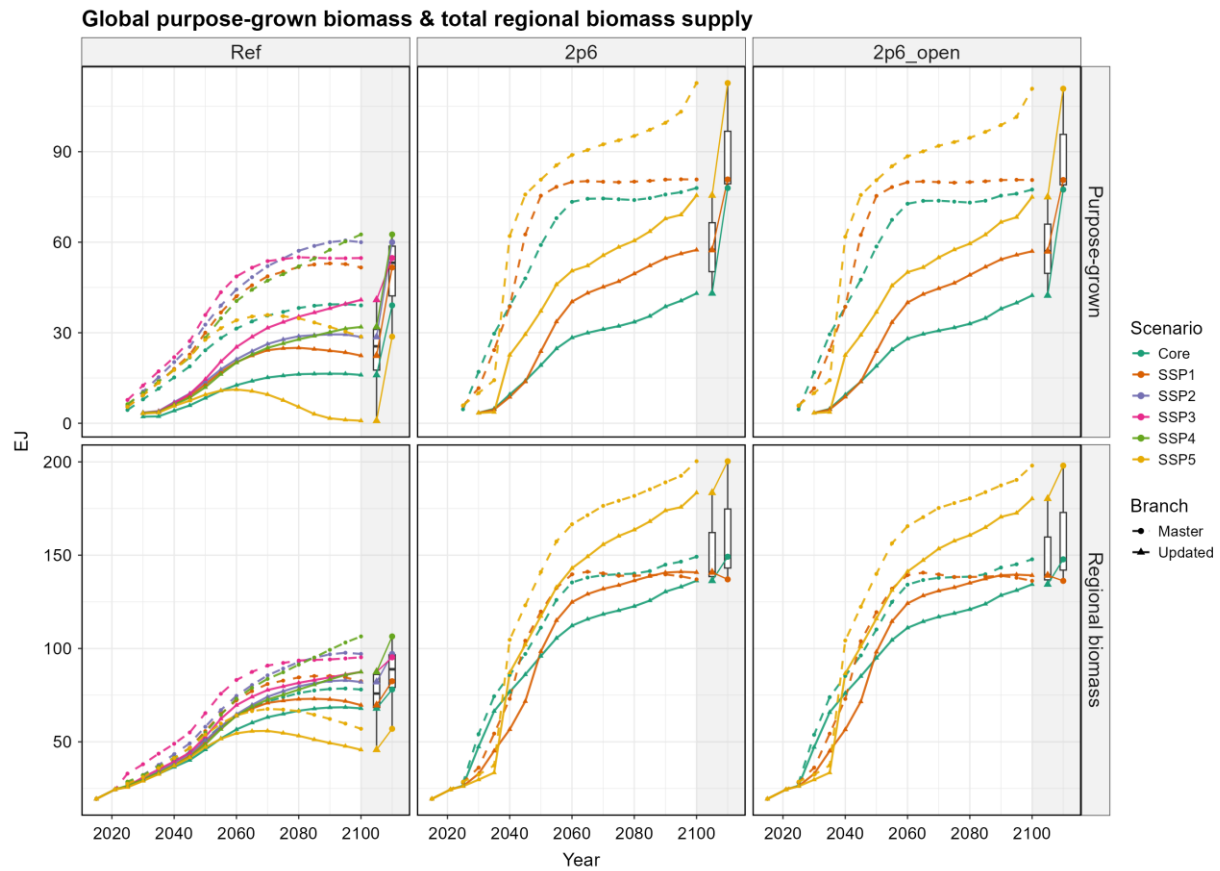
- Overall, global primary energy supply is higher, driven mainly by reduced supply from purpose-grown energy crops (a key improvement in this CMP), a shift toward solar and wind (which have higher primary energy accounting on the resource side), and contributions from other sources. There is also higher electricity generation.
- A sectoral breakdown is provided.
- The introduction of an endogenous capital market (with a lower long-term cost of capital) also affects energy supply, though its impact is relatively small in this context.
- The deployment of purpose-grown energy crops is delayed until 2030, with regionally differentiated assumptions; as a result, near-term regional biomass supply better aligns with socioeconomic conditions (e.g., slower expansion in less developed regions).
- Although supply from purpose-grown biomass declines, this reduction is partially offset by increased availability of crop residues, driven by market responses (e.g., higher biomass prices following reduced purpose-grown supply) and higher crop production.



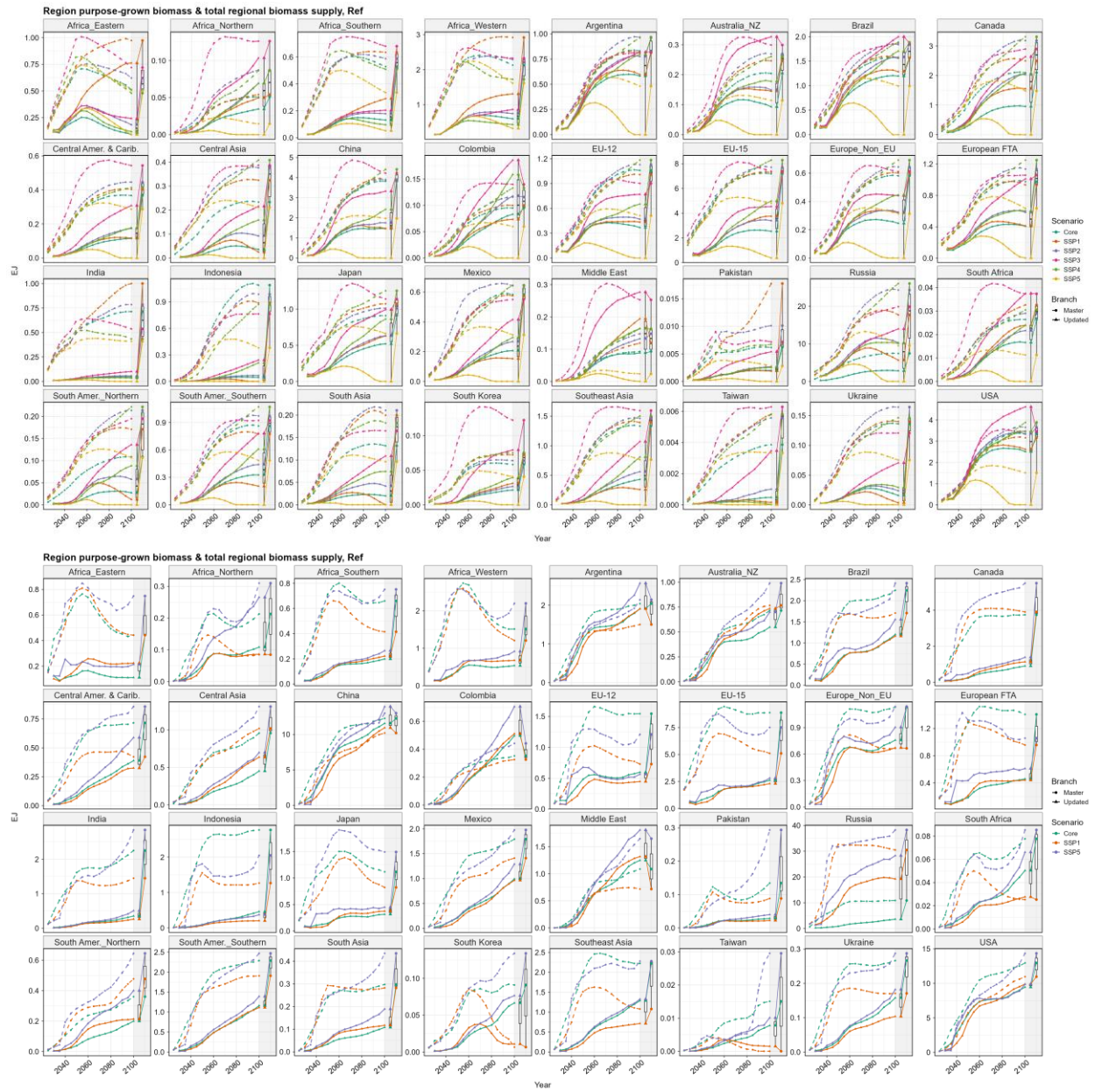
Global primary energy across SPA and GDP-response (fixed vs. open) scenarios, by sector.



Global electricity production across SPA and GDP-response (fixed vs. open) scenarios.



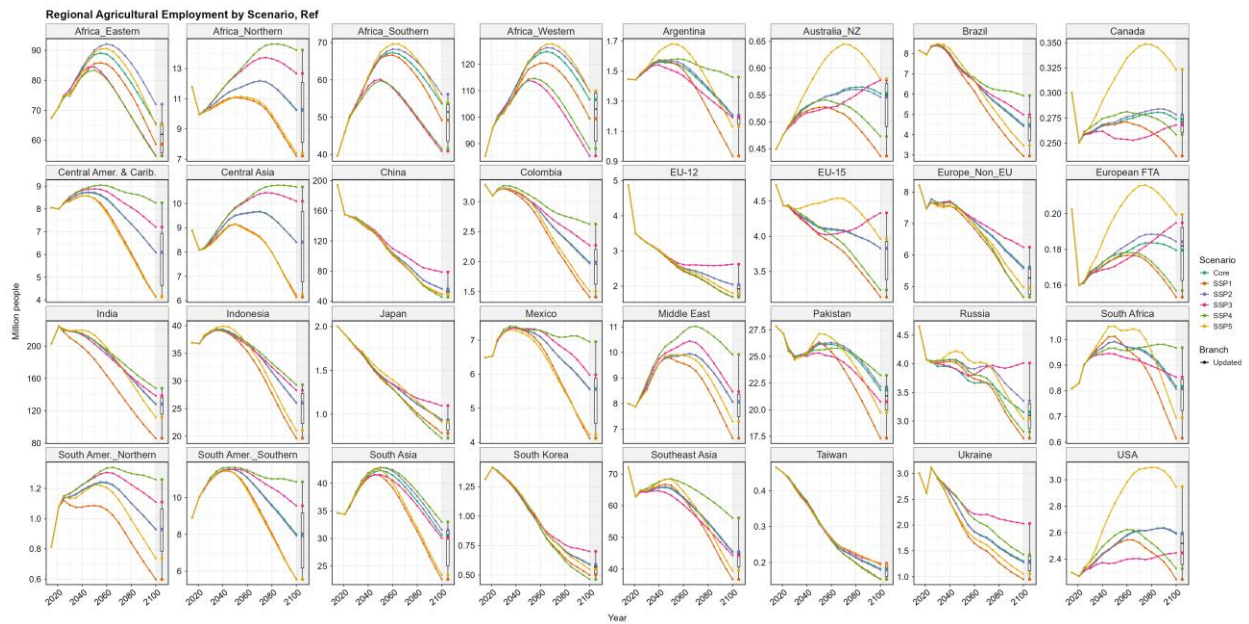
Global purpose-grown biomass and regional biomass supply across SPA and GDP-response (fixed vs. open) scenarios.

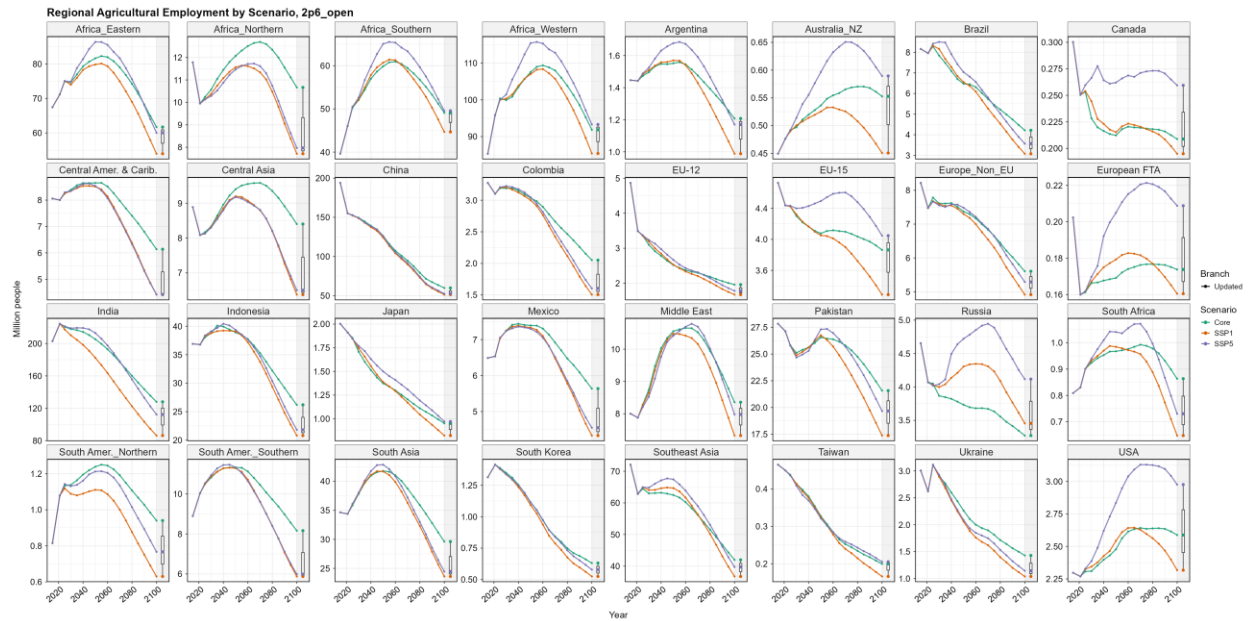


4.5. Agriculture

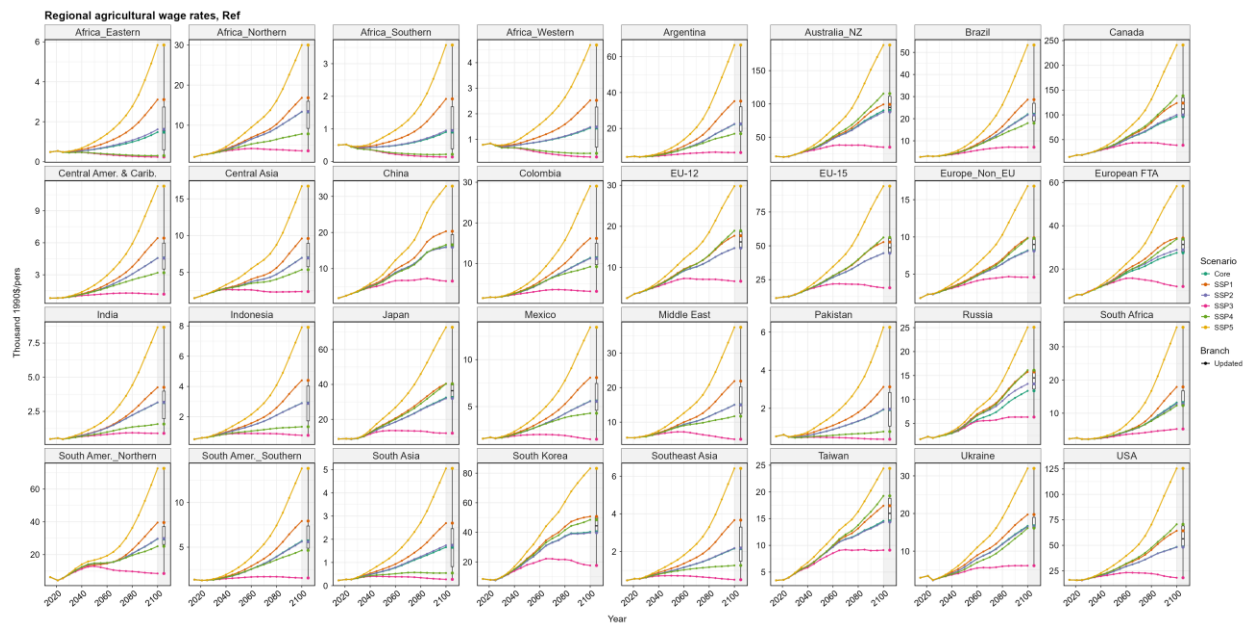


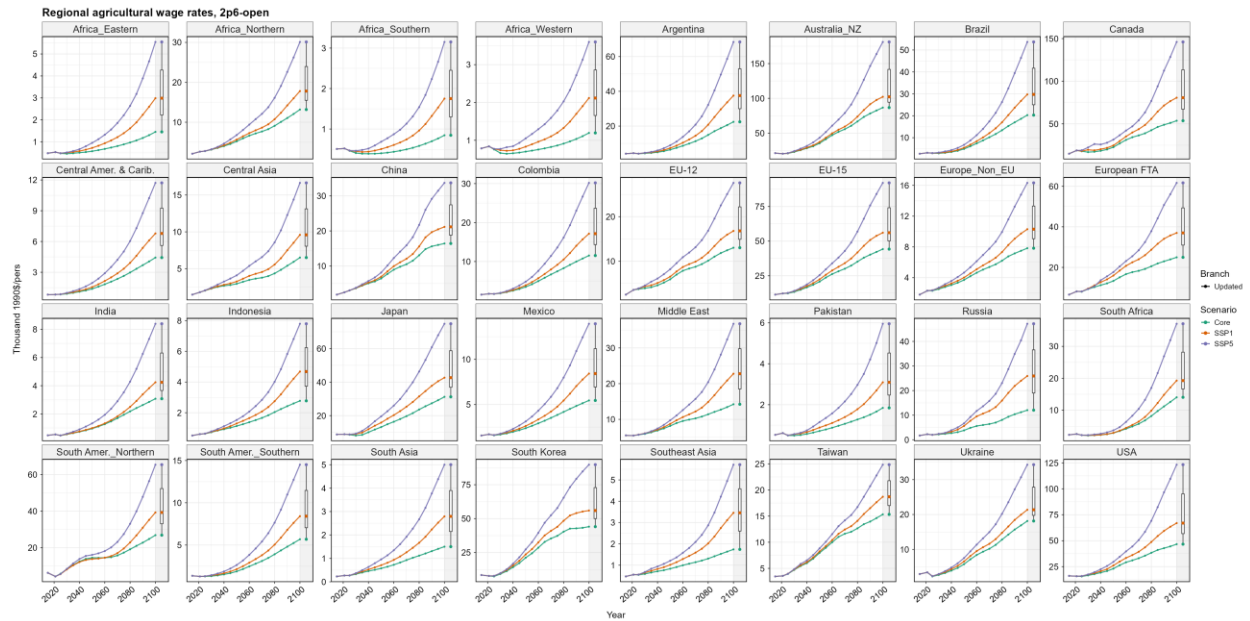
Fig. 8 Global agricultural employment across SPA and GDP-response (fixed vs. open) scenarios.





Regional agricultural employment





Regional agricultural wage rates

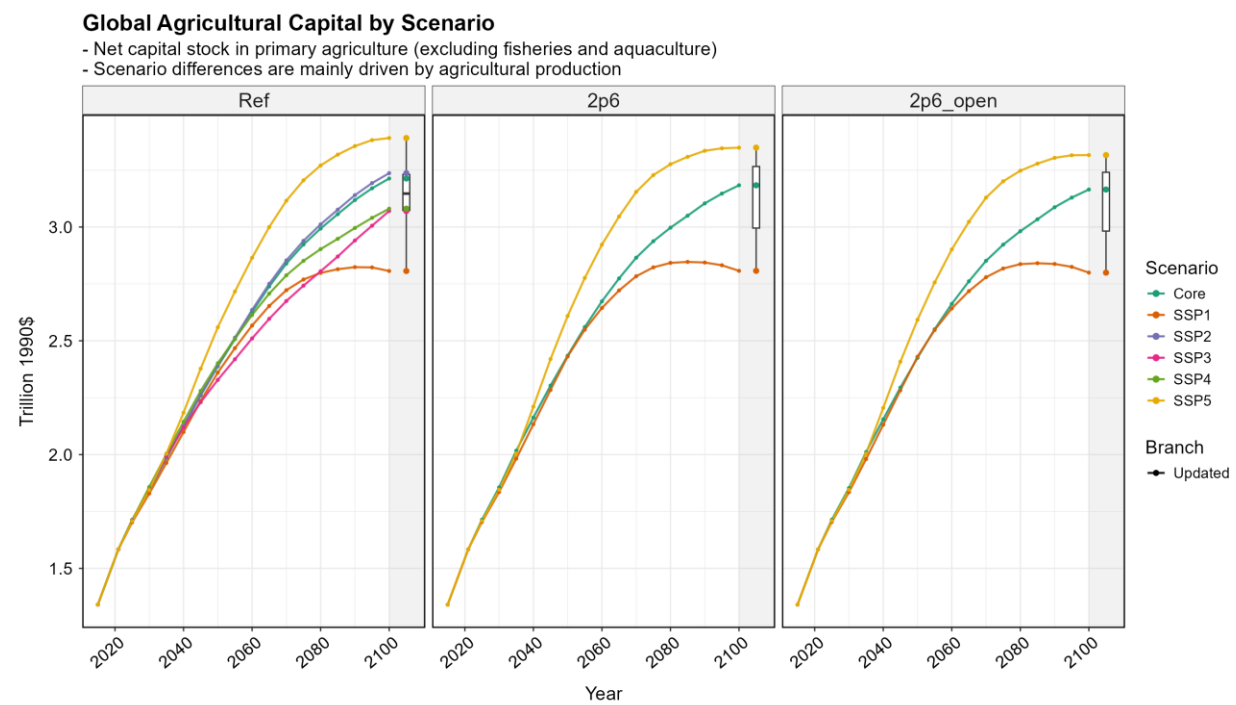
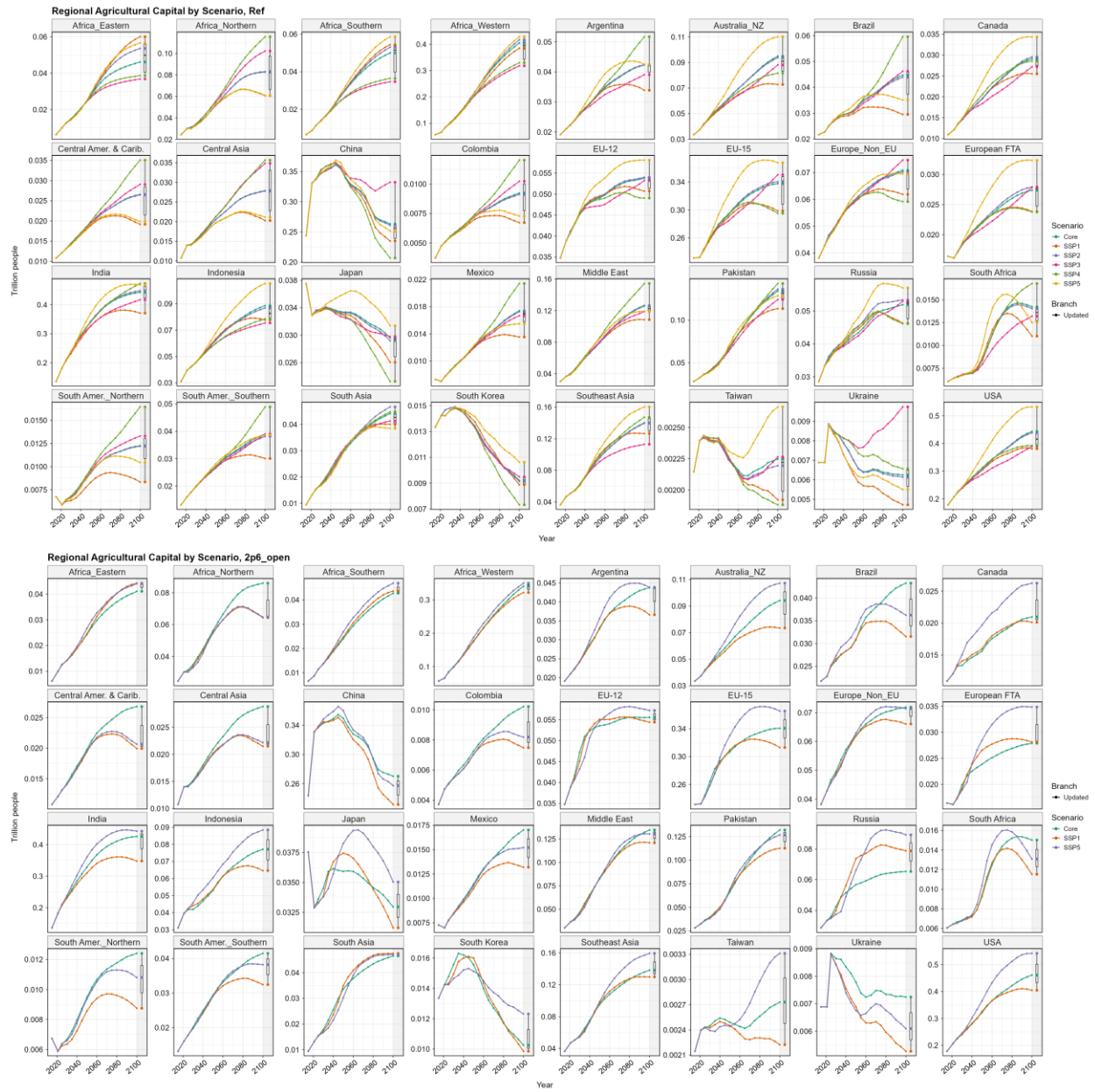
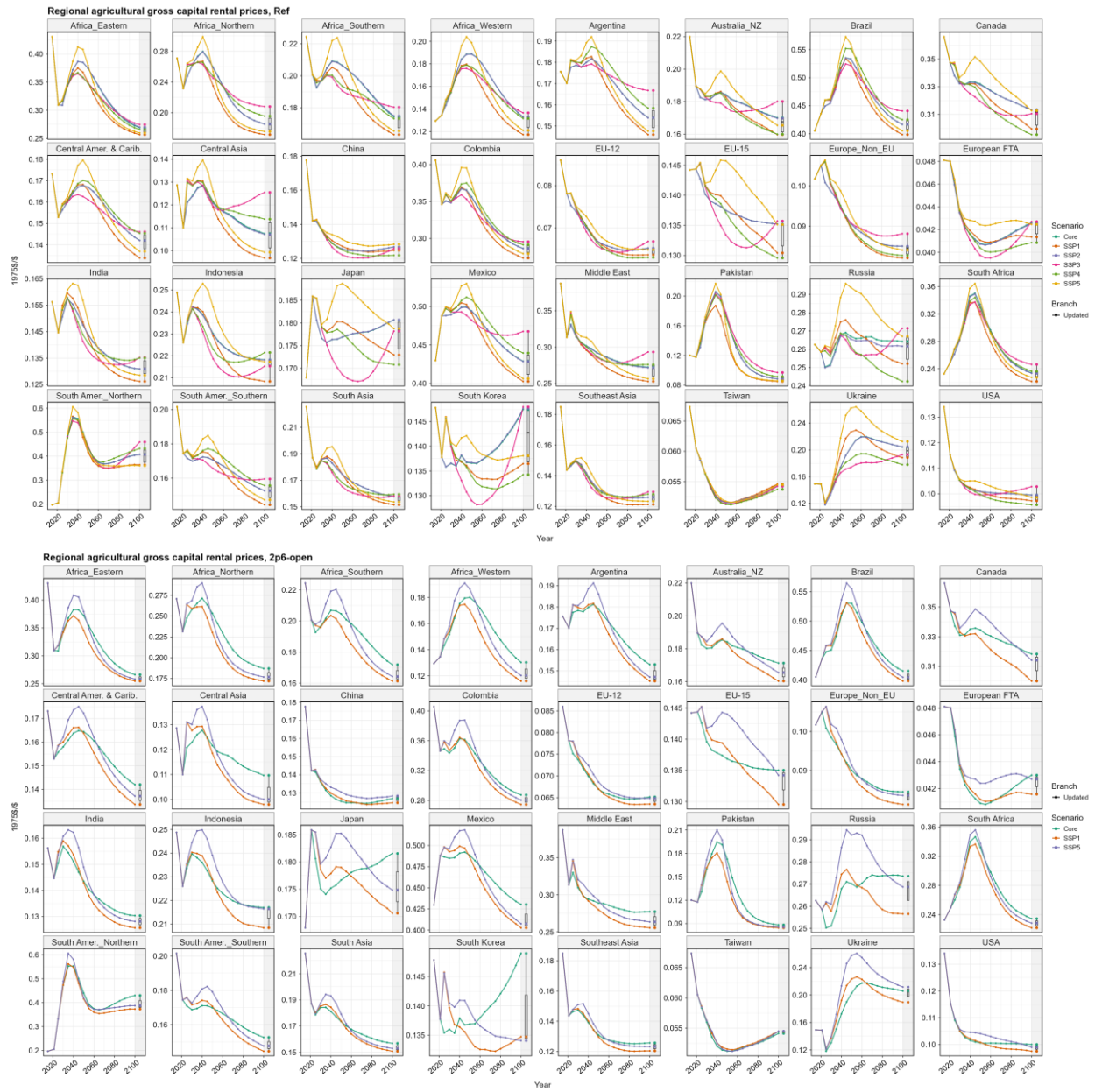


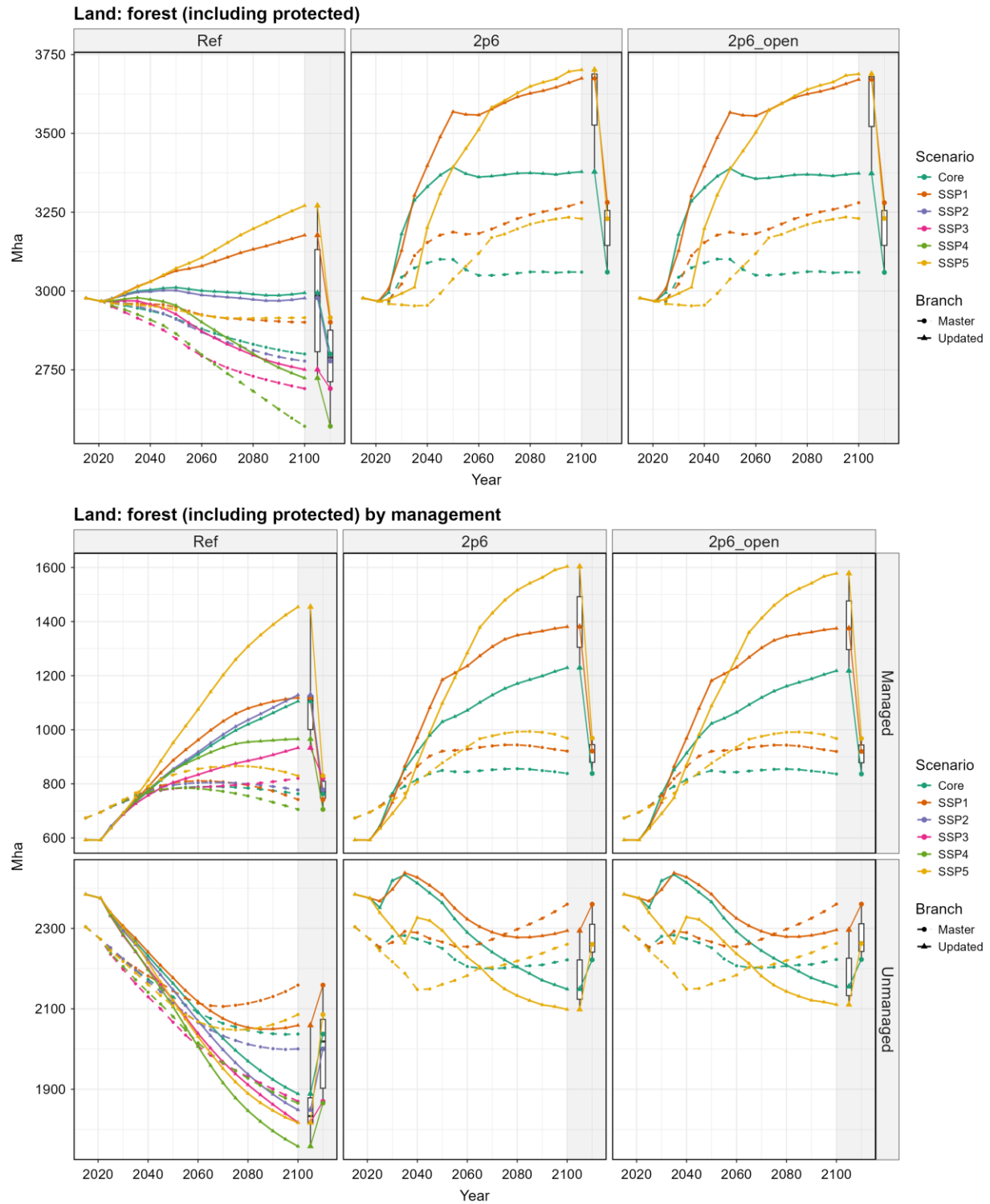
Fig. 9 Global agricultural net capital stock across SPA and GDP-response (fixed vs. open) scenarios.



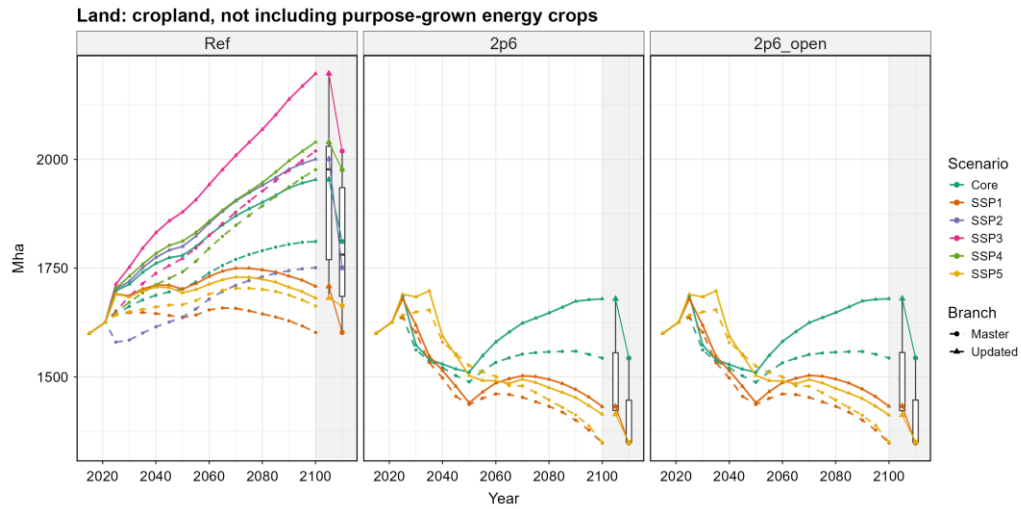
Regional agricultural capital input



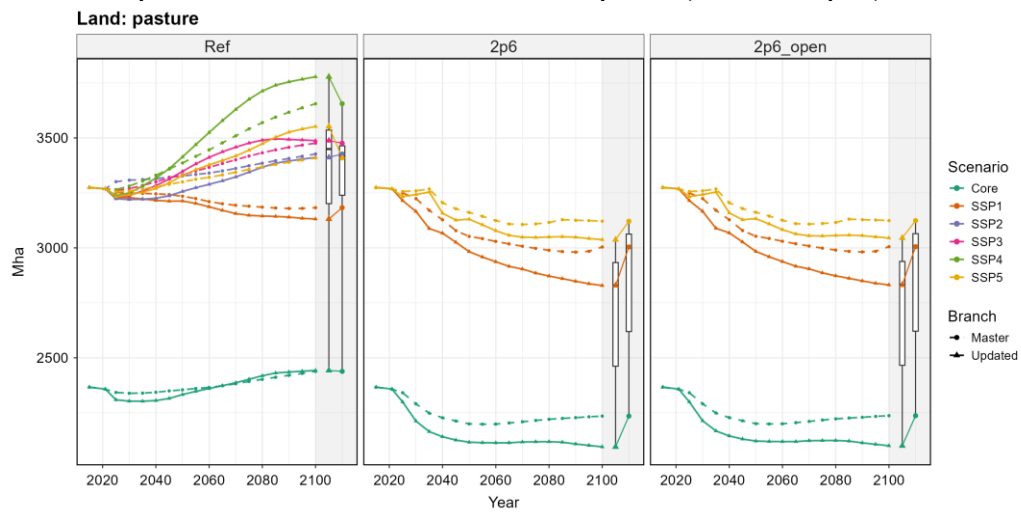
Regional agricultural capital rental prices



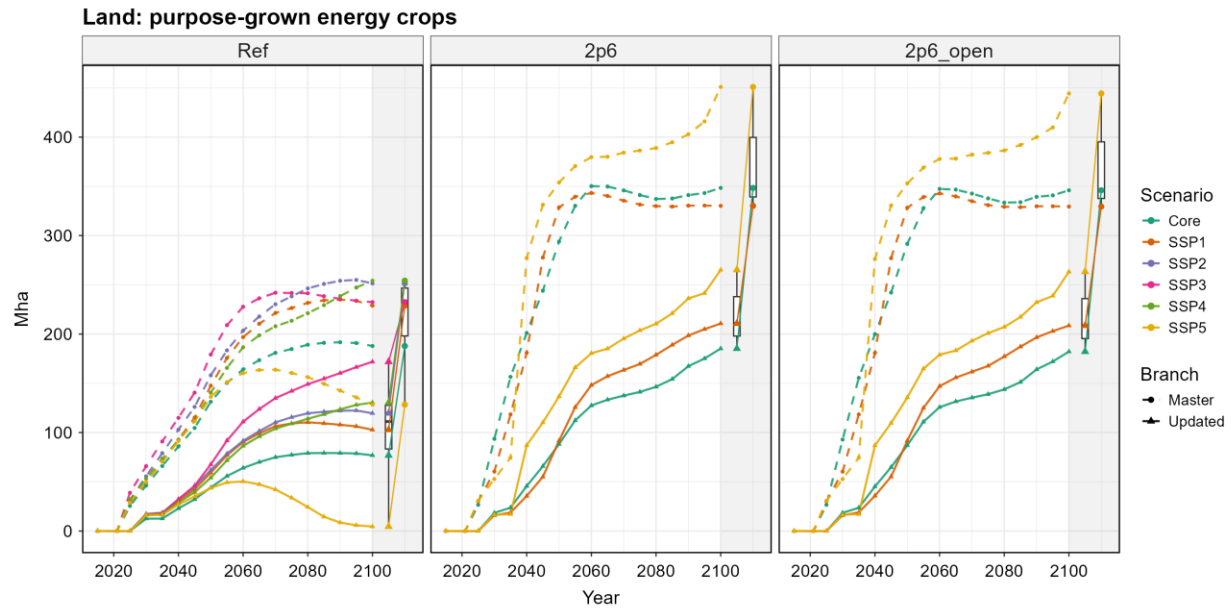
Global forest area (including protected) across SPA and GDP-response (fixed vs. open) scenarios.



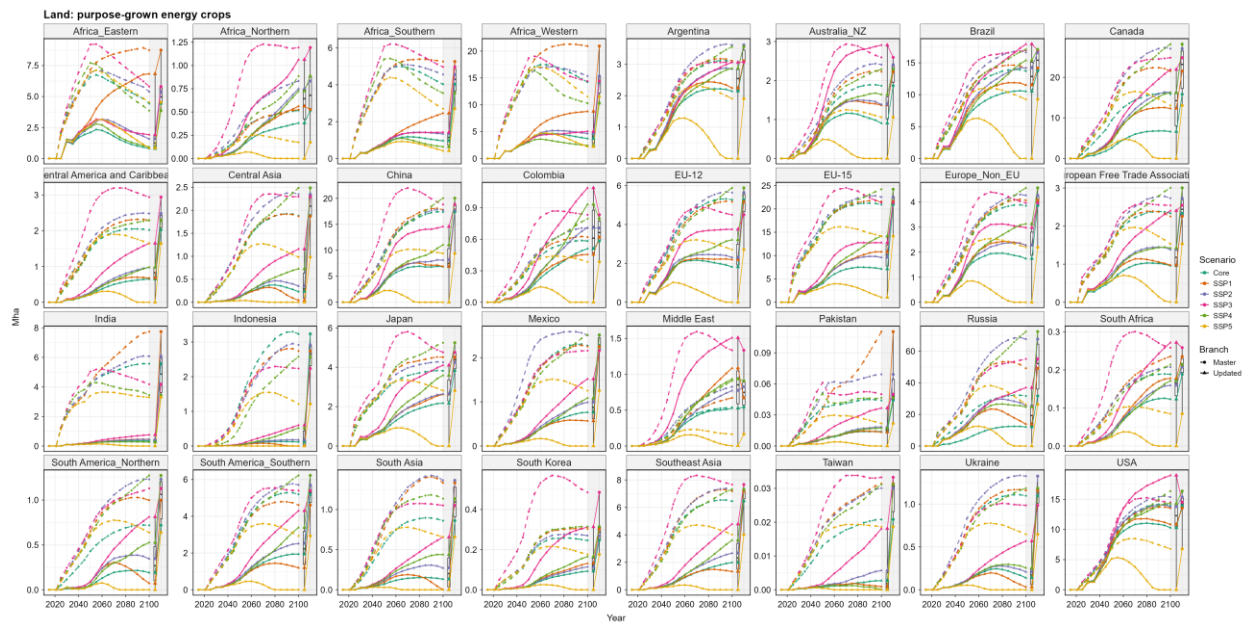
Global cropland area across SPA and GDP-response (fixed vs. open) scenarios.

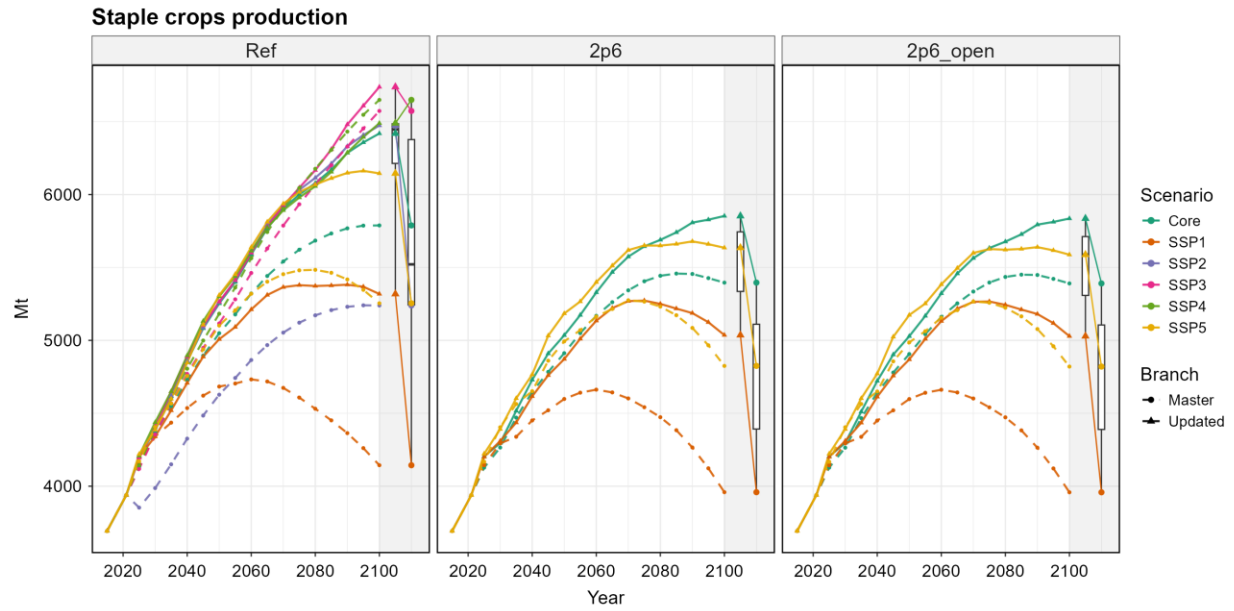


Global pastureland area across SPA and GDP-response (fixed vs. open) scenarios.

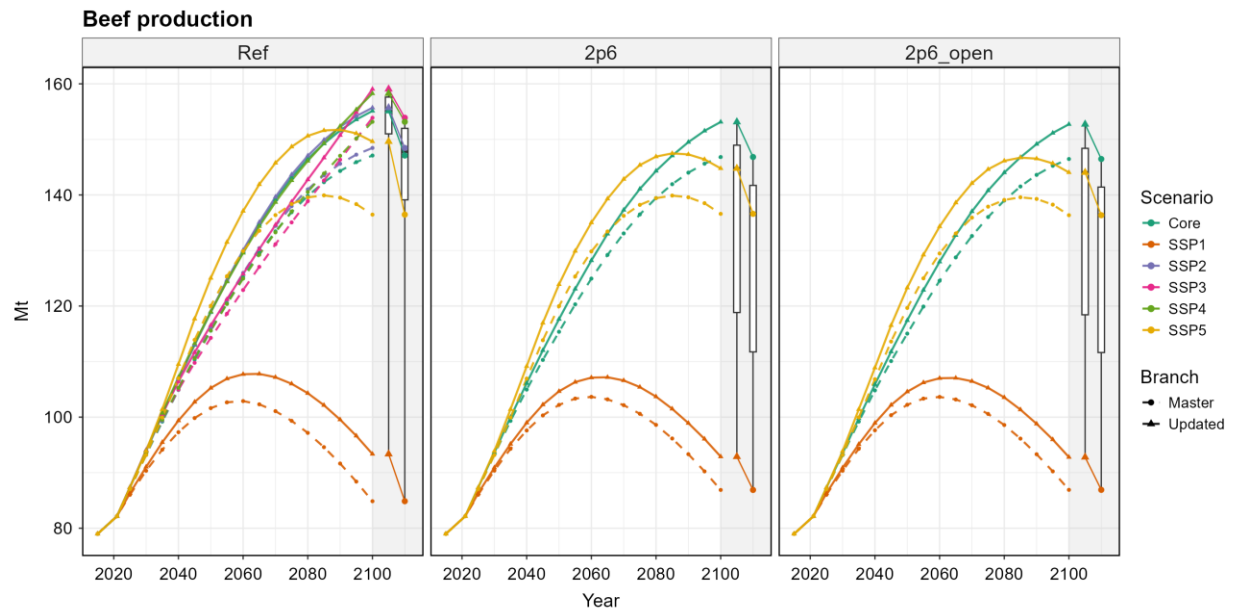


Global purpose-grown energy cropland area across SPA and GDP-response (fixed vs. open) scenarios.

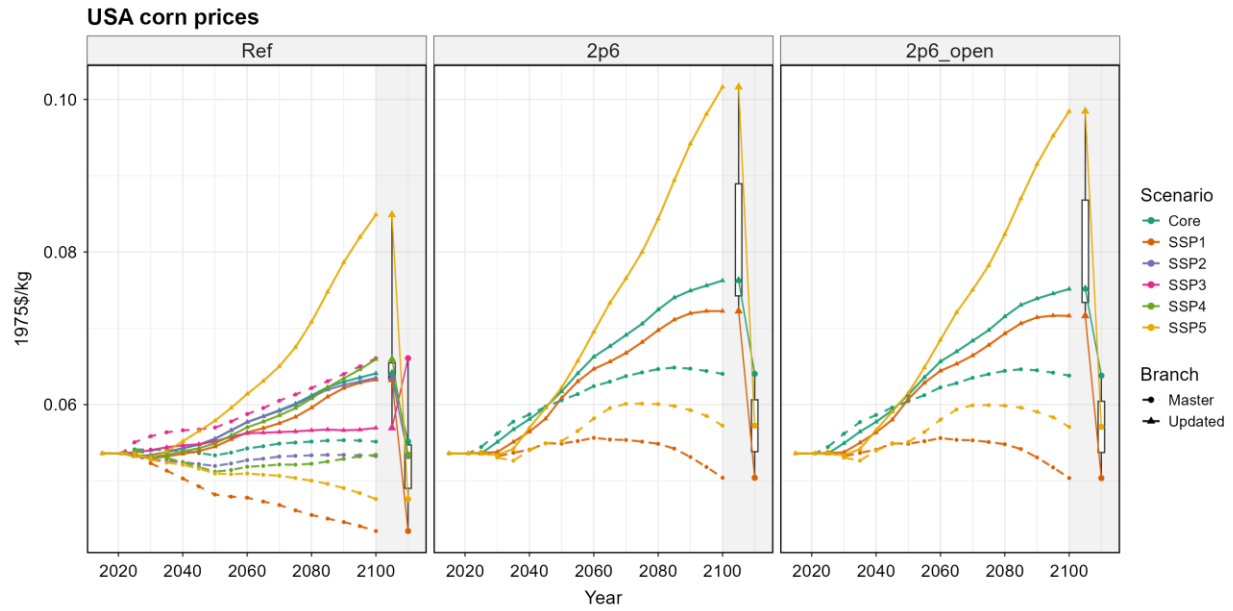




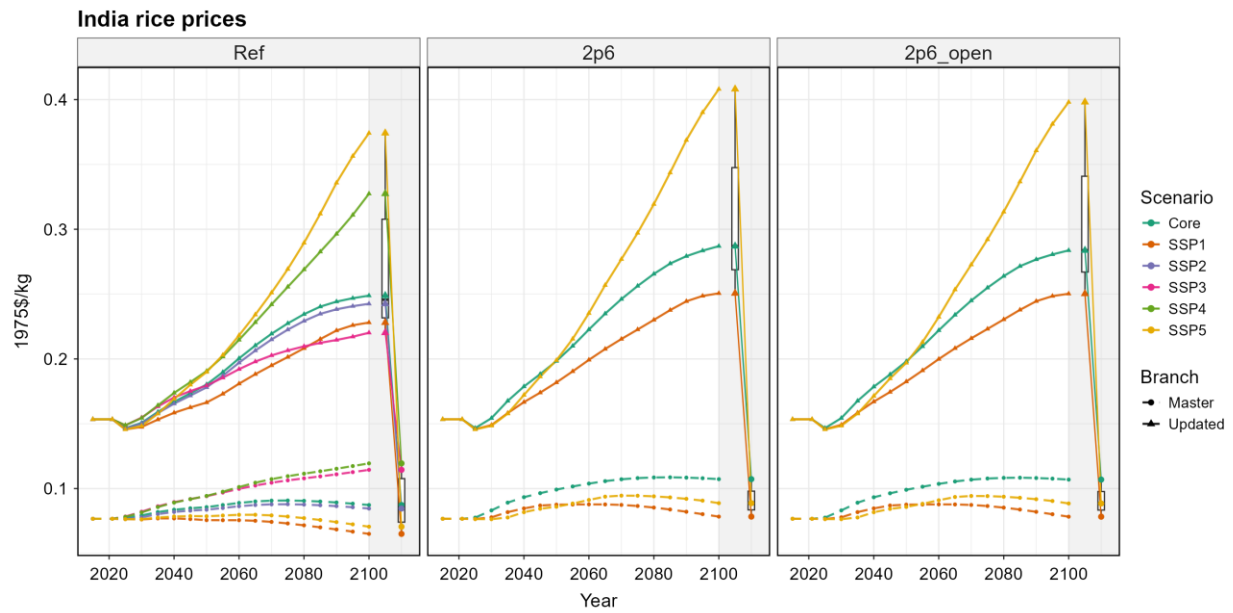
Global staple crop production across SPA and GDP-response (fixed vs. open) scenarios.



Global beef production across SPA and GDP-response (fixed vs. open) scenarios.

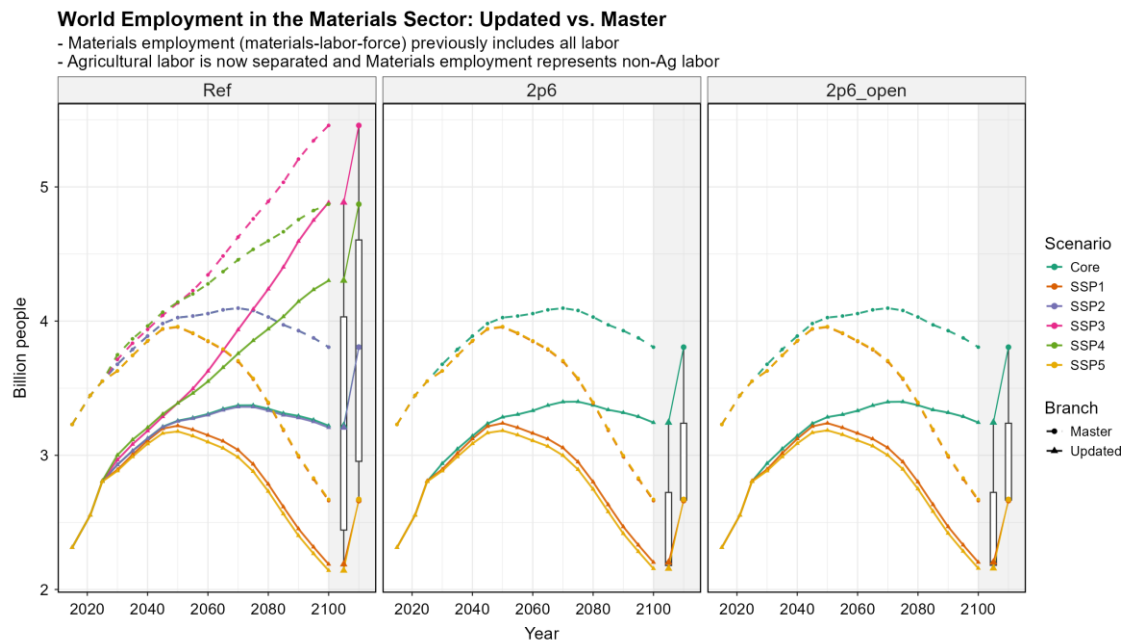
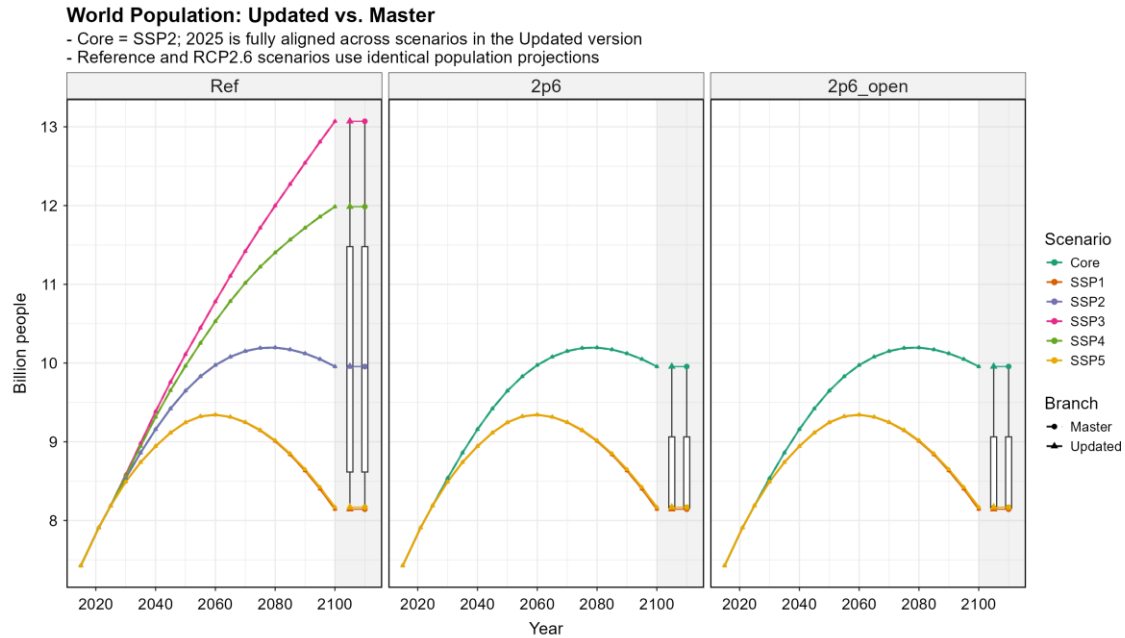


USA corn prices across SPA and GDP-response (fixed vs. open) scenarios.



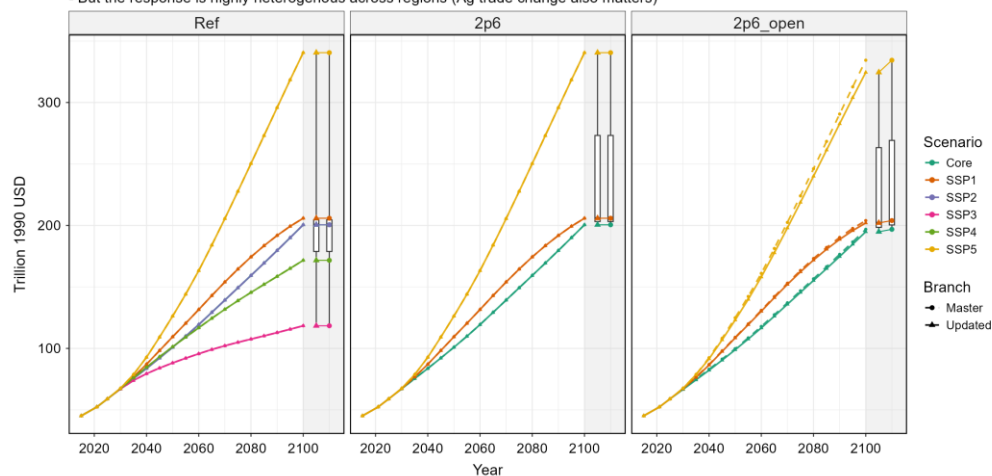
India rice prices across SPA and GDP-response (fixed vs. open) scenarios.

4.6. Socioeconomics



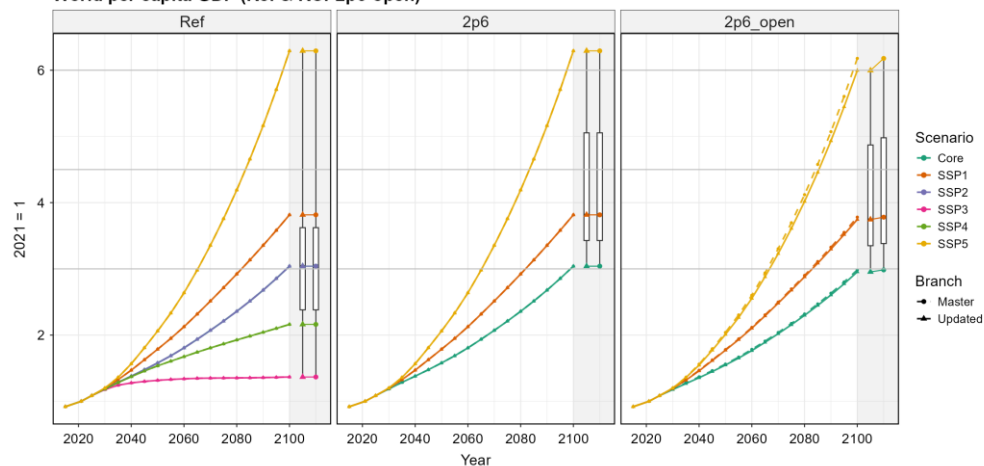
World GDP: Updated vs. Master

- Verifying no change in GDP in Ref. and 2p6
- GDP response in 2p6-open becomes relatively larger (expected)
- The higher global GDP response was driven by energy service value share updates
- But the response is highly heterogeneous across regions (Ag trade change also matters)

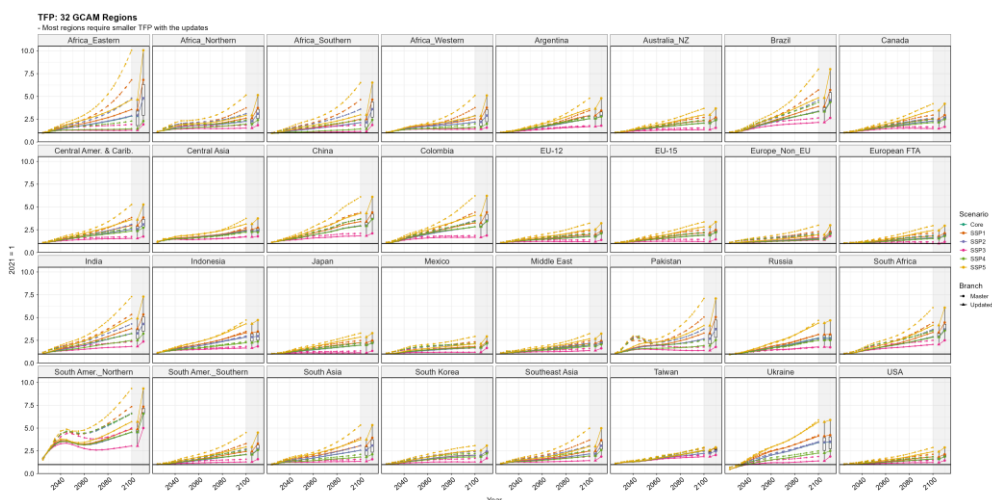


World GDP across SPA and GDP-response (fixed vs. open) scenarios

World per capita GDP (Ref & RCP2p6-open)



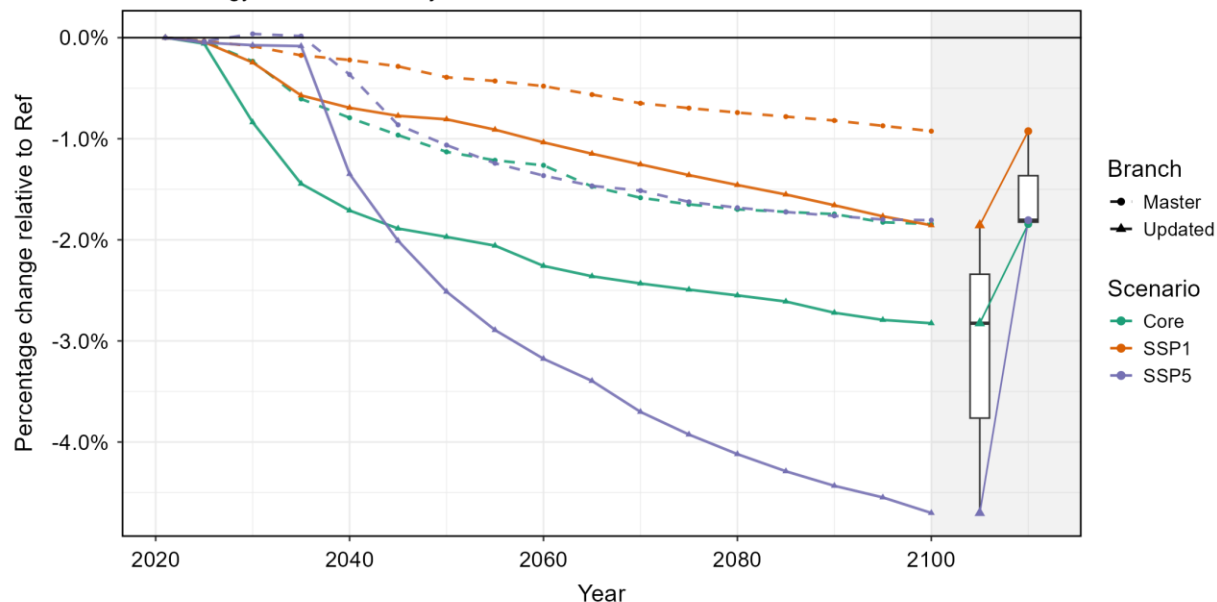
World per capita GDP across SPA and GDP-response (fixed vs. open) scenarios



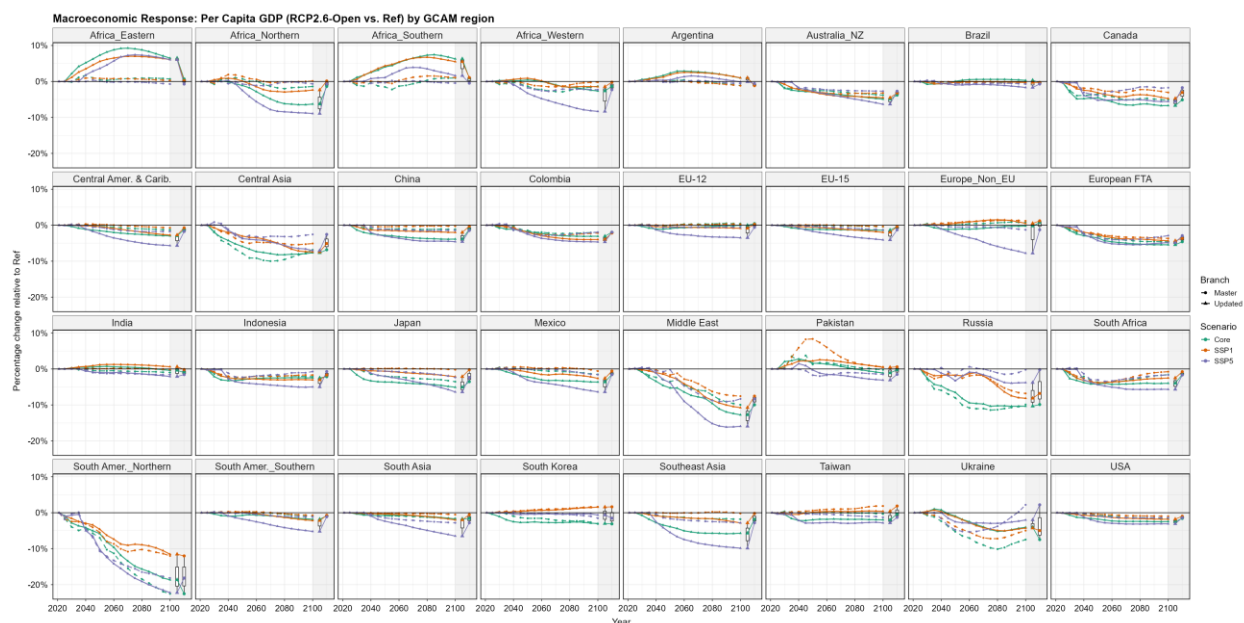
Updated TFP calibration by Core and SSP scenarios

Macroeconomic Response: World Per Capita GDP (RCP2.6-Open vs. Reference)

- GDP impacts from RCP2.6 carbon pricing
- Carbon prices differ slightly (particularly for the Core scenario)
- Stronger GDP responses with greater regional heterogeneity
- Combined effects of agricultural inclusion, capital feedbacks, labor responses, and energy service value adjustments



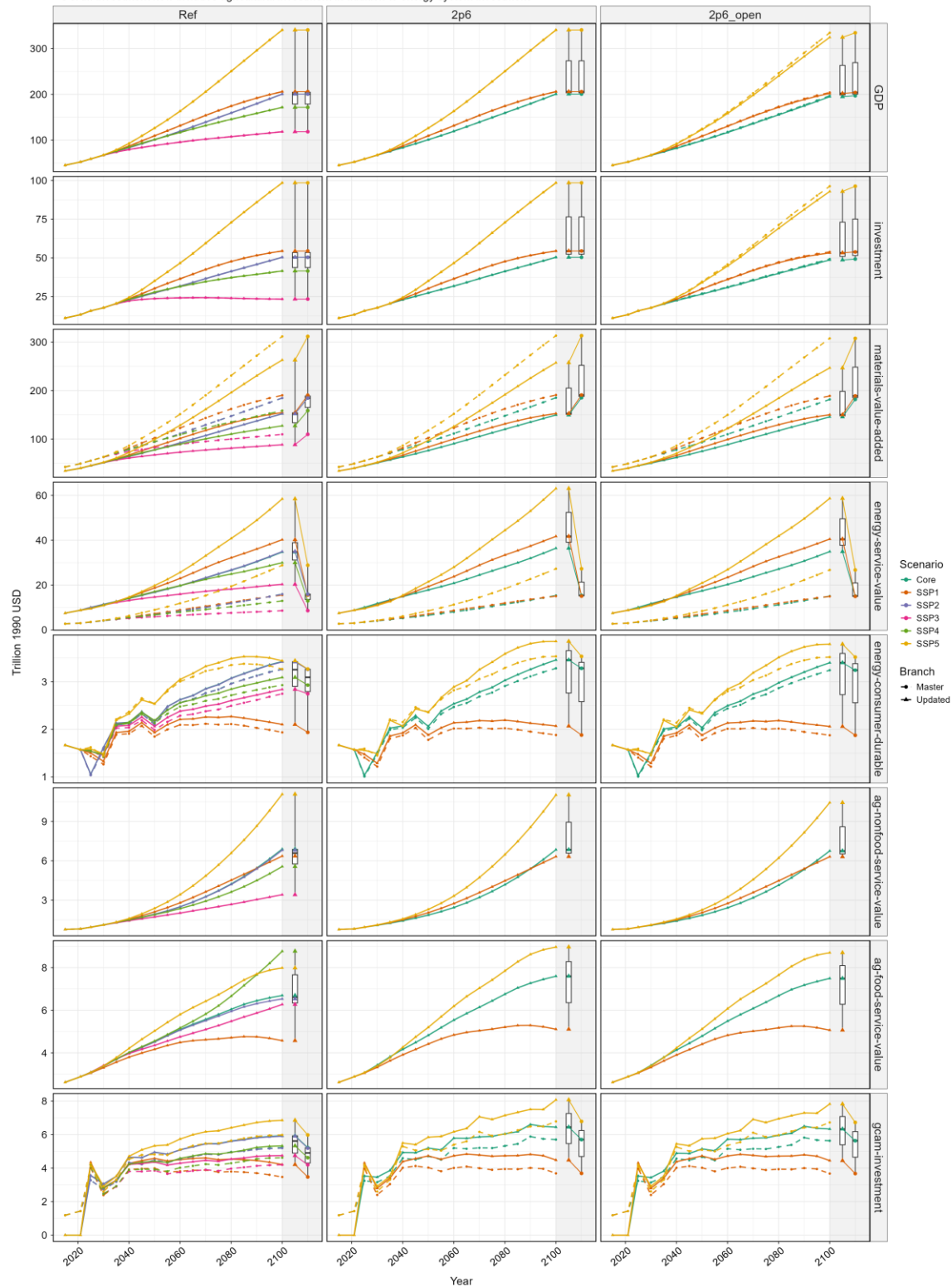
Global GDP impacts due to RCP2p6 policies (vs. Ref) across SPA



Regional GDP impacts due to RCP2p6 policies (vs. Ref) across SPA

Global Key National Account Variables by Scenario

- GDP is included for reference
- Investment equals savings at the global level and represents a share of GDP; saving rate derivation is unchanged in this CMP
- Materials value added declines due to the separation of agricultural value added and revisions to energy service valuation
- Agricultural food and non-food services are newly tracked variables; food value is higher in 2.6 scenarios (reflecting relatively inelastic demand)
- Agricultural non-food services grow over time, exceeding previous sectoral estimates, driven by income elasticity
- GCAM investment now includes agricultural investment in addition to energy system investment



Global Key National Account Variables by Scenario

- Investment equals savings at the global level and represents a share of GDP; saving rate derivation is unchanged in this CMP.
- Materials value added declines due to the separation of agricultural value added and revisions to energy service valuation.
- Agricultural food and nonfood services are newly tracked variables; food value is higher in 2.6 scenarios, reflecting relatively inelastic demand.
- Agricultural nonfood services grow over time, exceeding previous sectoral estimates, driven by income elasticity.
- GCAM investment now includes agricultural investment in addition to energy system investment.
- Sectoral investment is no longer calibrated in the GCAM base year due to limited data availability and the model's limited use of historical price information.

4.7. Other national account variables

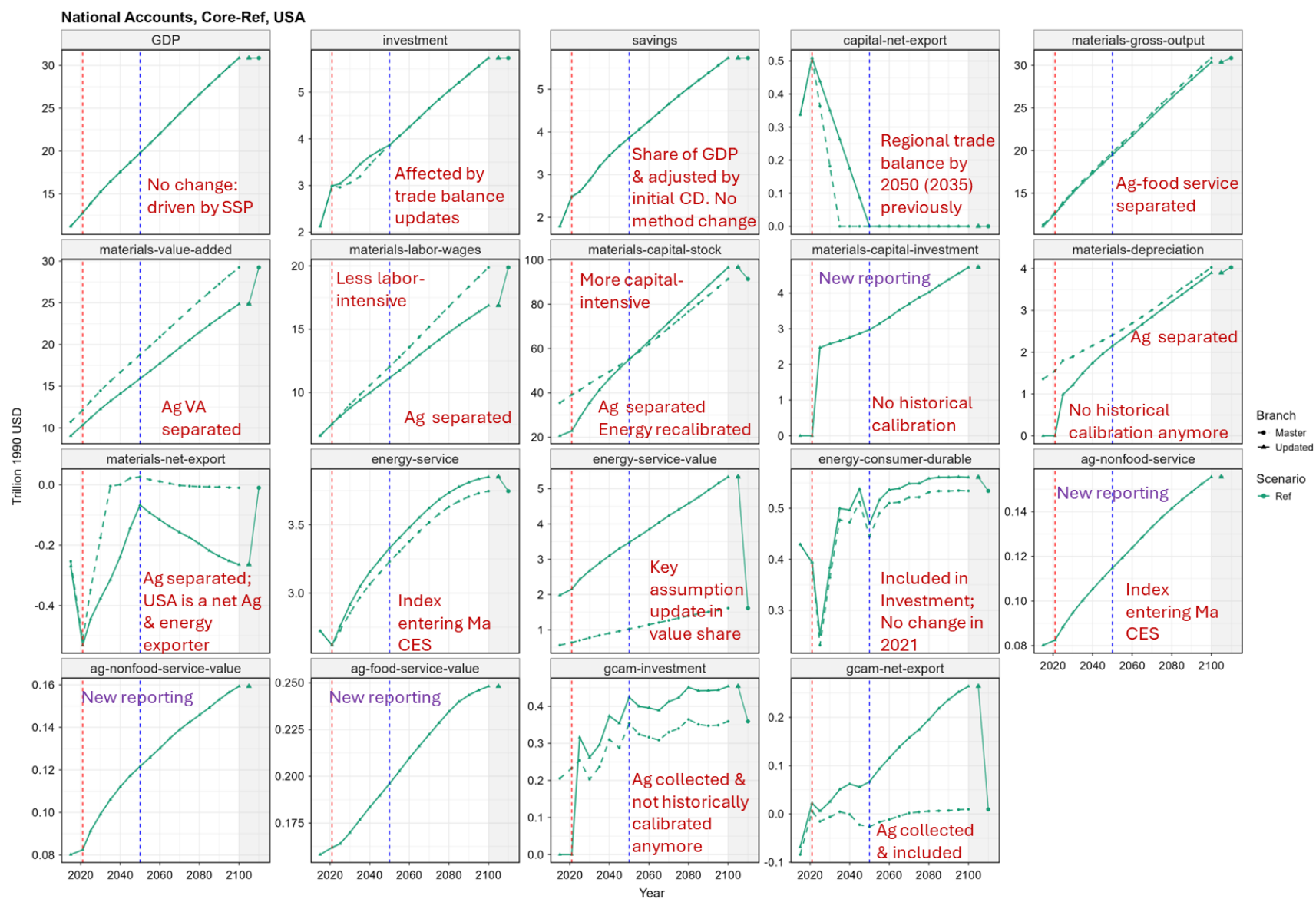


Fig. 10 National account variables in the Core Ref scenario, USA

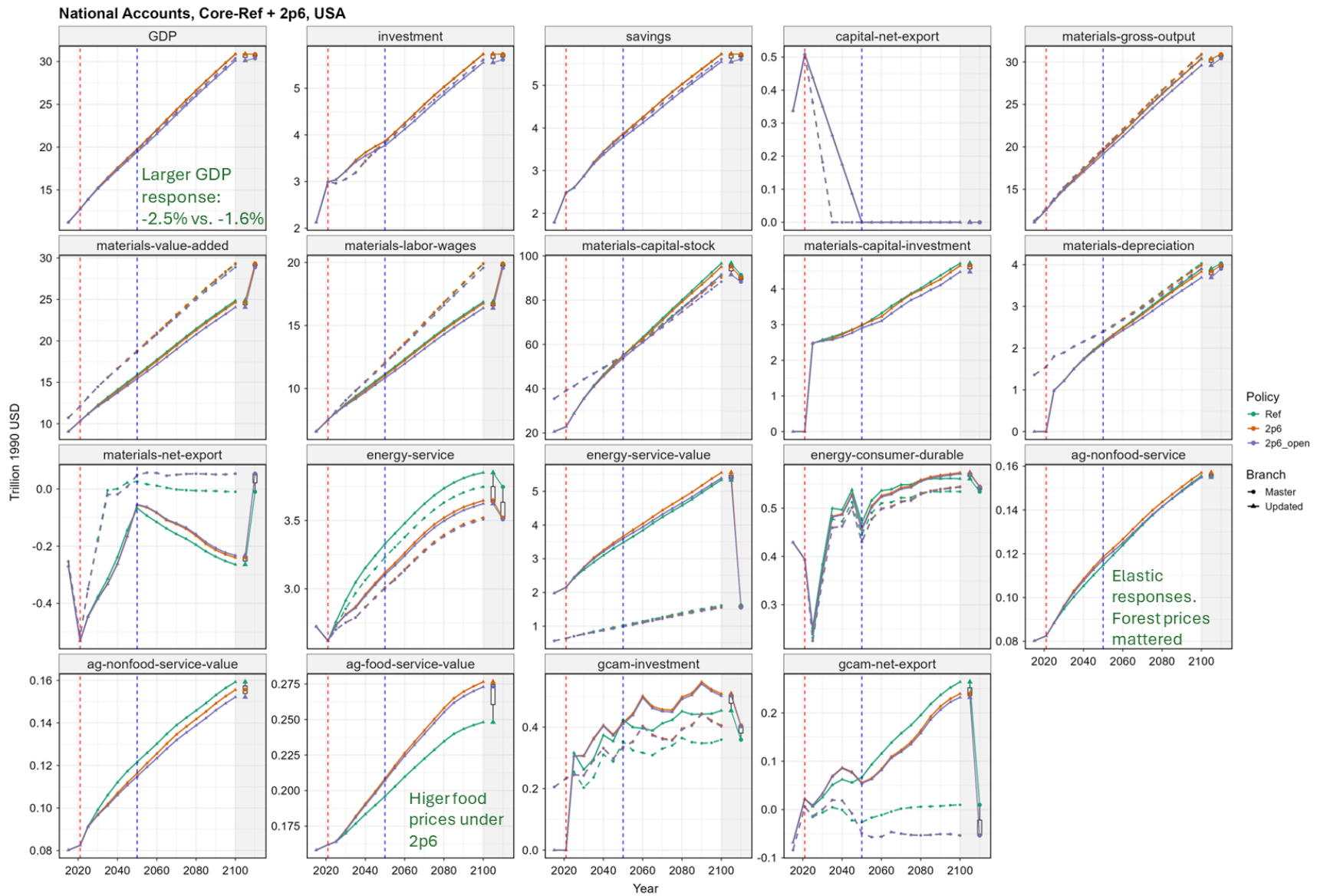
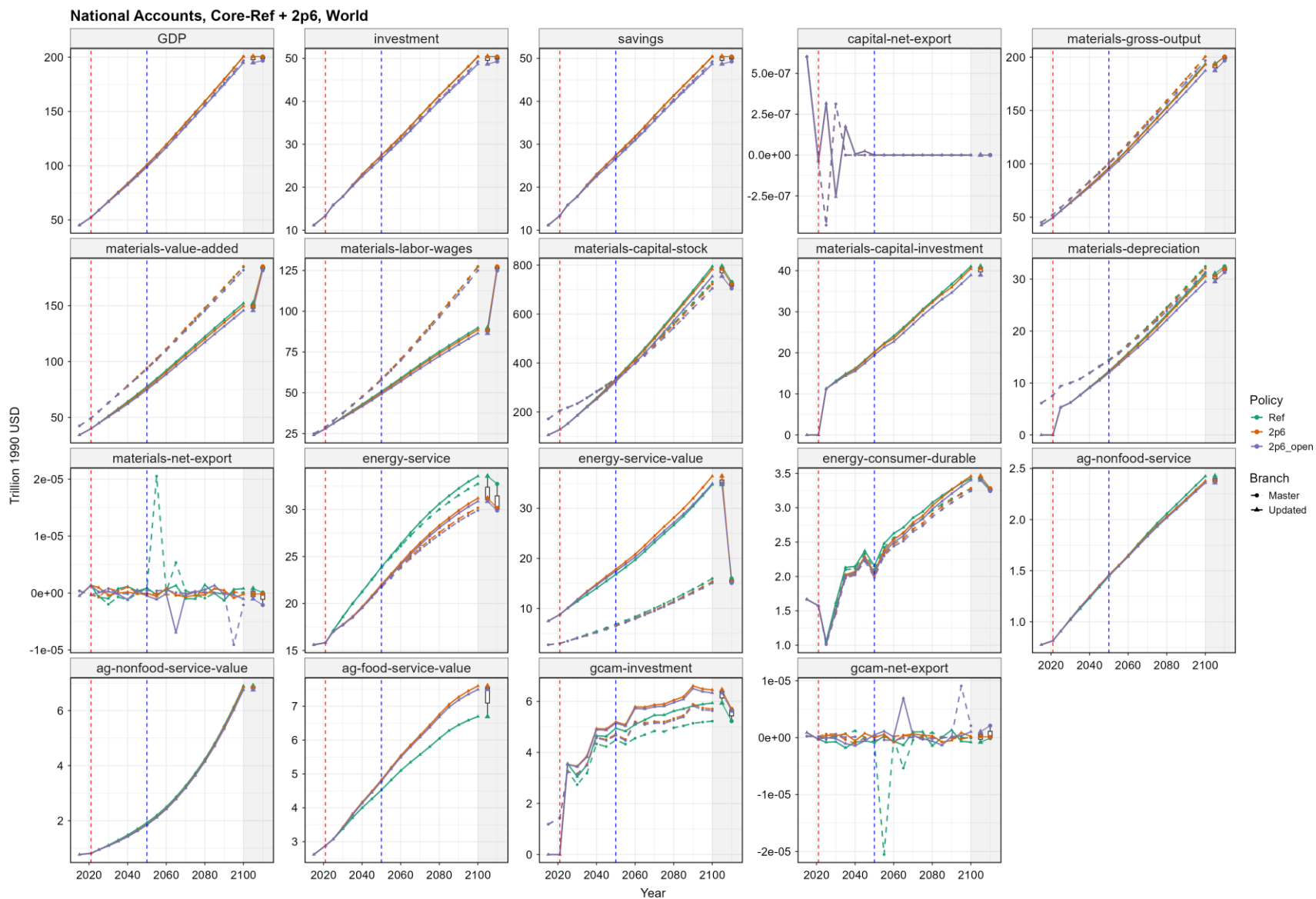


Fig. 11 National account variables in the Core Ref scenario and RCP 2p6 scenarios, USA



National account variables in the Core Ref scenario and RCP 2p6 scenarios, World

5. Summary and future work

This CMP introduces the GCAM-Macro KLEAM framework, extending the existing GCAM-Macro KLEM structure by explicitly integrating primary agriculture into the macroeconomic accounting, production, investment, and factor-market system. Building on the KLEM foundation established in CMP-332 and the socioeconomic and macroeconomic data updates in CMP-399 and CMP-410, this CMP advances GCAM's ability to represent two-way feedbacks among sectoral production decisions, factor markets, capital accumulation, and aggregate economic outcomes. It also builds on recent AgLU, forestry, and bioenergy updatesⁱⁱ, by improving agricultural value tracing, land-rental profit assumptions, biomass introduction assumptions, and macro-consistent accounting of agricultural production and final demand.

The main contribution of KLEAM is to strengthen two-way feedbacks between GCAM's detailed sectoral systems and the broader macroeconomy. Labor and capital are now represented explicitly in primary agricultural sectors, with value-added traced by region, sector, and technology. Agricultural labor is linked to regional employment and allocated between agriculture and materials, while agricultural capital is incorporated into the broader savings–investment closure. At the same time, the Materials production function is extended to include agricultural nonfood services, agricultural food services are represented in final demand, and investment demand from Agriculture, Energy, and Materials clears against regional savings through an endogenous capital rental price.

Initial validation results indicate that the updated framework preserves broad GCAM behavior while adding new macro-agricultural responses. The model now tracks agricultural labor, capital, investment, food and nonfood services, and expanded national-account variables in a more internally consistent way. The validation also highlights important areas for continued checking, including agricultural production and price responses, land-use change emissions, water withdrawals, capital rental prices, investment allocation, and GDP feedbacks under open-GDP scenarios. **The validation comparison presented in this CMP is based on GCAMv8.6 master compared with the KLEAM addition. The KLEAM development will be rebased to the recent GCAM core before final integration, which includes additional developments after GCAMv8.6. These newer core updates may have moderate effects on the validation results and are expected to further improve model behavior in several areas, for example through updated technoeconomic assumptions and other recent sectoral data improvements.**

ⁱⁱ CMP-410: 410 Updates to Socioeconomic and Macroeconomic Data, Processing Structure, and Visualization
CMP-399: 399 Updating the SSP Database (v3.0) (Population, GDP, and Labor Force) and Labor Productivity (KLEM)
CMP-332: 332 GCAM Macro-Economic Module (KLEM Version)
CMP-393: 393 Update AgLU parameters relevant to land-based mitigation policies
CMP-369: 369 Add detail to forest sectors: Breakout PFTs into hard, softwood & add explicit product pools for pulp and sawnwood
CMP-360: 360 AgLU data and method updates (connecting land hectares to food calories)
CMP-351: 351 Bioenergy Updates

Future work should focus on several areas. First, demand elasticity assumptions should be reviewed more broadly, especially for agricultural nonfood demand and other sectors affected by GDP feedbacks. Second, energy-service value calibration and capital allocation assumptions should be further tested, since the current treatment relies on a calibration assumption rather than directly observed national-account data. Third, sectoral investment calibration and historical value/price data should be improved as better data become available. Fourth, the agricultural productivity framework should be used for additional sensitivity analysis, including alternative assumptions for labor, land, water, fertilizer, capital, livestock, and forestry productivity. Fifth, remaining agricultural “other costs” should be further disaggregated, especially farm energy and non-nitrogen fertilizer inputs. Future development should also add fisheries, aquaculture, food processing, and potentially energy-sector labor once the corresponding sectoral supply and value-added representations are available.

Bioenergy assumptions should also continue to be evaluated. This CMP delays the introduction of purpose-grown energy crops to 2030 and introduces more regionally differentiated ghost-share assumptions, reflecting the lack of current large-scale deployment and updated land-rental profit assumptions. Future work should further improve the implementation and examine the parameter sensitivity.

Finally, **additional work is needed to integrate KLEAM consistently with GCAM-USA**. The global KLEAM framework closes labor and capital markets through regional production functions and endogenous factor-price feedbacks. In GCAM-USA, however, the U.S. energy system (in global GCAM) is replaced by detailed state-level energy systems, while the United States and individual states do not currently have corresponding KLEAM production functions (global GCAM and GCAM-USA share the same AgLU representation). Therefore, they do not generate dynamic demands for Materials, labor, and capital that can be used to close U.S. labor and capital markets. For the current implementation, U.S. agricultural labor and capital are treated as unlimited resources with fixed prices, allowing the U.S. agricultural system to operate without imposing an inconsistent macro closure. The rest of the world continues to use the full global KLEAM structure with endogenous labor, capital, savings–investment, and GDP feedbacks. Future work is underway to develop a more complete GCAM-USA macro treatment, potentially including national or state-level production functions and a consistent mechanism linking detailed state energy systems with labor and capital market dynamics.

6. Appendix (see attachments)

Appendix A:

Architecture of the GCAM-Macro KLEAM Framework, Accounting Structure, Materials Production Function, and Agricultural and Energy Service Inputs

Appendix B:

Value-Added (Land, Labor, Capital) Representation in Primary Agriculture, Labor Supply, and Labor Market Clearing

Appendix C:

Capital Costs, Capital Accumulation, Investment Allocation, Savings–Investment Closure, and Capital Rental Price Feedback

Appendix D:

Agricultural Factor Productivity Growth Representation

Appendix E:

Purpose-grown Energy Crop Introduction: Ghost Share Recalibration and Assumption Updates

Appendix F:

Visualization Document: Key Supplementary Figures for Macroeconomic Data and Parameter Visualization

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CMP-411 Appendix A:**Architecture of the GCAM-Macro KLEAM Framework, Accounting Structure, Materials Production Function, and Agricultural and Energy Service Inputs****1. Motivation: balanced accounts and micro–macro consistency**

Macroeconomic consistency in multisector economic models requires that production, income, and expenditure accounts are internally balanced. In standard national accounting frameworks, GDP can be equivalently measured from three perspectives: (i) the sum of factor compensation (income approach)¹, (ii) the value of final demand (expenditure approach), and (iii) the value of production (output approach). Ensuring consistency across these identities is essential for balanced data construction and for maintaining coherent economy-wide responses to sectoral changes.

At the same time, detailed sectoral models—such as those representing energy systems and agriculture in GCAM—operate in physical units and incorporate technology-specific processes, constraints, and behavioral responses. Linking these sectoral dynamics to macroeconomic outcomes therefore requires a framework that reconciles physical production systems with value-based economic accounting.

The GCAM-Macro framework, particularly with the KLEAM extension, addresses this challenge by embedding sectoral modules within a recursive-dynamic macroeconomic structure in which factor markets and national accounts are consistently balanced. In this structure, macroeconomic variables such as GDP, investment, and factor prices are determined endogenously and feed back to sectoral demand and production decisions.

All macroeconomic consistency is enforced in value terms, while physical quantities are determined through sectoral production systems. This separation allows GCAM to preserve detailed sectoral representations while ensuring internally consistent economy-wide accounting. Building on this foundation, the KLEAM extension expands the macroeconomic framework to more fully integrate agriculture alongside energy and materials production, strengthening the consistency and scope of micro–macro linkages.

2. Evolution of the accounting structure: from KLM to KLEM and KLEAM

The development of the GCAM-Macro framework can be understood as a sequence of extensions to the underlying accounting structure, progressively strengthening the integration between sectoral systems and the macroeconomy. Here, we also describe the KLM framework, which is the origin of the KLEM & KLEAM extensions. An overview of the accounting framework of KLEAM is presented in Fig. A1, and the corresponding KLEM framework is illustrated in Fig. A2².

¹ Taxes on production and imports (net of subsidies) are also part of income in standard national accounting but are not explicitly represented in GCAM-Macro. These components are implicitly absorbed within the aggregate value-based accounting structure (by capital compensation).

² Values in the accounts are not directly comparable across CMPs, as, in addition to sectoral disaggregation, there are also key updates in data and calibration methods.

GCAM-Macro-KLEAM Input-Output Framework and Accounting Structure

	Ag	En	Ma	Final Cons.	Trade	Sum
Land	land					
L	labor		labor			GDP: Income
K	capital /Inv	capital /Inv	capital /Inv			
Ag			ag non- food- service	ag food- service	ag-net- export	
En			energy service		energy- net- export	
Ma				cons. & capital goods	material- net- export	gross- demand
Sum			gross- output	GDP: Expenditure C & G + Inv + NX		

GDP decomposition by income:

GDP = sum of the compensation (factor rewards) from land, labor (L), & capital (K) across all sectors

GDP decomposition by expenditure:

GDP = household & government (GOV) consumption (C & G) + investment (INV) + net export (NX)

→ GDP = materials gross-output + ag food-service + gcam-net-export (ag & energy)

- Ma gross-output (supply) = nested CES production function (K, L, En, Ag; productivities; elasticities)
- Ma gross-output (demand) = consumption goods (HHD & Gov) + capital goods + material-net-export

Materials production function

Nested constant elasticity of substitution (CES) (En, Ag, (K, L))

- Ag nonfood services are collected and aggregated from GCAM sectors, with initial prices used as weights
- En is an energy service index, linked to GCAM energy service inputs in final demand
- En is endogenous, aggregating energy services using initial prices as weights (with value rescaled in calibration)

Clearing capital/investment market

sum of investment from Ag, En (incl. CD), and Ma = savings + capital-net-export

- ag-investment: derived based on Ag capital return and related assumptions
- energy-investment: derived based on GCAM energy sectoral assumptions at technology levels
- material-investment = depreciation-rate x capital stock (beginning) + capital stock increase
- savings = function(lagged savings-rate, per-capita GDP growth rate) x GDP, adjusted by CD in initial calibration
- capital-net-export: initially calibrated to -NX but being phased out to zero regionally (trade balance)

Clearing labor market

Labor supply (employment linked to population) = Labor demand from Ag and Materials

Fig. A1 Overview of the GCAM-Macro-KLEAM input-output and accounting framework. Agriculture (Ag), Energy (En), and Materials (Ma) use primary factors of production and supply services and goods to final demand. GDP is defined consistently by income and expenditure.

GCAM-Macro-KLEM Input-Output Framework and Accounting Structure

	En	Ma	Final Cons.	Trade	Sum
L		labor			GDP: Income
K	capital /Inv	capital /Inv			
En		energy service		energy- net- export	
Ma			cons. & capital goods	material- net- export	gross- demand
Sum		gross- output	GDP: Expenditure C & G + Inv + NX		

GDP decomposition by income:

GDP = sum of the compensation (factor rewards) from labor (L) & capital (K) across all sectors

GDP decomposition by expenditure:

GDP = household & government (GOV) consumption (C & G) + investment (INV) + net export (NX)

→ **GDP = materials gross-output + gcam-net-export (energy-net-export)**

- Ma gross-output (supply) = nested CES production function (K, L, En, Ag; productivities; elasticities)
- Ma gross-output (demand) = consumption goods (HHD & Gov) + capital goods + material-net-export

Materials production function

Nested constant elasticity of substitution (CES) (En, (K, L))

- En is an energy service index, linked to GCAM energy service inputs in final demand
- En is endogenous, aggregating energy services using initial prices as weights

Clearing capital/investment market

sum of investment from En, incl. Consumer-Durable (CD), and Ma = savings + capital-net-export

- energy-investment: derived based on GCAM energy sectoral assumptions at technology levels
- material-investment = depreciation-rate x capital stock (beginning) + capital stock increase
- savings = function(lagged savings-rate, per-capita GDP growth rate) x GDP, adjusted by CD in initial calibration
- capital-net-export: initially calibrated to -NX but being phased out to zero regionally (trade balance)

Clearing labor market

Labor supply (employment linked to population) = Labor demand from Ag and Materials

Fig. A2 Overview of the GCAM-Macro-KLEM input-output and accounting framework.

2.1. KLM: single-sector macroeconomic structure

In a single-sector KLM (Capital-Labor-Materials) formulation, the economy is represented by a single aggregated production sector (Materials), which combines capital and labor to produce goods for final consumption, investment, and trade. There are no explicit intermediate inputs from other sectors. Within this structure, standard national accounting identities hold:

- Income approach: GDP equals the sum of compensation to labor and capital.
- Expenditure approach: GDP equals the sum of household and government consumption, investment, and net exports.
- Production approach: GDP equals the gross output of the Materials sector.

Because Materials represents the entire economy, its gross output simultaneously corresponds to value added and final demand. This structure provides a simple and internally consistent macroeconomic representation but does not explicitly capture interactions with sectoral systems such as energy or agriculture.

2.2. KLEM: introducing energy system linkages

The KLEM framework (Patel et al., 2023; Zhao et al., 2025) extends the KLM structure by disaggregating the energy system and establishing linkages between sectoral outcomes (GCAM) and macroeconomic accounts. Three key accounting linkages (**blue cells in Figs A1 & A2**) connect the energy system to the macroeconomy:

- 1) **Energy investment:** capital investment associated with energy and energy service technologies contributes to aggregate investment demand. Consumer durable sectors relevant to energy systems (i.e., residential heating, cooling, and other uses, as well as passenger road transportation) are also included and tracked.
- 2) **Energy service input:** Energy services produced by the GCAM energy system enter the Materials production function as an intermediate input. These services are represented as a Laspeyres quantity index that aggregates detailed technology-level energy service outputs using base-period prices.
- 3) **Energy net exports:** Net exports from the energy system are aggregated and incorporated into the macroeconomic trade balance.

With these linkages, the Materials sector no longer represents the entire economy but instead corresponds to the non-energy portion of economic activity³. Its production is represented by a nested constant elasticity of substitution (CES) function that combines the value-added aggregate (capital and labor) and energy services (intermediate). Macroeconomic accounting identities are maintained through adjustments to the input–output structure. In particular:

- GDP remains consistent across income and expenditure definitions.
- Energy-sector activities are integrated through value flows rather than physical aggregation.
- Trade balance assumptions are imposed at the regional level, with net exports phased out over time to ensure long-run consistency.

A key feature of the KLEM framework is the introduction of endogenous GDP, which feeds back into GCAM sectoral demand through sector-specific income elasticities. GDP feedback extends beyond demand responses, as technological progress in certain domains is also tied to GDP, e.g., through

³ Labor in the energy system in GCAM has not yet been disaggregated from the Materials sector.

marginal abatement cost curves (MACCs). This establishes a two-way coupling between sectoral dynamics and macroeconomic outcomes so that changes in the energy system affect GDP, which in turn influences demand for energy and other goods.

2.3. KLEAM: integrating agriculture into the macroeconomic framework

The KLEAM framework further extends the accounting structure by explicitly incorporating primary agriculture into the KLEM macroeconomic system, alongside energy and materials. This extension involves several key modifications.

- 1) **Expanded factor representation:** In sectoral modules (GCAM), labor and capital are introduced as explicit factors of agricultural production in addition to land. Factor compensation from land, labor, and capital is represented at the sectoral and technology levels within the agricultural system and is used to partition value added across economy-wide sectors during calibration. As a result, value added previously embedded within the aggregated Materials sector is partially reallocated to agriculture, improving the consistency between sectoral and macroeconomic accounts.
- 2) **Sectoral integration with GCAM agriculture:** The agricultural system retains its detailed GCAM representation, including land-use allocation, crop and livestock production, and interactions with energy systems (e.g., bioenergy and feed). These interactions are resolved endogenously within the sectoral modules. The linkage to the macroeconomy is established through value-based accounting flows rather than through the direct aggregation of physical outputs while preserving traceability to physical quantities.
- 3) **Agricultural service flows:** Agricultural production is linked to the macroeconomy through two distinct service channels, including agricultural nonfood service and agricultural food service. This separation allows the model to maintain consistency between macroeconomic accounting and the detailed representation of food systems in GCAM.
 - a. **Agricultural nonfood service:** A Laspeyres quantity index representing agricultural outputs used in nonfood (also nonfeed & nonbioenergy) applications (e.g., primarily fiber crops and forestry products, but broadly from all agricultural sectors)⁴. This index is aggregated across GCAM sectors using base-period prices and enters the Materials CES production function as an intermediate input, analogous to energy services.
 - b. **Agricultural food service:** The value of food consumption derived from GCAM's food demand system. This component enters final demand directly (household and government consumption) and does not pass through the Materials production function, preserving the structure and behavioral detail of the food demand module⁵ in GCAM.
- 4) **Updated macroeconomic identity:** With the inclusion of agriculture, GDP is defined as the **sum of materials gross output, agricultural food services, and GCAM sectoral net export** (energy & agriculture). This formulation reflects the separation of food-related value flows from the Materials sector and ensures consistency between production, income, and expenditure accounts.

⁴ From the perspective of primary commodity equivalents (PCe), the “other use” category in GCAM captures all utilizations of a commodity that are not explicitly represented. Technically, however, it largely reflects industrial uses, including food processing, that are not fully captured within the PCe accounting.

⁵ Note that food prices are derived from primary producer prices, and value added along the supply chain (e.g., food processing) is not included.

Together, these extensions transform the GCAM-Macro framework from a system linking energy and macroeconomic dynamics into a more comprehensive, materials-centered macroeconomic structure that consistently integrates agriculture, energy, and factor markets.

2.4. Materials production function and agricultural services input in KLEAM

The Materials sector in GCAM-Macro KLEAM is represented using a nested CES production function that combines value-added inputs (capital and labor) with intermediate inputs, including energy services and agricultural nonfood services (**Fig. A3**). This structure extends the original KLEM formulation by explicitly incorporating agricultural services as an intermediate input, thereby strengthening the linkage between the agricultural system and the broader economy.

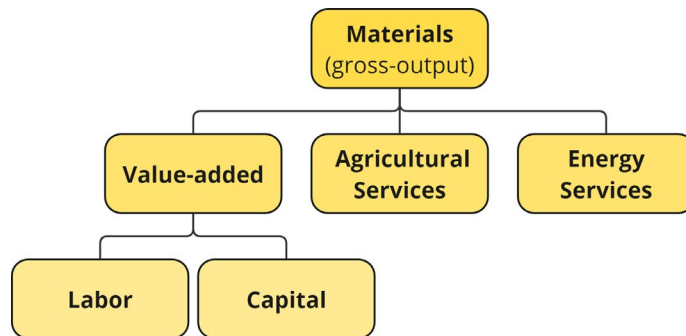


Fig. A3 Structure of the nest CES Materials production function with agricultural services added.

The nested CES structure is parameterized through substitution elasticities specified in *socioeconomics/gcam_macro_nested_CES_function.csv*. In the current implementation, the elasticity of substitution is set to **0.5 in the top nest**, governing substitution between value-added and intermediate inputs (including energy and agricultural services), and **1.2 in the value-added nest**, governing substitution between capital and labor. These values are applied uniformly across regions. Note that the CES function is implemented using its dual parameterization (both form specified in the input csv above), where the parameters (ρ and γ) are mapped from the elasticity of substitution ($\text{CES Elasticity} = 1 / (1 - \text{CES Parameter})$).

The parameterization is consistent with the empirical literature, e.g., including those used in computable general equilibrium (CGE) models, which generally finds lower substitution between value-added and intermediate inputs than among primary factors. Empirical estimates for the former typically range from 0.5 to 1.0, while substitution between capital and labor commonly falls between 0.8 and 1.5 (Gohin and Koutchade, 2024; Ivanic et al., 2023). The selected values therefore provide a conservative but empirically grounded representation of production behavior.

Agricultural nonfood services are constructed by aggregating outputs from GCAM agricultural sectors using base-year prices as weights. As a Laspeyres quantity index is used, macro-level demand drivers and price feedbacks are not explicitly represented in this aggregation. To ensure consistency between sectoral demand and the macroeconomic representation, the income elasticities governing agricultural nonfood demand in GCAM are updated. In the standard configuration, these demands (e.g., fiber crops, meat byproducts, and forestry products) often exhibit low or zero income elasticity. In KLEAM, however, these nonfood uses are aggregated into agricultural nonfood services that enter the Materials production function as intermediate inputs representing demand from the rest of the economy.

Accordingly, the income elasticities are increased to 0.6 for NonFoodDemand_Crops and NonFoodDemand_Meat (from 0), and to 0.8 for NonFoodDemand_sawnwood (from 0.4), while the price elasticity is set to -0.4 for all three categories (aglu/A_demand_supplysector.csv). These adjustments reflect the expectation that agricultural nonfood services scale with overall economic activity. As intermediate inputs to Materials production, their demand grows with gross output, subject to substitution effects governed by the CES structure. If income elasticities are too low, physical demand does not expand accordingly, leading to inflated implied service prices and distorted cost shares. The updated elasticities therefore ensure consistent scaling between physical quantities and value-based accounting while preserving substitution responses.

Future work is needed to further explore broader demand elasticity specifications in GCAM (**Fig. A4**) to improve consistency between sectoral demand and the macroeconomic framework.

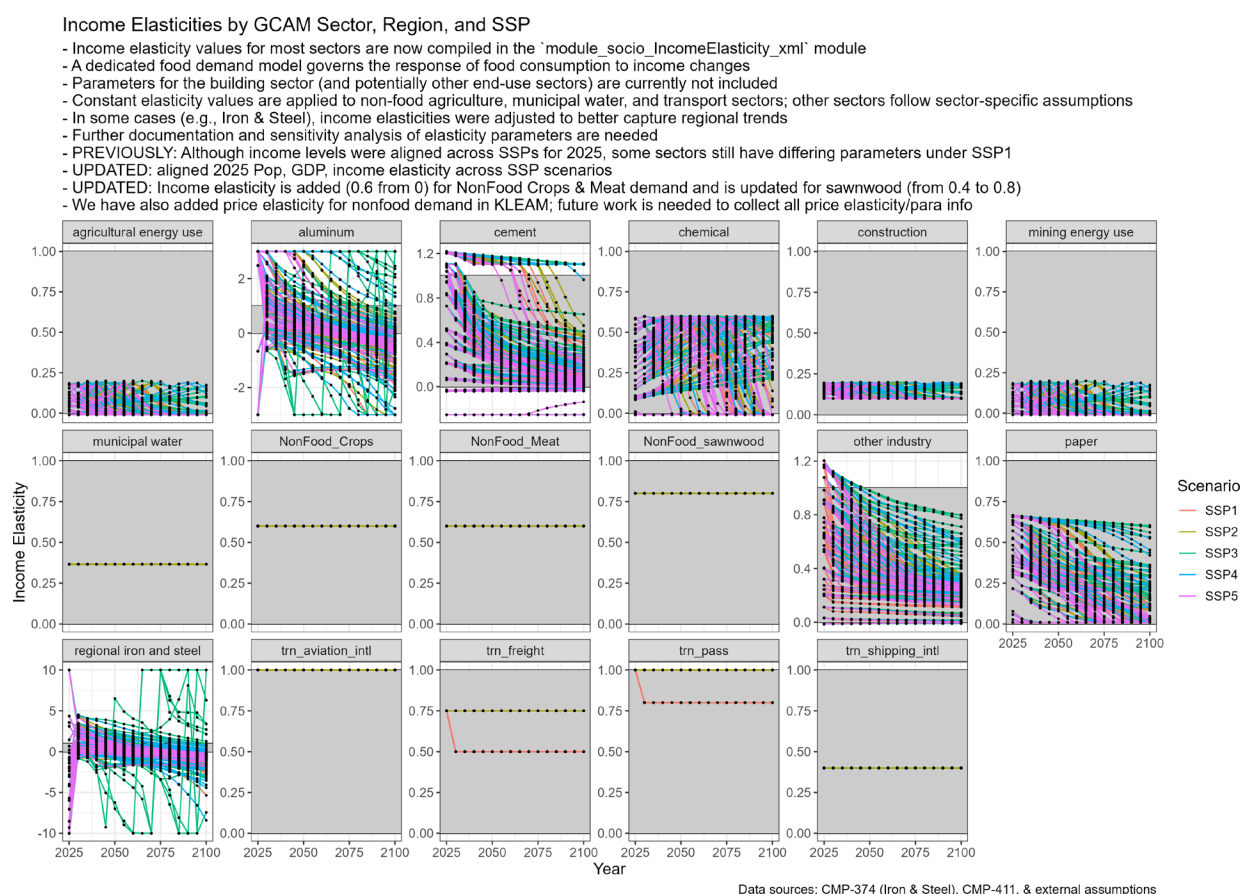


Fig. A4 Income Elasticities by GCAM Sector, Region, and SSP. There are 160 (32 regions x 5 SSPs) lines per panel. SSP2 assumptions may be applied to other scenarios (when not differentiated). NonFood_woodpulp was removed.

3. Energy service value calibration: uncertainty and assumptions

3.1. Conceptual role of energy services and limitations

In the GCAM-Macro framework, energy services represent the economic value of energy system outputs that enter the broader economy as intermediate inputs. Within the Materials production function, energy services are treated as a distinct input alongside value-added components (capital and labor) and, in KLEAM, agricultural nonfood services.

Energy services are constructed as a price-weighted quantity index, aggregating detailed energy system outputs across sectors (e.g., industry, buildings, and transport) using base-period prices. This formulation enables the integration of detailed physical energy-system dynamics into a value-based macroeconomic framework, in which “energy service value” is calibrated in the base year.

A key challenge in implementing this structure is the absence of directly observable data on the value of energy services in standard national accounts. Several factors contribute to this limitation:

- 1) The definition of energy services in GCAM does not correspond directly to sectoral classifications in national accounts (e.g., industries or final demand categories).
- 2) Energy system outputs in GCAM are represented at the technology level and are not explicitly mapped to value-added components such as capital and labor in national statistics.
- 3) Available datasets (e.g., GTAP) provide sectoral value-added and capital compensation shares, but do not offer a clear mapping to the energy service constructs used in GCAM.

As a result, the value of energy services cannot be directly observed or constructed from primary data sources.

To maintain consistency in the input–output accounting structure, the value of energy services is derived as a residual component within the Materials production account. Specifically, in the base-year calibration of KLEAM Materials production:

- **Energy service value = Materials gross output – labor compensation – capital compensation – agricultural nonfood service value**

This approach ensures that the Materials production function is fully balanced, with all inputs summing to total output. At the same time, it implies that the energy service value depends critically on how other components—particularly capital and labor compensation—are partitioned across sectors.

A major source of uncertainty arises from the allocation of capital and capital compensation between the Materials sector and energy-related activities. In previous implementations (e.g., CMP-410), sectoral capital shares derived from GTAP were used to partition value-added across sectors⁶. However, this approach did not fully account for capital associated with energy service provision, primarily due to the lack of a clear mapping between GCAM energy service outputs and standard sectoral classifications. As a result, a portion of capital services associated with energy systems was effectively attributed to the Materials sector. This led to an overestimation of Materials capital compensation and a corresponding underestimation of the residual energy service value.

⁶ We improved factor compensation data (including treatment of gross vs. net capital rate of return and depreciation) based on the Penn World Table in CMP-410, but this change inadvertently disrupted the calibration of energy service values.

3.2. Calibration adjustment in KLEAM

To address this issue, KLEAM introduces an explicit calibration parameter that allocates a portion of non-agricultural, non-energy capital to energy service provision. In the current implementation, **a fixed share (40%) of relevant capital is allocated to energy service activities across regions in the final base-year calibration**⁷. The assumed 40% share is informed by values used in the original KLEAM implementation and supported by initial sensitivity tests; it may be further refined at the regional level as additional data and evidence become available.

This adjustment increases the implied capital intensity of energy services and correspondingly raises the estimated value of energy service inputs in the Materials production function. This parameter should be interpreted as a calibration assumption that reflects structural uncertainty in the allocation of capital services across sectors, rather than as a directly observed empirical quantity. The calibration of energy service value has important implications for model behavior (per our initial sensitivity tests):

- A higher energy service value increases the contribution of energy to Materials production, strengthening the linkage between the energy system and the broader economy.
- Changes in energy system costs or policies (e.g., mitigation scenarios) have a larger impact on GDP through their effect on energy service inputs.
- The sensitivity of macroeconomic outcomes to energy system dynamics is therefore directly influenced by this calibration choice.

More broadly, this highlights the importance of consistent value partitioning in linking sectoral models to macroeconomic accounting, particularly in the absence of directly observed data.

4. Quantitative illustration

Fig. A5 presents the balanced KLEAM accounts for selected regions in the base year (2021). As expected, the accounting identity holds: GDP equals the sum of factor compensation across sectors and is consistent with the expenditure-side decomposition. To further clarify the internal structure of agricultural production, **Table A1** complements **Fig. A5** by decomposing value added for the aggregated GCAM sectors, alongside sectoral gross output and intermediate inputs. Notably, the values reported in **Table A1** are directly aggregated from detailed technology-level representations in GCAM (at the water-basin scale), preserving a clear physical foundation. In this CMP, we update key underlying datasets in GCAM to ensure consistency between micro-level representations and macroeconomic value flows (see Memo 2/Appendix B).

⁷ This assumption can be adjusted in *module_socio_L203.NationalAccounts* in *gcamdata*, see *socioeconomics.EN_SERVICE_CAPITAL_SHARE* (0.4).

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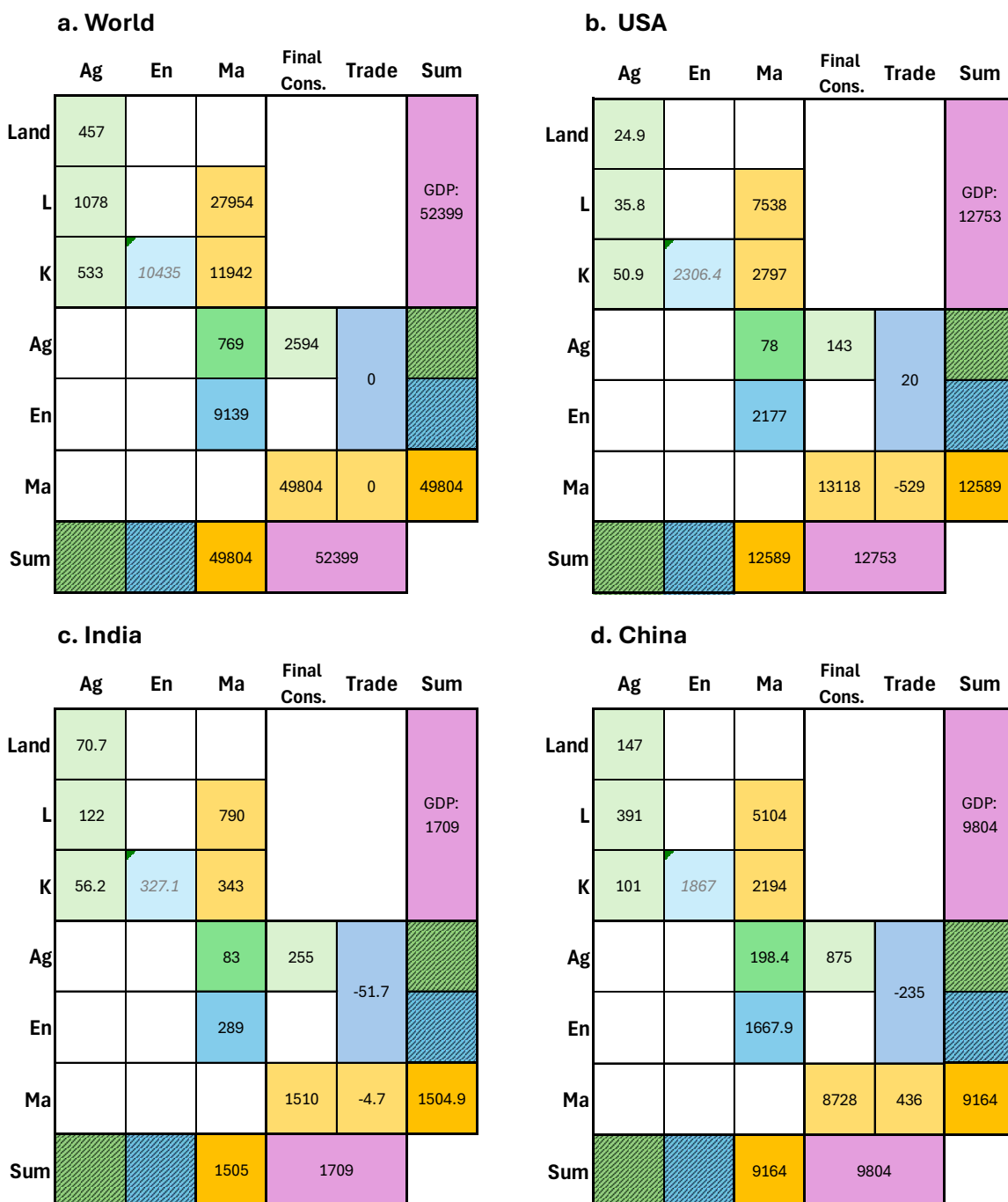


Fig A5 GCAM-Macro-KLEAM accounts for the selected regions (world, USA, India, & China) in 2021, in billion 1990 USD. Note that capita input in En is filled in as a residual term (GCAM clears the investment market).

Table A1 Decomposition of agricultural production value-added accounts by sector in 2021 (billion 1990 USD) for selected regions. Agricultural gross output is decomposed into value added (land, labor, capital) and intermediate inputs, including feed and other inputs (e.g., fertilizer, irrigation, and others).

Region	Input	Staple crops	Oil crops	Other crops	Pasture	Livestock	Forest	Total
World	Land	136	37	227	37		20	457
	Labor	257	60	493		236	33	1078
	Capital	90	31	178		118	117	533
	Feed					502	0	502
	Other inputs	216	69	292		305	112	995
	Revenue	727	201	1206	37	1160	282	
USA	Land	8	5	9	0.4		3	25
	Labor	9	6	10		8	3	36
	Capital	9	6	10		18	7	51
	Feed					40		40
	Other inputs	24	14	22		39	35	133
	Revenue	54	30	52		105	48	289
India	Land	29	3	33	1.2	0	5	71
	Labor	32	3	37	0	49	1	122
	Capital	11	1	15	0	15	15	56
	Feed	0	0	0	0	32		32
	Other inputs	20	1	9	0	12	42	84
	Revenue	97	8	97	1	108	62	
China	Land	33	5	97	7	0	4	147
	Labor	74	12	229		56	18	391
	Capital	15	3	47		12	25	101
	Feed					162		162
	Other inputs	60	4	104		69	6	242
	Revenue	188	24	481	7	299	52	

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CMP-411 Appendix B:

Value-Added (Land, Labor, Capital) in Primary Agriculture, Labor Supply, and Labor Market Clearing

1. Background and motivation

In GCAM, representative profit-maximizing producers in crop, livestock, and forestry sectors make production and management decisions by choosing input use under constant-returns-to-scale technologies, given a vector of input and output prices. Historically, agricultural production in GCAM has mainly focused on land competition. Land allocation is governed by a nested logit structure that relates land shares to relative rental profits, enabling endogenous price-induced yield responses through technology transitions and competition between managed and natural land.

In addition to land, irrigation water and nitrogen fertilizer are explicitly represented as inputs in agricultural production (crops). However, labor and capital—arguably more economically important in production decisions and long-run agricultural transformation—have not been explicitly represented. Instead, these inputs were embedded within “other costs” (and in some cases partially reflected in land costs), limiting the model’s ability to capture interactions between agricultural production, factor markets, and macroeconomic dynamics.

Recent work, including Sheng et al. (2025), highlights the importance of labor market evolution in shaping agricultural systems. Two key forces drive this evolution: (i) labor push, arising from productivity growth that releases labor from agriculture, and (ii) labor pull, driven by increasing labor demand in non-agricultural sectors and associated wage differentials (Alvarez-Cuadrado and Poschke, 2011). These dynamics are highly heterogeneous across regions, reflecting differences in demographic trends, structural transformation, and economic development. In parallel, capital deepening—through mechanization and increased use of capital-intensive technologies—has played a central role in agricultural development, reinforcing labor–capital substitution.

At the same time, agriculture is intrinsically linked to the broader economy through value-added accounting. Without explicit representation of labor and capital, these linkages remain incomplete. To address this gap, we introduce explicit labor and capital inputs into agricultural production at the technology level in GCAM and integrate them within a macro-consistent framework.

In KLEAM, labor and capital are explicitly represented in agricultural technologies, and markets for labor and investment–savings are closed (**Fig. B1**). This enables agriculture to transition from a cost-based representation to a factor-driven production system, establishing the foundation for linking agricultural production to endogenous wages and capital rental prices and enabling consistent interactions between agriculture and the rest of the economy.

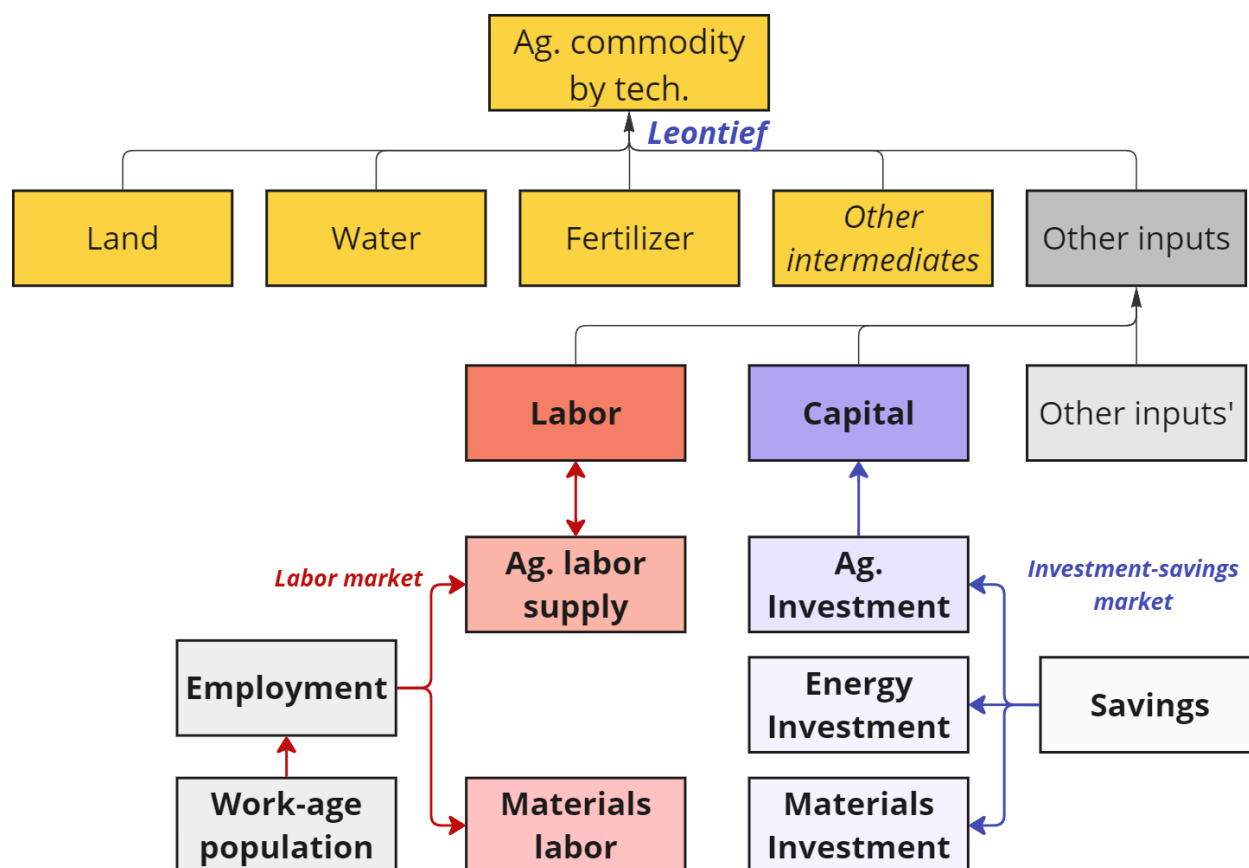


Fig. B1 Representation of labor and capital inputs in agricultural production and factor markets

2. Labor and capital input demand in agricultural production

Fig. B1 illustrates the updated representation of primary agricultural production in KLEAM. Agricultural output by technology is modeled using a Leontief structure (multiple technologies on the production frontier) that combines land, water, fertilizer, and other intermediate inputs. A key advancement is the decomposition of “other inputs” into explicit labor and capital components. This allows labor and capital to be represented as physical inputs while maintaining consistency with value-based accounting in GCAM-Macro.

Before partitioning labor and capital, input cost shares and prices are updated where necessary to ensure consistency between value flows and physical production. In particular, land rental cost shares and prices are revised in selected regions, and cost and price data for feed crops and forest products were substantially improved. These updates are important for ensuring that the residual “other cost” category can be consistently decomposed into labor and capital components.

Labor and capital costs are first identified at the sectoral level and then allocated to production technologies. This ensures that factor inputs are consistent with regional value-added accounting while preserving the structure of technology-level production in GCAM. To capture heterogeneity in production systems, we introduce parameters that differentiate labor and capital intensities across

technologies¹. Specifically, low-input technologies are associated with higher labor intensity, while high-input technologies are associated with higher capital intensity. This differentiation is implemented through adjustments to input–output coefficients while preserving total production costs and maintaining the zero-profit condition. This structure enables endogenous substitution across technologies in response to changes in factor prices. For example, increases in wages reduce the profitability of labor-intensive technologies, inducing a shift toward more capital-intensive production systems. As a result, the model captures key mechanisms of agricultural transformation, including mechanization and input intensification.

In addition, although considered in agricultural labor and capital-sector downscaling, fisheries and aquaculture are not included in the current KLEAM implementation because these sectors are not yet fully represented in the GCAM agricultural production framework.

3. Data construction and calibration

Introducing explicit labor and capital inputs requires maintaining consistency across physical quantities, value-added accounting, and prices. Agricultural labor and capital data are derived from multiple sources—including ILO, USDA, FAOSTAT, and GTAP—which differ in definitions, coverage, and aggregation. To address this, we construct a harmonized dataset of agricultural labor and capital inputs at the regional level and downscale these inputs to sectoral and technology levels. This process ensures that:

- physical input quantities are consistent with observed production,
- value flows align with regional value-added accounts, and
- implied factor prices are economically consistent.

Cost shares in agricultural production are updated using GTAP and FAO data, improving consistency with observed value-added structures. These updates generally reduce land cost shares and refine the distribution of costs across labor, capital, and intermediate inputs, with important implications for rental profitability and technology competitiveness.

At the global level (**Fig. B2**), agricultural employment increased through the late 20th century and peaked in the early 2000s, followed by a gradual decline associated with structural transformation and productivity growth. A recent increase in agricultural employment around 2020–2021 is observed, likely reflecting COVID-related disruptions, with India contributing significantly to this surge. In contrast to labor, global agricultural capital has exhibited sustained growth over time (**Fig. B2**), reflecting capital deepening through mechanization and increased use of capital-intensive technologies.

Regional dynamics differ markedly (**Figs. B3 and B4**). Agricultural labor continues to grow in many African regions due to rapid increases in working-age population and relatively slower structural transformation. In contrast, agricultural labor declines in regions such as China, driven by

¹ See section 4 in *gcamdata module_aglu_L2082.ag_an_for_laborcapital* and supplementary section 2.3 in Sheng et al. (2025).

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mechanization, productivity growth, and stabilization of labor supply. Capital accumulation follows a different trajectory, with strong growth in regions undergoing agricultural intensification, including China, Southeast Asia, and parts of Latin America.

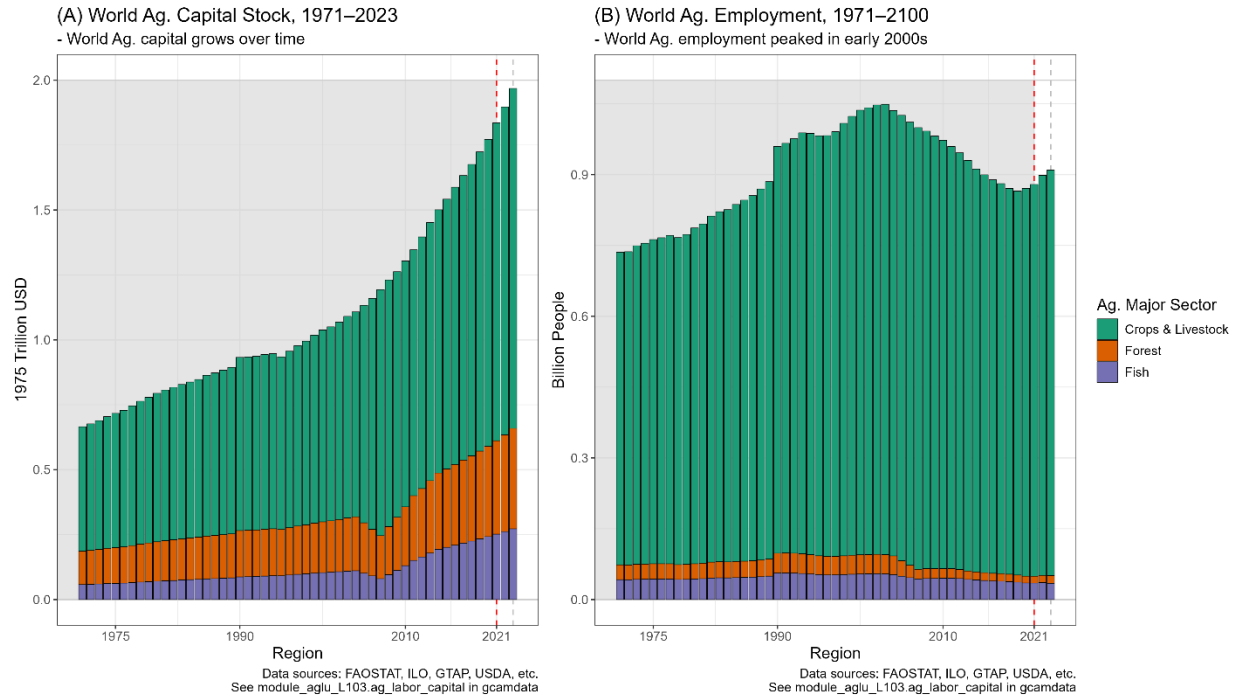


Fig. B2 Historical agricultural capital stock and employment, world, 1971–2023

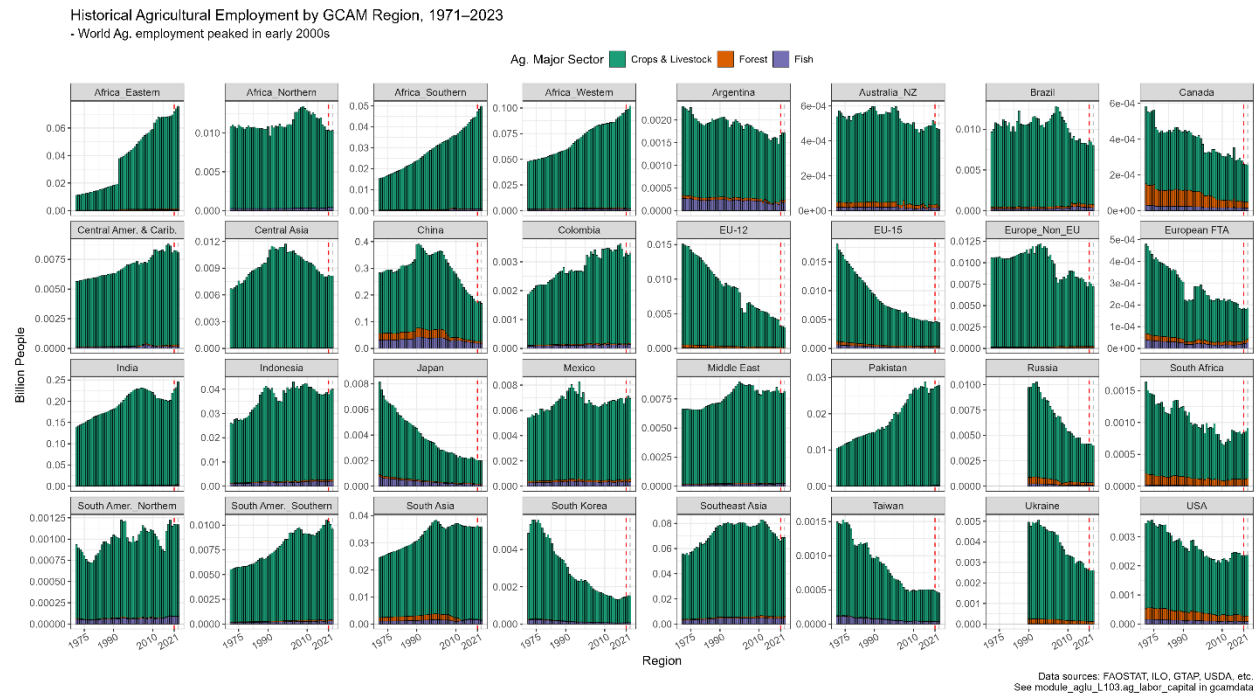


Fig. B3 Historical agricultural employment by GCAM region, 1971–2023

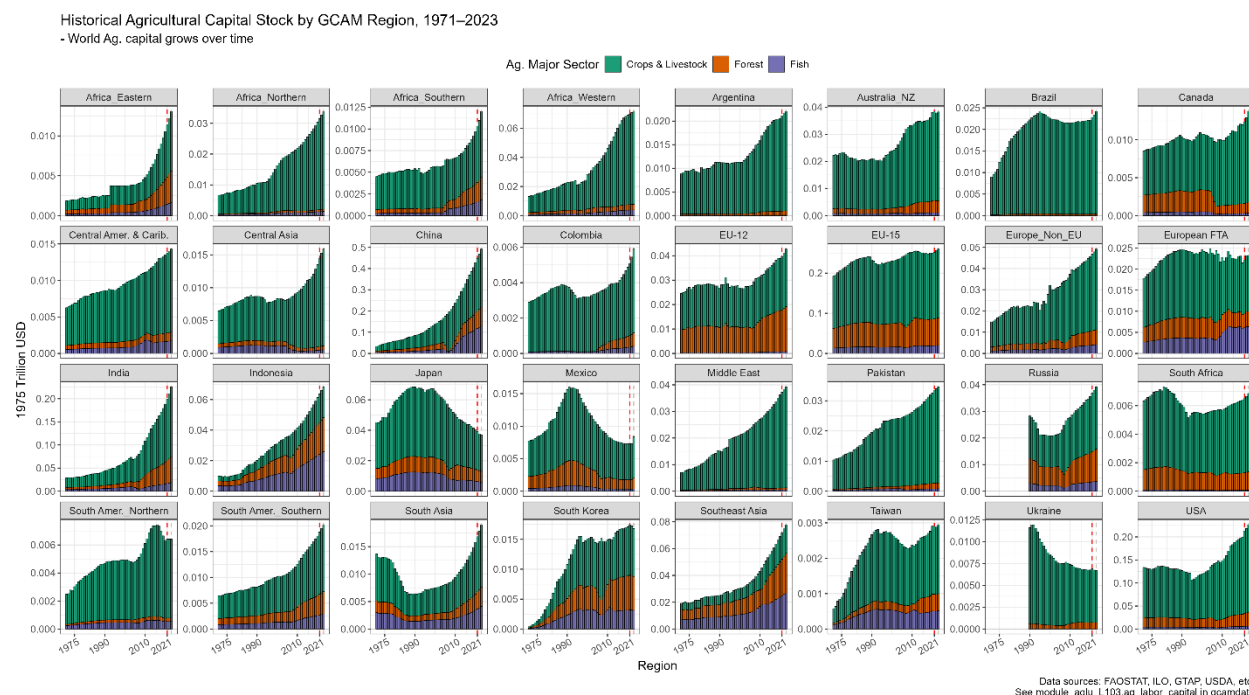


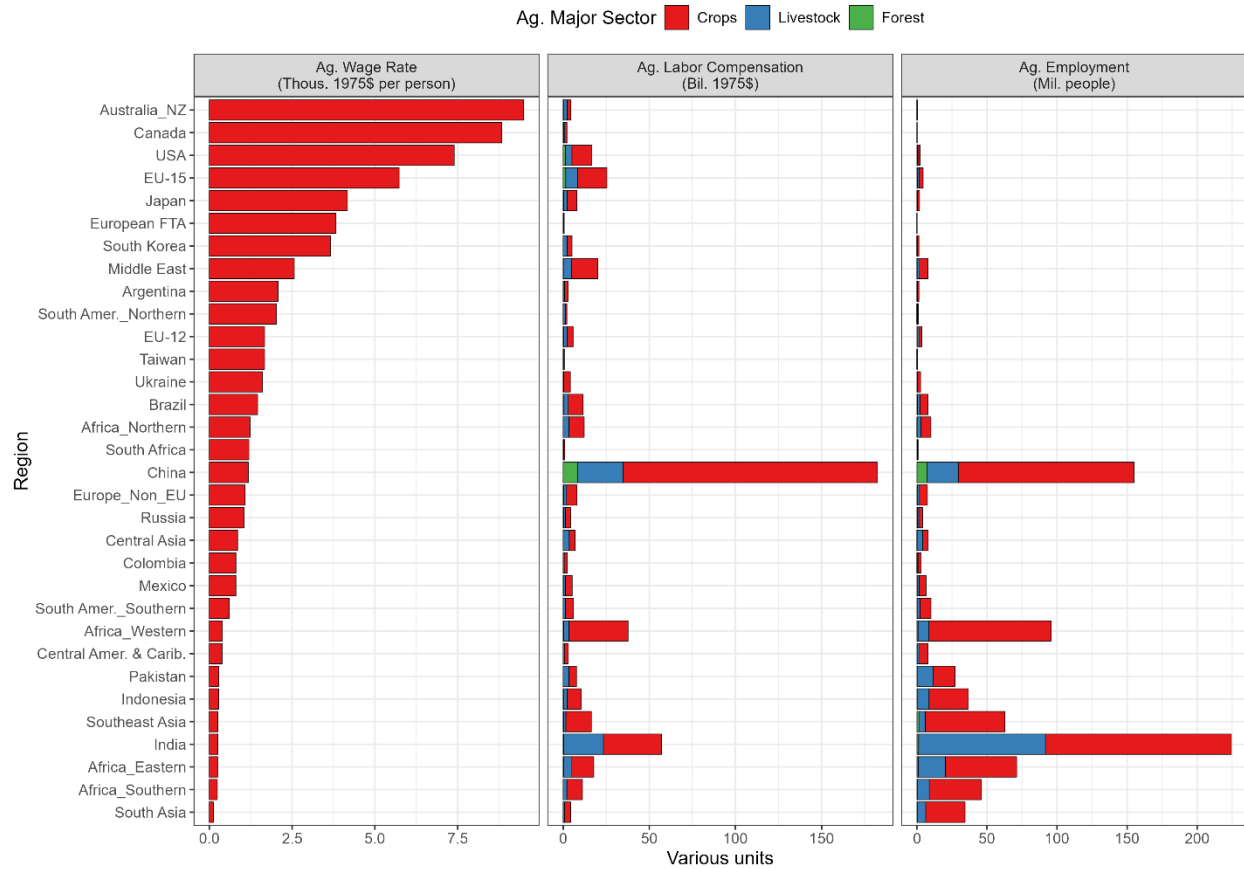
Fig. B4 Historical agricultural capital by GCAM region, 1971–2023

Fig. B5 presents base-year (2021) agricultural wage rates, labor compensation, and employment across GCAM regions. A single regional wage rate is assumed across all agricultural sectors, reflecting perfect labor mobility within primary agriculture. The data reveal substantial regional heterogeneity, with high-income regions exhibiting high wages but relatively small agricultural employment, while regions such as China and India account for a large share of global labor use. **Fig. B6** presents base-year capital rental prices, compensation, and capital stocks across regions. Capital stocks and compensation are concentrated in regions with higher productivity and mechanization, including China, the United States, and the European Union.

The divergence between declining labor input and increasing capital stock highlights the importance of labor–capital substitution in agricultural development. Rising wages and productivity growth incentivize shifts toward more capital-intensive production systems, reinforcing long-term structural transformation.

Base Year (2021) Agricultural Labor Wage Rate, Compensation, Employment by GCAM Region

- The same regional wage rate is used across all agricultural sectors
- The final base year prices for agricultural products and costs were improved based on observations
- Note that GCAM used 2021 Ag. prices for historical years
- $2021\$ = 1975\$ \times 3.96$



Data sources: FAOSTAT, ILO, GTAP, USDA, etc.
See L2082.Ag_LaborCapital_R_AgMajorSector_Yh_ValueAdded in gcamdata

Fig. B5 Base Year (2021) Agricultural Labor Wage Rate, Compensation, Employment by GCAM Region

Base Year (2021) Agricultural Labor Wage Rate, Compensation, Employment by GCAM Region

- The same regional wage rate is used across all agricultural sectors
- The final base year prices for agricultural products and costs were improved based on observations
- Note that GCAM used 2021 Ag. prices for historical years
- 2021\$ = 1975\$ * 3.96

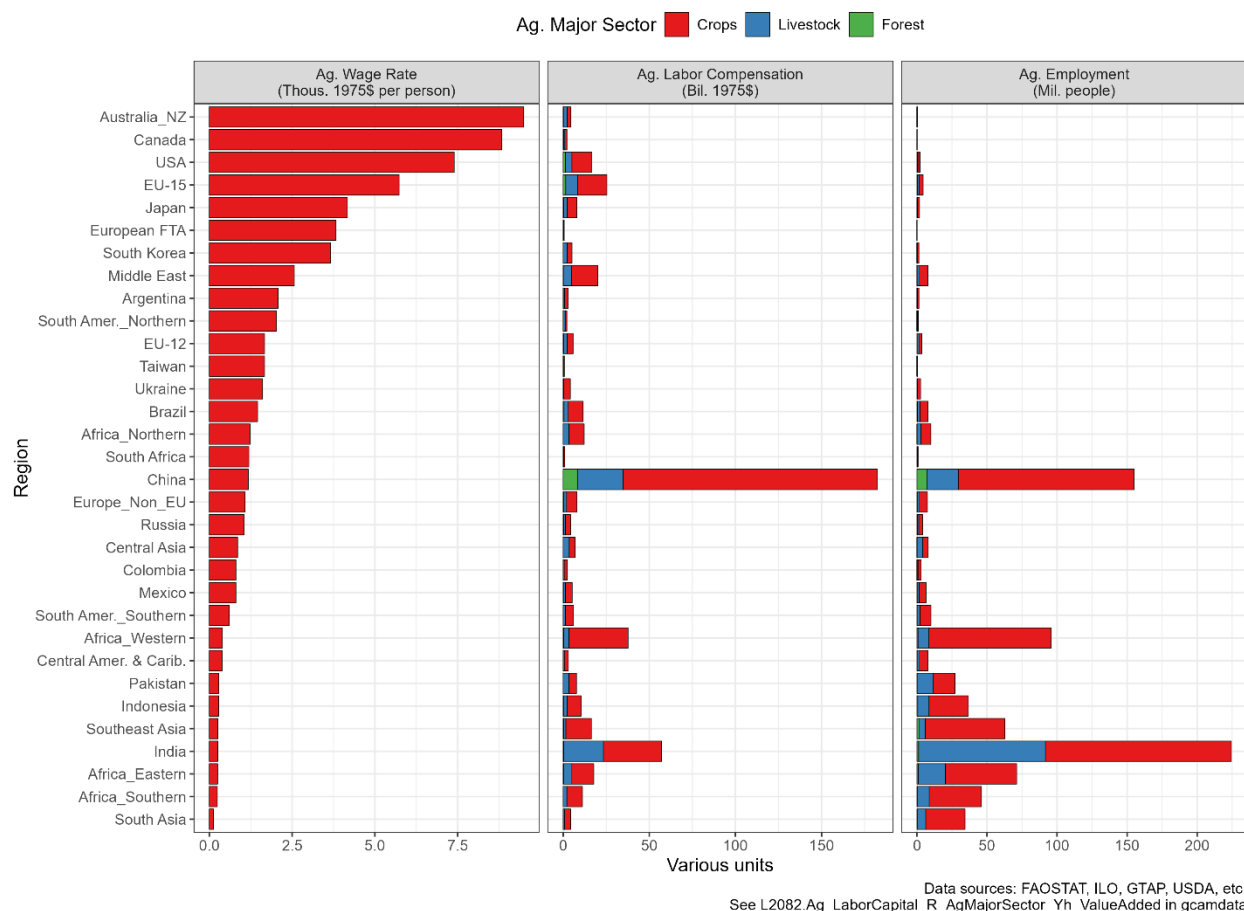


Fig. B6 Base Year (2021) Agricultural Capital Rental Prices, Compensation, Stock by GCAM Region

4. Labor supply and market clearing

The representation of labor in agriculture is fully integrated with the macroeconomic framework in KLEAM. Total labor supply is derived from SSP-based projections of working-age population and employment. Labor is allocated across agriculture and materials sectors using a logit-sharing function that captures sectoral labor mobility. Regional differences in structural transformation are reflected through the logit exponent. Regions undergoing rapid transformation are characterized by higher labor mobility (logit exponent = 2), while regions with largely completed transformation exhibit more limited reallocation (logit exponent = 0.5). Transitional regions fall in between (logit exponent = 1). The regional parameterization is specified in *gcamdata* (“*socioeconomics/A_labor_supply_sector.csv*”).

Within agriculture, labor is assumed to be perfectly mobile across sectors, resulting in a single regional agricultural wage rate. The regional labor market clears by equating total labor supply with aggregate labor demand from both agriculture and materials sectors.

Through these mechanisms, regional wage rates are determined endogenously and directly influence technology-level production decisions. This establishes a two-way linkage between agriculture and the broader economy: macroeconomic conditions shape agricultural production through factor prices, while agricultural value-added contributes to overall economic outcomes.

5. Impact of the agriculture value-added update on rental profit and revenue in GCAM core reference

As discussed earlier, we updated agricultural input cost shares and prices where necessary to prepare the cost data for consistently partitioning labor and capital inputs and the sectoral downscaling. Here we briefly compare KLEAM with the master to examine the impact of the data update of sectoral revenue and land rental profit in the base year (2021). The projections from the GCAM core reference scenario are also included.

As shown in **Fig. B7**, the data updates introduce substantial changes in base-year (2021) value shares, particularly for land rental profit. At the global level, land rental profit declines markedly in KLEAM relative to the master configuration—by approximately 50% for staple crops and 70% for oil crops, while other crops show a modest increase (+11%). Aggregated across all agricultural sectors, land rental profit is 43% lower (about \$350 billion 1990 USD). This adjustment primarily reflects improved factor accounting, as, in the previous configuration, land cost shares implicitly captured part of capital returns, which are now explicitly represented in KLEAM. In addition, the relative labor and capital cost shares derived from the GTAP Data Base were updated for several key regions² to improve value tracking and the derivation of base-year labor and capital prices. Regional agricultural value-added data from FAO were also used as an additional cross-validation source to improve consistency in the calibration process.

Looking beyond the base year, KLEAM generally projects higher future agricultural value supply relative to the master configuration. This is largely driven by higher income elasticities for non-food demand, which strengthen the linkage between agricultural production and overall economic growth. For purpose-grown energy crops, several structural changes are introduced. The introduction of the production is pushed from 2025 to 2030, and initial output levels are significantly lower due to updated regional parameterization. Over the long term, projected supply remains below the master configuration, reflecting stronger competition for land from conventional crops and forest sectors, both of which expand more rapidly under the updated KLEAM framework.

² These adjustments are documented in *socioeconomics/GTAP/GTAP_labor_capital_adjustments.csv*, with the corresponding implementation incorporated in the *gcamdata* module *zaglu_L2082.ag_an_for_laborcapital*.

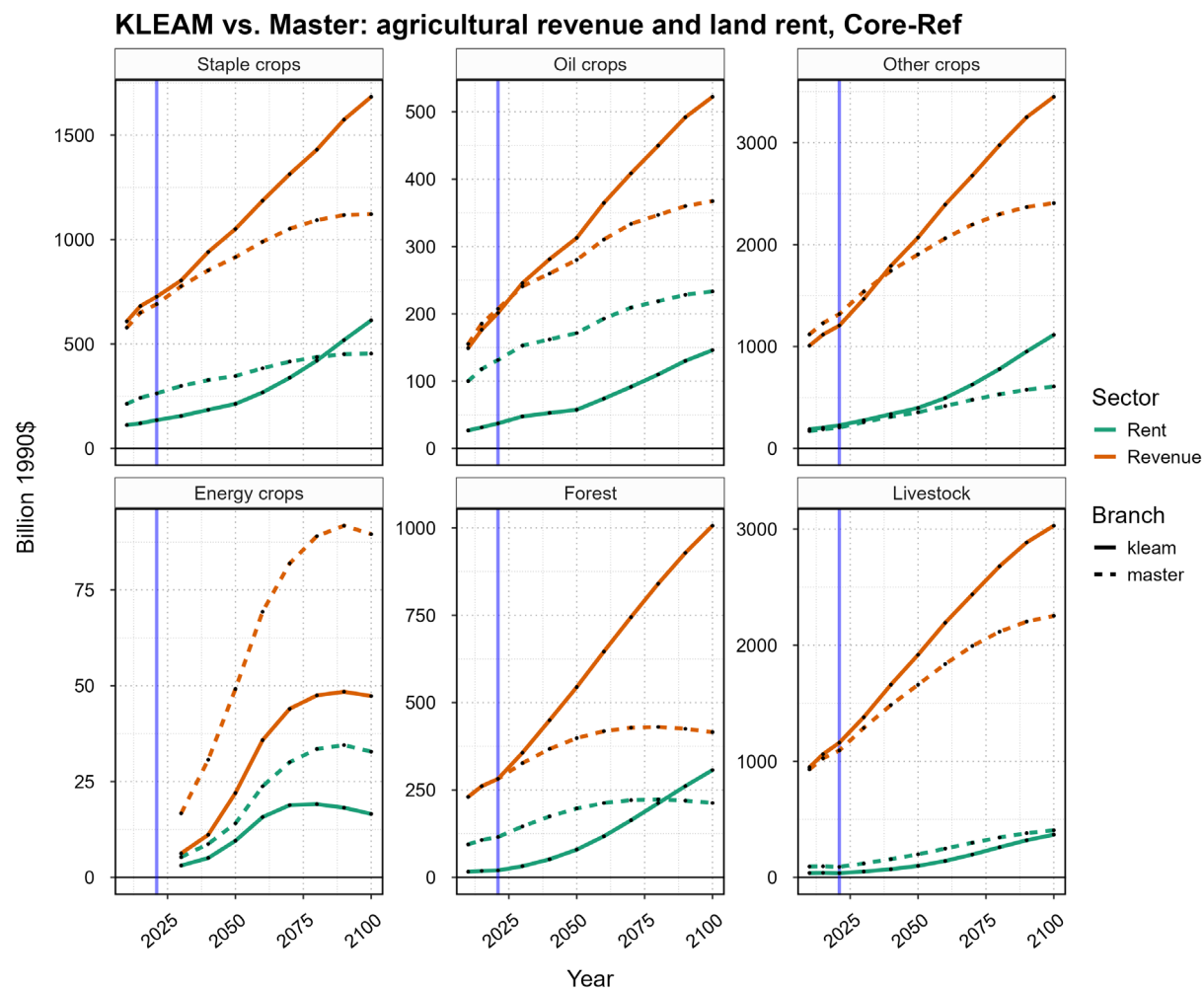
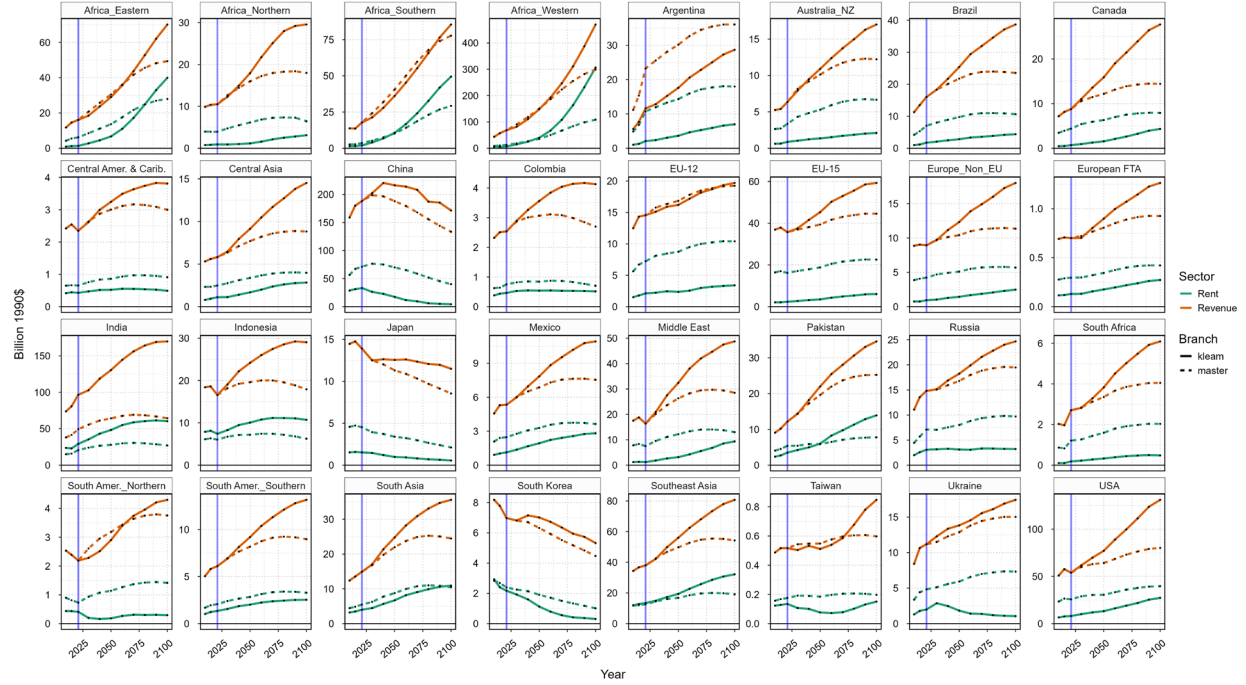


Fig. B7 Agricultural revenue and land rental profit by sector at the global level under the Core reference scenario, in billion 1990 USD, KLEAM vs. master. Regional results are added below.

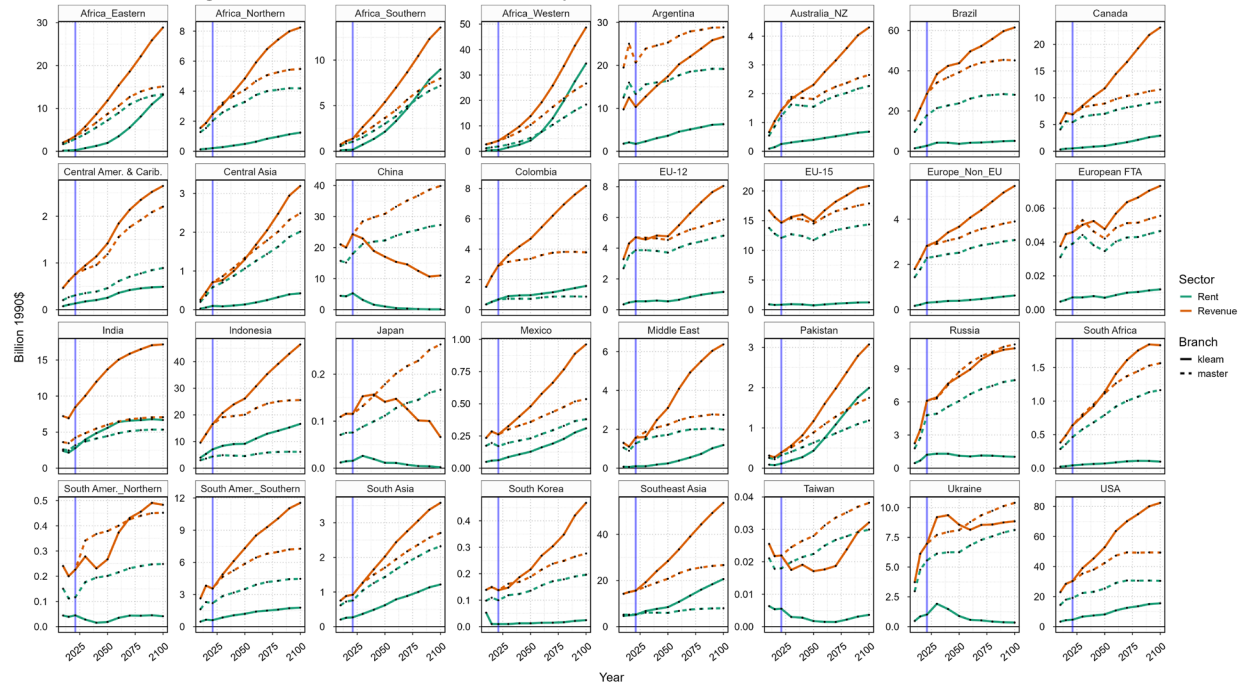
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KLEAM vs. Master: agricultural revenue and land rent, Core-Ref, Staple crops

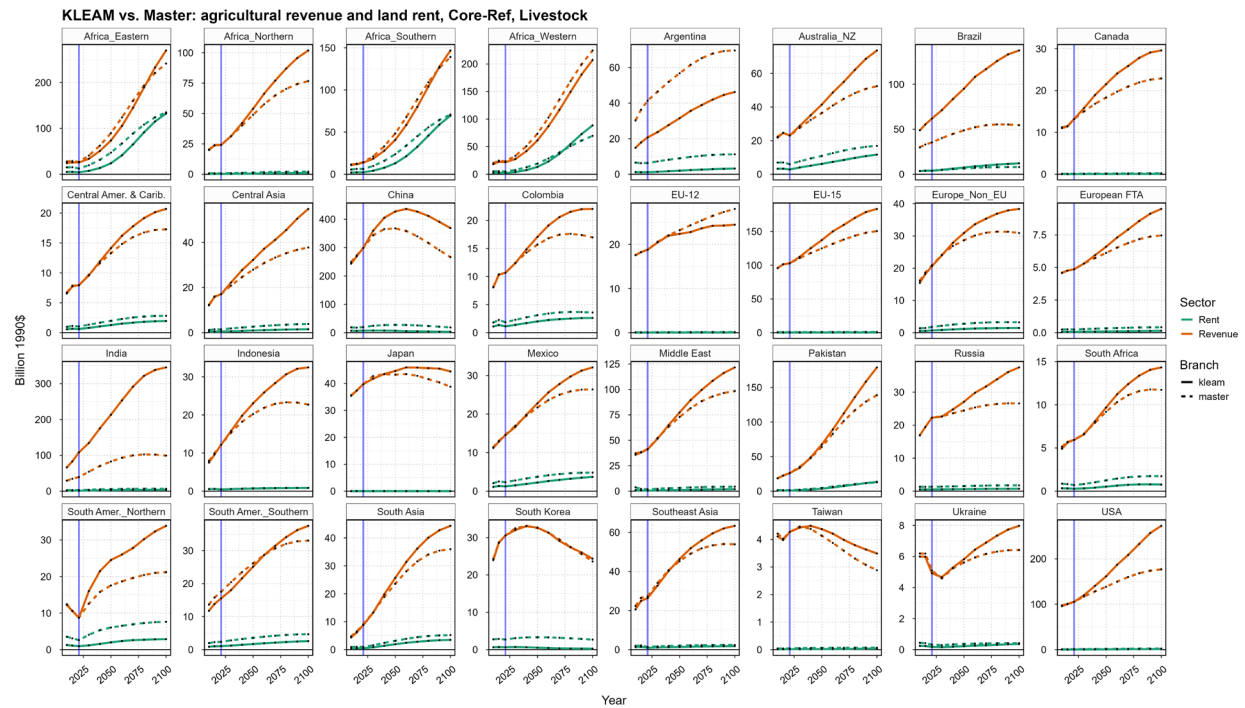
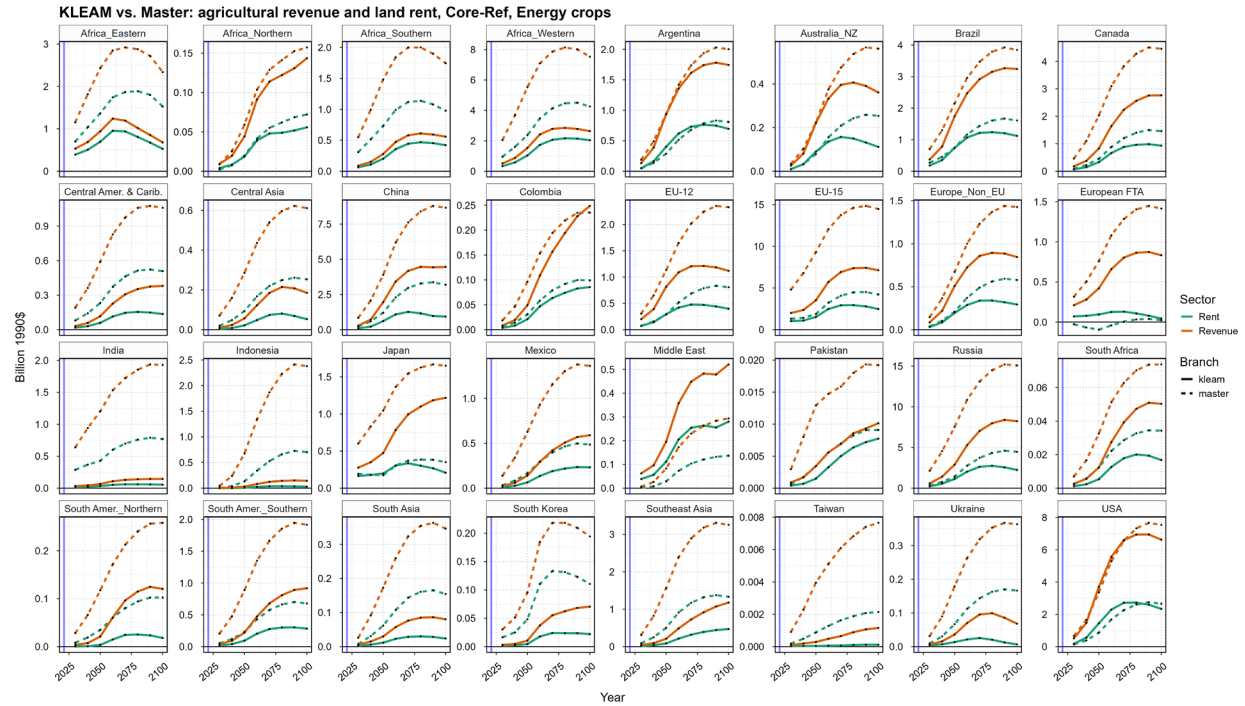


KLEAM vs. Master: agricultural revenue and land rent, Core-Ref, Oil crops



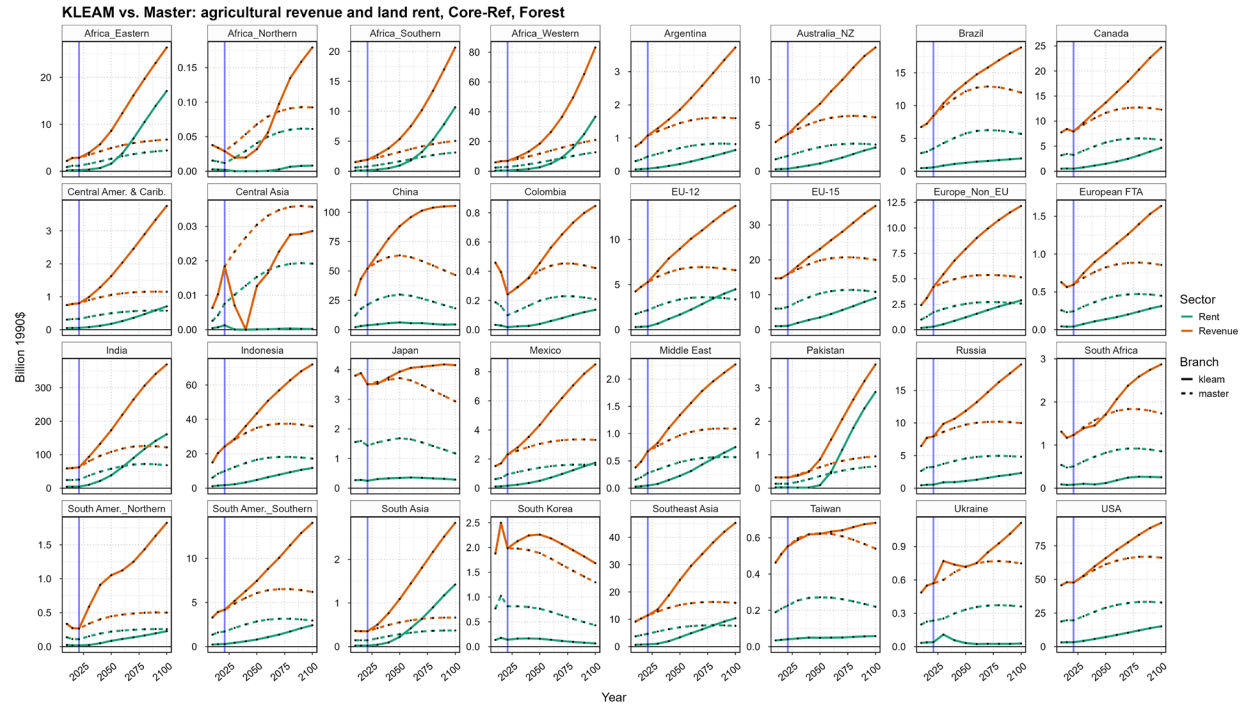
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CMP-411 Appendix C:**Capital Costs, Capital Accumulation, Investment Allocation, Savings–Investment Closure, and Capital Rental Price Feedback****1. Motivation and Scope**

The representation of capital accumulation and investment allocation is a core structural component of GCAM-Macro (Hogan and Manne, 2015). In the earlier KLEM implementation (CMP-332) (Patel et al., 2023), capital dynamics were only partially integrated across sectors. While the Materials sector maintained an explicit capital stock, energy-sector capital costs were embedded in exogenous levelized cost assumptions and did not respond to economy-wide capital conditions. In particular, there was no endogenous capital rental price linking macroeconomic conditions to sectoral investment costs. As a result, capital-intensive technologies in the energy system were not directly affected by changes in the regional rate of return on capital, and cross-sector competition for capital operated only indirectly.

Beyond integrating the agricultural sectors, the KLEAM extension (CMP-411) introduces a unified regional capital market and an endogenous capital rental price. Investment demand from the macro module (Materials) and sector modules (Energy¹ and Agriculture) is aggregated and cleared against savings-determined capital supply. The resulting regional capital rental price directly affects Materials-sector production decisions and, through scaling mechanisms in fixed charge rate (FCR) calculations, influences capital-intensive technology costs in the Energy and Agriculture sectors. This structure enables capital price feedback across sectors and strengthens macro–sectoral consistency while preserving GCAM’s recursive dynamic framework.

GCAM-Macro KLEAM follows the recursive-dynamic tradition of macro–energy modeling while incorporating an internally integrated capital market. Like EPPA and IMACLIM (CGE models), the model solves sequential equilibria with savings-driven capital supply and period-by-period market clearing (Chen et al., 2022; Luderer et al., 2012). At the same time, by introducing an endogenous regional capital rental price that feeds back into sectoral technology costs, KLEAM strengthens macro–sector consistency beyond earlier GCAM implementations. In contrast to intertemporal frameworks such as MESSAGE–MACRO, REMIND, or DICE (Luderer et al., 2012; Messner and Schrattenholzer, 2000)², KLEAM does not optimize investment over time but instead emphasizes transparent capital allocation and cross-sector competition within a recursive dynamic structure.

These advancements move GCAM-Macro closer to the recursive-dynamic IAM/CGE tradition while maintaining GCAM’s detailed bottom-up sectoral structure. In addition to documenting this architectural advancement, this memo/appendix provides a detailed description of how sectoral investment demand is derived, how capital stocks evolve over multi-year model periods, and how the savings–investment balance is enforced within the recursive dynamic framework.

2. Overview of the regional capital architecture in KLEAM

¹ Energy includes energy supply and energy service sectors in GCAM.

² REMIND, WITCH, and DICE are Ramsey-type growth models with endogenous savings and forward-looking investment determined through intertemporal optimization. MESSAGE–MACRO iteratively links the MESSAGE energy system model with MACRO, a macroeconomic growth module that also follows an intertemporal optimization framework.

GCAM-Macro KLEAM operates in a recursive dynamic framework in which each model period solves a static equilibrium given inherited capital stocks, exogenous depreciation rates, and a specified savings rule. Capital accumulation³ evolves sequentially across periods; there is no intertemporal optimization of savings or investment. Instead, savings behavior determines the supply of new capital in each period, and the regional capital rental price adjusts to clear the capital market.

Each GCAM region has a single capital market. In each period, total investment demand—derived from the Materials sector and the Energy and Agriculture modules—is aggregated and balanced against capital supply determined by regional savings (net of capital transfers during the transition period). The regional capital rental price equates aggregate investment demand with available savings.

The regional capital rental price represents the gross return on capital services in the Materials sector. It is not a financial market interest rate nor a social discount rate, but the endogenous price of capital services that clears the regional capital market. This rental price directly determines capital demand in the Materials production function and indirectly affects investment decisions in the Energy and Agriculture sectors through its role in scaling the interest rate used in fixed charge rate (FCR) calculations.

Capital stocks are explicitly partitioned across sectors in both historical calibration and projections. The Materials capital stock includes only non-energy and non-agricultural capital. Agricultural capital is tracked separately by technology and appears explicitly in model outputs and accounting identities. In the Energy sectors, while capital stock is not explicitly represented at the macro level, capital cost is tracked at the technology level for investment demand derivation.

This unified regional capital architecture enables cross-sector competition for capital while preserving sector-specific representations of technology and production structure.

3. Sectoral treatment of capital and investment demand

This section describes how capital accumulation and investment demand are derived in the Materials, Energy, and Agriculture sectors. Although all sectors ultimately compete within a unified regional capital market, the mechanisms through which investment demand is constructed differ across sectors.

3.1 Materials sector: stock-based capital accumulation

In the Materials sector, capital enters directly as a factor input in the production function. Capital demand is determined by the first-order conditions of the nested CES structure, given the regional capital rental price.

Capital stock evolves according to a multi-year law of motion. Let K_t^B denote the beginning-of-period capital stock, K_t^E the end-of-period capital stock used in production during period t , δ the annual depreciation rate, and Δ_t the length of the model period in years⁴. Depreciation over the multi-year period is compounded annually, and thus, the net capital accumulation over the period is defined as: $K_t^E - K_t^B(1 - \delta)^{\Delta_t}$.

³ Not explicit in energy sectors currently.

⁴ With an updated base year of 2021, GCAM uses uneven time steps; it runs in the first step to 2025 and then proceeds in five-year increments through 2100.

Average annual investment during the period is then calculated as:

$$I_t^{Materials} = \frac{K_t^E - K_t^B(1 - \delta)^{\Delta t}}{\Delta t}.$$

Note that the Materials capital stock includes only non-energy and non-agricultural capital, consistent with the sectoral partitioning used in the historical calibration.

3.2 Energy Sector: technology-level capital cost and investment tracking

In the Energy sectors, capital is implicitly represented at the technology level rather than through an aggregate production function as in the Materials sector. Although the Leontief production structure would allow a direct input of capital through a coefficient, this was traditionally not implemented because it would require an explicit capital rental price to track capital cost (i.e., levelized cost per unit of output). Instead, capital cost—either separately specified or embedded within non-energy cost components—is provided directly and treated as exogenous in KLEM (not necessarily constant over time).

In KLEAM, capital price feedback is introduced, making the capital component of technology cost endogenous to economy-wide capital conditions. Conceptually, the annualized capital cost of a technology reflects the product of the capital rental price and its capital intensity (input-output coefficient). While capital services are not explicitly modeled as a primary input in the Energy production structure, technology-level capital cost is linked to the regional capital rental price. This allows macroeconomic capital conditions to influence technology competitiveness and deployment decisions.

To clarify notation, we distinguish three related but distinct concepts:

- PKE_t denote the regional capital rental price,
- $\bar{K}_i$ denote the overnight capital cost per unit of capacity for technology i ,
- κ_i denote the capital requirement (capital intensity) per unit of new capacity or output, and
- N_i denote the economic lifetime of the technology.

The annualized capital cost is calculated using the standard fixed charge rate (FCR):

$$FCR(r, N) = \frac{r(1 + r)^N}{(1 + r)^N - 1}$$

where r is the interest rate.

For technologies with explicit overnight capital cost data, let $\bar{K}_i$ denote the capital cost per unit of capacity (e.g., \$/kW). The annualized capital cost component for technology i in period t is then:

$$C_{i,t}^{cap} = \bar{K}_i \cdot FCR(r_t^{tech}, N_i).$$

For technologies where only total non-energy costs are available, those costs are decomposed into a capital portion and an operating portion using a capital ratio (**Table C1**). The capital portion is annualized using the same FCR formulation.

In KLEAM, the capital price feedback is provided to technology-level interest rate. Specifically The interest rate used in the FCR is scaled proportionally to the regional capital rental price:

$$r_t^{tech} = r_0^{tech} \cdot \frac{PKE_t}{PKE_0},$$

As a result, changes in the regional capital rental price directly alter the annualized capital component of technology cost. An increase in PKE_t raises the capital-intensive portion of technology cost, while a decrease lowers it. Consequently, part of the non-energy cost becomes endogenous to macroeconomic capital conditions.

In addition to cost updating, investment demand must be derived in order to clear the unified regional capital market. The treatment differs depending on whether the technology is vintaged or non-vintaged (Table C1; depreciation rate is not specified for vintaged technologies).

1) Vintaged Technologies

For vintaged technologies (e.g., electricity generation technologies), new capacity additions are explicitly tracked. Let $\Delta Q_{i,t}$ denote new capacity installed for technology i in period t . Investment demand is given by:

$$I_{i,t}^{Energy} = \kappa_i \Delta Q_{i,t}.$$

Retirement of existing vintages is determined by the specified technical lifetime. In this case, capital stock evolution is handled at the vintage level rather than through an aggregate law-of-motion equation.

2) Non-Vintaged Technologies

For non-vintaged technologies, capital stock is not chosen independently but is inferred from output and capital intensity. Let $Q_{i,t}$ denote the level of output (or effective operating capacity) of technology i in period t . The implied end-of-period capital stock is given by:

$$K_{i,t}^E = \kappa_i Q_{i,t}.$$

Thus, capital stock is “backed out” from technology deployment decisions and capital intensity parameters. This implied stock then evolves according to a multi-year law-of-motion structure. Investment over the period is therefore:

$$I_{i,t}^{Energy} = \frac{K_{i,t}^E - K_{i,t}^B(1 - \delta_i)^{\Delta t}}{\Delta t}.$$

Thus, even in the absence of explicit vintaging, depreciation and capital accumulation are consistently represented. Total Energy-sector investment demand is then:

$$I_t^{Energy} = \sum_i I_{i,t}^{Energy}.$$

Energy capital is not incorporated into the Materials capital stock. Instead, technology-level investment demand enters the unified regional capital market while capital stocks remain tracked at the sectoral or vintage level.

Table C1 Energy supply and energy service sectors with capital-tracking in GCAM

sector.name	minicam.non.energy.input	capital.ratio	tracking.market	depreciation.rate
resid heating modern	non-energy	1	consumer durable	7%
resid heating coal	non-energy	1	consumer durable	7%
resid heating TradBio	non-energy	1	consumer durable	7%
resid cooling modern	non-energy	1	consumer durable	7%
resid others modern	non-energy	1	consumer durable	7%
resid others coal	non-energy	1	consumer durable	7%
resid others TradBio	non-energy	1	consumer durable	7%
trn_pass_road_LDV	non-energy	regional	consumer durable	7%
trn_pass_road_LDV_4W	non-energy	regional	consumer durable	7%
coal	investment-cost	0.6	capital	0
crude oil	investment-cost	0.6	capital	0
natural gas	investment-cost	0.6	capital	0
elect_td_bld	capital	1	capital	7%
electricity	capital	old approach	capital	0
elec_CSP	cooling system	old approach	capital	0
elec_coal (conv pul)	cooling system	old approach	capital	0
elec_coal (IGCC)	cooling system	old approach	capital	0
elec_coal (conv pul CCS)	cooling system	old approach	capital	0
elec_coal (IGCC CCS)	cooling system	old approach	capital	0
elec_gas (steam/CT)	cooling system	old approach	capital	0
elec_gas (CC)	cooling system	old approach	capital	0
elec_gas (CC CCS)	cooling system	old approach	capital	0
elec_refined liquids (steam/CT)	cooling system	old approach	capital	0
elec_refined liquids (CC)	cooling system	old approach	capital	0
elec_refined liquids (CC CCS)	cooling system	old approach	capital	0
elec_biomass (conv)	cooling system	old approach	capital	0
elec_biomass (IGCC)	cooling system	old approach	capital	0
elec_biomass (conv CCS)	cooling system	old approach	capital	0
elec_biomass (IGCC CCS)	cooling system	old approach	capital	0
elec_Gen_II_LWR	cooling system	old approach	capital	0
elec_Gen_III	cooling system	old approach	capital	0
elec_CSP_storage	cooling system	old approach	capital	0
elec_geothermal	cooling system	old approach	capital	0
refining	non-energy	0.6	capital	0
gas processing	non-energy	0.6	capital	3%
nuclearFuelGenII	non-energy	0.6	capital	3%
nuclearFuelGenIII	non-energy	0.6	capital	3%
H2 central production	non-energy	0.8	capital	0
H2 central production	electrolyzer	0.8	capital	0
H2 central production	nuclear electricity generation	0.8	capital	0
comm heating	non-energy	1	capital	7%
comm cooling	non-energy	1	capital	7%
comm others	non-energy	1	capital	7%
trn_freight	non-energy	regional	capital	3%
trn_shipping_intl	non-energy	regional	capital	3%
trn_freight_road	non-energy	regional	capital	3%
trn_pass	non-energy	regional	capital	3%
trn_aviation_intl	non-energy	regional	capital	3%
trn_pass_road	non-energy	regional	capital	3%
other industrial energy use	non-energy	0.9	capital	0
process heat cement	non-energy	0.9	capital	0
iron and steel	non-energy	0.9	capital	0
agricultural energy use	non-energy	0.9	capital	0
construction energy use	non-energy	0.9	capital	0
mining energy use	non-energy	0.9	capital	0
chemical energy use	non-energy	0.9	capital	0
alumina	non-energy	0.9	capital	0
process heat paper	non-energy	0.9	capital	0
waste biomass for paper	non-energy	0.9	capital	0
process heat food processing	non-energy	0.7	capital	0

3.3 Agriculture: hybrid capital representation

The Agriculture sector combines elements of the Materials and Energy representations. Agricultural production functions include capital as an explicit input, and agricultural capital stock is tracked and reported. However, new investment demand is derived using a fixed charge rate–based tracking approach similar to that used in the Energy sector.

For each agricultural technology, capital requirements are specified along with depreciation assumptions. Capital cost is annualized using an FCR formulation in which the interest rate is scaled proportionally to the regional capital rental price. This structure ensures that changes in the regional capital rental price influence agricultural investment costs.

Investment demand in Agriculture is derived from technology-specific capital requirements and output levels, and is aggregated to contribute to total regional capital demand. Agricultural capital stock is then updated using a law-of-motion structure consistent with multi-year depreciation compounding.

This hybrid representation allows agricultural capital to respond to economy-wide capital price signals while maintaining explicit stock accounting and sectoral detail.

4. Capital supply and regional market clearing

Capital supply in each region is determined by savings behavior within the recursive dynamic framework. A regional savings rate determines the share of GDP allocated to investment in each period.

Let:

- s_t denote the regional savings rate,
- GDP_t denote regional gross domestic product.

Total savings in period t is:

$$S_t = s_t \cdot GDP_t.$$

The savings rate may evolve over time according to exogenous assumptions or empirical calibration rules (e.g., based on lagged GDP growth and lagged saving rates), but savings are not forward-looking and do not respond to anticipated future returns.

Total regional investment demand is the sum of sectoral demands derived in Section 3:

$$I_t^{Total} = I_t^{Mat} + I_t^{Energy} + I_t^{Ag}.$$

Regional net capital exports may be specified during transition periods. In the long run, regional trade balances are phased out such that net capital exports converge to zero. Under this structure, available capital supply equals regional savings adjusted for net capital flows.

The regional capital rental price PKE_t adjusts to satisfy the capital market clearing condition:

$$I_t^{Total} = S_t.$$

This equilibrium condition defines the unified regional capital market. There is one capital rental price per region and no sector-specific capital prices.

The rental price affects sectors differently:

- In the Materials sector, PKE_t enters directly into first-order conditions of the production function and determines capital demand.
- In the Energy and Agriculture sectors, PKE_t influences investment indirectly by scaling the interest rate used in fixed charge rate (FCR) calculations.

Through this mechanism, cross-sector competition for capital emerges within each region. When savings are limited, an increase in investment demand in one sector raises the regional capital rental price, which in turn increases capital costs in other sectors and moderates their investment. Conversely, higher savings reduce the rental price and lower capital-intensive technology costs.

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CMP-411 Appendix D:**Agricultural Factor Productivity Growth Representation****1. Motivation and scope**

Productivity growth is a central driver of long-run projections in global economic and multi-sector dynamic models. Productivity trajectories shape projections of agricultural production, land use, labor allocation, capital accumulation, and structural transformation, with cascading implications for integrated human–Earth system dynamics (Charlton et al., 2021; Fuglie, 2018). At the same time, long-run projections are highly sensitive to underlying productivity assumptions, while the derivation and implementation of those assumptions are often complex and insufficiently documented. Differences in productivity specifications have also been identified as a major source of divergence across global economic models (Foure et al., 2020; Robinson et al., 2014; Schmitz et al., 2014).

In GCAM, agricultural sectors are integrated with the broader economy through land and water competition, food, fiber, timber, and bioenergy supply, and price feedbacks. GCAM has historically incorporated productivity growth in agriculture asymmetrically across factors and sectors, i.e., primarily land-augmenting and concentrated in crop production. While this structure provided a tractable baseline, it limited the model’s ability to transparently represent factor-biased technical change and to systematically explore alternative productivity scenarios. More importantly, how productivity growth is represented in agriculture is critical for macroeconomic consistency and structural transformation dynamics.

GCAM-Macro (KLEAM) generalizes the agricultural production structure by explicitly representing labor and capital, in addition to land, water, nitrogen fertilizer, and feed, as distinct factor inputs. With these inputs modeled explicitly, productivity is specified as factor-augmenting parameters embedded directly in the production function. This structure enables transparent specification of factor-biased technical change through factor-augmenting parameters and allows Hicks-neutral total factor productivity (TFP) to emerge as a special case when productivity growth is uniform across inputs¹.

This research memorandum documents the baseline agricultural productivity representation in GCAM, describes the generalized factor-specific framework introduced in KLEAM, and details the derivation of agricultural labor productivity growth relative to land productivity growth. The objective is to provide a transparent and internally consistent foundation for future scenario design and sensitivity analysis.

2. Baseline agricultural productivity representation in GCAM

¹ Note that in the literature, TFP refers to two related but conceptually distinct notions that are often conflated. In the empirical growth accounting literature, TFP is defined as an *ex post* residual that measures how much output growth cannot be explained by measured input growth. In contrast, here, in production theory and economic equilibrium models, **Hicks-neutral TFP** is specified as an *ex ante* technology shifter applied to the production function. The residual interpretation of TFP is not used in our modeling framework.

GCAM provides a detailed representation of agricultural sectors, including crops, livestock, and forestry production², and incorporates explicit technology differentiation for irrigation systems and nitrogen-fertilizer applications in crop production. However, prior to the introduction of explicit labor and capital in GCAM-Macro (KLEAM), the representation of productivity growth in primary agriculture was uneven across factors and sectors.

In crop production, exogenous productivity growth was primarily driven by land-augmenting yield improvements. These land productivity trajectories were developed based on FAO baseline yield projections (Alexandratos et al., 2006; Alexandratos and Bruinsma, 2012), assuming no additional atmospheric or other biophysical feedbacks. Land productivity growth was applied to all crop sectors (mapped from key FAO commodities), except for pasture and fodder grass, which are less intensively managed and therefore did not receive comparable exogenous productivity improvements.

Formally, land productivity growth was implemented as a land-augmenting productivity parameter term at the technology level. As this index increases over time, less land input is required per unit of output, implying rising yields in future periods. Across the 32 GCAM regions, these land productivity growth paths differ substantially (see **Fig. D1**), reflecting regional heterogeneity in projected yield improvements.

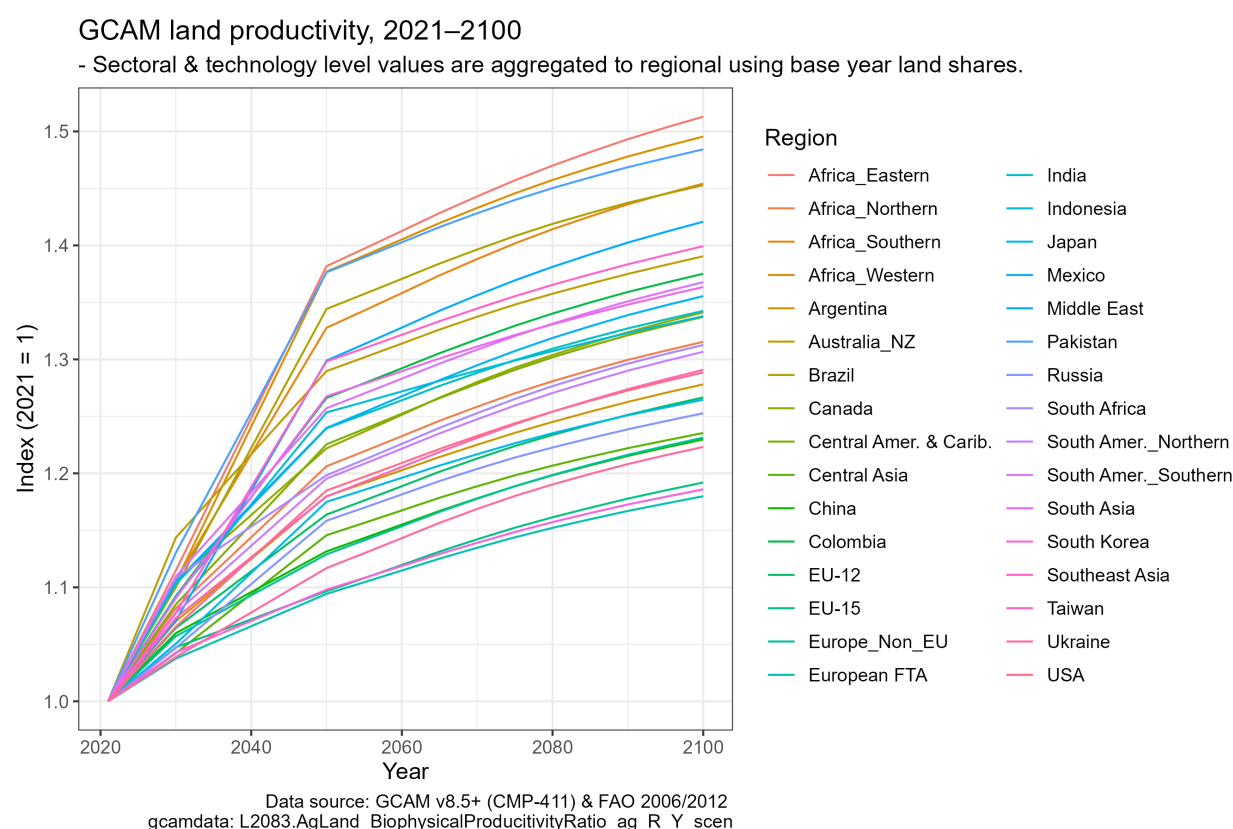


Fig. D1 GCAM land productivity assumptions

² Labor and capital inputs for aquaculture and fisheries will be incorporated in the upcoming CMP, where the sectoral supply dynamics are specified. Primary agricultural employment and capital will then be fully represented within GCAM.

While crop production incorporated explicit land-augmenting productivity growth, irrigation water and nitrogen fertilizer were already linked to production technologies in GCAM. Their effective productivity could improve endogenously through technology transitions (e.g., shifts in irrigation systems or fertilizer intensity), but no independent exogenous productivity growth trajectories were imposed on these inputs. Improvements in water or fertilizer efficiency, therefore, occurred only through changes in the technology mix rather than through explicit exogenous factor-augmenting productivity shocks.

In contrast, the livestock and forestry sectors did not include any explicit exogenous factor-augmenting productivity growth. Livestock production is represented through mixed and pastoral systems with intermediate feed inputs, while forestry production is linked to land allocation dynamics. Although prior GCAM studies have explored sensitivity to productivity assumptions in these sectors (e.g., improvements in feed conversion ratios and yield growth in managed forests (Luo et al., 2024; Zhao et al., 2024)), systematic exogenous factor-specific productivity growth paths were not embedded in the standard configuration. As a result, crop production constituted the primary channel through which long-run exogenous agricultural productivity growth entered the system.

In summary, baseline GCAM before KLEAM can be characterized as:

- Land-driven in exogenous productivity growth (primarily for crops),
- Technology-driven but not exogenously augmented for water and fertilizer,
- Without explicit labor or capital productivity growth in agriculture,
- Without systematic factor productivity growth in livestock and forestry sectors.

This asymmetric structure, strongly land-focused for crops and largely neutral for other factors and sectors, provides the motivation for the generalized, factor-specific productivity framework introduced in GCAM-Macro (KLEAM) and documented in the following sections.

3. Conceptual framework of factor productivity in agriculture

The introduction of GCAM-Macro (KLEAM) generalizes the agricultural production structure by explicitly representing land, labor, capital, irrigation water, and nitrogen fertilizer as distinct factor inputs³. As a result, the cost share previously attributed to residual “other inputs” is substantially reduced⁴. This extension enables the systematic and transparent specification of factor-augmenting productivity growth and avoids implicitly attributing productivity improvements solely to land.

Agricultural productivity growth arises from multiple underlying mechanisms. Land productivity increases are typically associated with improvements in crop genetics, seed technology, agronomic practices, irrigation management, and improved input applications. Labor productivity growth reflects mechanization, human capital accumulation, learning-by-doing, and structural transformation. These processes often interact, e.g., improved seed varieties, digital technologies, and better management practices may simultaneously enhance both land and labor productivity. Input-specific productivity growth may also occur for irrigation water and nitrogen fertilizer,

³ The related data processing modules in gcamdata have been greatly reorganized to make productivity scenario generation easier and more consistent.

⁴ We continue to hold the “other cost” per unit of output constant over time. Future work is needed to further disaggregate farm energy and additional non-nitrogen fertilizer inputs.

reflecting advances in irrigation efficiency, nutrient-use efficiency, precision agriculture, and improved input targeting. In practice, however, changes in effective input productivity may be driven by a combination of technological innovation, input substitution, and changes in production techniques.

Agricultural development frequently involves capital deepening, whereby increased mechanization and equipment use raise output per worker even in the absence of explicit capital-augmenting technical change. Recent empirical work emphasizes that technological progress in agriculture is increasingly embodied in capital equipment and interacts with capital deepening to drive labor productivity growth (Caunedo and Keller, 2021; Sheng, 2025). These studies highlight the importance of distinguishing between capital accumulation effects and productivity frontier shifts. At the same time, separating embodied technological change, input substitution, and factor-augmenting productivity shifts is inherently difficult in global models.

Rather than attempting to parameterize each of these channels separately, GCAM-Macro (despite its currently parsimonious baseline assumptions) adopts a flexible and internally consistent structure that allows factor-specific productivity assumptions to be specified explicitly and evaluated systematically through sensitivity analysis. Within this structure, agricultural capital productivity is assumed constant in the baseline configuration. This treatment remains appropriate under the updated KLEAM macro closure, in which the saving–investment market clears endogenously, and the gross rate of return on capital is determined endogenously within the integrated macroeconomic system. Under this closure, capital deepening emerges endogenously through investment allocation and accumulation decisions. An additional exogenous capital-augmenting productivity path would represent an independent frontier shift and could conflate capital accumulation effects with technological change. Maintaining constant capital productivity, therefore, preserves the distinction between capital accumulation and shifts in the productivity frontier and avoids potential double-counting of embodied technological change. This approach is consistent with the global economic equilibrium modeling practice (Chateau et al., 2020).

Similarly, exogenous productivity growth for irrigation water and nitrogen fertilizer is held constant in the baseline configuration. Improvements in their effective productivity occur only through endogenous technology transitions. This parsimonious treatment provides a transparent starting point while preserving flexibility for future exploration of input-specific productivity shocks.

Given these considerations, the present extension focuses on the development of agricultural labor productivity trajectories while maintaining the established FAO-based land productivity path as the structural anchor.

4. Agricultural labor productivity derivation

In most regions undergoing structural transformation, output per worker has historically grown faster than output per hectare, as labor productivity reflects both yield improvements and capital deepening (Fuglie, 2018; Gollin et al., 2014). Land productivity improvements primarily reflect biological and agronomic advances that raise output per hectare, including crop genetics, improved seed varieties, and enhanced management practices (Alexandratos and Bruinsma, 2012; Evenson and Gollin, 2003). In contrast, agricultural labor productivity incorporates not only these land productivity gains but also mechanization, human capital accumulation, scale economies, and labor reallocation within and across sectors. As agricultural economies modernize, output per worker increases not only because yields improve, but also because fewer workers operate larger and more capital-intensive production systems.

Agricultural labor markets are increasingly integrated with the broader economy (Sheng et al., 2025). As non-agricultural sectors experience productivity growth (captured in GCAM-Macro through the macro-calibrated materials TFP used to reproduce SSP per-capita GDP trajectories), wage convergence pressures emerge across sectors. To maintain labor market equilibrium and avoid implausible wage divergence, agricultural labor productivity growth must remain broadly comparable to economy-wide productivity growth over the long run⁵.

The adopted scaling approach therefore reflects two structural principles:

- (i) agricultural labor productivity growth should exceed land productivity growth due to mechanization and capital deepening, and
- (ii) it should remain broadly aligned with macro-calibrated economy-wide productivity growth, particularly in transforming economies.

Rather than specifying an independent productivity path for each region or directly linking labor productivity mechanically to materials TFP growth, agricultural labor productivity growth is defined as a multiple of the long-run average land productivity growth rate. Regions are grouped according to their stage of structural transformation in the baseline configuration:

- **Low (2x multiplier): Mature agricultural economies**, where labor transition is largely complete and agricultural productivity growth converges toward economy-wide dynamics.
- **Medium (3x multiplier): Transitional economies**, where modernization continues and agricultural labor productivity growth remains above land productivity growth.
- **High (4x multiplier): Structurally transforming regions**, where substantial labor reallocation potential and mechanization lead to accelerated agricultural labor productivity growth.

The multiplier is applied to the average annual land productivity growth rate over the modeling horizon, thereby anchoring labor productivity growth to biophysical yield trends while avoiding amplification of short-term volatility or mid-horizon kinks (e.g., around 2050 when FAO projections end).

To generate a smooth and economically plausible time profile, we assume agricultural labor productivity follows a generalized power function⁶:

$$G_{r,t}^{labor} = \left(1 + s_r \left((G_{r,2100}^{land})^{\frac{1}{T}} - 1 \right) \right)^{T \left(\frac{t-2021}{T} \right)^{\alpha}}$$

where:

- $G_{r,t}^{labor}$ denotes labor productivity index in region r and year t ($G_{r,2021}^{labor} = 1$).
- $G_{r,2100}^{land}$ denotes land productivity index in region r in 2100 ($G_{r,2021}^{land} = 1$).
- t is model year; 2021 is the base year; 2100 is the last model year; $T = 2100 - 2021$.

⁵ If agricultural labor productivity were to grow substantially more slowly than other sectors, labor reallocation would accelerate excessively; if it were to grow substantially faster, the model would imply a persistent agricultural wage premium inconsistent with structural transformation patterns.

⁶ The processing is included in *gcamdata module_aglu_L2083.ag_factor_productivity_scen*.

- s_r denotes regional scaling multiplier reflecting structural transformation stage: $s_r = 2$: **Low** (mature agricultural economies), $s_r = 3$: **Medium** (transitional economies), and $s_r = 4$: **High** (structurally transforming regions).
- α is the curvature (shaping) parameter for the time profile; $\alpha = 1$ yields the standard log-linear path; $\alpha < 1$ produces a less convex (more concave) trajectory. In the baseline, $\alpha = 0.7$.

Fig. D2 illustrates regional land productivity, derived agricultural labor productivity, and macro-calibrated materials TFP trajectories for key regions (full GCAM regional results are included in the **Appendix F** visualization dashboard).

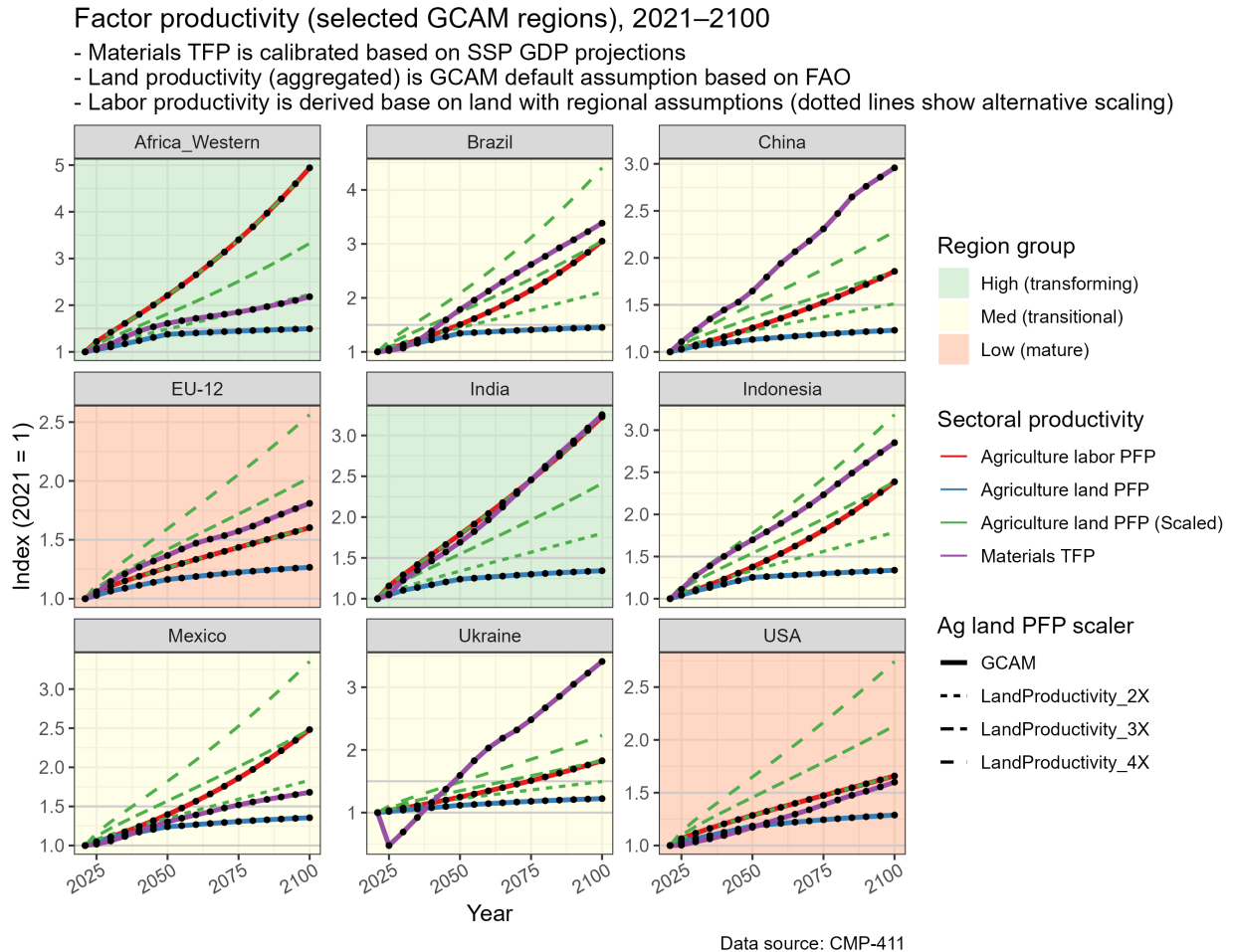


Fig. D2 Factor productivity derivation in selected GCAM regions

Across regions, agricultural labor productivity growth generally remains below (or comparable to) macro-calibrated materials TFP growth, reflecting continued convergence of agriculture toward broader economy-wide productivity levels. In structurally transforming regions, labor productivity growth may exceed materials TFP during periods of rapid mechanization and labor reallocation.

The regional grouping used for labor productivity scaling is aligned with the differentiated labor logit exponent in KLEAM. Regions with greater structural transformation potential are assigned higher

responsiveness in both labor allocation dynamics and labor productivity growth, ensuring internal consistency between productivity assumptions and labor market adjustment behavior.

5. Summary and key takeaways

The generalized factor-specific productivity structure introduced in GCAM-Macro (KLEAM) transforms agricultural productivity representation from a predominantly land-driven mechanism into a transparent and internally consistent framework. By explicitly distinguishing land, labor, capital, water, and fertilizer inputs and their productivity growth, the model enables systematic exploration of biased technical change while preserving macroeconomic consistency under endogenous saving–investment closure.

Anchoring labor productivity growth to land productivity while maintaining constant capital and other input factor-augmenting productivity parameters in the baseline provides a parsimonious yet flexible starting point. The structure allows alternative productivity scenarios to be implemented transparently and evaluated through sensitivity analysis, thereby improving both interpretability and robustness of long-run projections.

More broadly, this framework provides a structured input-augmenting technical change architecture that enables systematic evaluation of how agricultural factor productivity assumptions influence land use, water demand, fertilizer application, labor allocation, capital accumulation, and macroeconomic outcomes. It introduces an explicit and traceable degree of freedom in productivity specification, laying the groundwork for ensemble-based sensitivity analysis and alternative biophysical shock scenarios.

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CMP-411 Appendix E:**Purpose-grown Energy Crop Introduction: Ghost Share Recalibration and Assumption Updates****1. Background and problem**

In GCAM, modern biomass supply originates from three sources: municipal solid waste (MSW), agricultural and forestry residues, and purpose-grown energy crops (Zhao et al., 2024). In the current base year (**2021**), however, there is no production of purpose-grown energy crops. This remains effectively true as of **2026**¹. In GCAM, all modern biomass supply in the calibrated base year is derived from MSW and agricultural/forestry residues. MSW supply is represented using simple supply curves linked to socioeconomic variables, while agricultural and forestry residues are tied to GCAM crop and forestry production². In aggregate, base-year modern biomass supply from these sources is calibrated to match IEA bioenergy supply estimates.

Purpose-grown energy crops are introduced in future periods through the GCAM land allocation system by assigning a **ghost-unnormalized-share** to new land uses—specifically BiomassGrass in the crop nest and BiomassTree in the forest nest (Wise et al., 2014). This mechanism introduces a share weight for technologies with zero base-year land allocation, allowing them to enter the nested land competition structure.

The assumption that dedicated energy crops will become viable in the future is widely used in global economic multisector dynamic models, although it has also been critically discussed in the literature (Ai et al., 2021; Hanssen et al., 2022; Heck et al., 2018). Potential constraints—including additional labor, capital, irrigation requirements, biodiversity impacts, and other environmental tradeoffs—may limit large-scale expansion beyond what is implied by conventional land competition frameworks. Moreover, the anticipated large-scale deployment of dedicated bioenergy crops has not yet materialized.

Reflecting this uncertainty, previous GCAM updates have delayed the assumed introduction of energy crops. When the base year was 2015, CMP-351 moved the introduction year from **2020 to 2025**. However, this assumption was not revisited in the recent base-year update to 2021. Assuming linear interpolation of production between model periods, specifying a 2025 introduction effectively implies that biomass crop production began around **2022**, which is inconsistent with current observations.

This GCAM-Macro KLEAM CMP therefore further **delays the introduction year for purpose-grown energy crops to 2030**. At the same time, additional **regional differentiation in ghost share values** is implemented to allow a slower introduction in regions that currently lack strong bioenergy policy support. Note that this regional differentiation feature was already implemented and tested in CMP-391, although it was retained only as an optional feature (uniform values are still the default option).

¹ Despite policy support in some regions (e.g., the United States), large-scale deployment of dedicated bioenergy crops has not occurred due to high costs, market uncertainty, and investment risks.

² Recent updates in CMP-393 and CMP-369 revised aspects of agricultural residue supply, although further examination of residue availability remains an area for future work.

These adjustments are also motivated by two modeling considerations. First, the KLEAM updates introduce revised factor cost shares, which alter the implied rental profit rates³ for cropland and forest land and require recalibration of biomass ghost shares (see below for details). Second, the KLEAM framework aims to better represent near-term agricultural value-added, which should not include contributions from dedicated bioenergy crops in 2025, given the absence of commercial-scale production

2. Introduction of purpose-grown energy crops using *ghost-unnormalized-share*

Within the GCAM land allocation system, land uses compete through a nested logit formulation with land share (s_i) for land use i derived as

$$s_i = \frac{SW_i \cdot \pi_i^\lambda}{\sum_j SW_j \cdot \pi_j^\lambda},$$

where SW_i is the share weight, π_i the land profit rate, and λ the logit exponent.

For technologies with no base-year land allocation, GCAM introduces a ***ghost-unnormalized-share***, which directly specifies the initial competitiveness term U_i used to calibrate a share weight for the new land use.

$$U_i = SW_i \cdot \pi_i^\lambda$$

These unnormalized shares are calculated for all competing land uses within a nest, and land shares are then determined by normalizing these competitiveness terms across the alternatives.

Introducing a ***ghost-unnormalized-share*** in a future model period allows purpose-grown biomass crops to enter the land competition structure despite having zero observed land area in the base year. However, because the unnormalized competitiveness term depends on land profit rates (with share weights defined relative to other land uses), updates to the rental profit rates of cropland and forest land affect the relative competitiveness of existing land uses.

For example, if updated data reduces the average cropland rental profit by two-thirds, and the logit exponent is $\lambda = 1.75$, the corresponding unnormalized competitiveness term for cropland would decline to $(1/3)^{1.75} \approx 0.146$ times of the original value. To maintain similar implied share weights and entry competitiveness for purpose-grown biomass crops under the revised profit-rate environment, the biomass ghost-unnormalized-share values must therefore be recalibrated downward accordingly.

In this CMP, the cost shares in agricultural production, including land cost shares, were updated based on data from GTAP and FAO. As a result, land shares generally became considerably smaller, particularly for managed forest, as illustrated in **Fig. E1**. It is therefore essential to update the ghost share parameters for biomass introduction, as failing to do so would substantially increase the implied competitiveness of biomass and lead to much faster land expansion than previously assumed.

Table 1 presents the default parameter assumptions used in CMP-351 / CMP-391 and the current master branch, along with the updated assumptions. The “High” column under CMP-411 reports

³ Note that in CMP-393, the shadow rental profit for unmanaged land was updated so that it is calculated internally based on GCAM data; see Section 2.2 of CMP-393.

the revised values, with the introduction year postponed to 2030 and the parameter value substantially reduced in response to the base data updates. Despite these changes, the updated “High” assumption yields a similar long-term outcome for purpose-grown energy crop production. We also define an alternative “Low” assumption, relative to the “High” case, to facilitate simple regional differentiation.

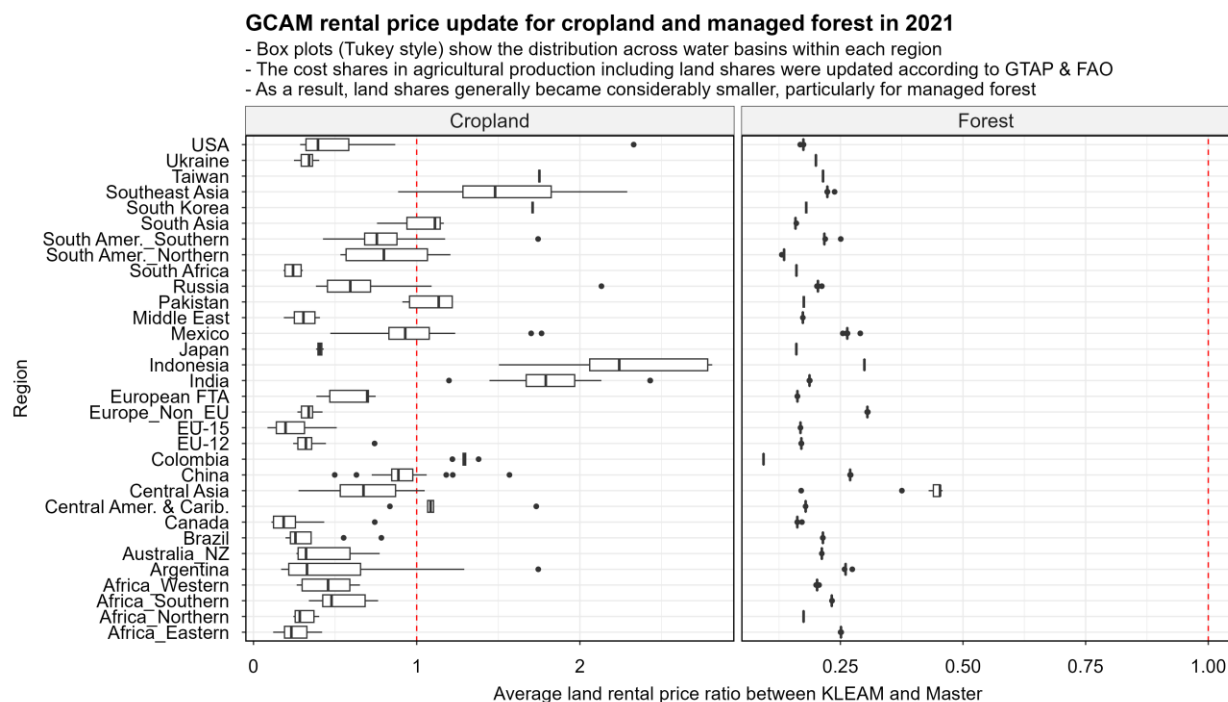


Fig. E1 GCAM land rental profit update for cropland and managed forest in the base year (2021)

Table E1 ghost share assumption updates (*aglu/A_bio_ghost_share.csv*)

Year	CMP-351 / CMP-391	CMP-411	
		High	Low
2020	0	0	0
2025	0.03	0	0
2030	0.0525	0.001	0.0003
2035	0.075	0.001	0.0003
2050	0.075	0.005	0.001
2100	0.075	0.010	0.005

3. Regional ghost share assumption updates

It is also notable that the updates to rental profit rates exhibit regional variation. More broadly, this regional heterogeneity should also be reflected in the ghost share specification, as many developing regions are unlikely to experience large-scale near-term expansion of purpose-grown bioenergy crops. Accordingly, this CMP further refines the regional differentiation of biomass ghost share parameters.

Table E2 summarizes the regional differentiation applied to the purpose-grown energy crop introduction assumption in A_biomassSupplyShare_R.csv. To reflect differences in current policy support and deployment readiness, only a limited set of key regions with relatively strong existing bioenergy support are assigned the “High” assumption, while all other regions are assigned the “Low” assumption. The “High” designation is therefore used selectively for regions such as the USA, Brazil, China, EU-12, Europe Non-EU, Australia_NZ, and Argentina, where stronger policy support, market development, or production potential make earlier or more sustained deployment more plausible.

This approach allows the model to retain substantial long-term production in a few key regions while avoiding unrealistically rapid expansion in regions that currently lack strong bioenergy policy support. E.g., the USA, the “High” assumption preserves a long-term production pathway that remains broadly comparable to that in previous CMPs, while the assumptions for many other regions are reduced relative to earlier specifications. These regional assumptions can also be further differentiated by scenario (e.g., SSPs) when needed.

Table E2 Regional differentiation of purpose-grown energy crop introduction assumption (A_biomassSupplyShare_R)

Region	Preference
USA	High
Africa_Eastern	Low
Africa_Northern	Low
Africa_Southern	Low
Africa_Western	Low
Australia_NZ	High
Brazil	High
Canada	Low
Central America and Caribbean	Low
Central Asia	Low
China	High
EU-12	High
EU-15	Low
Ukraine	Low
Europe_Non_EU	High
European Free Trade Association	Low
India	Low
Indonesia	Low
Japan	Low
Mexico	Low
Middle East	Low
Pakistan	Low
Russia	Low
South Africa	Low
South America_Northern	Low
South America_Southern	Low
South Asia	Low

South Korea	Low
Southeast Asia	Low
Taiwan	Low
Argentina	High
Colombia	Low

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GCAM-Macro-KLEM Input-Output Framework and Accounting Structure

	En	Ma	Final Cons.	Trade	Sum
L		labor			
K	capital /Inv	capital /Inv			GDP: Income
En		energy service		energy- net- export	
Ma			cons. & capital goods	material- net- export	gross- demand
Sum		gross- output	GDP: Expenditure C & G + Inv + NX		

GDP decomposition by income:

GDP = sum of the compensation (factor rewards) from labor (L) & capital (K) across all sectors

GDP decomposition by expenditure:

GDP = household & government (GOV) consumption (C & G) + investment (INV) + net export (NX)

→ **GDP = materials gross-output + gcam-net-export (energy-net-export)**

- Ma gross-output (supply) = nested CES production function (K, L, En, Ag; productivities; elasticities)
- Ma gross-output (demand) = consumption goods (HHD & Gov) + capital goods + material-net-export

Materials production function

Nested constant elasticity of substitution (CES) (En, (K, L))

- En is an energy service index, linked to GCAM energy service inputs in final demand
- En is endogenous, aggregating energy services using initial prices as weights

Clearing capital/investment market

sum of investment from En, incl. Consumer-Durable (CD), and Ma = savings + capital-net-export

- energy-investment: derived based on GCAM energy sectoral assumptions at technology levels
- material-investment = depreciation-rate x capital stock (beginning) + capital stock increase
- savings = function(lagged savings-rate, per-capita GDP growth rate) x GDP, adjusted by CD in initial calibration
- capital-net-export: initially calibrated to -NX but being phased out to zero regionally (trade balance)

Clearing labor market

Labor supply (employment linked to population) = Labor demand from Ag and Materials

GCAM-Macro-KLEAM Input-Output Framework and Accounting Structure

	Ag	En	Ma	Final Cons.	Trade	Sum
Land	land					
L	labor		labor			GDP: Income
K	capital /Inv	capital /Inv	capital /Inv			
Ag			ag non- food- service	ag food- service	ag-net- export	
En			energy service		energy- net- export	
Ma				cons. & capital goods	material- net- export	gross- demand
Sum			gross- output	GDP: Expenditure C & G + Inv + NX		

GDP decomposition by income:

GDP = sum of the compensation (factor rewards) from land, labor (L), & capital (K) across all sectors

GDP decomposition by expenditure:

GDP = household & government (GOV) consumption (C & G) + investment (INV) + net export (NX)

→ **GDP = materials gross-output + ag food-service + gcam-net-export (ag & energy)**

- Ma gross-output (supply) = nested CES production function (K, L, En, Ag; productivities; elasticities)
- Ma gross-output (demand) = consumption goods (HHD & Gov) + capital goods + material-net-export

Materials production function

Nested constant elasticity of substitution (CES) (En, Ag, (K, L))

- Ag nonfood services are collected and aggregated from GCAM sectors, with initial prices used as weights
- En is an energy service index, linked to GCAM energy service inputs in final demand
- En is endogenous, aggregating energy services using initial prices as weights (with value rescaled in calibration)

Clearing capital/investment market

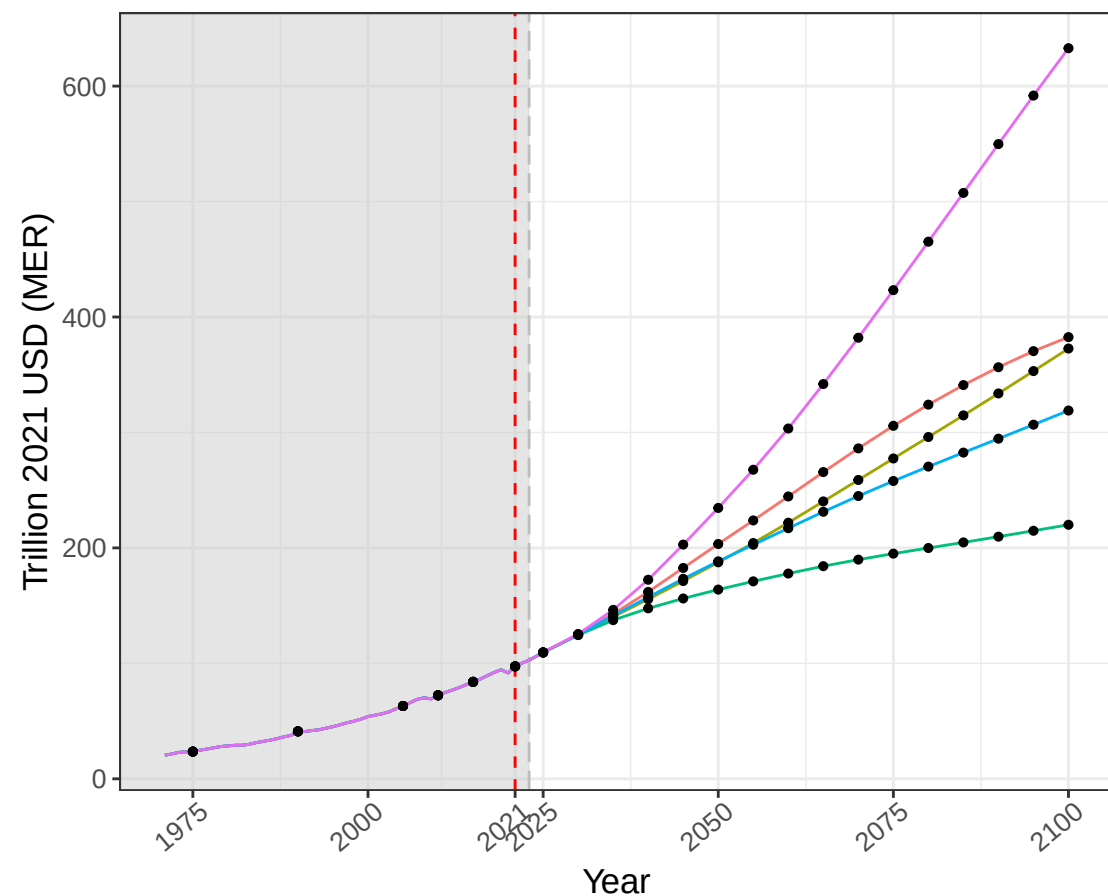
sum of investment from Ag, En (incl. CD), and Ma = savings + capital-net-export

- ag-investment: derived based on Ag capital return and related assumptions
- energy-investment: derived based on GCAM energy sectoral assumptions at technology levels
- material-investment = depreciation-rate x capital stock (beginning) + capital stock increase
- savings = function(lagged savings-rate, per-capita GDP growth rate) x GDP, adjusted by CD in initial calibration
- capital-net-export: initially calibrated to -NX but being phased out to zero regionally (trade balance)

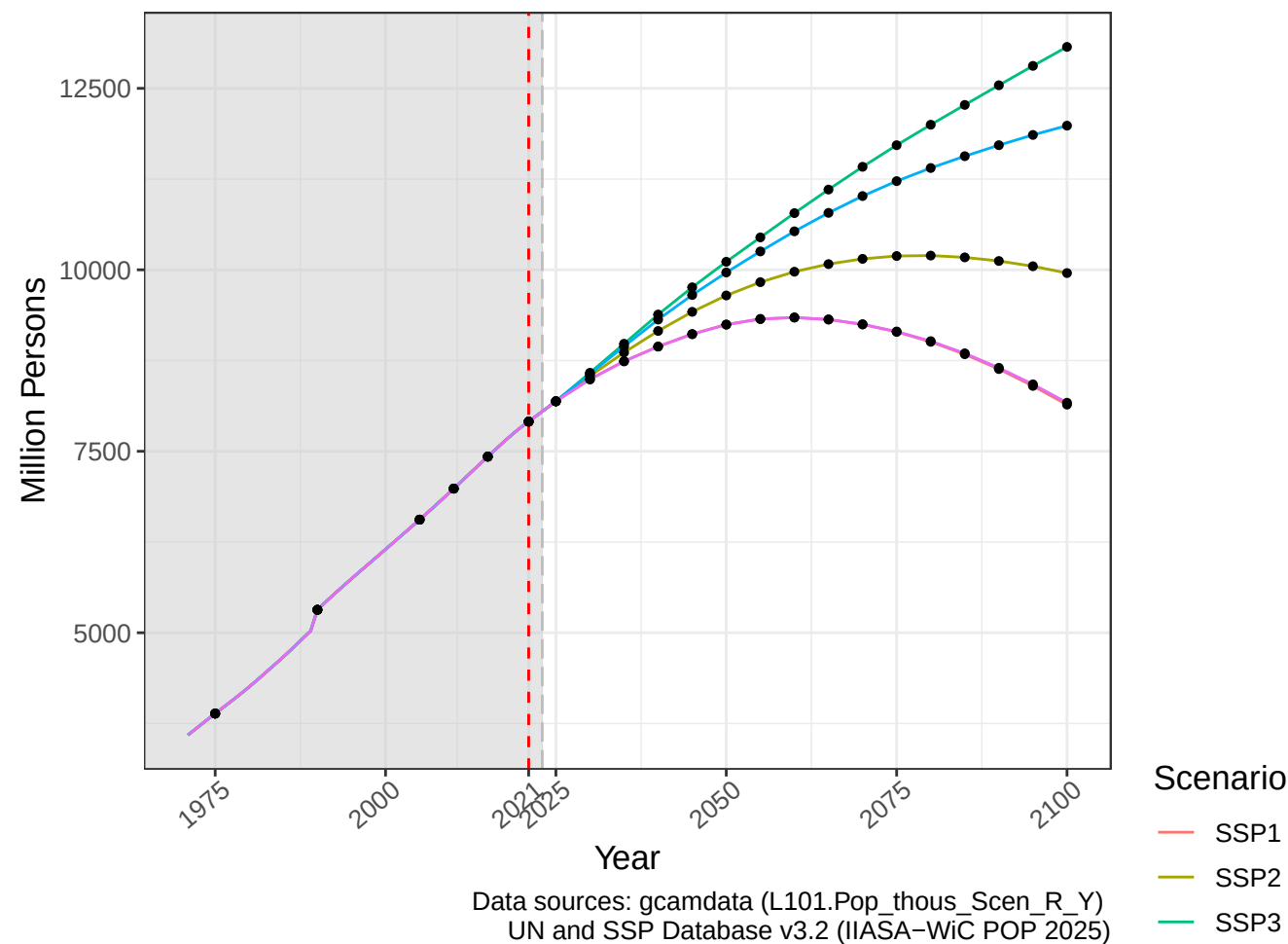
Clearing labor market

Labor supply (employment linked to population) = Labor demand from Ag and Materials

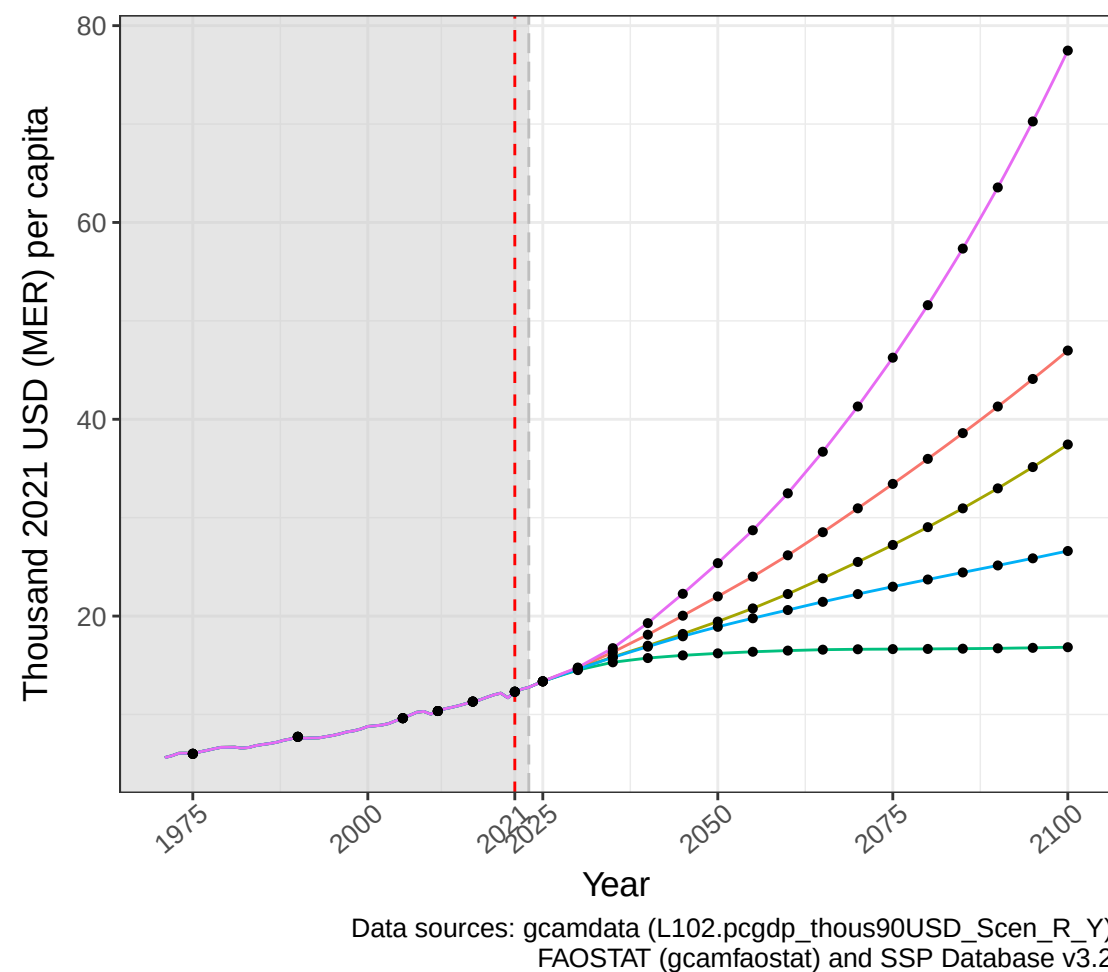
(A) World GDP, 1971–2100



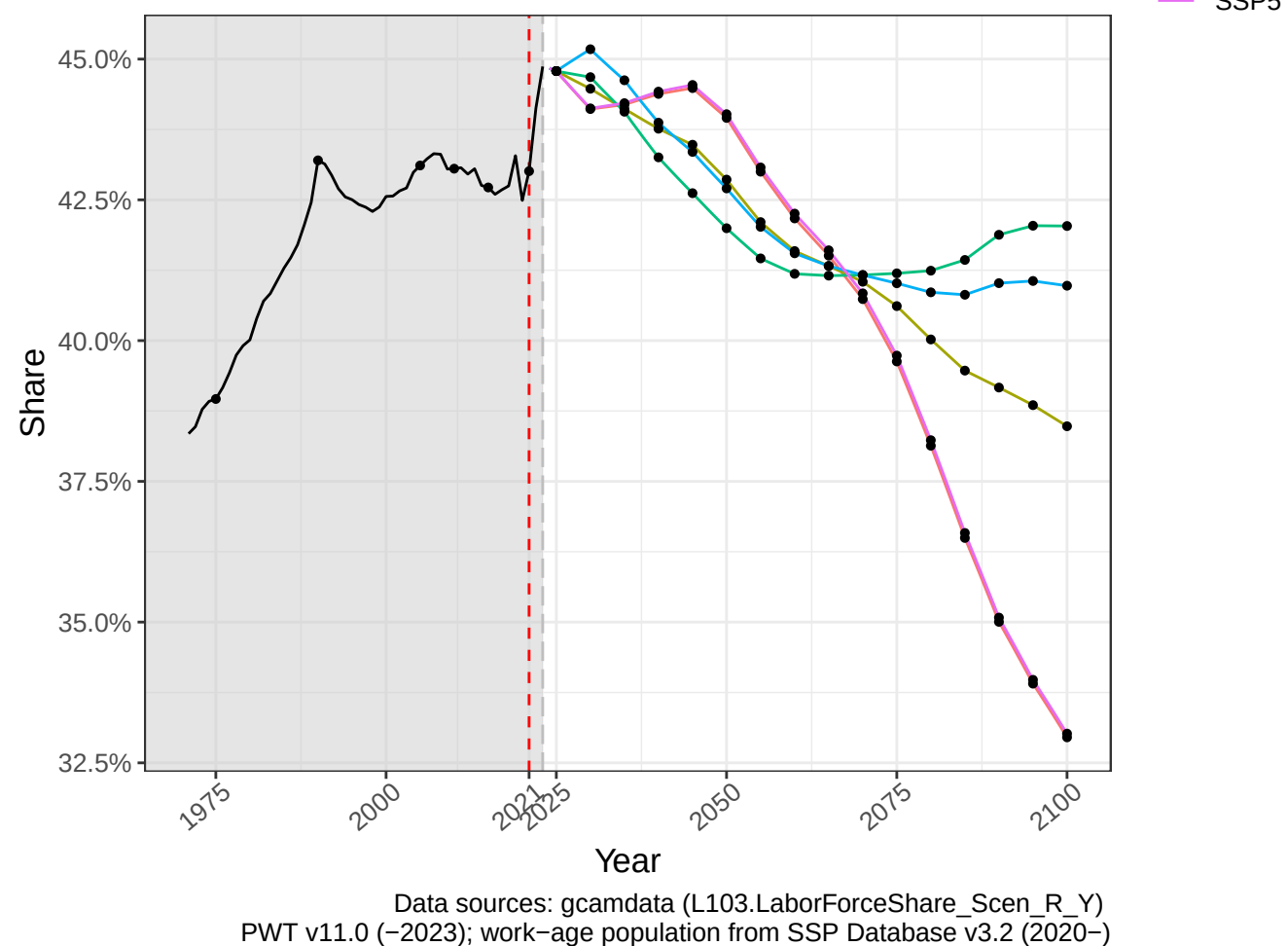
(B) World Population, 1971–2100



(C) World Per-Capita GDP 1971–2100

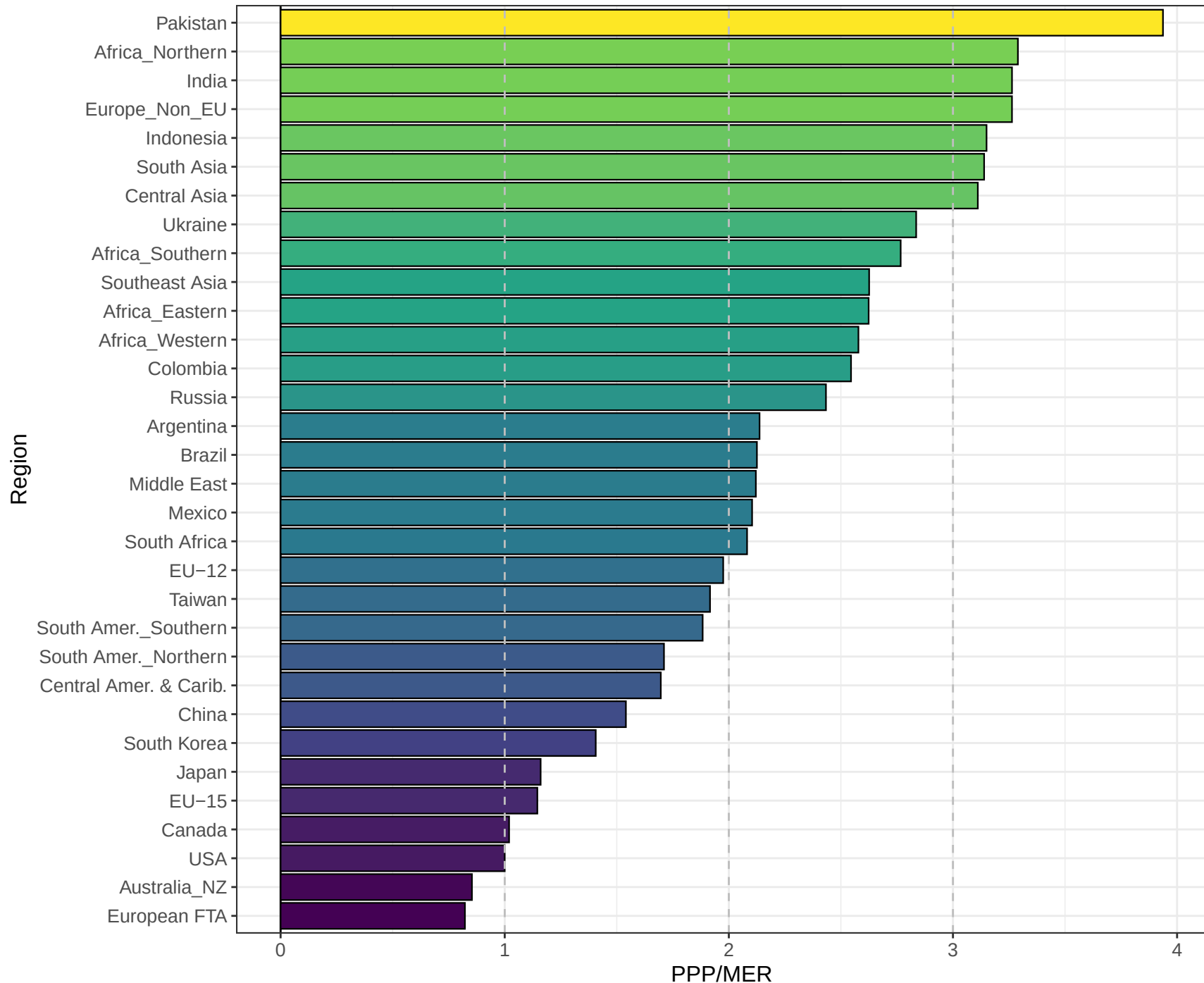


(D) Employment-to-Population Ratio, 1971–2100



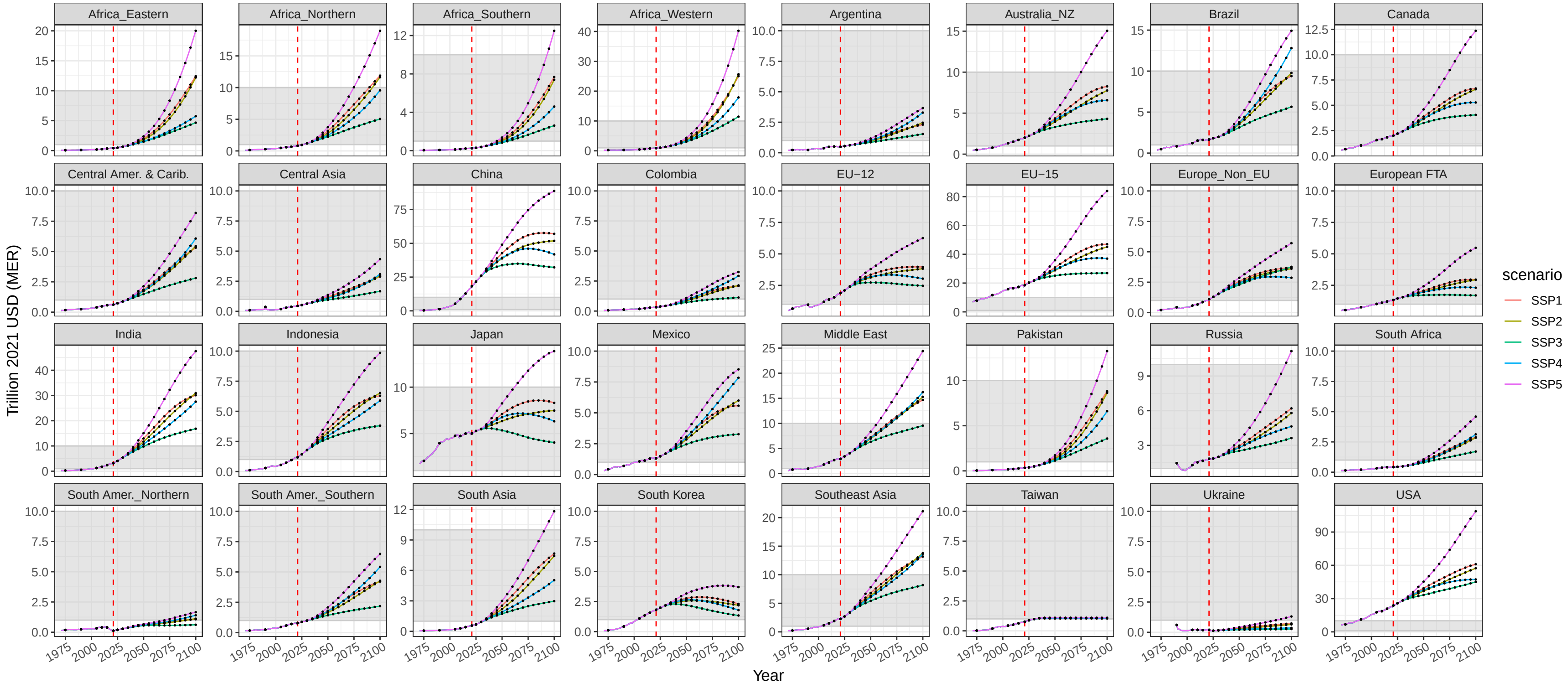
MER-to-PPP Conversion Factors by GCAM Region in 2021

- MER = Market Exchange Rate (used as the main unit in modeling to maintain balance)
- PPP = Purchasing Power Parity
- Conversion factors were derived using MER GDP (FAOSTAT) and PPP GDP (SSP database)
- The USA is exactly 1; higher values indicate lower national prices (& cost of living)
- These values are held constant in future periods
- Currently PPP values are used only in the food demand model and for reporting purposes



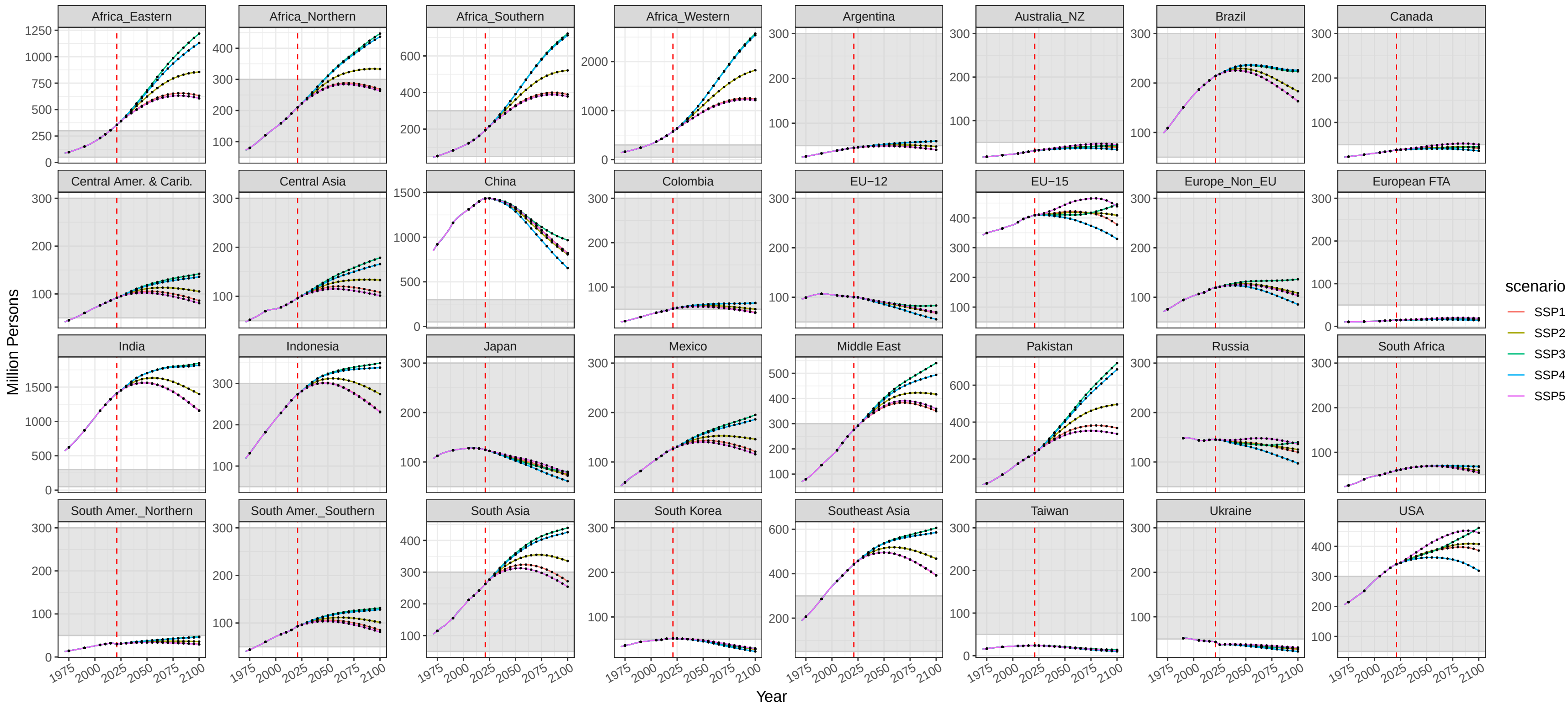
Reference GDP by GCAM Region and SSP, 1971–2100

- GDP levels are expressed in MER (2021 USD); post-2023 growth follows SSP GDP|PPP trajectories
- Colored lines show regional GDP trajectories by SSP (see legend); black dots indicate values in GCAM model years
- The shaded grey band highlights the 1–10 trillion USD range for cross-region (Panel) visual comparison
- Historical GDP is sourced from FAOSTAT (MER) and converted to 2021 USD using region-specific deflators
- GCAM base year is 2021 (red dashed vertical line), but GDP levels in 2025 are fully harmonized across all SSPs
- Taiwan exhibits negative GDP growth in the raw SSP projections; a zero-growth floor was applied to avoid implausible long-run contraction
- In GCAM-Macro (open GDP mode), GDP is endogenous; these reference trajectories are used for TFP calibration (Materials)



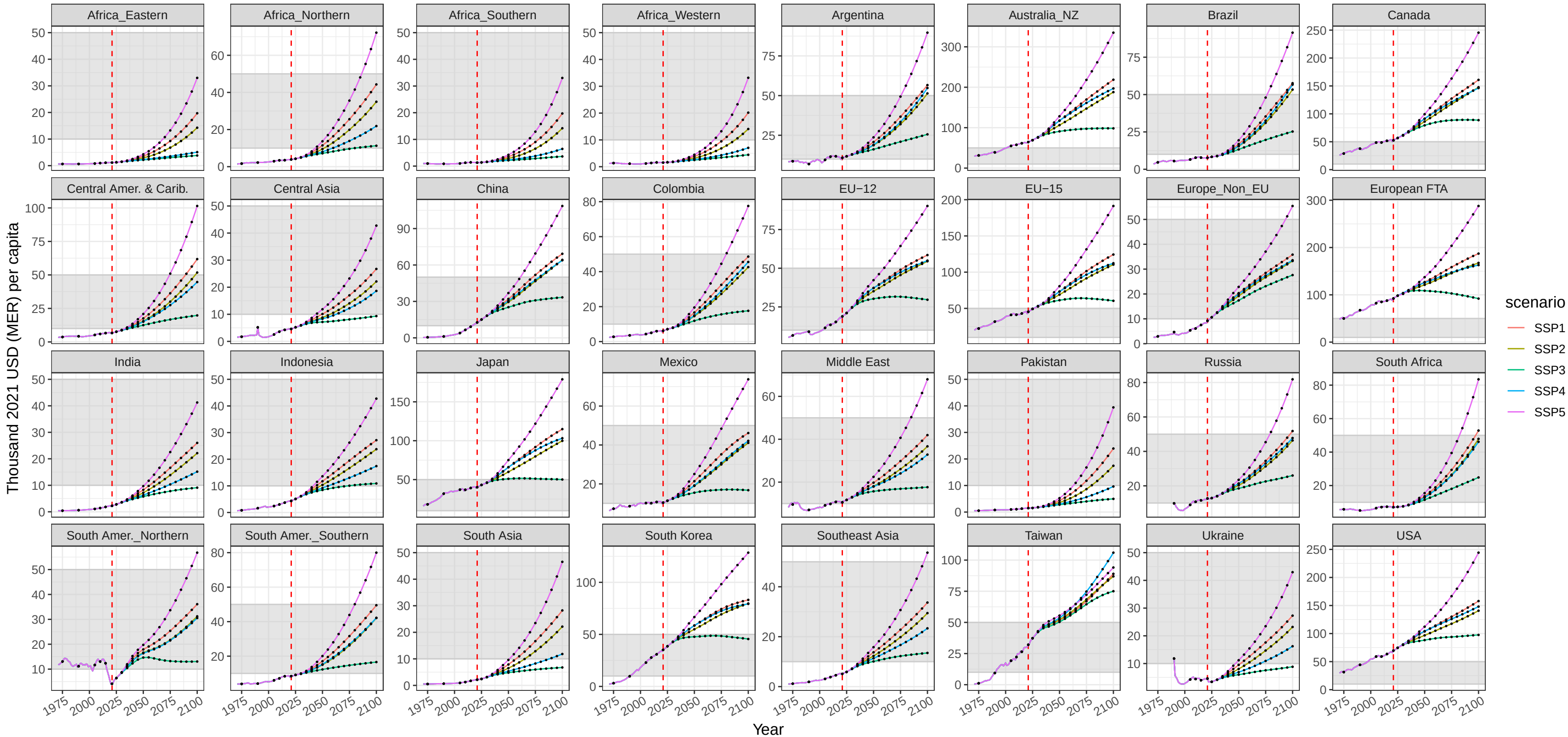
Reference Population by GCAM Region and SSP, 1971–2100

- Colored lines show regional GDP trajectories by SSP (see legend); black dots indicate values in GCAM model years
- The shaded grey band highlights the 50–300 million persons range for cross-region (Panel) visual comparison
- GCAM base year is 2021 (red dashed vertical line); historical population data (–2021) is sourced from the UN database
- Post-2021 growth follows SSP Population trajectories
- Population levels in 2025 are aligned across SSPs: 8.189 billion globally
- In GCAM–Macro, population is exogenous and labor force (&/ employment) is linked to population



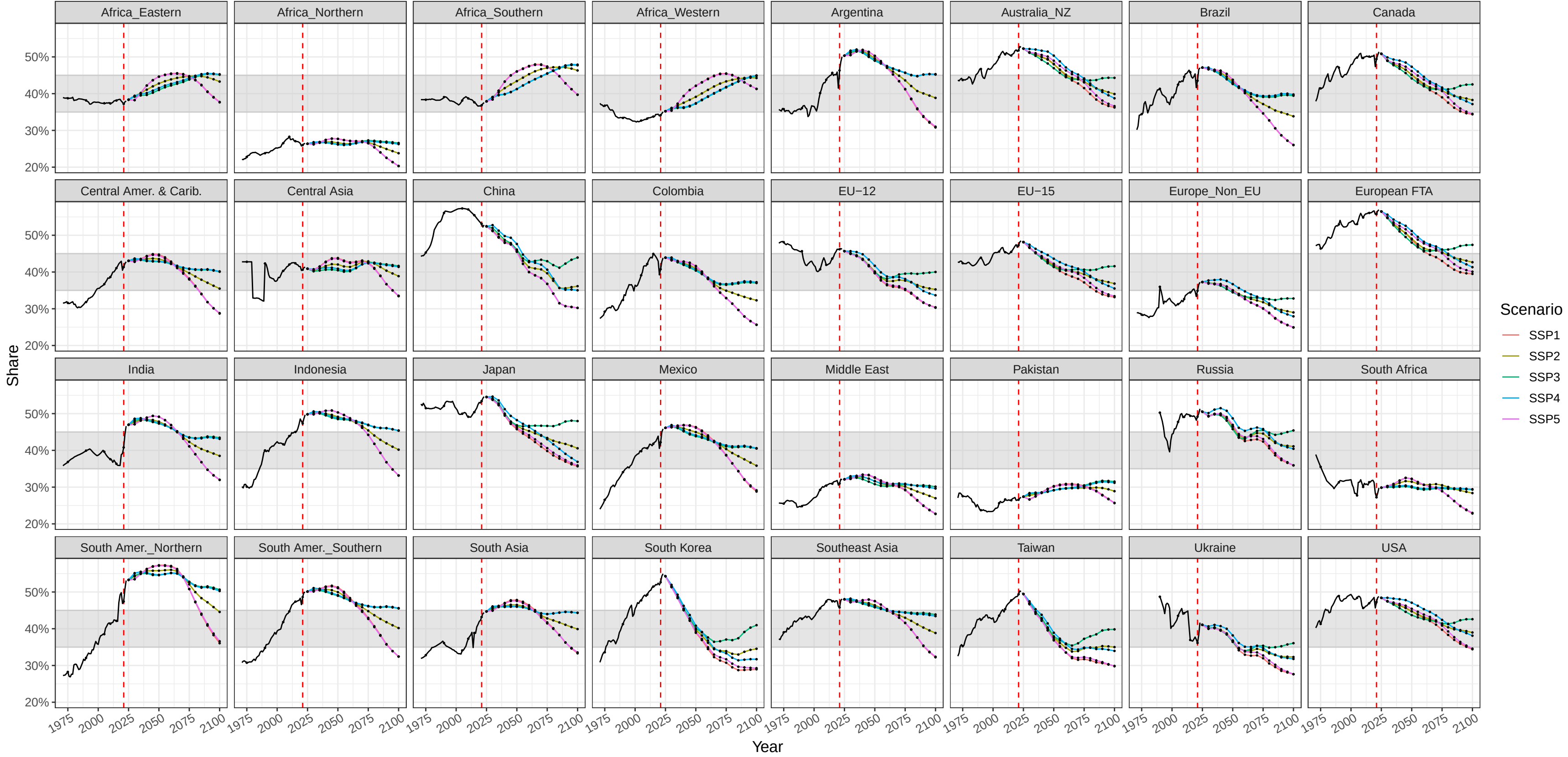
Reference per-capita GDP by GCAM Region and SSP, 1971–2100

- Values are expressed in MER (thousand 2021 USD per capita), calculated as GDP/population
- Colored lines show regional GDP trajectories by SSP (see legend); black dots indicate values in GCAM model years
- The shaded grey band highlights the 10–50 range (thousand 2021 USD per capita) for cross-region (Panel) visual comparison
- GCAM base year is 2021 (red dashed vertical line), but values in 2025 are fully harmonized across all SSPs



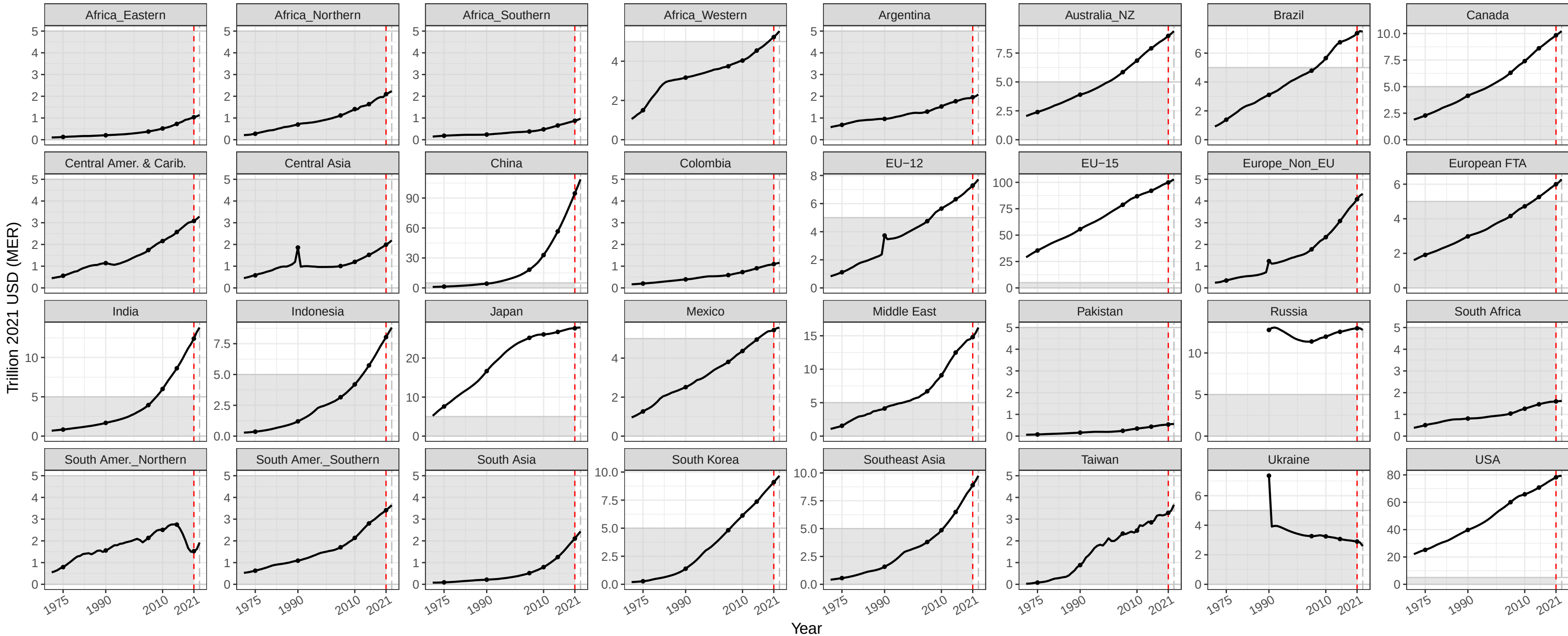
Reference Employment-to-Population Ratio by GCAM Region and SSP, 1971–2100

- Black lines show observed historical employment-to-population ratios from PWT (1971–2023)
- Colored lines (2024–2100) represent future trajectories derived from the SSP database
- Black dots indicate values in GCAM model years
- The GCAM base year is 2021 (red dashed vertical line); the data stitching year is 2023 (blue dashed vertical line)
- The shaded grey band (35–45%) highlights a common reference range for cross-region visual comparison
- Working-age population shares by SSP are sourced from the SSP database and drive future employment dynamics
- Historical employment data are from PWT; the employment-to-working-age-population ratio observed in 2023 is held constant through 2100
- This assumption implies constant labor force participation and employment rates beyond 2023
- Employment-to-population ratios in 2025 are aligned across SSPs and rebased to 2023, partially factored in post-COVID recovery and Russia-Ukraine war effects
- Note: the employment-to-population here differs from the U.S. BLS definition (<https://fred.stlouisfed.org/series/EMRATIO>)
- The BLS measure excludes individuals under age 16, active-duty military personnel, and institutionalized populations
- Conceptual flow: Population > Working-Age Population > Labor Force (incl. unemployed) > Employed
- In GCAM-Macro, the labor market clears with total labor demand constrained by available employment



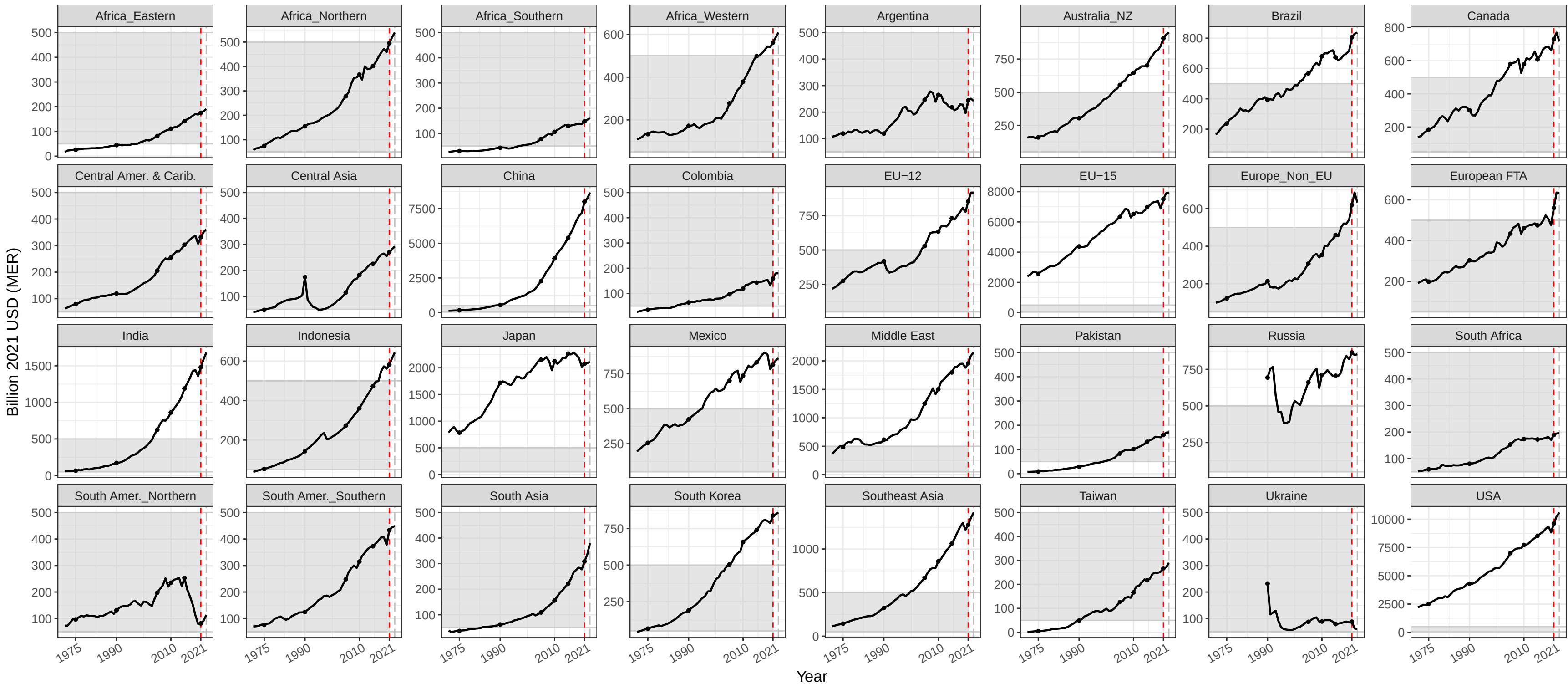
Historical Economy–Wide Capital Stock by GCAM Region, 1971–2023

- Estimated world total: \$448 trillion in 2021 (based on market exchange rates, MER); median: ~\$5.3 trillion
- Step 1: Derived capital–to–GDP ratios using PWT data in national prices (rnna / rgdpna), available through 2023
- Step 2: Applied capital–to–GDP ratios to FAOSTAT GDP data in MER
- The derived capital stock values are more comparable to GTAP estimates, as both are expressed in MER
- Step 3: (not done/shown here!) Partitioned capital stock by Ag, Energy, & Material in KLEAM
- In GCAM–Macro, capital enters the Material production function directly and investment is derived based on delta capital & depreciation
- Consistent with GDP treatment in GCAM, 2021 USD values are converted to 1990 USD using U.S. deflators, although capital should be interpreted as a physical quantity
- Care is required to ensure consistency in the unit of gross capital rate of return across sectors
- Note that MER is used here to maintain consistency with capital compensation and other national–accounts variables, though PPP is more appropriate for cross–regional comparisons.



Historical Economy-Wide Capital Compensation by GCAM Region, 1971–2023

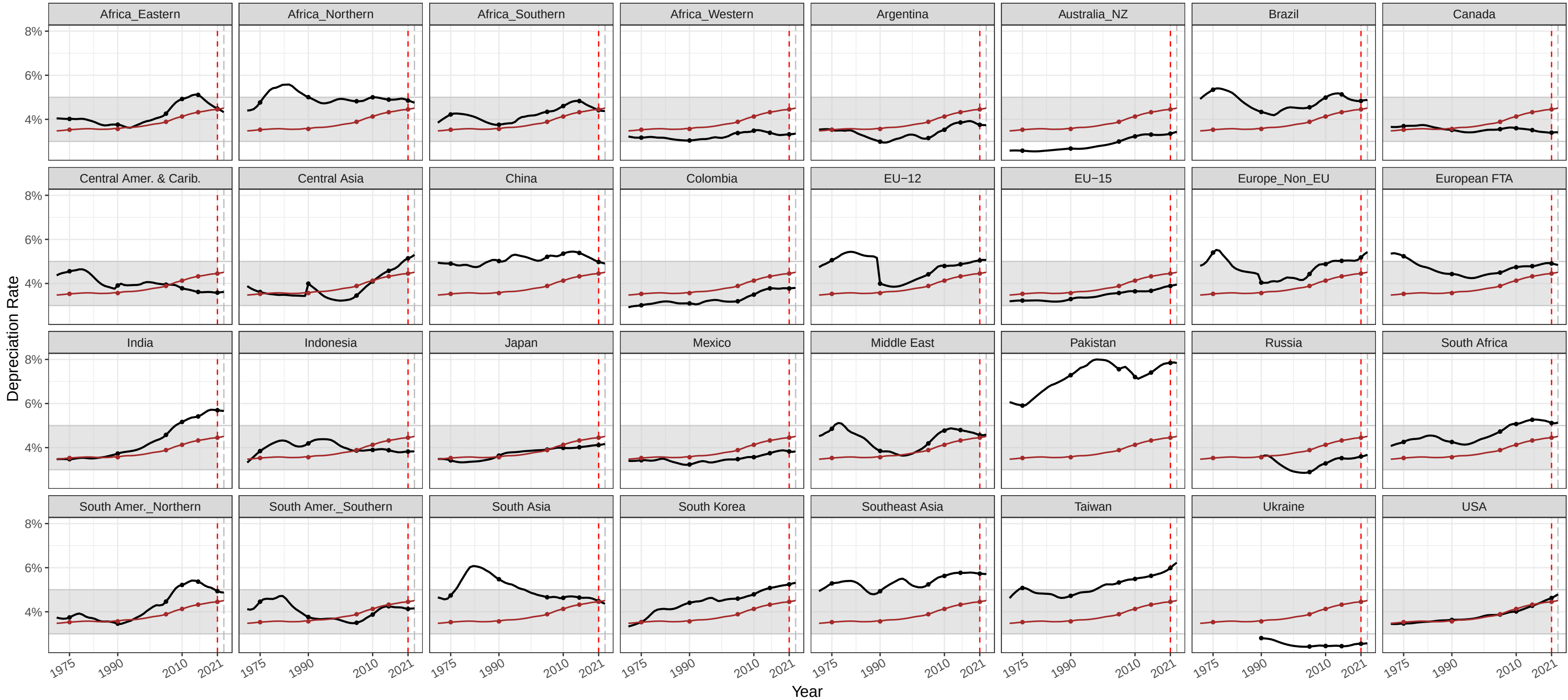
- Estimated global total: \$43.4 trillion (based on market exchange rates, MER); median regional value: ~\$0.57 trillion
- Step 1: Retrieved capital compensation shares relative to GDP as $(1 - \text{labsh})$ from PWT, available through 2023
- Step 2: Applied capital compensation shares to FAOSTAT GDP data in MER
- Step 3 (not done/shown here!): Partitioned capital compensation by Ag (& land), Energy, & Materials using sectoral shares from other sources
- In GCAM-Macro, capital stock enters directly into the Material sector production function
- The capital rate of return (gross) is calculated as capital compensation divided by capital stock
- The capital rate of return (gross) $\sim$ IRR (net from PWT) + depreciation rate



Data sources: PWT v11.0 & FAOSTAT
See L103.National_Accounts_mil90usd_R_Yh in gcamdata

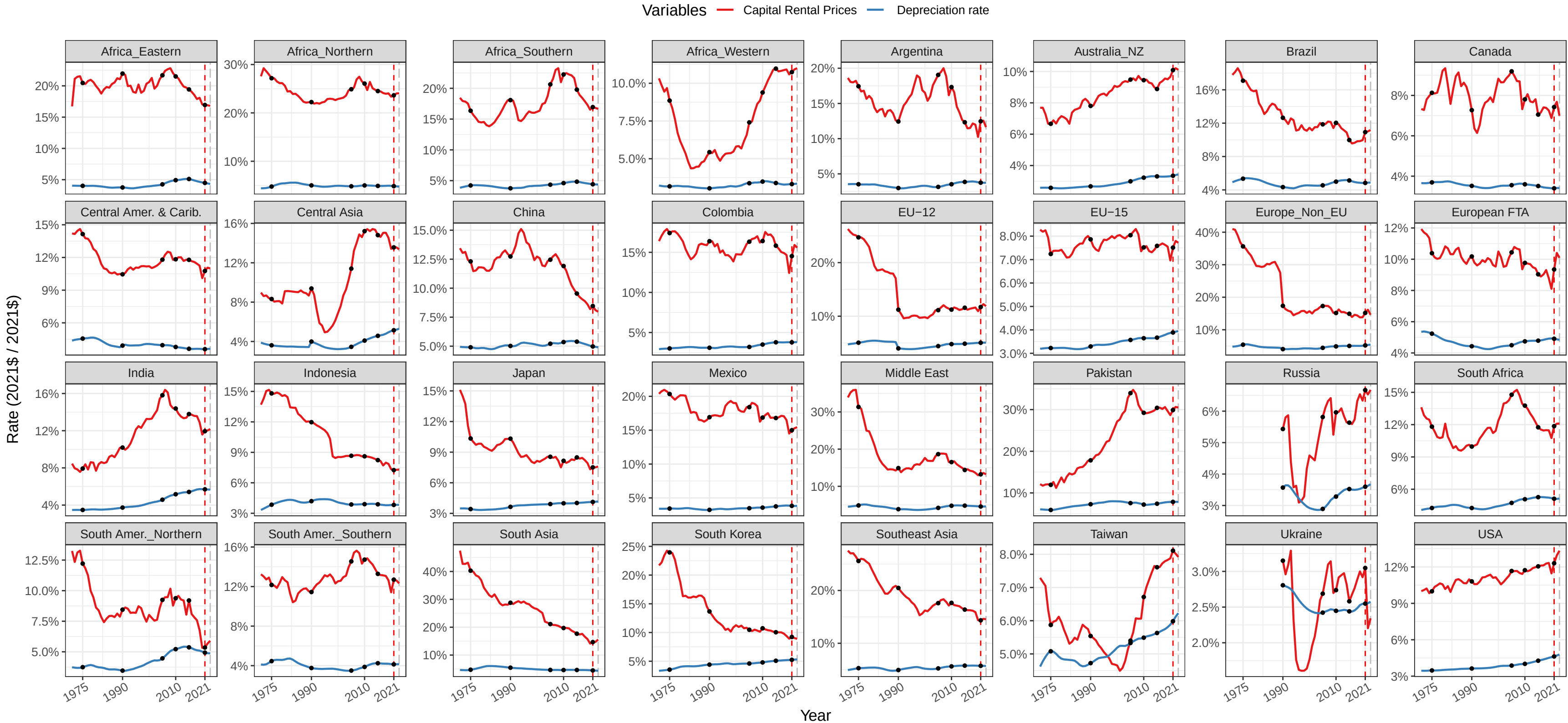
Historical Economy–Wide Depreciation Rates by GCAM Region, 1971–2023

- Aggregated to 32 GCAM regions using capital stock weights; black lines denote regional values and the dark red line denotes the world average
- A common gray ribbon (3%–5%) is shown in all panels for visual comparison
- The global average depreciation rate is 4.5% in 2021
- Future depreciation rates are assumed to remain constant at the 2021 level
- Sector–specific depreciation rates for agriculture are applied separately in GCAM based on FAO data
- Data are sourced from PWT v11 and processed in module_socio_L100.NationalAccounts and module_socio_L103.NationalAccounts



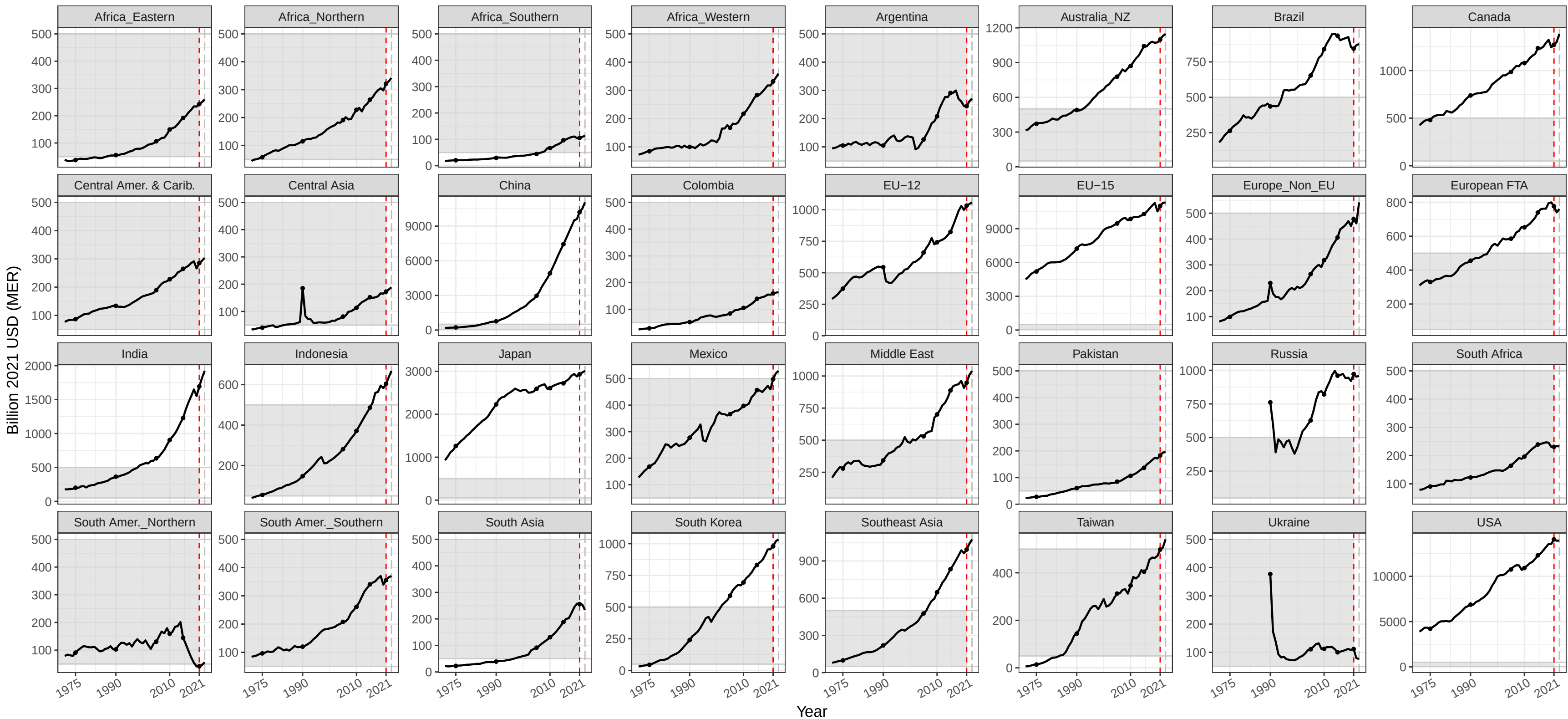
Historical Economy–Wide Capital Rental Prices (& Depreciation Rates) by GCAM Region, 1971–2023

- The capital rental price represents a gross, ex-post return to productive capital, including depreciation and risk premium.
- The global average capital rental price (gross capital rate of return) is 9.8% in 2021.
- Capital rental price = capital compensation / capital stock
- The depreciation rate is 4.5% in 2021, implying a global mean net capital rate of return of 5.3%.



Historical Economy–Wide Labor Compensation by GCAM Region, 1971–2023

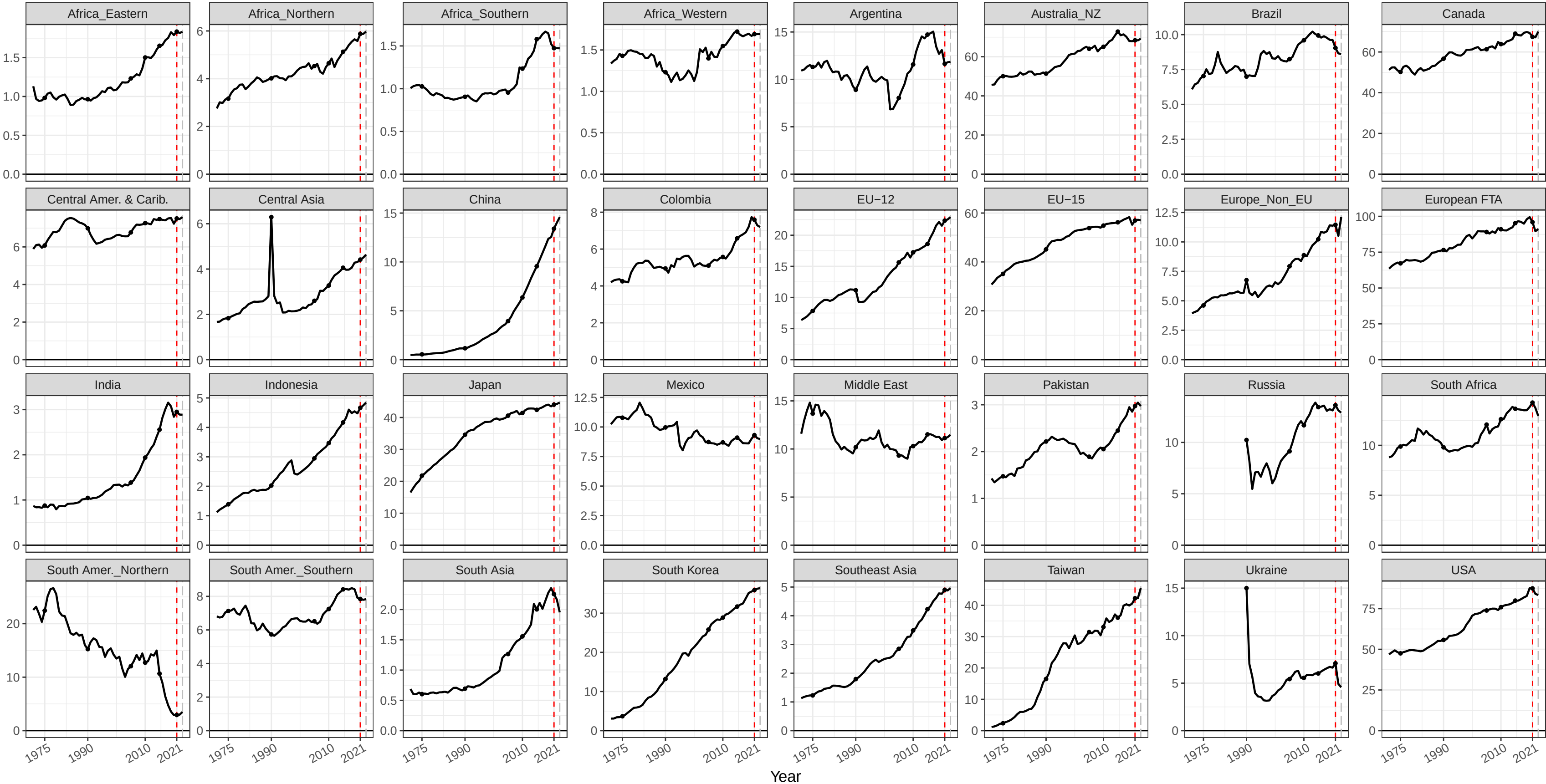
- Black lines represent regional values; blue line highlights Mexico; the same gray ribbon \$0.05–\$0.5 trillion is shown in all pannels
- Estimated world total: \$54 trillion (based on market exchange rates, MER, 2021 USD); median: ~\$0.5 trillion
- Step 1: Get labor compensation shares relative to GDP (labsh) from PWT data, available through 2023
- Step 2: Applied labor compensation shares to FAOSTAT GDP data in MER
- In GCAM–Macro, physical labor (employment) enters the Material production function directly and wage rate can be calculated (labor compensation / employment)



Historical Economy-Wide Labor Wage Rate by GCAM Region, 1971–2023

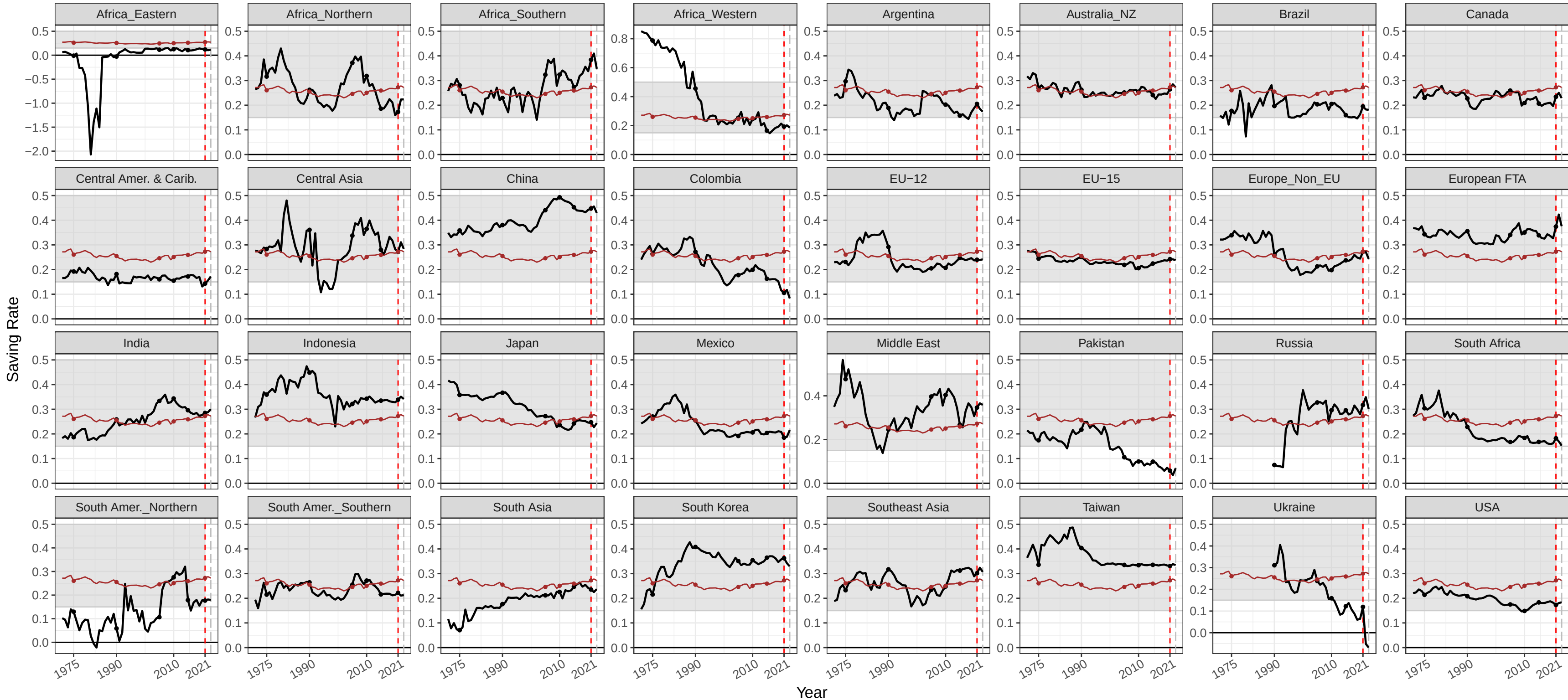
– Wage rate is calculated (labor compensation / employment)

Thousand 2021 USD (MER) per person



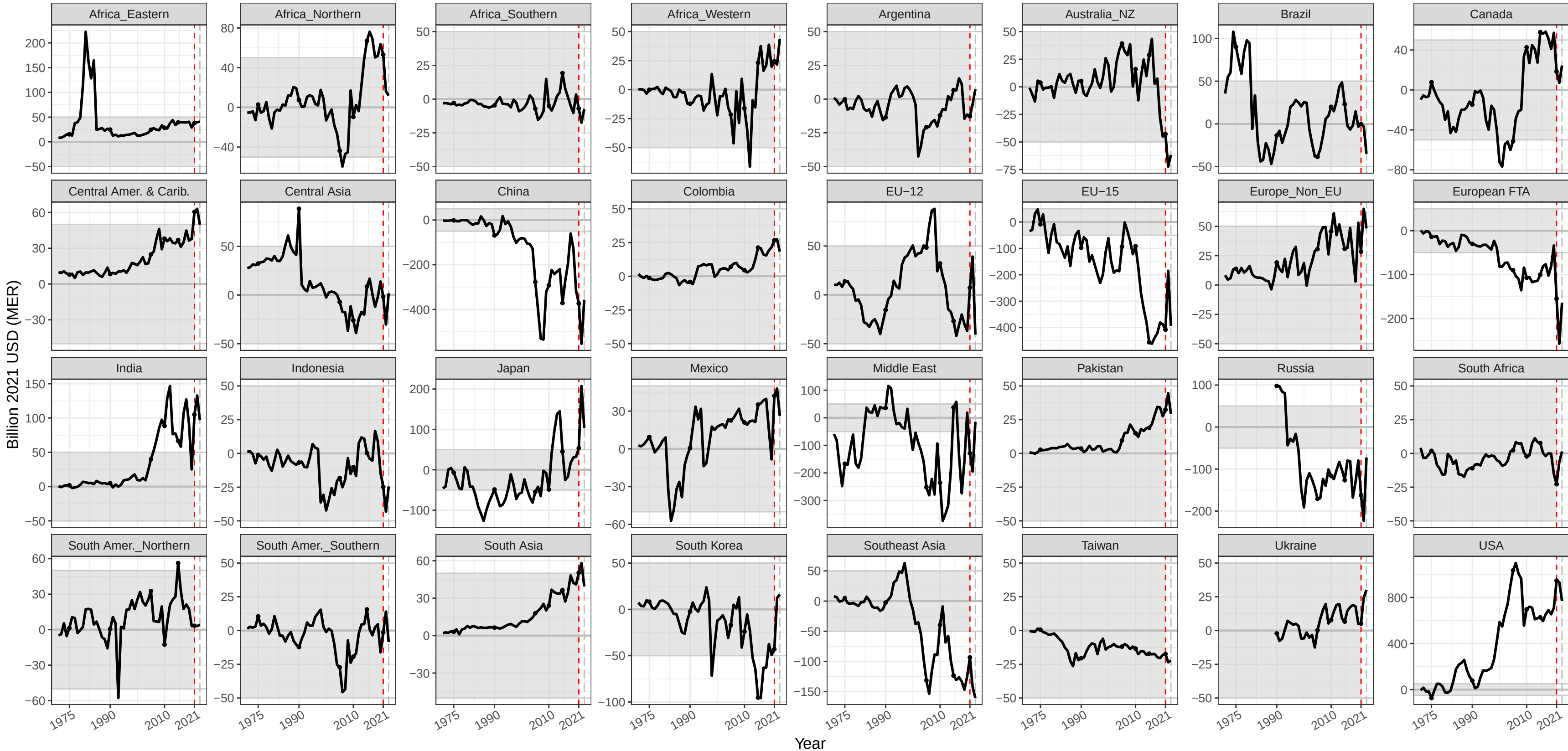
Historical Saving Rates (Gross Domestic Savings, % of GDP) by GCAM Region, 1971–2023

- Saving rate = (GDP – Final Consumption) / GDP
- Saving rate = (Investment – Capital Net Export) / GDP
- Aggregated to 32 GCAM regions using GDP as weights: black (regional) vs. dark red (world) lines
- Future regional saving rates are modeled as a function of lagged saving (coefficient = 0.892), with adjustment based on per capita income growth (coefficient = 0.144)
- Regional investment is constrained by savings and net capital exports (which are being phased out), with a cleared capital market
- Note that there is also adjustments from Consumer Durable (included as capital goods consumption) in GCAM



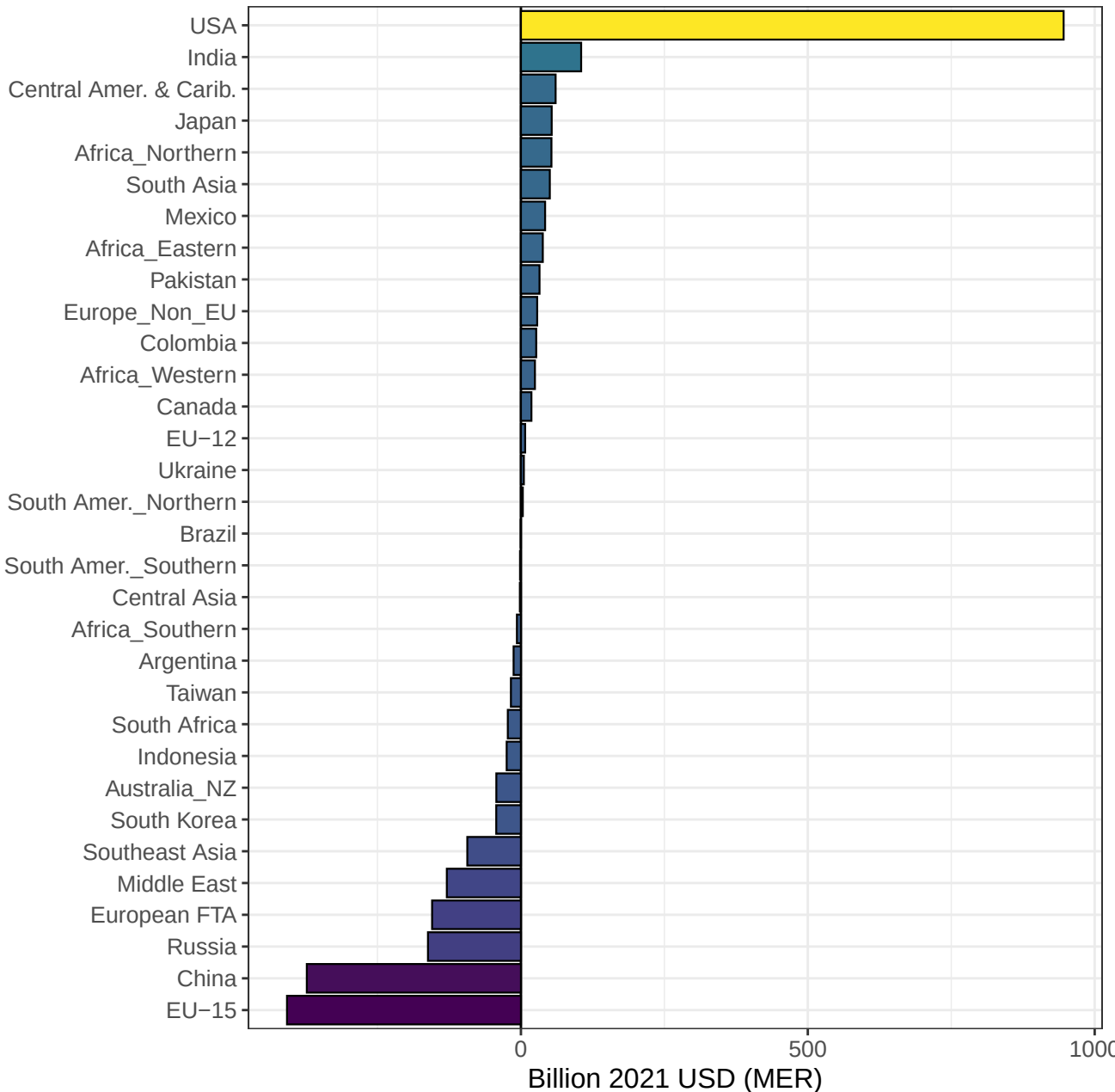
Historical Capital Net Exports by GCAM Region, 1971–2023

- Capital net export = – net export; the global net total is zero by construction each year
- Trade values (balanced) and ratios relative to GDP are sourced from the Global Macro Database (GMD); ratios are applied to FAOSTAT GDP to ensure consistency
- In GCAM–Macro, sectoral trade (e.g., Ag & Energy) is tracked and used to partition total trade flows in the model



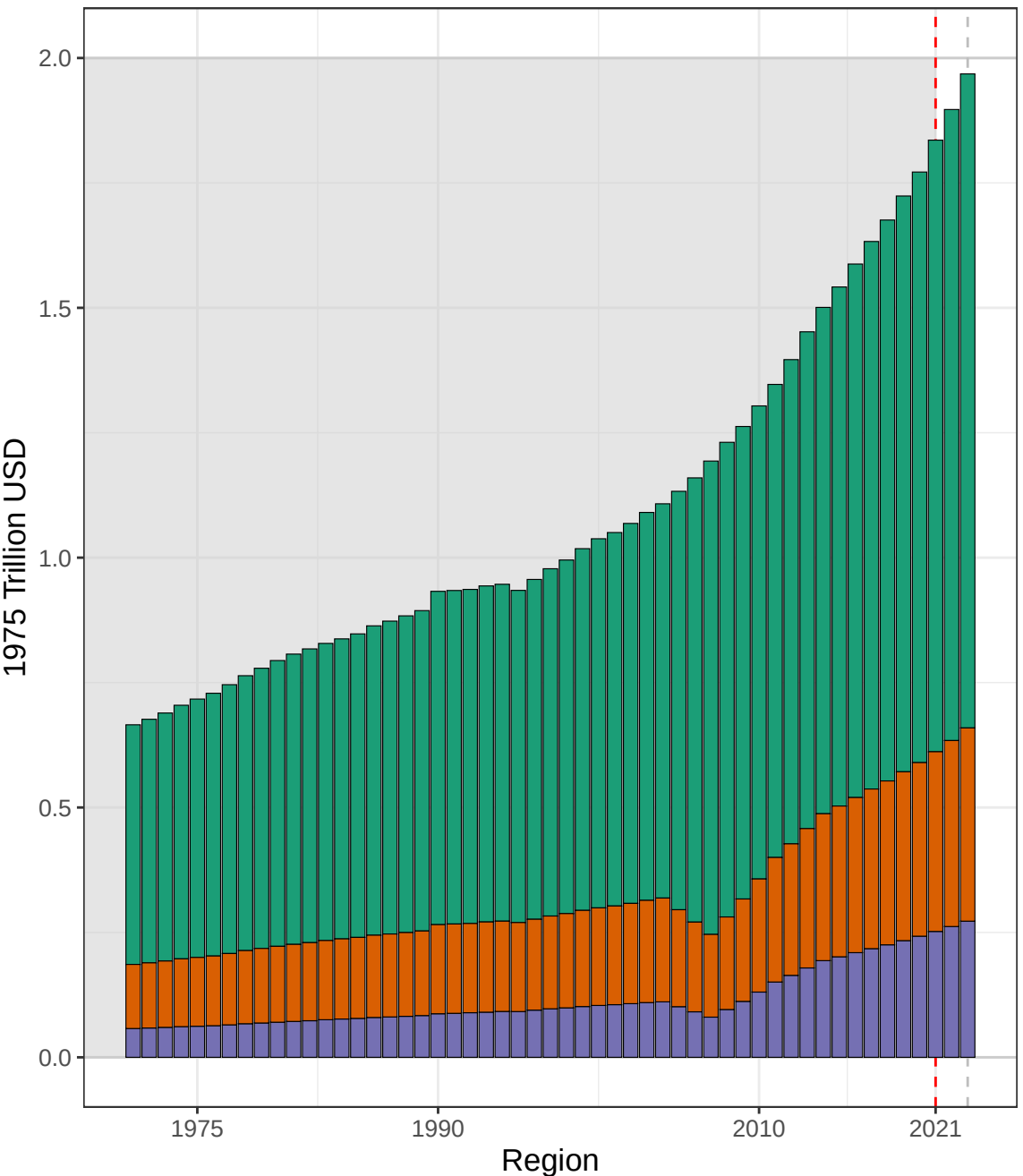
Capital net export (net import) by GCAM region in 2021

Region



(A) World Ag. Capital Stock, 1971–2023

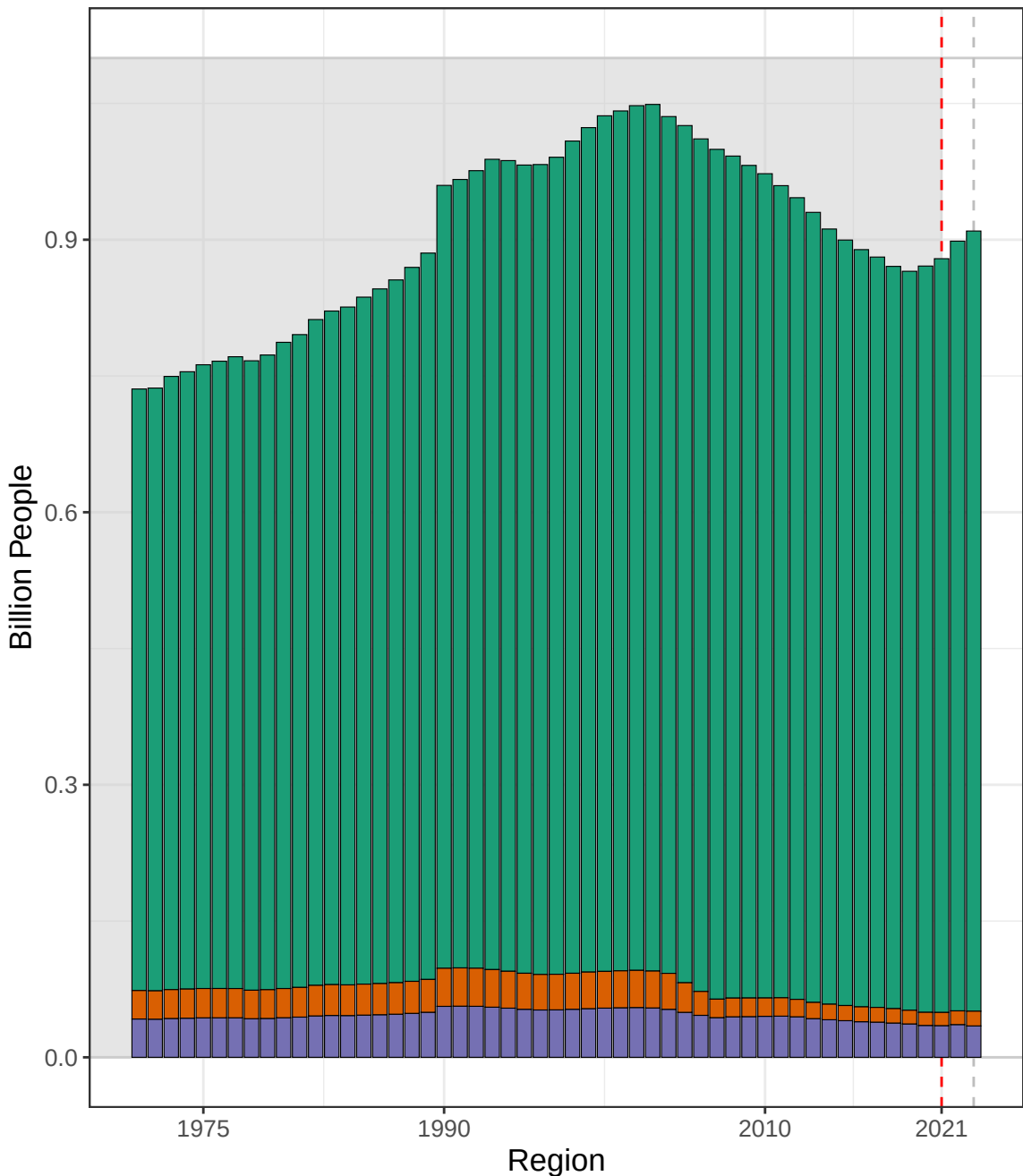
– World Ag. capital grows over time



Data sources: FAOSTAT, ILO, GTAP, USDA, etc.
See module_aglu_L103.ag_labor_capital in gcamdata

(B) World Ag. Employment, 1971–2100

– World Ag. employment peaked in early 2000s



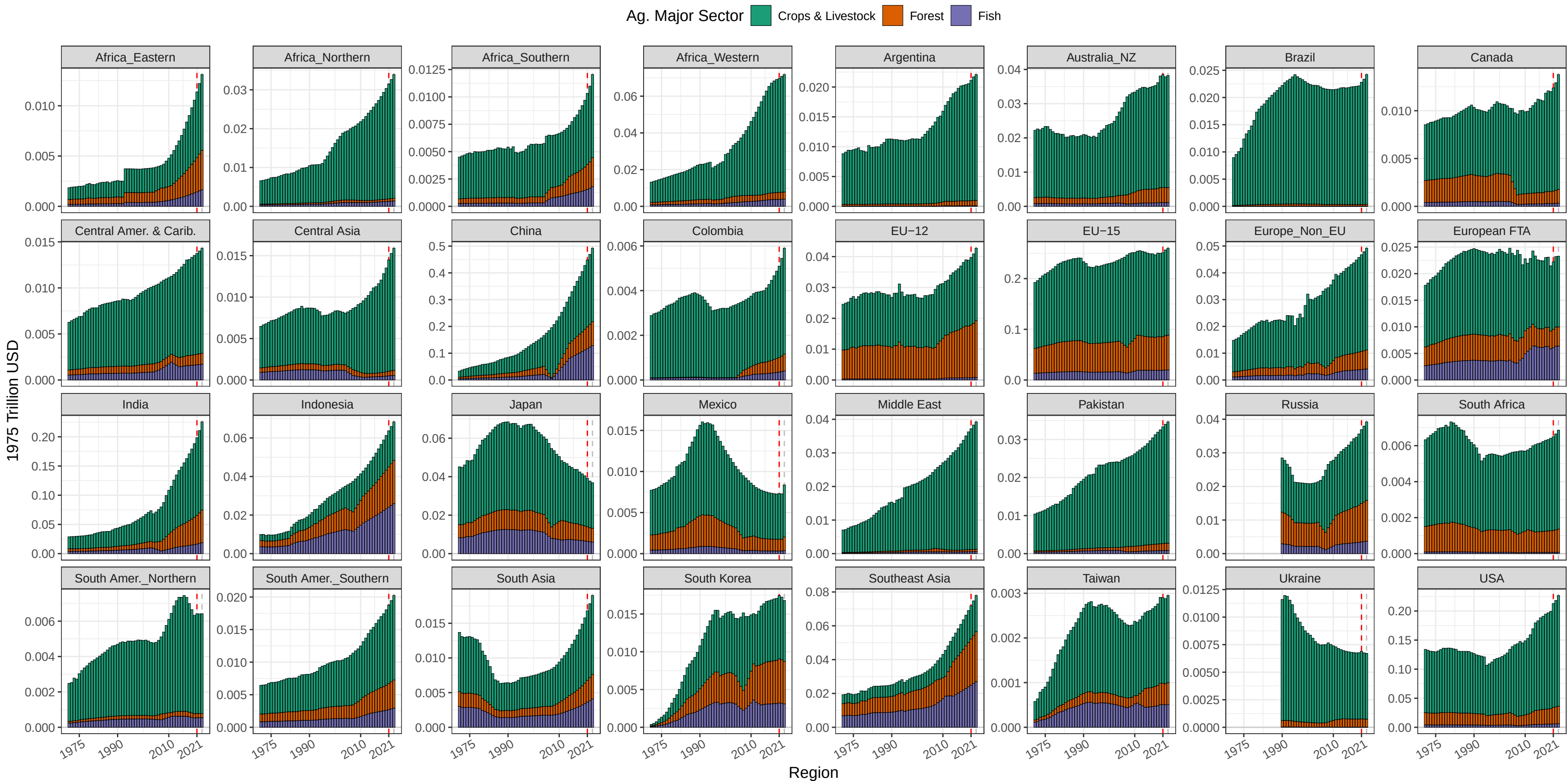
Data sources: FAOSTAT, ILO, GTAP, USDA, etc.
See module_aglu_L103.ag_labor_capital in gcamdata

Ag. Major Sector

- Crops & Livestock
- Forest
- Fish

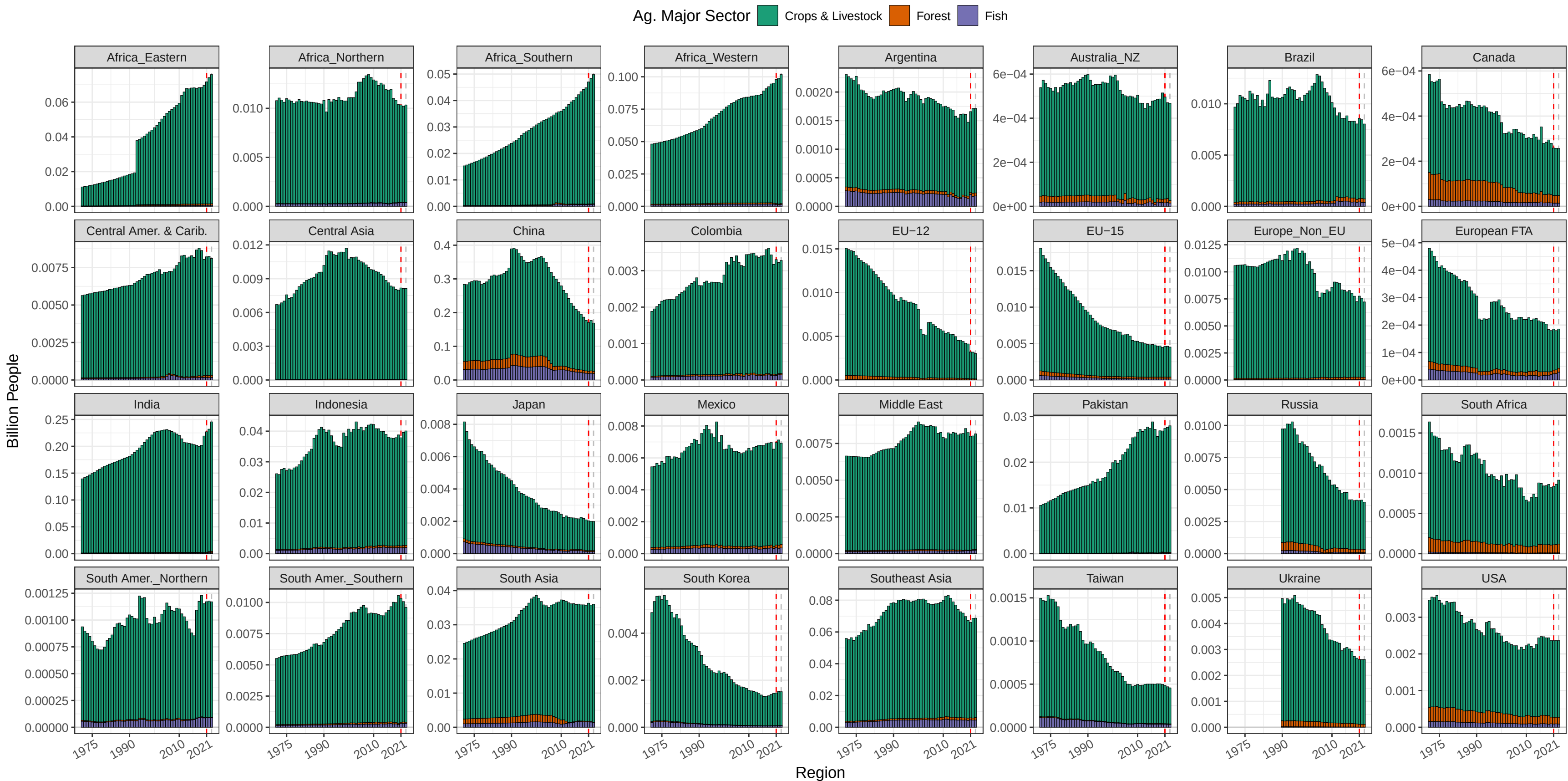
Historical Agricultural Capital Stock by GCAM Region, 1971–2023

– World Ag. capital grows over time



Historical Agricultural Employment by GCAM Region, 1971–2023

– World Ag. employment peaked in early 2000s

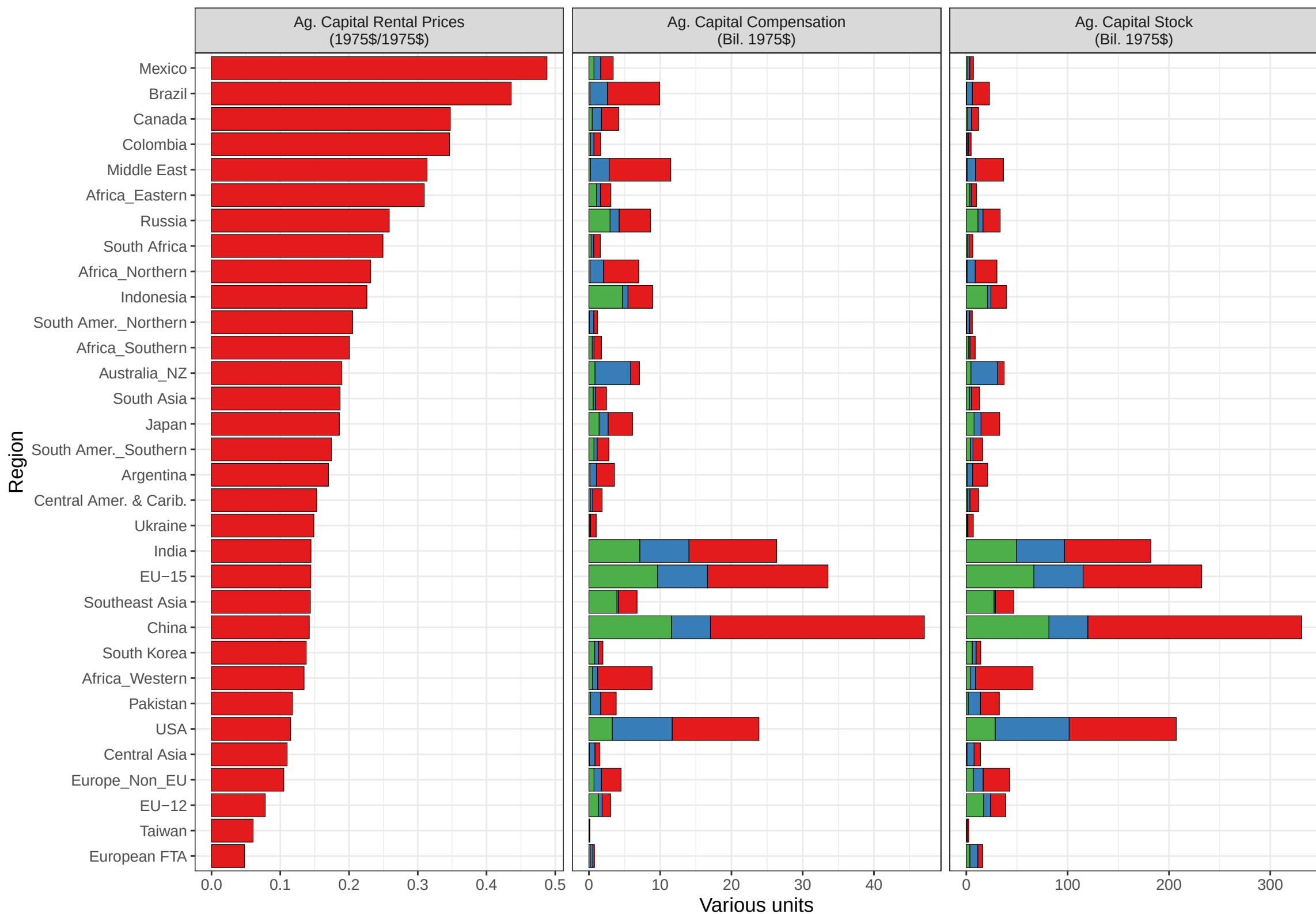


Base Year (2021) Agricultural Capital Rental Prices, Compensation, Stock by GCAM Region

– The same regional capital rental price is used across all agricultural sectors

– 2021\$ = 1975\$ * 3.96

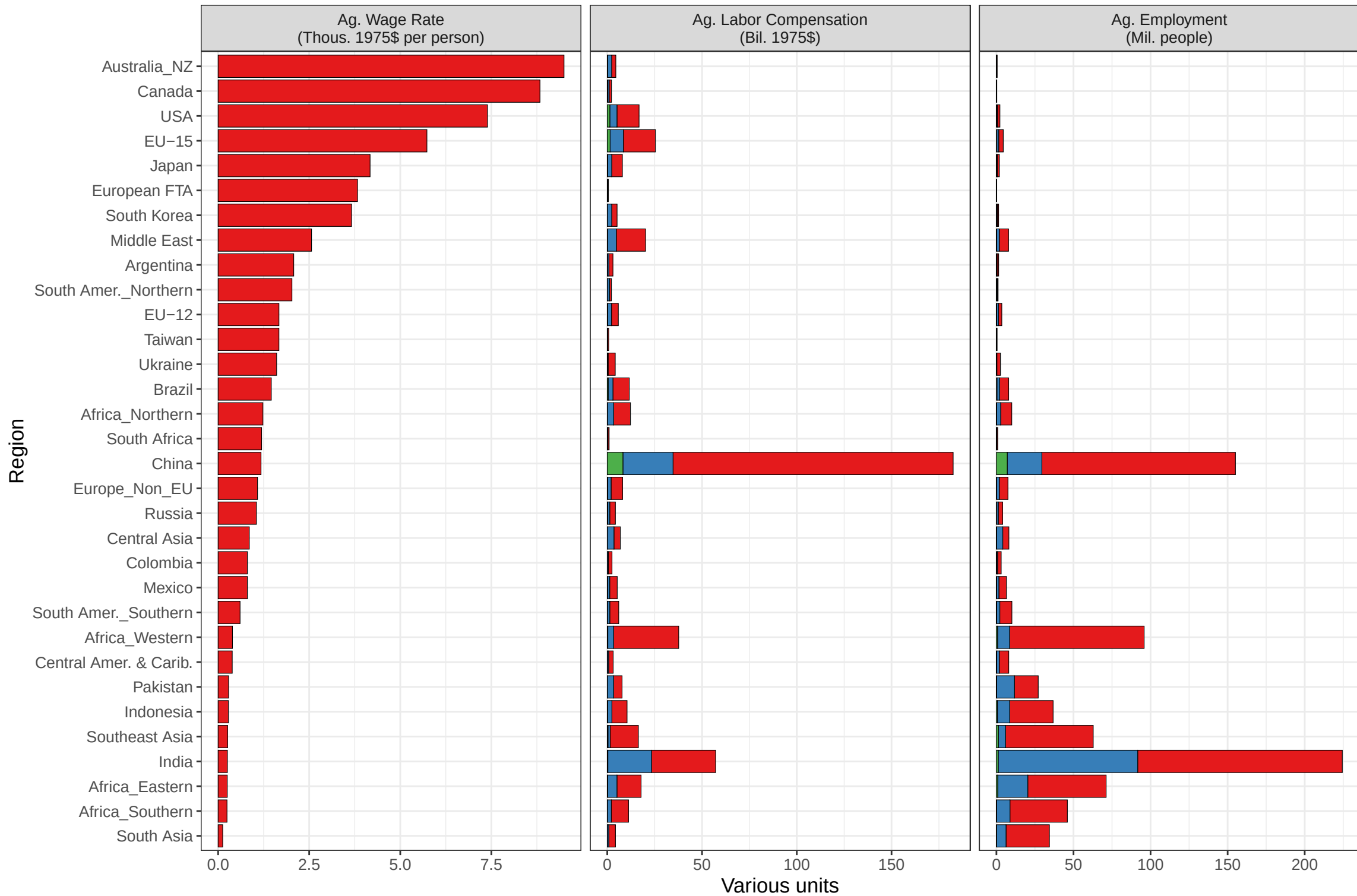
AgMajorSector Crops Livestock Forest



Base Year (2021) Agricultural Labor Wage Rate, Compensation, Employment by GCAM Region

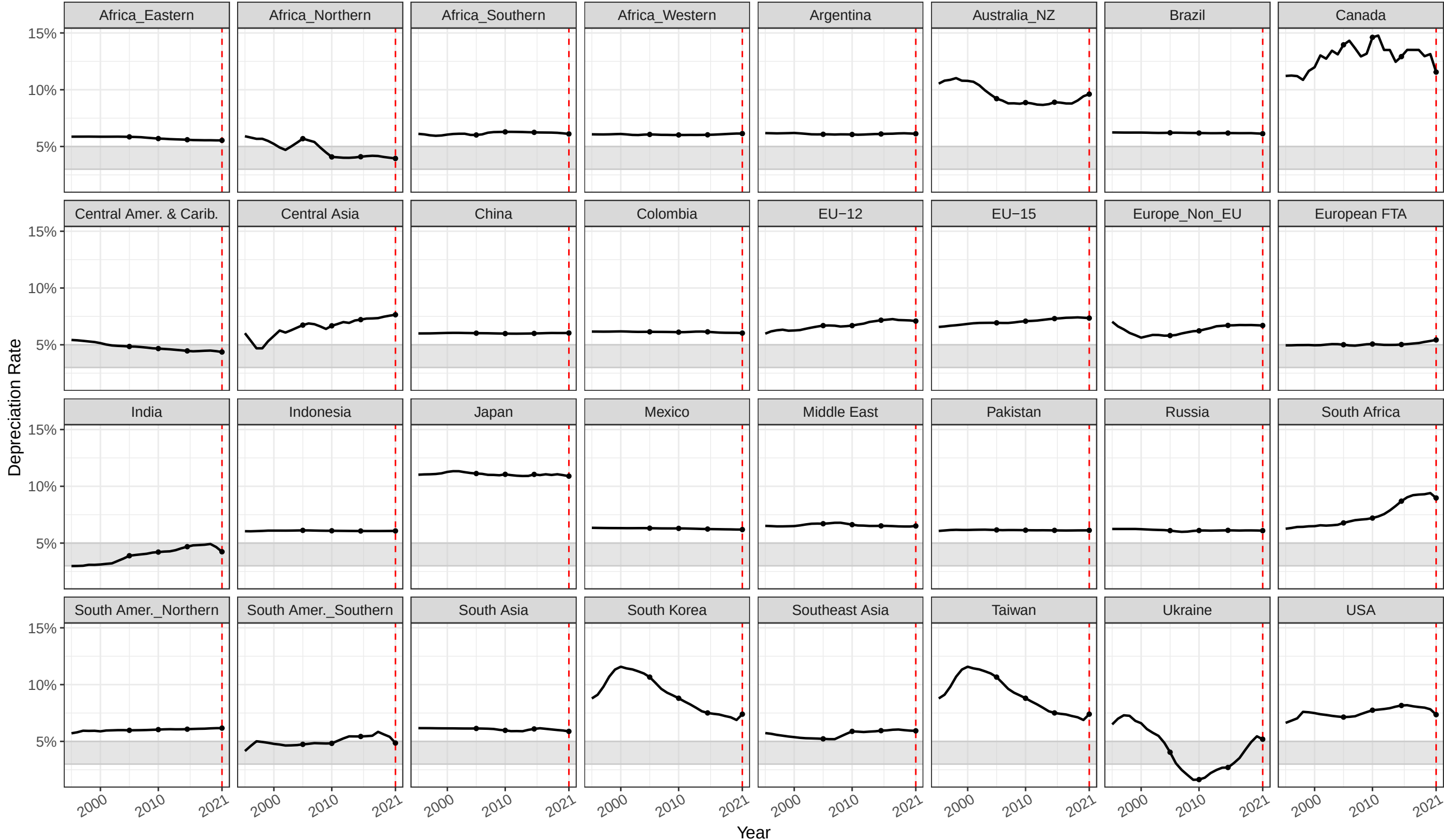
- The same regional wage rate is used across all agricultural sectors
- The final base year prices for agricultural products and costs were improved based on observations
- Note that GCAM used 2021 Ag. prices for historical years
- 2021\$ = 1975\$ * 3.96

Ag. Major Sector ■ Crops ■ Livestock ■ Forest



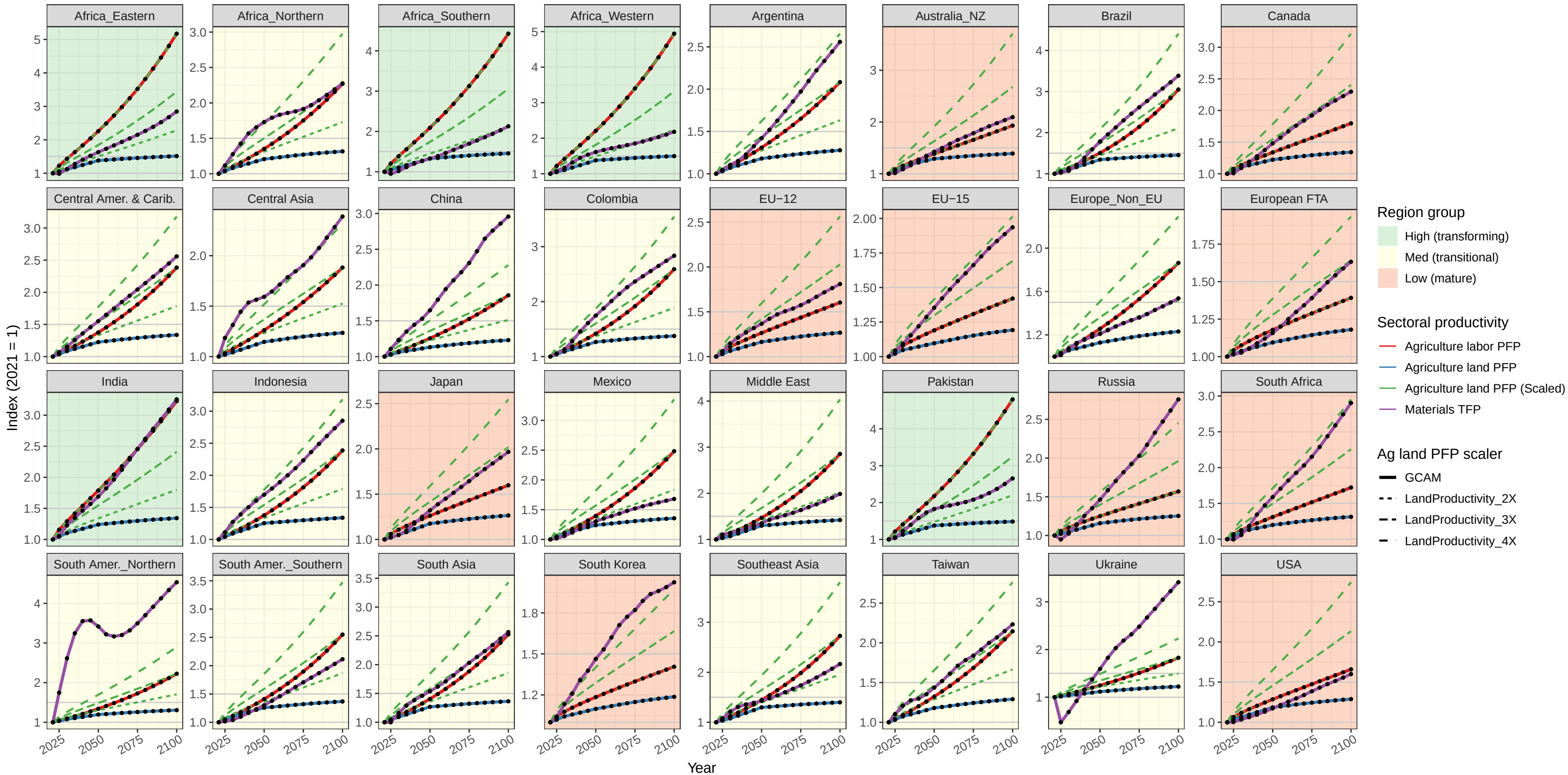
Primary Agricultural Depreciation Rates by GCAM Region, 1995–2021)

- 3-year rolling average
- Grey area shows 3%–5% range (economy-wide depreciation rate)
- Derived using FAO Macro-Economic indicators: Consumption of Fixed Capital / Net Capital Stocks (economic depreciation)
- Net capital stock represents the value of productive capital after deducting accumulated depreciation, measured at current replacement cost.
- Cultivated biological assets (livestock for breeding/dairy) are part of fixed capital
- Rates remain relatively stable over time compared to a rising trend in economy-wide depreciation rates



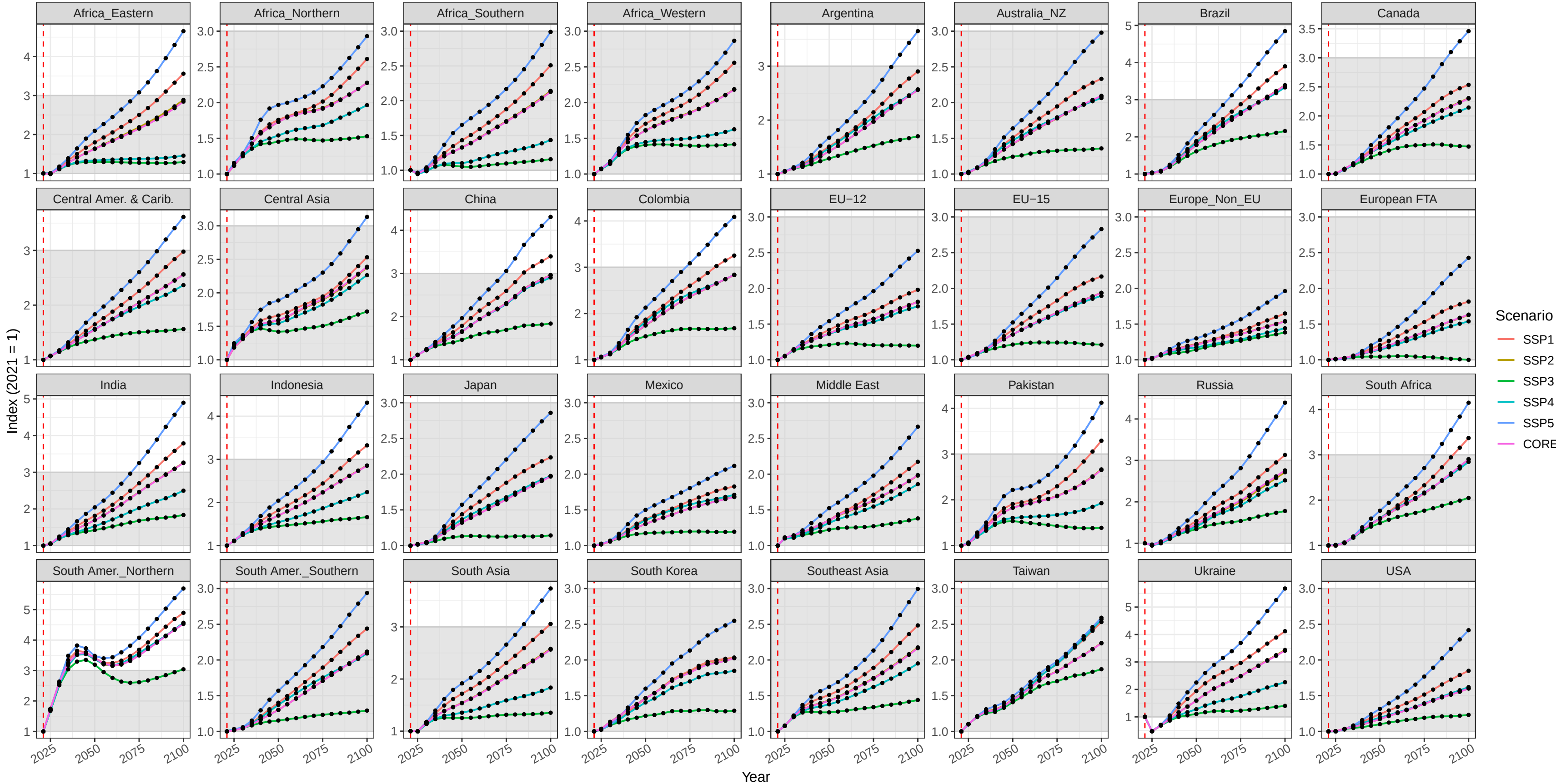
Materials TFP and Ag Factor productivity, Core, 2021–2100

- Materials TFP is calibrated based on SSP GDP projections
- Land productivity (aggregated) is GCAM default assumption based on FAO
- Labor productivity is derived base on land with regional assumptions (dotted lines show alternative scaling)



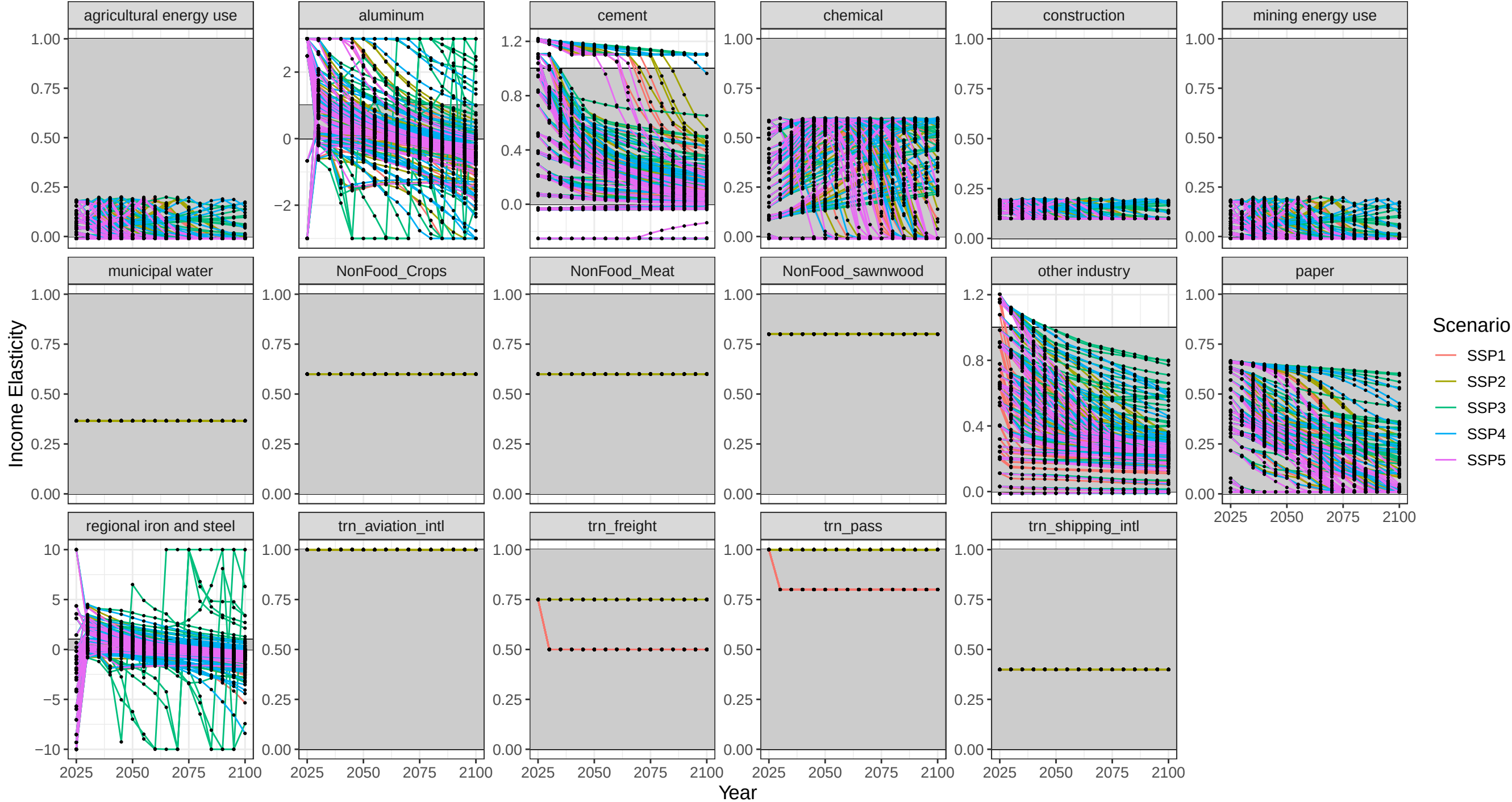
Calibrated TFP in the Material Sector by GCAM Region and SSP, 2021–2100

- These calibrated TFP values enable GCAM–Macro to reproduce SSP GDP trajectories
- TFP values are applied to the CES production function for the Material sector in GCAM–Macro

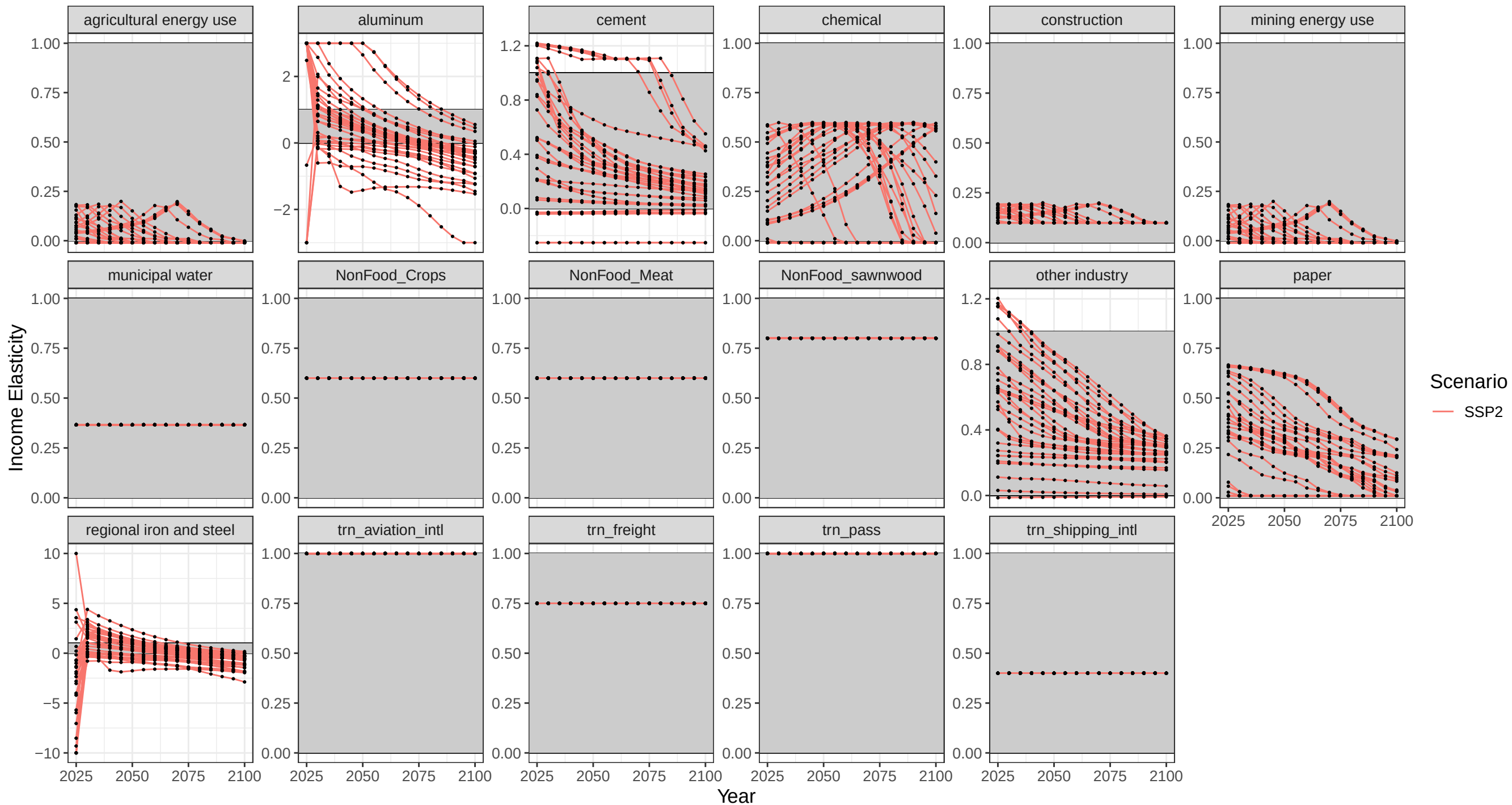


Income Elasticities by GCAM Sector, Region, and SSP

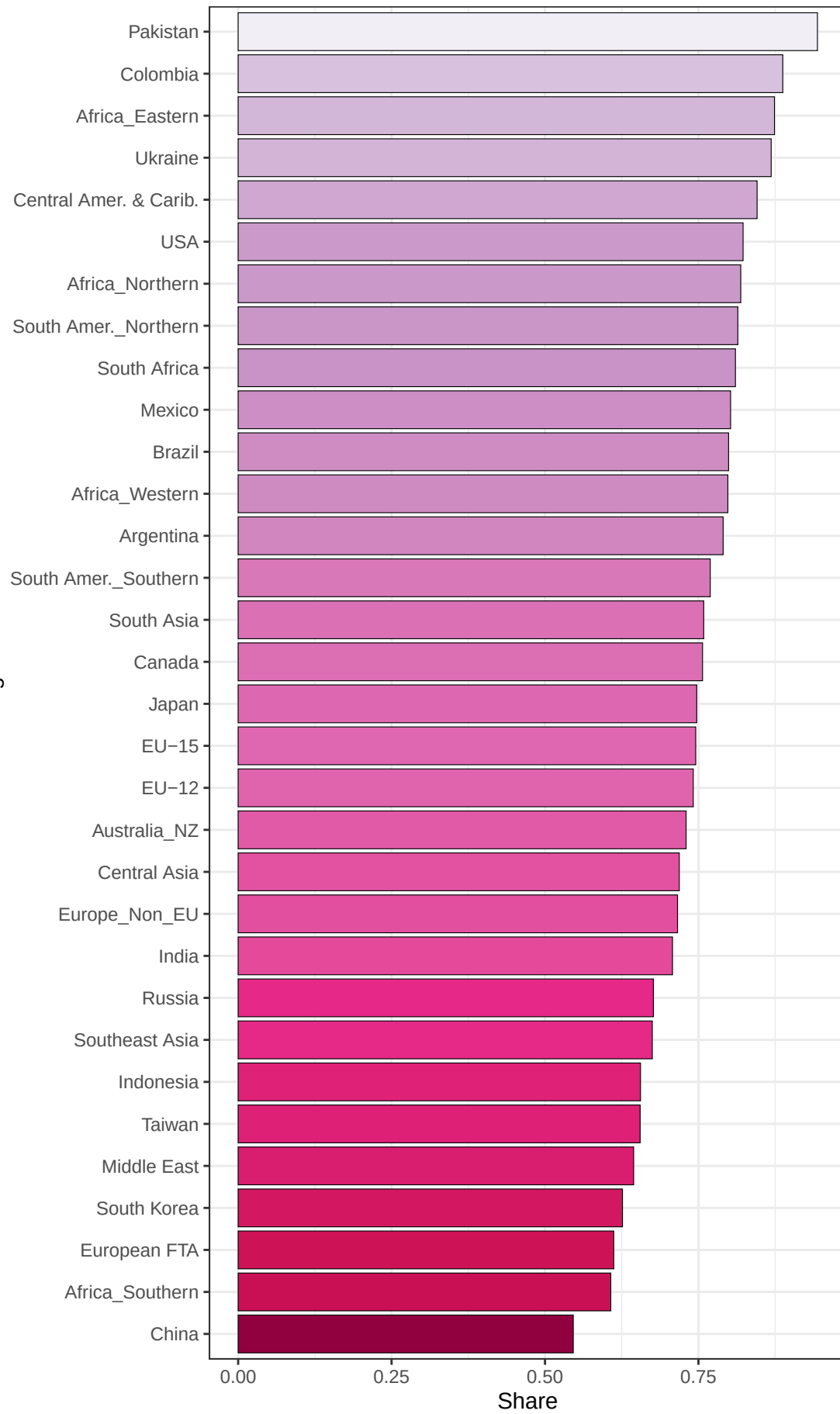
- Income elasticity values for most sectors are now compiled in the `module\_socio\_IncomeElasticity\_xml` module
- A dedicated food demand model governs the response of food consumption to income changes
- Parameters for the building sector (and potentially other end-use sectors) are currently not included
- Constant elasticity values are applied to non-food agriculture, municipal water, and transport sectors; other sectors follow sector-specific assumptions
- In some cases (e.g., Iron & Steel), income elasticities were adjusted to better capture regional trends
- Further documentation and sensitivity analysis of elasticity parameters are needed
- PREVIOUSLY: Although income levels were aligned across SSPs for 2025, some sectors still have differing parameters under SSP1
- UPDATED: aligned 2025 Pop, GDP, income elasticity across SSP scenarios
- UPDATED: Income elasticity is added (0.6 from 0) for NonFood Crops & Meat demand and is updated for sawnwood (from 0.4 to 0.8)
- We have also added price elasticity for nonfood demand in KLEAM; future work is needed to collect all price elasticity/para info



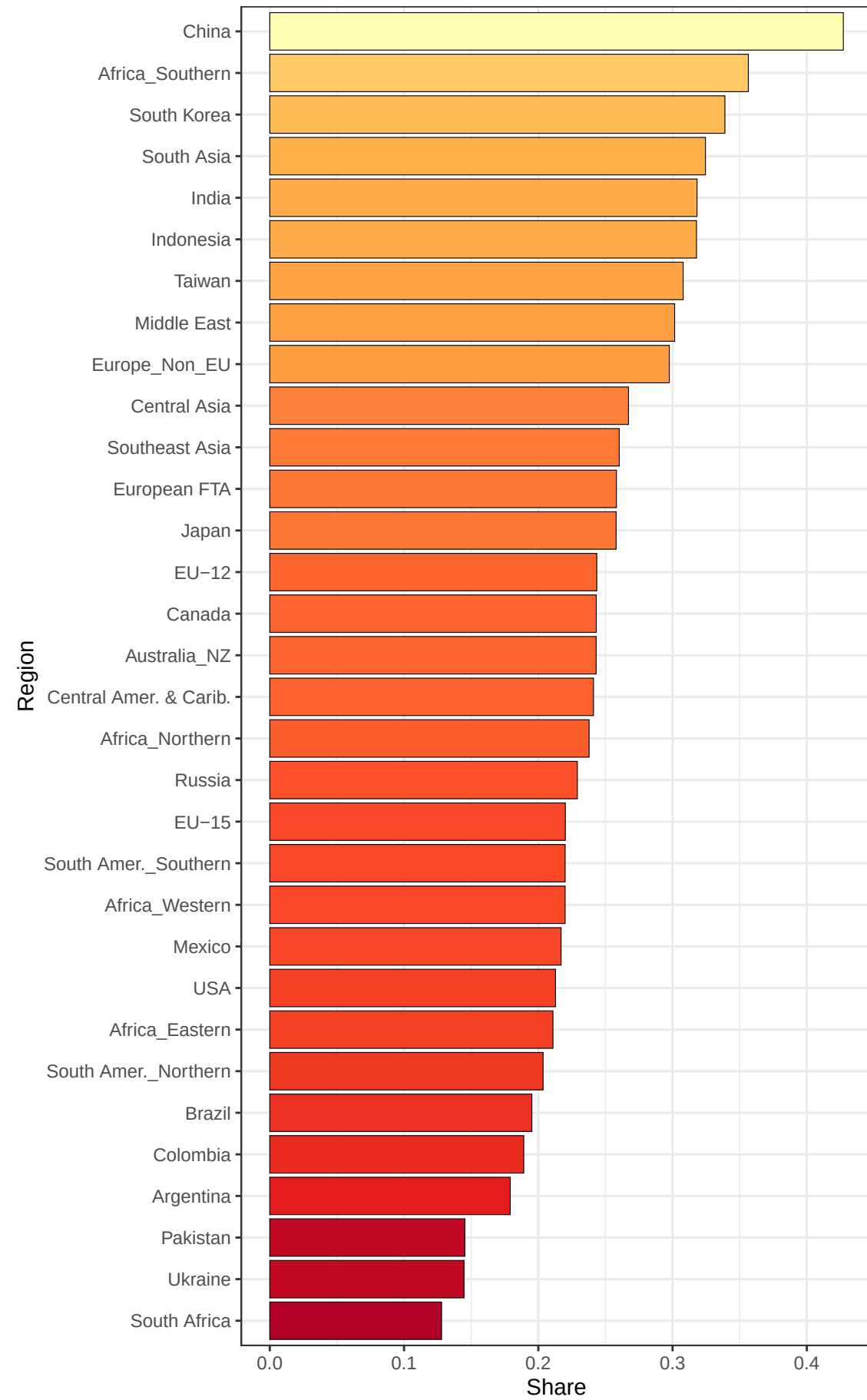
SSP2: Income Elasticities by GCAM Sector and Region (32 lines per panel)



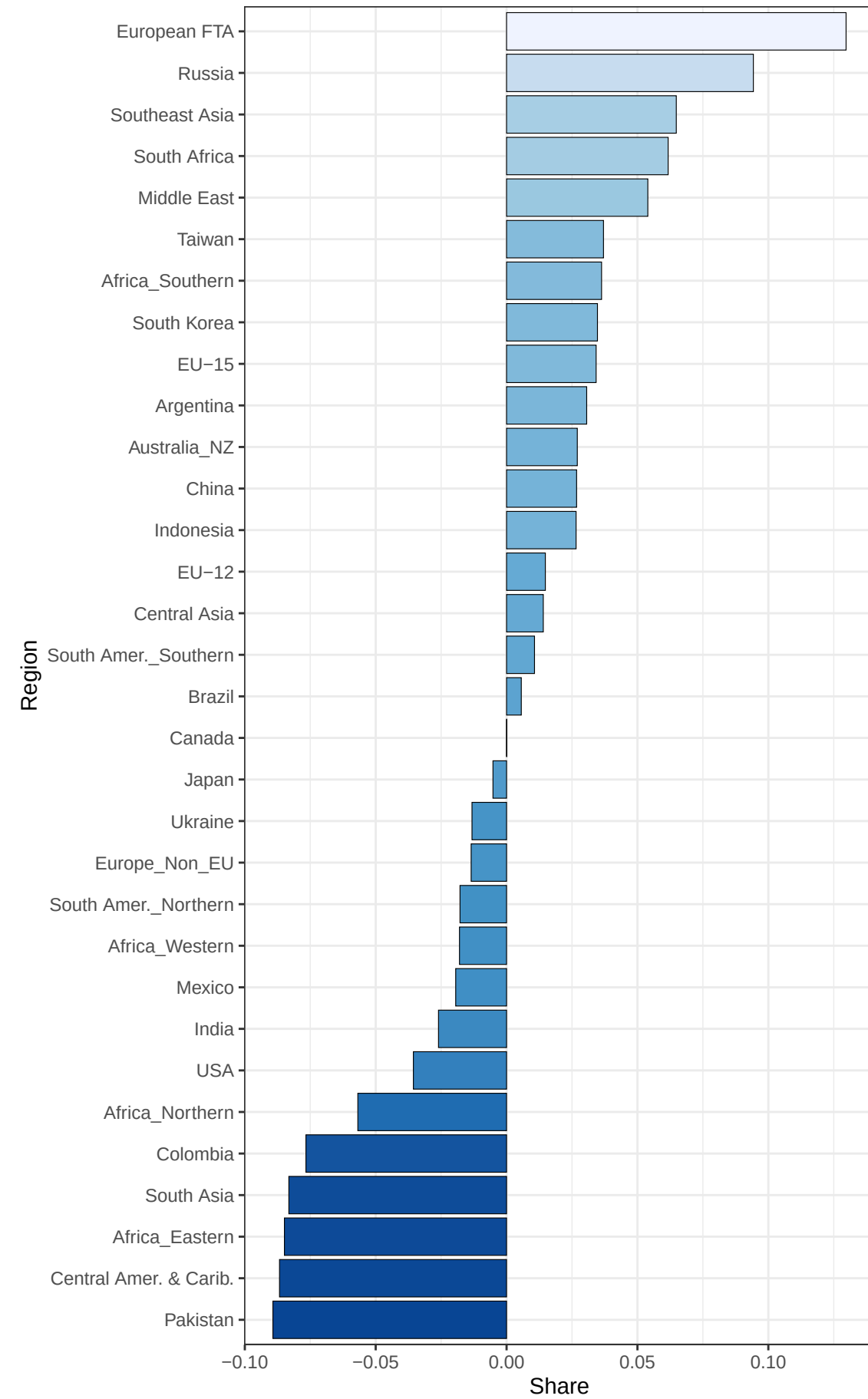
Consumption share in GDP by GCAM region, 2021



Investment share in GDP by GCAM region, 2021

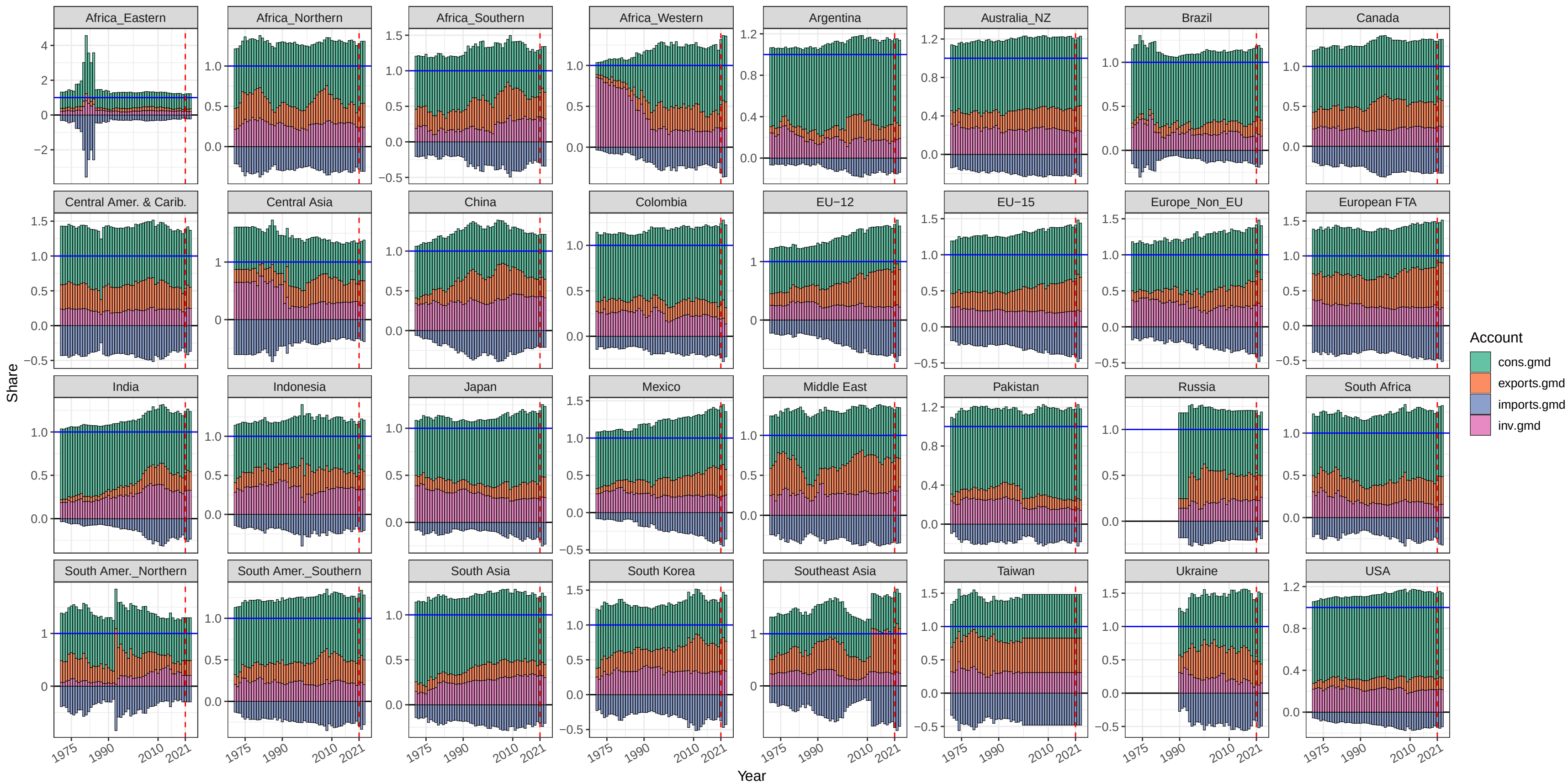


Net exports share in GDP by GCAM region, 2021

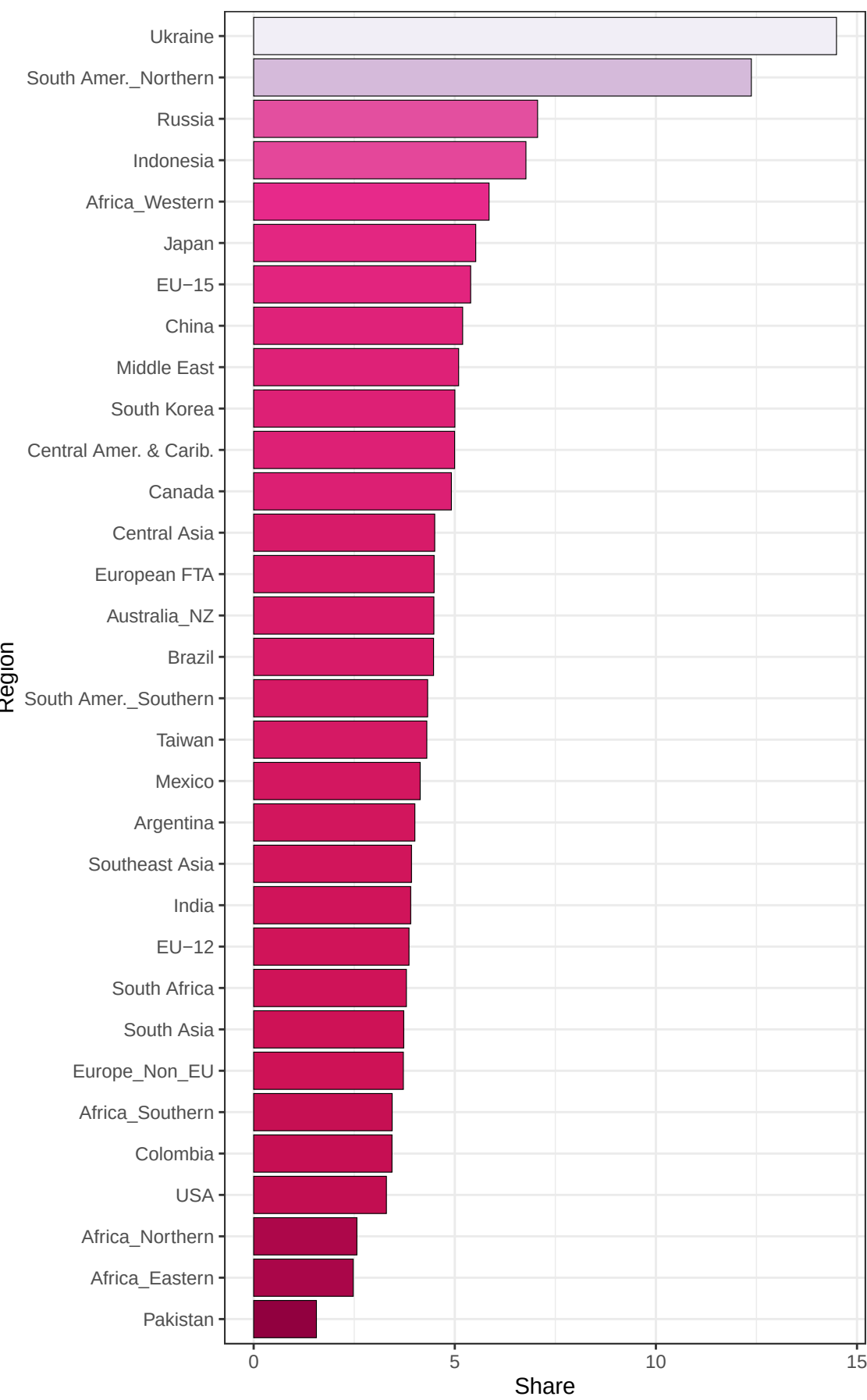


GDP Decomposition by Expenditure Share by GCAM region, 1971 – 2023

cons + inv + exports – imports

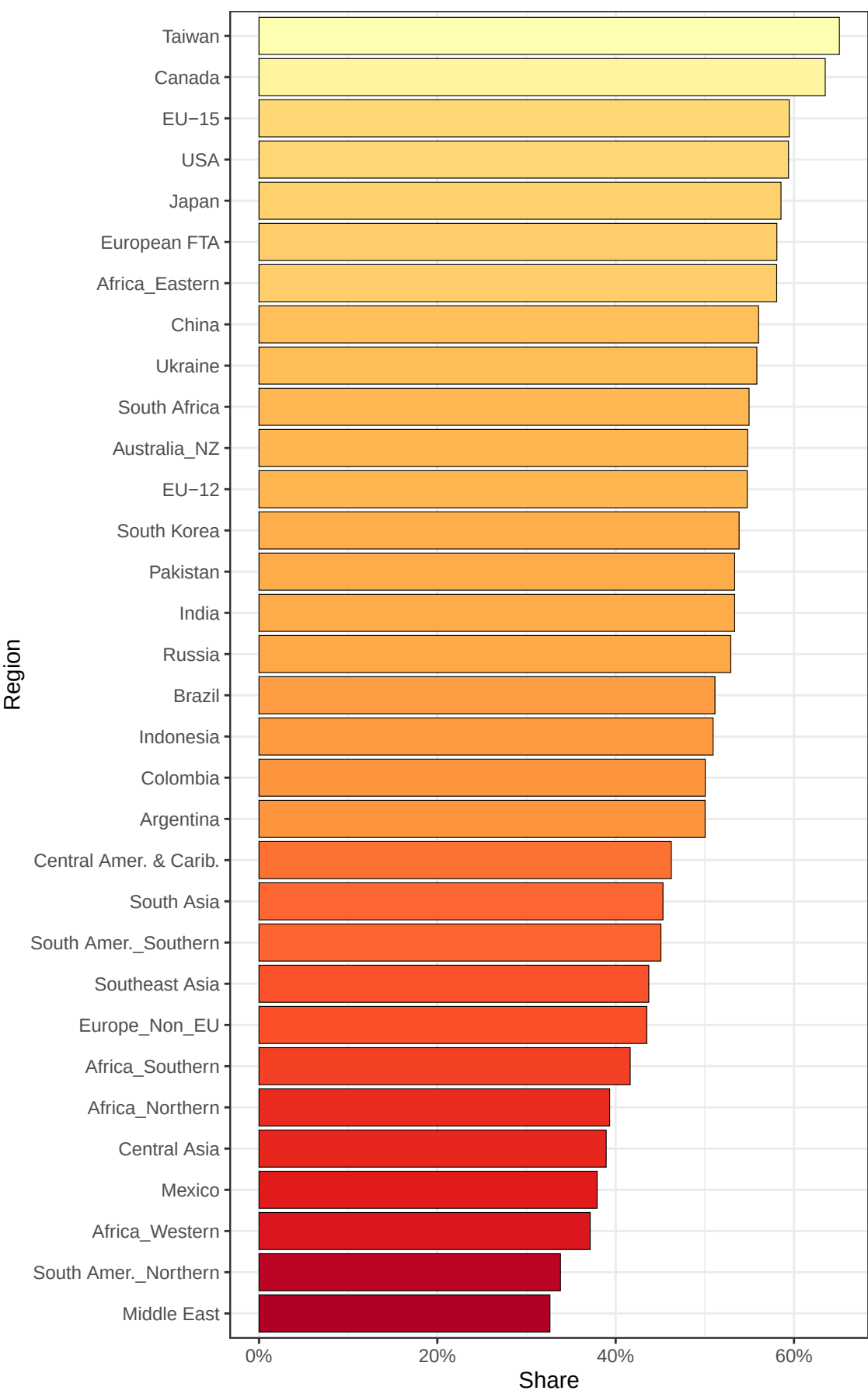


Capital-output ratio by GCAM region, 2021



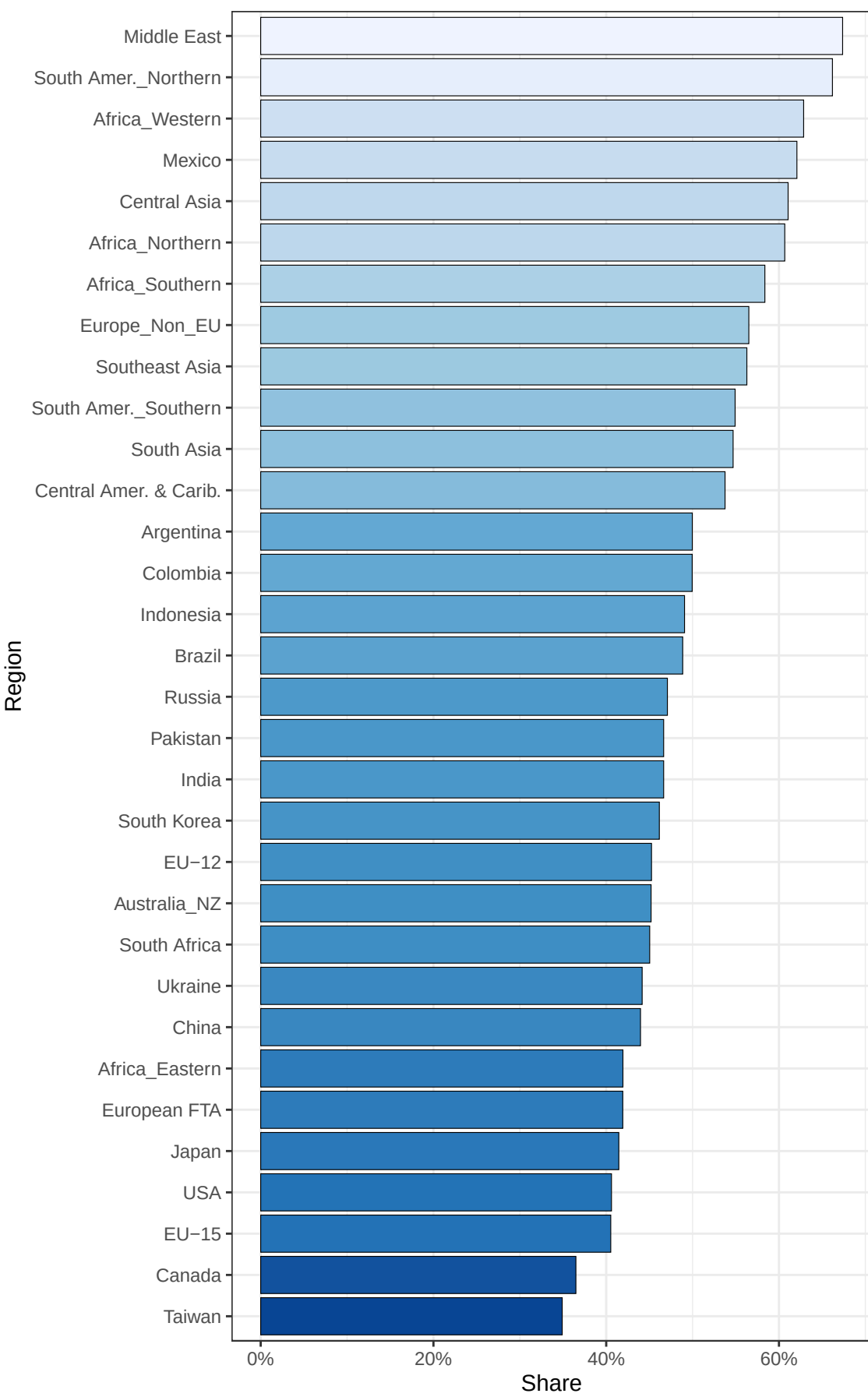
Source: PWT v11.0

Labor Reward Share in GDP, 2021



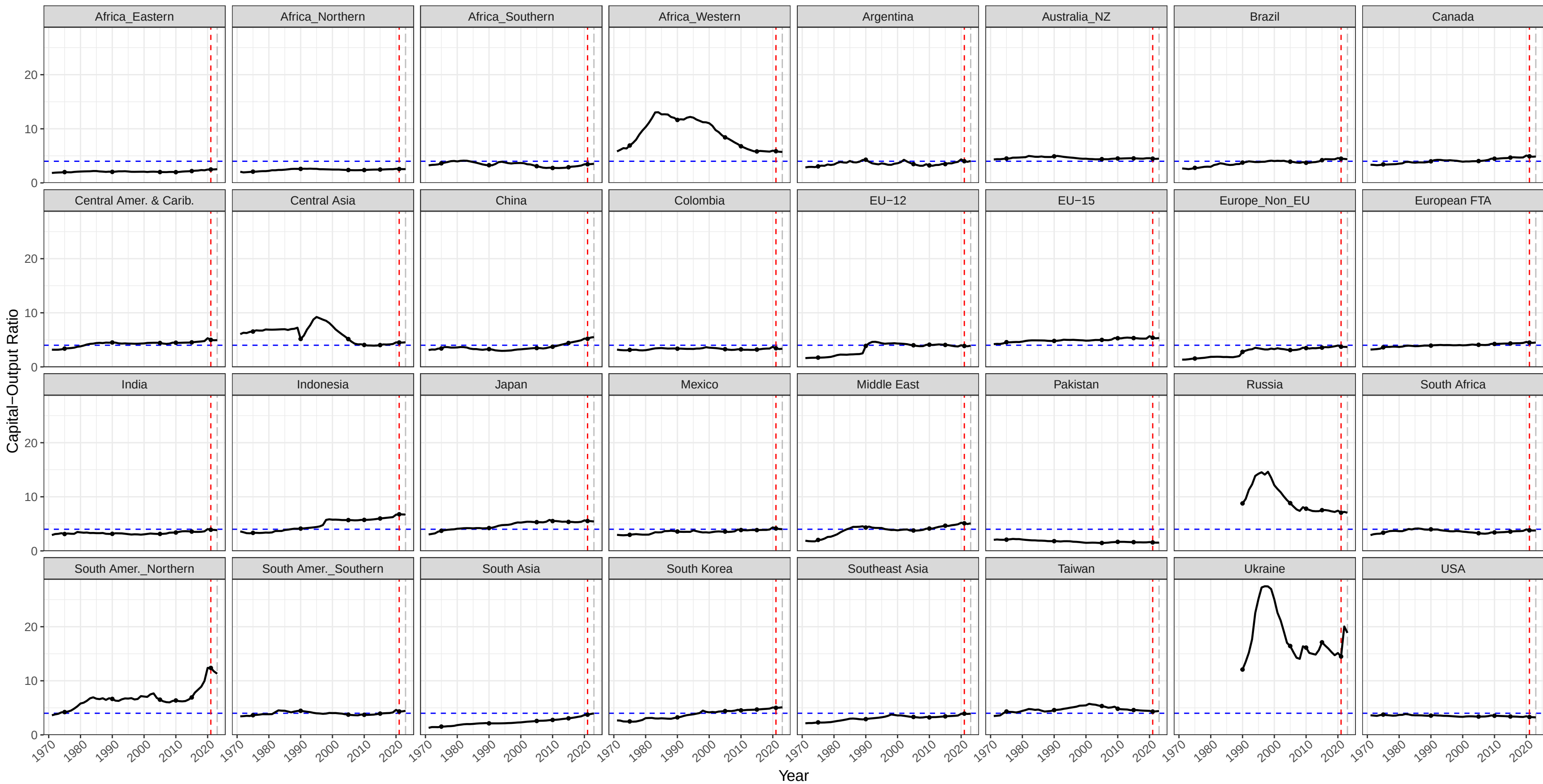
Source: PWT v11.0

Capital Reward Share (1-Labor), 2021

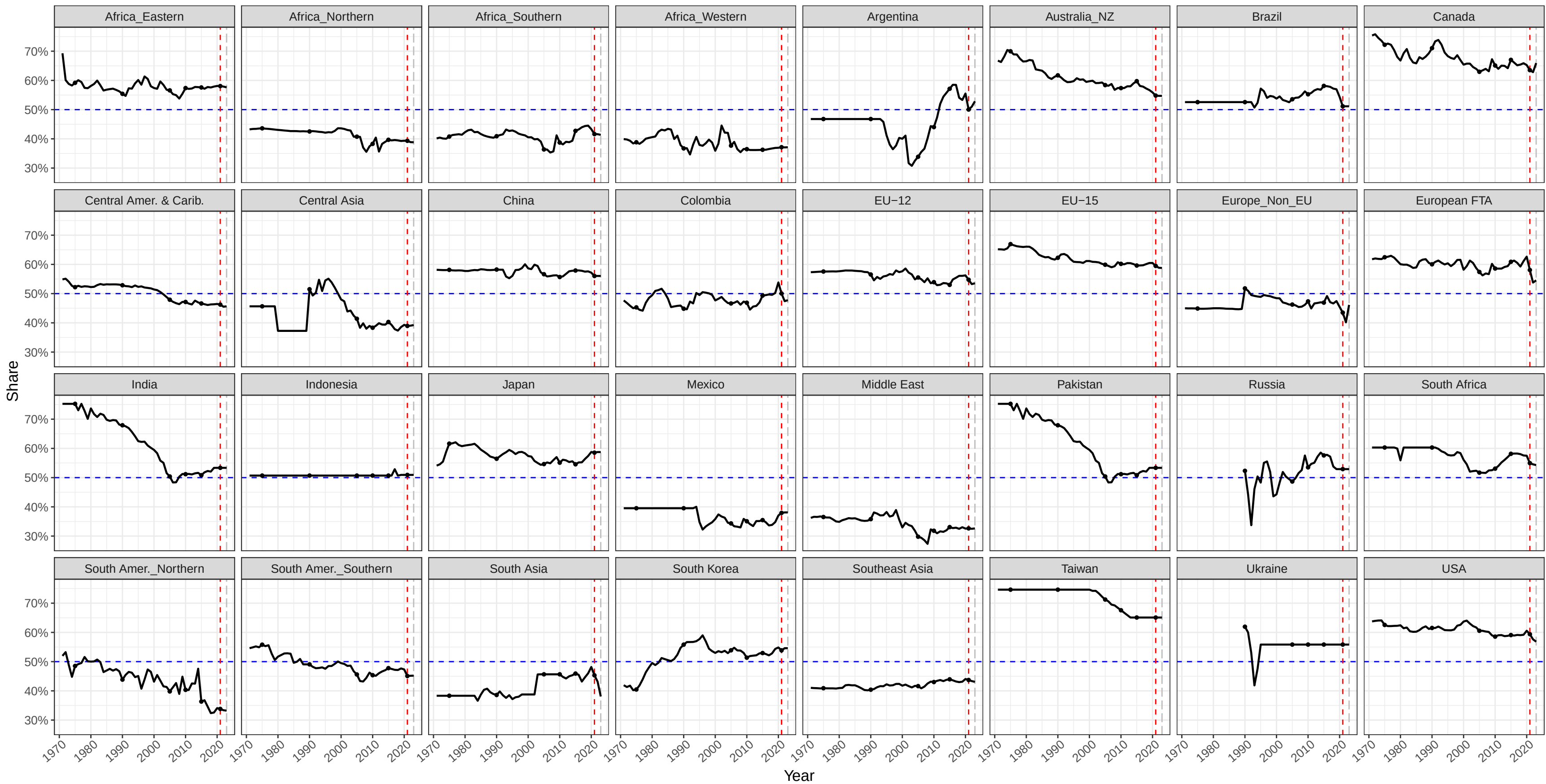


Source: PWT v11.0

Capital-Output (GDP) Ratio by GCAM Region, 1971 – 2023



Economy-Wide Labor Reward Share in GDP by GCAM Region, 1971 – 2023



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