Core Model Proposal #382: Representing agricultural and food storage

Product: Global Change Analysis Model (GCAM)

Institution: Joint Global Change Research Institute (JGCRI)

Authors: Xin Zhao, Pralit Patel, Ellie Lochner and Matthew Binsted

Reviewers: Marshall Wise and Maridee Weber

Date committed: 05/21/2024

IR document number: PNNL-36031

Related sectors: Agriculture, Land, and Economy

Type of development: Data, Code, and Queries

Purpose: This Core Model Proposal develops data and methods to represent agricultural storage and the inter-period stockholding behavior for agricultural and food products in global economic and multisector dynamic modeling. In particular, the proposal aims to (1) restructure and rebalance the supply-utilization accounts to separate stock variations, opening stock, closing stock, and loss associated with stockholding behavior, (2) incorporate agricultural stockholding behavior as a technology of regional consumers who allocate regional supply to current consumption or future consumption (storage carried over to the next period), and (3) explore the sensitivity of the key factors introduced that determine stockholder's responses.

Contents

1. Introduction

Stockholding of agricultural and food products plays a critical role in moderating market volatility, smoothing consumption and farm revenue across time, and enhancing global and regional food security and food resilience (Schewe et al., 2017; Wright, 2011). Stockholders engage in commodity transfers from one period to the next at the expense of physical storage service costs and associated losses. The economic role of storage has been theoretically explored, considering aspects such as competitive storage modeling, producer risk-aversion, and expectations of prices or volatility type (Bobenrieth et al., 2013; Mitra and Boussard, 2012; Wright and Williams, 1982). However, empirical studies on storage responses have primarily focused on individual markets (e.g., grains) or specific regions (e.g., the USA), with only a few incorporating stockholding behaviors into global economic multisector dynamic modeling. For instance, Hertel et al. (2005) developed a stockholding model within a computable general equilibrium (CGE) framework, validating behavior parameters for the staple grains sector by reconciling historical weather-induced supply shocks with Gaussian Quadrature simulation outcomes. While intuitive and parsimonious, the approach in Hertel et al. (2005) did not consider the forward-looking behavior, and it was based on stock variation, so boundary conditions were ignored.

The variability in storage is crucial for maintaining equilibrium within the supply-utilization accounts (SUA) for agricultural products. However, agricultural storage and its economic implications have been largely overlooked in global economic and multisector dynamic models, including GCAM. Consequently, elements related to storage remain absent from explicit consideration within the SUA, and the intricate dynamics of stockholding behaviors are left unrepresented in the modeling. Typically, agricultural storage variation is aggregated into the catch-all category of “other use” to maintain data balance, with “other use” often depicted as an exogenously determined factor. This simplification may lead to negative values in the “other use” category in base data, requiring additional data adjustments. More critically, when agricultural storage is not explicitly represented, the model cannot produce agricultural storage results in future periods, and the demand responses are usually more rigid due to the lack of the buffering function provided by storage. Given these limitations, there is a pressing need to reevaluate and enhance the treatment of agricultural storage within economic modeling frameworks.

The inclusion of stockholding behaviors in global economic models presents challenges due to the required information on storage cost, government interventions, stochastic exogenous shocks, etc., which are typically not available at a global scale. Moreover, traditional storage theories rely on rational expectations of future prices and dynamic stochastic intertemporal optimization, adding difficulties when incorporating them into commonly used static or recursive global economic modeling frameworks. Consequently, previous studies often omitted speculative interannual stockholder behavior even when examining interannual agricultural market variability (Diffenbaugh et al., 2012; Urban et al., 2012; Zhao et al., 2021).

Stockholding in agrifood systems, as a key market-mediating response and policy option to enhance food system resilience, deserves increased attention in global economic and integrated assessment modeling, particularly when exploring alternative futures. In this GCAM Core Model Proposal (CMP), we propose expanding the existing agrifood modeling structure to explicitly represent agricultural storage and corresponding factors (e.g., storage loss). Specifically, we (1) compile an SUA dataset with new elements, including opening stock, closing stock, and post-harvest loss, represented for all GCAM agricultural commodities, and (2) introduce a competitive storage modeling framework using a logit function to model storage behavior as the decision of representative regional consumers to determine current vs. future consumptions for 13 GCAM crop commodities.

It is important to highlight that GCAM operates by default in 5-year steps (2015 – 2100), with external drivers such as socioeconomic and biophysical changes assumed to progress smoothly. Thus, agricultural market prices and equilibriums are usually smooth over time. This is true even under RCP 2.6 scenarios where exponentially growing carbon prices are added. Thus, this CMP places a relatively higher emphasis on two key aspects: (1) projecting agricultural storage in future periods and (2) assessing the long-term implications of integrating agricultural storage into the model. Subsequent research is required to explore the role of agricultural storage in mediating interannual variability in agricultural markets under alternative futures.

2. Description of changes (Methods)

2.1. Agricultural storage in supply-utilization accounts (SUA)

GCAM recently updated its agricultural supply utilization in a comprehensive CMP by Zhao and Wise (2023). A new primary commodity equivalent approach was developed to establish a robust connection between primary agricultural supply and final consumption (Zhao et al., 2024a). **Fig. 1** shows the compiled data for the global supply-utilization balance in the GCAM base year and **Fig. 2** depicts the data for grains.

On the supply side, GCAM represents primary agricultural production, comprising 17 GCAM crop commodities (aggregated from approximately 180 FAO crop items, including fodder crops) and 6 GCAM livestock commodities (aggregated from over 60 FAO livestock items) (see the mapping in **Table S1**). On the demand side, the 21 GCAM commodities (excluding fodder crops), in their primary equivalent, were aggregated from over 450 FAO primary and processed products. These compiled data ensure a balanced representation of primary equivalents across supply-utilization, space, time, and vertical processing sectors. That is, at the regional utilization levels, both primary and secondary products are considered. Particularly, stock and loss along the supply chain are represented to the extent data was available. The data show key differences in the SUA element decomposition across sectors and regions. Despite the inclusion of agricultural stock and post-harvest loss elements in the balance, these factors were previously aggregated into the category of "other uses" as GCAM had not explicitly represented them.

If we look at the storage variation in the base year (5-year average), most region-commodities had a positive value since storage required (and capacity) is growing with the economy, leading to a relatively larger "other uses" (than otherwise). In other words, storage variation has been, to some extent, considered in GCAM to ensure the SUA balance. However, in GCAM, "other uses" of agricultural products is externally driven by population growth with no income and price responses. The developments in this CMP will improve the representation of storage by considering the relationship between stock and other agroeconomic variables (i.e., an endogenous stock-to-gross use ratio). We leverage the originally detailed SUA data compiled to separate opening stock, closing stock, and the corresponding storage loss (**Fig. 2**).

Fig. 3A compares the stock-to-gross-use ratio with the trade (import)-to-gross-use ratio for GCAM agricultural commodities. Gross use is defined as the sum of demand for food, feed, loss, other use, and closing stocks. The trade (import)-to-gross-use-ratio implies the Armington regional import share (when storage is included), indicating reliance on the international market of a commodity. Similar to the more widely used metric stock-to-use ratio (where storage is not included in the denominator), the stock-to-gross-use ratio communicates the availability and sufficiency of the commodity stock relative to consumption. While the role of international trade has been extensively studied, storage, which has not received adequate attention in global economic modeling, could play a significant role in SUA, particularly for grains (**Fig. 3B**). E.g. for grains, the global stock-to-gross-use ratio is 29.1%, while the trade (import)-to-gross-use ratio is 11.2% in the GCAM base year.

This CMP focuses on GCAM crop commodities for which interannual/interperiod storage is traditionally important. Specifically, storage responses are included for 13 GCAM crop commodities (the first 13 in **Fig. 3A**). Vegetables and fruits are not included due to their relatively small interannual storage potential, given their higher water content and respiration rate, making them more challenging to store for extended durations compared to grains. It is noteworthy that fruits show a relatively larger stock-to-gross-use ratio mainly because secondary products (processed or canned fruits or juice) are represented. Additionally, the storage of livestock products is not included in the CMP due to complexities in considering dynamics with live animals.

In the original SUA data, closing stock is carried over to the next year (i.e., closing stock in t-1 is equal to opening stock in t), and storage-related loss was not separated. Although post-harvest loss was included in SUA, only a portion of it can be attributed to storage. The detailed method is outlined in **Section 2.2**.

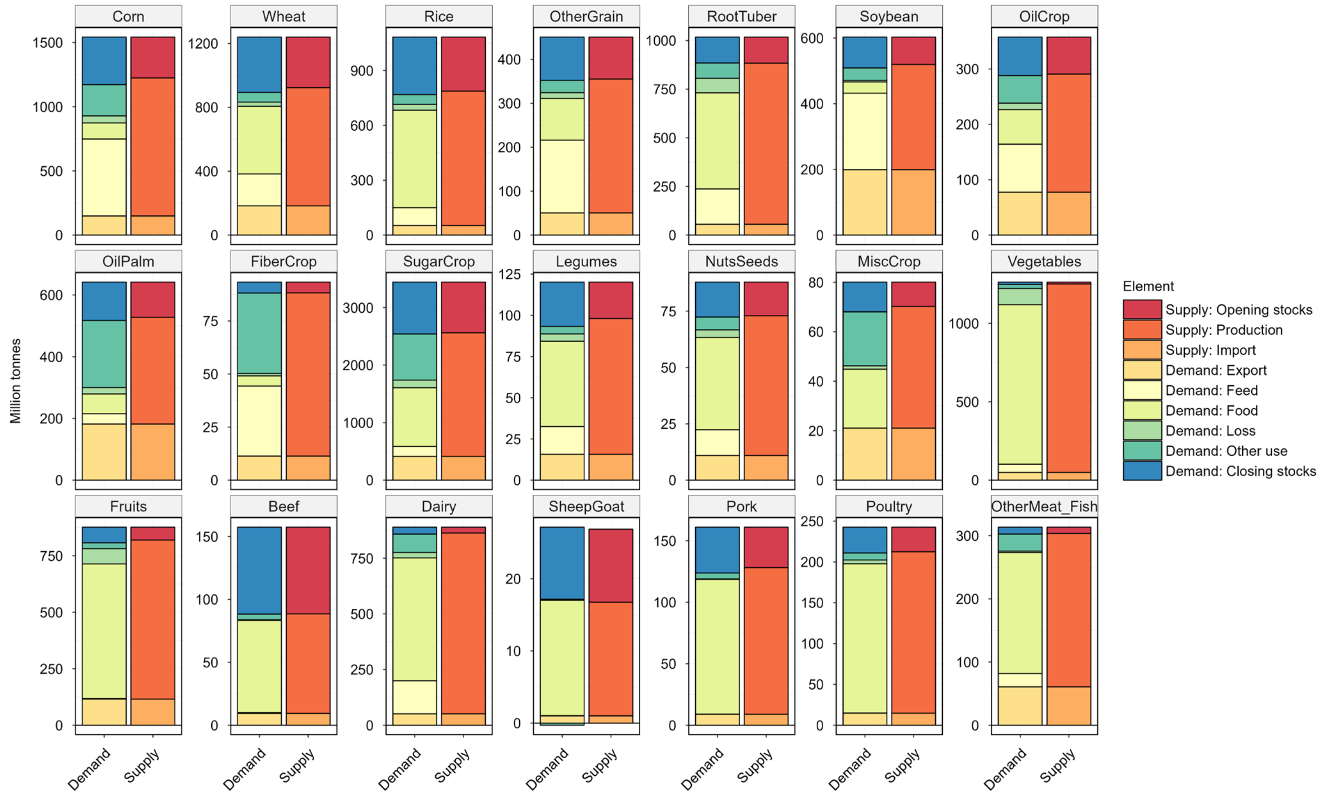

Fig. 1 Global supply utilization balance decomposition for 21 GCAM agricultural commodities in the base year (2013 – 2017 average). The commodity is in primary equivalent. Other use includes other balance elements not shown, e.g., seed, industrial use, residuals, etc. The total supply is equal to the total demand.

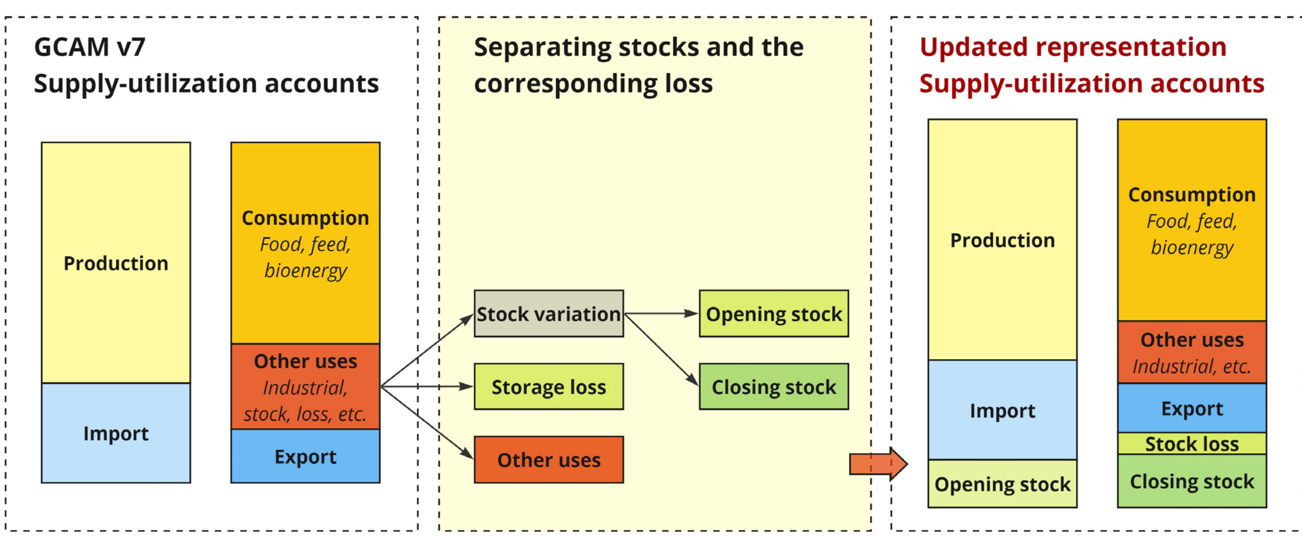

Fig. 2 Schematic of the restructuring of the supply-utilization accounts in GCAM to separate agricultural storage and the corresponding loss.

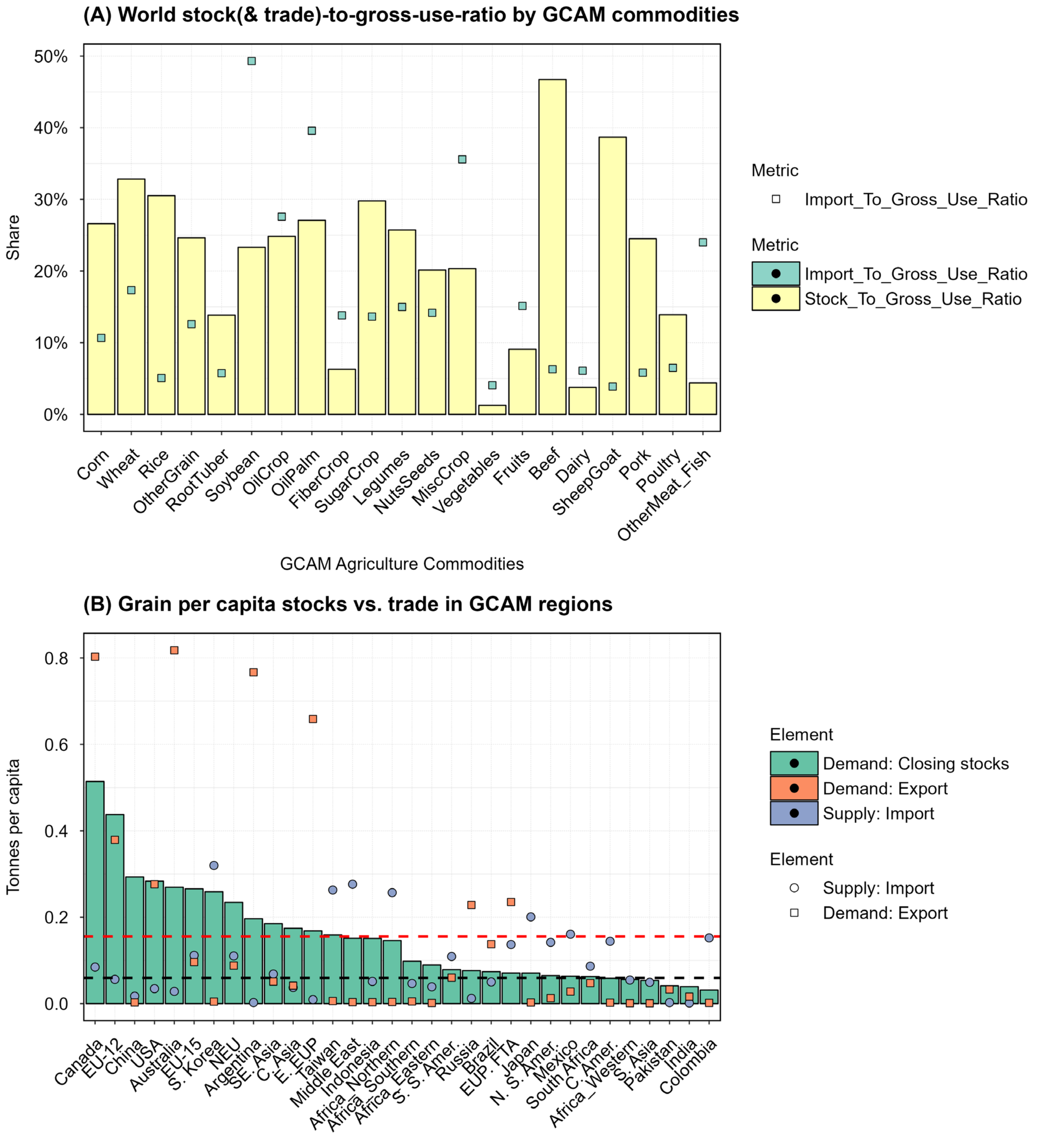

Fig. 3 Storage vs. trade in GCAM base year. World stock-to-gross-use-ratio vs. trade (import)-to-gross-use-ratio by GCAM commodities (A) and per capita grain stock vs. trade by GCAM regions (B). Grain in Panel (B) includes 4 GCAM crops, Corn, Wheat, Rice, and OtherGrain. The dotted lines in Panel (B) represent the world average values for stock (red; 0.16 t/ca./yr.) and trade (black; 0.06 t/ca./yr.).

2.2. Representing agricultural stockholding behavior in GCAM

The proposed updates to the model structure for representing storage in market equilibrium are illustrated in **Fig. 4**. In this framework, a representative regional stockholder makes decisions to allocate the "total demand" between "current consumption" and "future consumption" (closing stock) to maximize preferences and time-adjusted profit.

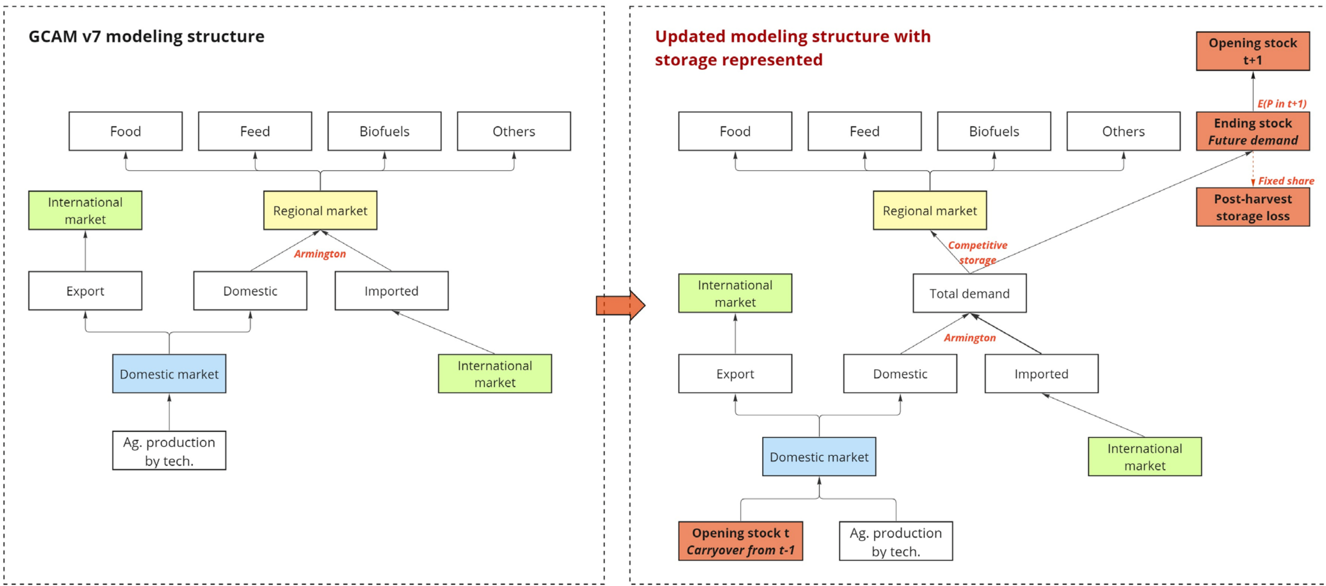

Fig. 4 Schematic of the updating GCAM modeling structure to represent stockholder behaviors.

The model employs a logit sharing (Clarke and Edmonds, 1993; Zhao et al., 2020), where changes in the ratio between closing stock and "current consumption" (i.e., stock-to-use ratio) are responsive to current market prices (p_{market}) and expected prices for storage ($p_{stroage}$) in the next period, as described in Eq. (1).

$$StockToUseRatio = \frac{s_{stroage}}{s_{current\ demand}} = \frac{\alpha_{stroage}}{\alpha_{current\ demand}} \cdot \left(\frac{p_{stroage}}{p_{market}}\right)^{\gamma} \quad (1)$$

Here, $s_{stroage}$ is the share of storage, $s_{current\ demand}$ is the share of current demand, α represents calibrated share-weights, and γ is the logit exponent parameter. Technically speaking, temporal arbitrage should be less responsive than spatial arbitrage, so the storage logit exponent parameters should be smaller than regional Armington elasticities (in absolute values). The regional Armington trade elasticity used in GCAM varies within the range of 1.3 to 4.5. For storage responses, we use a logit exponent of 1 in all sectors and regions, implying a response similar to that of a Cobb-Douglas production function with a unity elasticity of substitution.

The expected prices for storage are derived using Eq. (2) whereas an interannual storage cost and loss rate[1] are factored in. For simplicity, we use a lagged price expectation ($\mathbb{E}p_{t+1}^{market} = p_{t-1}^{market}$), which has

[1] In GCAM, a "LossCoefficient" which is "1-LossRate" was indeed used.

been widely used in empirical studies. r is the private discount rate (which is calibrated into share weights for simplicity).

$$p_{stroage} = \left(\mathbb{E}p_{t+1}^{market} - interannual\ storage\ cost\ per\ unit\ output\right) \cdot (1 - LossRate) \cdot (1 + r)^{-1} \qquad (2)$$

It is worth noting that, in our design, storage behavior is introduced at the regional demand side rather than the supply side. This choice was primarily made because the stock-to-supply ratio exhibits much larger variations across regions, while the stock-to-use ratio is relatively more consistent (refer to **Fig. 5** top panels). Additionally, the post-harvest loss included in the SUA is not entirely associated with the interannual storage under consideration. Instead, this loss is attributed to the total production or consumption of a product. Loss-to-production ratios and loss-to-consumption ratios are depicted in **Fig. 5** bottom panels. The disparity is mainly driven by international trade. Developing regions and large exporters tend to have higher losses along the supply chain but also during storage. In our study, we select the lower value between the loss-to-production ratio and loss-to-consumption ratio, applying it to closing stock to derive the loss associated with interannual storage in a region for a given sector (see examples in **Fig. 6**). In essence, the storage loss represents the difference between closing stock (before loss) and the carryover to the next period.

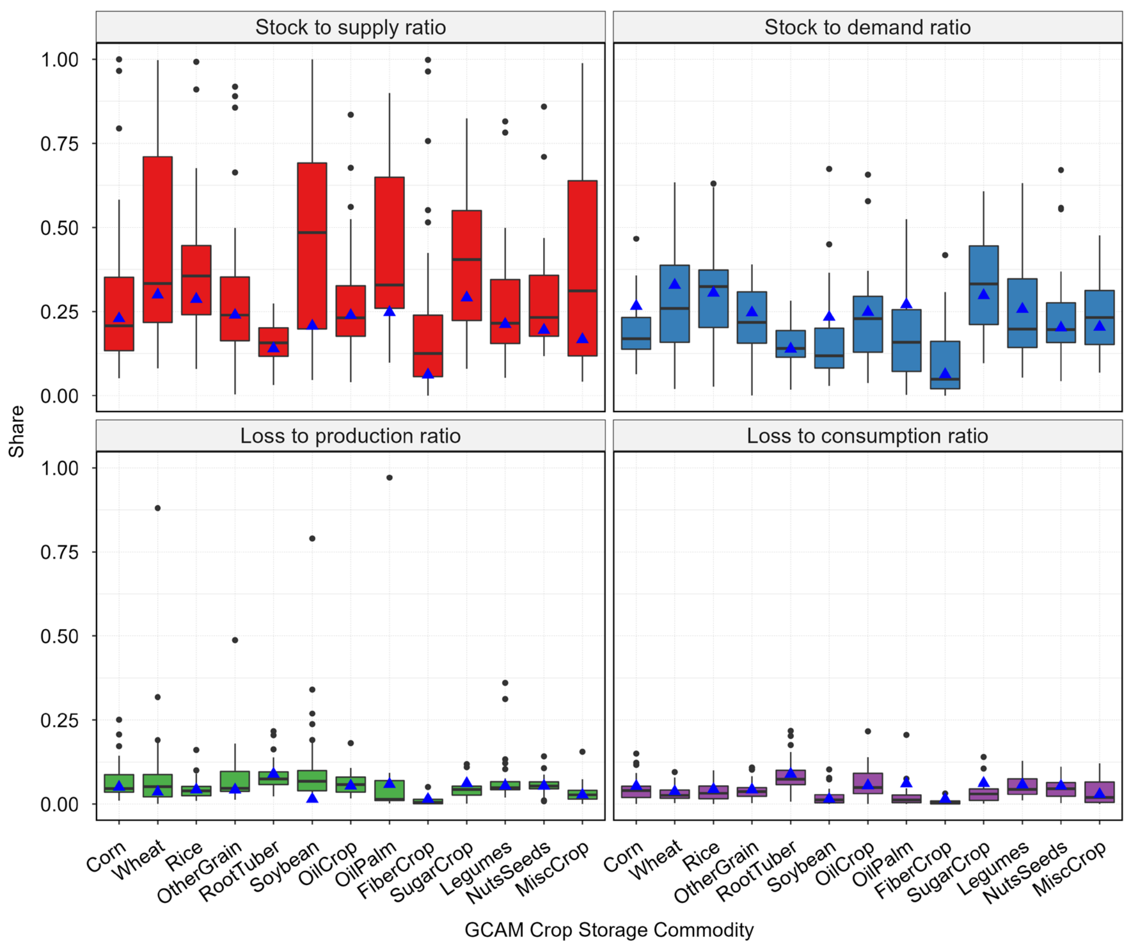

Fig. 5 Distributions of stock and loss metrics across GCAM regions for GCAM commodities. The blue triangle points indicate the world mean value.

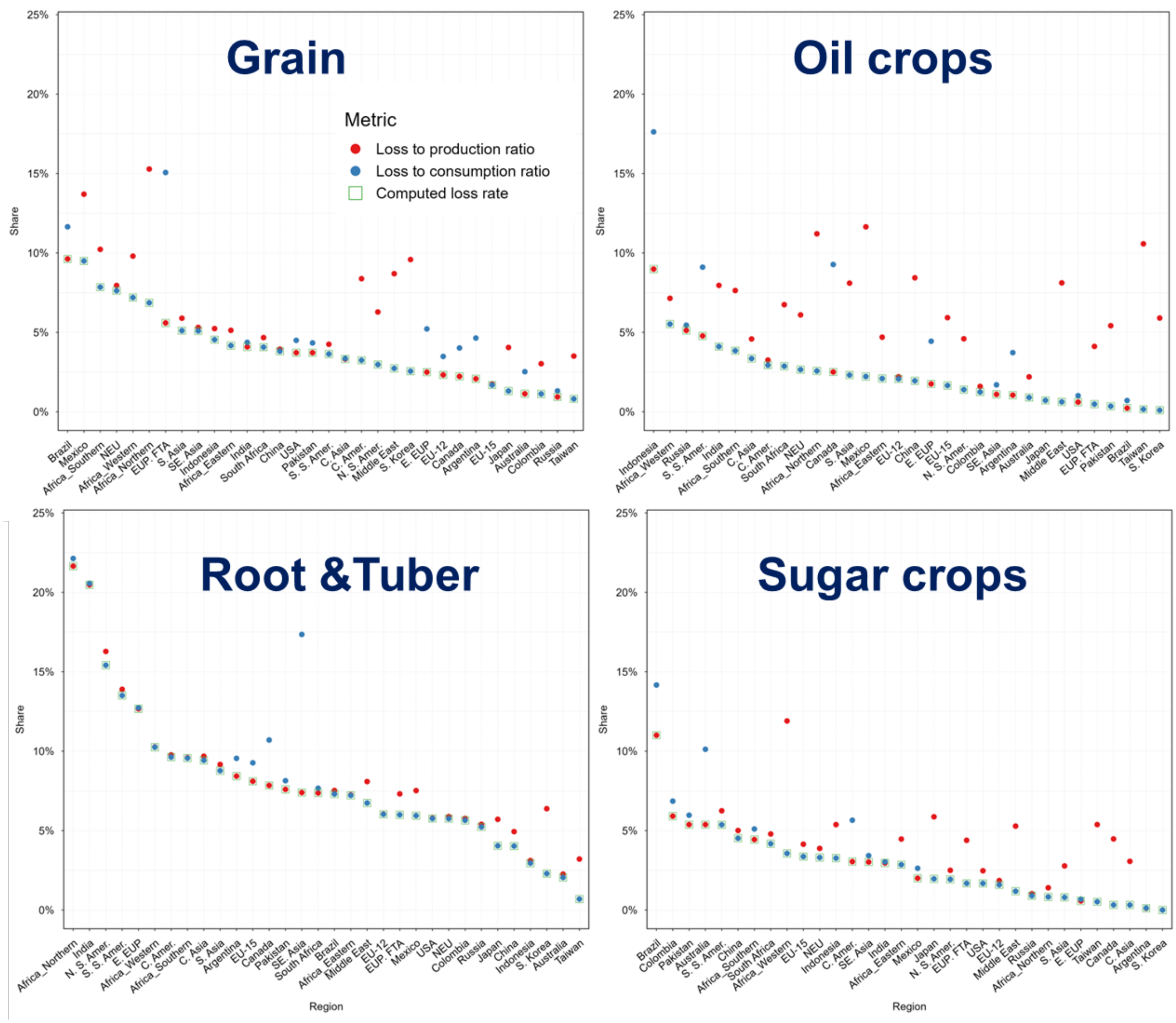

Fig. 6 Loss-to-production ratio and loss-to-consumption for key GCAM commodities by GCAM region. The lower value between the two is used as the interannual storage loss rate.

Agricultural storage cost data is not widely available, with limited literature focusing on grains in specific regions of interest (**Table 1**). It is crucial to consider that, in modeling interannual storage, only the cost specifically associated with interannual storage should be included. Intraannual storage costs are typically factored into market prices used for pricing current consumption. Therefore, our aim is to account for the additional cost incurred by a speculative stockholder when storing across periods within the logit competition framework. Based on the summarized data points in **Table 1**, we will assume an interannual storage cost to be 3% of the producer prices in all regions and sectors for simplicity, and this cost is set to be constant over time by default.

Table 1 Summary of storage cost in the literature

Region	Description Interannual storage cost share	Source
USA (& developed regions)	In the USA and other developed regions, advanced storage technologies (e.g., grain bins with drying systems), either on-farm or commercially rented, are commonly employed. Several extension studies have outlined the calculation of the levelized cost for grain storage using grain bins. Based on the values provided by Edwards et al. (2014), the one-year storage cost for corn ranges from \$0.8 to \$1.1 per bushel, constituting approximately 11% to 13% of the producer prices (as of 2015). Assuming the last six months are considered "interannual", the share would be 3% to 7%. The storage cost for soybeans is slightly lower than that for corn, with a comparable "interannual" cost share of 3% to 5%.	(Duncan et al., 2022; Edwards, 2014)
Arab Countries /Middle East	The marginal storage cost in 2009 ranged from \$1.69 (Jordan) to \$3.47 (Tunisia) per ton per month. Converting these values to full-year (12-month) costs in 2015\$ and assuming 50% of the cost is "interannual", the overall cost represents 2% to 4.5% of producer prices for grains such as corn, rice, wheat, and other grains.	(David, 2012; Larson et al., 2014)
African countries	In Africa and other underdeveloped regions, crop storage practices tend to be less efficient, leading to relatively higher losses. Recently, Purdue Improved Crop Storage (PICS) bags were developed to enhance grain storage, reducing losses in African regions at a lower capital cost. The cost is approximately \$12.5 per ton per year, whereas standard bags cost \$1.7 per ton per year. Even with a 100% overhead cost assumption, storage costs using standard bags would be about 1.2% of producer prices. However, the cost could range from 5% to 8% when utilizing PIC bags. If we assume 50% of the cost to be "interannual", the overall cost would be in the range of 1% to 4%.	(Baributsa et al., 2015; Dijkink et al., 2022; Kotu et al., 2019; Manandhar et al., 2018; Ndegwa et al., 2016; Sudini et al., 2015)

2.3. Overview of key changes in GCAM, gcamdata, and Model Interface queries

The key data and code changes implemented in GCAM and gcamdata are summarized in **Table 2**, with the query changes illustrated in **Fig. 4**. Also, throughout the development stages, several technical challenges were successfully addressed through data or code improvements. One notable example pertains to initial price data and related parameter calibration. Specifically, in regions where crops are both import-dependent and storage-dependent, such as Wheat in South Korea, the inclusion of storage (opening) in the Armington domestic supply can influence trade and make responses more sensitive to initial calibration and parameters (Armington/trade elasticities). This sensitivity may lead to price oscillations, theoretically possible with lagged expectations but more related to parameters than expectation schemes. In previous tests, cases of this nature were identified, such as South Korea Wheat and Corn, where oscillations could potentially be transmitted to other regions.

Further investigation revealed that the issue was driven by the extremely large difference between domestic and imported prices in the base year (e.g., South Korea Wheat: 0.3 vs. 0.04). Such significant price differences typically require "extreme" share-weights for calibration, rendering the model more sensitive to parameters and challenging to solve. Additionally, after incorporating storage in the "domestic" supply (even though most wheat stored in South Korea was imported in the last period), the issue was exacerbated. To address this challenge, we updated domestic prices to partially value storage at international prices during initial calibration. This adjustment proved particularly beneficial for region-crops that are both import-dependent and storage-dependent. Further details are documented in the file zaglu_L100.regional_ag_an_for_prices.R in gcamdata, where two storage- and trade-related metrics are now employed.

Table 2 key data and code changes made in gcamdata

Data file/R chunk/CPP	Changes made
ag_storage_technology.cpp ag_storage_technology.h	New GCAM codes specifying the storage technology.
configuration_ref.xml & all other configuration files	Add the new ag_storage.xml <Value name = "ag_storage">../input/gcamdata/xml/ag_storage.xml</Value>
aglu/A_agRegionalSector.csv aglu/A_agRegionalSubsector.csv aglu/A_agRegionalTechnology.csv	Regional crop and livestock commodities are renamed to "total" commodities. E.g., regional corn to total corn. Forestry sectors are not changed.
aglu/A_agStorageSector.csv	New ag. storage parameter and configuration file. • When storage_model = T in the file for a sector, the supply utilization will include storage data and stockholding behavior will be modeled. • When storage_model = F, a pass-through tech will be used. • The logit exponent governs the responses.
ModelInterface_headers.txt	Headers added for FOOD STORAGE TECHNOLOGY
module-helpers.R	Improve functions: Moving_average() and GROSS_TRADE_ADJUST()
zaglu_L100.FAO_SUA_PrimaryEquivalent.R zaglu_L100.FAO_SUA_connection.R	Separate storage data and process the data needed for calculating storage loss rates. Ensure data consistency in aggregation
zaglu_L109.ag_an_ALL_R_C_Y.R	Adding storage data into supply-utilization balance in gcamdata
zaglu_L113.ag_storage.R zaglu_xml_ag_storage.R	New chunk for processing storage data and parameters and generating ag_storage.xml.
zaglu_L240.ag_trade.R	Adjust domestic supply to add the opening stock.
zenergy_L122.gasproc_refining.R zenergy_L221.en_supply.R	Fix the linkage since A_agRegionalSector.csv was updated.
zaglu_L100.regional_ag_an_for_prices.R	Update initial prices since opening stock is added to the domestic market. We need to make sure the initial parameter calibrations make sense.
zaglu_xml_prune_empty_ag.R	The pruning of the technologies was updated with the consideration of storage.

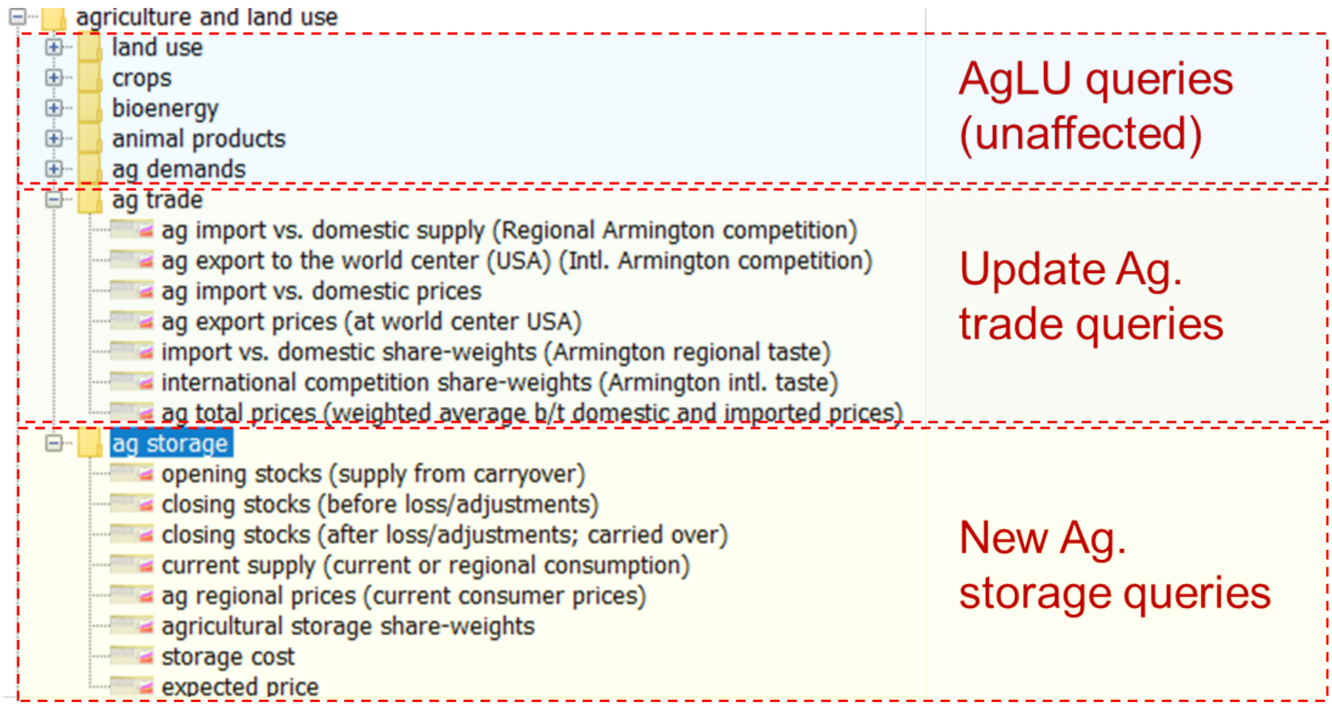

Fig. 7 GCAM query updates in Model Interface. A few trade queries are updated due to the variable naming changes, e.g., "total corn" is now the Armington aggregation of domestic and imported corn. And new queries for agricultural storage related results are added.

3. Shared policy assumption (SPA) GCAM validation runs

In accordance with the GCAM CMP convention, we present GCAM projection results, comparing the Updated (Agstor.) branch with a recent Master branch (CMP-393; AgLU parameter updates) for reference and RCP 2.6 scenarios across shared socioeconomic pathways (GCAM core & SSP1-5 assumptions; excluding SSP3-RCP2p6). It is worth noting that the land supply and food demand parameters updated in CMP 393, developed by Zhao et al. (2024b), lay the foundation for agricultural storage development in this CMP, as the economic responses of stockholding could be sensitive to these parameters as well. In addition, we provide key global results in the figures below, with more detailed results available in supplementary information (SI).

With the proposed updates, we can now address the first question: What are the projected agricultural storage and corresponding losses by the end of the century across the SPA scenarios? GCAM is now capable of extending the base year storage and loss data into the future, and these projections vary with GCAM's socioeconomic and biophysical drivers, resulting in differences across the SPA scenarios (**Fig. 8**). The full SUA for GCAM staple crops is illustrated in **Fig. 9** for both branches and the differences between them.

In addition to presenting additional results in the SUA accounts, the update has also influenced market equilibrium by revealing changes in storage demand that differ from what was implied in "other use" in the original branch. In the original approach, storage increase is demanded (growing with population) so the stock cannot decrease, while the new approach includes a dynamic representation of storage changes. In the updated projection, “other use” decreased since the storage variation was separated in the base year. Importantly, the updated branch’s projection indicates that the expansion of storage slows down over time (due to saturating demand, dietary transitions, etc.; compared to “other use”). Relatively, the lower demand for storage resulted in lower production as well. Similar patterns are observed for most GCAM storage commodities (impacts on the sugar crops and oil crops were different likely due to stronger demand responses; see SI for detailed results), while the impact of the updates on the SUA of non-storage commodities is relatively small.

For the long-term agroeconomic projections, the impact of the updates proposed in this CMP directly influenced demand responses, specifically weakening stock demand even considering storage loss. This, in turn, encouraged ripple effects across agriculture, energy, and other systems. Generally, these ripple effects are reasonable and mostly moderate, as expected.

The land use change results are depicted in **Figs. 10 & 11**. The decreased production, resulting from weaker demand, led to reduced harvested areas for most crops (excluding sugar and oil crops). Consequently, other arable land and various land covers, including pasture and forest, as well as other natural land, increased. Notably, afforestation in SSP1 under 2p6 was higher than in other SSPs, partly due to the earlier commencement of land carbon policies. This afforestation led to a tradeoff with the terrestrial carbon sink, resulting in a lower carbon budget (**Fig. 12**) and slightly higher carbon prices (**Fig. 13**) for SSP1. Lower carbon prices were observed in other scenarios, and land use change emissions decreased across all scenarios. Furthermore, the updates resulted in lower crop prices for storage commodities, reflecting the less rigid demand, while the price impacts on non-storage commodities were negligible (**Fig. 14**).

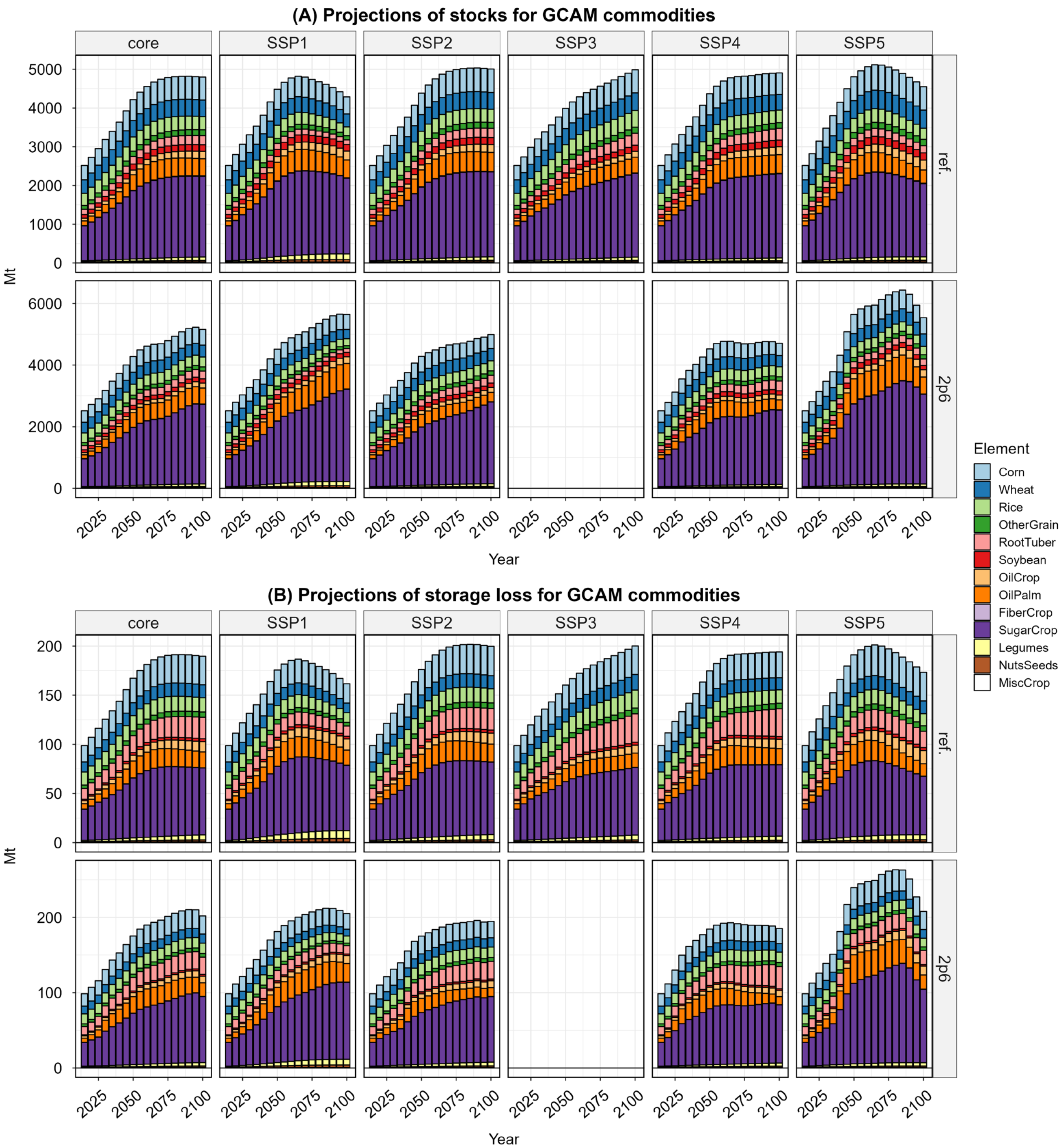

Fig. 8 Global agricultural storage and the corresponding losses in SPA projections in the updated branch

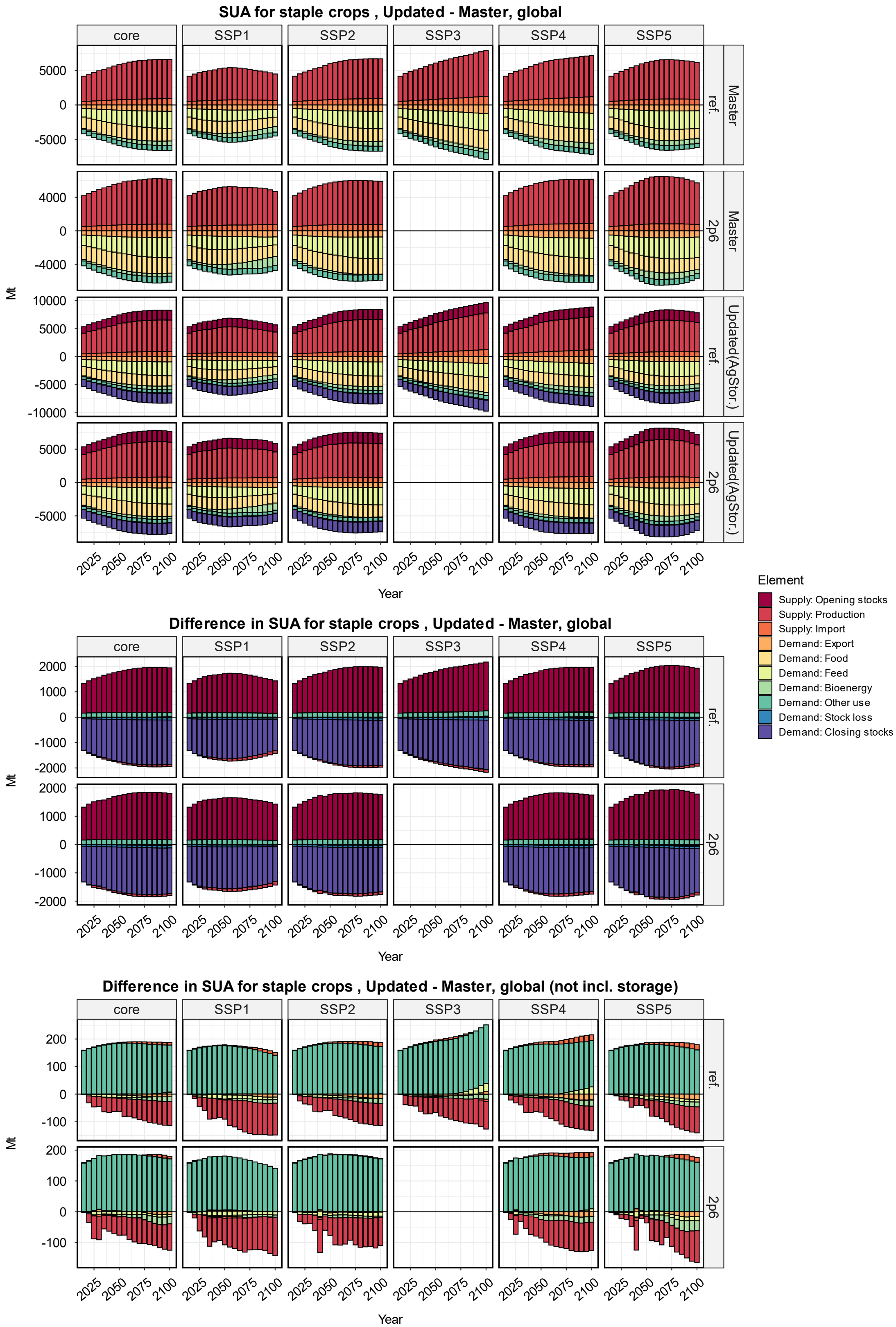

Fig. 9 Global agricultural supply utilization accounts for GCAM staple crops across SPA runs. Note that negative values are used for demand elements. The negative imbalance in the bottom panel indicates smaller stock variation (increase) in the updated branch.

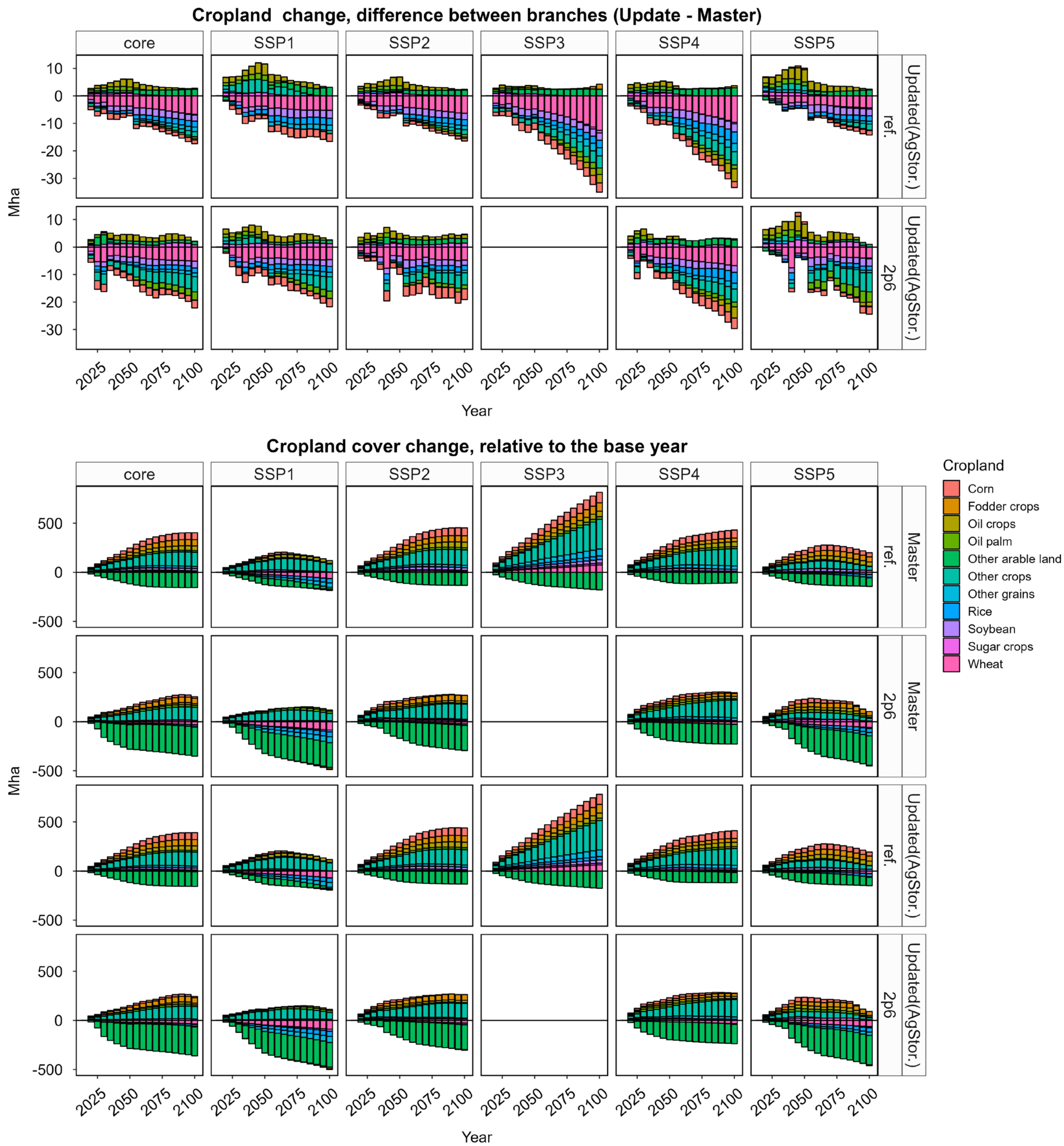

Fig. 10 Global cropland use change by sectors across SPA runs.

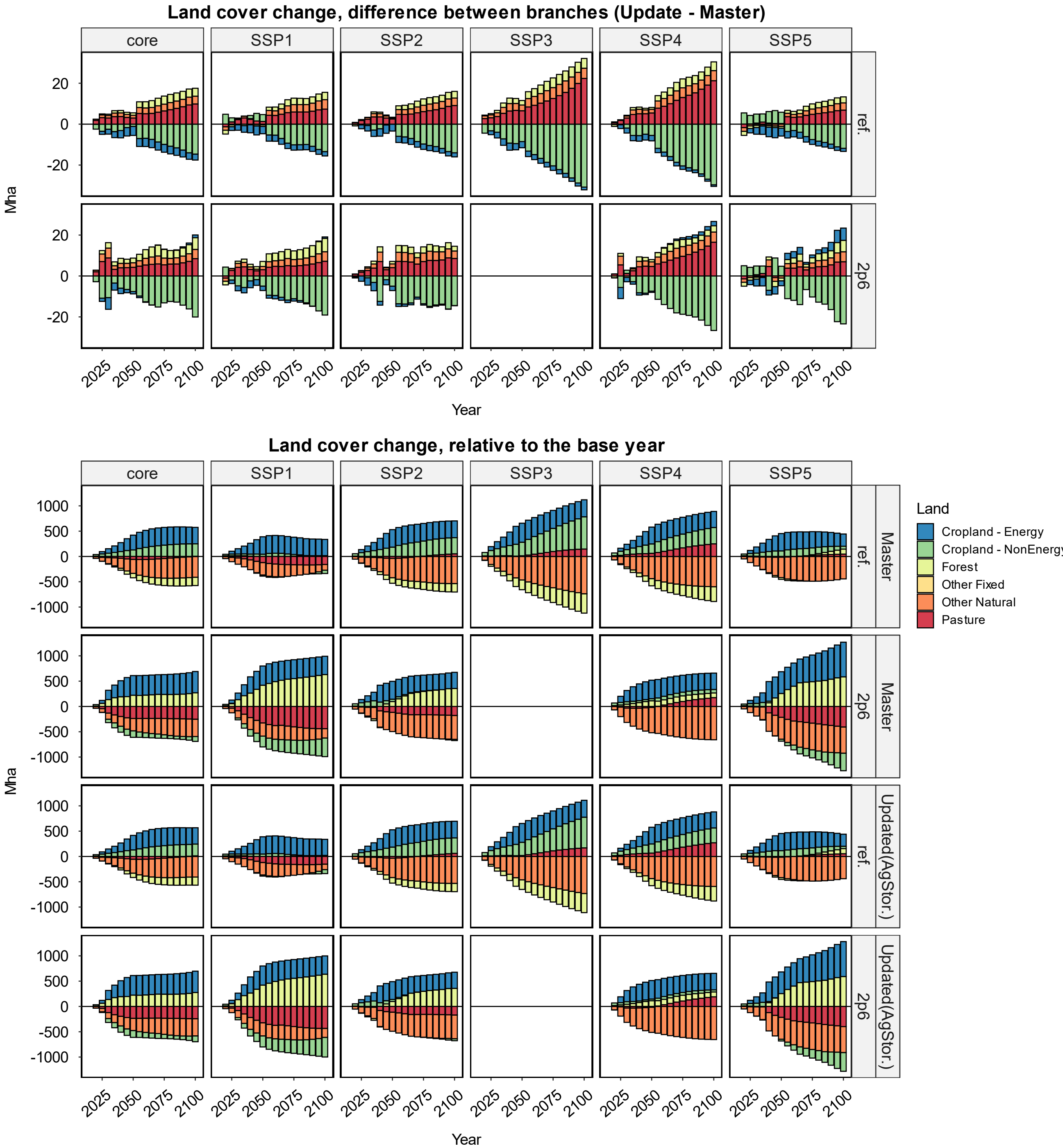

Fig. 11 Global land cover change across SPA runs.

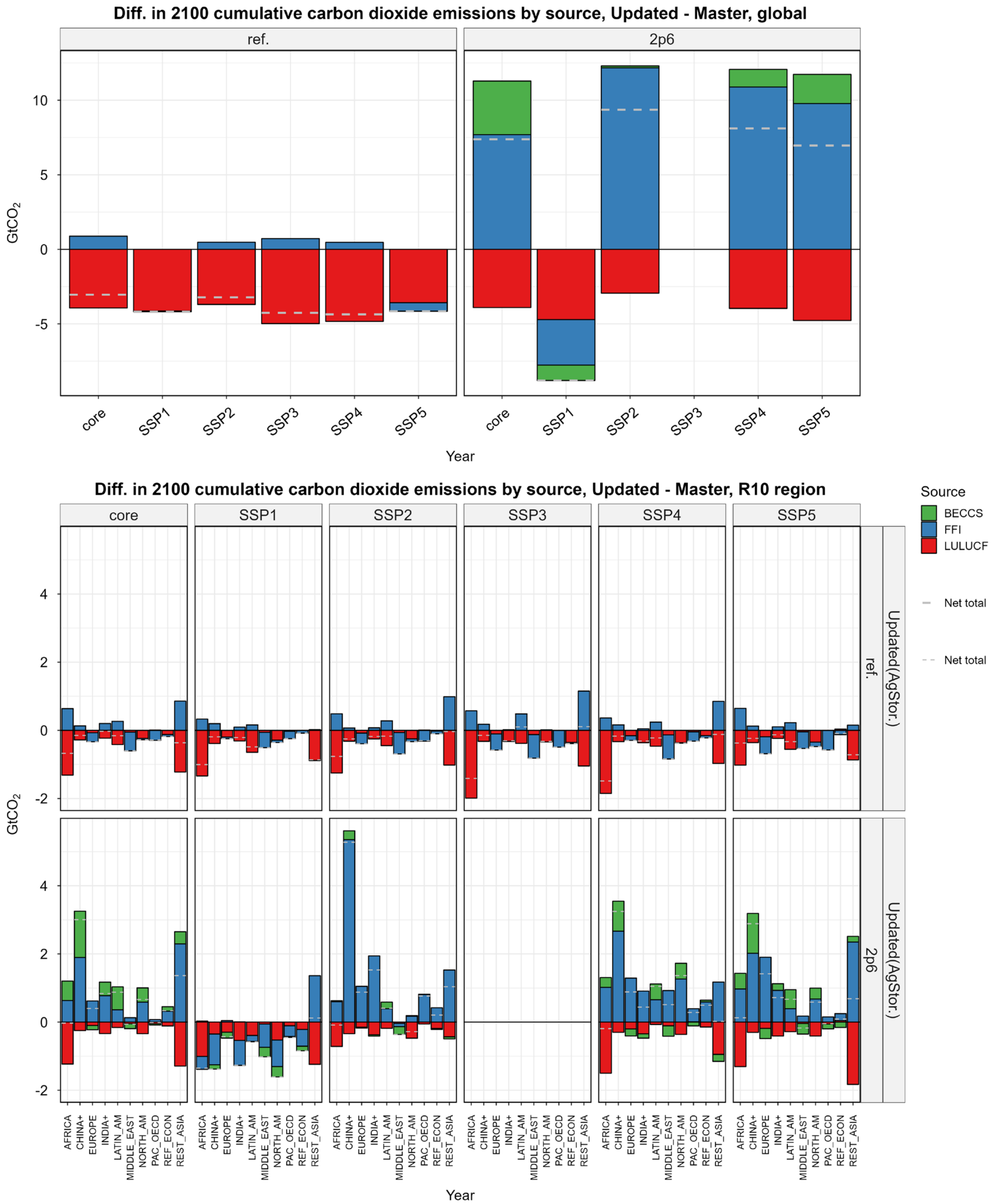

Fig. 12 Global and regional changes in cumulative carbon dioxide emissions in 2020 - 2100. LULUCF stands for Land Use, Land-Use Change and Forestry.

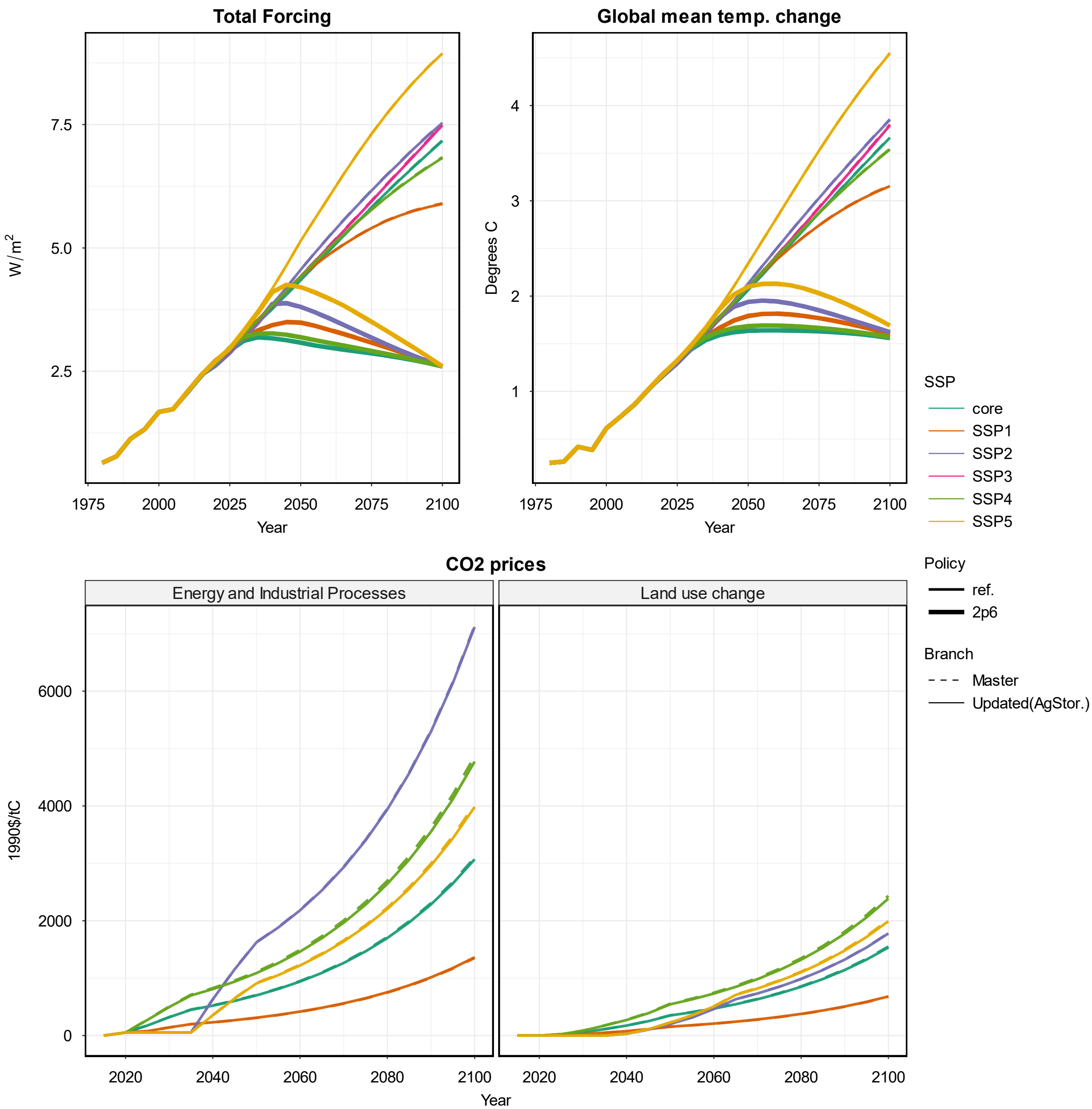

Fig. 13 Forcing, mean temperature change, and carbon prices.

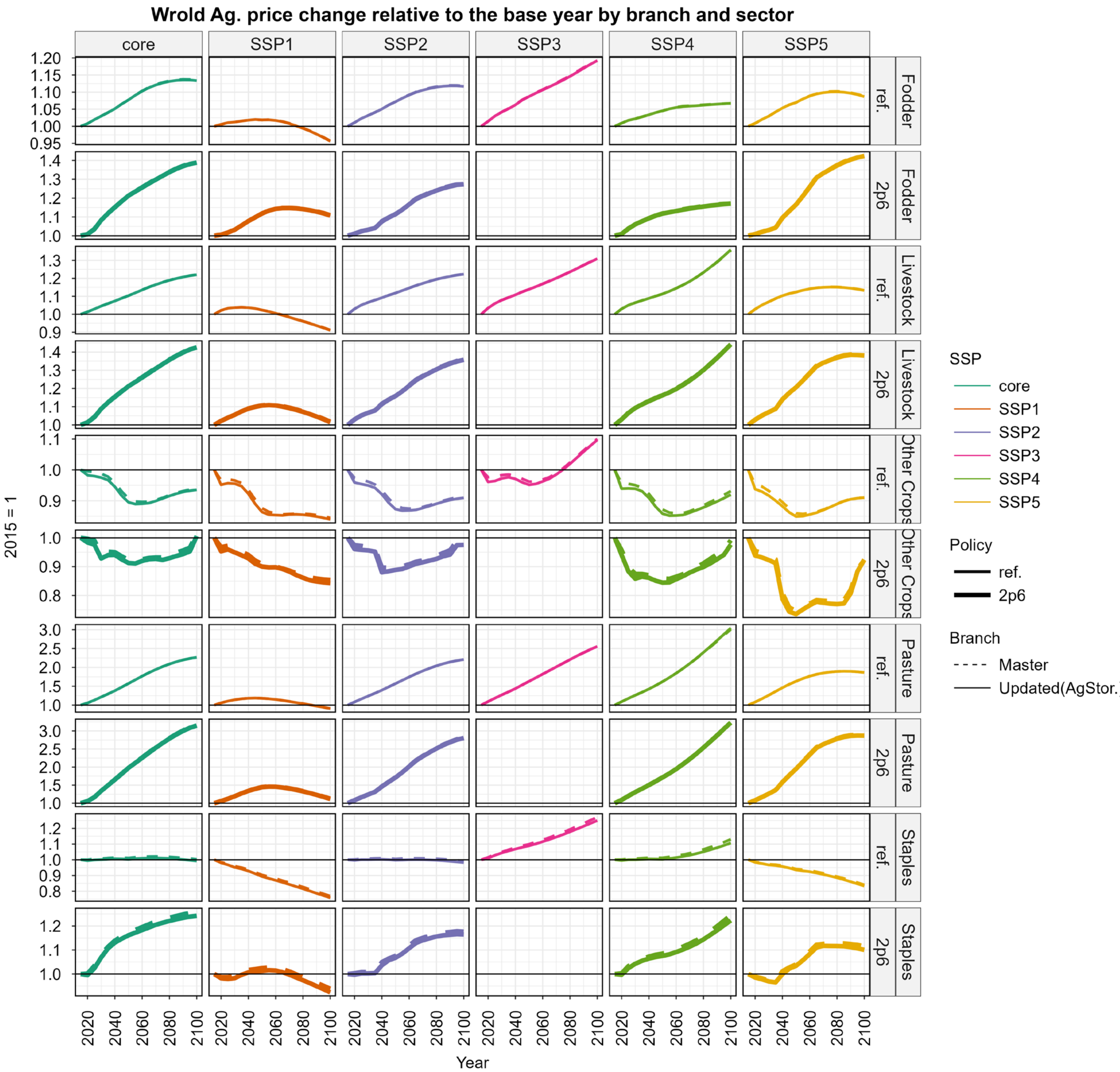

Fig. 14 Global agricultural prices by sector.

4. Additional sensitive analysis

In addition to the conventional SPA runs, we also tested a set of scenarios with alternative storage parameters or assumptions based on the GCAM core 2p6 scenario. Note that these additional tests were run based on a version of GCAM with regional biomass parameters (see CMP-393 future work) in all scenarios. We did not update those parameters (to global values) here since the results shown here are likely not sensitive to those regional parameters and the goal is only to showcase the sensitivity of storage parameters.

- GCAM_2p6: the default GCAM core 2p6 scenario included in SPA. This scenario has a logit exponent of 1 for storage, and the loss rate is constant.
- GCAM_2p6_LE0 and GCAM_2p6_LE2: varying the storage logit parameter to 0 (LE0) or 2 (LE2).
- GCAM_2p6_LowLoss: linearly decreasing the storage loss rate to zero by 2050.

The goal of these scenarios is to highlight the potentially diverse responses of the stock-to-gross-use ratio across different regions, sectors, and scenarios (**Fig. 15**). Overall, the variation in the stock-to-gross-use ratio is relatively small, primarily because market prices did not vary significantly, despite drops in 2025 when carbon policies were introduced. Regional variations may be more pronounced than global variations, influenced by aggregations. When comparing sensitivity scenarios, the results align with theoretical expectations. A larger logit exponent encourages stronger storage responses, and vice versa. Lower loss leads to reduced costs for storage, encouraging higher stocks (and also lower supply).

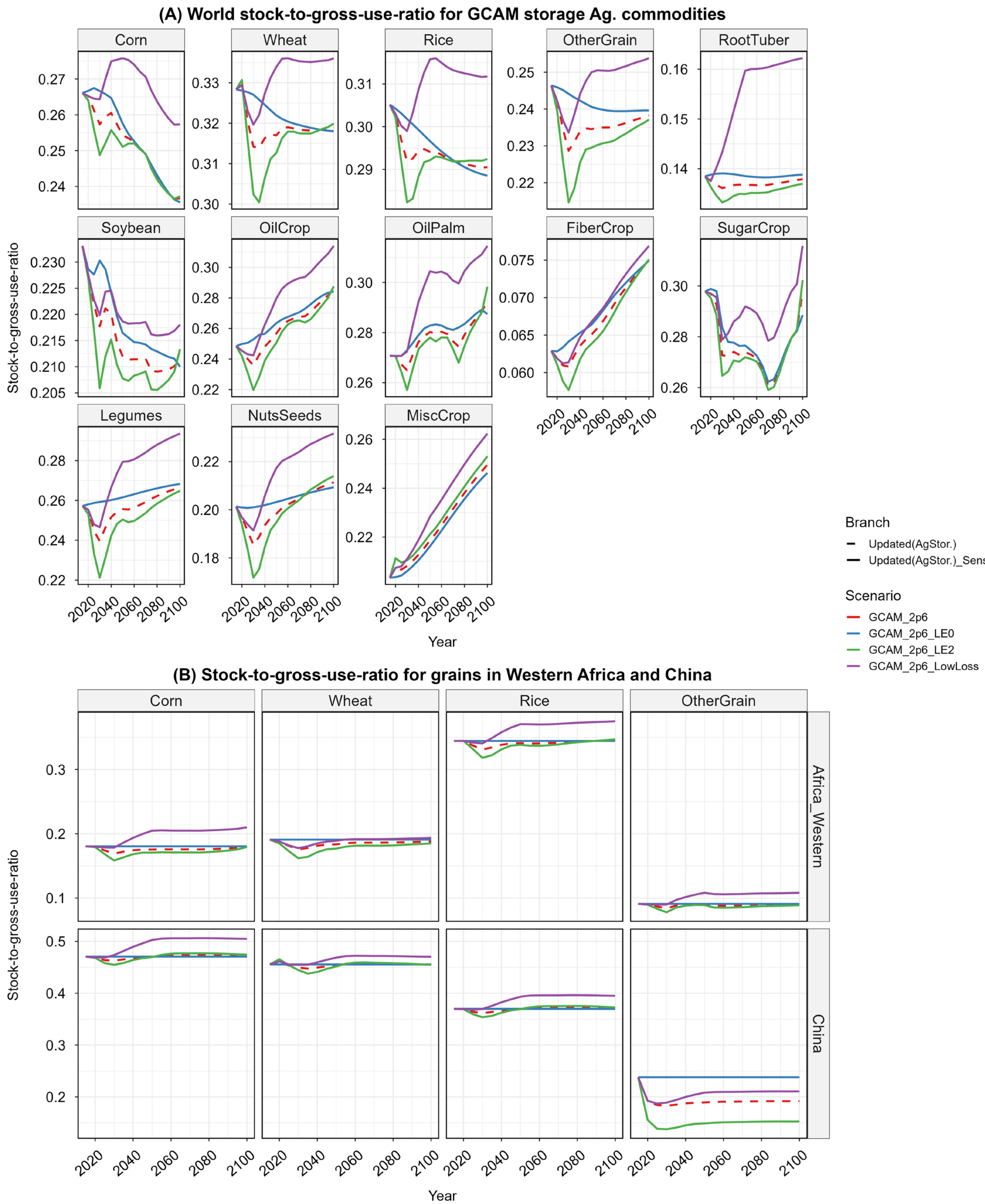

Fig. 13 Stock-to-gross-use ratio in sensitivity scenario.

5. Summary and future work

In this CMP, we provide detailed documentation of the changes made to represent agricultural storage and the inter-period stockholding behavior for agricultural and food products in GCAM. Specifically, we leveraged newly compiled supply-utilization account data that explicitly includes storage-related accounts and developed a competitive storage model where current consumption competes with future consumption within a logit framework. By incorporating these changes into GCAM, we generated projections of agricultural storage and related variables for all regions and storage crops (most food crops except vegetables and fruits) across SSPs and corresponding RCP2.6 scenarios. Our results demonstrated overall improvements in evaluating agroeconomic outcomes and multisectoral implications. These data and behavioral developments can be utilized in any global economic and multisector dynamic model.

The CMP lays the foundation for future work in the following areas:

a) Parameters and expectation schemes
   - Currently, we use lagged expectations to price future consumption for simplicity. However, alternative expectation schemes could be tested.
   - It may be beneficial to test regional and sectoral parameters for stockholding behavior when relevant literature is available.
   - Check rationality: Ensure long-term profit/loss from speculative stockholding to confirm that expectations are not systematically incorrect.

b) Storage for livestock and other sectors
   - Currently, storage is modeled for major food crops. Future work is needed to represent the stockholding behavior of livestock products, dedicated energy crops, and fishing and agricultural products.

c) The role of storage in mediating interannual variability
   - While storage modeling is developed for the default 5-year step in GCAM, the functionality should also work with different temporal resolutions, such as an annual step version.
   - Future work can leverage this development to study the role of storage and its interactions with trade under annual biophysical or socioeconomic shocks.

6. Supplementary information

Table S1 Agricultural commodity mapping between GCAM commodity and FAO.

GCAM commodity	FAO primary item (240)
Wheat	Wheat
Rice	Rice, paddy
Corn	Maize
OtherGrain	Barley; Buckwheat; Canary seed; Cereals nes; Fonio; Grain, mixed; Oats; Quinoa; Rye; Triticale; Millet; Sorghum
Soybean	Soybeans
OilPalm (Tree)	Oil palm fruit
OilCrop	Castor oil seed; Hempseed; Jojoba seed; Linseed; Melonseed; Mustard seed; Oilseeds nes; Poppy seed; Rapeseed; Safflower seed; Sesame seed; Sunflower seed
OilCrop (Tree)	Coconuts; Kapok fruit; Karite nuts (sheanuts); Olives; Tallowtree seed; Tung nuts
RootTuber	Cassava; Potatoes; Roots and tubers nes; Sweet potatoes; Taro (cocoyam); Yams; Yautia (cocoyam);
FiberCrop	Fibre crops nes; Flax fibre and tow; Hemp tow waste; Jute; Manila fibre (abaca); Ramie; Seed cotton; Sisal
NutsSeeds	Groundnuts, with shell
NutsSeeds (Tree)	Almonds, with shell; Areca nuts; Brazil nuts, with shell; Cashew nuts, with shell; Chestnut; Hazelnuts, with shell; Kola nuts; Nuts nes; Pistachios; Walnuts, with shell
Legumes	Bambara beans; Beans, dry; Broad beans, horse beans, dry; Chick peas; Cow peas, dry; Lentils; Lupins; Peas, dry; Pigeon peas; Pulses nes; Vetches
SugarCrop	Sugar cane; Sugar beet; Sugar crops nes
Vegetables	Artichokes; Asparagus; Beans, green; Cabbages and other brassicas; Carobs; Carrots and turnips; Cassava leaves; Cauliflowers and broccoli; Chicory roots; Chillies and peppers, dry; Chillies and peppers, green; Cucumbers and gherkins; Eggplants (aubergines); Garlic; Leeks, other alliaceous vegetables; Lettuce and chicory; Maize, green; Melons, other (inc.cantaloupes); Mushrooms and truffles; Okra; Onions, dry; Onions, shallots, green; Peas, green; Pumpkins, squash and gourds; Spinach; String beans; Tomatoes; Vegetables, fresh nes; Vegetables, leguminous nes; Watermelons
Fruits	Berries nes; Blueberries; Cranberries; Currants; Gooseberries; Grapes; Pineapples; Raspberries; Strawberries
Fruits (Tree)	Apples; Apricots; Avocados; Bananas; Cashewapple; Cherries; Cherries, sour; Dates; Figs; Fruit, citrus nes; Fruit, fresh nes; Fruit, pome nes; Fruit, stone nes; Fruit, tropical fresh nes; Grapefruit (inc. pomelos); Kiwi fruit; Lemons and limes; Mangoes, mangosteens, guavas; Oranges; Papayas; Peaches and nectarines; Pears; Persimmons; Plantains and others; Plums and sloes; Quinces; Tangerines, mandarins, clementines, satsumas
MiscCrop	Anise, badian, fennel, coriander; Ginger; Hops; Pepper (piper spp.); Peppermint; Pyrethrum, dried; Spices nes; Tea; Tobacco, unmanufactured; Vanilla
MiscCrop (Tree)	Cinnamon (cannella); Cloves; Cocoa, beans; Coffee, green; Mate; Nutmeg, mace and cardamoms; Rubber, natural;
FodderGrass	forage Products; Grasses Nes for forage; Grasses Nes for forage; Rye grass for forage & silage
FodderHerb	Alfalfa for forage and silage; Beets for Fodder; Cabbage for Fodder; Carrots for Fodder; Clover for forage and silage; Green Oilseeds for Silage; Leguminous for Silage; Swedes for Fodder; Turnips for Fodder; Vegetables Roots Fodder; Maize for forage and silage; Sorghum for forage and silage
Beef	Meat, cattle; Meat, buffalo
Dairy	Milk, whole fresh cow; Milk, whole fresh camel; Milk, whole fresh buffalo; Milk, whole fresh goat; Milk, whole fresh sheep
Pork	Meat, pig
Poultry	Meat, duck; Meat, goose and guinea fowl; Meat, turkey; Meat, chicken; Meat, chicken; Eggs, other bird, in shell; Eggs, hen, in shell;
SheepGoat	Meat, sheep; Meat, goat
OtherMeat &Fish	Freshwater Fish; Fish, Body Oil; Fish, Liver Oil; Demersal Fish; Pelagic Fish; Marine Fish, Other; Crustaceans; Cephalopods; Molluscs, Other; Aquatic Animals, Others; Aquatic Plants; Meat, Aquatic Mammals; Meat, rabbit; Meat, camel; Meat, other camelids; Meat, horse; Meat, ass; Meat, mule; Meat, other rodents; Meat, bird nes; Meat, game; Meat nes; Offals, edible, cattle; Offals, edible, buffaloes; Offals, pigs, edible; Offals, sheep,edible; Offals, edible, goats; Offals, horses; Offals, edible, camels; Offals, liver chicken; Offals, liver geese; Offals, liver duck; Offals, liver turkeys; Offals nes; Liver prep.; Fat, cattle; Fat, buffaloes; Fat, sheep; Fat, goats; Fat, pigs; Fat, camels; Fat, other camelids; Oils, fats of animal nes; Degras; Grease incl. lanolin wool; Fat nes, prepared; Honey, natural; Snails, not sea

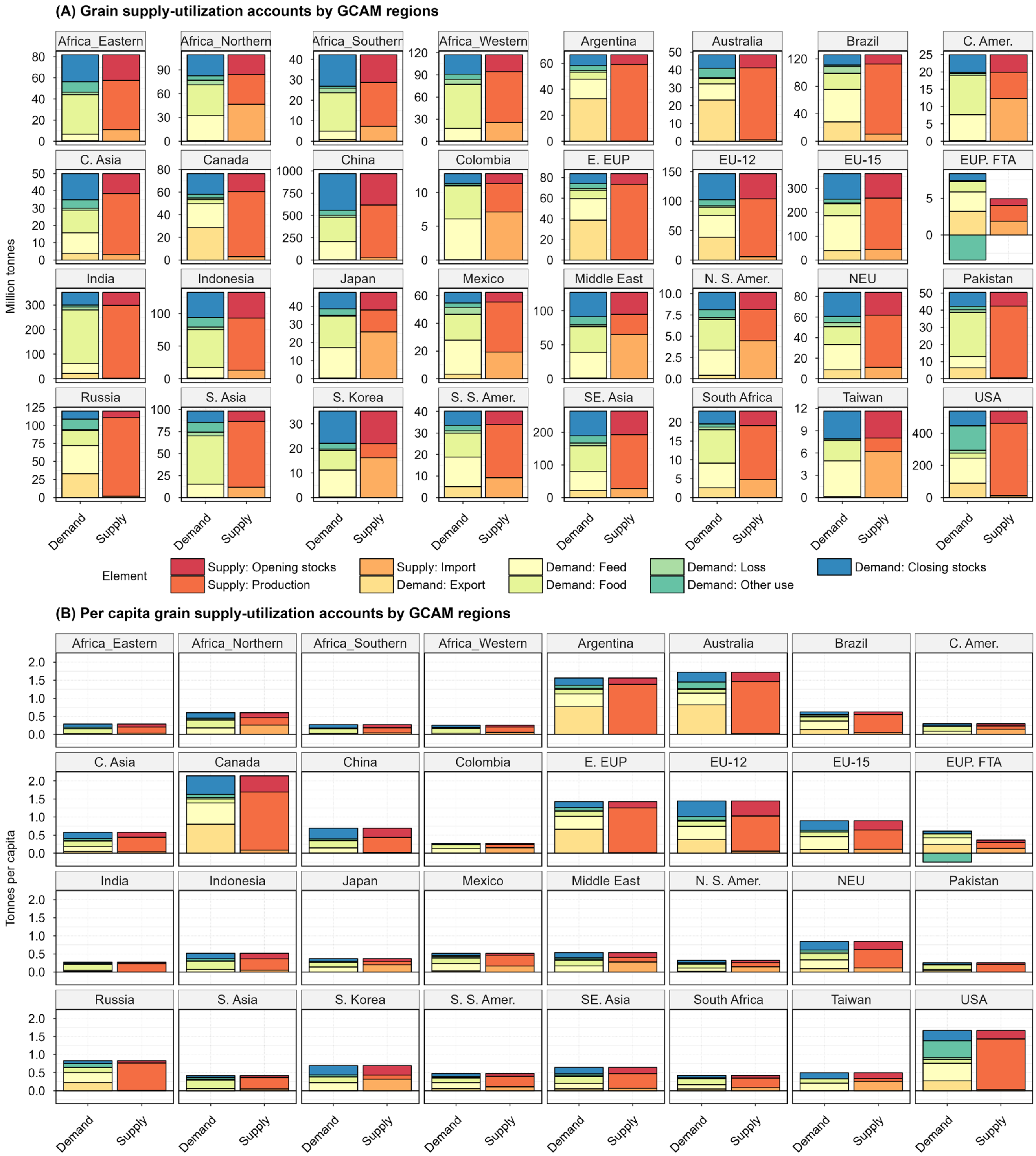

Fig. S1 Supply-utilization for total grains accounts (A) and per capita accounts (B) in GCAM 32 regions in GCAM base year. Grains include Corn, Rice, Wheat, and OtherGrain in GCAM.

References

Baributsa, D., Baoua, I., Djibo, K., Murdock, L., 2015. Using and Recycling Purdue Improved Crop Storage (PICS) Bags.

Bobenrieth, E., Wright, B., Zeng, D., 2013. Stocks-to-use ratios and prices as indicators of vulnerability to spikes in global cereal markets. Agricultural Economics 44, 43–52. https://doi.org/10.1111/agec.12049

Clarke, J.F., Edmonds, J.A., 1993. Modelling energy technologies in a competitive market. Energy Economics 15, 123–129. https://doi.org/10.1016/0140-9883(93)90031-L

David, B., Michelle L. ,Erekat,Dana Mohamed,Lampietti,Julian A. ,De Hartog,Arnold H. ,Michaels,Sean, 2012. The grain chain : food security and managing wheat imports in Arab countries (Text/HTML).

Diffenbaugh, N.S., Hertel, T.W., Scherer, M., Verma, M., 2012. Response of corn markets to climate volatility under alternative energy futures. Nature Clim Change 2, 514–518. https://doi.org/10.1038/nclimate1491

Dijkink, B., Broeze, J., Vollebregt, M., 2022. Hermetic Bags for the Storage of Maize: Perspectives on Economics, Food Security and Greenhouse Gas Emissions in Different Sub-Saharan African Countries. Frontiers in Sustainable Food Systems 6.

Duncan, W.H., Smith, S.A., Narayanan, C.R., Martinez, C.C., 2022. Estimating Costs for Grain Storage: Bags and Bins.

Edwards, W., 2014. Cost of Storing Grain. Ag Decision Maker.

Hertel, T.W., Reimer, J.J., Valenzuela, E., 2005. Incorporating commodity stockholding into a general equilibrium model of the global economy. Economic Modelling 22, 646–664. https://doi.org/10.1016/j.econmod.2005.02.001

Kotu, B.H., Abass, A.B., Hoeschle-Zeledon, I., Mbwambo, H., Bekunda, M., 2019. Exploring the profitability of improved storage technologies and their potential impacts on food security and income of smallholder farm households in Tanzania. Journal of Stored Products Research 82, 98–109. https://doi.org/10.1016/j.jspr.2019.04.003

Larson, D.F., Lampietti, J., Gouel, C., Cafiero, C., Roberts, J., 2014. Food Security and Storage in the Middle East and North Africa. The World Bank Economic Review 28, 48–73. https://doi.org/10.1093/wber/lht015

Manandhar, A., Milindi, P., Shah, A., 2018. An Overview of the Post-Harvest Grain Storage Practices of Smallholder Farmers in Developing Countries. Agriculture 8, 57. https://doi.org/10.3390/agriculture8040057

Mitra, S., Boussard, J.-M., 2012. A simple model of endogenous agricultural commodity price fluctuations with storage. Agricultural Economics 43, 1–15. https://doi.org/10.1111/j.1574-0862.2011.00561.x

Ndegwa, M.K., De Groote, H., Gitonga, Z.M., Bruce, A.Y., 2016. Effectiveness and economics of hermetic bags for maize storage: Results of a randomized controlled trial in Kenya. Crop Protection 90, 17–26. https://doi.org/10.1016/j.cropro.2016.08.007

Schewe, J., Otto, C., Frieler, K., 2017. The role of storage dynamics in annual wheat prices. Environ. Res. Lett. 12, 054005. https://doi.org/10.1088/1748-9326/aa678e

Sudini, H., Ranga Rao, G.V., Gowda, C.L.L., Chandrika, R., Margam, V., Rathore, A., Murdock, L.L., 2015. Purdue Improved Crop Storage (PICS) bags for safe storage of groundnuts. Journal of Stored Products Research, Integrated Protection of Stored Products: sustainability in practice 64, 133–138. https://doi.org/10.1016/j.jspr.2014.09.002

Urban, D., Roberts, M.J., Schlenker, W., Lobell, D.B., 2012. Projected temperature changes indicate significant increase in interannual variability of U.S. maize yields. Climatic Change 112, 525–533. https://doi.org/10.1007/s10584-012-0428-2

Wright, B.D., 2011. The Economics of Grain Price Volatility. Applied Economic Perspectives and Policy 33, 32–58. https://doi.org/10.1093/aepp/ppq033

Wright, B.D., Williams, J.C., 1982. The Economic Role of Commodity Storage. The Economic Journal 92, 596–614. https://doi.org/10.2307/2232552

Zhao, X., Calvin, K.V., Wise, M.A., 2020. The critical role of conversion cost and comparative advantage in modeling agricultural land use change. Clim. Change Econ. 11, 2050004. https://doi.org/10.1142/S2010007820500049

Zhao, X., Calvin, K.V., Wise, M.A., Patel, P.L., Snyder, A.C., Waldhoff, S.T., Hejazi, M.I., Edmonds, J.A., 2021. Global agricultural responses to interannual climate and biophysical variability. Environ. Res. Lett. 16, 104037. https://doi.org/10.1088/1748-9326/ac2965

Zhao, X., Chepeliev, M., Patel, P., Wise, M., Calvin, K., Narayan, K., Vernon, C., 2024a. gcamfaostat: An R package to prepare, process, and synthesize FAOSTAT data for global agroeconomic and multisector dynamic modeling. Journal of Open Source Software 9, 6388. https://doi.org/10.21105/joss.06388

Zhao, X., Mignone, B.K., Wise, M.A., McJeon, H.C., 2024b. Trade-offs in land-based carbon removal measures under 1.5 °C and 2 °C futures. Nat Commun 15, 2297. https://doi.org/10.1038/s41467-024-46575-3

Zhao, X., Wise, M., 2023. Core Model Proposal #360: GCAM agriculture and land use (AgLU) data and method updates: connecting land hectares to food calories (Core Model Proposal No. PNNL-34313). Joint Global Change Research Institute, PNNL, College Park, USA.