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Key Points:
- We use a spatially explicit model to attribute C fluxes to land use activities
- We compare several accounting options for a post-Kyoto climate agreement
- The different choices result in grossly different estimates of carbon fluxes

Supporting Information:
- Table S1
- Text S1, Figures S1 and S2, and Table S1 caption

Correspondence to:
J. Pongratz,
julia.pongratz@mpimet.mpg.de

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Relevance of methodological choices for accounting of land use change carbon fluxes

Eberhard Hansis[1], Steven J. Davis[2], and Julia Pongratz[3]

[1]Hamburg, Germany, [2]Department of Earth System Science, University of California, Irvine, Croul Hall Irvine, California, USA, [3]Max Planck Institute for Meteorology, Hamburg, Germany

Abstract Accounting for carbon fluxes from land use and land cover change (LULCC) generally requires choosing from multiple options of how to attribute the fluxes to regions and to LULCC activities. Applying a newly developed and spatially explicit bookkeeping model BLUE (bookkeeping of land use emissions), we quantify LULCC fluxes and attribute them to land use activities and countries by a range of different accounting methods. We present results with respect to a Kyoto Protocol-like "commitment" accounting period, using land use emissions of 2008–2012 as an example scenario. We assess the effect of accounting methods that vary (1) the temporal evolution of carbon stocks, (2) the state of the carbon stocks at the beginning of the period, (3) the temporal attribution of carbon fluxes during the period, and (4) treatment of LULCC fluxes that occurred prior to the beginning of the period. We show that the methodological choices result in grossly different estimates of carbon fluxes for the different attribution definitions.

1. Introduction

Emissions from land use and land cover change (LULCC) have contributed about one third of cumulative anthropogenic CO_2 emissions [*Houghton*, 2003] and represent about 10% of current annual CO_2 emissions [*Le Quéré et al.*, 2014]. This flux of emissions is usually called "net LULCC flux," because it consists of both source terms, e.g., biomass burnt or being decomposed after clearing of natural vegetation, and sink terms, e.g., regrowth of forest when agricultural land is abandoned.

The nonnegligible size of the net LULCC flux and the corresponding potential for emission reduction and mitigation make investigating its causes relevant. The net LULCC flux may be attributed to specific LULCC activities, such as clearing and wood harvest; to their underlying physical processes, such as soil decomposition and regrowth; and to the region where the LULCC takes place. The geography of LULCC emissions is relevant for policies aimed at avoiding the emissions. Under the Kyoto Protocol and subsequent UNFCCC (United Nations Framework Convention on Climate Change) decisions, emissions related to land use, land use change, and forestry are included in evaluating the Annex I Parties' commitments [e.g., *Birdsey et al.*, 2001].

However, such attribution requires model simulations because the net LULCC flux is not directly observable. The net exchange between atmosphere and land can be inferred as residual from carbon stocks and fluxes of atmosphere and ocean. However, models are needed to split the net exchange into natural sinks (and sources) on the one hand and the net LULCC flux on the other hand. As LULCC, unlike the burning of fossil fuels, may result in carbon fluxes that occur over many years after the LULCC event, analysts must make various methodological choices of how to simulate these delayed fluxes and how to attribute them in time. In the present study, we apply our model "Bookkeeping of Land Use Emissions" (BLUE), which extends the widely used bookkeeping approach of estimating carbon fluxes, to illustrate and quantify the relevance of different methodological choices in attribution of the net LULCC flux.

An LULCC activity leads to delayed carbon fluxes because it usually alters the relationship between CO_2 taken up by photosynthesis (the net primary production) and decomposition of organic carbon in litter, soils, and product pools. Both uptake and release act on various timescales, leading to complex temporal patterns of carbon fluxes following a given LULCC activity, which may be modified further by subsequent LULCC events.

Multiple approaches exist to model the net LULCC flux. The simplest approach ignores temporal dynamics of delayed processes and assumes that carbon stocks before and after an LULCC event are at equilibrium. Under this approach, the net LULCC flux can be simply derived from information on carbon stocks of each land use state and the change in area. This approach is most commonly used in combination with remote sensing data [e.g., *Fearnside*, 1997; *Harris et al.*, 2012] and reflects a form of "committed flux," which attributes both instantaneous and delayed emissions related to a specific LULCC event to the time when the event occurred.

As an alternative to attributing the difference in equilibrium carbon fluxes to the time when the LULCC event occurs, the fluxes can also be spread uniformly over some time period. Such distribution is also conceptually simple (it only introduces one additional parameter, the choice of time horizon) but may be advantageous in the case of LULCC types that can be anticipated to succeed each other [*Davis et al.*, 2014]. If, for example, forest is cleared for a certain type of cultivation (e.g., soybean) that is later transformed to another type (e.g., wheat), such a uniform distribution over time allows carbon fluxes to be attributed to both crops. Analysts could thus conceivably distribute emissions in time according to whether and to what extent the successive uses are foreseeable or intended by the parties who are clearing land [*Davis et al.*, 2014].

A physically more accurate representation of the distribution of delayed carbon fluxes in time can be produced by process-based or bookkeeping models. Process-based models, such as dynamic global vegetation models, simulate carbon stocks and fluxes as a result of photosynthetic and decomposition processes interacting with environmental conditions. However, the current generation of dynamic global vegetation models does not allow for attributing the resulting carbon fluxes to an individual LULCC event because of computational constraints. Fulfilling this task requires bookkeeping models capable of tracking the area and type of LULCC and combining these with empirical response curves [e.g., *Houghton et al.*, 1983; *Reick et al.*, 2010; *Gasser and Ciais*, 2013]. We call a spatially and temporally explicit modeling of carbon stocks, which also accounts for the succession of LULCC events, the "legacy scheme." See section 4 for details on how the succession of LULCC events leads to redistribution of carbon fluxes between land uses.

The above-cited references illustrate two important choices when attributing carbon fluxes to specific LULCC activities: first, whether the temporal evolution of carbon stocks is simulated (as in a legacy scheme) or not (as when the difference of equilibrium states is assumed) and, second, to which point or period in time the modeled carbon fluxes are attributed to: as they are simulated to occur in time, as committed fluxes at the time of the LULCC event, or as committed fluxes distributed over time (e.g., a uniform distribution over a given time span). Further choices emerge when only specific periods of LULCC are of interest. This becomes particularly relevant in the context of the Kyoto Protocol and follow-up UNFCCC decisions [*United Nations Framework Convention on Climate Change (UNFCCC)*, 2011, 2012]. These require parties to count only LULCC during the "commitment period" toward their debits or credits and thereby exclude any carbon fluxes from LUCC events preceding that period. Investigating LULCC of a specific time period — whether an arbitrary commitment period, the year 1850 (the typical start date of the simulations for the coupled model intercomparison project contributing to the reports of the Intergovernmental Panel on Climate Change), or even earlier years in the history of LULCC — always requires a further choice on how to initialize carbon stocks. If earlier LULCC is known, simulations can start earlier than the time period of interest to represent the actual state of carbon stocks when entering the period; a simpler method is to assume that carbon stocks are in equilibrium with the existing vegetation distribution [e.g., *DeFries et al.*, 2002a].

This list of choices is not comprehensive but represent typical and, as we will show later, important choices that have to be made when setting up a model for attribution studies. Only some of them have been discussed in earlier studies, mostly on the issue of temporal attribution of fluxes: *Fearnside* [1997] has discussed the difference between committed and actual emissions, which was later quantified exemplarily for tropical emissions by *Ramankutty et al.* [2007]. *Davis et al.* [2014] compared conceptually several ways of temporal attribution, including committed, actual, and uniformly distributed fluxes. *Ramankutty et al.* [2007] further showed that estimates of tropical emissions in the 1990s differ substantially when the beginning of the simulation (which assumes equilibrium carbon stocks) is placed at 1961, 1981, or 1991. However, a consistent comparison of the effects of these methodological choices on attributed emissions using the same model does not yet exist. Our study fills this gap and shows for historical LULCC that the choices lead to vastly different results. We simulate carbon fluxes due to LULCC since the year 1500 but focus on the consequences of different choices in attribution during a recent time period of 5 years (2008–2012), which is a typical time frame for a UNFCCC commitment period [*UNFCCC*, 2011].

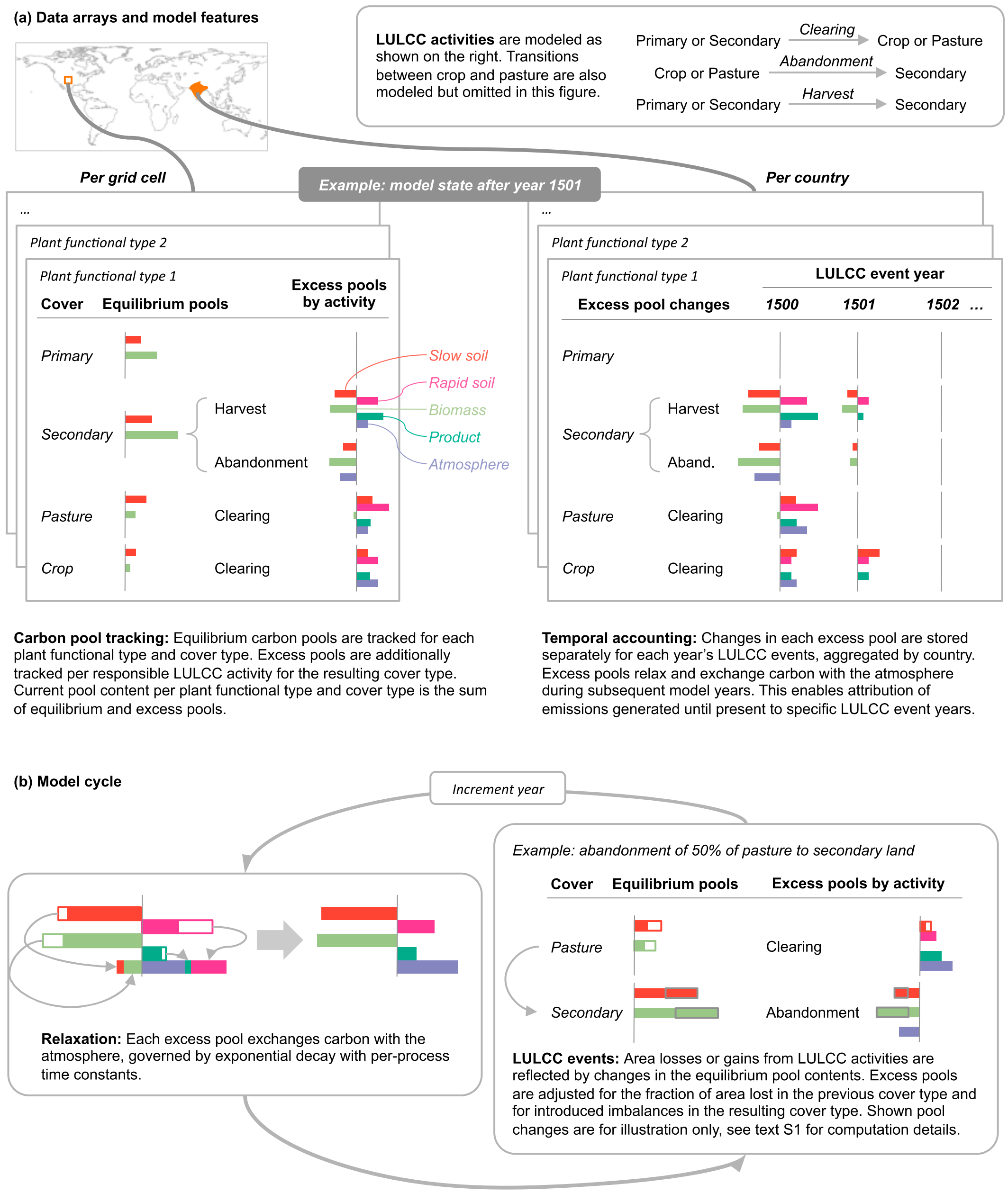

Figure 1. Illustration of the BLUE modeling scheme. (a) Data arrays and model features and (b) model cycle. See Text S1 for details on model implementation.

2. Methods

2.1. BLUE Model

The following is a brief description of the BLUE model. The modeling scheme is illustrated in Figure 1. A detailed model documentation is included in Text S1 in the supporting information.

BLUE largely follows the bookkeeping approach as developed by *Houghton et al.* [1983] and *Houghton* [2003] but adds several features required for our further analysis: the model is spatially explicit (as is the bookkeeping approach by *Reick et al.* [2010], but not the regional model by *Gasser and Ciais* [2013]). It further tracks individual histories of successive LULCC events in each grid cell, including their interactions. Here, with its approach of cumulating excess carbon pools by LULCC activity, as explained below and in Text S1, BLUE is computationally much more efficient than the model by *Reick et al.* [2010], which tracks individual histories by splitting each grid cell into individual plots of land. Unlike these previous approaches, BLUE is capable of tracking the carbon fluxes caused by each year's LULCC events through time (see "temporal accounting" later in this section).

The model runs on a grid of half-degree cells. Land properties and LULCC transitions are prescribed per grid cell. Typical of a bookkeeping model, BLUE tracks the areas undergoing transitions and the types of change and combines these with empirical data on densities of soil and vegetation carbon stocks. Upon a transition, carbon is transferred between pools (including product pools and atmosphere) with prescribed fractions. Response curves for growth and decomposition track subsequent changes in carbon pools. A major modeling challenge is posed in that LULCC transitions generally affect only a fraction of each cell, such that different plots of land within a cell undergo different transition sequences. Explicitly modeling the history of each single plot of land would require a model resolution resolving the typical minimum plot size, which is on the order of 1 ha [*Bruun et al.*, 2006; *Lojka et al.*, 2011]. This is inefficient in terms of computation time and memory. Instead, we adopted a modeling scheme with exponential response curves, which enables accurate representation of multiple LULCC histories within a grid cell using a finite number of carbon pools only. This is made possible by the fact that annual changes from relaxation processes assuming exponential response curves are directly proportional to the "excess" carbon present—the amount of carbon separating a pool's state from its equilibrium. Relaxation fluxes can therefore be computed accurately by accumulating changes in excess pools resulting from successive LULCC events, without storing information about when these events happened. This makes modeling of separate plots of land within a grid cell unnecessary. The BLUE setup thus accurately models legacy effects and process interdependencies, as illustrated further in Figure 2.

The model tracks carbon stocks in a number of discrete "pools" for each combination of (1) cover type (primary land, secondary land, crop and pasture), (2) transition type (i.e., LULCC activity: harvest, clearing to crop, clearing to pasture, and abandonment), (3) pool type (vegetation biomass, soil carbon with rapid or slow relaxation processes, product pools with 1, 10, and 100 year life times, and atmosphere, i.e., emissions), and (4) plant functional type (11 plant functional types are distinguished, see Table S1).

Emissions from each combination of cover type, transition type, pool type, and plant functional type can be extracted separately. For an LULCC transition, the affected cover types and plant functional types are prescribed. However, land of the respective cover type and plant functional type within a grid cell may have undergone different LULCC sequences in the past, and the LULCC transition data set used here [*Hurtt et al.*, 2011] does not specify the history of subgrid cell areas to which new transitions should be applied. The BLUE modeling approach corresponds to distributing each new LULCC event proportionally by area across the different histories present in the cell.

Historical attribution studies require attributing carbon fluxes to specific transition years. For this purpose, we added a "temporal accounting" layer to the model that tracks on a per-country basis (spatially explicit temporal accounting would be too memory intensive) the contribution of each past year's LULCC events to the current year's carbon fluxes. The excess carbon caused by LULCC events of a year is stored for each of the carbon pools defined above, per country. Resulting carbon fluxes in subsequent years are computed by applying exponential response curves. Consecutive LULCC events are also accounted for in the temporal accounting—see Text S1 for details.

Figure 2a shows model output from an exemplary single-point run: a pixel of 0.5° × 0.5°, located at 50°N, 10°E and with potential vegetation of temperate/boreal deciduous broadleaf forest, is initially covered by secondary forest. In model year 10, the land is harvested (remaining secondary land); in year 25, it is cleared with a transition to crop; in year 40, it is abandoned back to secondary land. Each LULCC event affects the entire grid cell. The figure shows the progress of the different carbon pools, as well as emissions attributed to each of the LULCC events. In addition to the modeled legacy emissions, a second set of curves shows emissions for scenarios disregarding LULCC events before or after each of the three events (Figures 2b–2d).

The harvest event depletes vegetation biomass (green curve) and reduces the "slow" soil pool (red curve) stock, while depositing large amounts of dead vegetation and soil biomass in the "rapid" soil pool (pink curve) and adding to the product pools (turquoise curve). Each pool relaxes toward its equilibrium state in the following period. Rapid release of carbon from the soil and product pools causes emissions into the atmosphere (blue curve), which are only partially countered by uptake as biomass regrows and the slow soil pool recovers. The subsequent clearing to crop again lowers carbon in the biomass and slow soil pools, while increasing carbon in the rapid soil and product pools. The clearing event results in biomass and slow soil pools that

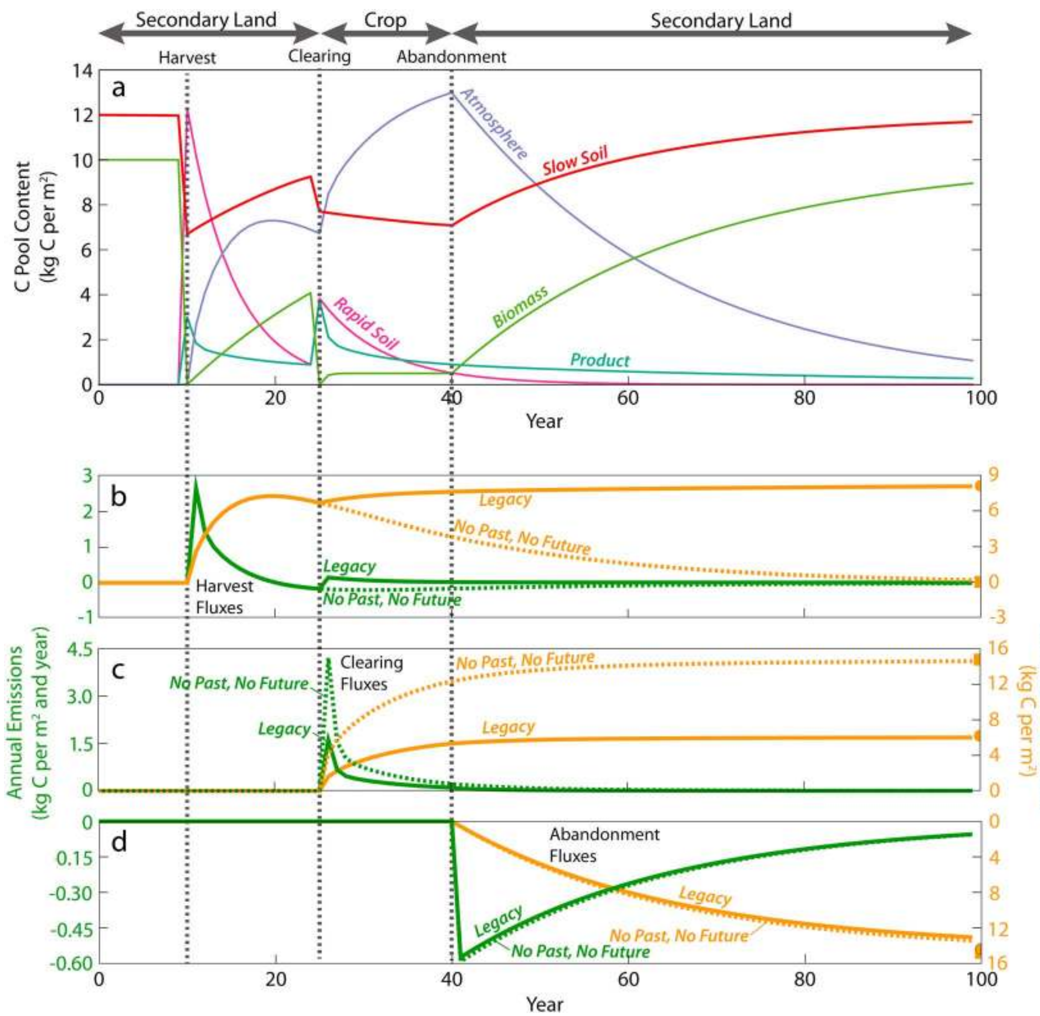

Figure 2. (a) Model output from an exemplary single-point run. Land cover types and transition events are noted at the figure top. Depicted are carbon pool stocks for vegetation biomass (green curve), slow-process soil pool (red curve), rapid-process soil pool (pink curve), product pool (turquoise curve; for display purposes, all three product pools are combined in one curve), and accumulated emissions to the atmosphere (blue curve), plotted over simulation time. (b–d) Annual carbon fluxes (green) and cumulative carbon fluxes (yellow) attributed to each of the three LULCC events, shown for the legacy modeling scheme (Legacy) and for simulations with realistic temporal evolution of carbon stocks but disregarding changes in carbon stocks from LULCC events preceding and following the respective transition (No Past, No Future). The latter set of curves is shown for reference. Dots (for Legacy) and squares (No Past, No Future) on the right vertical axes denote cumulative carbon fluxes reached when running the model until infinity (without additional LULCC events occurring). See text for further details.

are already close to the equilibrium values of cropland, so that subsequent relaxation results in small carbon stock changes.

Inspecting the cumulative carbon fluxes (yellow curves) attributed to the harvest event in Figure 2b, one sees a clear difference between a legacy accounting scheme (solid yellow curve) and one disregarding both past and future LULCC events (dotted yellow curve). In the legacy scheme, the clearing event prevents relaxation of biomass and slow soil carbon pools after harvest to equilibrium values of secondary land, leaving cumulative fluxes attributed to the harvest event. Annual carbon fluxes (green curves) change from carbon uptake to a release at the time of the clearing event: in BLUE, carbon fluxes from the rapid soil and product pools continue to be accounted toward the harvest event but are no longer counteracted by uptake in biomass and slow soil carbon. When disregarding the clearing event, cumulative emissions for the harvest event return to zero as the secondary land completely recovers. Correspondingly, carbon fluxes attributed to the clearing event, Figure 2c, are smaller in a legacy scheme taking into account the reduced biomass and slow soil carbon stocks before clearing, compared to a scheme disregarding prior LULCC events and assuming equilibrium carbon stocks.

The clearing event is followed by abandonment back to secondary land, Figure 2d. At this time, biomass and soil carbon pools have almost relaxed to equilibrium values of cropland. Therefore, carbon fluxes attributed to the abandonment event are similar when modeling with or without taking into account the LULCC history.

The figure illustrates that emissions attributed to an LULCC event depend on the LULCC history, which changes carbon stocks at the time of the event, as well as on subsequent events, which impact relaxation processes. A scheme modeling transitions as instantaneous would attribute to each event the total committed emissions of the event (yellow square dots on right vertical axes in Figures 2b – 2d) in the respective event year, assuming equilibrium carbon stocks before and after the event. Note that we refer to committed fluxes as all future fluxes attributable to the land use activity [*Fearnside*, 1997; *Davis et al.*, 2014], not just future fluxes over a given time horizon [e.g., *Achard et al.*, 2004, computed "committed emissions" as future emissions within 10 or 25 years]. When modeling transitions as instantaneous, prior and subsequent LULCC events have no impact on the events of the current year. In the legacy scheme, by contrast, committed emissions from an event can be computed that take into account prior and subsequent events (yellow round dots). We call these "committed from legacy" fluxes; section 2.3 explains how they are computed.

2.2. Input Data

In the present study, BLUE is driven by the LULCC transition data set by *Hurtt et al.* [2011]. This data set is spatially explicit at half-degree resolution and provides information on subgrid-scale transitions between primary land, secondary land, cropland, and pasture. Primary land is defined as land not under active use at the start of the historical reconstruction. Secondary land is defined as land affected by LULCC at some point in the past and is not allowed to return to primary land. The data set accounts for additional subgrid-scale transitions including shifting cultivation (referred to as "gross transitions" in the following) and wood harvest. It also provides information on the amount of harvested wood. The original data set for the historical period covers the years 1500 to 2005. An update created for the Global Carbon Project/TRENDY [*Le Quéré et al.*, 2014] covers the recent years until 2012. However, this update revised LULCC transitions prior to 2005 and introduced substantial co-occurrence of clearing and abandonment within individual countries for 1990 that are not supported by the original country statistics [*Food and Agricultural Organization (FAO)*, 2014], which leads to an implausible peak of regional and global net LULCC emissions. We therefore rely on the data of *Hurtt et al.* [2011] from 1500 to 2004 and use the Global Carbon Project update only for years 2005 to 2012.

The LULCC transitions are overlain over a map of potential natural vegetation [*Pongratz et al.*, 2008] to split the natural land (primary and secondary) into specific plant functional types. To allocate cropland and pasture in a grid cell, we proportionally reduce all existing natural plant functional types.

Each plant functional type is associated with a set of parameters for (1) carbon stock densities as primary land, secondary land (degraded), and after transformation to cropland or pasture and (2) response curves after transitions (Table S1). These parameters are based on the study by *Houghton et al.* [1983]. While the original response curves were piecewise linear, we approximate these curves exponentially. This allows for the computationally efficient summation of fields with different histories as explained above.

2.3. Simulations

The comparison of different accounting schemes requires several runs of the BLUE model with different setups. We performed three model runs, which, combined with different ways of data postprocessing, result in eight different accounting schemes. The accounting schemes are labeled "#1" to "#8" and are illustrated in Figure 3. Model runs and data processing are described in the following, indicating to which of the eight accounting schemes they apply. The quantitative aspects of Figure 3 are discussed in section 4.

2.3.1. Model Runs

As a first choice, the model can either be run with realistic temporal evolution of carbon stocks in a legacy scheme or by realizing each LULCC event's carbon stock changes instantaneously. To simulate the latter, all process time constants are set to a very small value (here 10^{-12} years).

In the legacy scheme, carbon stocks at the start of the accounting period can have realistic values taken from the LULCC history or may be assumed to be in equilibrium at the start of the period. The former amounts to running the legacy scheme from 1500 on with no further changes. For the latter, process time constants are

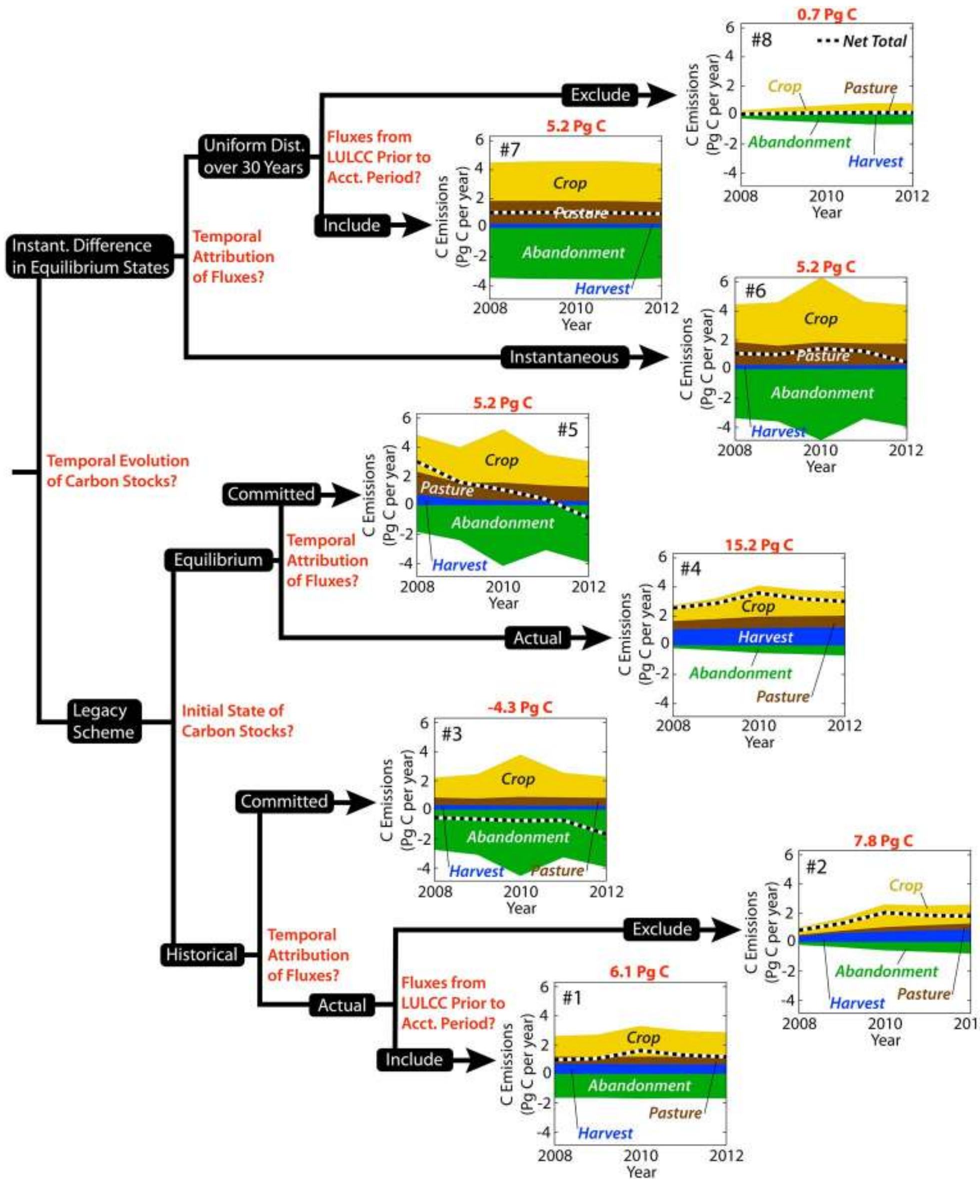

Figure 3. Comparison of eight different methods (labeled #1 to #8) for accounting of the net LULCC flux during the 2008–2012 accounting period. See section 2.3 for simulation setup and section 4 for discussion.

set to 10^{-12} years for the single year preceding the accounting period (2007), to purge any excess carbon and reset the carbon pools to equilibrium values.

A model run with realistic temporal evolution and realistic carbon stocks at the start of the accounting period forms the basis of methods #1, #2, and #3; a run with realistic temporal evolution but equilibrium carbon stocks at the start of the accounting period is used for methods #4 and #5; a run with instantaneous changes is the basis of #6, #7, and #8.

2.3.2. Data Postprocessing—Legacy Model Runs

The next choice is whether to attribute to each year the simulated carbon fluxes occurring in that year or the fluxes committed by transitions occurring in that year. The former is a direct model output and is used in methods #1, #2, and #4. For the latter choice, used in methods #3 and #5, an extra simulation year is appended at the end of the model run in which all process time constants are set to 10^{-12} years. This way, the cumulative carbon fluxes for all time can be computed for each year's events from the temporal accounting layer of the model. Note that these are committed from legacy fluxes, as discussed at the end of section 2.1.

A final choice lies in including or excluding emissions from events prior to the accounting period. These are computed from the temporal accounting layer of the model output by including or excluding the time prior to the accounting period (methods #1 and #2, respectively). This final choice is not relevant in the case of equilibrium carbon stocks at the beginning of the accounting period, as there are no more emissions from LULCC events that occurred prior to the accounting period. When considering committed emissions, these prior LULCC events are naturally excluded from fluxes during the accounting period.

A legacy model with historical carbon stock values, with simulated temporal emissions, and including LULCC fluxes from events preceding the accounting period, i.e., method #1, is considered the most physically realistic and the "default" scheme.

2.3.3. Data Postprocessing—Model Runs With Instantaneous Transitions

The previous paragraph applied to the legacy scheme only. For instantaneous realization of new states, the state of carbon stocks at the beginning of the accounting period is in equilibrium by definition. Fluxes can be attributed instantaneously to the respective simulation years (method #6) or, in a crude model of temporal evolution, be distributed uniformly over a given time span (methods #7 and #8). Here a time frame of 30 years was chosen, independent of carbon pool and land properties. One could envision a slightly more realistic approach that uses different time spans for different pools, plant functional types, or cover types or that uses more complicated temporal attribution curves instead of a uniform distribution. For example, the bookkeeping approach by *Houghton et al.* [1983] uses response curves mimicking typical timescales of biological processes to distribute over time the change in equilibrium carbon stocks that results from an area changing from one type of land use to another. BLUE uses similar response curves but in its default setup (method #1) takes into account that carbon stocks may be out of equilibrium due to earlier LULCC events or may not reach the new equilibrium due to successive LULCC events. In the case of a uniform distribution, one again can choose whether to include or exclude carbon fluxes from LULCC events prior to the accounting period (methods #7 and #8, respectively). In our implementation, uniform distribution is computed by temporal filtering of instantaneous emissions with a shifted boxcar filter, including or excluding years before the accounting period.

2.3.4. Additional Model Runs

Further model runs were carried out for other questions discussed in the paper: to estimate the influence of net versus gross transitions, a model run was performed but with net transitions computed from the LULCC transition data set. In doing this, any clearing and abandonment transitions were accounted against each other (see section 3). For the analysis of interprocess dependencies, the model was run with all harvest transitions during the accounting period switched off. Comparing nonharvest emissions from this run to the default scheme shows the effects of harvest for carbon fluxes of other LULCC activities.

2.4. Summary of the Eight Accounting Methods

Here we summarize the eight accounting schemes and describe their relationship to previously published accounting schemes.

1. Method #1 is the physically most accurate estimate of carbon fluxes occurring during the accounting period and is the "default" output of BLUE. It includes carbon fluxes from LULCC events prior to the accounting period and is computed with a legacy scheme. As this method simulates fluxes as they actually occur, it is used in annual CO_2 budget estimates [e.g., *Le Quéré et al.*, 2014]. This method is the most common approach to determine the net LULCC flux in process-based models as well as the UNFCCC approach for accountability of forest management activities.
2. Method #2 differs from #1 in that carbon fluxes from LULCC events prior to the accounting period are excluded. This method is used by *Ramankutty et al.* [2007] to illustrate the importance of different starting dates in the simulation. It is also the alternative UNFCCC approach for accountability of forest management activities. The UNFCCC decisions [*UNFCCC*, 2012] leave it up to the Parties to include or exclude legacy fluxes from LULCC prior to the accounting period, as long as this choice is made consistently in the simulation including the forestry activity and the reference simulation excluding it. We will show in section 4.1 that the underlying assumption of effects of certain LULCC activities (e.g., wood harvest prior to the accounting period) on others (e.g., clearing during the accounting period) canceling in scenario and reference simulation does not hold due to dependencies of LULCC activities. This means that method #2, as the difference of a scenario (a simulation that includes a specific accountable activity) and a reference simulation (without the accountable activity) that both include LULCC prior to the accounting period, gives different results than a direct simulation of only LULCC during the period.

Table 1. Net LULCC Flux Estimates of BLUE and Their Split-Up Into LULCC Activities

BLUE Carbon Flux in Petagram of C by Land Use Activity	1500–1849	1850–2012
Cumulative net LULCC flux	113	269
— of which clearing for cropland	114	211
— of which clearing for pasture	86	133
— of which wood harvest (net flux)	20	63
— of which abandonment	−106	−138

3. Method #3 quantifies committed carbon fluxes from the legacy scheme as discussed at the end of section 2.1. This method is not used in the literature but could be useful to extend the approach of method #6 to account for known LULCC successions within a given time span.
4. Method #4 resets the carbon pools to equilibrium levels before the start of the accounting period. This method has often been used in combination with remote sensing data, which exist only for a relatively recent period of time and prescribe equilibrium carbon stocks for the vegetation distribution at the beginning of the sensor's era [e.g., *DeFries et al.*, 2002a].
5. Method #5 quantifies committed emissions from #4 and is thus computed in the same way as #3 is computed from #1. This method is not used in the literature and only discussed here for completion.
6. Method #6 represents what has been described in the introduction as the simplest of all schemes in terms of required input data and methodological complexity, starting from equilibrium carbon stocks, instantaneously realizing new states, and attributing all future fluxes to the point in time that the LULCC event occurs. For the difference between this scheme and the committed from legacy fluxes of methods #3 and #5, see the discussion at the end of section 2.1. Besides method #1, this method has often been used to estimate the net LULCC flux, e.g., by *Harris et al.* [2012] and, as committed flux, by *Fearnside* [1997].
7. Method #7 differs from #6 in that the carbon fluxes are distributed uniformly over a given time horizon, in our case over 30 years. Depicted fluxes therefore include effects of LULCC preceding the accounting period by up to 30 years. Using more realistic response curves instead of a uniform distribution, this method (or method #8, depending on the starting date) is used in the bookkeeping model by *Houghton et al.* [1983] and subsequent studies applying this model [e.g., *DeFries et al.*, 2002b; *Achard et al.*, 2004; *Erb et al.*, 2013].
8. Method #8 differs from #7 in that it excludes LULCC prior to the accounting period (in the same way as #2 differs from #1). This scheme would be the second easiest modeling approach after #6, as it requires only the additional parameter of a time horizon but does not require knowledge of history of LULCC prior to the accounting period. This method is used to account for foreseeable successive LULCC types [see *Davis et al.*, 2014]. Product carbon footprint standards suggest methods #7 and #8 depending on availability of data [*The Greenhouse Gas Protocol*, 2011; *British Standards Institution*, 2011].

3. Evaluation of Simulated Carbon Stocks and Fluxes

The net LULCC flux is the most uncertain component of the global carbon budget [*Houghton et al.*, 2012]. Although the spread in independent estimates can be substantially reduced by comparing only estimates accounting for the same processes [*Houghton et al.*, 2012; *Wilkenskjeld et al.*, 2014] and the same definition of which component fluxes and carbon cycle feedbacks to include [*Pongratz et al.*, 2014], best guesses associate the average flux 2002–2012 (about 0.8 Pg C/year) with an uncertainty range of ±0.5 Pg C [*Le Quéré et al.*, 2013]. The average flux estimated by our BLUE model over the same time period is 1.2 Pg C, at the high end of this uncertainty range; see Figure 4 and Table 1. As found in previous studies [*Hurtt et al.*, 2011; *Houghton et al.*, 2012], gross sink and source fluxes are substantially offsetting each other. In our global estimates, carbon uptake following abandonment compensates for roughly half of the clearing emissions and net emissions from wood harvest.

Comparing to estimates by other models over longer timescales in the past, emissions estimated by our model are again high, but the spread across studies is large; see Figure 5 and Table 2. Three factors explain our high estimates:

1. We chose the LULCC data set by *Hurtt et al.* [2011] due to its process comprehensiveness, including subgrid-scale (gross) transitions and wood harvest. By contrast, the published studies with the lowest estimates [most studies cited by *Houghton et al.*, 2012; *Jain et al.*, 2013] neglect the effects of gross transitions,

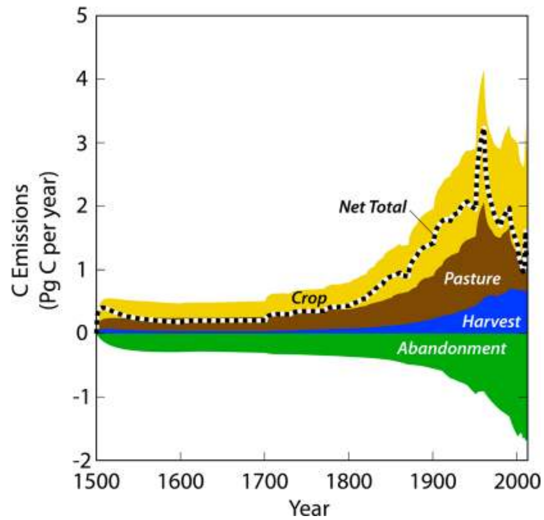

Figure 4. Net LULCC flux estimates of BLUE and their split-up into LULCC activities. See Figure S1 for a map of the cumulative net flux.

the inclusion of which would increase the studies' estimates by 20–60% [*Stocker et al.*, 2014; *Wilkenskjeld et al.*, 2014] and thus result in estimates greater than those from our model. Many earlier studies also disregard wood harvest, which contributes 6–13% [*Wilkenskjeld et al.*, 2014; *Stocker et al.*, 2014] (net emissions of harvest and regrowth) to total emissions.

2. The specific choice of using the carbon density estimates by *Houghton et al.* [1983] produces global vegetation and soil carbon stocks that are within other models' estimates and close to observation-based reference data (Figure 6) but leads to rather high carbon losses over time. These losses would be lower (224 Pg C as compared to 259 Pg C for vegetation carbon and 45 Pg C as compared to 109 Pg C for soil carbon) if we used the modification of Houghton's carbon density data set by *Reick et al.* [2010] (Table S1). This modification assigns, in comparison to the original data set, generally lower vegetation densities to natural vegetation, less degradation from the primary to secondary states, and a smaller difference in carbon densities between natural and managed land.

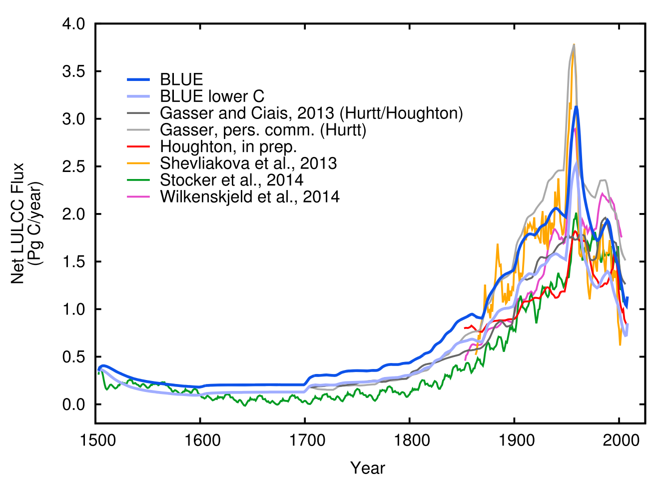

Figure 5. Comparison of the net LULCC flux simulated by BLUE to other recent studies; only studies including gross transitions and wood harvest are included. A 5 year running mean is applied. The studies by *Gasser and Ciais* [2013], Gasser (personal communication), and Houghton (personal communication) apply bookkeeping models on the regional level, and those by *Shevliakova et al.* [2013], *Stocker et al.* [2014], and *Wilkenskjeld et al.* [2014] process-based models. The study by *Gasser and Ciais* [2013] applied the data set by *Hurtt et al.* [2011] but scaled transitions down to the regional values by *Houghton et al.* [2012], while the original data set was kept in the estimate by Gasser (personal communication).

Table 2. Comparison to Other Recent Studies (Modified From [*Schneck et al.*, 2015])[a]

Reference	Time Period	LULCC Data Set	LULCC Implementation	Cumulative Net LULCC Flux (Pg C)
This study	1850–2005	*Hurtt et al.* [2011]	GT, WH, AProp	261
Houghton et al. [2012] multimodel range	1920–1999	various	various	72–115
Houghton (personal communication)	1850–2010	FAO/FRA (on regional basis)	GT, WH, APasture	182
Shevliakova et al. [2013]	1850–2005	*Hurtt et al.* [2011]	GT, WH, AProp	210
Jain et al. [2013]	1900–2005	various	NT, WH, AProp	160–178
Stocker et al. [2014]	1850–2004	*Hurtt et al.* [2011]	GT, WH, AProp	171
Wilkenskjeld et al. [2014]	1850–2005	*Hurtt et al.* [2011]	GT, WH, APasture	225
Gasser and Ciais [2013], Hurtt	1850–2005	*Hurtt et al.* [2011] (on regional basis)	GT, WH, AProp	294
Gasser and Ciais [2013], Hurtt/Houghton	1850–2005	*Hurtt et al.* [2011] (on regional basis) transitions scaled to Houghton data set	GT, WH, AProp	203

[a]Implementation choices refer to gross (subgrid-scale) versus net LULCC transitions (GT versus NT), if wood harvest is included (WH) and if agricultural land is taken proportionally from natural vegetation types (AProp) or if pasture is preferentially taken from grasslands (APasture). Where possible, we report numbers for 1850–2005 for better comparison, although individual studies may have comprised a longer time period.

3. In order to simulate agricultural land in grid cells that contain a mixture of plant functional types, BLUE and most other studies proportionally reduce all vegetation types. Some studies, however, assume that pasture reduces only grassland if there is sufficient grassland in the grid cell [e.g., *Houghton et al.*, 1983; *Wilkenskjeld et al.*, 2014; *Schneck et al.*, 2015]. *Reick et al.* [2013] showed that such preferential allocation of pasture on grassland substantially reduces the amount of simulated cleared forest cover, thereby reducing emissions.

We performed additional simulations to quantify the effect of gross LULCC transitions. When subgrid-scale LULCC, such as shifting cultivation, and wood harvest are accounted for, substantially more area is estimated to be affected by LULCC than when only net transitions are accounted for [*Hurtt et al.*, 2006, 2011]. As a result, there are important implications for carbon in accounting for these processes. *Shevliakova et al.* [2009] and *Hurtt et al.* [2011] quantified the effects of shifting cultivation and wood harvest for carbon using process-based and empirically based models, respectively. Here, we study the contribution of gross transitions to the total (vegetation and soil carbon) net LULCC flux. Two studies quantifying the same effect are *Stocker et al.* [2014] and *Wilkenskjeld et al.* [2014]; BLUE falls between these studies' estimates (Table 3). In one simulation, we let abandonment (to secondary land) compensate for clearing of secondary land only, and vice versa. In this case, the influence of gross LULCC transitions is small and stems from temporarily lowered

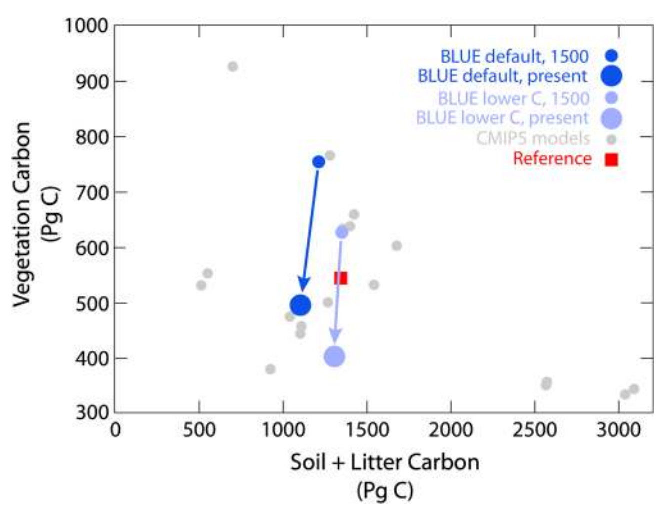

Figure 6. Comparison of vegetation and soil carbon stocks simulated by BLUE to those simulated by Coupled Model Intercomparison Project 5 (CMIP5) models and reference data sets [taken from *Anav et al.*, 2013]. Default values of BLUE for carbon densities are based on *Houghton et al.* [1983], and lower carbon densities based on *Reick et al.* [2010]. Stocks refer to present day (CMIP5 and BLUE output is averaged over 1986–2005); additionally, initial carbon stocks for BLUE are shown.

Table 3. Comparison of the Net LULCC Flux Simulated for Gross LULCC Transitions and for Net LULCC Transitions[a]

Reference	Time period	Net LULCC Flux (Pg C) Gross Transitions	Net Transitions		Contribution of Gross Transitions, Pg C (%)
Stocker et al. [2014]	1850–2004	171		146	25 (15%)
Wilkenskjeld et al. [2014]	1850–2005	225		140	85 (38%)
This study	1500–2012	382	secondary land only	374	8.5 (2%)
This study	1500–2012	382	primary land first	290	92.4 (24%)
This study	1500–2012	382	primary land last	296	85.8 (22%)

[a]See text for the explanation of the three different methods of calculating net transitions from gross transitions tested in our study. The last column gives the difference between the net LULCC flux estimates for gross and net transitions (absolute in Pg C and relative to the net LULCC flux for gross transitions).

carbon stocks due to more frequent transitions. In two additional simulations, we let abandonment compensate for clearing of both primary and secondary land, using clearing of primary land first or last, respectively, to compensate for abandonment. Here, the influence of gross transitions is much larger (whether one uses primary land first or last for the compensation has little influence). This is because of degradation of primary land caused by clearing and subsequent abandonment to secondary land, which has lower equilibrium carbon stocks. This indicates that, at least in BLUE, the main effect of accounting for gross transitions is not the fact that carbon densities are lower due to more frequent transitions on secondary land, but the fact that more primary land is transformed. The succession from primary to secondary land is frequent in the data set by *Hurtt et al.* [2011], because the authors used primary land as a priority for land conversion on all continents except Europe and Asia.

4. Relevance of Methodological Choices for LULCC Carbon Flux Accounting

As discussed above, four key methodological choices for quantifying emissions within a given time frame or accounting period are analyzed: (1) on simulating the temporal evolution of carbon stocks, (2) on the initial state of carbon stocks, (3) on the temporal attribution of carbon fluxes, and (4) on accounting for LULCC prior to the accounting period. Figure 3 compares the eight methods for an accounting period spanning 2008–2012 of our historical simulation, based on the simulations described in section 2.3 (figure shows global emissions; see Figure S2 for regional breakdown). The eight methods differ vastly in terms of temporal evolution of the net LULCC flux and in terms of cumulative emissions: over the 5 year accounting period, global cumulative emissions range from an uptake of 4.3 Pg C to a release of 15.2 Pg C. Maximum carbon release (from clearing and wood harvest) over the period ranges from 1 to 6 Pg C/year across methods, maximum uptake (from abandonment) from 1 to 5 Pg C/year.

In the following, we analyze and discuss the relevance of each of the key choices of accounting, with the four levels in Figure 3 covered from left to right by sections 4.1 to 4.4. For each aspect, we are able to pick and compare two methods that differ only with respect to the analyzed choice.

4.1. Temporal Evolution of Carbon Stocks

Our default method of calculating carbon fluxes is the legacy scheme, which quantifies the occurrence of delayed fluxes as they occur in reality. This makes the legacy scheme the only applicable method for annual carbon budget estimates [e.g., *Le Quéré et al.*, 2013]. The legacy methods contrast with those assuming instantaneous realization of new states, in particular with method #6, which does not assume any spread of carbon fluxes over time unlike methods #7 and #8. The resulting conceptual difference between a physically correct attribution to a specific point in time and the attribution to the time the LULCC event occurs will be further discussed in section 4.3 on actual versus committed schemes. Here, however, we discuss more subtle effects that results from the legacy scheme's physical accuracy: that successive LULCC events influence each others' carbon stock response by redistributing carbon flux potentials.

The legacy scheme takes into account that LULCC events occur in a sequence, so that delayed carbon fluxes from one event may be prevented by a subsequent event happening on the same plot of land. The contrasting choice is to realize any changes in carbon stocks instantaneously and thus treat subsequent LULCC events as independent of each other. This difference is most clearly illustrated by comparing methods #5 and #6; method #5 applies a full legacy scheme but otherwise imitates method #6: Both methods assume that car-

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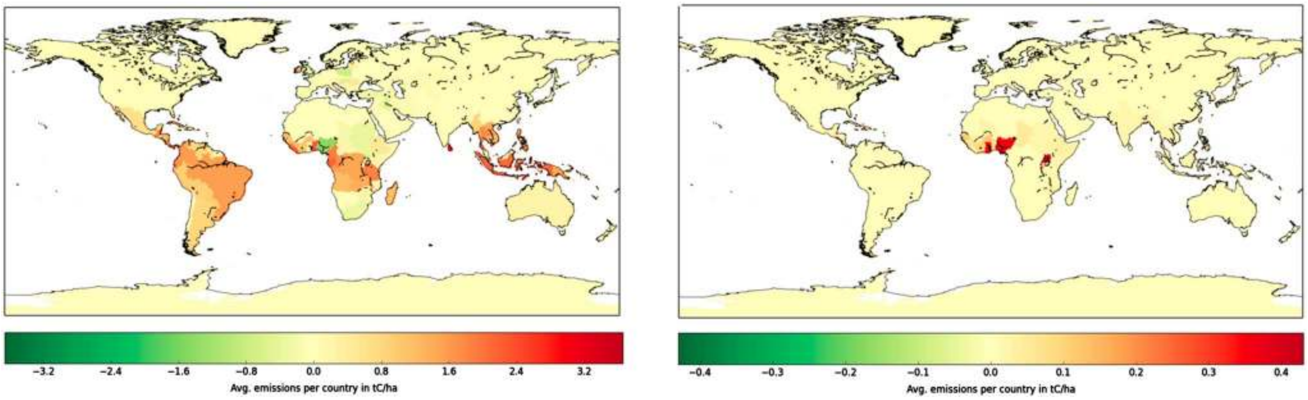

Figure 7. (left) Net LULCC flux from abandonment and clearing for cropland or pasture during 2008–2012 for a simulation including wood harvest. (right) Difference in net LULCC flux for a comparable simulation excluding wood harvest.

bon stocks are in equilibrium when entering the accounting period and attribute emissions to the year the LULCC event occurs. Methods #5 and #6 result in the same cumulative emissions because they start from the same state and end with the end of our simulation, i.e., no subsequent LULCC occurs that could influence carbon fluxes during the accounting period. However, the temporal evolution of fluxes as well as the relative importance of LULCC activities differs between the two methods: land abandoned at the beginning of the accounting period stands a high chance of being put under management again within the accounting period, partially preventing carbon uptake in method #5 and thus roughly doubling net emissions in the beginning of the accounting period as compared to method #6; in other words, the uptake potential of abandonment is redistributed to the successive clearing event, which is then attributed lower net emissions. A similar argument applies to wood harvest. Method #5, however, has lower emissions from clearing toward the end of the accounting period than #6, because wood harvest or an earlier clearing-abandonment sequence has lowered carbon stocks in some areas undergoing subsequent clearing. This is not the case for method #6 because regrowth after harvest is realized instantaneously.

That successive LULCC events influence each other with respect to their carbon fluxes also implies that determining the effects of one LULCC activity depends on which other activities are included in the simulation. For example, results for the carbon fluxes associated with wood harvest differ between simulations of forestry in combination with other LULCC activities and simulations of only forestry (Figure 7). The most extreme case, in relative terms, in our example illustrating the dependency of LULCC activities within the accounting period is Nigeria: here clearing and abandonment cause a total of 0.13 Pg C to be taken up during the accounting period when harvest activities occur in parallel during the accounting period (method #1), compared to 0.10 Pg C taken up (26% less) when no wood harvest is simulated during the accounting period. Therefore, a specification of the approach is required, e.g., in the UNFCCC protocols, to account for the interdependency of LULCC activities in a consistent way of either including or excluding all but the analyzed activity.

4.2. Initial State of Carbon Stocks

The methods assuming instantaneous realization of new states automatically assume that carbon stocks are in equilibrium whenever an LULCC event occurs. Different choices, however, can be made in the legacy scheme. Sensible choices of the carbon stocks when entering a given time period are to derive them from a transient simulation or to assume that carbon stocks are in equilibrium with the existing vegetation distribution when entering the accounting period. Figure 8 shows the difference in vegetation and soil carbon pools prior to the beginning of our accounting period in 2008, with substantially reduced vegetation carbon stocks as compared to equilibrium values. Soil carbon stocks are comparable on global average. They may regionally be even higher than their equilibrium values because clearing and wood harvest add aboveground biomass as litter to the soil pools or because of recent abandonment. (Note that in our default parameter set used for Figure 8, crop and pasture always have lower or the same soil carbon densities as the respective natural vegetation, while the parameter set by *Reick et al.* [2010] would allow for an increase in soil carbon densities with transformation to pasture).

Comparing methods #3 and #5 (similarly, #2 and #4) illustrates the effect of which initial state of carbon stocks is assumed at the beginning of the accounting period and shows that this choice is crucially important.

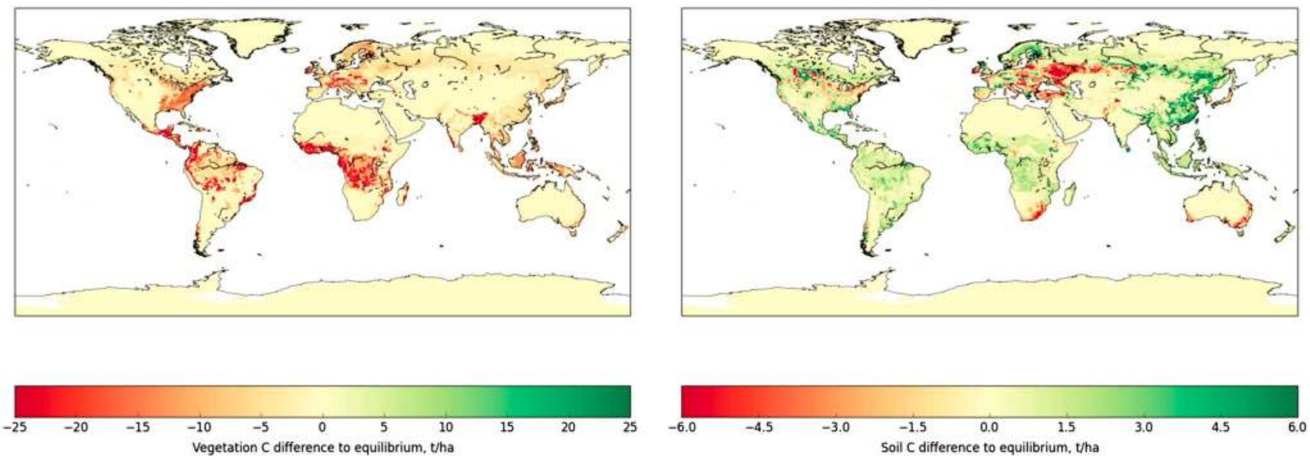

Figure 8. Difference in carbon stocks to equilibrium values in 2007 for (left) vegetation carbon and (right) soil carbon.

Methods #3 and #5 both quantify committed emissions from the legacy scheme. However, starting from equilibrium carbon pools leads to 5.2 Pg C cumulative emissions in #5 over the accounting period, an estimate in the middle of the eight accounting choices investigated here. Method #3, by contrast, is the only method that leads to a cumulative uptake; with 4.3 Pg C, it is substantial. The key effect responsible for the much lower net emissions when starting from realistic states of carbon stocks are lower emissions from clearing due to smaller estimates of standing biomass.

4.3. Temporal Attribution of Emissions

Section 4.1 has treated the subtle effects of redistribution of carbon fluxes among successive LULCC events or activities. Here we return to the more obvious distinction of actual versus committed fluxes with respect to when in time the fluxes caused by an LULCC event are counted. The concept of committed emissions counts all carbon fluxes caused by a specific LULCC event independently of whether they occur instantaneously or as delayed flux at some point in the future. As discussed in the introduction, this concept has been widely applied, in particular in the remote sensing community [e.g., *Fearnside*, 1997; *Harris et al.*, 2012], because it requires little further input: information is needed only on equilibrium carbon stocks of the initial and target vegetation distribution, as well as on the change in vegetation distribution caused by the LULCC event, independent of any history in LULCC. This information is much better constrained by observational data than the processes and ranges of parameters describing the temporal response of delayed fluxes required to simulate actual emissions at each point in time. The committed emissions concept therefore provides a way of comparing regions and time periods independent of many uncertain parameters. Note that this applies to the simplest committed approach, in which the time horizon over which to integrate carbon fluxes is long enough such that all delayed fluxes have ceased at the end and in which the dependency of successive LULCC events is ignored—in all other cases, a legacy approach is required. However, the concepts of actual and committed fluxes have different intended uses, with the committed concept being useful in particular for comparison of the overall impact of different LULCC with each other and with other human activities such as the burning of fossil fuels [*Fearnside*, 1997].

Comparison of method #2 with #3 and comparison of method #4 with #5 isolate the difference between actual and committed carbon fluxes. All four methods include only carbon fluxes attributable to LULCC during the accounting period. Compared to the other choices discussed here, committed versus actual attribution of the net LULCC flux has the largest effect on cumulative emissions in our example, with a difference of 12.0 Pg C under historical carbon stocks and 10.0 Pg C starting from equilibrium carbon stocks. The key reason lies in the asymmetry in timescales of regrowth and decomposition: the timescales for vegetation regrowth are generally slower than those for decomposition after clearing and wood harvest (which include fast processes such as burning and use of wood in short-lived products). Therefore, there is a larger discrepancy between actual and committed carbon fluxes from abandonment events during the accounting period than for fluxes by clearing and wood harvest—Figure 3 shows the smaller uptake by regrowth in the actual fluxes (methods #2 and #4). This effect is emphasized in our example in two ways: (1) by the used LULCC scenario—unlike data sets that account for vegetation states only, the LULCC data by *Hurtt et al.* [2011] account for subgrid-scale (gross) transitions by shifting cultivation, which continuously creates large areas of abandonment; and (2) by the relatively short time horizon of 5 years, reflecting a typical Kyoto Protocol accounting period. The identified large difference between actual and committed fluxes is in line with previous studies that investigated tropical deforestation [*Ramankutty et al.*, 2007].

As an alternative to applying a legacy scheme, it may be useful for some applications to keep the simple scheme of instantaneous realization of new states but nevertheless account to some extent for the asymmetry in timescales for decomposition and regrowth. Distributing instantaneous emissions uniformly in time over a chosen time horizon has thus been suggested as an alternative method [*Davis et al.*, 2014], shown by methods #7 and #8 for a 30 year time frame. Note that cumulative emissions for methods #6 and #7 are similar only by coincidence and differ when analyzing geographic regions separately (Figure S2).

4.4. Accounting for Fluxes From LULCC Events Prior to the Accounting Period

The last choice investigated here refers to the inclusion or exclusion of carbon fluxes that occur during the accounting period but are caused by LULCC prior to the accounting period. The choice for one or the other approach is driven by whether attribution should be based on the point of time when the carbon fluxes occur or when the LULCC causing them occurs. Political considerations usually aim at attributing to specific LULCC events [*UNFCCC*, 2012] and thus require us to exclude fluxes caused by LULCC events prior to the accounting period, either by directly simulating only LULCC during the accounting period or by differencing to a reference scenario that quantifies delayed emissions from earlier LULCC (although, as we have discussed in section 4.1, the two methods are not equivalent). By contrast, studies quantifying the annual carbon budget [e.g., *Le Quéré et al.*, 2013] need to account for all actually occurring carbon fluxes.

Comparing methods #1 and #2 illustrates the difference between including and excluding fluxes from LULCC that occurred prior to the accounting period in the legacy scheme, and comparing methods #7 and #8 illustrates the same difference under instantaneous realization of new states with uniform temporal distribution of fluxes. The most striking difference lies in smaller fluxes at the beginning of the accounting period in the schemes excluding emissions from LULCC events that preceded the accounting period. Further, a seemingly counterintuitive result arises with respect to the cumulative net LULCC flux over the accounting period: although global LULCC historically has always created a carbon flux that is positive into the atmosphere, i.e., net emissions, cumulative emissions over the accounting period are smaller when fluxes from LULCC events prior to the accounting period are excluded than when they are included in the accounting. To explain this, we turn again to the asymmetry in timescales of regrowth and decomposition. LULCC prior to the accounting period thus contributes, relative to each other, less emissions from harvest and clearing and more uptake from abandonment during the accounting period. This effect is seen clearly in regions with decreasing deforestation rates before the accounting period and/or strong abandonment due to shifting cultivation (such as Latin America and tropical Africa), but not such of increasing clearing rates (such as Southeast Asia; see Figure S2).

A legacy scheme approach had been applied by *Pongratz and Caldeira* [2012] to highlight the importance of a clear definition of the accounting period, showing that a substantial part of carbon fluxes from preindustrial LULCC (pre-1850) has been released during the industrial era. Results for the approach assuming instantaneous realization of new states are highly dependent on the time frame over which carbon fluxes are spread. At constant LULCC rates, results from method #7 are independent of the choice of time horizon, while cumulative fluxes in the accounting period increase with a decreasing time horizon in method #8.

5. Summary and Conclusion

We have presented a computationally efficient bookkeeping model for estimating carbon fluxes associated with LULCC (Bookkeeping of Land Use Emissions, BLUE). Based on the bookkeeping approach originally developed by *Houghton et al.* [1983], the new model applies the LULCC transition data set of *Hurtt et al.* [2011] to simulate carbon stocks and fluxes on a spatially explicit basis and in a full legacy modeling scheme. BLUE accounts for gross transitions, which are important to represent subgrid-scale LULCC such as shifting cultivation, includes wood harvest as a LULCC activity, and is equipped with a “temporal accounting” layer that allows for tracking, on a per-country basis, the contribution of each past year’s LULCC events to the current year’s carbon fluxes. The resulting estimates of the global net LULCC flux are at the high end of but within the range of numbers published for several process-based and bookkeeping models.

The unique features of BLUE have allowed us to compare several different methods for attributing carbon fluxes to specific LULCC activities during a commitment period for a Kyoto-like protocol. Here we compare results from eight distinct methods that reflect permutations of four methodological choices; this is the first such comparison that uses a consistent modeling framework. The first choice relates to simulating the temporal evolution of carbon stocks in a legacy scheme (with a physically accurate representation of the distribution of delayed carbon fluxes in time) as compared to instantaneously realizing new states of carbon stocks after an LULCC transition. Only the legacy scheme represents the redistribution of carbon fluxes in a succession of LULCC events and the interdependency of carbon fluxes from different LULCC activities. The second choice concerns the modeling of the initial state of carbon stocks at the beginning of the accounting period (equilibrium versus historical). The lower values for vegetation carbon starting from the historical, transient, state leads to less emissions from clearing. The third choice relates to the temporal attribution of carbon fluxes. A key aspect here is the asymmetry in timescales between decomposition (faster) and regrowth processes (slower) in combination with the historical evolution of globally increasing clearing of natural vegetation. This leads to lower net emissions in the approach of committed fluxes as compared to actual fluxes. The fourth choice is whether or not to include emissions from LULCC events that occurred prior to the accounting period in the accounting. Again due to the asymmetry of decomposition and regrowth, including carbon fluxes from LULCC that occurred prior to the accounting period leads to less emissions during the accounting period.

The key aim of this study was not the accurate attribution of carbon fluxes to LULCC activities for a specific accounting protocol—the time period used to illustrate the eight different methods was typical in length for a Kyoto Protocol accounting period but arbitrarily chosen in time. Instead, our study highlights the sensitivity of attributed emissions to the methodological choices made by analysts and explains the processes underlying different results. We find complex interactions between carbon fluxes of different LULCC activities and events and that estimates of the net LULCC flux are quite sensitive to each of the methodological choices we examined, with a range from −4 to +15 Pg C for the global net LULCC flux over the exemplary 5 year accounting period as well as substantially different temporal evolutions of carbon fluxes. While we illustrate the consequences of key choices on the quantification of carbon fluxes, the decision of what method to use depends on a study's purpose. Applications aimed at attributing emissions to specific LULCC activities may benefit from the committed approach and from excluding carbon fluxes related to LULCC events that occurred prior to the accounting period. By contrast, flux estimates for carbon budget analysis require simulation of the actual fluxes and therefore must include fluxes related to these prior LULCC events if they affect emissions during the accounting period. For many applications, simple schemes that are less dependent on parameters and their associated uncertainties by instantaneously realizing the new state after a LULCC transition are advantageous. But regardless of which method is used and why, our findings show that it is crucial to clearly define the method used in order to ensure consistency and comparability across studies. Although critical, such methodological clarity has been lacking in the past.

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