ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Land-use change emissions based on high-resolution activity data substantially lower than previously estimated

To cite this article: R Ganzenmüller *et al* 2022 *Environ. Res. Lett.* **17** 064050

IOP Publishing Environ. Res. Lett. 17 (2022) 064050 https://doi.org/10.1088/1748-9326/ac70d8

ENVIRONMENTAL RESEARCH
LETTERS

RECEIVED
15 October 2021

REVISED
12 May 2022

ACCEPTED FOR PUBLICATION
17 May 2022

PUBLISHED
7 June 2022

LETTER

Land-use change emissions based on high-resolution activity data substantially lower than previously estimated

R Ganzenmüller[1,*], S Bultan[1], K Winkler[2,3], R Fuchs[2], F Zabel[1] and J Pongratz[1,4]

[1] Department of Geography, Ludwig-Maximilians-Universität München, Munich, Germany
[2] Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany
[3] Laboratory of Geo-information Science and Remote Sensing, Wageningen University & Research (WUR), Wageningen, The Netherlands
[4] Max Planck Institute for Meteorology, Hamburg, Germany
[*] Author to whom any correspondence should be addressed.

E-mail: r.ganzenmueller@lmu.de

Keywords: global carbon cycle, land-use and land-cover change, emission uncertainties, high-resolution data

Supplementary material for this article is available online

Abstract

Land-use and land-cover changes (LULCCs) contributed around one third to the cumulative, anthropogenic CO_2 emissions from 1850 to 2019. Despite its great importance, estimates of the net CO_2 fluxes from LULCC (E_{LUC}) have high uncertainties, compared to other components of the global carbon cycle. One major source of uncertainty roots in the underlying LULCC forcing data. In this study, we implemented a new high-resolution LULCC dataset (HILDA+) in a bookkeeping model (BLUE) and compared the results to estimates from simulations based on LUH2, which is the LULCC dataset most commonly used in global carbon cycle models. Compared to LUH2-based estimates, results based on HILDA+ show lower total E_{LUC} (global mean difference 1960–2019: 541 TgC yr^{-1}, 65%) and large spatial and temporal differences in component fluxes (e.g. CO_2 fluxes from deforestation). In general, the congruence of component fluxes is higher in the mid-latitudes compared to tropical and subtropical regions, which is to some degree explained with the different implementations of shifting cultivation in the underlying LULCC datasets. However, little agreement is reached on the trend of the last decade between E_{LUC} estimates based on the two LULCC reconstructions. Globally and in many regions, E_{LUC} estimates based on HILDA+ have decreasing trends, whereas estimates based on LUH2 indicate an increase. Furthermore, we analyzed the effect of different resolutions on E_{LUC} estimates. By comparing estimates from simulations at 0.01° and 0.25° resolution, we find that component fluxes of estimates based on the coarser resolution tend to be larger compared to estimates based on the finer resolution, both in terms of sources and sinks (global mean difference 1960–2019: 36 TgC yr^{-1}, 96%). The reason for these differences are successive transitions: these are not adequately represented at coarser resolution, which has the effect that—despite capturing the same extent of transition areas—overall less area remains pristine at the coarser resolution compared to the finer resolution.

1. Introduction

The net CO_2 flux from land-use and land-cover change (E_{LUC}) is a key component of the global carbon cycle (Friedlingstein *et al* 2020). E_{LUC} includes the carbon transfer from soil and biomass to the atmosphere through e.g. deforestation, harvest activities, and pasture to cropland conversions as well as the uptake and storage of carbon from the atmosphere in biomass and soil through e.g. afforestation and regrowth of vegetation after abandonment of agricultural land or harvest (Pongratz *et al* 2014). These land-use and land-cover change (LULCC) activities can be targeted as means to reduce emissions or to re-sequester carbon (often called carbon dioxide removal or negative emissions technologies in the latter case) and will be essential for meeting the 1.5 °C climate target (Griscom *et al* 2017, Harper *et al* 2018, Goldstein *et al* 2020, Crippa *et al* 2021). Especially, halting deforestation and forest degradation on the one side (Maxwell *et al* 2019, Roe *et al* 2019, Gatti *et al* 2021) and supporting afforestation and regeneration of natural forests on the other side are widely discussed, available, and effective measures for climate mitigation (Hoegh-Guldberg *et al* 2019, Lewis *et al* 2019, Roe *et al* 2019). The implementation of these also greatly influences national abilities to reach net-zero emissions (van Soest *et al* 2021).

Compared to fossil CO_2 emissions, estimates of E_{LUC} are subject to high relative uncertainties (Arneth *et al* 2017). In the Global Carbon Budget 2020 (GCB2020), the uncertainty in E_{LUC} estimates was specified to be, with a likelihood of at least 68% ($\pm 1\sigma$), in the range of ± 0.7 GtC yr^{-1} based on a best-value judgement (Friedlingstein *et al* 2020). In relative terms, this translates to an uncertainty of 43.8% (in comparison, fossil CO_2 emissions: 5.2%). The high uncertainty of E_{LUC} estimates has various reasons as summarized by Pongratz *et al* (2021): different terminologies and definitions (Pongratz *et al* 2014, Grassi *et al* 2018, 2021, Malins *et al* 2020, Obermeier *et al* 2021), different model assumptions and parameters (Bastos *et al* 2020, Gasser *et al* 2020, Hartung *et al* 2021), and different considerations of management processes (Stocker *et al* 2014, Arneth *et al* 2017, Hartung *et al* 2021). Furthermore, several studies have attributed major parts of this uncertainty to underlying LULCC datasets. From a set of sensitivity experiments based on the high, low, and baseline LULCC scenarios, Hartung *et al* (2021) estimate that about 22% of the sensitivity in cumulative E_{LUC} stems from LULCC inputs. Similarly, Gasser *et al* (2020) find substantial differences between E_{LUC} estimates based on different versions of LUH2, LUH1 and Global forest resources assessments (FRAs). Houghton and Nassikas (2017) use different versions of FRA to highlight differences in E_{LUC} estimates after 1950, while Peng *et al* (2017) compile multiple historical plant functional type (PFT) maps and conclude that different transition rules result in large differences in E_{LUC} estimates. Moreover, different regional studies (Yu *et al* 2019: USA, Kondo *et al* 2021: Southeast Asia, Rosan *et al* 2021: Brazil) discuss the influence of underlying LULCC forcing data on E_{LUC} estimates.

For this study, we implemented the new LULCC dataset HIstoric Land Dynamics Assessment + (Winkler *et al* 2021, hereafter HILDA+) in the bookkeeping of land use emissions model (Hansis *et al* 2015, hereafter BLUE). HILDA+ is a global high-resolution data product with a spatial resolution of $0.01° \times 0.01°$, covering common LULCC classes and a decent time period (1900/1960–2019), which makes it suitable as LULCC forcing for carbon cycle models. BLUE is one of three bookkeeping models in the yearly global carbon budgets (GCBs) (Friedlingstein *et al* 2020, 2021). Within the high uncertainties associated with E_{LUC}, BLUE is generally in line with other bookkeeping model and dynamic global vegetation model (DGVM) estimates, such that we use it here as a representative state-of-the-art model to quantify E_{LUC} and expect our qualitative conclusions to be robust against the choice of model. Detailed comparisons of BLUE to other models can be found in Bastos *et al* (2021), Friedlingstein *et al* (2021), and Obermeier *et al* (2021). The implementation of HILDA+ in BLUE opens up the novel possibility to compare and evaluate E_{LUC} based on two spatially explicit and independently derived LULCC datasets. Given the high uncertainty arising from LULCC inputs, the verification of E_{LUC} estimates based on HILDA+ with estimates based on other LULCC forcings is an important step to identify causes of the E_{LUC} uncertainty. We take this opportunity to investigate mechanisms beyond the specific LULCC data and E_{LUC} model used and investigate the relevance of initialization time and, for the first time, the sensitivity of results to spatial resolution, highlighting a previously under-appreciated role of successive transitions in global carbon cycle modeling.

By using BLUE, we make use of the computationally efficient design of the model that enables us to estimate E_{LUC} at the original resolution of HILDA+ at 0.01°. In the past, E_{LUC} has been estimated globally at 0.25° resolution (Le Quéré *et al* 2018a, 2018b, Friedlingstein *et al* 2019, 2020, Bastos *et al* 2021, Hartung *et al* 2021), at 0.5° resolution (Hansis *et al* 2015), at country level (Houghton and Nassikas 2017, Le Quéré *et al* 2018a, 2018b, Friedlingstein *et al* 2019, 2020, Bastos *et al* 2021), and at regional and biome level (Friedlingstein *et al* 2020, Gasser *et al* 2020). Thus, E_{LUC} estimates based on HILDA+ have an at least 25 times higher information content than any previous studies. The high resolution of HILDA+ allows us a spatially more precise detection of LULCC events and consequently a better location of E_{LUC} sinks and sources. Nevertheless, subgrid-scale omissions of transitions can still not be completely avoided, for which a field-scale resolution of roughly 1 ha would be needed (Wilkenskjeld *et al* 2014). An example of such subgrid-scale transitions are transitions from shifting cultivation (also called swidden agriculture/-cultivation or slash-and-burn), which are small-scale land use systems with rotational cycles of shorter cultivation phases of annual crops and longer natural fallow phases of woody regrowth, separated by fire clearances (Mertz *et al* 2009). Using LULCC data of less than 100 m resolution, studies such as Spawn *et al* (2019) and Feng *et al* (2022) might be able to account for subgrid-scale transitions. However, these studies are restricted in their spatial extent (Tropics, USA), do not cover legacy fluxes due to their temporal limitation, and provide only specific component fluxes of E_{LUC}. The latter is a general problem of E_{LUC} estimates based on satellite-derived data of vegetation dynamics, such as forest cover changes

(Hansen *et al* 2013): since land-use dynamics coincide with natural disturbances (e.g. natural wildfires or insect outbreaks), satellite-derived data of vegetation cover changes, although increasingly available at high resolution, cannot be used directly as input to carbon cycle models (Pongratz *et al* 2021). Typically, only component fluxes such as from cropland expansion of specific types of land-use-induced forest cover losses can be derived directly from satellite data. Due to the increasing availability of time series from satellite products, there is a clear tendency towards spatially higher resolutions of LULCC datasets and E_{LUC} estimates, but research on the influence of the resolution of underlying LULCC reconstructions on E_{LUC} estimates is limited.

HILDA+ provides annual data for the time period 1960–2019 and based on that data interpolated trends for the time period 1900–1960 (Winkler *et al* 2021). In comparison, LUH2 (Hurtt *et al* 2020, Chini *et al* 2021) covers a LULCC history dating back to AD 850 with data provided every 100 years until 1700, every 10 years between 1700 and 2000, and annually afterwards. To create annual LULCC maps, the data before 2000 is linearly interpolated between the above-mentioned time steps (Hurtt *et al* 2020). The importance of the starting year of a model simulation is analyzed by Hartung *et al* (2021) for cumulative LULCC fluxes. Accordingly, based on simulations starting in AD 850, 1700, and 1850, the uncertainty introduced by the initialization year amounts to 15% for estimates of cumulative E_{LUC} in the time period 1850 to 2014. However, it remains unclear to what degree the starting year influences estimates of the more recent years, which are most important, e.g. as reference years or for the global stocktake, and if an initialization in 1900 is sufficient for estimating emissions from 1960 onwards.

The goal of this study is to highlight spatial and temporal uncertainties in E_{LUC} estimates related to (a) LULCC reconstructions, (b) the resolution of the LULCC forcing, and (c) the initialization year.

2. Methodology

For this study, HILDA+ is implemented in a bookkeeping model (BLUE) and results are compared to estimates of simulations based on LUH2, which is the LULCC dataset most commonly used in global E_{LUC} models. In simulations of BLUE, E_{LUC} fluxes from transitions between natural vegetation, cropland, and pasture, as well as from wood harvesting are considered (Hansis *et al* 2015). Vegetation and soil carbon densities for each combination of LULCC states and eleven PFTs are based on literature values and provided in Hansis *et al* (2015). Response curves derived from literature represent the carbon dynamics of different carbon pools following land-use changes and describe the decay and accumulation of vegetation and soil carbon. This includes the transfer of carbon to product pools of different lifetimes or the increase of carbon in different vegetation and soil pools due to regrowth of natural vegetation (Hansis *et al* 2015).

BLUE simulations with three different LULCC inputs (HILDA+ at 0.25° and at 0.01°, and LUH2 at 0.25°) were initialized. Four BLUE simulations were carried out based on HILDA+ at 0.25° with different initialization years (1900, 1920, 1940, 1960), and six simulations with the HYDE 3.2 based LUH2 data that was used for the BLUE estimates in the GCB2020 (initialized in 1700, 1850, 1900, 1920, 1940, 1960). The runs with different years of initialization are important to identify the minimum required starting year for robust E_{LUC} estimates. The initialization year 1700 corresponds to pre-industrial times, the year 1850 marks the approximate beginning of the industrial era, and the years 1900, 1920, and 1940 relate to the time period of interpolated trends of HILDA+, while 1960 is the first data-driven year of HILDA+. The simulation with HILDA+ at 0.01° was initialized in 1900.

Unlike LUH2, HILDA+ does not provide information on wood harvest and does not distinguish primary and secondary land, which is both required to capture important aspects of the carbon cycle. Thus, HILDA+ had to be processed and complemented before implementing it in BLUE. A detailed description of the processing of the data as well as a comparison of HILDA+ and LUH2 in terms of total area, spatial patterns, and annual change rates of LULCC states is provided in the supplementary materials (sections A and B) (available online at stacks.iop.org/ERL/17/064050/mmedia).

3. Land-use change emissions based on HILDA+ and LUH2

3.1. Differences in global estimates

Global E_{LUC} estimates based on HILDA+ and LUH2 differ in size and trends (figures 1 and 2). Total E_{LUC} estimates from the simulations with HILDA+ alternate around 1.0 PgC yr^{-1} and decrease after 2012 from 1.3 to 0.8 PgC yr^{-1} in 2019. Contrary, E_{LUC} estimates based on LUH2 decrease from 2.3 PgC yr^{-1} in 1960 to about 0.9 PgC yr^{-1} in 1999 and increase afterwards to 2.0 PgC yr^{-1} in 2019. Gross source and sink fluxes are greater in estimates based on LUH2 compared to the one based on LUH2. Trends in the last two decades are dominated by emissions from cropland expansions, with increasing tendencies forLUH2-based estimates and decreasing tendencies for estimates based on HILDA+.

Overall cropland emission estimates are on average almost three times higher, and the sink from abandonment of agricultural land is more than twice as big in the simulation with LUH2 compared to the one based on HILDA+ (figure 2). The differences

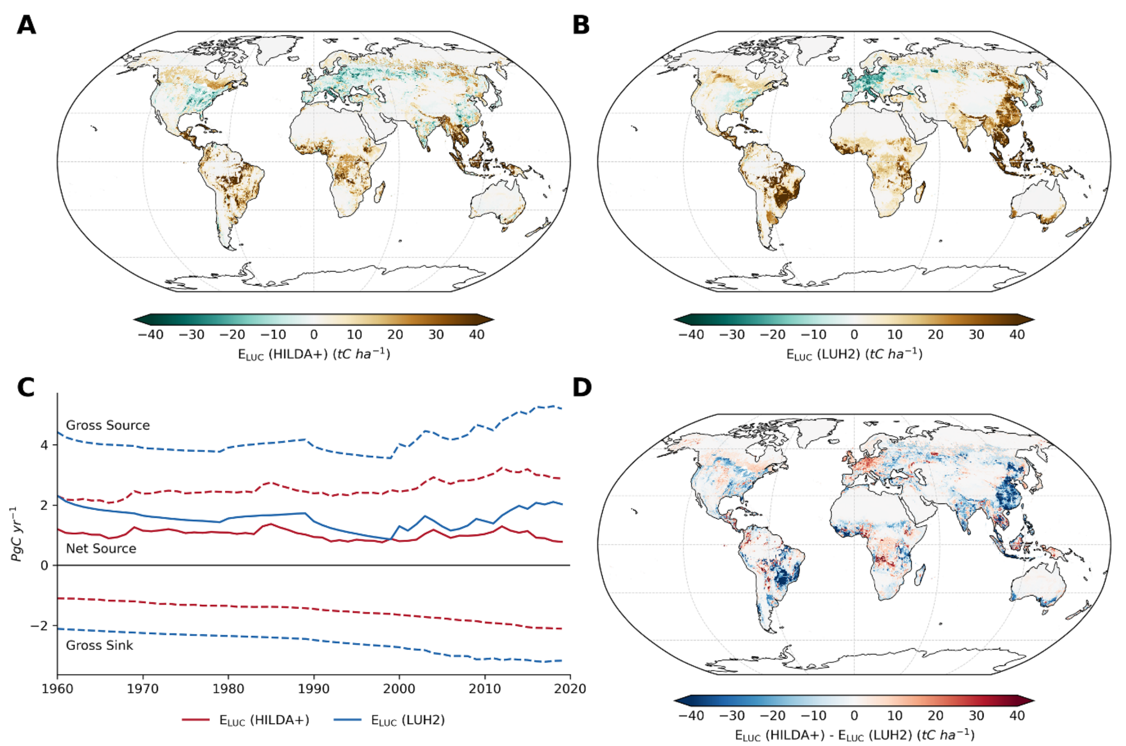

Figure 1. Global estimates of net CO_2 fluxes from LULCC (E_{LUC}) at 0.25° resolution between 1960 and 2019. (A) Cumulative E_{LUC} based on HILDA+, (B) cumulative E_{LUC} based on LUH2, (C) E_{LUC} based on HILDA+ and LUH2 over time (dashed: gross sink and source fluxes), (D) difference between cumulative E_{LUC} estimates based on HILDA+ and LUH2. Global estimates of total E_{LUC} are lower, and gross sources and sinks are smaller based on HILDA+ compared to estimates based on LUH2. The largest differences in total E_{LUC} estimates exist in tropical regions, China, and Europe.

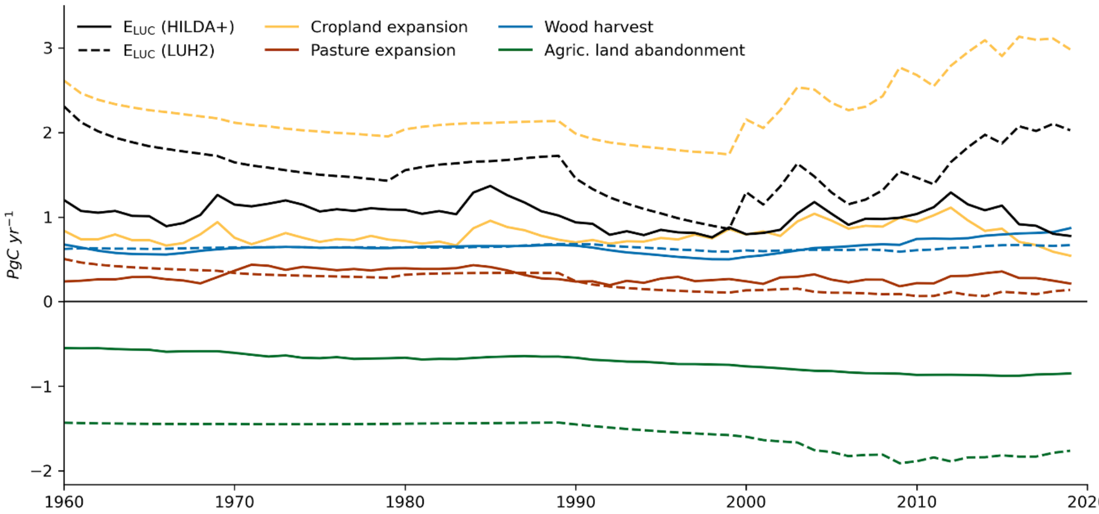

Figure 2. Global estimates of total and component CO_2 fluxes from LULCC (E_{LUC}) based on HILDA+ and LUH2 at 0.25° resolution between 1960 and 2019. E_{LUC} estimates based on LUH2 are higher than estimates based on HILDA+, mainly due to much higher emissions from cropland expansion. Also note the different dynamics since 2000 with increasing trends of LUH2-based estimates and decreasing trends with estimates based on HILDA+.

in cropland expansion and agricultural land abandonment estimates are connected to differences in the annual change rates of the LULCC input datasets. Due to the implementation of shifting cultivation in LUH2, gross gains and losses in cropland and secondary land area are higher in LUH2 compared to HILDA+, resulting in higher cropland emissions and a larger sink from agricultural land abandonment (figure 3). Compared to cropland expansion and agricultural land abandonment, emission estimates from pasture expansion and wood harvest are of similar magnitudes on a global level. However, larger regional differences exist for pasture emission estimates.

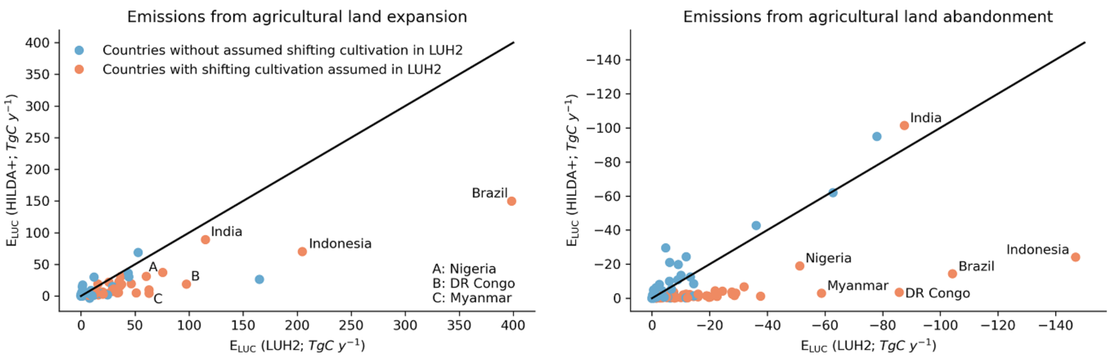

Figure 3. National estimates of yearly mean CO_2 fluxes (1960–2019) from expansion and abandonment of agricultural land based on HILDA+ and LUH2 (both at 0.25° resolution). Countries with shifting cultivation according to Heinimann *et al* (2017) are highlighted in red. The estimates based on LUH2 of countries with shifting cultivation are mostly much higher compared to the ones based on HILDA+, while the estimates of countries without shifting cultivation coincide more. India is the only exception, which can be explained by the small area of shifting cultivation relative to the size of the country.

3.2. Differences in regional estimates

Regional total E_{LUC} estimates based on HILDA+ and LUH2 have different levels of agreement (figure S5, tables S1 and S2). The highest agreement in terms of mean total E_{LUC} for 1960–2019 is found for Canada, Central and northern South America, Southern Africa, Mideast, and 'Korea and Japan' with less than 10 TgC yr^{-1} difference. However, some of these regions have far less total E_{LUC} emissions compared to other regions or estimates differ substantially in certain time periods. The largest differences in total E_{LUC} estimates exist in China and Brazil (mean differences: 159 resp. 148 TgC yr^{-1}).

Individual component fluxes show further regional differences (figure S5). Mostly in tropical and subtropical regions, emissions from cropland expansion are higher and the sink from abandonment is larger, with estimates based on LUH2 compared to HILDA+. As mentioned above, the magnitude of these differences originates from the implementation of shifting cultivation in LUH2. In the study by Heinimann *et al* (2017), which is underlying LUH2 shifting cultivation assumptions, it is particularly the tropical and subtropical regions on all three continents that are affected by shifting cultivation in varying intensity. In the case of Central America, northern South America and Southern Africa, mean total E_{LUC} estimates based on HILDA+ and LUH2 might have a high agreement despite large differences in component fluxes from cropland expansion and agricultural abandonment. Only in Europe and the Mideast, cropland emissions are mostly higher and abandonment emissions lower in the simulation based on HILDA+. Emissions from pasture expansion are higher or similar in the simulation with HILDA+ in most regions, except for Central Asia, China, and in some years Brazil. Emissions from wood harvest differ greatly in the USA, Canada, Brazil, Equatorial Africa, Russia, and Southeast Asia due to a depletion of biomass to harvest over the years in the simulations based on HILDA+. The HILDA+ version used in BLUE contains less primary land area compared to LUH2, which can lead to a concentration of harvesting events. In regions, where this is not the case, harvest emissions of the two simulations are similar.

Another substantial difference between estimates of the two simulations are opposing E_{LUC} trends within the last two decades in many regions, namely Southwest South America, Northern and Equatorial Africa, China, Southeast Asia, and to a certain degree also Oceania (figure S5). While total E_{LUC} in the run based on LUH2 is increasing in these regions, it is decreasing in the run based on HILDA+. The increase in E_{LUC} in these regions is mostly driven by an increase in emissions from cropland expansion. Thus, the increase resp. decrease of cropland area in recent years is one crucial difference between HYDE3.2 based LUH2 and HILDA+.

Furthermore, regional E_{LUC} plots reveal for some regions the occurrence of extreme E_{LUC} changes in one or multiple years (figure S5). Especially, emission spikes, where emission estimates strongly increase in one year and drop again to previous levels in the following years, are striking. This phenomenon, being present in estimates based on HILDA+ and LUH2, is apparent in the E_{LUC} time series of the USA, Canada, Russia, China, Oceania, and others. In all regions, these spikes can be attributed to extreme increases and soon after decreases in the annual change of single land cover states. It seems unlikely that these extreme changes reflect the actual development in the specific years, but rather originate from inconsistencies or misclassifications in the underlying datasets of LUH2 and HILDA+, especially since they do not occur in the same region and years in the two BLUE simulations.

3.3. Influence of spatial resolution

BLUE simulations, when forced with HILDA+ at 0.01° and 0.25° resolution (original HILDA+ resp.

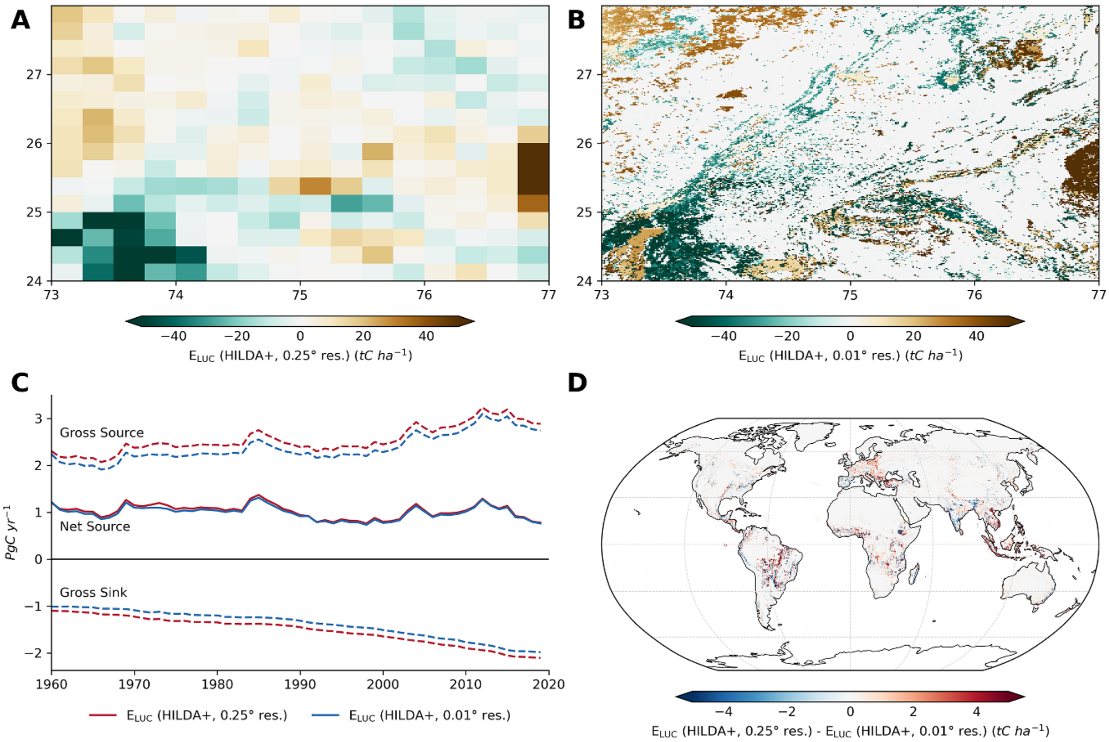

Figure 4. Global estimates of net CO_2 fluxes from LULCC (E_{LUC}) based on HILDA+ at 0.25° and 0.01° resolution between 1960 and 2019. (A) Map extract of cumulative E_{LUC} estimates based on the LULCC input at 0.25° for an exemplary area south-west of New Delhi, India with high positive and negative E_{LUC} fluxes, (B) map extract of cumulative E_{LUC} estimates based on the LULCC input at 0.01° for the same area as (A), (C) E_{LUC} based on HILDA+ at 0.25° and 0.01° resolution over time (dashed: gross sink and source fluxes), (D) difference between cumulative E_{LUC} estimates based on HILDA+ at 0.25° and 0.01° resolution. Total E_{LUC} estimates based on the LULCC input at 0.25° resolution are slightly higher than estimates based on 0.01°. Gross sources and sinks are larger at the coarser resolution.

LUH2 res.) as LULCC input, reveal substantial differences mainly in component fluxes (figures 4, S6, S7, tables S1 and S3). Globally, the mean difference between the two simulations is 36 TgC yr^{-1} for the time period 1960–2019. The highest differences in component fluxes are observed in Europe, South Asia, and the Mideast. In general, emission estimates from cropland and pasture expansion tend to be larger and the sink from abandonment of agricultural land tends to be greater at 0.25° resolution.

Additional idealized BLUE simulations with artificial LULCC input data (section G in supplementary materials) revealed that these differences are related to the occurrence of successive transitions in grid cells, i.e. these grid cells experience at least two, but mostly more transitions in the covered time period. In the prepared HILDA+ dataset at 0.01° resolution, 84% of the global land grid cells do not undergo any transition between 1900 and 2019, 10% experience one transition and 5% have more than one transition (table S4). In comparison, in Europe 21%, in South Asia 15%, and in the Mideast 7% of the grid cells have two or more transitions. Oceania (34%) and USA (9%) have high numbers of grid cells with successive transitions as well. However, the differences in component fluxes in these two regions are rather small, balancing out spatial differences. Also other regions have substantial amounts of successive transitions, but relative to the total transitions less than Europe, South Asia or the Mideast. Figure 5 illustrates the effect of successive transitions at different resolutions.

3.4. Influence of initialization

E_{LUC} estimates of simulations with different initialization years show relatively small differences when the initialization year is at least 60 years prior to the analyzed time period (figure 6). The difference in cumulative E_{LUC} estimates of the time period 1960–2019 for the simulation based on HILDA+ (res. 0.25°) and initialized in 1900 versus the simulation based on HILDA+ (res. 0.25°) and initialized in 1920 is less than 2%. For simulations based on LUH2 and initialized in 1700 and 1900, the difference in cumulative E_{LUC} estimates (1960–2019) is less than 0.1% (figure S9). The difference of cumulative E_{LUC} emissions of later time periods such as 1990–2019 or 2010–2019 is even smaller, since E_{LUC} estimates with different years of initialization converge with increasing time.

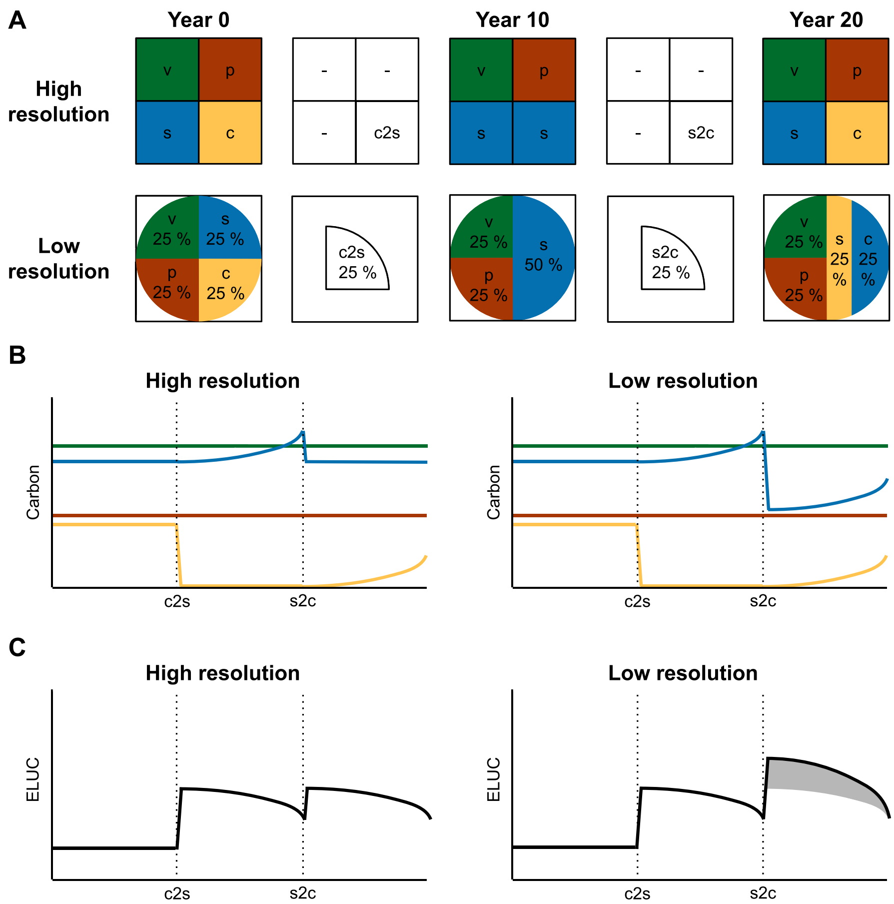

Figure 5. Illustration of the resolution dependent 'effect of successive transitions' on estimates of the CO_2 flux from LULCC (E_{LUC}). (A) Exemplary land-use and land-use cover change data as used in BLUE (c: cropland, p: pasture, s: secondary land, v: primary land). The area of four grid cells at high resolution (e.g. 0.01°) corresponds to one grid cell at low resolution (e.g. 0.25°). In three out of the four grid cells at high resolution, LULCC does not change in the selected time period. Only the grid cell with cropland at the beginning is abandoned in year 10 and then transitions back to cropland in year 20. States and transition areas are exactly the same at low resolution, but are expressed as fractions of the grid cell area. Less area remains unchanged at low resolution compared to the land cover at high resolution. (B) The carbon pools of the four state types, shown in a simplified way. Carbon pools, are the same before and after the first transition from cropland to secondary land (c2s) at both resolutions. However, with the second transition (secondary land to cropland; s2c) the carbon pool of secondary land drops by half at low resolution, while at high resolution it 'only' descends to the level that corresponds to one grid cell of secondary land in equilibrium. At low resolution the carbon pools are affected proportionally by transitions, which results in less area being in equilibrium, when there are successive transitions. (C) E_{LUC} at high and low resolution. The gray area marks the higher emissions at low resolution compared to the emissions at high resolution shown on the left. Additional BLUE experiments and explanations on the 'effect of successive transitions' are provided in the supplementary materials (section G).

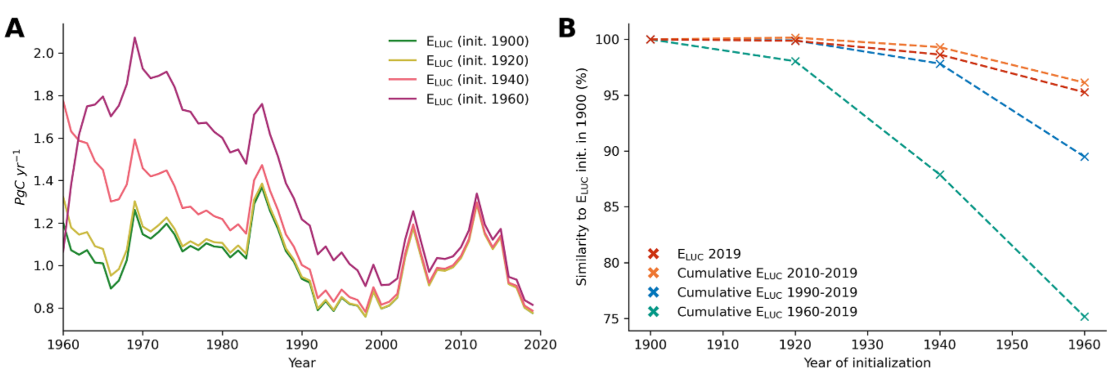

Figure 6. Comparison of BLUE simulations with different initialization years based on HILDA+ (res. 0.25°). (A) The net CO_2 fluxes from LULCC (E_{LUC}) with different initialization years converge over time. At the end of the time period, differences between runs initialized in 1900, 1920, and 1940 are marginal. (B) The larger the difference between the initialization years and the larger the time period of interest, the higher is the difference in cumulative E_{LUC} estimates. The difference in cumulative E_{LUC} estimates is less than 2% for the time period 1960 to 2019 between simulations initialized in 1900 and 1920.

4. Discussion

The alignment of E_{LUC} emission estimates based on different underlying LULCC forcing data differs globally, between regions and in certain regions depending on the time periods. Comparing E_{LUC} estimates from the BLUE model based on HILDA+ with estimates based on LUH2, the highest agreement for the total E_{LUC} is reached for Europe and Central America, while estimates for Brazil, China, and Oceania disagree substantially (figure S5). For other regions, the level of agreement varies over time. For Europe, a high consensus among estimates based on different LULCC forcing data and models is confirmed by several studies (Gasser *et al* 2020, Bastos *et al* 2021, Petrescu *et al* 2021). For Brazil, similar to our analysis, Rosan *et al* (2021) find little agreement of E_{LUC} emission estimates based on HYDE 3.2, the newer HYDE 3.3 version, and a national LULCC forcing. However, the suggested decline of total E_{LUC} emission estimates based on HYDE 3.3 by Rosan *et al* (2021) in the last two decades cannot be reproduced by our estimates based on HILDA+ due to increasing emissions from pasture expansion. The change in trend in the global E_{LUC} estimates that occurred in the GCB2020 as compared to the GCB2021 (Friedlingstein *et al* 2021) and that resulted from the change from a HYDE3.2 to a HYDE3.3 based LULCC forcing as described by Rosan *et al* (2021) is thus not confirmed by our simulations based on HILDA+ for Brazil. The decreasing trend in global emissions described in section 3.1 (figure 1(C)) for the last two decades in E_{LUC} based on HILDA+ in contrast to LUH2 is instead strongly attributable to Southeast Asia, where cropland emissions are revised down in our simulations using HILDA+. For Southeast Asia, a regional study (Kondo *et al* 2021) that uses DGVMs and bookkeeping models with different LULCC forcing data concludes a higher reliability of estimates based on LUH1 (Chini *et al* 2014) compared to the ones based on LUH2 for the region. The estimates based on HILDA+ confirm decreasing E_{LUC} emissions in Southeast Asia since the 2000s, although they suggest a later peak than Kondo *et al* (2021). For the USA, Yu *et al* (2019) reason that E_{LUC} emission estimates based on LUH2 overestimate the carbon sink, when comparing it to estimates based on a national land cover dataset. Contrary, our estimates based on HILDA+ do not suggest such a substantial overestimation compared to estimates based on LUH2 for the USA. These regional examples highlight a lack of agreement between different LULCC datasets and the implementation of LULCC dynamics in different models, in particular on regional level. Newer estimates do not necessarily converge. Given the fact that the most recent years are most important for tracking mitigation efforts such as policies to halt deforestation or reforestation programs, the disagreement of LULCC datasets since 2000 urgently needs to be resolved.

Another major difference in E_{LUC} estimates, mainly in tropical regions, are much higher emissions from cropland expansion and a larger sink from abandonment of agricultural land (cropland and pasture) in estimates based on LUH2. As explained in section 3.1, this is connected to the implementation of shifting cultivation in LUH2 and the omission of it in HILDA+. According to Heinimann *et al* (2017), the area influenced by shifting cultivation is spatially limited to roughly 280 Mha in the tropics between 30° S and 30° N. The inclusion of shifting cultivation in models, usually treated as a net vs. gross transition issue, is reported to lead to higher E_{LUC} estimates (Stocker *et al* 2014, Wilkenskjeld *et al* 2014, Hartung *et al* 2021). Arneth *et al* (2017) estimate an increase by 20%–30% when considering processes such as shifting cultivation. Furthermore, Bastos *et al* (2020, 2021), Gasser *et al* (2020) highlight substantial differences due to the implementation of gross transitions in estimates based on LUH2 compared to estimates based on other LULCC datasets. We do not find considerably higher E_{LUC} estimates based on LUH2 and HILDA+ that can be attributed to shifting cultivation as long as we consider the total E_{LUC}. Despite much higher annual area gross changes of cropland and secondary land in certain tropical regions in LUH2 compared to HILDA+, which we ascribe to the implementation of shifting cultivation in LUH2, the component fluxes of cropland expansion and agricultural land abandonment mostly compensate for each other, and as a consequence total E_{LUC} estimates match fairly well in most of the affected regions (at least before the increase in the last two decades, which is not connected to shifting cultivation). Similarly, Gasser *et al* (2020) note that shifting cultivation has a long-term effect of zero net emissions in the OSCAR model. Based on our findings, we argue that (a) gross transitions and shifting cultivation should be treated differently and (b) the implementation of shifting cultivation in LULCC reconstructions and carbon cycle models needs to be reconsidered. As described in section 3.3, in LULCC reconstructions with low resolution more area is assumed to be under transition compared to the same data at high resolution ('effect of successive transitions'), which shows that the rotational cycles of shifting cultivation cannot accurately be represented at 0.25° resolution, neither can they at 0.01° resolution, since patches of shifting cultivation are usually maximum a few hectares in size (Villa *et al* 2020, Bruun *et al* 2021). Moreover, several case studies (Bruun *et al* 2009, 2021, McNicol *et al* 2015, Terefe and Kim 2020) point out substantial differences in the carbon fluxes of the expansion and abandonment cycles of shifting cultivation compared to other expansion or abandonment transitions (e.g. clearing of former shifting cultivation areas for palm oil plantations), due to different regrowth rates and soil carbon dynamics. It remains unclear, if these drawbacks of current implementations in models can fully explain the large influence that shifting cultivation has on global and regional E_{LUC} component fluxes according to simulations based on LUH2 or if the implementation of shifting cultivation in LUH2 leads to an additional overestimation.

The spatial resolution of the LULCC input data has a significant influence on E_{LUC} component fluxes. Our estimates based on gross transitions of HILDA+ at 0.01° and 0.25° resolution and the BLUE experiments with artificial LULCC input revealed that component fluxes are smaller at higher resolutions, which can lead to overall higher or lower total E_{LUC} estimates. As described above, these differences are caused by successive transitions. According to Winkler *et al* (2021), successive transitions were prevailing in the Global North (USA, Europe, Australia) and rapidly growing economies such as India, Nigeria, and Turkey. Most of the transitions in these regions were changes between managed and unmanaged land (crop/pasture to secondary land or reverse) (Winkler *et al* 2021). However, potential explanations are needed for these diverse and region-specific high land-use dynamics: in the USA cropland abandonment was driven over time by federal policies and changes in commodity prices among others (Chen and Khanna 2018, Hendricks and Er 2018, Lark *et al* 2022), in Mediterranean Europe and Australia certain pasture-shrubland dynamics were influenced by climatic and socioeconomic changes (Eldridge and Soliveres 2014, Rolo and Moreno 2019), in Eastern Europe the agricultural sector experienced massive changes following the breakdown of the former Soviet Union (Prishchepov *et al* 2013, Schierhorn *et al* 2019), in Turkey a mix of industrialization, urbanization, and migration led to rapid changes in land use practices (Tanrivermis 2003), in India the heavy usage of irrigation and fertilizer enabled agricultural intensification (Ambika *et al* 2016, Chen *et al* 2019), and in Nigeria conversions to cultivated land dominated LULCC dynamics (Arowolo and Deng 2018). Moreover, crop rotation or mixed crop-livestock systems may also be linked to the observed successive transitions in Australia, the USA, and Europe (Peyraud *et al* 2014, Rosenzweig *et al* 2018, Ghahramani *et al* 2020).

The resolution-dependent 'effect of successive transitions' has not been described in the literature so far, although different studies discuss the importance of spatial resolution and transition types for E_{LUC} estimates in other respects. For example, Wilkenskjeld *et al* (2014) point out that a coarser resolution of net LULCC data leads in a reduction in area affected by LULCC and thus affects E_{LUC} estimates. Several studies highlight the importance of using gross over net LULCC transitions to account for the actual area changes (i.e. Hansis *et al* 2015, Arneth *et al* 2017, Bayer *et al* 2017, Bastos *et al* 2020, 2021). However, Yue *et al* (2018) conclude from simulations with sub-grid secondary forests of different age classes that the contribution from gross transitions to overall E_{LUC} estimates tend to be overestimated due to the non-consideration of age classes in most models. The findings from Yue *et al* (2018) go in a similar direction as our observation that successive transitions are not adequately represented in gross transitions at coarse resolution (nor with net transitions), and consequently different land areas are affected by successive transitions, when compared to the same LULCC data at high-resolution. It is likely that the 'effect of successive transitions' is also of greater importance for DGVMs and other bookkeeping models.

Our simulations starting at different years showcase the importance of a prudent choice for the year of initialization. E_{LUC} estimates of simulations based on HILDA+ for 2019 differ by more than 5% when initialized in 1960 compared to simulations with the same LULCC forcing but initialized in 1900. Further, the results indicate that the influence decreases over time and differences between simulations with earlier and later starting years become marginal after a few decades. The simulations highlight that (a) the initialization year needs to be well before the satellite area to capture present-day fluxes accurately (at least 95% similarity in cumulative emission estimates compared to simulations starting 20 years earlier), (b) a lead time of 60 years seems sufficient (95% similarity criterion, see above) and (c) the time period covered by HILDA+ starting in 1900 is suitable for the estimation of E_{LUC} after 1960 without introducing large uncertainties due to the initialization year.

5. Conclusions

E_{LUC} estimates have high uncertainties, which are partly caused by underlying LULCC datasets among other drivers and parameters. The implementation of a new LULCC reconstruction dataset (HILDA+) in a bookkeeping model (BLUE) enabled us to evaluate and compare E_{LUC} estimates based on HILDA+ to E_{LUC} estimates based on the widely-used default LULCC dataset LUH2. Results show that global E_{LUC} estimates based on HILDA+ are substantially lower than estimates based on LUH2. Regionally, a pattern of higher E_{LUC} emissions from cropland expansion and a larger sink from agricultural land abandonment in estimates based on LUH2 can be observed in most tropical regions. The larger sources and sinks can partly be explained by the inclusion of shifting cultivation in LUH2, which raises questions about the influence of shifting cultivation on the global carbon cycle and the implementation of shifting cultivation in LULCC datasets and carbon cycle models. Another significant difference are opposing trends of E_{LUC} estimates globally and in many regions in the last two decades. These substantial differences highlight the need for more reliable LULCC reconstructions for more accurate and robust E_{LUC} estimates.

Independent estimates for the evaluation of LULCC dynamics, including knowledge of regionally specific LULCC activities, component-specific evaluations, and complementing default global runs, such as in the GCBs, by alternative LULCC data could increase the understanding of differences and provide better estimates of uncertainties. Furthermore, we run simulations based on LULCC data at different spatial resolutions (0.01° vs. 0.25°) and find significant differences in E_{LUC} component fluxes. The reason for this phenomenon are successive transitions. These cannot adequately be represented at the coarse resolution, which has the effect that at the coarser resolution overall a larger area is affected by LULCC events. Moreover, a lead time of at least 60 years has been found crucial to account for legacy emissions and retrieve robust E_{LUC} estimates. This rather long lead time to capture legacy emissions, together with the need for ancillary data or methods to split anthropogenic from natural drivers of land use dynamics, challenges the application of purely satellite-based LULCC datasets, although their often high spatial resolution could provide an important step forward to capture successive transitions. Both the sensitivity to spatial resolution and initialization year are qualitatively independent of the concrete LULCC dataset, such that we recommend accounting for these issues in future studies with other LULCC activity data and carbon cycle models.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

R G and K W acknowledge support from the European Commission through Horizon 2020 Framework Programme (VERIFY, Grant No. 776810). S B was supported by German Stifterverband für die Deutsche Wissenschaft e.V. in collaboration with Volkswagen AG. This work used resources of the Deutsches Klimarechenzentrum (DKRZ) granted by its Scientific Steering Committee (WLA) under Project ID bm0891.

ORCID iDs

R Ganzenmüller https://orcid.org/0000-0002-2337-0915
S Bultan https://orcid.org/0000-0002-9191-9906
K Winkler https://orcid.org/0000-0002-2591-0620
R Fuchs https://orcid.org/0000-0003-3830-1274
F Zabel https://orcid.org/0000-0002-2923-4412
J Pongratz https://orcid.org/0000-0003-0372-3960

References

Ambika A K, Wardlow B and Mishra V 2016 Remotely sensed high resolution irrigated area mapping in India for 2000 to 2015 *Sci. Data* **3** 160118

Arneth A *et al* 2017 Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed *Nat. Geosci.* **10** 79–84

Arowolo A O and Deng X 2018 Land use/land cover change and statistical modelling of cultivated land change drivers in Nigeria *Reg. Environ. Change* **18** 247–59

Bastos A *et al* 2020 Sources of uncertainty in regional and global terrestrial CO_2 exchange estimates *Glob. Biogeochem. Cycles* **34** e2019GB006393

Bastos A, Hartung K, Nützel T B, Nabel J E M S, Houghton R A and Pongratz J 2021 Comparison of uncertainties in land-use change fluxes from bookkeeping model parameterization *Earth Syst. Dyn.* **12** 745–62

Bayer A D, Lindeskog M, Pugh T A M, Anthoni P M, Fuchs R and Arneth A 2017 Uncertainties in the land-use flux resulting from land-use change reconstructions and gross land transitions *Earth Syst. Dyn.* **8** 91–111

Bruun T B, de Neergaard A, Lawrence D and Ziegler A D 2009 Environmental consequences of the demise in swidden cultivation in Southeast Asia: carbon storage and soil quality *Human Ecol.* **37** 375–88

Bruun T B, Ryan C M, de Neergaard A and Berry N J 2021 Soil organic carbon stocks maintained despite intensification of shifting cultivation *Geoderma* **388** 114804

Chen C *et al* 2019 China and India lead in greening of the world through land-use management *Nat. Sustain.* **2** 122–9

Chen X and Khanna M 2018 Effect of corn ethanol production on conservation reserve program acres in the US *Appl. Energy* **225** 124–34

Chini L *et al* 2021 Land-use harmonization datasets for annual global carbon budgets *Earth Syst. Sci. Data* **13** 4175–89

Chini L, Hurtt G and Frolking S 2014 LUH1: harmonized global land use for years 1500–2100, V1 (available at: https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1248)

Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello F N and Leip A 2021 Food systems are responsible for a third of global anthropogenic GHG emissions *Nat. Food* **2** 198–209

Eldridge D J and Soliveres S 2014 Are shrubs really a sign of declining ecosystem function? Disentangling the myths and truths of woody encroachment in Australia *Aust. J. Bot.* **62** 594–608

Feng Y *et al* 2022 Doubling of annual forest carbon loss over the tropics during the early twenty-first century *Nat. Sustain.* **5** 444–51

Friedlingstein P *et al* 2019 Global carbon budget 2019 *Earth Syst. Sci. Data* **11** 1783–838

Friedlingstein P *et al* 2020 Global carbon budget 2020 *Earth Syst. Sci. Data* **12** 3269–340

Friedlingstein P *et al* 2021 Global carbon budget 2021 *Earth Syst. Sci. Data* **14** 1917–2005

Gasser T, Crepin L, Quilcaille Y, Houghton R A, Ciais P and Obersteiner M 2020 Historical CO_2 emissions from land use and land cover change and their uncertainty *Biogeosciences* **17** 4075–101

Gatti L V *et al* 2021 Amazonia as a carbon source linked to deforestation and climate change *Nature* **595** 388–93

Ghahramani A, Kingwell R S and Maraseni T N 2020 Land use change in Australian mixed crop-livestock systems as a transformative climate change adaptation *Agric. Syst.* **180** 102791

Goldstein A *et al* 2020 Protecting irrecoverable carbon in Earth's ecosystems *Nat. Clim. Change* **10** 287–95

Grassi G *et al* 2018 Reconciling global-model estimates and country reporting of anthropogenic forest CO_2 sinks *Nat. Clim. Change* **8** 914–20

Grassi G *et al* 2021 Critical adjustment of land mitigation pathways for assessing countries' climate progress *Nat. Clim. Change* **11** 425–34
Griscom B W *et al* 2017 Natural climate solutions *Proc. Natl Acad. Sci.* **114** 11645–50
Hansen M C *et al* 2013 High-resolution global maps of 21st-century forest cover change *Science* **342** 850–3
Hansis E, Davis S J and Pongratz J 2015 Relevance of methodological choices for accounting of land use change carbon fluxes *Glob. Biogeochem. Cycles* **29** 1230–46
Harper A B *et al* 2018 Land-use emissions play a critical role in land-based mitigation for Paris climate targets *Nat. Commun.* **9** 2938
Hartung K *et al* 2021 Bookkeeping estimates of the net land-use change flux—a sensitivity study with the CMIP6 land-use dataset *Earth Syst. Dyn.* **12** 763–82
Heinimann A, Mertz O, Frolking S, Christensen A E, Hurni K, Sedano F, Chini L P, Sahajpal R, Hansen M and Hurtt G 2017 A global view of shifting cultivation: recent, current and future extent *PLoS One* **12** e0184479
Hendricks N P and Er E 2018 Changes in cropland area in the United States and the role of CRP *Food Policy* **75** 15–23
Hoegh-Guldberg O *et al* 2019 The human imperative of stabilizing global climate change at 1.5°C *Science* **365** 6459
Houghton R A and Nassikas A A 2017 Global and regional fluxes of carbon from land use and land cover change 1850–2015 *Glob. Biogeochem. Cycles* **31** 456–72
Hurtt G C *et al* 2020 Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6 *Geosci. Model Dev.* **13** 5425–64
Kondo M *et al* 2021 Are land-use change emissions in Southeast Asia decreasing or increasing? *Glob. Biogeochem. Cycles* **36** e2020GB006909
Lark T J, Hendricks N P, Aaron S, Nicholas P, Spawn-Lee S A, Matthew B, Booth E G, Kucharik C J and Holly K G 2022 Environmental outcomes of the US Renewable Fuel Standard *Proc. Natl Acad. Sci.* **119** e2101084119
Le Quéré C *et al* 2018a Global carbon budget 2017 *Earth Syst. Sci. Data* **10** 405–48
Le Quéré C *et al* 2018b Global carbon budget 2018 *Earth Syst. Sci. Data* **10** 2141–94
Lewis S L, Wheeler C E, Mitchard E T A and Koch A 2019 Restoring natural forests is the best way to remove atmospheric carbon *Nature* **568** 25–28
Malins C, Plevin R and Edwards R 2020 How robust are reductions in modeled estimates from GTAP-BIO of the indirect land use change induced by conventional biofuels? *J. Clean. Prod.* **258** 120716
Maxwell S L *et al* 2019 Degradation and forgone removals increase the carbon impact of intact forest loss by 626% *Sci. Adv.* **5** eaax2546
McNicol I M, Berry N J, Bruun T B, Hergoualc'h K, Mertz O, de Neergaard A and Ryan C M 2015 Development of allometric models for above and belowground biomass in swidden cultivation fallows of Northern Laos *For. Ecol. Manage.* **357** 104–16
Mertz O, Padoch C, Fox J, Cramb R A, Leisz S J, Lam N T and Vien T D 2009 Swidden change in Southeast Asia: understanding causes and consequences *Human Ecol.* **37** 259–64
Obermeier W A *et al* 2021 Modelled land use and land cover change emissions—a spatio-temporal comparison of different approaches *Earth Syst. Dyn.* **12** 635–70
Peng S, Ciais P, Maignan F, Li W, Chang J, Wang T and Yue C 2017 Sensitivity of land use change emission estimates to historical land use and land cover mapping *Glob. Biogeochem. Cycles* **31** 626–43
Petrescu A M R *et al* 2021 The consolidated European synthesis of CO_2 emissions and removals for the European Union and United Kingdom: 1990–2018 *Earth Syst. Sci. Data* **13** 2363–406
Peyraud J-L, Taboada M and Delaby L 2014 Integrated crop and livestock systems in Western Europe and South America: a review *Eur. J. Agron.* **57** 31–42
Pongratz J, Reick C H, Houghton R A and House J I 2014 Terminology as a key uncertainty in net land use and land cover change carbon flux estimates *Earth Syst. Dyn.* **5** 177–95
Pongratz J, Schwingshackl C, Bultan S, Obermeier W, Havermann F and Guo S 2021 Land use effects on climate: current state, recent progress and emerging topics *Curr. Clim. Change Rep.* **7** 99–120
Prishchepov A V, Müller D, Dubinin M, Baumann M and Radeloff V C 2013 Determinants of agricultural land abandonment in post-Soviet European Russia *Land Use Policy* **30** 873–84
Roe S *et al* 2019 Contribution of the land sector to a 1.5 °C world *Nat. Clim. Change* **9** 817–28
Rolo V and Moreno G 2019 Shrub encroachment and climate change increase the exposure to drought of Mediterranean wood-pastures *Sci. Total Environ.* **660** 550–8
Rosan T M *et al* 2021 A multi-data assessment of land use and land cover emissions from Brazil during 2000–2019 *Environ. Res. Lett.* **16** 074004
Rosenzweig S T, Stromberger M E and Schipanski M E 2018 Intensified dryland crop rotations support greater grain production with fewer inputs *Agric. Ecosyst. Environ.* **264** 63–72
Schierhorn F, Kastner T, Kuemmerle T, Meyfroidt P, Kurganova I, Prishchepov A V, Erb K-H, Houghton R A and Müller D 2019 Large greenhouse gas savings due to changes in the post-Soviet food systems *Environ. Res. Lett.* **14** 065009
Spawn S A, Lark T J and Gibbs H K 2019 Carbon emissions from cropland expansion in the United States *Environ. Res. Lett.* **14** 045009
Stocker B D, Feissli F, Strassmann K M, Spahni R and Joos F 2014 Past and future carbon fluxes from land use change, shifting cultivation and wood harvest *Tellus* B **66** 1–15
Tanrivermis H 2003 Agricultural land use change and sustainable use of land resources in the mediterranean region of Turkey *J. Arid Environ.* **54** 553–64
Terefe B and Kim D-G 2020 Shifting cultivation maintains but its conversion to mono-cropping decreases soil carbon and nitrogen stocks compared to natural forest in Western Ethiopia *Plant Soil* **453** 105–17
van Soest H L, Den Elzen M G J and van Vuuren D P 2021 Net-zero emission targets for major emitting countries consistent with the Paris Agreement *Nat. Commun.* **12** 2140
Villa P M, Martins S V, de Oliveira Neto S N, Rodrigues A C, Hernández E P and Kim D-G 2020 Policy forum: shifting cultivation and agroforestry in the Amazon: premises for REDD+ *For. Policy Econ.* **118** 102217
Wilkenskjeld S, Kloster S, Pongratz J, Raddatz T and Reick C H 2014 Comparing the influence of net and gross anthropogenic land-use and land-cover changes on the carbon cycle in the MPI-ESM *Biogeosciences* **11** 4817–28
Winkler K, Fuchs R, Rounsevell M and Herold M 2021 Global land use changes are four times greater than previously estimated *Nat. Commun.* **12** 2501
Yu Z, Lu C, Tian H and Canadell J G 2019 Largely underestimated carbon emission from land use and land cover change in the conterminous United States *Glob. Change Biol.* **25** 3741–52
Yue C, Ciais P and Li W 2018 Smaller global and regional carbon emissions from gross land use change when considering sub-grid secondary land cohorts in a global dynamic vegetation model *Biogeosciences* **15** 1185–201