

Response to Reviewer #2 Comments

This paper presents an ambitious effort to develop a new partial-equilibrium model for agriculture and land use to be integrated in the AIM integrated assessment model framework. The comprehensive development is impressive and the paper and model documentation are a good basis for follow-up work. Some components of the model are unclear though and need further explanation, and some model dynamics are counter intuitive. Generally I do commend this work and support publication after my concerns have been addressed.

Response:

We sincerely thank the reviewer for the encouraging and constructive evaluation of our manuscript. We appreciate the reviewer's positive assessment of the model development and the helpful suggestions for clarifying several parts of the model. We have carefully considered all comments and revised the manuscript accordingly. Please see below our point-by-point responses.

General comments:

The resolution of the model is at the country and basin level. It is unclear however which dynamics are represented at the country-level and which at the basin-level and how these dimensions interact. Also the benefit of the basin-level at this stage of the model is unclear as water does not seem to be represented. Please explain better how this works and why this choice is made.

Response:

We have revised Sect. 2.2 to explicitly distinguish the spatial levels of the main model components. In AIM-ALPHA, food demand, domestic markets, imports and exports, and country-level market prices are represented at the country level, whereas primary crop production, livestock production, yields, land-use allocation, and land rents are represented at the production-unit level, defined as country–river-basin intersections. To make this distinction clearer, we added a new Table 1, which summarises the spatial level at which each major model variable is resolved.

Line 138: “At the country level, the model resolves all demand components, country-level imports and exports, and country-level market prices, including producer, consumer, border, import, and export prices, while world prices are determined at the global commodity level. Each of the 166 countries therefore constitutes a single domestic market that interacts with the rest of the world through international trade. Processed goods, which are assumed to require no land input, are also produced at this scale. These country-level variables are summarised in Table 1.

Within each of the 400 production units, the model determines primary-crop and livestock production, their yields, the nested allocation of land across cropland, pasture, forest, and other natural land, and the corresponding unit land rents. Resolving these variables at the production-unit level allows competition

between crop, pasture, and natural land uses, together with the underlying yield heterogeneity, to be represented explicitly.”

We further clarified how the two spatial scales interact. Production-unit-level outputs are aggregated to the country level to determine domestic supply, while country-level producer prices and demand conditions feed back to production units through profitability, land rents, and land allocation. We added an equation showing this aggregation explicitly. Processed goods are treated at the country level because they do not directly require land inputs.

Line 149: “The two scales are linked by two consistency conditions. First, for primary crops and livestock products, the country-level supply of commodity c in country cty , denoted $QSUP_{c,cty}$, is required to equal the sum of production-unit-level output $QS_{c,bas,cty}$ across all basins bas of that country (Eq. (1)), ensuring physical consistency between the demand and supply representations.

$$QSUP_{c,cty} = \sum_{bas} QS_{c,bas,cty} \quad (1)$$

Second, producer prices are defined at the country level and are therefore common to all production units within a country for a given commodity c . Differences in production conditions across production units are reflected through yields, non-land production costs, land requirements, and land rents, which determine the profitability of production and land allocation at the production-unit level.”

Finally, we clarified why basin-level production units are used even though water resources are not yet endogenously represented in AIM-ALPHA v1.0. The basin-level structure captures subnational heterogeneity in yields, agro-ecological suitability, slope, and soil constraints, all of which affect production and land-use competition. It also provides a hydrologically meaningful spatial structure for future coupling with an explicit water-resource module. We now state clearly that water resources are not an endogenous component of the current model version.

Line 159: “Although water resources and other basin-scale biophysical processes are not yet explicitly represented in this version of the model, the basin-level land-use representation is retained for two reasons. First, it enables the model to capture subnational heterogeneity in yields, agro-ecological suitability, slope, and soil constraints through the country–basin production units, which directly affects agricultural production and land-use competition. Second, it provides a hydrologically meaningful spatial structure onto which an explicit water-resource module can be added in future work.”

Allocation is driven by land rents (section 2.7) which is therefore quite a fundamental variable. What is this information based on? Please explain better how this works.

Response:

We have revised Sect. 2.7 to clarify the data sources and the role of land rents. Because globally consistent observed land-rent data are not available for all commodities and production units, AIM-ALPHA constructs base-year land rents from FAOSTAT producer prices, base-year yields, and GTAP-based cost shares. Specifically, the GTAP database is used to estimate the share of production costs attributable to land for each

commodity and country. This share is multiplied by the FAOSTAT producer price and base-year yield to obtain a unit land rent per hectare.

Line 374: “Because comprehensive observed land-rent data are not available globally for all commodities and production units, AIM-ALPHA constructs base-year land rents using FAOSTAT producer prices, base-year yields, and GTAP-based cost shares. For each commodity c and country cty , the GTAP database is used to estimate the land factor-cost share $LND_{c,cty}$, which is used as a proxy for the share of production value attributable to land. Other cost-share components used in the producer-price identity introduced in Sect. 2.6 are calculated consistently from the same GTAP-based decomposition. The base-year unit land rent (per hectare) is then

$$PL_{c,cty}^0 = LND_{c,cty} \cdot PP_{c,cty}^0 \cdot YLD_{c,cty}^0 \quad (13)$$

where $PP_{c,cty}^0$ is the FAOSTAT producer price and $YLD_{c,cty}^0$ is the base-year yield. The product of producer price and yield thus represents the base-year production value per hectare, and LND converts this value into the portion attributed to land. The country-level rents are then disaggregated to production units using GAEZ-based relative yields and land productivity information (FAO and IIASA, 2025). Detailed cost-share calculations are provided in the model documentation.”

We also clarified how land rents operate in future periods. For market-based agricultural activities, land rents are determined endogenously together with production, prices, and land allocation, so that the producer-price identity and land-balance conditions are satisfied. Land categories without direct market production, such as forest, other natural land, fallow land, and low-intensity or ungrazed pasture, are assigned exogenous rents fixed at their base-year levels, with forest rents augmented by carbon values in mitigation scenarios.

Line 386: “In future periods, land rents $PL_{c,bas,cty}$ for market-based agricultural activities are determined endogenously, jointly with production, prices, and land allocation. They adjust so that the Leontief producer-price identity introduced in Sect. 2.6 and the land-balance conditions hold across active production units for each country–commodity combination. Land categories without direct market production—forest, other natural land, fallow land, and low-intensity or ungrazed pasture—are assigned exogenous land rents fixed at their base-year levels. These exogenous rents enter the same land-allocation logit as the endogenous agricultural rents, allowing their areas to change in response to relative profitability and land-balance constraints. In mitigation scenarios, the forest rent is augmented by the carbon value of forest carbon stocks, as described in Sect. 2.9. The logit formulation, together with the balance condition below, maintains land balance among competing uses (Fujimori et al., 2014).

The land area available for endogenous allocation in each production unit is obtained by subtracting land uses that are fixed or unavailable for agricultural conversion from the total production-unit area:

$$QLVEG_{bas,cty} = QLTOT_{bas,cty} - QLOTH_{bas,cty} - QLURB_{bas,cty} - \sum_l QLPROT_l_{bas,cty} \quad (14)$$

where $QLTOT$ is the total production-unit area, $QLOTH$ is ice/water and other non-vegetated land, $QLURB$ is the urban area, and $QLPROT_l$ are the areas of protected land categories l (UNEP-WCMC and IUCN, 2024). $QLVEG$ is the area entering the top node of Fig. 4 as the parent of cropland, pasture, forest, and other natural land. At every node n of the nested structure, the share-based allocation in Eq. (16) is paired with the

balance condition that the child areas exhaust the parent,

$$\sum_{i \in \mathcal{N}(n)} QL_i = QL_{parent(n)} \quad (15)$$

so that the nested application of (15) closes the land balance from *QLVEG* down to each individual land-use activity. At every node of the nested structure shown in Fig. 4, the share of each child use *i* in the parent area is determined by a generalised logit in land rents,

$$share_i = \frac{\delta_i \cdot PL_i^{\rho_i}}{\sum_{j \in \mathcal{N}} \delta_j \cdot PL_j^{\rho_j}} \quad (16)$$

where \mathcal{N} is the set of competing uses at that node, δ_i a scale parameter calibrated to base-year shares, and ρ_i is a substitution parameter that controls how strongly allocation responds to relative rents. Production-unit indices are suppressed; the nested structure is implemented by repeated application of Eq. (16) along the branches shown in Fig. 4.”

The validation to 5 years of data is underwhelming. It would be very valuable if a back casting exercise could be added, e.g. from 2015 to 2000 to assess model dynamics based on a longer time series.

Response:

We thank the reviewer for the suggestion. We added a backcasting exercise from the 2015 base year to 2000 to assess model performance over a longer historical period. The revised validation section compares the backcast results with historical observations for major agricultural and land-use indicators, including consumption, production, cropland, pasture, and forest area. Because the temporal coverage of the observational datasets differs by variable and data source, the comparison period varies across indicators.

Line 585: “To further evaluate the longer-term dynamic behaviour of the model, we conducted a backcasting exercise for 2000–2015 using the 2015 benchmark calibration. In this exercise, historical population and GDP data, together with the exogenous yield-growth assumptions (Robinson et al., 2015), were used as exogenous drivers, while agricultural production, demand, land use, prices, and related outputs were simulated endogenously over the historical period. The backcast results are overlaid on the future projections in Figs. 7, 8, and 9 (dashed lines over 2000–2015), so that the historical and projected dynamics can be assessed in a single view. At the global scale, AIM-ALPHA reproduces the historical trends in livestock consumption, cropland, and forest area over 2000–2015. The main deviation is in pasture area, for which the model produces a slight increase against an observed mild decline; this is driven largely by Middle East and Africa and likely reflects an underestimation of pasture productivity in that region. At the regional level, the historical expansion of cropland in Latin America and the Middle East and Africa, and the decline in OECD&EU, are reproduced only in attenuated form, likely owing to the assumed yield trajectories and trade representation. Overall, the backcasting exercise provides an additional check on the model's dynamic behaviour for the main global indicators, while also highlighting remaining uncertainties in regional land-use dynamics.”

The new backcasting exercise therefore provides an additional check of model performance over a longer historical period. We also revised the discussion to make clear which indicators are reproduced reasonably

well and where differences remain.

Line 695: “The backcasting exercise for 2000–2015 further suggests that AIM-ALPHA captures the broad global dynamics of major agricultural and land-use indicators, although regional discrepancies remain for some variables.”

Line 718: “Third, because international trade is formulated using complementarity conditions, trade volumes may respond sharply to small changes in prices, rendering model outcomes volatile. This may also affect regional production and land-use projections through shifts between domestic production and imports.”

Regarding the results, notably the pasture trend is very surprising. Historically pasture has been gradually declining for quite some time, but this model projects a steady increase from 2015-2040 in all scenarios. In line 360 it is stated that this depends on the ratio of roughage to concentrate feed which in turn is based on GDP/capita, but then this relationship does not seem to reflect recent trends as GDP has increased while pasture has decreased... I would say this really needs to be improved as it dominates the land use results. Similarly on the regional level the cropland area trend from recent trends in LAM and MEA. How can this be explained and can it be improved?

Response:

We agree with the reviewer that the original pasture trend was counter-intuitive and needed improvement. In the original formulation, increases in roughage demand were reflected too directly in pasture-area requirements. The original formulation did not explicitly account for changes in pasture utilization intensity, even though this is an important way in which grazing systems can respond to increasing roughage demand. This meant that growth in livestock demand could lead to a large expansion of pasture area, even though in practice such growth can also be accommodated by more intensive use of existing pasture.

We therefore revised the livestock–pasture representation to include changes in pasture utilization intensity. In the revised model, the aggregate pasture category in each production unit is divided into actively grazed pasture and low-intensity or ungrazed pasture. These two components are allocated through the same land-rent-based logit structure used for the other land-use categories. The rent of actively grazed pasture is linked to the profitability of grazing-based livestock production, whereas the rent of low-intensity or ungrazed pasture is fixed at its base-year level, as for forest, other natural land, and fallow land. Although this rent is exogenous, the area of low-intensity or ungrazed pasture still changes endogenously through the logit allocation, because its share responds to changes in the rents of the competing land uses.

This revision allows higher roughage demand to be met through both expansion of total pasture area and more intensive use of pasture. In the updated results, pasture area still increases gradually under the baseline scenarios, but the increase is much more moderate than in the original version. We revised the model description, equations, and results accordingly.

Line 337: “Forage supply is linked to pasture use, but the model distinguishes between total pasture area and the actively grazed portion of pasture, so that increases in roughage demand can be met both by area expansion and by more intensive use of existing pasture (Sect. 2.7).”

Line 367: “Pasture is further subdivided into an actively grazed component and a low-intensity or ungrazed component. The actively grazed component is allocated among individual livestock-production activities, while the low-intensity or ungrazed component competes with active grazing through the same land-rent-based logit structure.”

For the regional cropland trends in Latin America and the Middle East and Africa, the discrepancy is not fully resolved in the revised model. We have, however, identified its likely source and revised the results and discussion to explain this remaining limitation more clearly. Historical datasets indicate cropland expansion in these regions, whereas the near-term projections show more limited changes. This difference is mainly associated with the modelled balance between domestic production and imports, as part of the increase in crop demand is met through higher imports rather than domestic production expansion. We now discuss this as an uncertainty related to trade responses and regional production allocation.

Line 578: “The regional cropland trends in Latin America and the Middle East and Africa are not fully reproduced. Historical datasets indicate cropland expansion in these regions, whereas the near-term projections show more limited changes. This difference is mainly associated with the modelled balance between domestic production and imports: part of the increase in crop demand is met through higher imports rather than domestic production expansion. This result indicates that regional cropland outcomes are sensitive to trade responses and domestic production allocation, and remains an important source of uncertainty in the near-term regional projections.”

Line 718: “Third, because international trade is formulated using complementarity conditions, trade volumes may respond sharply to small changes in prices, rendering model outcomes volatile. This may also affect regional production and land-use projections through shifts between domestic production and imports.”

Specific comments:

Line 110: figure 1 shows water and nitrogen resources but these are not mentioned at all in the methodology section. How are they represented?

Response:

We revised Figure 1 by showing these components as grey dashed boxes indicating potential future linkages, and clarified this in the caption and limitations discussion.

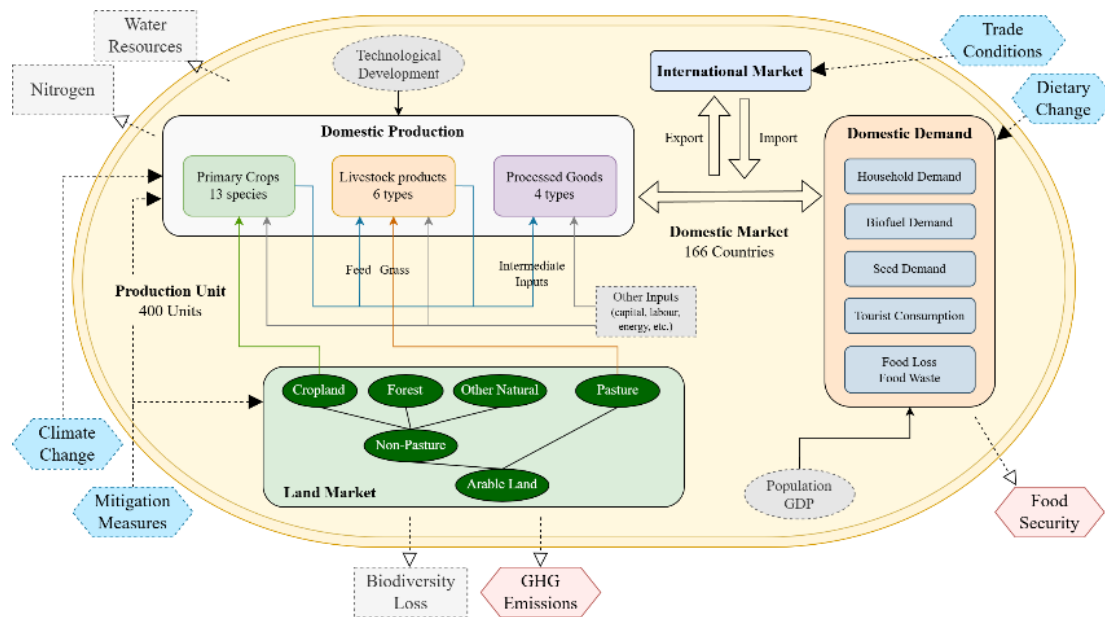


Figure 1. Conceptual structure of AIM-ALPHA and its linkages to related environmental systems. Water resources, nitrogen flows, and biodiversity impacts are shown as grey dashed boxes because they are not explicitly represented in AIM-ALPHA v1.0; they indicate potential future extensions or linkages with external impact models.

Line 721: “Fourth, water resources, fertilizer inputs, and other resource constraints are not yet explicitly represented. The potential biophysical limitations of—and the input-price feedbacks on—agricultural production are not captured.”

Line 144: I am a bit puzzle by the processed foods category ‘sweeteners’. This also includes sugar right, so it would be better to call it ‘Sugar and sweeteners’ as sugar is the bulk of the product. Also it now sounds like inputs for sweeteners can only come from sugar crops (‘primarily’), while maize is also in important input (10-12%), especially in the USA. Is this accounted for? If not, why is this a reasonable assumption? If it is accounted for this should be better described.

Response:

We have renamed the processed-good category from “sweeteners” to “sugar and sweeteners” to better reflect the FAOSTAT food-balance category and the fact that sugar is the dominant product in this aggregate.

Line 183: “Processed goods are assumed to be produced using specific raw materials. Sugar and sweeteners are represented using sugar crops; vegetable oils from oilseeds; dairy products from raw milk; and alcoholic beverages from wheat, rice, maize, other grains, and fruit. The four processed-food categories represented in the model are selected to correspond to major FAOSTAT FBS commodity aggregates, but they do not cover all processed or derived products in the FBS framework. The model does not resolve region-specific differences in raw-material composition within each category, because the FAOSTAT FBS processing line does not provide a globally consistent mapping from processed raw commodities to final processed-product categories.”

We also revised the description of processed-good production to clarify the raw-material assumptions. In the current version, sugar and sweeteners are represented as an aggregate processed-good category derived from sugar crops. Maize-based sweeteners are not represented as a separate processing pathway in this version. This simplification reflects the current aggregation of processed goods, where broad FAOSTAT-consistent processed categories are represented rather than sub-product-specific or country-specific processing technologies. We now state this explicitly in the manuscript and identify it as a limitation in Sect. 5.

Line 723: “Fifth, processed goods are represented as broad aggregate categories with fixed raw-material coefficients, so sub-product-specific or country-specific processing pathways within each aggregate are not distinguished.”

Line 236: also here the assumption on input for processed foods is unclear. Is it calibrated to historical shares? Or assumed to be 1 primary crop only?

Response:

We have revised Sect. 2.6.3 to clarify that processed-food inputs are calibrated to historical FAOSTAT Food Balance Sheet processing data rather than being determined endogenously. For each processed-food category, we first define a set of possible raw commodities. Base-year input coefficients are then constructed from the FAOSTAT processing quantities of those raw commodities. Some categories are represented by one main raw input—sugar crops for sugar and sweeteners, oilseeds for vegetable oils, and raw milk for dairy products—whereas alcoholic beverages use multiple raw commodities (wheat, rice, maize, other grains, and fruit). These input coefficients are fixed over time in the current version, so substitution among raw materials within each category is not represented.

Line 342: “Processed-food products are produced using intermediate input goods drawn from the predefined set of raw commodities listed in Sect. 2.3. For each processed-food category, a set of corresponding raw commodities is assigned, and their base-year processing quantities reported in the FAOSTAT FBS are used to construct fixed input coefficients. The resulting coefficients reflect the base-year composition of FBS processing use among the raw commodities assigned to each processed-food aggregate. Domestic raw-material prices affect processed-food production through the corresponding input costs, while the input coefficients themselves are fixed after base-year calibration. This is a reduced-form representation of the processing sector: each processed-food category is modelled as a single composite product, and sub-product pathways within each aggregate are not separately distinguished.”

Line 261-262: can you give more details on the available land constraints. Are there more than the two constraints mentioned? How much does this restrict the model? Are there also minimal yields constraints or is that taken into account through prices? And how are protected areas taken into account?

Response:

We revised Sect. 2.7 to clarify how agricultural land availability is constrained. In each production unit, urban areas, ice and water bodies, and protected areas are treated as fixed at their base-year extent and excluded from the land area available for endogenous allocation. Cropland and pasture are then constrained by the area suitable for agricultural use, based on slope and soil suitability from GAEZ. We added an explicit equation for this constraint and clarified that the associated suitable-land area is treated as an exogenous parameter.

Line 396: “The land area available for endogenous allocation in each production unit is obtained by subtracting land uses that are fixed or unavailable for agricultural conversion from the total production-unit area:

$$QLVEG_{bas,cty} = QLTOT_{bas,cty} - QLOTH_{bas,cty} - QLURB_{bas,cty} - \sum_l QLPROT_l_{bas,cty} \quad (14)$$

where $QLTOT$ is the total production-unit area, $QLOTH$ is ice/water and other non-vegetated land, $QLURB$ is the urban area, and $QLPROT_l$ are the areas of protected land categories l (UNEP-WCMC and IUCN, 2024). $QLVEG$ is the area entering the top node of Fig. 4 as the parent of cropland, pasture, forest, and other natural land.”

Line 412: “A biophysical constraint further restricts agricultural land allocation. The total area of cropland and pasture cannot exceed the area suitable for agricultural use in each production unit, based on slope and soil suitability from GAEZ (FAO and IIASA, 2025):

$$QLCRO_{bas,cty} + QLPAS_{bas,cty} \leq QLAG_{bas,cty}. \quad (17)$$

where $QLCRO$ and $QLPAS$ are cropland and pasture areas, and $QLAG$ is an exogenous parameter representing the agriculturally suitable land area. ”

Line 266: it is unclear to me what calculations happen at the country-level and which at the river basin level. I assume trade is at the country-level, but how is this then connected to the basins? This needs to be made more clear throughout the methodology.

Response:

This point is closely related to the first general comment above, and we addressed both by revising Sect. 2.2 and the related methodology sections. Trade is represented at the country level: imports and exports are determined for each country and commodity through the country-level market-clearing and trade complementarity conditions, whereas primary crop and livestock production, yields, land allocation, and land rents are represented at the production-unit level. The two scales are connected by aggregating production-unit-level outputs within each country to obtain country-level domestic supply, which enters the country-level market balance with domestic demand, imports, and exports. We added a new Table 1 and an explicit aggregation equation to make this connection clear.

Line 300: ‘SSP1 models’ is a weird phrasing, reformulate to ‘SSP1 represents’ or similar.

Response:

We agree and have revised the wording from 'SSP1 models' to 'SSP1 represents'.

Line 307: this section mostly describes the SSP narratives which better fits in section 3. It would be useful to describe takes population and gdp changes into account.

Response:

We moved the general SSP narratives to Sect. 3, as suggested.

Line 481: “This section describes the scenarios used for the following analyses. The SSP framework considers alternative global development trajectories, SSP1 to SSP5, each featuring distinct levels of economic growth, demographic change, and technological development (Riahi et al., 2017). These contrasts are reflected in the global population and GDP trajectories shown in Fig. 5. SSP1 represents a sustainable world in which the global population peaks around the middle of the century and subsequently declines, while GDP grows steadily. SSP2, the middle-of-the-road pathway, lies between the other SSPs in both population and GDP. SSP3 assumes slow economic growth but persistently high population growth, resulting in the largest population and the smallest GDP among the SSPs, leading to regional disparities and development challenges. SSP4 depicts a world with large inequalities between and within countries, with a population trajectory close to SSP3 but substantially lower GDP than SSP1 and SSP2. SSP5 represents rapid economic growth based on fossil-fuel use and extensive globalisation, with a population trajectory similar to SSP1 but the highest GDP among all SSPs. For each SSP, a business-as-usual (BaU) scenario is simulated without climate-change mitigation measures or impacts. Table 3 summarises the key socioeconomic assumptions specific to each SSP.”

Line 379-380: it is stated that ‘livestock consumption is higher because of the assumptions in table 1’. But table 1 does not explain this in my view as only the gdp-based food demand relationship is mentioned. The difference in SSP1 is most likely caused by omitting the assumption of reduced preference for livestock products that is typically adopted.

Response:

We thank the reviewer for this comment. We agree that the original SSP1 lacked the dietary-shift assumption typically adopted for sustainability scenarios. We have added an exogenous reduced-preference factor for livestock food demand in SSP1, following the IMAGE dietary-shift representation (Stehfest et al., 2014): meat and dairy consumption in high- and upper-middle-income countries is reduced by 5%, 10%, 20%, and 30% in 2020, 2030, 2050, and 2100, respectively. No such adjustment applies to SSP2–SSP5. Table 3 and the corresponding text describing Fig. 8 have been updated, and SSP1 livestock consumption now decreases relative to the other SSPs, consistent with the sustainability narrative.

Line 495-497: This statement is correct, as figure 8 show for quite a few variables that the results are outside the SSP database range.

Response:

We agree that the original statement was too strong. The revised discussion notes broad qualitative agreement with other IAMs but not full quantitative consistency, and attributes deviations from the SSP database range to model-specific assumptions on yield growth, livestock-system dynamics, pasture utilization, and land allocation.

Line 697: “The baseline projections are broadly comparable to those of other IAMs in terms of the direction of major global trends, although some variables fall outside the SSP database range. These deviations likely reflect differences in model assumptions and structure, including yield growth, livestock productivity and feed requirements, trade representation, and land-allocation mechanisms.”

Textual comments:

Line 55: replace ‘capture of’ by ‘representation of’ or something similar.

Response:

We agree and have replaced 'capture of' with 'representation of'.

References

Fujimori, S., Hasegawa, T., Masui, T., and Takahashi, K.: Land use representation in a global CGE model for long-term simulation: CET vs. logit functions, *Food Sec.*, 6, 685–699, <https://doi.org/10.1007/s12571-014-0375-z>, 2014.

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