Core Model Proposal :424
Title: Moirai LULC data & pasture productivity update

Product: Global Change Analysis Model (GCAM)

Institution: Joint Global Change Research Institute (JGCRI)

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Related sector: Land

Type of development: Data

Purpose: The purpose of this core model proposal is to update carbon densities for managed land types, and to provide additional years of land use and land cover data through 2025 for the GCAM aglu module. Updating the managed land carbon data aligns these values with the previous update (CMP #356) which focused on unmanaged vegetation carbon values. Additional years of land data enables a later GCAM base year.

Introduction

There are two main updates included in this proposal:

1. Land use data from moirai is updated to 2025. This led to an update of all land use category data more broadly in GCAM from 2000 to 2025. Table 1 below shows the main files that were changed as a part of this update. The updates to moirai are documented here: https://github.com/JGCRI/moirai/pull/48. **See summary of changes below for details on the update.**
2. Updates to carbon densities (vegetation and soil) to include updated carbon densities for cropland and pasture. Moirai was updated to impute pasture carbon densities based on latest available pasture carbon data. This is documented in this paper: https://www.nature.com/articles/s41597-025-04723-4 **See summary of changes below for details on the update.**

Summary of Changes

1. **Land use data updates**- In this update, we updated moirai to include the latest HYDE land use dataset (which was used for the Global Carbon Budget 2025). The updated dataset (HYDE 3.5) is available here- https://public.yoda.uu.nl/geo/UU01/F45D44.html.
   The HYDE dataset presents different types of land use (Cropland, Pasture, Urbanland and Unmanaged) at the pixel scale at a resolution of 5 arcmins. These are combined with different vegetation maps from ISAM, and the GCAM region basin boundaries to create tabular inputs to the GCAM agricultural and land use system (inputs are located in the LDS folder in gcamdata). Figure 1 below summarizes the data processing in the moirai land data system (Adapted from Di Vittorio et al. 2020). With our updates, the lulc input data for GCAM is effectively extended to the year 2025. It is important to note that the HYDE data is used in the harmonization of land use inputs across the land system in moirai and GCAM, therefore the updates to LULC data affect all of the tabular outputs generated by the moirai land data system. The most consequential update from a GCAM perspective is to the estimates of land cover designated as Cropland or Pasture (both Managed and Unmanaged). The irrigated and harvested area fractions from the MIRCA dataset (a moirai output and input to gcamdata) have not been affected by this update. Note that in the data system we still harmonize GCAM cropland to the same FAO harvested area, so total cropland would likely not be affected significantly but there will be some updates to other arable land (i.e. unharvested cropland). However, there are much more significant updates to unmanaged land cover and pasture, and to forested area from this update. The HYDE data was updated from the year 2000 onwards, leading to changes in historical values from 2000 onwards. Note that moirai is currently being updated to include updated irrigation maps from the IFPRI-MapSpam dataset. We do not include the same here and that update will be a part of a different CMP (See future improvements).

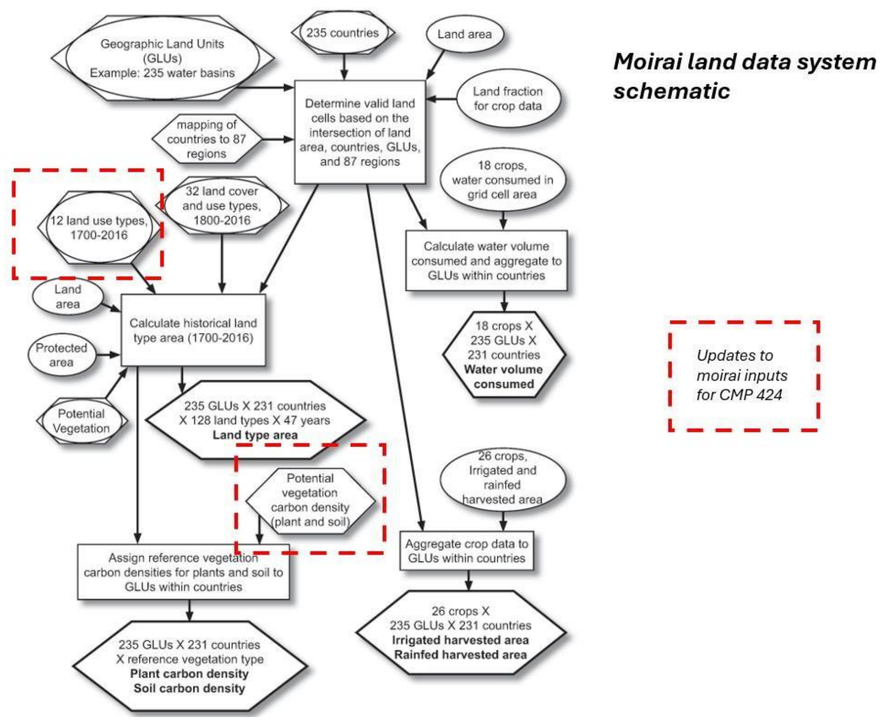


Figure 1: Schematic summarizing data processing in moirai land data system. Red boxes indicate updates made to input data as a part of this proposal.

2. Pasture **carbon density update-** Previously (as a part of CMP 356- [356 Update soil and vegetation carbon densities in GCAM (updates from moirai 3.1)]), we had updated land carbon densities (for soil and vegetation) in GCAM based on an approach by Narayan et al. (2025). However, in that CMP, we had only updated the carbon densities for unmanaged land cover and pasture carbon densities were re-computed based on unmanaged grassland carbon densities. Here we update the density values to include pasture carbon densities. To summarize our approach, we take contemporary vegetation carbon density maps for the year 2010 (Spawn et al. 2020) and similar soil carbon maps (Hengl et al. 2017) at a fine resolution of 300 m, and combine them with underlying land cover maps to derive land area specific carbon densities (e.g. Forest vegetation/soil carbon, Crop vegetation/soil carbon). These are then harmonized to moirai/GCAM land use and cover in 2010. Finally, in the resampling process we derive a distribution of carbon values for each pool, land type, basin in the moirai land data system and use this distribution to derive an estimate of a pre-industrial carbon density (by pool). This is then used to spin up GCAM (spin up being conducted from 1700-2021) and determines productivity for Pasture and Forests. The entire process is described in detail in Narayan et al. 2025, but we show a schematic summary of our approach in Figure 2 (Taken from that paper). Note that users should consult CMP 356 or the paper cited above which describes this approach in more detail. Figure 3 shows resultant maps of crop, pasture, and unmanaged vegetation carbon at a 5-arcmin scale.

For this proposal, pasture carbon densities are derived based on existing pasture maps and are differentiated from unmanaged grassland. This resulted in generally lower pasture yields than used in GCAM (See Figure 5 below).

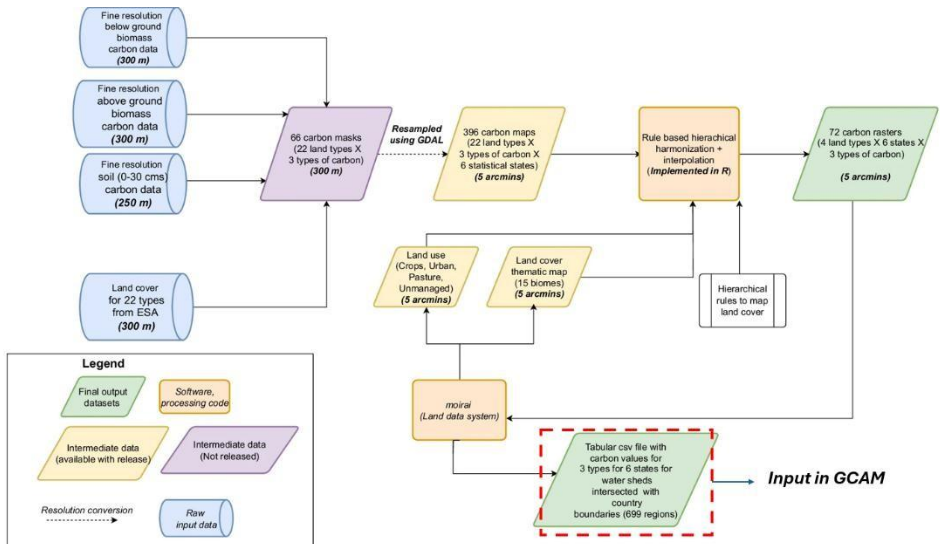


Figure 2: Schematic showing process used in moirai 3.1 for processing carbon data

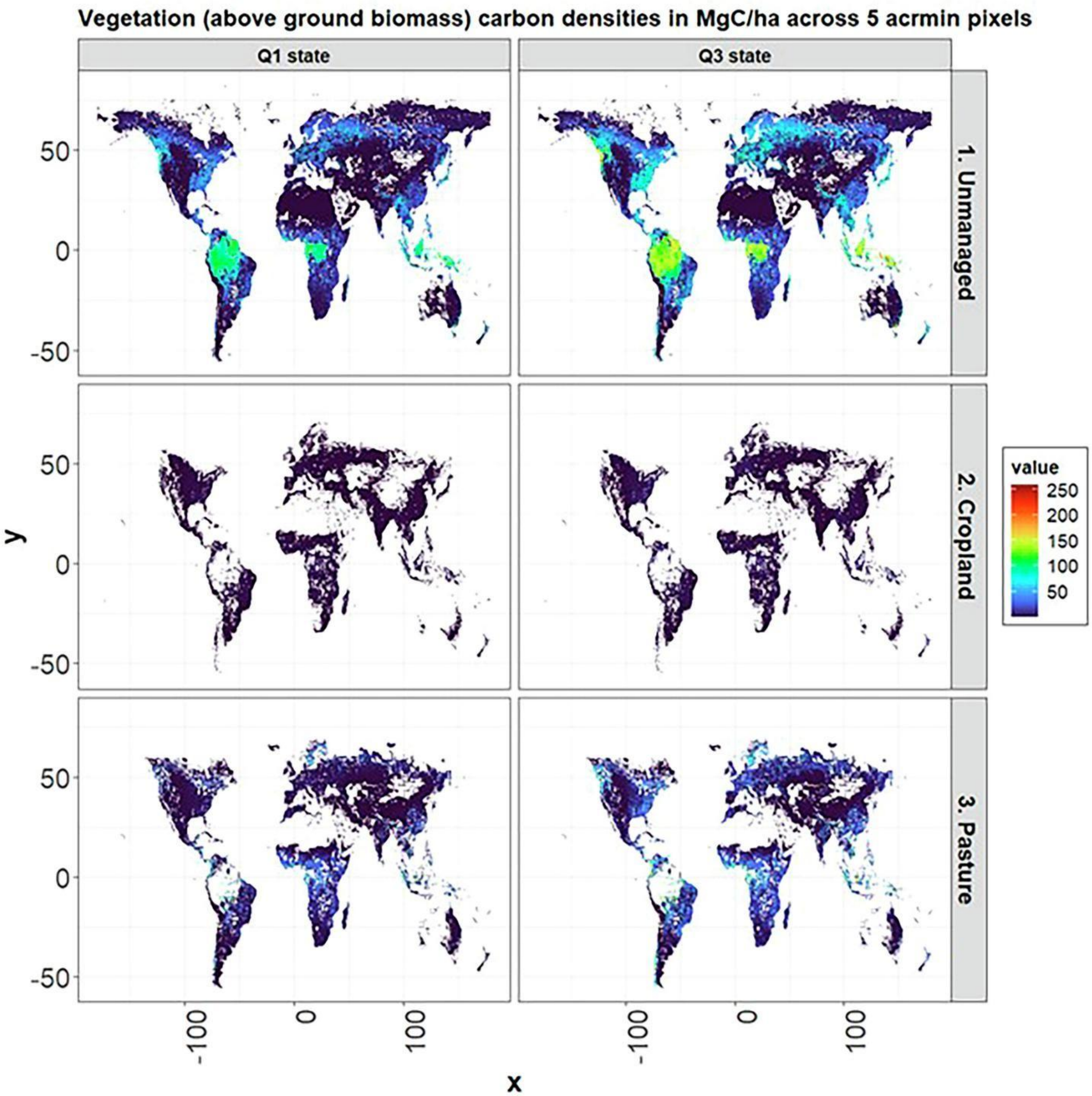


Figure 3: Veg carbon (aboveground) in MgC /ha across 5 arcmin grid cells for aggregate land types for the Q3 state. Values are shown for two statistical states, namely the Q1 and the Q3. As mentioned in the text, the Q3 values are used to spin up GCAM.

3. ***List of changes***

The model changes are contained within aglu inputs and zaglu L1xx chunks. They consist primarily of land input data updates with some small code changes that reflect differences in those input files. The outcome of these updates is an improved representation of soil and vegetative carbon for managed land types which has impacts on both land productivity and land allocation. Table 1 below describes the files updated in gcamdata as a part of this update. The validation section includes several figures that demonstrate the impacts of these data updates across a range of GCAM scenarios.

Object	Change
input/gcamdata/	
inst/extdata/aglu/	
LDS/	
Land_type_area_ha.csv	Updated land area to 2025 based on HYDE land area data and ISAM vegetation data
LDS_ag_HA_ha.csv	Harvested area updated in the year 2000 due to HYDE land area update
LDS_ag_prod_t.csv	Crop production updated in the year 2000 due to HYDE land area update
MIRCA_irrHA_ha.csv	Irrigated harvested area updated in the year 2000 due to HYDE land area update
MIRCA_rfdHA_ha.csv	Rainfed harvested area updated in the year 2000 due to HYDE land area update
Ref_veg_carbon_Mg_per_ha.csv	Carbon density data updated to include updated crop and pasture carbon area data
R/	
constants. R	Increased aglu. LAND_TOLERANCE to 0.42 from 0.005 Added an absolute land area tolerance set at 3 billion m2
zaglu_L100.0_LDS_preprocessing. R	Removed year remapping to reflect data year update
zaglu_L120.LC_GIS_R_LTgis_Yh_GLU.R	Code updated to ingest latest carbon data
zaglu_L123.LC_R_MgdPastFor_Yh_GLU.R	Defined default pasture yield to complete missing values
zaglu_L124.LC_R_UnMgd_Yh_GLU.R	Added constraints on the unmanaged land adjustment ratio

Table 1: Summary of changes by file

Validation

Land allocation and production

We begin by describing changes in overall land allocation globally by land type (Figure 4). In GCAM pasture yields are defined by the vegetation carbon of pasture which is adjusted for cellulose content and grazing intensity. These updates result in pasture yields which are lower overall (Figure 5). Therefore, impacts to land allocation are dominated by increases in managed pasture and grassland to compensate for lower productivity of these land types. Specifically, vegetative carbon values result in increased grazed pasture and grassland allocation and proportionally decreased unmanaged pasture and shrubland allocation. Across the 9 GCAM validation scenarios, pasture (grazed) sees increases up to 20.2% with the largest relative increase occurring in the SSP1 scenario (+20.2%), followed by SSP5 (+13.2%), and SSP2 (+12.8%). Pasture (other) decreases up to 23.3% with the largest relative decrease occurring in the SSP5_2p6 scenario (-23.3%) which had the smallest corresponding increase in pasture (grazed) indicating a net decrease in pastureland allocation under SSP5_2p6. SSP1_2p6 also sees a large decrease in pasture (other) allocation (-20.9%) and a slight decrease in pasture (grazed) allocation (-3.6%) as well. Generally, net pasture and grassland allocation decreases in 2p6 scenarios and remains relatively stable under non-2p6 scenarios (Figure 6). We also see increased grassland allocation, decreased shrubland allocation, and decreased biomass allocation across all of our validation scenarios. Historical estimates of Urban land have also changed as a result of updates from the HYDE dataset. We want to note that Urban land is not modeled in GCAM and is held constant over time. The HYDE dataset updated historical urban land cover but this increase ~200 thous km2 is still minuscule relative to other land types and does not influence results.

One additional observation in the new GCAM land use data is that urban land now increases historically from ~300 thous km2 globally to ~800 thous km2 between 2000 and 2021 (Previously this increase was to ~600 thous km2 by 2021). This is largely a result of updated representation of urban land cover data within HYDE. historical levels of total pasture (managed + unmanaged) from HYDE have decreased globally from ~32 million km2 to 30.5 million km2 in 2021. This has driven increases in overall grassland cover. Moreover, increases in urban land and changes in the pasture areas have also led to reclassification of land from shrubland. The release documentation for the HYDE dataset suggests that this is because of updated MODIS maps historically which led to changes in vegetation classification.

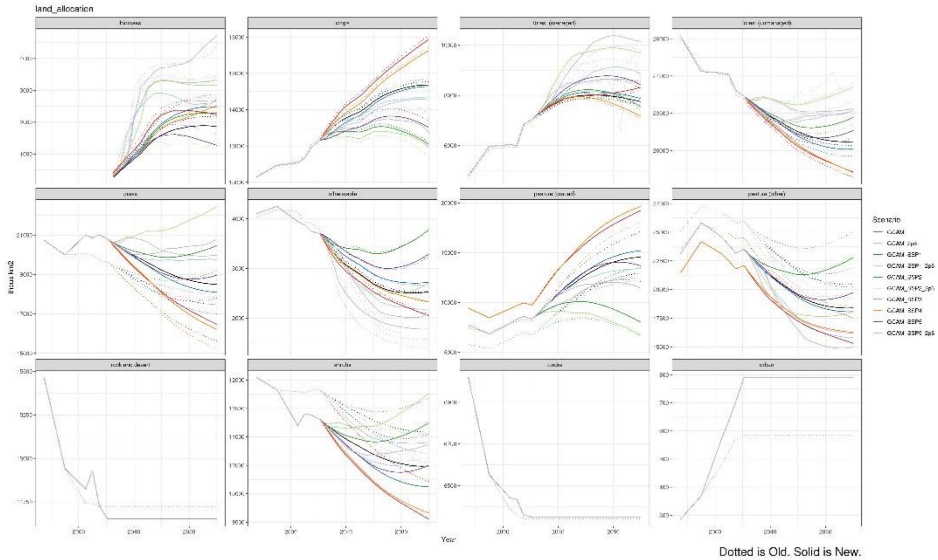


Figure 4: Detailed land allocation across scenarios. Impacts to land allocation are dominated by a shift towards managed and away from unmanaged pasture and grassland land types. Slight decreases in biomass land allocation are also observed consistently across all scenarios.

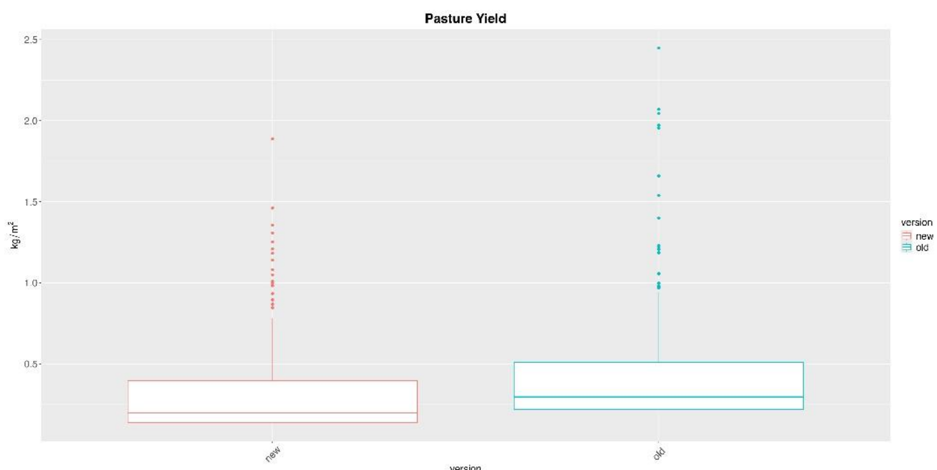


Figure 5: Pasture economic yield distribution (kg/m2) by GLU. Yields are consistently lower in the updated data (red) compared to the core (blue).

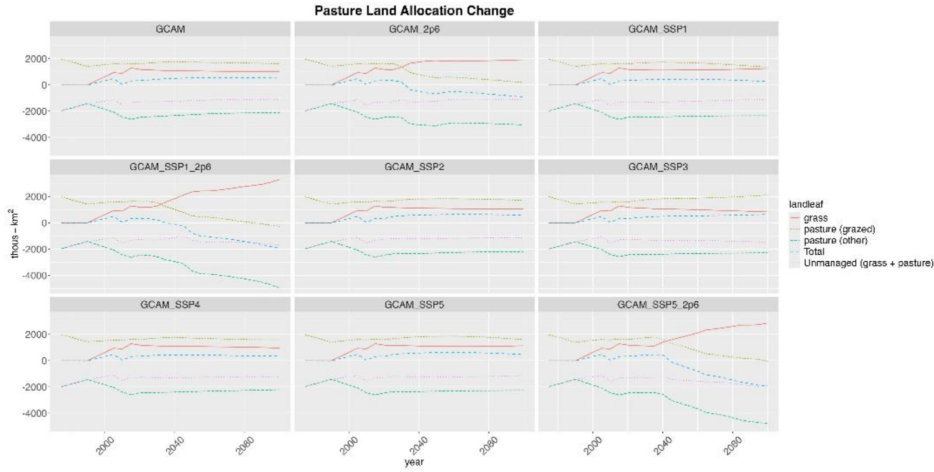
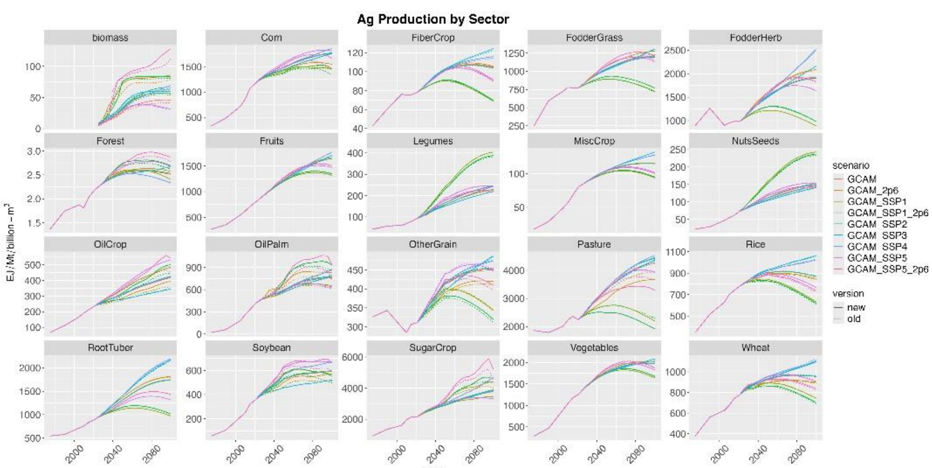


Figure 6: Detailed land allocation for pasture and grassland allocation. 2p6 scenarios present overall lower pasture by 2100, both grazed and unmanaged, compared to non-2p6 scenarios.

Pastureland allocation is largely stable in non-2p6 scenarios but tends to decrease overall in 2p6 scenarios as reductions in demand for meat and dairy drives lower grazing demands. The total unmanaged pasture and grassland remain relatively more stable, demonstrating that the decrease in unmanaged pasture allocation is mostly offset by the increase in unmanaged grassland.

a)



b)

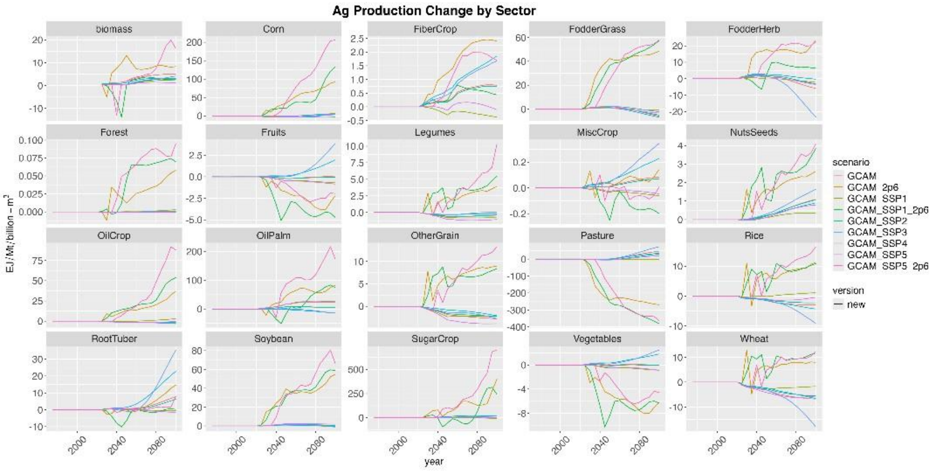


Figure 7: a) Ag production by crop type globally. b) Ag production change by crop type globally. Units vary by sector. Biomass is given in EJ, Forest is given in billion m^3, and all other crops are reported in Mt.

These data updates result in small increases in agricultural production for most crops and land types with the most significant impacts seen in pastureland with an increase of about 5% globally by 2100 under a baseline scenario.

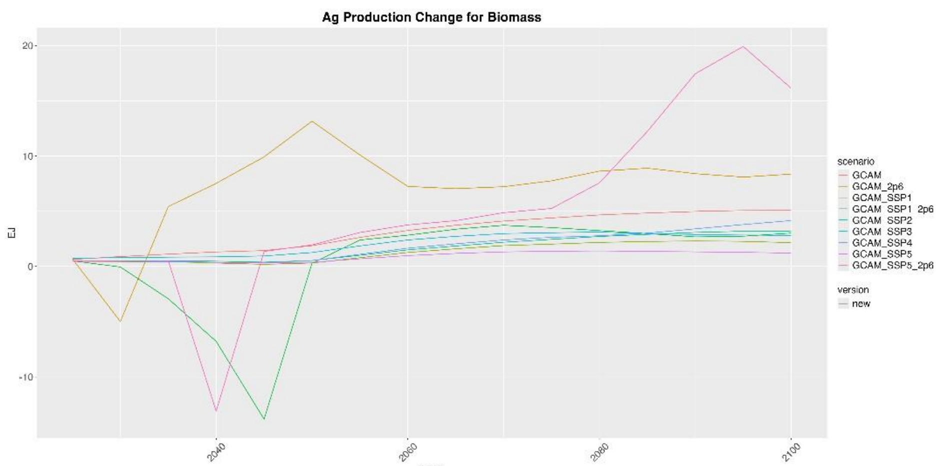


Figure 8: Change in Agricultural Production for Biomass from the core model. There is a general trend of increasing biomass production even as biomass land allocation decreases with these data updates.

For biomass we also see significant increases in agricultural productivity across most GCAM scenarios, particularly those with 2p6 climate forcing. This is likely in response to the decreased land allocation for biomass as demand for pastureland allocation increases. To compensate for reduced biomass land allocation there is a shift toward irrigated biomass and fertilized biomass production, both of which drive increases in land productivity and therefore production. This is especially true in the 2p6 scenarios where shifts in the global energy mix drive further increases in demand for biomass. These changes in irrigation and fertilization practices result in the increase in biomass commodity prices that we see in these scenarios (see Figure 13 for more detail).

Land use change emissions

Global LUC emissions (Figure 9) are largely stabilized as a result of updated land use data, especially when it comes to historical years (See reduced spike between 2000 and 2015). Cumulative LUC emissions are generally lower on a global scale compared to master across all scenarios (this also results in slightly larger sinks in the 2p6 scenarios). This is mainly driven by more productive pasture lands from this update. On a regional scale (Figure 10), there are some more noticeable differences. Regions such as Africa Eastern see higher LUC emissions historically since pastures are less productive with the updates while regions like Argentina see lower LUC emissions since pastures are now more productive in the region and hence less land is transitioned to Pasture.

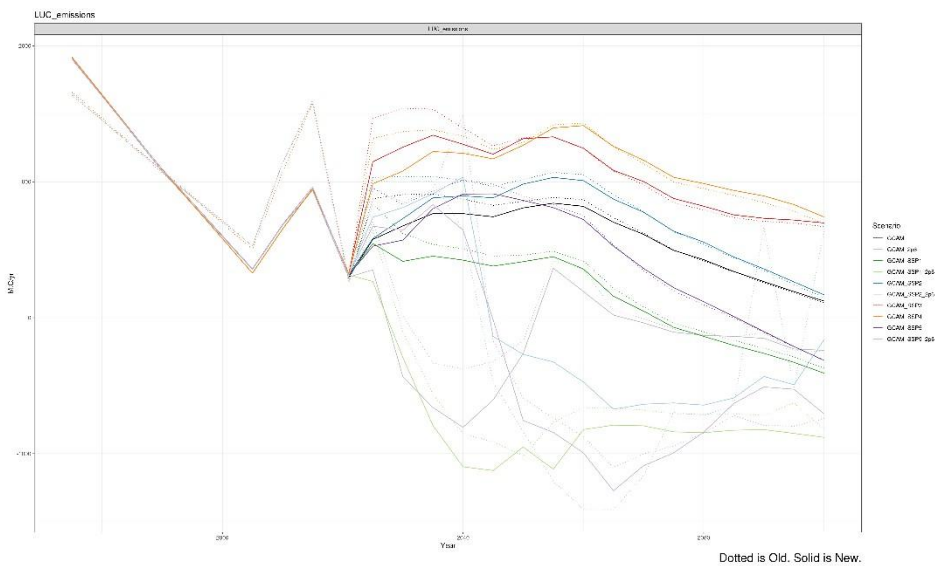


Figure 9: Global LUC emissions. Historical LUC emissions are smoothed out considerably with these data updates. Generally lower mid-century LUC emissions are observed across all scenarios though end of century LUC emissions remain fairly consistent.

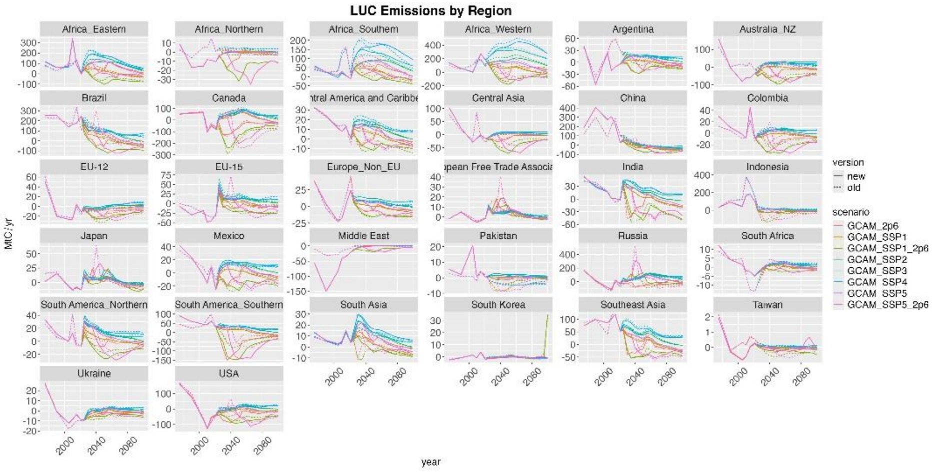


Figure 10: Regional LUC emissions

Land use change emissions remain relatively stable in future periods though emissions in calibration periods are smoothed considerably. Specifically, we reduce the 2015 spike in emissions and corresponding high interpolated values up through 2021. There are several notable exceptions to this consistency. Differences in land use change emissions are most prominent in regions in Africa, China, Russia, and Brazil. Most regions experience reductions in land use change emissions though a few, notably South Asia, Pakistan, and Indonesia, see increased land use change emissions.

Climate forcing

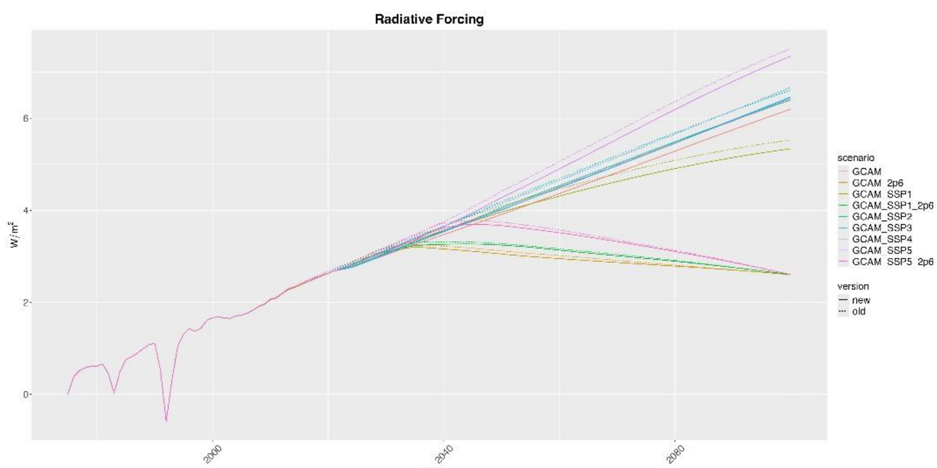
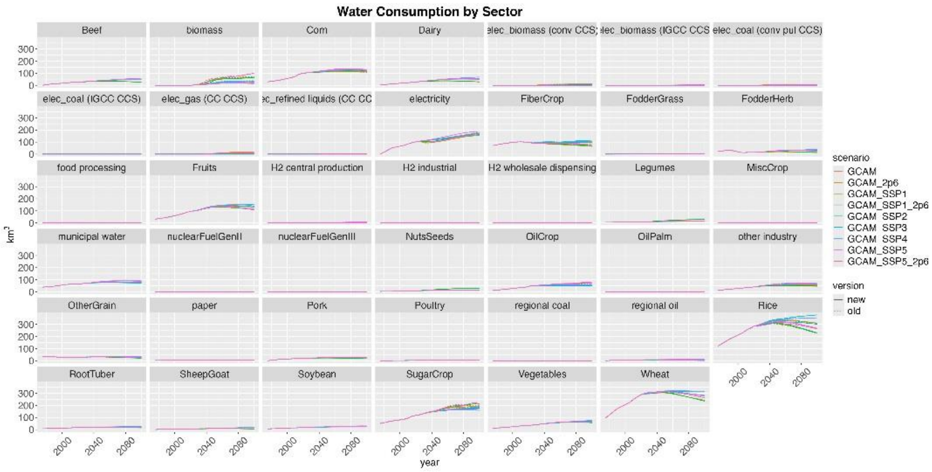


Figure 11: Radiative forcing by GCAM scenario. Radiative forcing in non-2p6 scenarios decreases by approximately ~0.2W/m^2 by 2100.

Slight decreases in radiative forcing in non-2p6 scenarios can be attributed to decreases in unmanaged pasture natural lands resulting from increased managed pasture allocation to compensate for land carbon-related productivity changes.

Water consumption

a)



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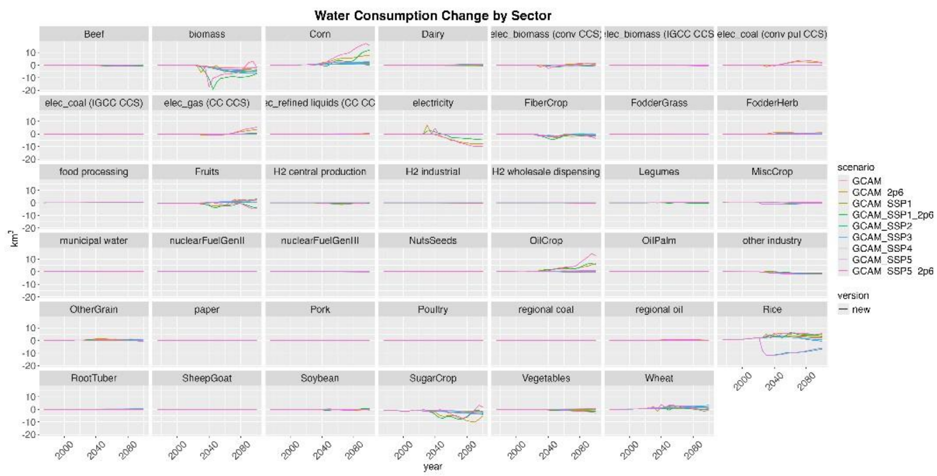
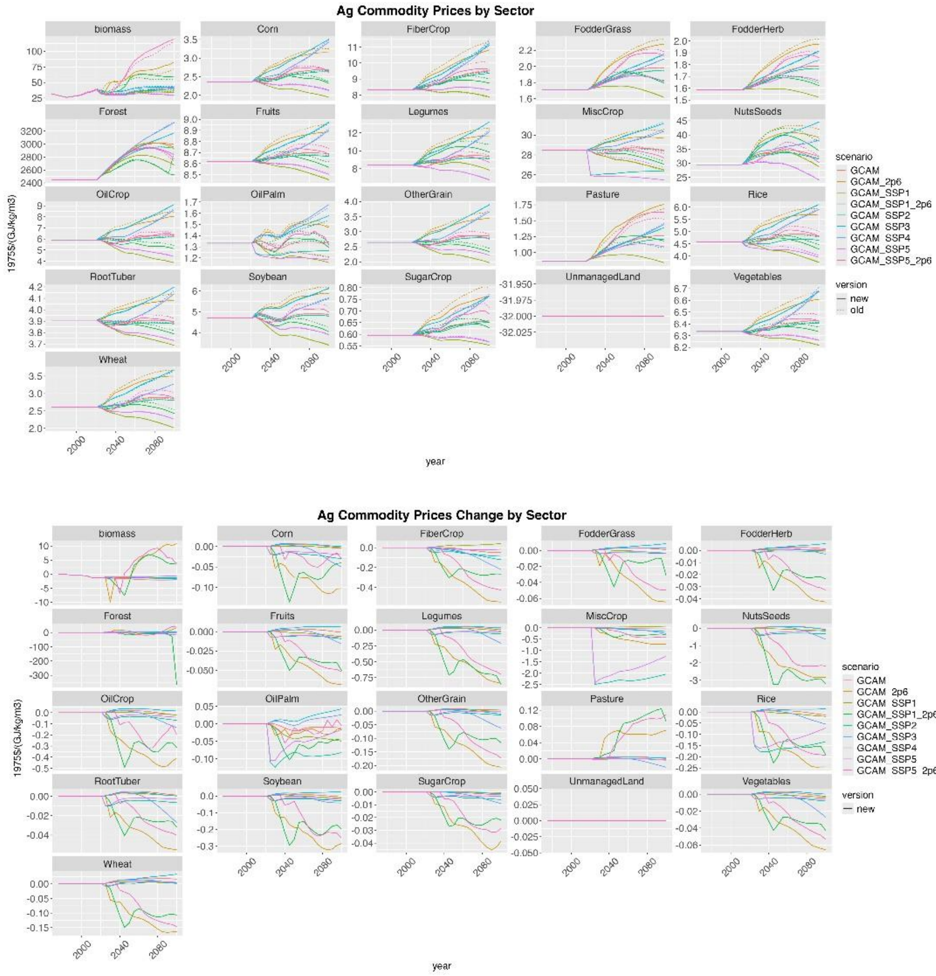


Figure 12: a) Global water consumption by sector. b) Global water consumption change by sector. Water consumption remains relatively stable for all sectors. The largest magnitude shift in water consumption occurs in biomass water consumption which is tied to decreased biomass land allocation and to shifts toward fertilized land for biomass production. **Agricultural and animal commodity prices** a)



b)

Figure 13: a) Agricultural commodity prices by sector. b) Agricultural commodity price change by sector. Note that units vary by sector. Biomass is given in 1975$/GJ, forest is given in 1975$/m^3, unmanaged land is unitless, and all other crops are reported in 1975$/kg. All sectors except for biomass and pasture show decreased commodity prices.

As mentioned above with respect to biomass land allocation decreases and the resulting increase in productivity driven by fertilizer use, we see biomass prices increase. Particularly in the 2p6 scenarios where biomass demand is high.

Documentation Updates

Likely no documentation updates since data sources have not changed

Future improvements/planned updates

As mentioned above, moirai is currently being updated to include updated irrigation maps from the IFPRI-MapSpam dataset (to replace the current MIRCA dataset). We do not include the same here and that update will be a part of a different CMP since that data is expected to affect several variables such as water use, yields, spatial distribution of crops etc.

Moreover, while this proposal only updated pasture productivity (through its update of pasture carbon densities), it did not update how pasture carbon densities are converted to economic productivity through the usage of a grazing intensity. In general, this should be a point that should be revised in a future proposal which directly validates the carbon yields and the economic yields for pasture through comparisons with observed data.

References

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3. Spawn, Seth A., et al. "Harmonized global maps of above and belowground biomass carbon density in the year 2010." *Scientific data* 7.1 (2020): 112.
4. Hengl, Tomislav, Jorge Mendes de Jesus, Gerard BM Heuvelink, Maria Ruiperez Gonzalez, Milan Kilibarda, Aleksandar Blagotić, Wei Shangguan et al. "SoilGrids250m: Global gridded soil information based on machine learning." *PLoS one* 12, no. 2 (2017): e0169748.