# Land-Use Harmonization Datasets for Global Carbon Budget 2019 and Beyond

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**Abstract.** Land-use change has been the dominant source of anthropogenic carbon emissions for most of the historical period, and is currently one of the largest and most uncertain components of the global carbon cycle. Advancing the scientific understanding on this topic requires that the best data be used as input to the best models in well-organized scientific assessments. The Land-Use Harmonization dataset (LUH2), previously developed and used as input for CMIP6 simulations, has been updated annually to provide required input to land models in the annual Global Carbon Budget (GCB) assessment. These annual LUH2-GCB updates and extensions have incorporated annual FAO wood harvest data updates for dataset years after 2015 and HYDE gridded agriculture area data updates (based on annual FAO agricultural area data updates) for dataset years after 2012, along with extrapolations to the current year due to a lag of one or more years in the FAO data releases. The resulting updated LUH2-GCB datasets have provided global, annual gridded land-use and land-use change data relating to agricultural expansion, deforestation, wood harvesting, shifting cultivation, regrowth and afforestation, and crop rotations and pasture management and are used by both book-keeping models and Dynamic Global Vegetation Models (DGVMs) for the GCB. For GCB 2019, a more significant update to LUH2 was produced (LUH2-GCB2019) to correct cropland and grazing area errors in the underlying input datasets for the globally important region of Brazil, as far back as 1950. From 1951-2012 the LUH2-GCB2019 dataset begins to diverge from the LUH2 v2h dataset, with peak differences in Brazil in the year 2000 for grazing land (difference of 100,000 $km^2$) and in the year 2009 for cropland (difference of 77,000 $km^2$), along with significant sub-national reorganization of agricultural land-use patterns within Brazil. These LUH2-GCB2019 corrections for Brazil provide the base for future LUH2-GCB updates including the recent LUH2-GCB2020 dataset, and present a starting point for operationalizing the creation of these datasets to reduce time-lags due to the multiple input dataset and model latencies.

## 1 Introduction

Human-induced changes to the Earth's carbon cycle are now known to have driven changes in the Earth's climate system, with far-reaching consequences for all components of the Earth system including the atmosphere, oceans, land, and human society. To gain improved understanding of the global carbon cycle and provide decision-support for climate policies, the Global Carbon Project has coordinated the publication of an annual carbon budget since 2005 (Friedlingstein et al. 2019). These Global Carbon Budgets (GCBs) use models and observations to quantify and partition annual emissions and sinks in the carbon cycle and provide the underlying data for use by the wider community.

For most of the historical period, land-use change activities such as deforestation for agriculture and wood harvesting were the primary sources of anthropogenic carbon emissions (Ciais et al., 2013). From 1750-2018, land use change emissions total 235+/-75 and fossil fuel emissions total 440+/-20, with annual fossil fuel emission surpassing land use change emissions in the mid 20$^{th}$ century (Friedlingstein et al. 2019). Although they are no longer the dominant source of human-generated carbon emissions, contemporary land-use emissions remain a large, and highly uncertain term in the global carbon budget. Over the last decade (2009–2018) the Global Carbon Budget 2019 (Friedlingstein et al. 2019) estimated the net annual $CO_2$ flux from land-use, $E_{LUC}$, to be 1.5±0.7 GtC yr$^{-1}$ (compared with fossil fuel emissions over that same time period of 9.5±0.5 GtC yr$^{-1}$). In addition, land-use related carbon emissions are likely to become increasingly important in the future with the potential adoption of climate mitigation strategies that heavily involve the terrestrial biosphere (such as biofuel crop production, afforestation and forest restoration, and more sustainable agricultural management practices) (Popp et al. 2017).

For the annual Global Carbon Budget (GCB) publications, the net land-use carbon flux, $E_{LUC}$, is the sum of $CO_2$ fluxes from anthropogenic deforestation, afforestation, wood harvesting, forest degradation, shifting cultivation, regrowth of forests following wood harvest or abandonment of agriculture, and some land management activities, as well as decomposition from product pools. The book-keeping models H&N2017 (Houghton and Nassikas 2017) and BLUE (Hansis et al. 2015) and an ensemble of Dynamic Global Vegetation Models (DGVMs, as part of the TRENDY model synthesis project) are used to compute $E_{LUC}$ and its uncertainty. One of the ways in which BLUE differs from H&N2017 is that it utilizes gridded historical land-use and land-use change maps from the Land-Use Harmonization 2 (LUH2) dataset (Hurtt et al., 2019a, 2019b, 2020), whereas H&N2017 makes use of national-level land-use data, primarily from FAO. Many of the DGVMs also utilize the LUH2 dataset to prescribe the gridded historical land-use and land-use changes used by those models. The availability of LUH2 has facilitated the development of more comprehensive representations of LUC in DGVMs. Originally DGVMs represented only net LUC change at coarse gridcell resolution (typically greater than 0.5° / ~50km), whereas LUH datasets have enabled models to account for sub-gridcell heterogeneity, i.e. shifting cultivation practices, and comprehensive LUC transitions. Arneth et al., 2017 suggests LUC emissions are likely greater than previously assumed as more LU detail is included in DGVMs.

The LUH2 dataset was developed as a required forcing dataset for CMIP6 DECK and historical climate simulations (Meehl et al., 2014; Eyring et al., 2016), with its predecessor, Land-Use Harmonization 1, having already been used extensively for the CMIP5 simulations (Hurtt et al. 2011). In addition, LUH2 datasets have now also been used for CMIP6 future scenarios (ScenarioMIP, O'Neill et al., 2016), the Land-Use Model Intercomparison Project (LUMIP, Lawrence et al., 2016), the Inter-Sectoral Impact Model Intercomparison Project 2b (ISIMIP2b, Frieler et al. 2017), Paleoclimate Modeling Intercomparison Project (PMIP, Jungclaus et al. 2017), the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES, Kim et al. 2018), MsTMIP, as well as the annual Global Carbon Budgets (Le Quéré et al., 2016; Le Quéré et al., 2017; Le Quéré et al., 2018; Friedlingstein et al., 2019). This wide usage of the LUH2 datasets provides a consistent treatment of land-use across multiple scientific studies.

LUH2 brings together multiple datasets at multiple different spatial and temporal scales and harmonizes them to produce a single dataset of global, gridded land-use and all associated land-use transitions, annually for the years 850-2100, in a consistent format for use in Earth System Models (ESMs). All data layers are provided as fractional values within 0.25° spatial grids and include the area of 12 different land-use states, the age and biomass density of secondary land, wood harvest area and biomass, and agricultural management practices such as irrigated area and synthetic nitrogen fertilizer application. For the historical period the LUH2 dataset uses inputs from HYDE 3.2 (Klein Goldewijk et al., 2017) for gridded cropland, grazing land, and urban area, as well as population data, and uses national wood harvest production data from FAO (2019).

Early versions of LUH datasets have been used in annual GCBs from 2013 onwards (Le Quéré et al. 2014, 2015a, 2015b, 2016, 2018a, 2018b, Friedlingstein et al. 2019). For use in CMIP6 simulations, the LUH2 historical-period dataset (LUH2 v2h) was developed for the years 850-2015 and this LUH2 v2h (where 'h' is historical) dataset was extended for use as an input into the Global Carbon Budget 2017 by incorporating updated data from FAO and HYDE for the years 2013-2014, as well as an linear extrapolation to the year 2016 (described in Methods). The intended strategy for subsequent annual LUH2-GCB updates was to use the significant updates to LUH that are typically made on the same cycle as CMIP analyses, and then provide annual extensions to those each year, while also ingesting any new/modified data from FAO and HYDE for recent years. Although this strategy involves multiple dataset and model update latencies, it was successfully used to extend the LUH2 v2h dataset for GCB 2017 and GCB 2018 with updated FAO and HYDE inputs, along with extrapolations for years without underlying data. However, for the LUH2-GCB2019 dataset a more major update was provided to address several inadvertent errors in previous inputs to LUH2, particularly the sudden drop in cropland related fluxes during the 2000-2010 period in Brazil, which is a region of significance for the global carbon budget.

With multiple versions of LUH2 datasets now being used for different synthesis studies, and multiple versions of key inputs to LUH2 also in existence, it is important to have a documented record of these datasets and their intended uses. In this paper

we will describe and document the general approach for generating the LUH-GCB datasets, as well as specific details of the changes made to the LUH2-GCB2019 dataset to correct previous issues, and comparisons with previous LUH datasets.

## 2 Methods

### 2.1 Land-Use Harmonization 2 Datasets

The Land-Use Harmonization 2 datasets (Hurtt et al. 2019a, 2019b) provide global, annual, gridded land-use states and all associated land-use transitions between those states, fractionally, at 0.25° degrees spatial resolution for the years 850-2100 (Hurtt et al. 2020). The twelve LUH2 land-use states include gridded fractions of cropland (which is further sub-divided into fractions of C3 annuals, C4 annuals, C3 perennials, C4 perennials, and C3 N-fixers), grazing land (sub-divided into fractions of managed pasture and rangeland), urban land, primary land (both forested and non-forested) and secondary land (both potentially forested and potentially non-forested). In addition, the LUH2 datasets provide estimates of the age and biomass density of secondary lands, gridded areas and biomass associated with wood harvest, and gridded cropland management data including irrigated areas and synthetic nitrogen fertilizer application rates (all provided at the same spatial and temporal scales as the land-use states and transitions). As described in Hurtt et al. 2020, the LUH2 datasets were computed with the Global Land-Use Model 2 (GLM2) which harmonizes multiple input datasets at multiple different temporal and spatial scales to produce a single land-use dataset in the format required for use in climate, carbon, and vegetation models. LUH2 includes major updates to several features including a new historical national wood harvest reconstruction (Kaplan et al. 2017), a new representation of shifting cultivation (Heinimann et al. 2017), use of Landsat remote sensing data (Hansen et al., 2013) to constrain patterns of wood harvesting, and crop rotations. The version of GLM2 that was used for generating the LUH2-GCB2019 dataset is identical to that used for generating the LUH2 datasets, with the exception of some minor corrections to the method for determining the spatial patterns of wood harvesting.

For the historical period (years 850-2015), the LUH2 dataset was based on two key inputs: the HYDE 3.2 dataset and FAO wood harvest data. The HYDE 3.2 dataset (Klein Goldewijk et al. 2017) provides gridded cropland, grazing land, and urban land data, and is itself based on national FAO agricultural data for the years 1961-2012, along with extrapolations based on a 5-year trend for the years 2013-2015. The FAO wood harvest data provides national forestry statistics for the years 1961-2015 (FAO 2016) that were used by LUH2 to determine the spatial patterns of wood harvesting.

### 2.2 General approach for annual LUH extensions for GCB

Each year, for the annual Global Carbon Budget (for publication years 2013-2020), the LUH dataset was extended in time for use in the participating DGVM and book-keeping model simulations. In general, these LUH extensions were built off the most recent LUH release (i.e. either LUH1 or LUH2) and incorporated updated and extended agricultural area data from HYDE (based on newly released data from FAO) along with newly released national wood harvest data from FAO. This not only

extended the LUH datasets beyond their final year (2005 for LUH1 and 2015 for LUH2) but also updated the LUH data for years that were not previously based on FAO inputs (i.e. years for which data was previously extrapolated but for which FAO data was now available).

The HYDE dataset updates used an anomaly approach to update the cropland, grazing land, and urban land grids by applying the annual differences in new FAO data to the last "data-based" year of the current HYDE dataset. The updated HYDE data was also extrapolated using a 5-year trend for years without underlying FAO data. The national wood harvest reconstruction used by LUH was updated with new data from FAO by replacing any extrapolated wood harvest data from the current LUH dataset with the new wood harvest data from FAO, and then extrapolating national wood harvest rates for any remaining years without underlying FAO data.

The schematic diagram in Figure 1a shows the interactions and dependencies between the LUH datasets prepared for use in CMIP, the LUH-GCB datasets prepared for use in GCB simulations, as well as the inputs used by LUH that are typically updated on both CMIP as well as annual cycles. The FAO data that informs the HYDE dataset and the LUH national wood harvest reconstruction, typically lags behind the current year by one or more years because the FAO is published every five years. As a result, the LUH-GCB datasets contain several data latencies and data extensions. A typical timeline for this process is shown in Figure 1b, illustrating the sequence of dataset updates, and associated latencies, that occur during the creation of a generalized 'LUHx-GCBi' dataset.

For GCB publication years 2013-2015, the LUH-GCB dataset was built off the LUH1 dataset and was identical to that dataset for years 1500-2005. The data for the years 2006 to the end of the LUH-GCB timeseries was based on new data from FAO and HYDE (for years that FAO data existed at the time of dataset creation) and extrapolations for years without FAO data. Table 1 provides the specific years that are based on updated FAO and HYDE data in each of these LUH-GCB datasets. For LUH data years without specified FAO data, extrapolations were used to fill data gaps.

For GCB 2016, an updated LUH dataset was not provided due to ongoing work on the creation of the LUH2 dataset. The LUH year 2015 was the same as 2014.

For GCB publication years 2017-2018, the LUH-GCB dataset was built off the LUH2 dataset and was identical to that dataset for years 1500-2012 (i.e. to the end of the time period for which FAO data was used in the creation of LUH2). The data for the years 2013 to the end of the LUH-GCB timeseries was based on new data from FAO and HYDE, along with extrapolations for years without underlying FAO data, as outlined in Table 1.

For GCB publication years 2019-2020, a more significant update was performed to correct an error in the previously used input datasets, especially for the country of Brazil, as described in Section 2.3. These LUH-GCB datasets were built off the LUH2 dataset and were identical to that dataset for all years up to and including the year 1950. The data for the years 1951 to the end of the LUH-GCB timeseries was based on new data from FAO and corrections from HYDE, along with extrapolations for years without underlying FAO data, as outlined in Table 1.

### 2.3 HYDE land-use data update for GCB 2019

The HYDE-GCB2019 dataset used for LUH2-GCB2019 corrected some inadvertent errors present in its underlying input datasets, specifically the sudden drop in cropland-related fluxes in Brazil during the 2000-2010 period, and an overestimate of grazing land area between 1990 and 2010. HYDE-GCB2019 was based upon the HYDE3.2-August2016 beta version but incorporated updated cropland and grazing land data from FAO from 1960-2015, as well as sub-national data for Brazil from IGBE for the years 1920-1995, and ESA-derived data for the year 2010. In addition, the HYDE-GCB2019 dataset was extrapolated to 2019 using a 5-year trend.

For each year up to and including 2012, the HYDE-GCB2019 was closely matched to the HYDE3.2-Aug2016 dataset, with the exception of grid-cells in the corrected regions of Brazil. The global areas provided by the HYDE-GCB2019 dataset differ from the HYDE3.2-Aug2016 dataset by up to 0.5% for cropland and up to 0.3% for grazing land. However, within Brazil the areas in HYDE-GCB2019 differ from that in HYDE3.2-Aug2016 by up to 11% for total cropland (in 2009) and up to 5% for total grazing land (in the year 2000). In the year 1960 (the first year of corrected data in HYDE-GCB2019) 0.4% of grid-cells (at 5 minute spatial resolution) outside Brazil had cropland area differences of greater than 10% from the HYDE3.2-Aug2016 data, and 0.01% had grazing land area differences of greater than 10% from the HYDE3.2-Aug2016 data.

### 2.4 National wood harvest data update for GCB 2019

The version of wood harvest data used for LUH2 v2h was based on a previous FAO release (FAO 2016) that included data up to and including the year 2014 – those inputs remained the same in this new GCB dataset. The new wood harvest data, prepared for GCB 2019, was based on the recent FAO 2019 release, which includes data up to and including the year 2017. The annual changes in FAO wood harvest data for the years 2015-2017 were applied to the year 2014 data from the previous release to get the new 2015-2017 data used for GCB 2018. After the year 2017, wood harvest data was extrapolated to the year 2018, the last year in which GLM2 simulates wood harvest for LUH2-GCB2019.

### 2.5 Computing the LUH2-GCB2019 dataset

Since the data in HYDE-GCB2019 for the year 1960 was not identical to that in HYDE3.2-August2016 (the version used for LUH2 v2h) for that year, it was necessary to run LUH2 from 1950 (the last year of HYDE data before the 1960 data-layer). The HYDE-GCB2019 dataset for the years 1960-2019, along with the HYDE3.2-August2016 data for the year 1950, were

aggregated to 0.25° spatial resolution and interpolated to annual time-steps, to create the cropland, grazing land, and urban land input datasets for LUH2 for the period 1950-2019. LUH2 was then run with the processed HYDE data, and the FAO-based national wood harvest data, as inputs for the years 1950 to 2019, using the LUH2-v2h data for the year 1950 as an initial condition. Using this approach, the LUH2-GCB2019 data for the years 1950-2019 connected continuously to the LUH2-v2h dataset for the years 850-1950.

## 3 Results

The LUH2-GCB2019 dataset shares many of the same properties as its predecessors LUH2 v2h, LUH2-GCB2017, and LUH2-GCB2018, and is identical to those datasets for all years up to 1950. Figure 2a shows the global area of the five aggregated land-use states represented by LUH2-GCB2019 for the years 1950-2019. Global cropland area increased from $12.2\times10^6$ km$^2$ in 1950 to $15.9\times10^6$ km$^2$ in 2015 (for LUH2 v2h) or $16.1\times10^6$ km$^2$ in 2015 (for LUH2-GCB2019) and $16.8\times10^6$ km$^2$ in 2019 (for LUH2-GCB2019). Global grazing land area increased from $26.1\times10^6$ km$^2$ in 1950, peaked in the year 2000 at $33.2\times10^6$ km$^2$ (for LUH2 v2h) or peaked in 2001 at $33.1\times10^6$ km$^2$ (for LUH2-GCB2019), then decreased to $32.8\times10^6$ km$^2$ in 2015 (for LUH2 v2h) or $32.7\times10^6$ km$^2$ in 2015 (for LUH2-GCB2019) and $32.6\times10^6$ km$^2$ in 2019 (for LUH2-GCB2019). Cropland, grazing land, and urban land areas in LUH2-GCB2019 were identical to those areas provided by the HYDE dataset at global, regional, and 0.25 degree spatial scales (by design).

Looking at cropland area in Brazil specifically, Figure 3a shows that the new input data underlying LUH2-GCB2019 has modified the previously observed feature of LUH2 v2h in which cropland area anomalously leveled-off, and then quickly increased, during the 2000-2010 time-period. The cropland area over the same time period in LUH2-GCB2019 now increases monotonically. Similarly, LUH2-GCB2019 has also reduced the area of grazing land in Brazil between the years 1990 and 2010, when compared with the LUH2 v2h grazing land area.

Land-use states began to differ between LUH2-GCB2019 and LUH2 v2h from 1951 onwards. Figure 2b shows the differences in global areas of the five LUH2 land-use states between these two datasets from 1950-2015. Although differences in cropland and grazing land areas didn't become significant until 1990 onwards, differences in primary and secondary land areas appeared in the time series from around 1960 onwards, due to slightly different methodology for determining the spatial patterns of primary vs. secondary wood harvesting in some locations of the world, compared with the methodology used in preparation of the LUH2 dataset. Figure 3b shows the same variables but focused only on the country of Brazil. Prior to 2010, the differences between the LUH2 v2h and LUH2-GCB2019 datasets in Brazil were of similar magnitude to the global differences in the five land-use variables, indicating that the changes made to the LUH2-GCB2019 dataset within Brazil account for the majority of the global differences in this dataset. Cropland and grazing land differences between the LUH2 v2h and LUH2-GCB2019 datasets became largest during the 2000-2019 timeframe when input datasets (based on FAO) began to diverge

more significantly, especially in the country of Brazil. The difference in global cropland area between the two datasets has a low point in 2009 of -77,500 $km^2$ of which 99% comes from cropland differences within Brazil. The maximum difference in global cropland area of -203,900 $km^2$ occurred in 2015. The difference in global grazing land area between the two datasets was highest in year 2000 with a difference of 102,600 $km^2$, of which 98% comes from grazing land differences within Brazil.

Figure 4 shows that global wood harvest, one of the dominant land-use transitions in the LUH2 datasets, remained largely unchanged between LUH2 v2h and LUH2-GCB2019, with global wood harvest differences being less than $2\times10^{-3}$ PgC each year. Total gross transitions, (the sum of the absolute value of all land-use transitions) are a measure of all land-use change activity. Gross transitions in the LUH2 datasets tend to have higher annual variability after year 2000 when the input data to LUH2 (from HYDE) becomes annual, rather than decadal. Figure 5a shows that global gross transitions between 1950 and 2012 (years that are based on the same FAO data) were very similar between the LUH2 v2h and LUH2-GCB2019 datasets, with maximum global annual differences of less than 3%. After 2012, differences between the two datasets increased slightly due to the use of different FAO data in the HYDE dataset, but global differences still remained less than 10%. Gross transitions within Brazil (Figure 5b) showed more significant differences between these two datasets, with the largest absolute differences occurring in 2008 (-52,000 $km^2$/yr difference) and 2009 (47,000 $km^2$/yr difference), which was consistent with the timeframe of the maximum cropland area differences within Brazil.

The spatial patterns of differences (of the fractional content of each quarter degree grid-cell) between the LUH2 v2h and LUH2-GCB2019 datasets for 3 key variables at 3 different time points, are shown in Figure 6. The cropland patterns illustrate that in the year 2000 and 2009 almost all grid-cell differences were located within Brazil, with grid-cells elsewhere having only very minor differences, if any (fraction of grid-cell of $\sim10^{-3}$). Although the total difference in Brazil cropland area between the two datasets in 2000 was very small (504 $km^2$), Figure 6 shows that sub-national differences existed that both increased cropland in some sub-regions of Brazil, and reduced it in others (and aggregated to a small national total difference). In the year 2009, when the Brazil total cropland difference between LUH2 v2h and LUH2-GCB2019 was greatest, the gridded differences in Brazil were almost all in the same direction, which in aggregate led to a 77,000 $km^2$ correction from the LUH2 v2h values. In 2015 gridded cropland differences in Brazil were small (and the aggregate national difference for Brazil was also small) but significant gridded differences in other locations in the world appeared, especially within China, Southeast Asia, and Australia. These differences were due to new FAO data for the years 2013-2015 being used by the HYDE dataset within LUH2-GCB2019 (compared with the extrapolated data used for LUH2 v2h).

The patterns for grazing land in Figure 6 show that in the year 2000, although the country of Brazil had a total grazing land decrease of 10,000 $km^2$ in LUH2-GCB2019 (compared with LUH2 v2h), there were sub-regions within Brazil that were exhibiting increases in grazing land that offset some of these decreases. In the year 2009, grazing land differences between LUH2 v2h and LUH2-GCB2019 were small (fractions of grid-cell $\sim10^{-3}$), both within Brazil and elsewhere in the world. In

2015, grazing land differences between the datasets showed larger differences throughout the world, due to the use of new FAO data for the years 2013-2015, as was also observed with cropland.

Secondary forest patterns in Figure 6 showed that LUH2-GCB2019 had greater secondary forest area in high latitude locations, as well as in China and Southeast Asia, and lower areas of secondary forest in the Amazon and Congo regions, across all time periods after 1950. These changes in secondary forest patterns reflected the related changes to the updated GLM2 methodology for the spatial patterns of wood harvesting, which resulted in more primary wood harvest in the high latitudes, generating more secondary land, with the converse occurring in the Amazon and Congo regions.

## 4 Discussion

The LUH2-GCB2019 dataset is the annual update to the LUH2 dataset for use in the TRENDY DGVM model synthesis (Sitch et al., BG 2015) and the 2019 Global Carbon Budget. It was based on existing LUH2 methodology with updated inputs from HYDE (for gridded cropland, grazing land, and urban land areas at decadal and/or annual timesteps) and from FAO (for annual national wood harvest amounts). In contrast with previous LUH2 annual updates for GCB that incorporated new data from HYDE and FAO for the years 2013 onwards and extrapolated the time-series to the current year, the LUH2-GCB2019 dataset provided a more significant update to correct the anomalous decrease in cropland area within Brazil over the years 2000-2009 due to errors in the previously used FAO and HYDE data for Brazil. This correction was successful and resulted in a national cropland area difference for Brazil of up to 77,000 $km^2$ in the year 2009, and also modified the national grazing land area within Brazil over the years 1990-2009 with a difference of up to 100,000 $km^2$ in the year 2000. Differences between LUH2-GCB2019 and LUH2 v2h in other regions of the world were more minor, as shown in Figures 2 and 6, with the exception of small differences in the spatial patterns of wood harvesting that resulted in an increase of secondary forest area in the northern latitudes, and a reduction of secondary forest area in the Amazon and Congo regions.

The differences between the LUH2 v2h and LUH2-GCB2019 datasets have implications for the global and regional carbon budgets. Although the LUH2 datasets do not provide a complete carbon budget, the land-use transitions from the LUH2 datasets do offer a related metric that can be used to infer possible carbon budget changes (when the results of DGVM simulations using LUH2-GCB2019 are published, those will provide more precise carbon budget changes from the LUH2-GCB2019 dataset). Global gross transitions (a measure of all land-use change activity) were very similar between LUH2 v2h and LUH2-GCB2019, although slightly higher for LUH2-GCB2019 after the year 2000. In contrast, the gross transitions for Brazil tended to be lower for LUH2-GCB2019 compared with those for LUH2 v2h, with the exception of the 2000-2009 period when gross transitions within Brazil for LUH2-GCB2019 became much larger than those in LUH2 v2h. Those land-use transitions in the early-2000s, when the main correction to the Brazil land-use data was applied, are likely to provide the biggest changes to the global carbon budget. The high annual variability in land use transitions after year 2000 was an artifact

of the input data from HYDE, which was provided to LUH2 each decade from 1700 to 2000 and then annually for the years 2000-2019, and does not necessarily indicate that land-use transitions were fluctuating more quickly in the years 2000-2009 when compared with the earlier part of the historical period.

The LUH2 land-*use* changes/transitions are typically converted into land-*cover* changes by DGVMs for use in those models. DGVM groups have often asked for guidance on which land-cover change(s) to associate with each LUH2 land-use change, and in particular have asked for a recommendation on whether natural vegetation should be lost when converting to managed pasture and/or rangeland. Based on recommendations from HYDE, as well as the study by Ma et al. 2020, the LUH2 recommendation is that all natural vegetation should be cleared for managed pasture, and only cleared for rangeland if it is forested. Using this rule/guideline gives maps of forest area, carbon density, and carbon emissions that are consistent with other published maps.

A challenge when producing the annual LUH2 updates for the Global Carbon Budget is handling the inherent latencies associated with input data updates and model developments that exist in this process, as illustrated in Figure 1. FAO wood harvest data is updated annually, but typically lags behind the current year by 2 years, requiring extrapolation to complete the time-series. FAO cropland and grazing land data (used by HYDE) is updated less frequently and sometimes lags behind the current year by several years. Previously published values for existing years in the FAO datasets can also be modified as part of the FAO dataset updates, resulting in dataset inconsistencies. In addition to data input updates, the models themselves are also constantly evolving. The model underlying the HYDE dataset is updated frequently to incorporate new data, to use new methodology for computing gridded land-use states, and to provide additional data layers, while the LUH2 model itself is typically updated for every CMIP cycle with minor updates and bug fixes in between those updates. These widely varying timescales for updates to data and models present some challenges for providing a consistent, yet annually updated dataset for large model synthesis projects such as the Global Carbon Budget, while also making use of the latest data and model improvements. Our approach thus far has involved a desire to provide consistency with climate simulations and with previous GCBs, and as a result we have been hesitant to incorporate major updates to the LUH methodology and input datasets between CMIP updates. However, the downside of this approach is that important input-data updates do not always appear in the LUH-GCB datasets in a timely manner. An alternative approach, and an aspirational goal, would be to update the LUH-GCB datasets in a more operational mode, in which model and input-data updates would be automated annually. This would require coordination between FAO, HYDE, and the LUH teams, to update their various products consistently and collaboratively.

Subsequent to generating the LUH2-GCB2019 dataset, we also recently generated the LUH2-GCB2020 dataset for use in GCB2020 simulations. This dataset used LUH2-GCB2019 cropland, grazing land, and urban land grid-cell fractions for years up to and including 2019, and extrapolated those land-use states to 2020 using a 5-year trend from HYDE. The national wood harvest inputs used for LUH2-GCB2019 were used for all years up to and including 2014, after which new wood harvest data

from FAO was used, including extrapolations for the years 2019 and 2020. The differences in wood harvest inputs for the years 2015-2019 between LUH2-GCB2019 and LUH2-GCB2020, resulted in some small differences for primary and secondary land fractions for those years.

Looking ahead, we anticipate providing an LUH2 update for use in the Global Carbon Budget 2021 simulations. This is likely to be another incremental update that incorporates new HYDE and FAO data for very recent years and extends the time-series to 2021. However, with a new version of the HYDE dataset currently under development, and plans beginning for CMIP7, a more significant update to LUH2 is likely to come soon as well. Possible inclusions in a potential "LUH3" could include the use of additional satellite remote sensing data, additional guidance on translating the LUH land-use changes into land-cover changes in vegetation models, and the introduction of additional land-use processes such as forest degradation and plantation forestry.

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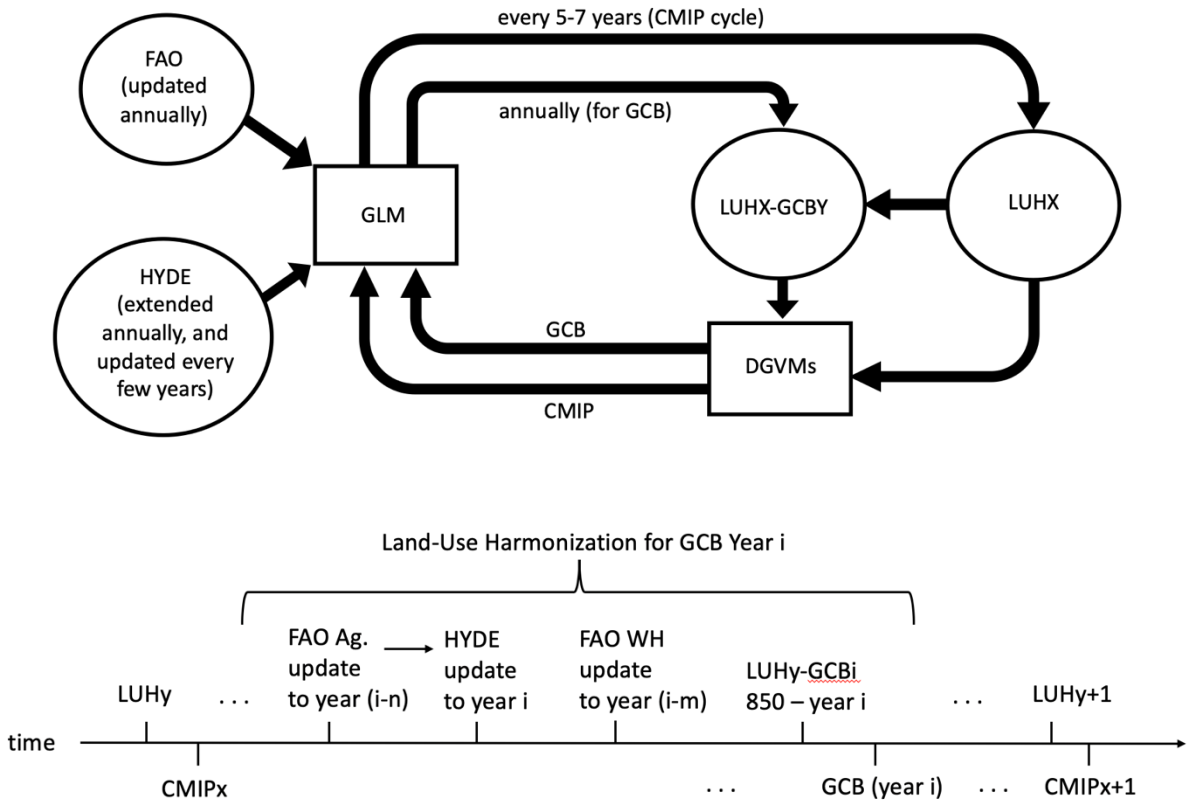
| Publication | LUH base version | LUH-GCB simulation years | HYDE base version | FAO agricultural data | FAO WH Data |
|---|---|---|---|---|---|
| GCB 1959-2011 (TRENDY v1) | | | | | |
| GCB 2013 (TRENDY v2) | LUH1 | 1750-2012 | 3.1 | 1961-2010 | 1961-2011 |
| GCB 2014 (TRENDY v3) | LUH1 | 1750-2013 | 3.1 | 1961-2010 | 1961-2012 |
| GCB 2015 (TRENDY v4) | LUH1 | 1750-2014 | 3.1 | 1961-2012 | 1961-2013 |
| GCB 2016* (TRENDY v5) | None | | | | |
| GCB 2017** (TRENDY v6) | LUH2 | 1750-2016 | 3.2*** | 1961-2014 | 1961-2015 |
| GCB 2018 (TRENDY v7) | LUH2 | 1750-2018 | 3.2 | 1961-2015 | 1961-2016 |
| GCB 2019 (TRENDY v8) | LUH2 | 1750-2019 | 3.2 | 1961-2015 | 1961-2017 |
| GCB 2020 (TRENDY v9) | LUH2 | | 3.2 | 1961-2015 | 1961-2018 |

**Table 1. Input datasets and simulation years for annual LUH-GCB datasets**

*** LUH data not used while new LUH2 dataset was under development**

**** First year LUH used for BLUE as well as for DGVMs/uncertainty**

***** The specific version of HYDE 3.2 that was used for LUH2 is the August 2016 beta release**




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**Figure 1: The logo of Copernicus Publications.**

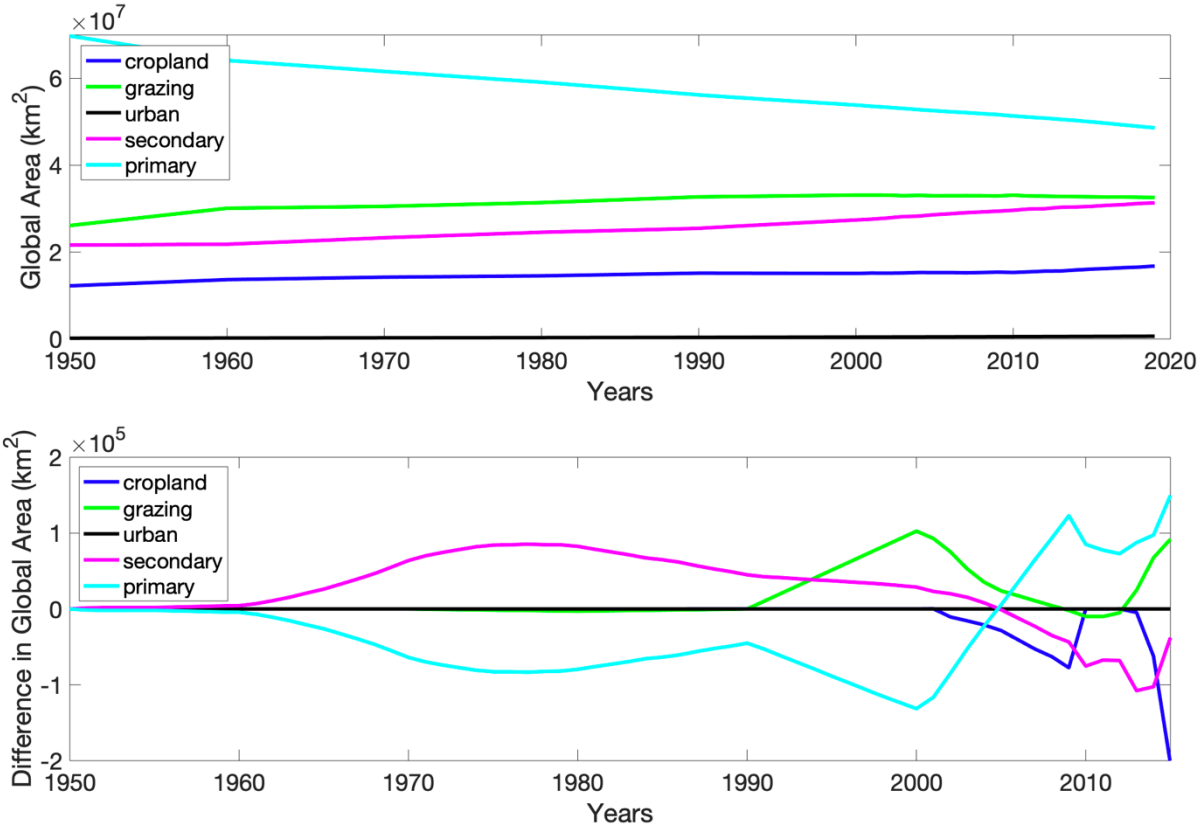
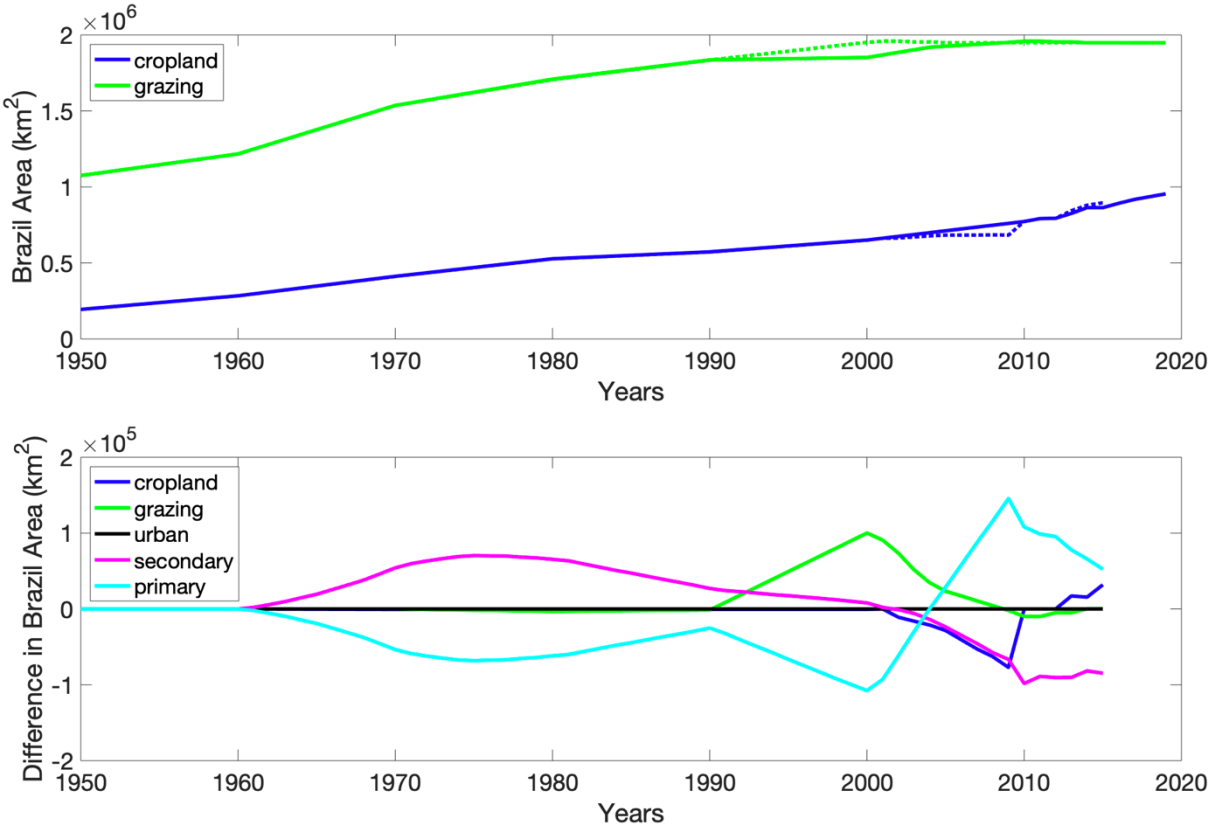



**Figure 2. a) Global area of key land-use states in LUH2-GCB2019, b) Differences between global areas of key land-use states (LUH2 v2h – LUH2-GCB2019).**




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**Figure 3. a) Area of cropland and grazing land in Brazil in both LUH2-GCB2019 (solid line) and LUH2 v2h (dashed line), b) Differences between Brazil areas of key land-use states (LUH2 v2h – LUH2-GCB2019).**

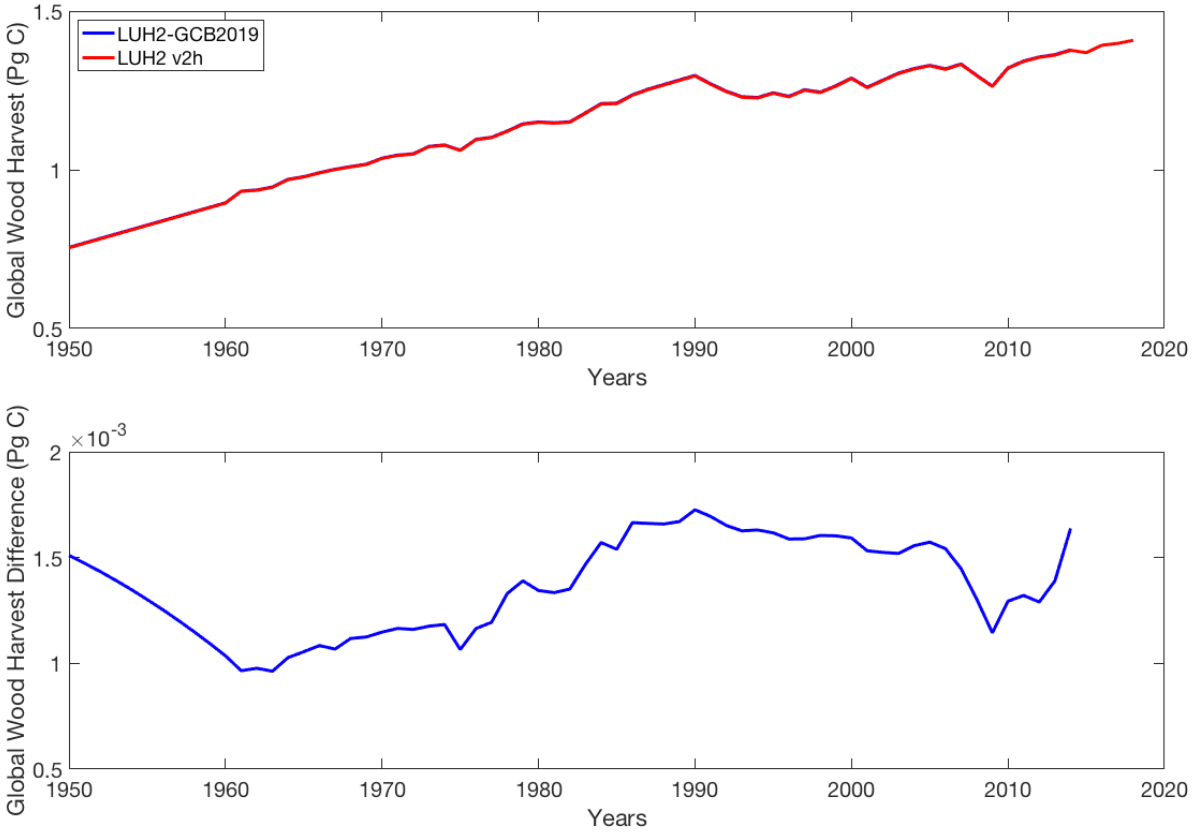



**Figure 4. a) Global wood harvest for LUH2-GCB2019 and LUH2 v2h, b) difference between global wood harvest of LUH2-GCB2019 and LUH2 v2h**

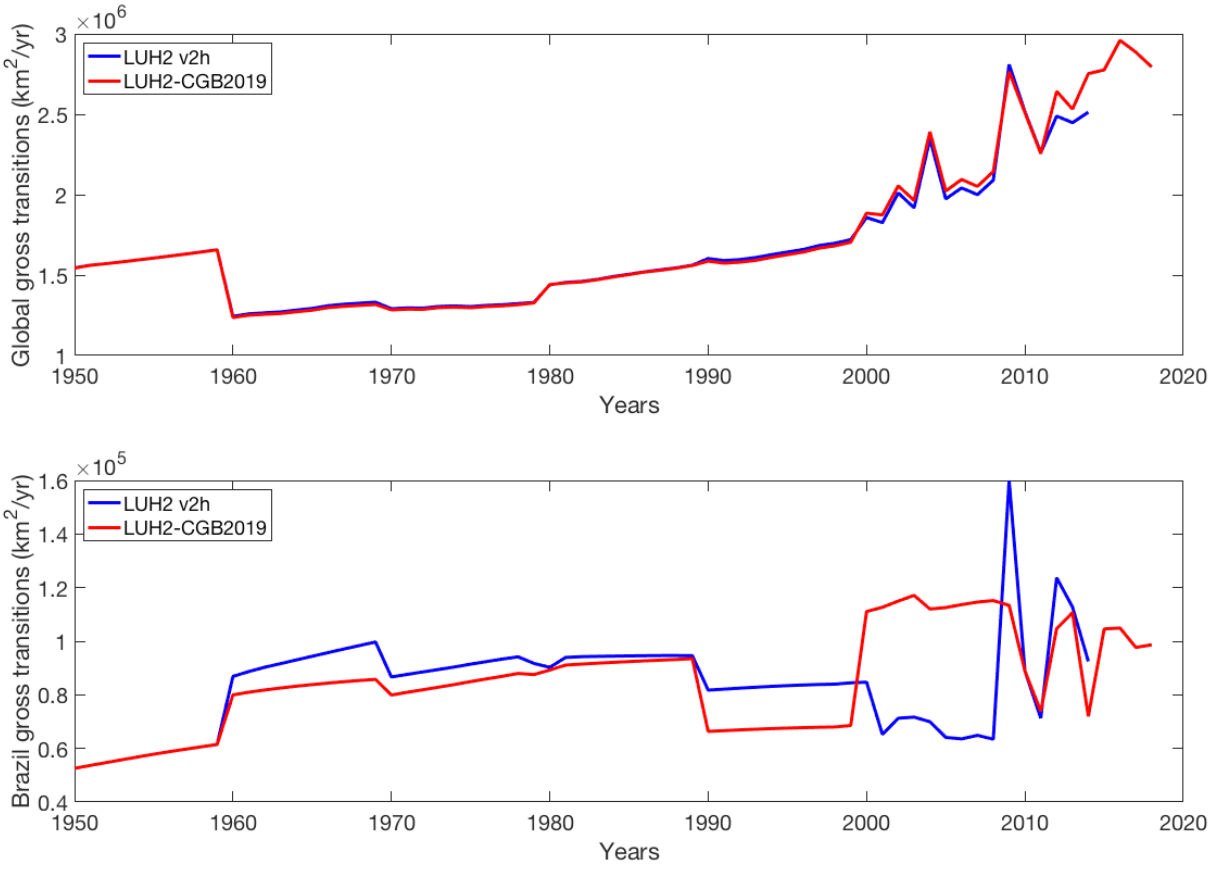



**Figure 5. a) Global and b) Brazil annual gross transitions, for LUH2 v2h and LUH2-GCB2019 for the years 1950-2014/2018**

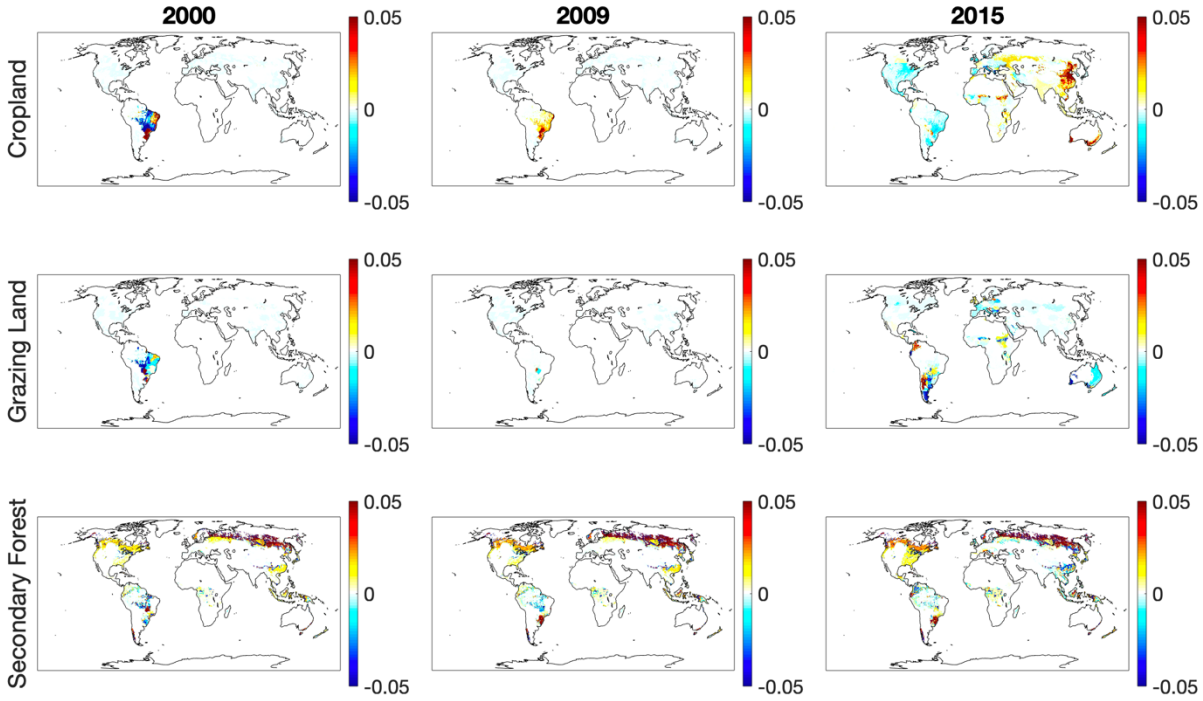



**Figure 6. Mapped differences (LUH2-GCB2019 – LUH2 v2h) of 0.25° grid-cell fractions of cropland, grazing land, and secondary forest in 2000, 2009, and 2015.**