Core Model Proposal #338: Regional Forest Markets and Crop Trade Updates

Product: Global Change Analysis Model (GCAM)

Institution: Joint Global Change Research Institute (JGCRI)

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Date committed: 5/21/2021

IR document number: PNNL-34611

Related sector: Agriculture, Land, Trade

Type of development: Data and Queries

Purpose: The main purpose of this proposal is to update the forest (i.e., Roundwood) trade modeling in GCAM from HOV (Heckscher-Ohlin Vanek) based fully integrated world market to segmented regional markets using the logit-based Armington approach. We also improve agricultural trade-related data, update trade (Armington) parameters based on literature information, and allow elastic forest demand responses. This CMP is an extension of previous GCAM agricultural trade CMPs (289 & 312).

Contents

Highlights & Key Takeaways

1) With this update, there are regional prices and gross trade for forest in GCAM (compared to one world price and net trade previously).
2) Trade parameters (Armington elasticities) are now updated to literature values for all traded crops, livestock, and forest sectors (not including biomass).
3) In general, the impacts from the updates in this CMP are more regional (relatively larger changes in African regions, S.E. Asia, and China) than global. Globally, there will be more land for forest and biomass (from both biomass tree and residues). There were also small impacts on the energy system due to the increased biomass (e.g., 6.7 EJ or 6% in 2100) supply.
4) *FAO_GDP_deflators* for all regions were used only for converting agricultural price data to constant prices in the base year (e.g., 2015). This was important for calculating 5-year average prices. Note that the gcamdata function *gdp_deflator()* includes only GDP deflators for the USA. So, we denominated prices from 2015$ back to 1975$ using USA deflators. *FAO_GDP_deflators* is now moved from Aglu/FAO/ to Common/ for potential future uses in other places, e.g., regional energy prices.
5) We create an R project to generate data in *Aglu/FAO/* directly from FAOSTAT (API) to have more consistent mappings/headers/data updates. Only forest and ag trade-related data are updated for now.

1 Introduction

The objective of this proposal is to introduce regional markets for forest production and trade in core GCAM (v5.3). Currently, forest is modeled following a Heckscher-Ohlin Vanek (HOV) framework with a global market. We will update this using the logit-based Armington approach; see Zhao et al. (2022). Also, GCAM currently assumes perfectly inelastic demand with respect to price and income for forest, i.e., zero price and income elasticities. We will test and update these elasticities based on literature information. Note that demand in GCAM is elastic for crops and livestock products for food use. Nonfood demand for agricultural products (including forest), if not explicitly modeled (e.g., biofuels feedstock uses were modeled), is assumed to be perfectly inelastic and change linearly with population. Altering demand response assumptions for forest could significantly impact projections, particularly when regional markets are incorporated.

Drawing a step back, before making modifications for forest trade, we first update bilateral trade and price data from 2010 (2008-2012) to 2015 (2013-2017) since these data are now available from FAO. Note that regional markets had been introduced for crops and livestock sectors in GCAM, though trade parameters were not distinguished for crop sectors. Along with data updates, trade parameters for crops will also be updated based on literature information. In addition, we also find inconsistencies in processing land area and productivity data for the managed forest for Pakistan and African regions. These are fixed after incorporating regional forest markets and demand elasticities. In the code review process, we found additional inconsistencies in the region mappings in FAO GDP deflators. We, thus, developed an R project to systematically download, track, and preprocess FAO data. We use this R project to update GDP deflators and all forest trade-related data. Thus, there are five tasks (sub-proposals) for this proposal:

1. Update existing trade data and parameters
2. Incorporate regional forest markets
3. Test and update forest demand parameters
4. Adjust forest land data to correct forest yield
5. Additional data updates (i.e., GDP deflators, forest production & trade)

For all the tasks, only changes in the GCAM data system are required, and the changes made are documented in **Table 1**. In this proposal, we demonstrate the impacts of these updates step-by-step on the reference projections, with a focus on agroeconomic implications. Also, we committed the changes sequentially so one can git reset the model to easily replicate results from the sub-tasks of this proposal. We will also discuss areas for future improvements or explorations.

Table 1 Modifications made in the data system for the proposed updates

Task	Files	Changes made
T1. Update existing trade data and parameter	Related trade and demand csv files (8 in total)	Change "root_tuber" to "roottuber" to be consistent with other crops. Also, correct typo ("dariy" to "dairy", from livestock trade update), which did not affect anything.
	aglu/FAO/FAO_ag_an_ProducerPrice.csv.gz aglu/FAO/FAO_BilateralTrade.csv.gz	Update FAO_BilateralTrade and FAO_ag_an_ProducerPrice to 2017 from 2012 based on FAO data. Note that empty cells in price data are filled as much as possible using FAO regional producer price index.
	constants.R	The aglu.TRADE_CAL_YEARS is updated to 2013:2017 to reflect the base year update to 2015
	zchunk_LB1091.ag_GrossTrade.R zchunk_LB1321.regional_ag_prices.R	Minor changes are made to process the updated trade and price data.
	aglu/A_agRegionalSector.csv aglu/A_agTradedSector.csv	Update (differentiate by sectors) regional and international gross trade (Armington) parameters for crops based on GTAP data (see Table). -3 and -6 were used previously.
T2. Incorporate regional forest markets	aglu/A_agRegional*.csv (3) aglu/A_agTraded*.csv (3) aglu/A_agSupplySector.csv aglu/A_demand_technology.csv	Where applicable, change "Forest" to "regional forest" or "traded forest" to make forest a regional demand sector. That is change the names along from supply to demand. Also, change supply to regional instead of global market. Note that Armington parameters of -2.5 (regional) and -5 (international) are used for forest.
	constants.R	Add aglu.TRADED_FORESTS for forest sectors. Add aglu.FOR_COST_SHARE (59%), which is nonland forest cost share implied by 2011 GTAP database (A fixed value of $29.59 per m3 was used previously).
	zchunk_L240.ag_trade.R	Using forest export data to back-calculate gross trade data from net trade data.
	zchunk_LB1091.ag_GrossTrade.R	Minor changes of crop sets.
	aglu/FAO_For_Exp_m3_USD_FORESTAT.csv	Add FAO forest export data to calculate export prices to be used as producer prices.
	zchunk_LB1321.regional_ag_prices.R	Process the new forest export data to calculate regional forest price (L1321.expP_R_F_75USDm3).
	zchunk_L2012.ag_For_Past_bio_input_irr_mgmt.R	Process regional forest prices.
	zchunk_L2052.ag_prodchange_cost_irr_mgmt.R	Differentiate forest cost by region in the base data based on aglu.FOR_COST_SHARE.
T3. Test and update forest demand parameters	A_demand_supplysector.csv	Change price and income elasticities for forest. A range of price (-0.2 - - 1) and income (0.2 - 1) elasticities are tested for sensitivity. Based on the sensitivity tests, -0.4 and 0.4 are used for price and income elasticities, respectively.
T4. Adjust forest land data based on FAO information	zchunk_LB120.LC_GIS_R_LTgis_Yh_GLU.R	Use managed forest to adjust total forest cover and other land covers (L120.LC_bm2_R_LT_Yh_GLU) to ensure that total forest cover is larger than managed forest. As a result, issues of forest yield are fixed.
	aglu/LDS/L123.LC_bm2_R_MgdFor_Yh_GLU_beforeadjust.csv	This file came from the original data system output (L123.LC_bm2_R_MgdFor_Yh_GLU), which includes processed managed forest.
T5. Additional data updates	aglu/FAO/FAO_GDP_deflators.csv	Updated and included Taiwan data. The dataset is moved to common/ for potential uses in other places.
	aglu/FAO/FAO_For_Imp_m3_FORESTAT.csv aglu/FAO/FAO_For_Prod_m3_FORESTAT.csv aglu/FAO/FAO_For_Exp_m3_FORESTAT.csv aglu/FAO/FAO_For_Imp_m3_FORESTAT.csv	Updated to the latest data using an R project created.

2 Task 1: update existing trade data and parameter

We make use of the latest FAO data to update GCAM data of producer price and bilateral trade for crops and livestock sectors used from 2010 (2008-2012) to 2015 (2013-2017). The data updates affect modeling results through impacts on (1) initial data and (2) the associated calibration parameters (e.g., logit share-weights). Even though the updates in this proposal reflect a bugfix of data inconsistency issue, results also potentially imply how base year updates affect long-term projections, which could be an important source of uncertainty.

Changes in producer prices in this update were fairly large, given that 2008 – 2012 covers two food crises. Generally speaking, 2015 could likely be more representative than 2010 as a base year for long-term projections. Note that bilateral trade data was only used for the backward calculation of gross trade from net trade. In fact, with the gross trade modeling framework used in GCAM, we do not need bilateral trade data as gross trade data were available in the model and used for calculating net trade. However, we kept the bilateral data, given the potential future need to update bilateral trade modeling. But when bilateral trade is not available, e.g., roundwood (forest), gross trade will be employed directly.

In addition, the logit-based Armigngton trade parameters for crops are also differentiated by sectors (from -3 for regional and -6 for international) based on GTAP information (see **Table 2**). We demonstrate price, trade, and land use implications from the updates (see **Table 3** for experiments).

Table 2 Logit-based Armington parameters implied by the GTAP Data Base (Aguiar et al., 2019)

Sector	Regional	International
Corn	-1.3	-2.6
Fibercrop	-2.5	-5
Misccrop	-2.41	-4.82
Oilcrop	-2.99	-5.98
Othergrain	-1.3	-2.6
Palmfruit	-2.99	-5.98
Rice	-2.9	-5.8
Roottuber	-2.41	-4.82
Sugarcrop	-2.7	-5.4
Wheat	-4.45	-8.9

Table 3 Experimental design for Task 1

Task	Test	Experiment	Description
T1. Update existing trade data and parameter	Core	S1_0	Reference (original gcam-core)
	Core	S1_1	S1_0 + Update agricultural price and trade data to 2015
	Core	S1_2	S1_1 + Update Armington trade parameters for crops (Aguiar et al., 2016)

2.1 Impacts from data updates

The impacts of updating trade and prices data on prices, trade, and land use are shown in **Figs. 1 – 3**. The regional results for trade and land use are provided in Supplementary Information (**SI) Figs S1- S2**.

We used the producer price index to fill in missing values for producer price as much as possible. It had a major impact on India, where FAO prices were missing after 2008 (previously, 2008 prices were used for 2008:2012 in India). For the 544 sector-region combinations (17 sectors x 32 regions) shown in **Fig. 1**, due to the price data update, the base year (2015) price increased for 52% of the combinations, decreased for 39% of the combinations, and remained unchanged for the rest (mainly forest or Taiwan). Even though initial prices changed significantly for many regions, the impacts tend to be stable over future periods. Thus, the impact (of data update) on the impact (of future shocks) would likely be small.

Globally, trade volume increased in 2015 relative to 2010 for most sectors (mostly by around 5%), and the initial data updates also affected future trade projections. Regionally, the impacts tend to be larger and more unstable over time. The updates of trade and price data affected the initial calibration of preference parameters (share-weights), reflecting changes in trade patterns and relationships. The new trade pattern/relationship implies regions became relatively more connected (**Fig. 2 & Fig. S1**) and better prepared for future demand shocks. As a result, there will be relatively less global cropland expansion (driven by African regions, S.E. Asia, and India), and relatively more land is available for biomass expansion (**Fig. 3 & Fig. S2**).

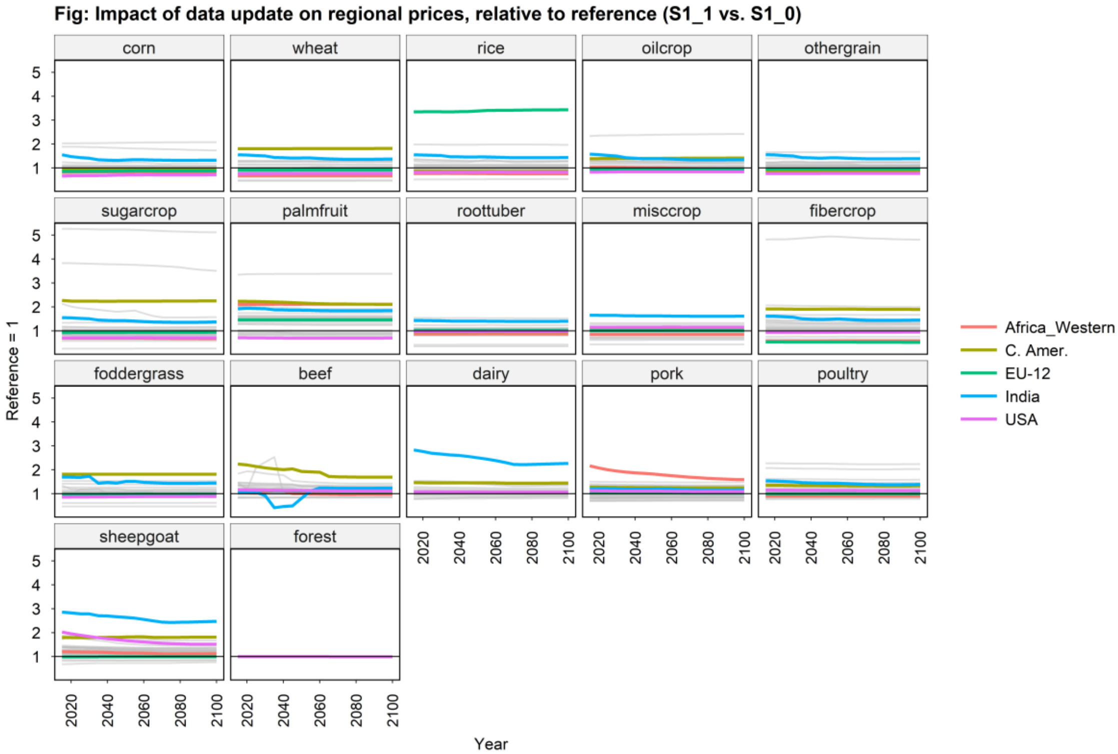

Fig. 1 Impact of data update on regional prices, S1_1 vs. S1_0 (ref.)

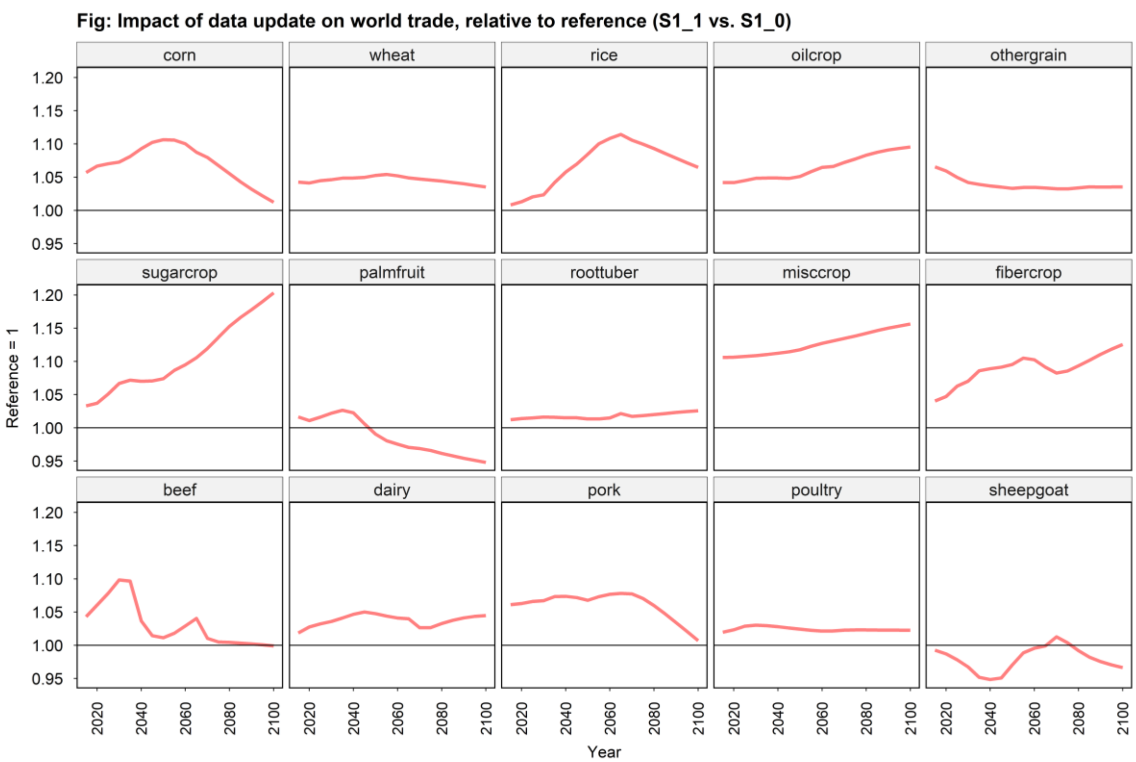

Fig.2 Impact of data update on world trade, S1_1 vs. S1_0 (ref.). Note that world trade is the sum of the gross export (or import) over all GCAM regions.

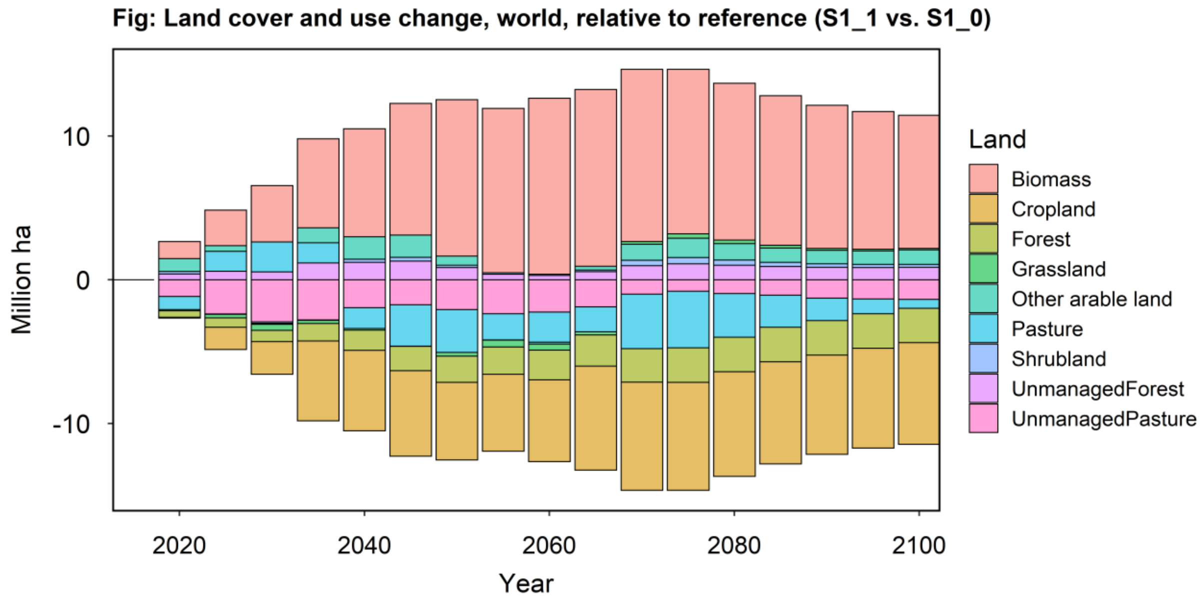

Fig. 3: Impact of data update on global land use, S1_1 vs. S1_0 (ref.)

2.2 Impacts from trade parameter updates

When differentiating trade parameters by sectors, corn, other grain, and wheat are the sectors with the largest changes (**Table 2**). Thus, the results of these sectors are more sensitive to the parameters update. The magnitude of the impact is within [-10%, 10%] for prices (**Fig. 4**) and about [-5%, 5%] for global trade (**Fig. 5 & Fig. S3**). With increased trade elasticity for wheat, its trade also grows. The opposite responses are seen for other crops. The impacts of the crop trade parameter updates on the results of non-crop sectors are small. The impacts on land use change are mainly driven by the increase in domestic corn and other grain areas in major importing regions (e.g., African regions), particularly in the second half of the century (**Fig. 6 & Fig. S4-S5**). The land use change impacts were relatively small (e.g., less than 2 Mha). See **Figs. S3 - S5** for regional trade and land use results.

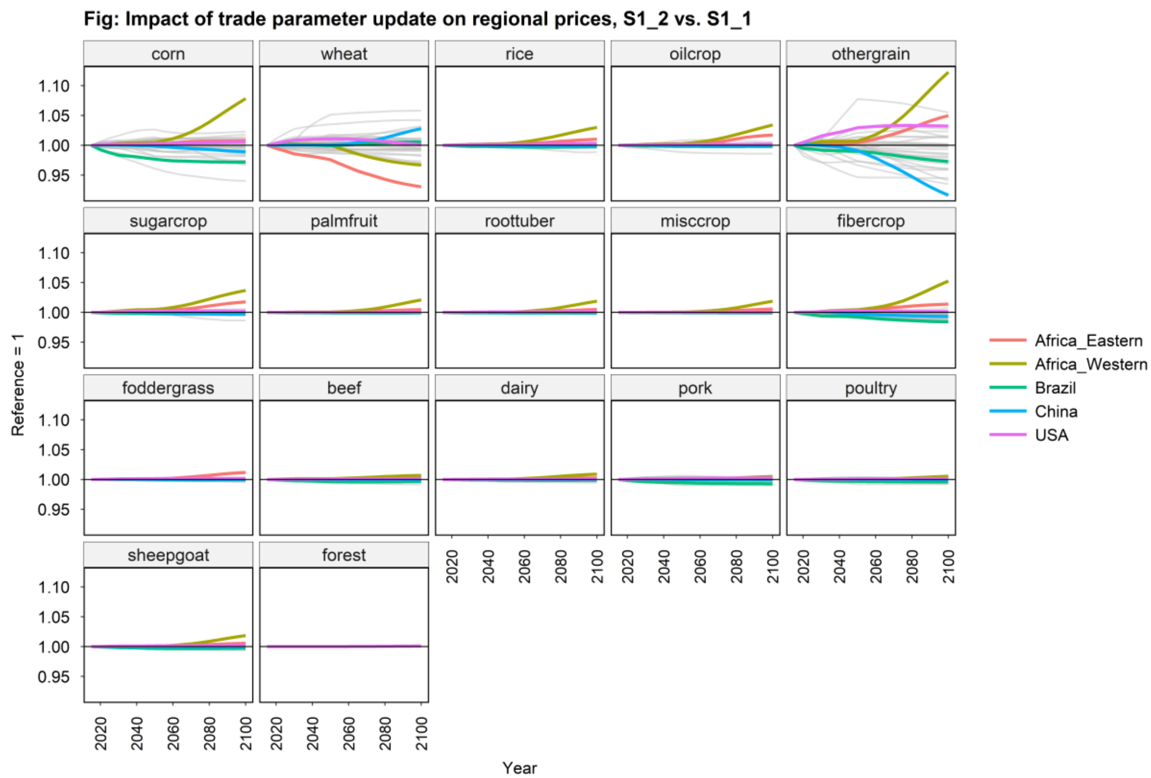

Fig. 4 Impact of trade parameter update on regional prices, S1_2 vs. S1_1

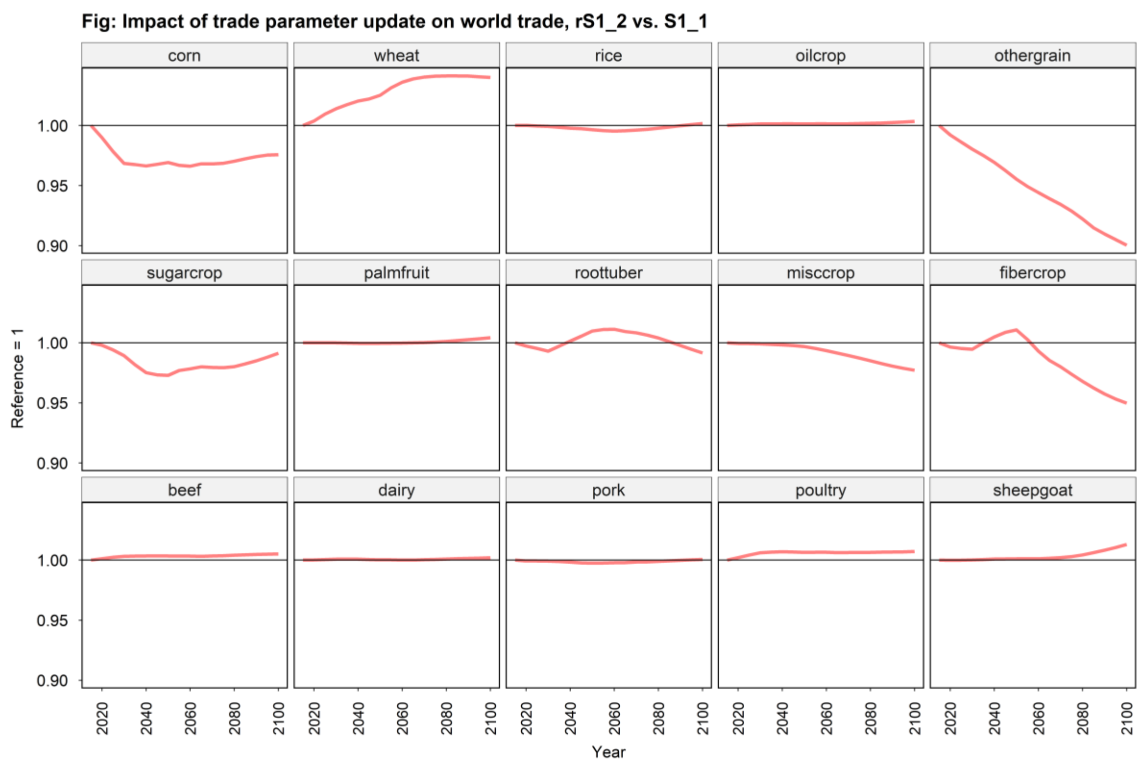

Fig. 5 Impact of trade parameter update on world trade, S1_2 vs. S1_1. Note: comparing roottuber and misccrop, we saw a spike in the world trade around 2050 for roottuber (see here for regional trade results

for roottuber and misccrop); this was likely because (1) roottuber, as a staple, has more rigid demand responses than misccrop (2) interactions across crops through regional land competition due to the parameters updates.

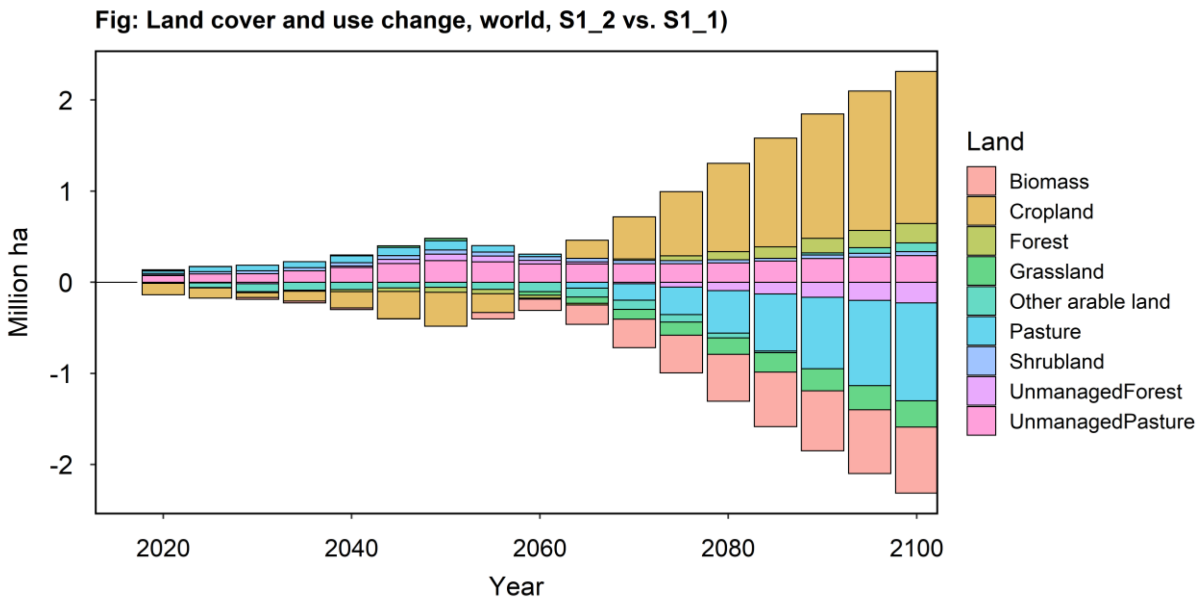

Fig. 6 Impact of trade parameter update on global land use, S1_2 vs. S1_1

3 Task 2: incorporate regional forest markets

FAO provides detailed definitions for forest products (see here for definitions and **Fig. 7** for roundwood data structure). In 2017, 3.9 Bm^3 of roundwood was produced globally, 50% of which was wood fuel, with the rest being industrial roundwood. Of the total roundwood production, only 3.5% (0.14 Bm^3) was internationally traded, and only 6% of the traded roundwood was wood fuel. That is, though production was large, wood fuel is mostly consumed domestically (except for trade within the EU). Also, wood fuel has a smaller value, and developing regions tend to consume and produce more wood fuel than developed regions. On the world average, industrial roundwood price ($58/m3) was about half of wood fuel price ($128/m3). Note that FAO does not provide producer prices for forest. Where applicable, export prices are used, which provide a good approximation of producer prices.

Note that secondary forest products are more widely traded internationally than roundwood. For example, the world's production of 60% of wood pellets, 28% of paper and paper board, and 34% of veneer sheets were internationally traded in 2017 (3.5% for roundwood). More background information is provided in **SI Section 2**.

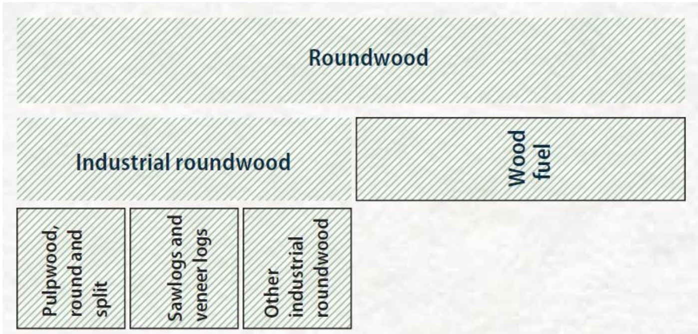

Fig. 7 FAO data structure for roundwood. See the full structure here.

In GCAM, by forest in production, it only includes roundwood, which is the primary forest product that is consumed by intermediate forestry sectors (e.g., industrial roundwood and related products, wood fuels, etc.). The intermediate forestry sectors are not modeled in GCAM. Instead, a final sector consumes all the forest (roundwood). Generally speaking, neglecting secondary forest product modeling would likely have relatively small impacts on land use change estimates because the modeling of roundwood accounts for the regional heterogeneity in forest productivity, and productivity in secondary sectors is likely less differentiated across regions. However, more detailed modeling of the product heterogeneity (e.g., industrial roundwood & wood fuel) and considering substitutions across secondary products would improve forest related projections. Future updates can consider further introduce other forestry sectors as FAO provides data for these intermediate sectors.

3.1 Forest trade modeling in GCAM and updates

Currently, in GCAM, producers in each region supply forest to a global market, and consumers in each region also source forest demand only from this global market (HOV). As a result, international trade is not specified, and we can only calculate, ex-post, the net trade of a region as the difference between production and consumption. And there is only a single price for all regions. We were using the US export price in base data for all regions. With the current framework, detailed trade data (gross or bilateral) and prices cannot be used. Also, HOV does not distinguish products across sources, which, together with a uniform world price, could result in sensitive and unstable trade responses. Also, as we do not include the intermediate demand for forest, there is a final forest demand (NonFoodDeamnd_Forest) with zero price and income elasticities.

Modifications for enabling regional forest market and trade are listed in Table 1. Unlike other agricultural sectors where gross trade data were shared out using bilateral trade data, gross trade data were directly used for forest since bilateral trade data are not available for roundwood. These updates also include both data and modeling changes. We design experiments to demonstrate the step-by-step impacts of the forest trade-related updates (**Table 4**). For the core developments, from S2_0 to S2_1, the logit-based Armington approach is incorporated with parameters of -2.5 (regional) and -5 (international) from the GTAP Data Base. In S2_1, though gross trade data were applied, a uniform price across regions is still used. This allows us to add a sensitivity experiment of S2_1_1, in which trade parameters are set to large values (-30) to reconcile HOV results in the Armington framework. In S2_2, price and cost are then differentiated across regions. Note that previously under HOV, the US forest export price (based on FAO data, i.e., 47$ per m3 for 2010 and 48$ per m3 for 2015) was used as the world price, and a fixed uniform cost of 29 $ per m3 was used. In this update, we use FAO regional export prices (updated to 2015) in the Armington framework. Also, we calculate the regional nonland cost using a uniform cost share of 59% (of regional prices) based on GTAP data (averaged across regions in the GTAP-BIO database). Additional information is provided in SI section S4. The differentiation of prices and costs will affect both initial data and parameter calibrations. In addition, we add sensitivity tests (S2_2_1 - S2_2_3) for Armington parameters for forest.

Table 4 Experimental design for Task 2

Task	Test	Experiment	Description
T2. Incorporating regional forest markets	Core	S2_0	S1_2
	Core	S2_1	S2_0 + Regional forest market with Armington parameters of -2.5 (regional) and -5 (international). Uniform price is used in the base year.
	Sensitivity	S2_1_1	S2_1 + Test large trade elasticities for forest to reflect HOV using Armington parameters of -30 (regional) and -30 (international).
	Core	S2_2	S2_1 + Using regional prices and costs for forest data base on FAO and GTAP information
	Sensitivity	S2_2_1	S2_2 + Armington parameters of -0.75 (regional) and -1.5 (international) for forest
	Sensitivity	S2_2_2	S2_2 + Armington parameters of -3 (regional) and -6 (international) for forest
	Sensitivity	S2_2_3	S2_2 + Armington parameters of -30 (regional) and -30 (international) for forest

3.2 Impacts from the updates in Task 2

Here, we focus on the price, trade, and land use change results for forest from the core experiments. The impact of the forest trade updates on other sectors is relatively small. The results from the sensitivity experiments are provided in **SI** and briefly discussed in **Section 3.2.4**.

3.2.1 Price impacts

A comparison of regional prices across task 2 core scenarios is shown in **Fig. 8** (in $ per m3) and **Fig. 9** (relative to 2015). In S2_1, forest price changes in future periods are differentiated (e.g., a strong upward trend in Africa_Eastern and Africa_Western), even with a uniform initial price. Relatively, differentiating initial prices in S2_2 has smaller impacts compared to the update from HOV to ARM (**Fig. 9**). This is also true in trade and land use change results shown later. The updates will have relatively large impacts on African regions and Pakistan, where land competition is stronger as unmanaged forest area was limited (potential data issues discussed in the next section). In S2_2, prices in the two African regions will increase by about 6 times by the end of the century. Population growth in those regions plays a key role in driving up agricultural demand and land competition. Also, higher forest price elasticity will likely alleviate the price rise.

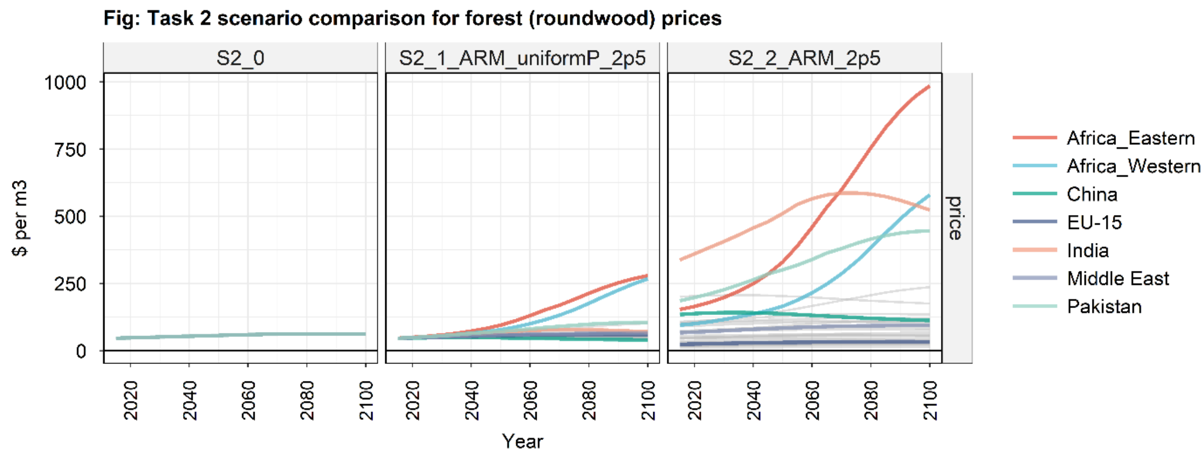

Fig. 8 Task 2 scenario comparison for price projections. See Table 4 for the scenario description

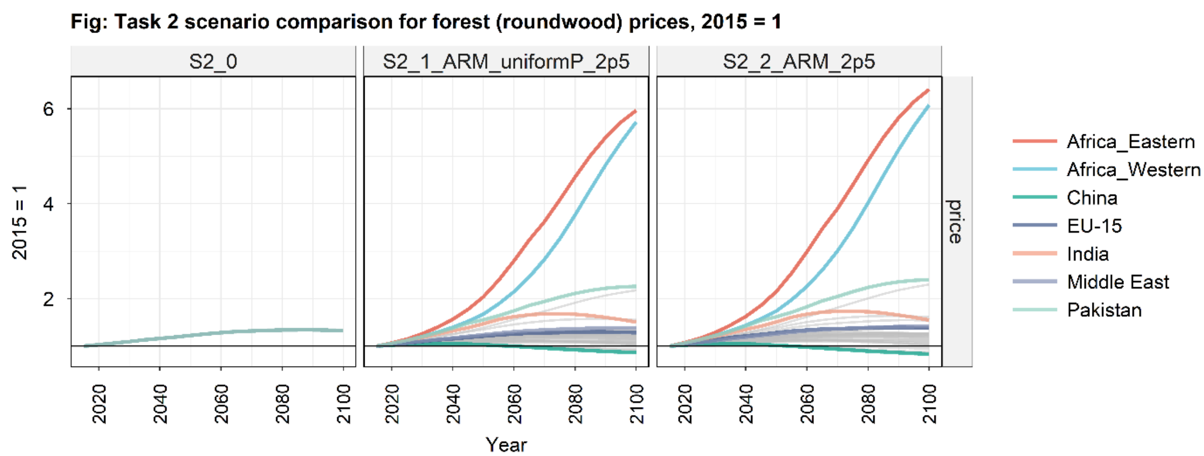

Fig. 9 Task 2 scenario comparison for price projections, relative to 2015

3.2.2 Consumption, production, and trade impacts

A comparison of regional consumption, production, and trade across task 2 core scenarios is shown in **Fig. 10** (in bm3) and **Fig. 11** (relative to 2015). Since the demand elasticity is zero for all regions and forest demand is only driven by population growth, the consumption results would not be affected by the forest trade structure or parameter changes. Thus, the question becomes, given regional demand, what should be the sources of the region's supply?

In S2_0, we won't observe gross trade results, and regional net trade was projected to change dramatically (**Fig. 10**). Both net export from China and net import from African regions would skyrocket, even without additional trade liberation assumptions. These variations are really large compared with historical changes.

With the updates to the regional forest markets with the Armington approach, regions are relatively less integrated, so they would consume more domestically produced forest. We would still see large production and gross trade changes in China and African regions in relative terms (**Fig. 11**).

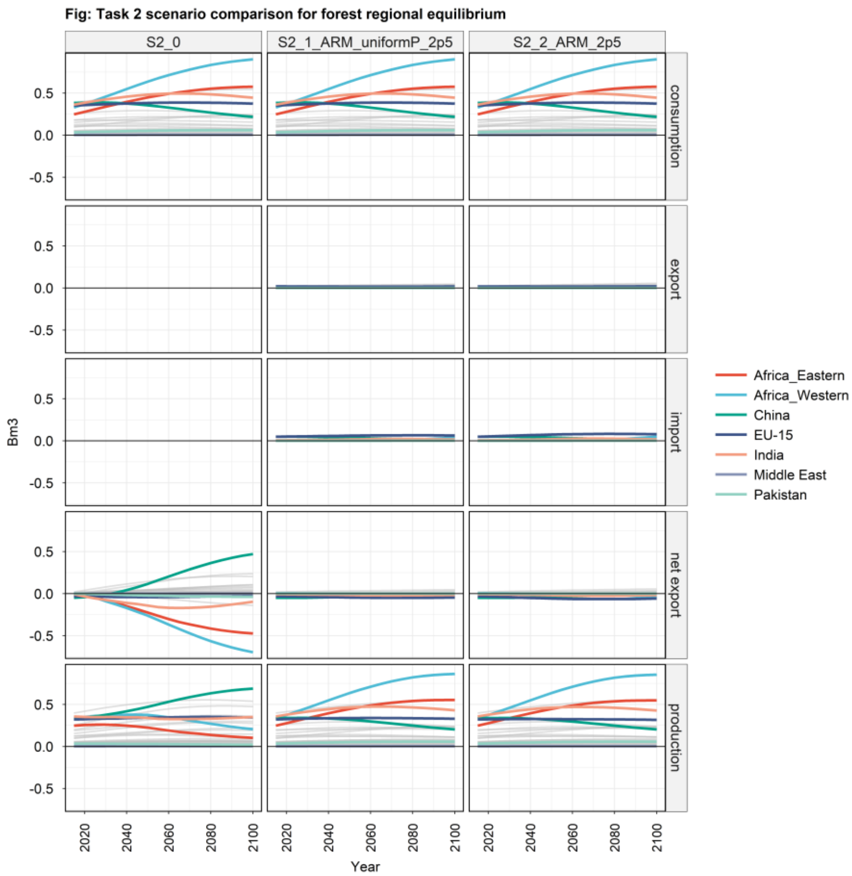

Fig. 10 Task 2 scenario comparison for regional forest equilibrium (in Bm3)

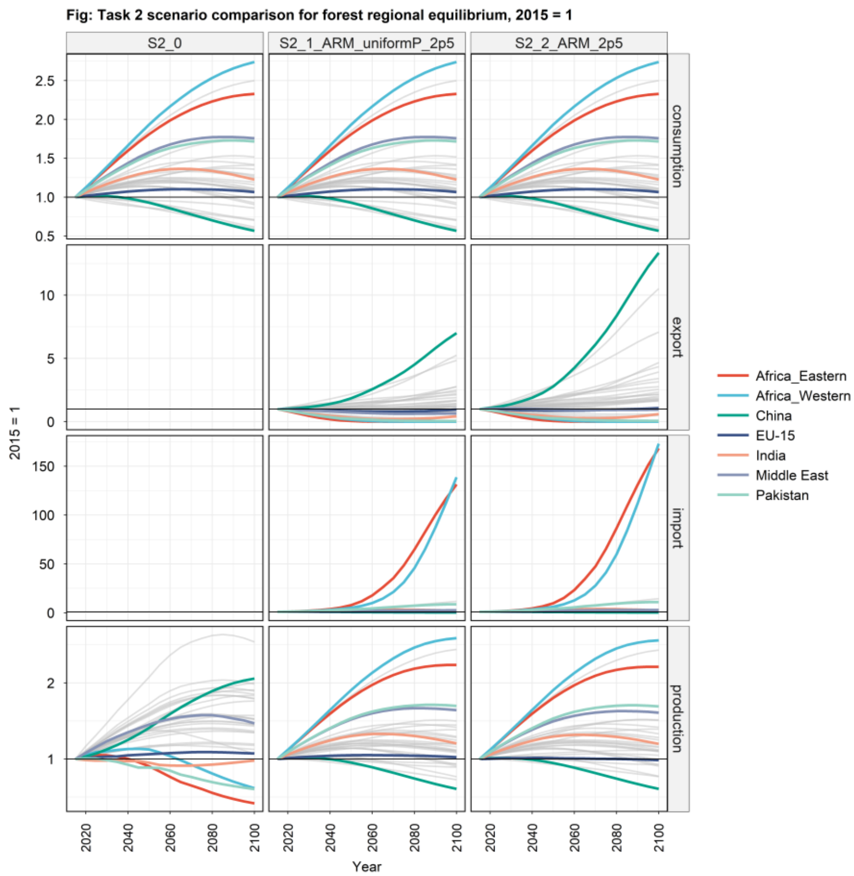

Fig. 11 Task 2 scenario comparison for regional forest equilibrium, relative to 2015

3.2.3 Managed forest land use impacts

A comparison of managed forest land use change across task 2 core scenarios is shown in **Fig. 12**. With the updates on forest trade, regions will source more forest from the domestic market relative to international markets. The pattern of regional production directly determines regional land use change for forest. As a result of the updates, regions with increasing export will have lower production and managed forest area expansion (e.g., China), while regions with increasing imports will have higher domestic production and managed forest expansion (e.g., African region & India) (**Fig. 13**). For example, China was a major net exporting region under the integrated world market assumption; under regional markets, the international demand will decrease so that China will export and produce less (Chinese producer prices also decrease relatively). In contrast, African regions, as major importing regions under integrated world market, become more difficult to source demand from the international market under regional markets. Thus, the domestic prices would increase more relative to international prices, and there will be relatively higher domestic forest production and land expansions. Note that even though imports in the African regional will still increase significantly in the future, the magnitude is much smaller than the net import increase under the integrated world market.

Globally, due to the forest trade update (more segmented markets), forest area will decrease by about 33 Mha, most of which (22 Mha) is a net conversion of unmanaged forest (**Fig. 14**). Note that global demand was exogenous. Thus, forest productivity increased due to the updates. This was mainly because the importing regions (e.g., African regions, Pakistan) had larger forest productivity than exporting regions. This was somewhat counterintuitive. A closer check later indicated some potential issues with forest productivity data. This is discussed in detail in Task 4. The data issues mainly affect results in Africa_Eastern, Africa_northern, and Pakistan and won't affect general responses and analysis in this proposal.

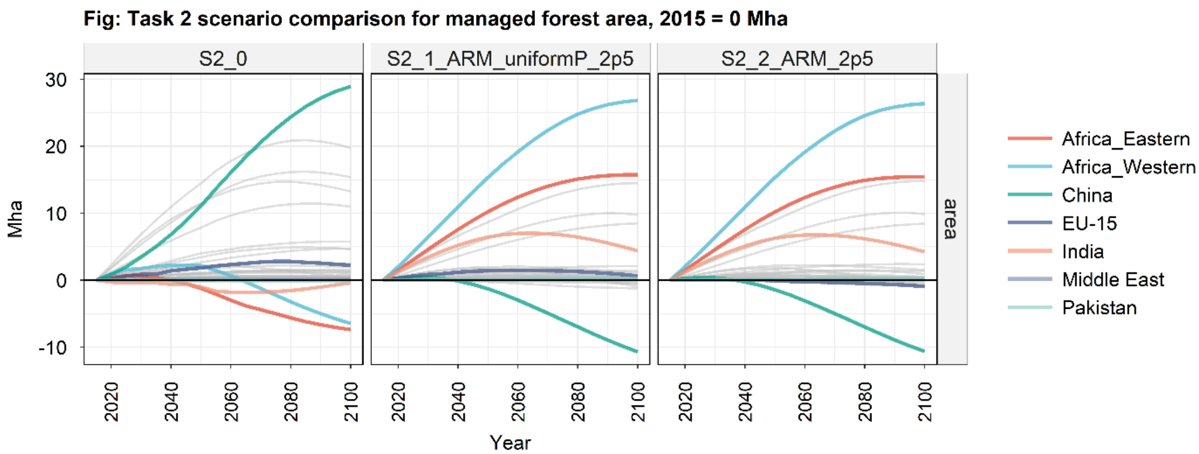

Fig. 12 Task 2 scenario comparison for managed forest area change relative to 2015 (2015 = 0 Mha)

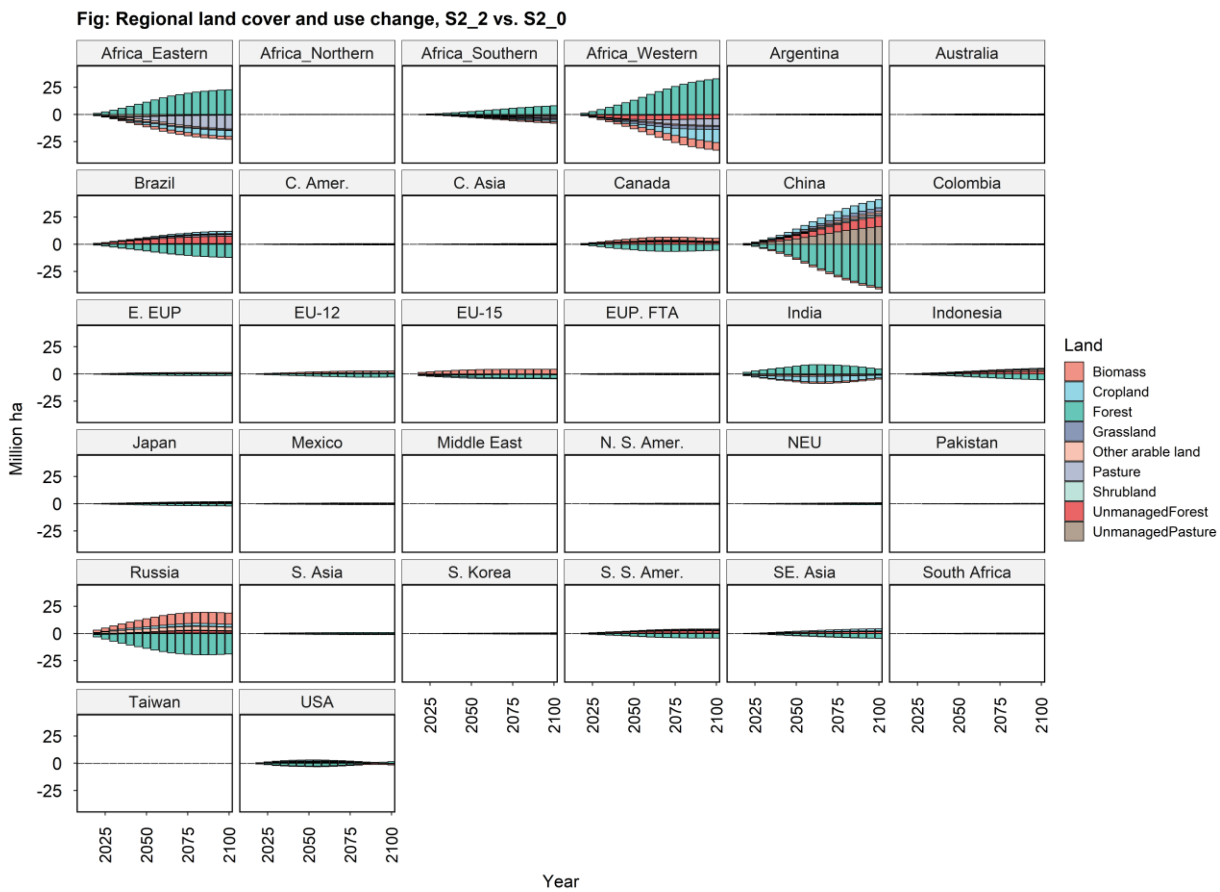

Fig. 13 Impact on regional land use change from Task 2 updates (S2_2 vs. S2_0)

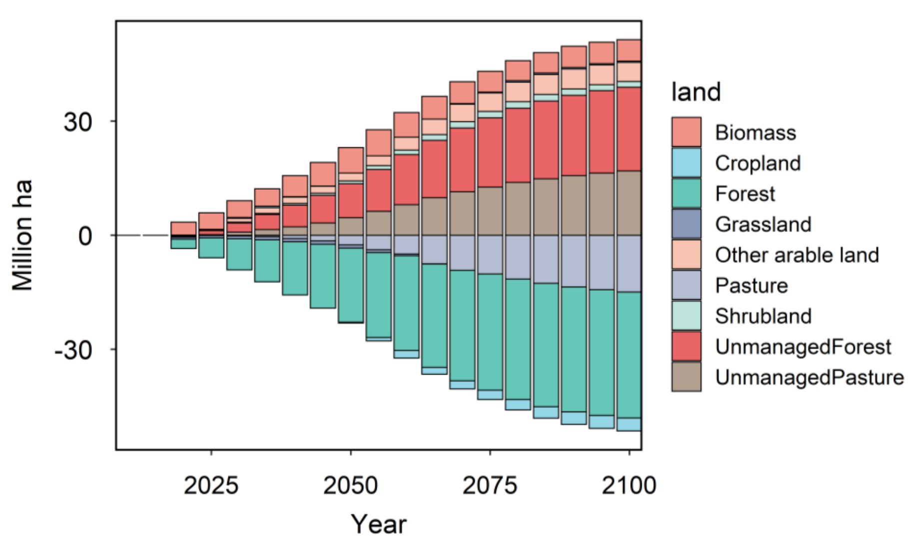

Fig. 14 Impact on global land use change from Task 2 updates (S2_2 vs. S2_0)

3.2.4 Sensitivity scenarios

The results from the sensitivity scenarios are provided in **SI Figs S6 – S9**. The results are consistent with expectations. Results from S2_1_1, using very large trade elasticities and uniform prices in the Armington framework, are closer to the HOV results from S2_0, e.g., (1) prices changes are relatively homogeneous and (2) dramatic changes in net trade projections. Sensitivity across trade parameters also demonstrated consistent responses. When trade parameters are larger, net importing (exporting) regions can source more forest from the international market, leading to smaller (larger) domestic production and land use change.

4 Task 3: test and update forest demand parameters

In this task, we test price and income elasticities for forest in GCAM. There are not many literature estimates of the elasticity for forestry products, likely due to limited data and studying interests. And most available estimates focused on developed regions (e.g., the US) and or specific intermediate/final forestry products. We reviewed related literature for these parameters, e.g., Sohngen et al. (1999) , Kangas and Baudin (2003), Michinaka et al. (2011), and related parameters used in the GTAP Data Base (see a summary in **SI Section 3**). These studies indicate that the demand parameters are higher heterogeneous across regions and forestry products. However, the forest in GCAM only includes the primary product of roundwood, which should be less elastic than the final products. Also, we are currently using a uniform parameter for all regions. Thus, we will test a range of demand and income elasticities to examine the sensitivity (see **Table 6** for experimental design for Task 3).

Table 6 Experimental design for Task 3

Task	Test	Experiment	Description
T3. Testing forest demand parameters	Core	S3_p0p0	S2_2 (zero price and income elasticities for forest)
	Sensitivity	S3_ePeInc	Test combinations of price elasticity (**eP** in [-0.2, -0.4, -0.6, -0.8]) and income elasticity (**eInc** in [-0.2, -0.4, -0.6, -0.8]) for forest.
	Core	S3_p4p2	S2_2 + price elasticity (-0.4) and income elasticity (0.2)

The impact of allowing elastic demand and income responses (relative to S3_p0p0) are presented in **Figs. 15 – 18** for forest consumption, production, price, and land use, respectively. The corresponding figures with fixed scales are provided in **SI Figs. S10-S16,** along with trade results. The projections of global forest economics equilibrium are strikingly sensitive to these demand parameters through the direct impacts on regional consumption. Price and income elasticity will have the opposite impact on demand. For example, higher income growth leads to a higher increase in demand, while such demand responses would be weaker when price elasticity is higher. However, it is important to note that the income response in GCAM is exogenous, while the price response is always endogenous. In other words, income responses are largely affected by the assumed regional GDP growth. Higher-income elasticities will always encourage higher regional consumption given the assumptions of monotonically income growth to the end of the century (e.g., very strong growth in African regions). Conversely, responses to price elasticity changes will be dependent on the direction and magnitude of regional price changes in the baseline. Thus, the projection results are generally more sensitive to income elasticity than price elasticity. And compared with inelastic demand responses (S3_p0p0), regional forest demand could increase by 4-5 times with relatively large income elasticity (e.g., 0.8) and small price elasticity (e.g., -0.2) (**Fig. 15**). With uniformly large income elasticity across regions, regional price and supply responses could become outrageous, e.g., regional production could be 5 – 10 times higher (**Fig. 16**), regional prices could be 20 plus times higher (**Fig. 17**), and global managed forest area would be higher by hundreds Mha (**Fig. 18**).

Considering that (1) GCAM currently does not consider the future growth of forest productivity and (2) demand responses are not distinguished by regions, it is reasonable to use a relatively smaller income elasticity, e.g., 0.2 or 0.4. Regarding price elasticity, regions with relatively large forest price changes in the reference scenario are more sensitive. For example, forest prices are projected to increase by 5-6 times in African regions in 2100 relative to 2015 in the reference scenario, much higher than in other regions. Allowing elastic price response alleviates such price growth relative to other regions. E.g., when income elasticity is small (i.e., 0.2), forest demand and prices in African regions could become relatively lower (**Figs. 15 and 17**). For the reasons discussed above, it is reasonable to narrow the range of the parameters to [-0.6, -0.4] for price elasticity and [0.2, 0.4] for income elasticity.

To help make informed decisions on choosing forest demand parameters, we also compare the projections for global land expansions between cropland and forest (**Fig. 19**). In S3_p0p0 (ref.), the global cropland area (not including dedicated biomass) is projected to increase by 170 Mha from 1188 Mha in 2015 to 1358 Mha in 2100, while the global managed forest area increases by 74 Mha from 273 Mha in 2015 to 347 Mha in 2100. That is, the managed forested area was about 23% of the cropland area in 2015, and this relative area relationship tends to be stable at the global scale (e.g., historically, the value was 25% in 1990, 24% in 2005, and 22% in 2010). Note that this area ratio (forest/cropland) varies between 23% and 26% in the ref. (S3_p0p0) projections. However, when income elasticity (eInc) is 0.4, this area ratio would increase to 35% (eP = -0.6) and 39% (eP = -0.4). In contrast, when eInc = 0.2, the area ratio would be relatively more reasonable, with the highest value being 27% (eP = -0.6) and 29% (eP = -0.4).

Furthermore, given that (1) forest productivity is assumed to be constant over time and (2) demand for roundwood as a primary forest product could be relatively less elastic than secondary products, we decided to choose the combination of eP = -0.4 and eInc = 0.2. With this combination, the impacts from the updated demand responses tend to be relatively more regional than global.

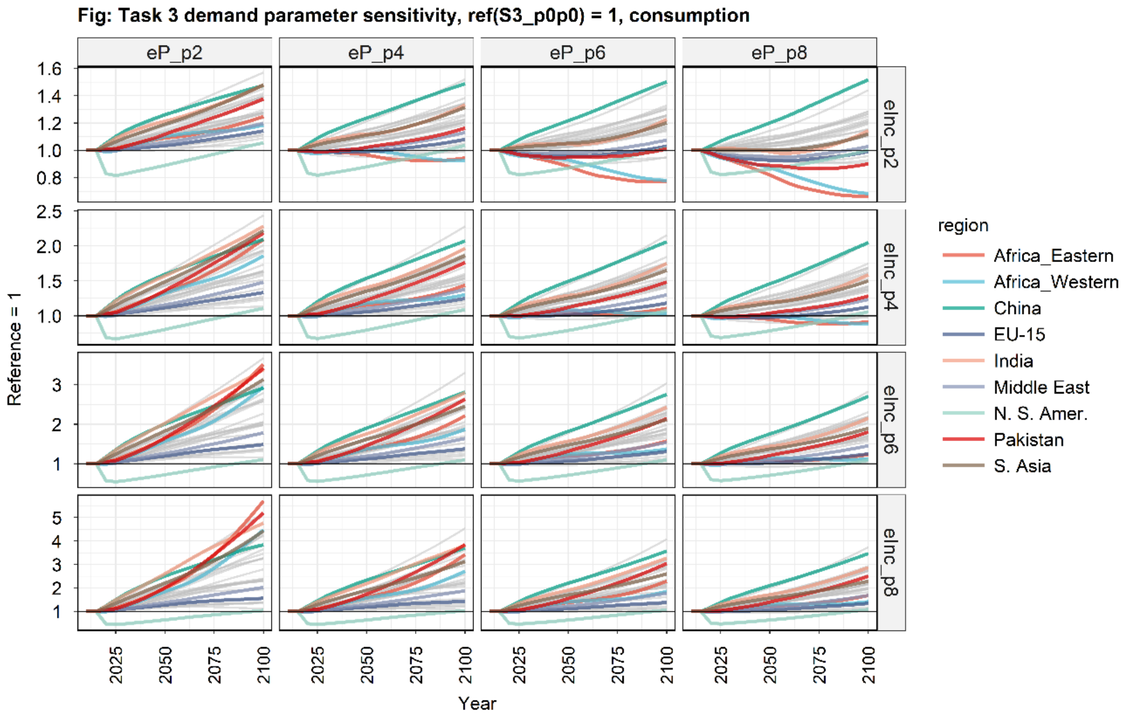

Fig. 15 Regional forest consumption relative to ref. (S3_p0p0) by price elasticity (rows) and income elasticity (columns)

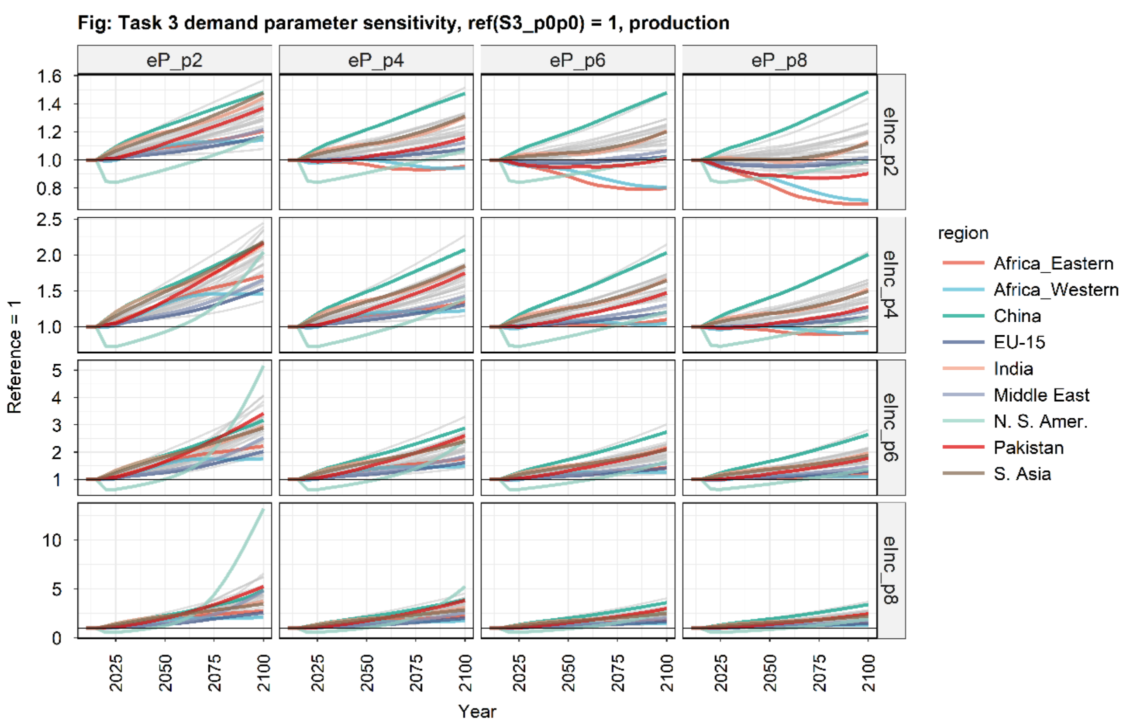

Fig. 16 Regional forest production relative to ref. (S3_p0p0) by price elasticity (rows) and income elasticity (columns)

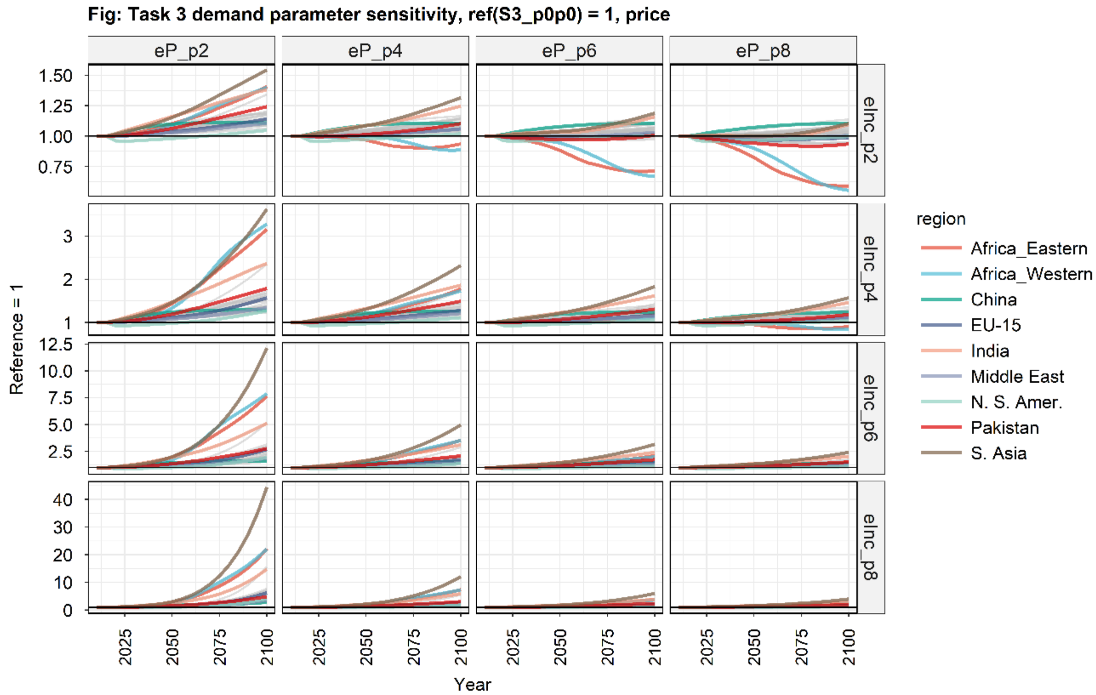

Fig. 17 Regional forest price relative to ref. (S3_p0p0) by price elasticity (rows) and income elasticity (columns)

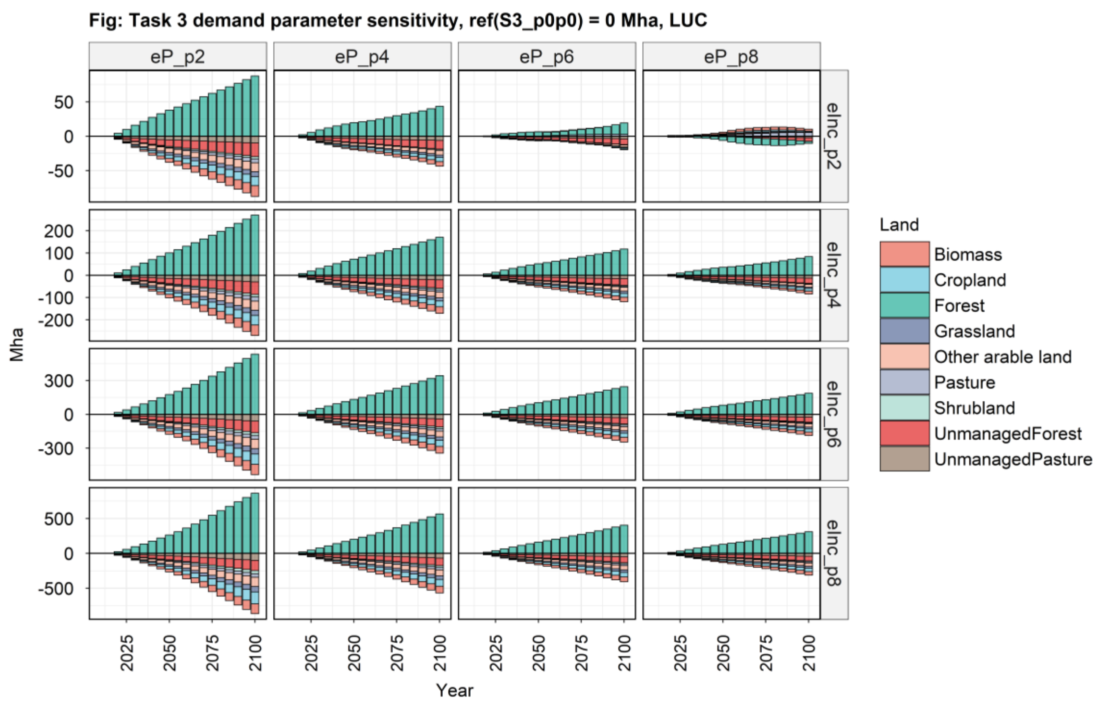

Fig. 18 Global LUC relative to ref. (S3_p0p0) by price elasticity (rows) and income elasticity (columns)

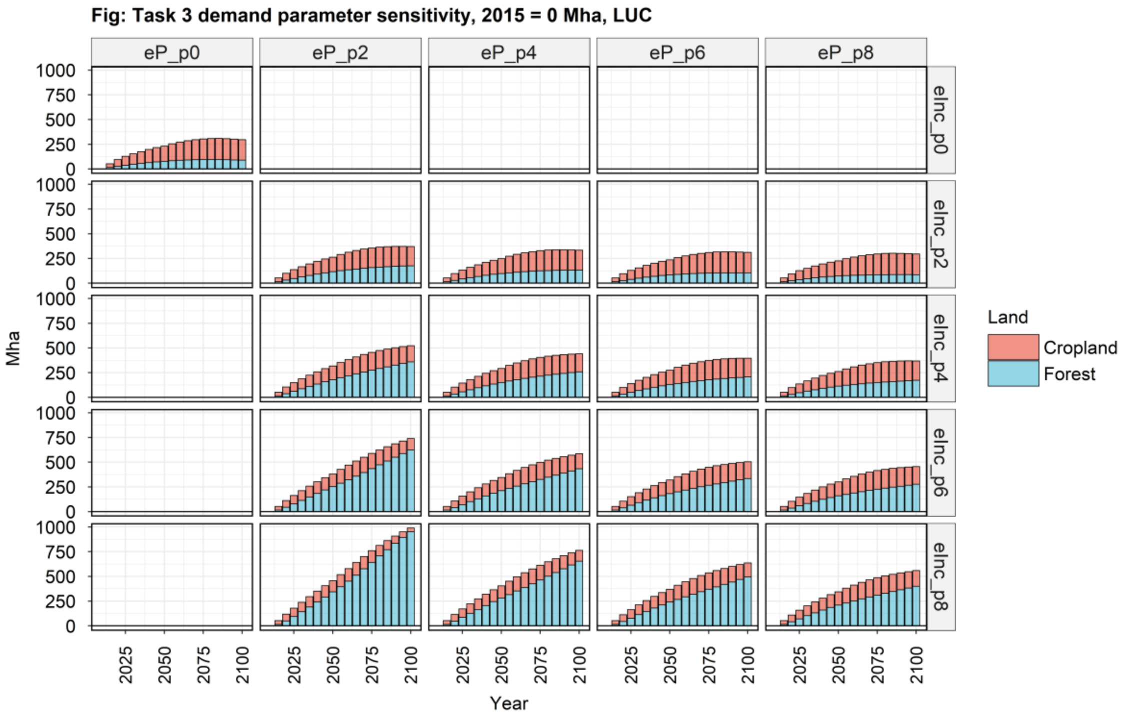

Fig. 19 Global changes in forest and cropland by 2100 relative to 2015 by price elasticity (rows) and income elasticity (columns)

5 Task 4: adjust forest land data to correct forest yield

In the previous analysis, we found potential issues in forest yield data that yield in several basin/region was remarkably higher than others (**Fig. 20**). A closer investigation finds this was caused by data inconsistency between FAO forest production data and forest land area data processed from our land data system (LDS). During the process of calculating managed land area, the managed forest area calculated based on yield information, and FAO production is be bounded by the forest area from LDS. This assumption mainly affected managed forest areas in three regions, including Africa_Northern, Africa_Eastern, and Pakistan. Due to the data inconsistency, forest yield in Africa_Northern would be 10 – 17 times upward adjusted, and the adjustment was about 6 times in Pakistan but to a small extent in Africa_Eastern (1.02). After a quick comparison of forest area between data from LDS and FAO, we find FAO generally had a much larger total (managed) forest area in these regions. That is, if we were to trust FAO production, we need to double-check the managed forest area data as well to maintain yield consistency. The current inconsistency led to higher yield and also no unmanaged forest area in those regions. Thus, in this task, we provide a temporary fix to increase the total forest area in historical data to the calculated managed forest area that implies correct yield so that the managed forest area would not be adjusted and yield is maintained. We still need to examine the data inconsistency issue later.

In this section, we investigate the impact of the forest yield update on GCAM projections (**Table 6**). We also study the impact of this update on the sensitivity analysis for demand parameters performed in Task 3 by testing the sensitivity of demand parameters in a narrower range.

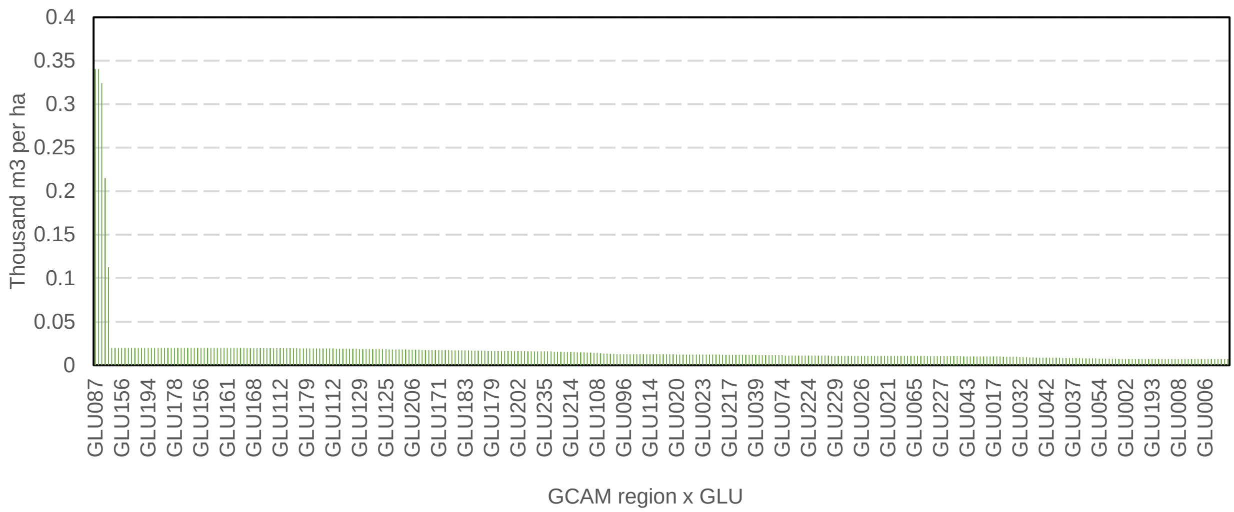

Fig. 20 Forest yield across 344 GLU in GCAM in 2015 (before adjustment)

Table 6 Experimental design for Task 4

Task	Test	Experiment	Description
T4. Adjust forest land data	Core	S4_0	S3_p4p2
	Core	S4_1	Adjust forest area in Africa_Northern, Africa_Eastern, and Pakistan to correct forest productivity.
	Sensitivity	S4_ePeInc	S4_1 + Test combinations of price elasticity (eP in [-0.4, -0.6]) and income elasticity (eInc in [-0.2, -0.4]) for forest.

5.1 Impacts from forest data updates

The forest yield issue is confirmed by comparing yield results across scenarios (S4 vs. S3 in **Fig. 21**). **Fig. 22** compared managed forest vs. unmanaged forest from S4. There is no unmanaged forest in the three regions of yield issues. The forest land data and associated assumptions (e.g., unmanaged forest protection) need to be reviewed (e.g., check consistency across sources). **Fig. 23** shows the impact of forest data updates on global land use change. Note that in this task, the forest area in base data was adjusted so that the total managed forested area increased by about 4.4 Mha in 2015. The increase in the initial forest area was mainly for Africa_Northern and Pakistan (**Fig. 24**). Also, because of the lower forest yield in the three regions, the future land requirement for forest expansion in these regions increased, and regional forest prices also increased (e.g., by about 7% in Africa_Northern in 2100 see **Fig. 25**), and forest import also relatively increases (**Fig. 26**). In general, impacts from the forest data updates are mostly regional, and the magnitude at the global scale tends to be small because the yield adjustment was either small (Africa_Eastern) or for regions that were relatively segmented from the global forest market. For similar reasons, the impacts on future projections in the demand parameter sensitivity analysis performed in Task 3 are small (**Fig. 27** and additional results in SI **Figs. S16 – S21**)

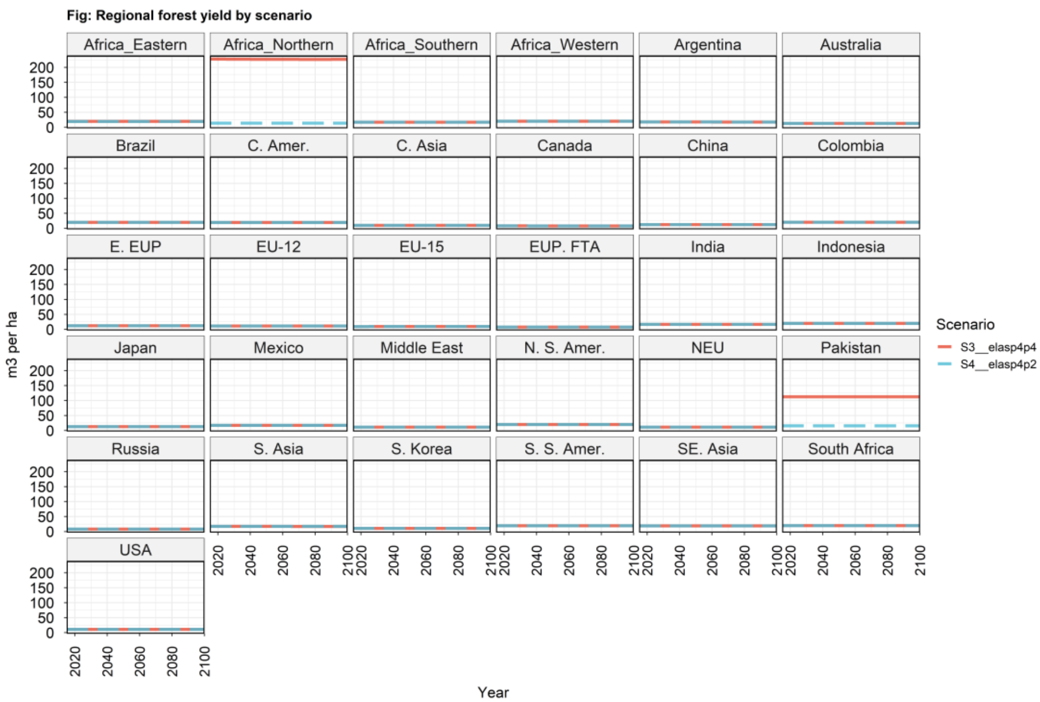

Fig. 21 Comparing projected regional forest yield across scenarios

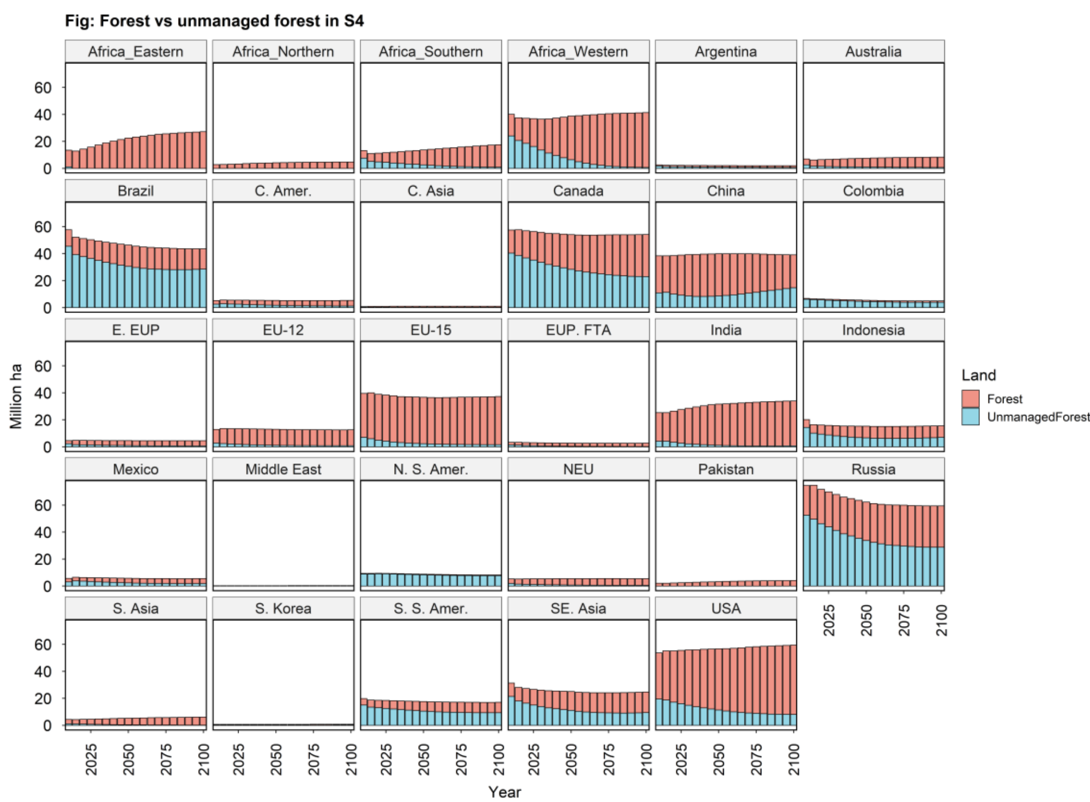

Fig. 22 Managed forest vs. unmanaged forest in S4

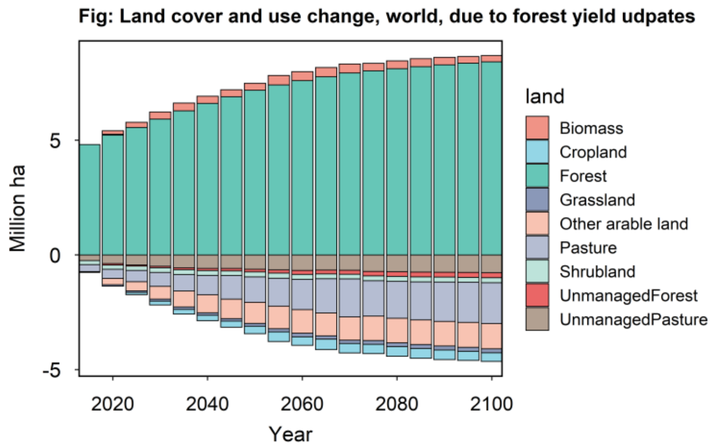

Fig. 23 Impact of forest data update on global land use change (S4 vs. S3)

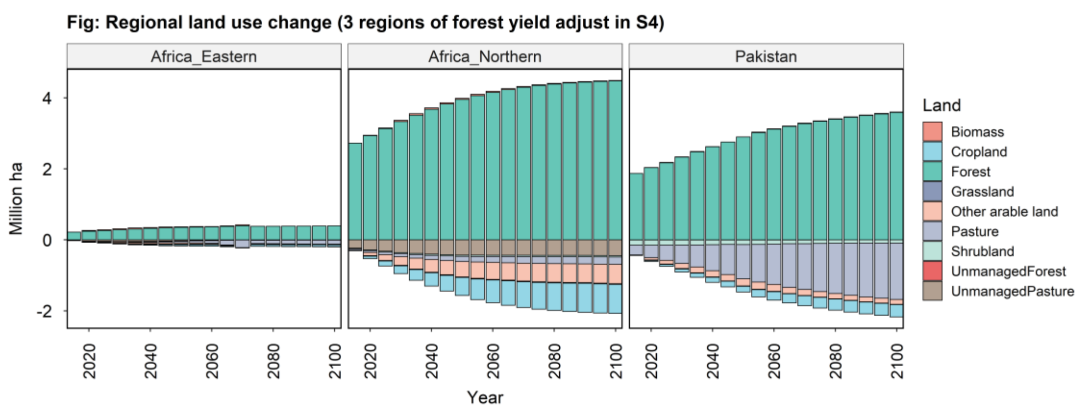

Fig. 24 Impact of forest data update on regional land use change (S4 vs. S3)

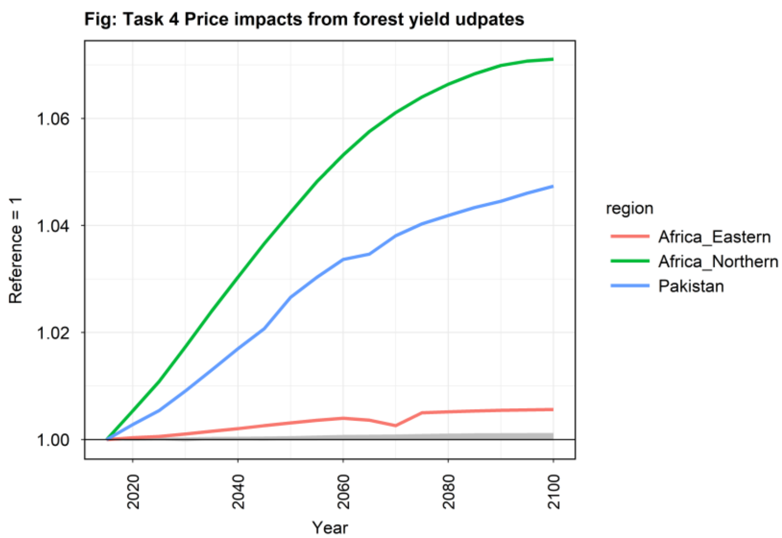

Fig. 25 Impact of forest data update on forest price (S4 vs. S3)

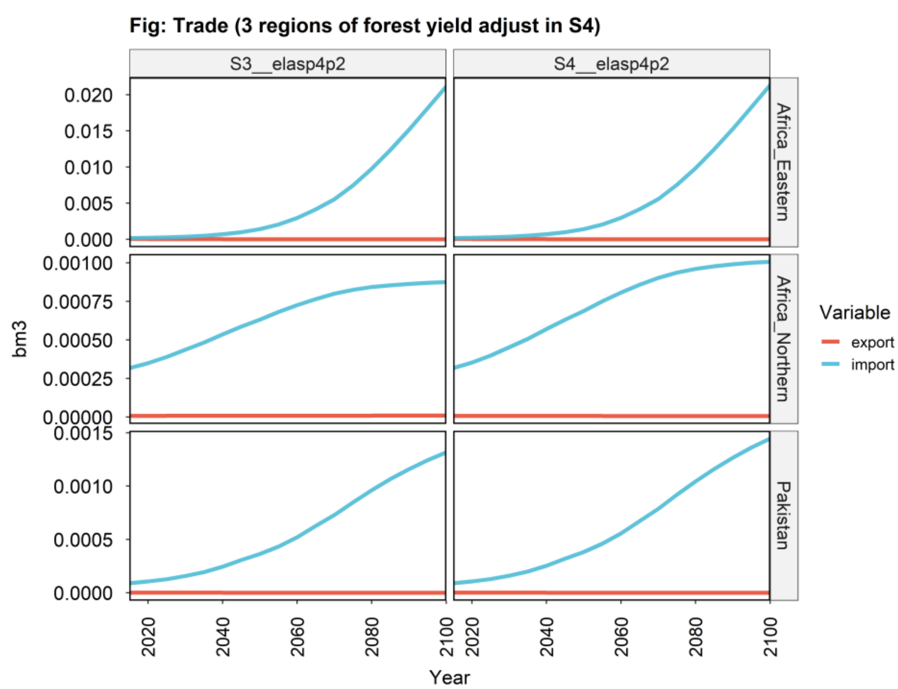

Fig. 26 Impact of forest data update on export and import (S4 vs. S3)

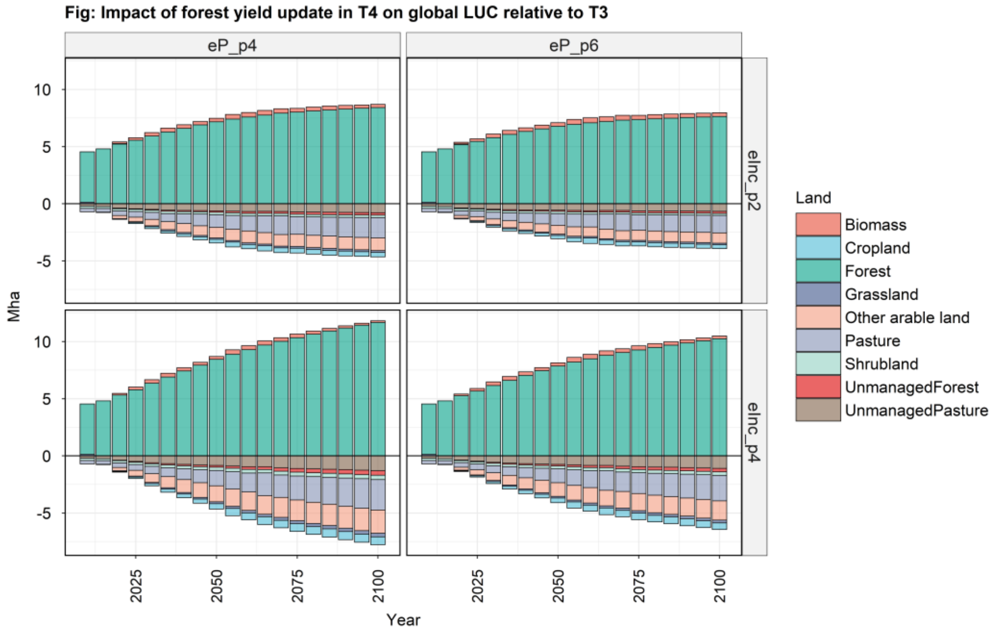

Fig. 27 Impact of forest data update on global land use change across demand parameters (S4 vs. S3)

6 Additional data updates

During the PR review, we found additional issues related to region mapping in regional GDP deflators (FAO_GDP_deflators), e.g., wrong data for China and missing Taiwan data. There are other mapping issues in forest production and trade data. We thus made another round of data updates. In particular, we create an R project to generate data in Aglu/FAO/ directly from FAOSTAT (API) to have more consistent mappings/headers/data updates. Only forest and ag trade-related data are updated for now (see **Table 7**).

Table 7 Metadata log information generated by FAO data preprocessing R project. This R project will be extended to include all FAO data.

dataset	ncountry	nitem	nyear	start_year	end_year	NA_perc	FAO_domain_code	FAO_update_date
FAO_GDP_deflators	215	1	50	1970	2019	9.30%	PD	5/25/2020
FAO_ag_an_ProducerPrice	175	235	29	1991	2019	48.40%	PP	12/18/2020
FAO_BilateralTrade	169	401	10	2008	2017	56.50%	TM	12/20/2020
FAO_For_Exp_m3_USD_FORESTAT	234	1	59	1961	2019	43%	FO	3/1/2021
FAO_For_Imp_m3_FORESTAT	233	1	59	1961	2019	37%	FO	3/1/2021
FAO_For_Prod_m3_FORESTAT	213	1	59	1961	2019	14.20%	FO	3/1/2021
FAO_For_Exp_m3_FORESTAT	234	1	59	1961	2019	43.10%	FO	3/1/2021

Similar to Task 4, impact from data updates in Task 5 are not significant and mostly regional. Globally, the new data indicated more forest production and managed area (~2 Mha) in the base year (**Fig. 28**). The new forest area was mainly in EU15 and S.E. Asia (**Fig. 29**). Regional forest prices (mainly, China, Taiwan, and S.E. Asia) were also changed due to the deflator updates (see **SI Fig. S21**). However, these data updates had only minor impacts on regional forest market equilibrium (**SI Figs. S22-S23**).

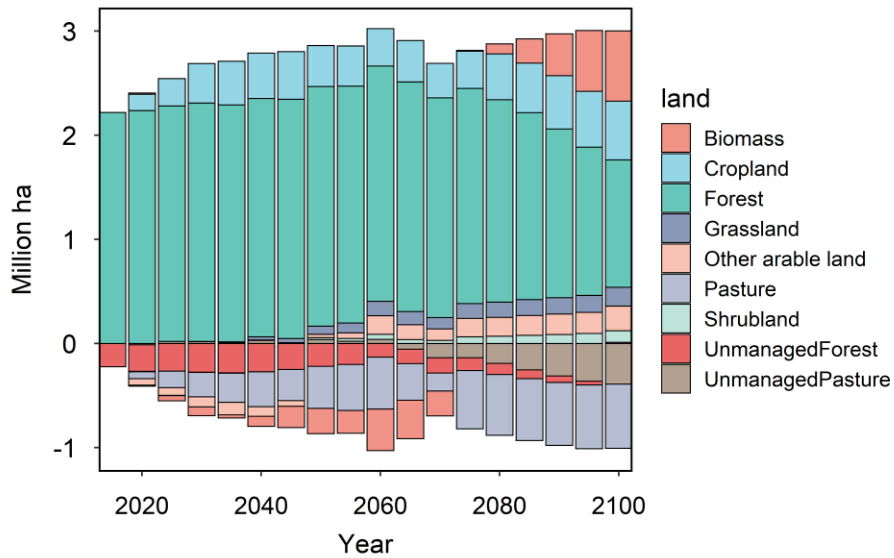

Fig. 28 Impact of forest data update on global land use change (S5 vs. S4)

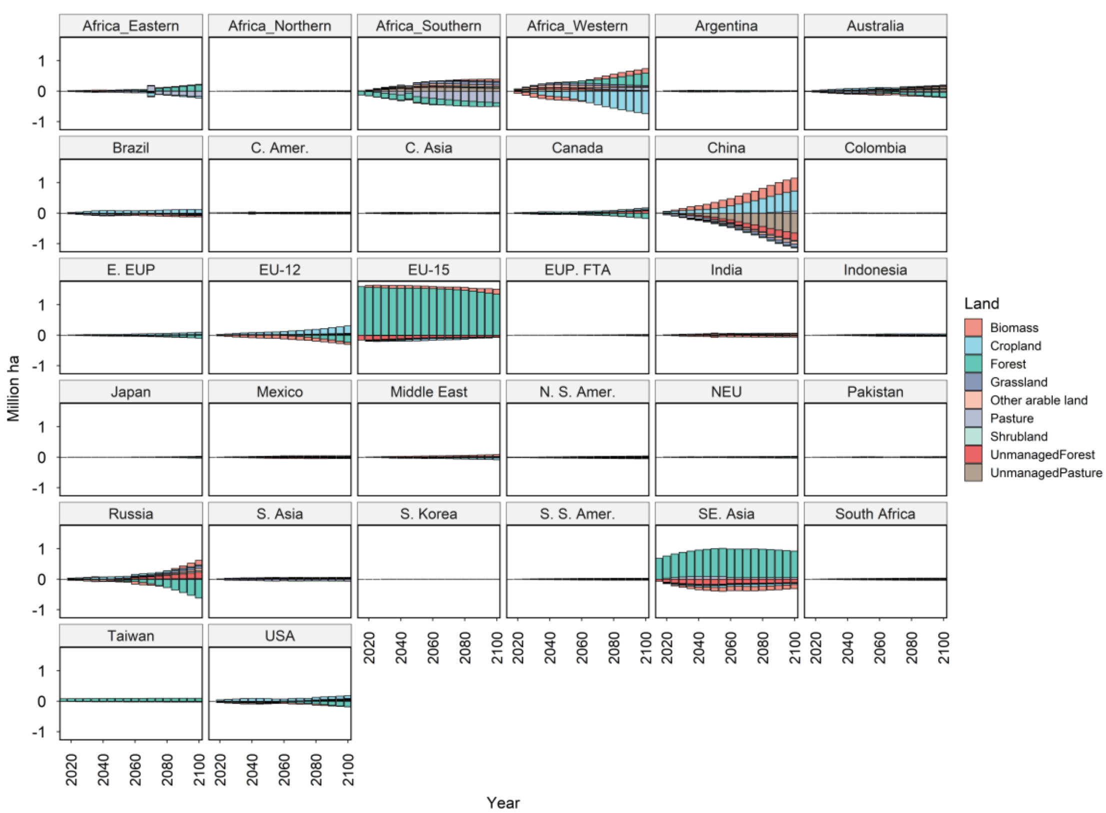

Fig. 29 Impact of forest data update on regional land use change (S5 vs. S4)

7 Overall impacts from all tasks

The impacts of all updates in this proposal on global and regional land use change are presented in **Figs 30 and 31**. These results combine impacts from all tasks. Overall, there will be relatively less global cropland and managed pasture expansion (mainly due to data updates) and higher global land in forest (driven by forest trade and demand updates), biomass, and unmanaged land. Regional land use impacts could be more pronounced and heterogeneous. Since there are more land for forest and biomass (from both dedicated biomass and forest residues), there are also small impacts on the energy system due to the increased biomass (e.g., 6.7 EJ or 6% in 2100, globally) supply.

Figs. 32 and **33** provide comparisons across all scenarios for 2100 land covers, forest production, and forest trade. Across all tasks/updates, those results were more sensitive to forest demand parameters. Net forest trade in 2100 became much more constrained with the regional forest market. However, the trade could still be responsive and sensitive to demand parameters.

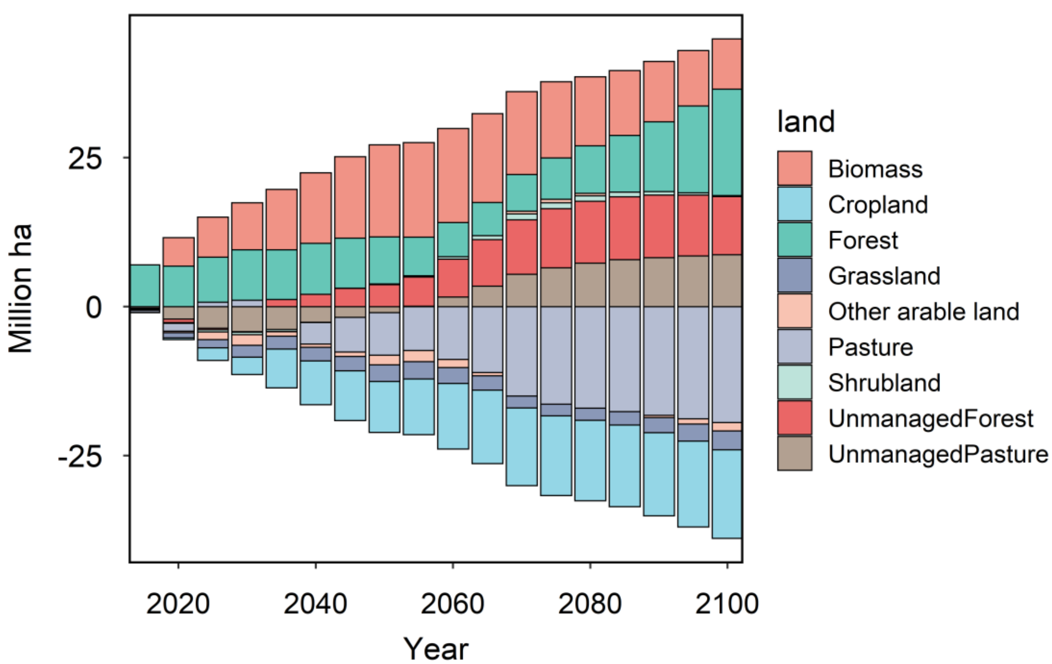

Fig. 30 Impact of all updates on global land use change

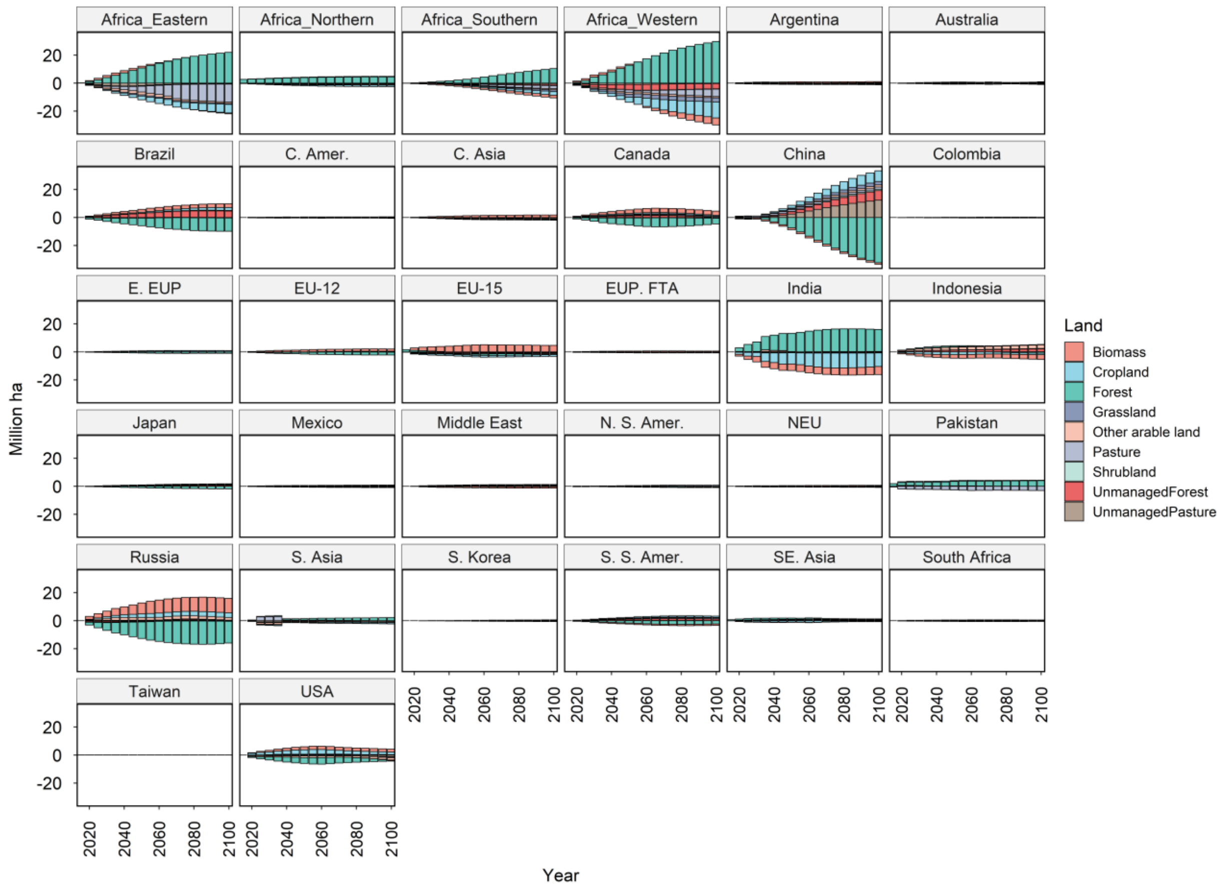

Fig. 31 Impact of all updates on regional land use change

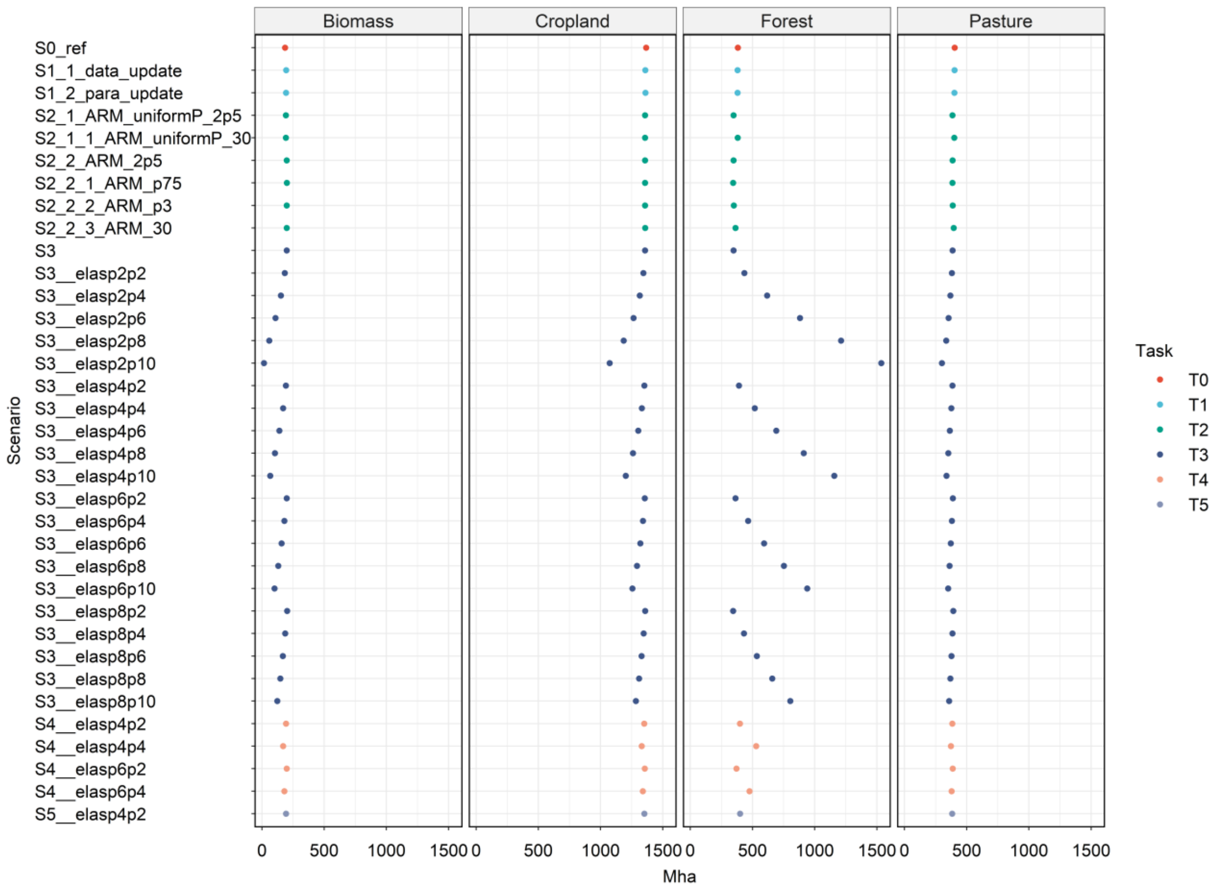

Fig. 32 Comparison of 2100 land area (cropland, forest, pasture, and biomass) across all scenarios

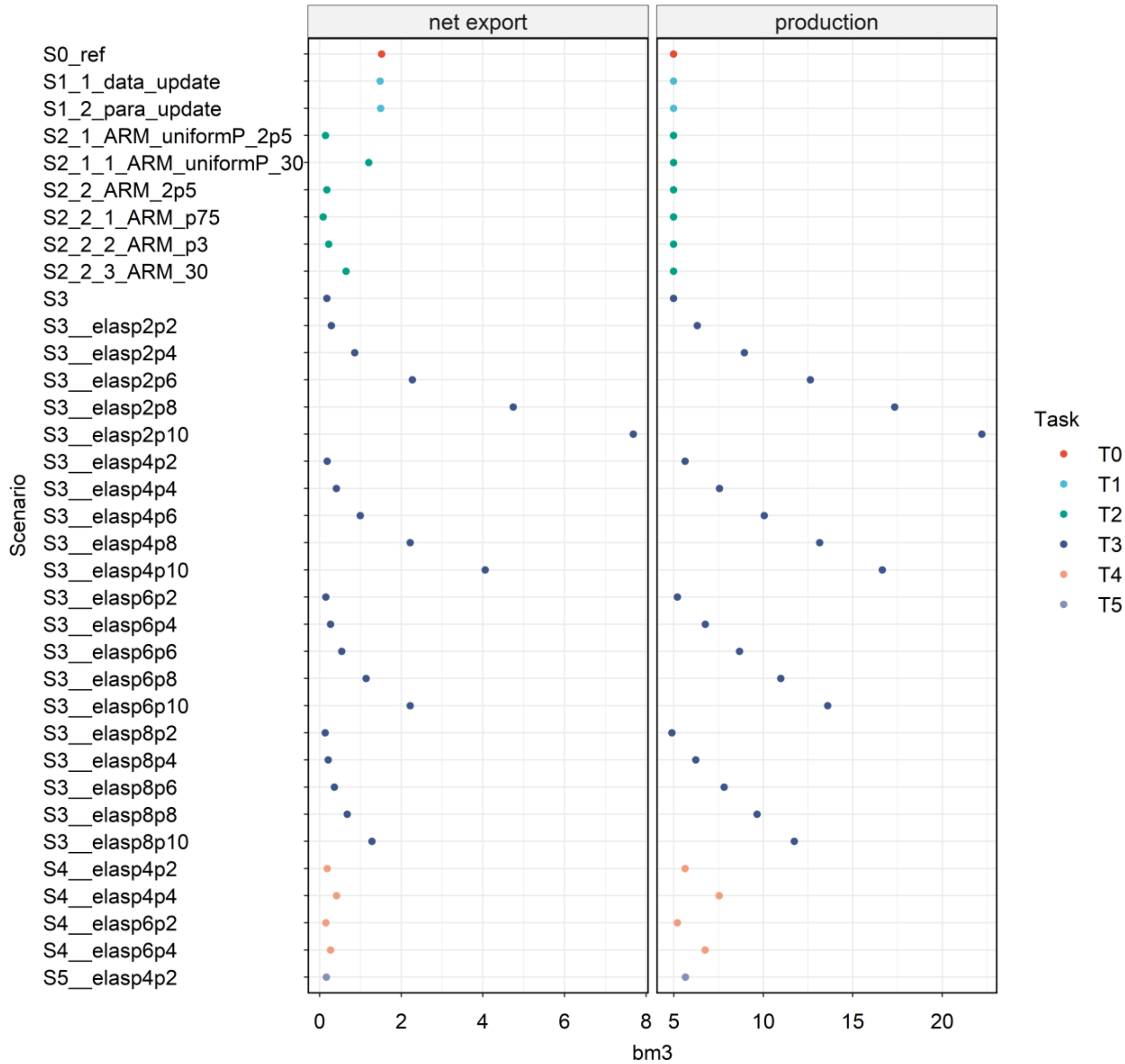

Fig. 33 Comparison of 2100 forest net trade and production across all scenarios

8 Shared policy assumption (SPA) GCAM validation runs

Here we show the high-level results from the SPA runs (SSP & RCP2.6). Note that SSP3-2p6 cannot be solved historically in GCAM or many other IAM models due to high mitigation challenges and limited technologies. However, this scenario was solved correctly since enabling livestock trade. So, results from SSP3-2p6 are also provided here. Results from the branch of this CMP (forest-trade) are compared with the master (recently merged and updated from CMP-313). The GCAM-core. results are consistent with the results discussed above. Also, we only highlight key results here, and more detailed results are provided in the attached **SI SPA results** results.

In general, we did not see significant changes in global climate results due to the updates in this CMP. The total forcing decreased slightly across all SSP & core scenarios (**Fig. 34**) due to the relatively higher global forest & biomass area and production. As a result, carbon prices also became relatively lower across all RCP scenarios (**Fig. 35**).

The most pronounced impact of the updates was on managed forest areas (**Fig. 36**) and production. Previously, global forest consumption and production were exogenously linked to the population with zero demand elasticities. After allowing elastic forest demand responses, we see more pronounced changes in global forest markets, particularly under policy scenarios. These responses are generally expected since, with elastic demand responses and regional markets, forest will behave closer to biomass trees as they are in the same land nest (**Fig. 37**). The total of forest and biomass tree areas was similar across the two branches (**Fig. 38**). In other words, there will also be stronger land substitution between forest and dedicated biomass when allowing flexible forest demand responses. Also, the impacts on land use change emissions were small for all scenarios (**Fig. 39**), likely because the emission factors for forest and biomass trees are similar.

In GCAM, biomass, as an energy supply, can be produced from dedicated energy crops, MSW, and residues (from crops, forest, and final forest demand). Due to the updates in this CMP, there was relatively more global production of both forest and dedicated energy crops. As a result, there was more biomass energy supply from the increased forest residues and energy crops across scenarios (**Fig. 40**), though the additional biomass energy supply had a relatively small impact on the energy system. **Fig. 41** and **Fig. 42** show the absolute and relative impacts, respectively, of the updates on the world primary energy supply across SPA scenarios. Global biomass energy supply increases by around 10% by 2100 under the reference scenarios. Under the policy scenarios, we also see more global changes in other energy supplies, but mostly within +-10%. We need to pay attention to the connection between biomass and forest (e.g., land competitions, energy substitutions, & demand and trade responses) in future biomass or forest-related updates.

In addition, with the regional forest market-related updates, GCAM can now report regional forest prices and gross trade. The trade responses became much more rigid with the Armington framework (see net trade in **Fig. 43**).

Notes on SSP3-2p6 results:

- Note that compared with other SSPs, SSP3 has much lower GDP growth and much higher population growth (see here GDP and Population). Also, the population in SSP3 won't reach a peak before 2100. Crops and forest demands are "inelastically" linked to population growth but elastically linked to GDP growth (positive income elasticities). Thus, under RCP scenarios, cropland and managed forest land under SSP3-2p6 won't be affected by policies as much as in other SSPs because SSP3 is more "population driven" than "GDP driven". In contrast, biomass area is not directly linked to the population so that it will be affected by policies under SSP3 in a way similar to other SSPs.
- Though SSP3_2p6 results were not provided in CMP-313, the LUC emissions results from SSP3_2p6 (e.g., spikes in the mid-century) are consistent with results in LUC emissions results from livestock-trade CMP-312.

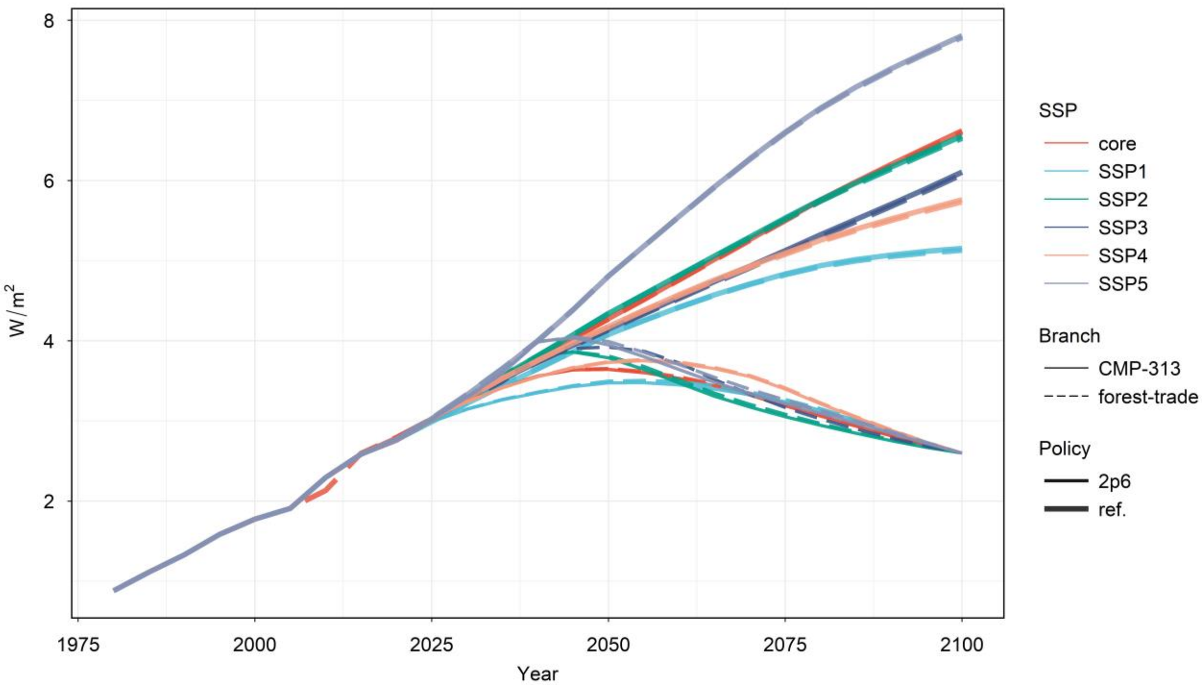

Fig. 34 Total forcing across SPA scenarios

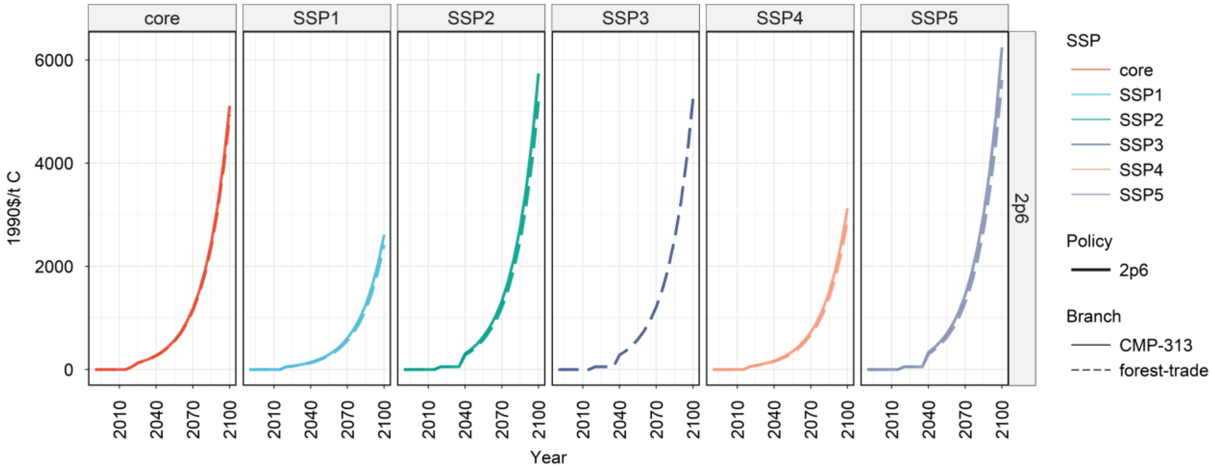

Fig. 35 Carbon price across RCP scenarios

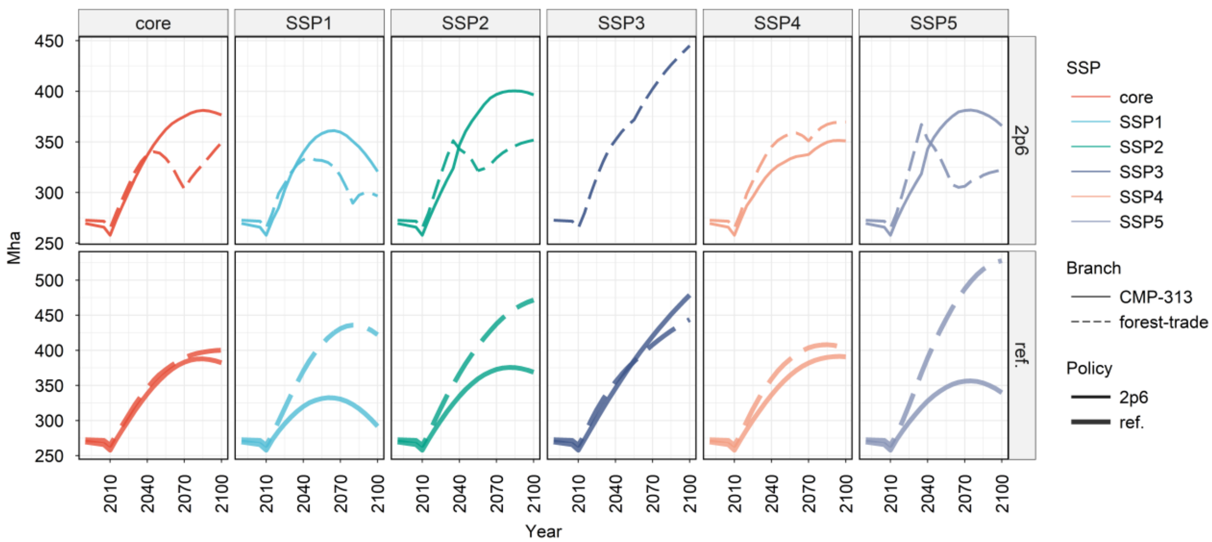

Fig. 36 Managed forest area across SPA scenarios

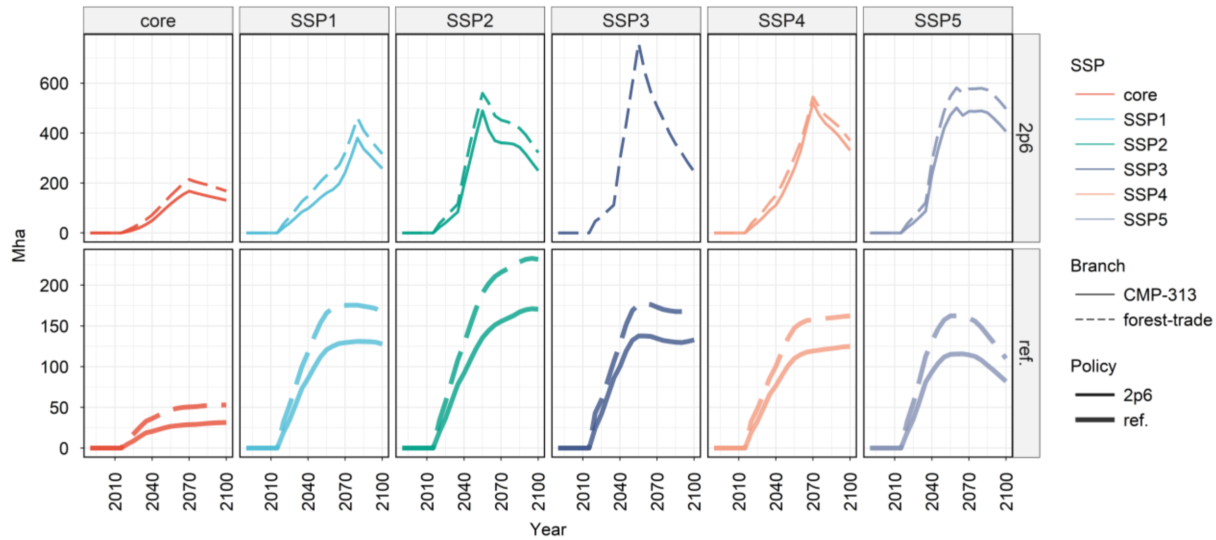

Fig. 37 Biomass tree area across SPA scenarios

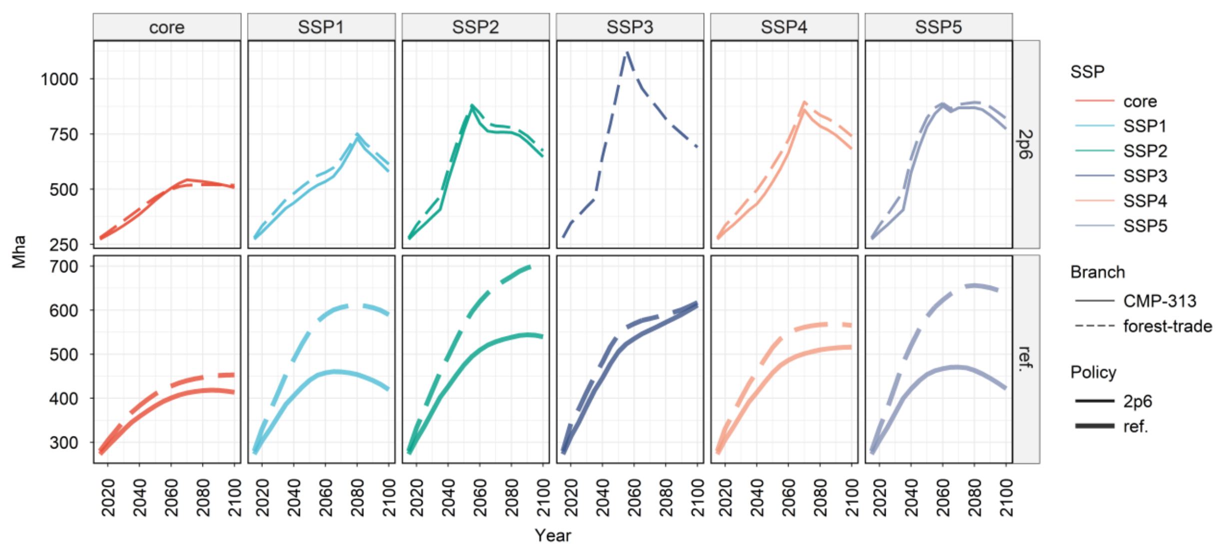

Fig. 38 Managed forest & biomass tree area across SPA scenarios

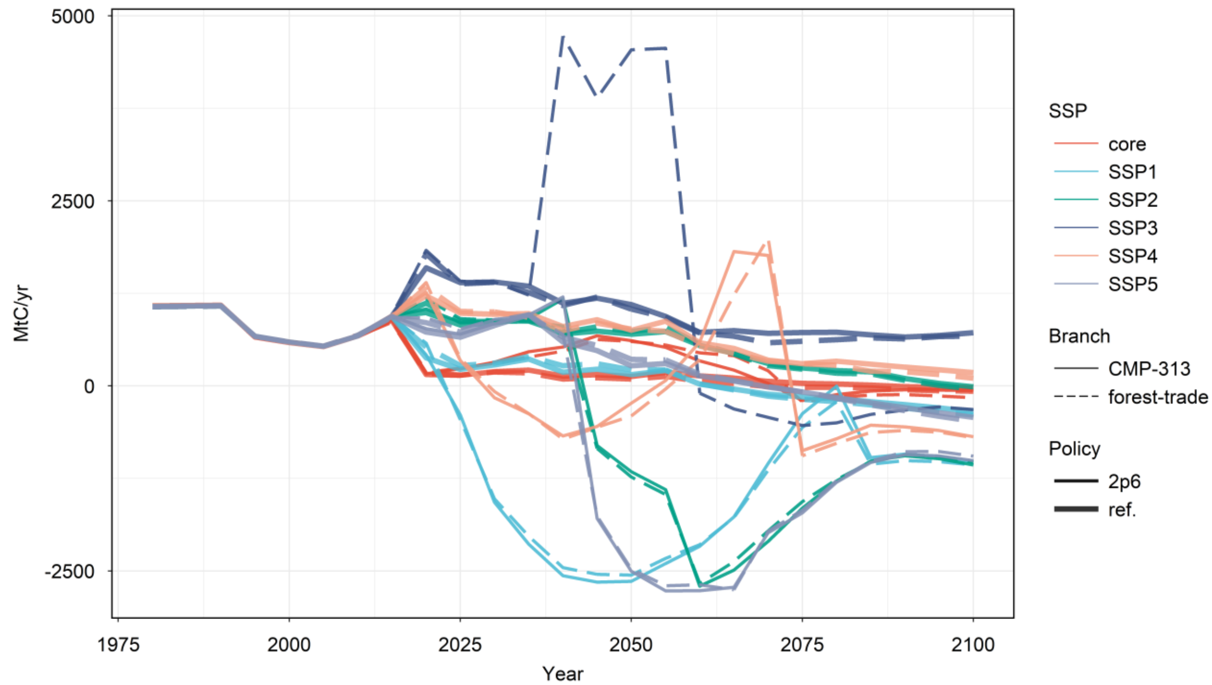

Fig. 39 Annual LUC carbon emissions across SPA scenarios

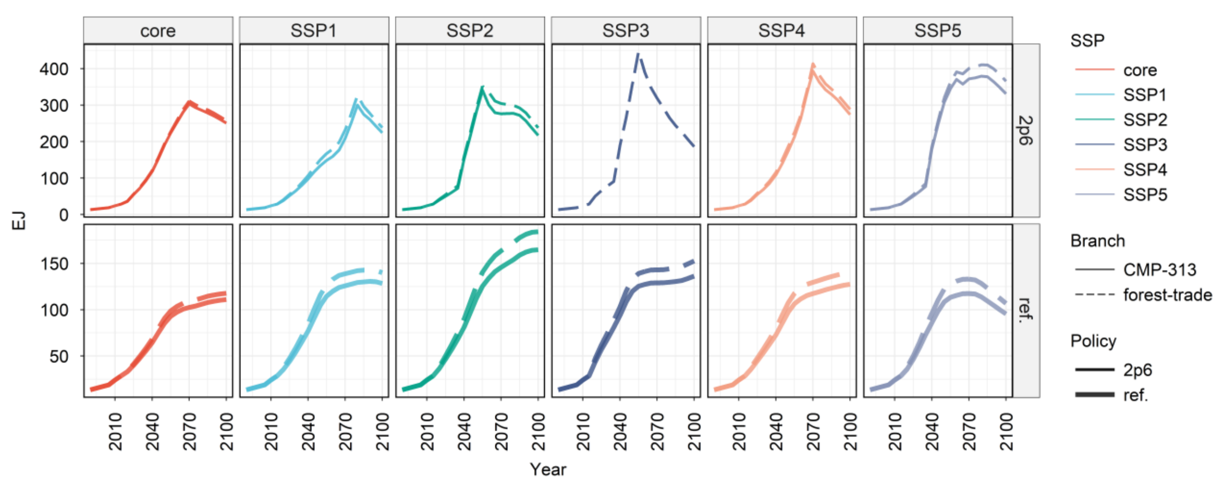

Fig. 40 World biomass energy supply across SPA scenarios

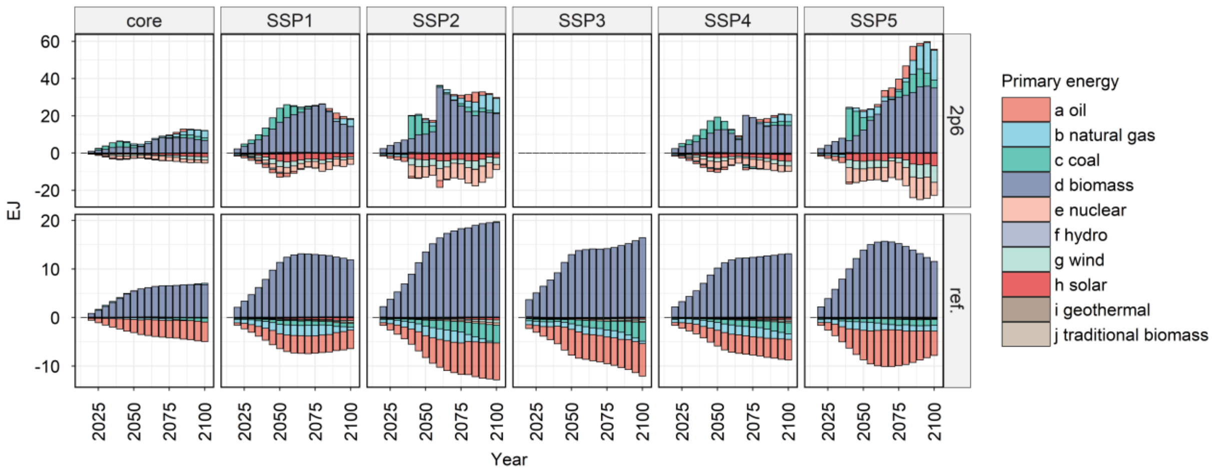

Fig. 41 Impacts (volume difference between forest-trade and CMP-313) on world primary energy supply across SPA scenarios (see more detailed primary energy supply results from the two branches in supplementary SPA results)

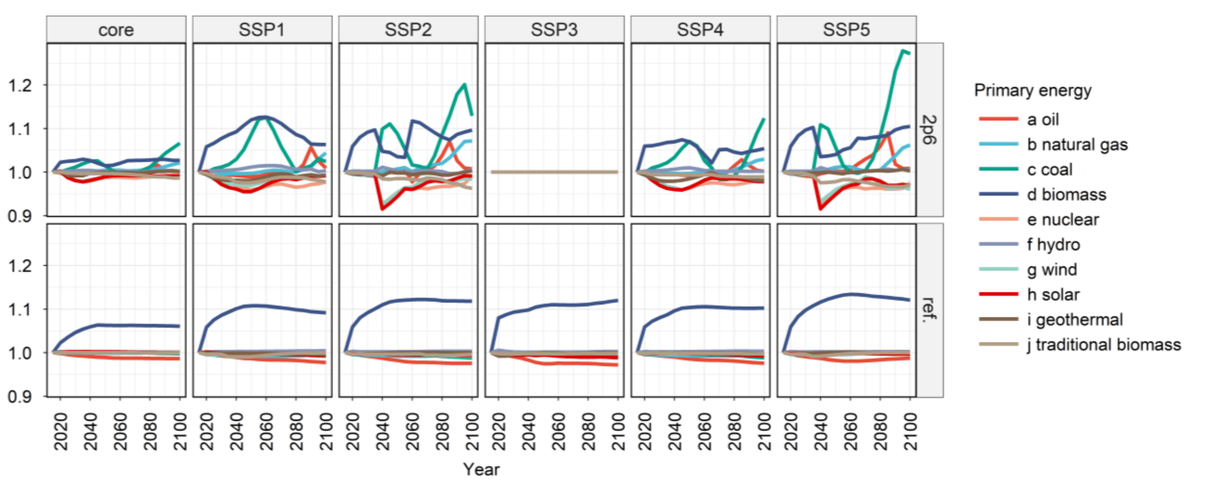

Fig. 42 Impacts (relative ratio between forest-trade and CMP-313) on world primary energy supply across SPA scenarios

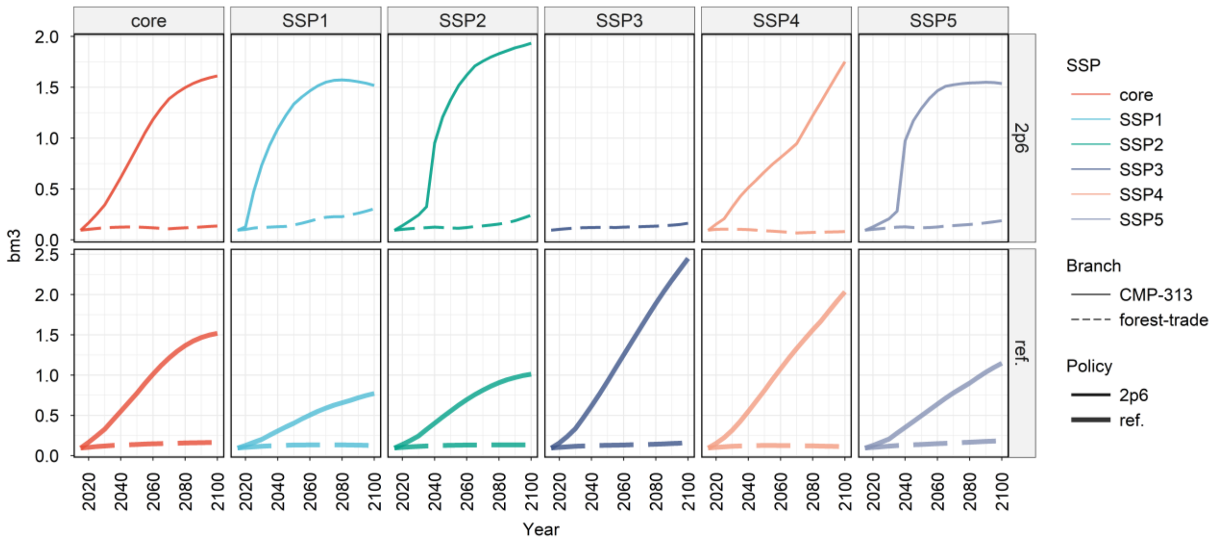

Fig. 43 World forest net trade across SPA scenarios

9 Future work

1) An R package to preprocess FAO agricultural data
    - We created an R project to directly download, update, and preprocess FAOSTAT data (for forest and trade-related data only for now). We can leverage and extend this project to process (e.g., adding headers and comments) all FAO or other raw data into csv files to be used in gcamdata. Alternatively, we can also consider generating xml files directly for all historical data directly since they are sunk (requires additional work in gcamdata as well). Separating historical data from parameters and future shocks allows us to (1) provide a more consistent framework for data and base year updates, (2) improve the quality of historical data by being more explicit on the assumptions used in preprocessing, (3) communicate better the parameters and external drivers, (4) reduce processing time in gcamdata, and (5) use alternative sources of data to feed GCAM.
2) Forest productivity
    - GCAM currently considers a strong future growth in crop yield, while the productivity growth for the managed forest is assumed to be consistent.
    - Allowing future changes in managed forest productivity will likely have important land use and trade implications.
3) Bilateral trade in GCAM
    - Incorporating bilateral trade in the current gross trade modeling framework only needs changes in the data system by disaggregating the internationally traded sectors (at the US right now) to regional levels.
    - We can consider adding a switch in the data system to allow bilateral trade for agricultural sectors.

- Note that we added additional processes in gcamdata_FAO_raw to generate ag_trade_bi.xml (add-on in configuration) to enable bilateral trade in GCAM. The XML (for major crops) is attached here (unzipped ~100Mb).

4) Aglu data update
   - We are using forest production data from FAO and forest land cover data from our LDS.
   - The inconsistency between LDS and FAO land cover data may lead to issues in forest productivity.
   - Agricultural production data were updated to 2013. We need to revisit the food balance data from FAO to check for updates.
5) Differentiating Roundwood
   - As discussed above, under roundwood, industrial roundwood, and wood fuel have different trade patterns, prices, and uses. Thus, differentiating industrial roundwood and wood fuel will likely have a large impact on forest-related projections.
6) The linkage between forest wood fuel and energy supply
   - About 50% of the primary forest (roundwood) production was used for wood fuel. However, we have not linked this energy supply to the energy system in GCAM.
   - GCAM includes traditional biomass (solid biofuels), residue biomass, and charcoal in the energy system. Ideally, fuel wood produced from the forest sector plays an important role in bioenergy supply with linkage to these energy sources.
   - We can consider adding this link between forest and energy sectors to better reflect real data and have more sophisticated responses. For example, the demand responses for wood fuel could be very different from the demand for industrial round wood. Also, adding this linkage will affect undeveloped regions (e.g., Africa and South Asia) as they are using significantly more traditional biomass (e.g., for cooking and heating).

Acknowledgments

We acknowledge Kate Calvin as a core contributor to this Core Model Proposal. We also appreciate the GCAM AgLU team for their support.

Supplementary Information

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