Simulated carbon emissions from land-use change are substantially enhanced by accounting for agricultural management

T A M Pugh 1, A Arneth 1, S Olin 2, A Ahlström 2, A D Bayer 1, K Klein Goldewijk 1,5, M Lindeskog 3 and G Schurgers 1,6

1 Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research-Atmospheric Environmental Research (IMK-IFU), Kreuzackerbahnstraße 19, 82467 Garmisch-Partenkirchen, Germany
2 Department of Physical Geographical and Ecosystem Science, Lund University, SE-223 62 Lund, Sweden
3 Department of Earth System Science, School of Earth, Energy and Environmental Sciences, Stanford University, Stanford, CA 94305, USA
4 Utrecht University, PO Box 80.115, 3508 TC Utrecht, The Netherlands
5 PBL Netherlands Environmental Assessment Agency, PO Box 303, Bilthoven, The Netherlands
6 University of Copenhagen, 1350 Copenhagen, Denmark

E-mail: almut.arneth@kit.edu

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Abstract
It is over three decades since a large terrestrial carbon sink ($S_T$) was first reported. The magnitude of the net sink is now relatively well known, and its importance for dampening atmospheric CO$_2$ accumulation, and hence climate change, widely recognised. But the contributions of underlying processes are not well defined, particularly the role of emissions from land-use change ($E_{\text{LUC}}$) versus the biospheric carbon uptake ($S_L$; $S_T = S_L - E_{\text{LUC}}$). One key aspect of the interplay of $E_{\text{LUC}}$ and $S_L$ is the role of agricultural processes in land-use change emissions, which has not yet been clearly quantified at the global scale. Here we assess the effect of representing agricultural land management in a dynamic global vegetation model. Accounting for harvest, grazing and tillage resulted in cumulative $E_{\text{LUC}}$ since 1850 ca. 70% larger than in simulations ignoring these processes, but also changed the timescale over which these emissions occurred and led to underestimations of the carbon sequestered by possible future reforestation actions. The vast majority of Earth system models in the recent IPCC Fifth Assessment Report omit these processes, suggesting either an overestimation in their present-day $S_T$, or an underestimation of $S_L$, of up to 1.0 Pg C a$^{-1}$. Management processes influencing crop productivity per se are important for food supply, but were found to have little influence on $E_{\text{LUC}}$.

1. Introduction
In the three decades since a large terrestrial carbon sink ($S_T$) was first reported (Broecker et al 1979), its net size in the multi-annual mean is now relatively well known, based primarily on the residual of the global carbon budget equation (Ciais et al 2013, Le Quéré et al 2014):

$$S_T = S_L - E_{\text{LUC}} = E_{\text{FF}} - S_O - \frac{d[\text{CO}_2]}{dt}\delta_{\text{CO}_2},$$

where $[\text{CO}_2]$ is the atmospheric CO$_2$ mixing ratio, $S_O$ is the oceanic CO$_2$ sink, $E_{\text{FF}}$ is anthropogenic fossil fuel and cement emissions and $\delta_{\text{CO}_2}$ is a conversion ratio for CO$_2$ from ppmv to mass. Budget calculations of $S_T$ are also supported by isotopic observations (Joos et al 1999). However, the partitioning of $S_T$ into increased biospheric carbon uptake resulting from environmental change ($S_L$), versus emissions from land-use change ($E_{\text{LUC}}$) remains poorly constrained (Houghton et al 2012, Ciais et al 2013, Le Quéré et al 2014). As there are no direct observations of either $S_L$ or $E_{\text{LUC}}$, these terms can only be modelled, either directly for each term, or indirectly by modelling the other term and solving the carbon budget equation. Dynamic Global Vegetation Models
(DGVMs) often simulate an \( S_P \) of about the right magnitude (Le Quéré et al 2014), giving increased confidence in our understanding of the response of the terrestrial biosphere to environmental change. However, if these models were to miscalculate \( E_{\text{LUC}} \) then that implies they would also miscalculate \( S_L \), reducing confidence in their efficacy. For Earth system models (ESMs) used in global climate projections the situation is less clear-cut, with simulated \( S_L \) over the recent historical period often differing substantially from global budget estimates (Anav et al 2013, Hoffman et al 2013). In this letter we address the extent to which agricultural processes may modify land-use change emissions, which has thus far not been clearly quantified at the global scale.

One third of the global land area has been converted to croplands and pasture (Klein Goldewijk et al 2011), releasing an estimated 205 ± 70 Pg C to the atmosphere since 1750, around one third of the cumulative anthropogenic \( \text{CO}_2 \) emissions (Le Quéré et al 2014). Conversions from natural vegetation to agriculture generally result in an observed long-term decrease in soil carbon stocks, whilst conversions to natural grasslands generally see an increase (Guo and Gifford 2002). This effect has, at least partially, been implicitly captured in bookkeeping models of land-use change (Houghton et al 2012), due to their use of observed carbon densities from individual land-use categories. More detailed descriptions of agriculture are starting to make their way into dynamic global vegetation models (DGVMs) (Le Quéré et al 2014, Levis et al 2014). In contrast, representations of agriculture which go beyond the prevailing paradigm of treating crops as natural grasses were absent in the vast majority of ESMs contributing to the latest IPCC report (table S1) (Gias et al 2013). Thus far, the importance of agricultural processes for \( E_{\text{LUC}} \) has not been quantified, nor the most important processes identified. We apply here the DGVM LPJ-GUESS to identify the effect, globally, of agricultural processes for \( E_{\text{LUC}} \) and consequently on \( S_L \). The model adopts the crop functional type (CFT) approach (Bondeau et al 2007, Lindeskog et al 2013), and incorporates management, such as sowing, harvesting, grazing, irrigation, tillage, residue removal, and vegetation recovery after abandonment. For the first time we (i) quantify the effects of inclusion of agriculture-specific processes and management options on historical \( E_{\text{LUC}} \), and (ii) provide a global-scale simulation of the future land-use change emissions including a rigorous treatment of agriculture.

### 2. Methods

We compute \( E_{\text{LUC}} \) using a detailed treatment of crops and pasture, and their management (CPManaged). These results are compared with those from a ‘classic’ representation of land-use change, i.e. using our model to simulate crops using the ‘grass’ plant functional types without additional processes such as harvest or grazing (GnoHarvest), as often used in previous calculations of \( E_{\text{LUC}} \) (Strassmann et al 2008, Ahlström et al 2012, Betts et al 2013), and with a ‘classic-plus’ representation which includes a simple treatment of harvest and grazing (GHarvest) (Piao et al 2009).

#### 2.1. Model setup

We followed the LPJ-GUESS setup for land-use change and agricultural lands described in detail in Lindeskog et al (2013) with three distinct land-use types: natural vegetation, pasture, and cropland. The pasture land-cover type was used to represent croplands in the GnoHarvest and GHarvest simulations, with 50% of above-ground biomass removed and oxidised each year in GHarvest (Piao et al 2009, Lindeskog et al 2013) (same set-up as for grazing in pastures). Resolution was 0.5° × 0.5°. Plant functional type classification for natural vegetation was as in Ahlström et al (2012). Crop-specific processes in the CPManaged simulations were represented by: 11 CFTs with dedicated carbon allocation and phenology, explicit sowing and harvest representation, cover crops, irrigation, and adaptation of crop variety to prevailing climate (Lindeskog et al 2013). Harvestable organs (e.g. grain, tubers) were represented explicitly, and 75% of above-ground crop residues were assumed to be removed at harvest. Sowing dates, maturity and variety varied spatially and temporally as a function of climate (Lindeskog et al 2013). Soil carbon was represented by a two pool model, with decay rates modified by temperature and water content (Sitch et al 2003). We also increased the rate of heterotrophic respiration for the fast soil carbon pool in croplands by 100% in CPManaged simulations following Chatskikh et al (2009), to account for the effects of tillage. Pasture in CPManaged simulations was represented as for GHarvest. Sensitivity studies on these management options are described in section 2.2. The model showed skill at replicating observed crop yields (supplementary figure 3), and growing season cycles at the site scale (Lindeskog et al 2013).

Historical-only simulations used CRU TS 3.21 (University of East Anglia Climatic Research Unit (CRU) 2013) global climate for the period 1901–2012, in order to best capture observed variability. 1850–1900 climate data was provided by repeating detrended 1901–1930 climate. Atmospheric [\( \text{CO}_2 \)] was provided from observations for 1850–2012, based on air in ice-cores, and direct measurements of the atmospheric composition (Le Quéré et al 2014). Simulations for the period 1850–2100 were driven with global climate model data taken from six CMIP5 global climate models (table S2), bias corrected following Ahlström et al (2012). GCM climate was used throughout to avoid an inconsistency in the transition to future climate. All simulations were spun up for 500 years.
years at 1850 conditions, using land-use fractions from the first simulation year. Soil carbon pool size was solved analytically during spin-up to reduce computation time (Sitch et al. 2003).

Simulations made for this study and the rationale behind them are summarised in Table 1. Historical-only simulations used land-use fractions from HYDE 3.1 (Klein Goldewijk et al. 2011), which is available up until 2012. GCM simulations used Hurtt et al. (2011) land-use throughout in order to avoid a discontinuity between historical and future scenario periods. As the Hurtt et al. product is based closely on HYDE, the differences between the products during the historical period are relatively minor (Hurtt et al. 2011). Future land-use and climate might develop along many different paths. In order to explore the influence of these paths on ELUC we tested multiple combinations of land-use change and climate change. For GCM-driven simulations four land-use/climate combinations were used. RCP 8.5 climate and land-use was our baseline simulation to assess effects under strong climate and \([\text{CO}_2]\) change. Simulations with RCP 2.6 climate and RCP 8.5 land-use allowed isolation of climate effects (RCP 2.6 and 8.5 land-use scenarios are in any case very similar globally). Using RCP 8.5 climate along with RCP 4.5 or 6.0 land-use (which differ substantially from RCP 8.5 land-use) allowed isolation of land-use scenario effects. For the RCP 4.5 and 6.0 land-use simulations, only the MPI-ESM-LR GCM was used as forcing instead of the full ensemble, as the choice of GCM did not influence the conclusions drawn. The crop cover fraction was partitioned into different CFTs and irrigated/non-irrigated areas according to estimates for the year 2000 (Portmann et al. 2010) (table S3). Although the total cropland cover in a grid cell could change over the course of the simulation, the relative fractions of CFTs within that cover fraction were held constant. Where cropland was expanded into a hitherto un-cropped grid cell, average CFT fractions from the nearest neighbouring cropland cells were used to populate it.

### 2.2. ELUC calculations

Multiple methods exist in the literature for the calculation of ELUC, each differing in the processes incorporated (Pongratz et al. 2014). The results presented here, unless otherwise stated, adopt the most comprehensive method available for offline DGVM simulations, i.e. comparing the net biospheric exchange of carbon between the land surface and the atmosphere from a simulation with transient climate, \([\text{CO}_2]\) and land-use, with that from a baseline simulation that is entirely potential natural vegetation (PNV). This method (referred to as \(\text{ELUC},3\) in table 1 and the supplementary information) includes emissions directly attributable to land-use change and changes in the sink capacity of ecosystems during the transient simulation period. PNV is calculated dynamically by LPJ-GUESS, including the effects of natural disturbances, as described in Smith et al. (2001), and using parameters as in Ahlström et al. (2012). For comparisons with bookkeeping estimates (figure 1c), which are effectively conducted for fixed climate and \([\text{CO}_2]\) (Houghton et al. 2012), simulations are carried out for 1850–2012 with \([\text{CO}_2]\) fixed at the 1980 mixing ratio (338 ppmv) and using detrended, repeated 1965–1994 CRU climate (\(\text{ELUC},1\)). \(\text{ELUC}\) in this case was calculated by comparing net biospheric exchange of carbon between a simulation with transient land-use with one with land-use fixed at 1850. To assess the influence of

### Table 1. Summary of simulations carried out in this study. See methods and supplementary information for further details of inputs and purpose.

| Code | Period | Managements | Climate | Climate data | \([\text{CO}_2]\) | Land-use | Land-use data | No. yrs. | Purposea |
|------|--------|-------------|---------|-------------|----------------|----------|--------------|----------|----------|
|      |        |             |         |             |                |          |              |          |          |
| A1   | 1850   |             |         |             |                |          |              |          |          |
| A2   | 1850   |             |         |             |                |          |              |          |          |
| A3   | 2012   |             |         |             |                |          |              |          |          |
| B1   | 1850   |             |         |             |                |          |              |          |          |
| B2   | 1850   |             |         |             |                |          |              |          |          |
| B3   | 1850   |             |         |             |                |          |              |          |          |
| C1   | 1850–1930, repeated |         |         |             |                |          |              |          |          |
| C2   | 1850–1930, repeated |         |         |             |                |          |              |          |          |
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environmental change on $E_{\text{LUC}}$ simulations representing pre-industrial conditions were carried out with $[\text{CO}_2]$ fixed at 285 ppmv, and climate as during the spin-up ($E_{\text{LUC,1a}}$). Using this combination of simulations with fixed and transient climate and land-use, it was possible to partition $E_{\text{LUC}}$ into component fluxes relating to emissions from vegetation, soil, and changes in the potential sink capacity of the biosphere (supplementary information). Further calculations of $E_{\text{LUC}}$ under different definitions, for comparison with previously published estimates, are presented in the supplementary information.

Further to the $G_{\text{noHarvest}}, G_{\text{Harvest}}$, and CPManaged simulations, additional management sensitivities were tested using the CPManaged set-up for the historical period: CPManaged,notill ignored increased soil respiration rates in croplands; CPManaged,noreros left all crop residues (excluding the harvested products) on the field, instead of 75% residue removal as in the standard simulation; CPManaged,noirr excluded irrigation of croplands; CPManaged,mostprod enforced the use of only the most productive crop at each location; CPManaged,fixvar did not allow crop varieties (represented with a dynamic adaptation of heat unit sums) to be adapted to change in climate (see supplementary information for further details). A further set of simulations of 105 years were made in order to deduce the timescale for re-equilibration of soil carbon pools due to changes in inputs (figure 3; see table 1). Detrended, repeated CRU 1901–1950 climate was used, and simulations were carried out both with $[\text{CO}_2]$ fixed at the 1850 mixing ratio (285 ppmv) and at the 2075 mixing ratio (following RCP 8.5, 717 ppmv). These involved a complete global transition in year 6 of the simulation from PNV to (a) $G_{\text{noHarvest}}$, (b) $G_{\text{Harvest}}$, and (c) CPManaged (based on the most productive crop at each location).

3. Results and discussion

3.1. Historical land-use emissions

We find that the classic ($G_{\text{noHarvest}}$) representation of agriculture results in cumulative historical land-use change emissions since 1850 which are 42% less than the 225 Pg C calculated using the full agricultural model (CPManaged, figure 1). Including simple harvest/grazing ($G_{\text{Harvest}}$) reduces this difference to 15%. To understand these emission differences we break down $E_{\text{LUC}}$ into component fluxes broadly consistent with...
The net short-term deforestation emission (deforested biomass minus new crop/grass biomass) barely changes between $G_{\text{noHarvest}}$ and $CP_{\text{Managed}}$. Instead, most of the change in $E_{\text{LUCE}}$ induced by agricultural processes results from the soil legacy flux.

Figure 2. Decomposition of the land-use change flux, $E_{\text{LUCE}}$, into component parts representing the gross land clearance flux ($E_G$), the additional gross land clearance flux due to environmental changes since the preindustrial period ($E_{\text{env,def}}$), the uptake of carbon in the biomass of new agricultural vegetation following clearance ($E_{\text{ncrop}}$), the soil legacy flux ($E_{\text{soil,ag}}$ note the opposite sign between $CP_{\text{Managed}}$ and $G_{\text{noHarvest}}$ for this flux), and the modification of the sink capacity change driven by environmental conditions for vegetation ($E_{\text{LS,veg}}$) and soil ($E_{\text{LS,soil}}$). Fluxes in black are for the $CP_{\text{Managed}}$ simulation, whilst those in grey are for $G_{\text{noHarvest}}$. See supplementary information for derivation of fluxes. Fluxes are accumulated over 1850–2012 for simulations forced by CRU climate and given in Pg C.

Figure 3. Change in soil carbon stocks (kg C m$^{-2}$), excluding litter, from natural vegetation to 100 years after a conversion to agriculture ($CP_{\text{Managed}}$, most productive crop chosen at each location) under constant climate and [CO$_2$]. Red shading indicates a decrease in soil carbon. Insets show the evolution of regional carbon stocks (Pg C) across this period for geographical regions enclosing vegetation of similar seasonal structure and carbon exchange ($CP_{\text{Managed}}$ in black, $G_{\text{Harvest}}$ in magenta, $G_{\text{noHarvest}}$ in cyan). Regional calculations were based upon the TransCom 3 regions (Gurney and Denning 2008).
The increased legacy flux in CP Managed results from harvest/grazing and increased heterotrophic respiration rates in tilled soils, which, respectively, reduce soil carbon inputs and increase the soil carbon turnover rate, thus causing soil carbon stocks to move towards a lower equilibrium state. When ignoring these processes (G_noHarvest) modelled agricultural land almost universally accumulates more soil carbon than forests under the same climatic conditions (figure 3), consistent with observational studies of grasslands (Guo and Gifford 2002). $E_{\text{LUC}}$, by the definition used here, also includes a change in the terrestrial carbon sink capacity under environmental change (Pongratz et al. 2014), which depends on the climate and [CO$_2$]. This change in sink capacity may be realised in both vegetation and soil, but is not substantially affected by the choice of agricultural representation over the historical period (figure 2).

There is a great deal of uncertainty over how agricultural land has, and will be, managed, dependent as it is on socioeconomic factors. No-till agriculture can reduce carbon loss from agricultural soils (Angers and Eriksen-Hamel 2008), although the magnitude of this loss is controversial (Powelson et al. 2014), whilst leaving crop residues on the field increases soil carbon inputs. Removal of residues (representing e.g. in situ burning, use as fuel, or forage) and tillage effects constitute, respectively, 6% and 8% of simulated $E_{\text{LUC}}$ from 1850 to 2012 (figure 1). Our simulations do not discriminate those areas of the world in which no-till farming methods have been introduced (Derpsch et al. 2010). This may result in a slightly high bias in our carbon losses due to tillage. Likewise we do not account for possible variations over time due to changes in technology and farming practices. However, tillage is still practised in most croplands globally, and many of those areas in which no-till methods have been adopted still till occasionally (Derpsch et al. 2010). Further uncertainties in tillage parameterisation are discussed in the supplementary information. The one previous global study to consider the effects of tillage in a process-based model (Levis et al. 2014) simulated losses of ca. 12 Pg C over a period of 30 years, assuming all global cropland areas commenced tillage in the same year. Although their calculation was not made over a realistic land-use time series, the soil carbon loss is comparable to our simulations, despite the quite different tillage representation employed by the study.

In contrast, management processes influencing crop productivity per se, such as irrigation or the choice of crop species and variety, had a large effect on crop yields, but much less influence on $E_{\text{LUC}}$. In simulations in which irrigation was switched off (CP Managed, noirr) global crop production (carbon harvested from yield organs) decreased by 22% for the period 2003–2012, whilst when only the most productive crop was specified for each location (CP Managed, mostprod) production increased by 18%, reflecting their known importance for global crop yields (Godfray et al. 2010). However, the effect on $E_{\text{LUC}}$ over this period was less than 1% (figure 4). Fixing crop varieties, rather than allowing them to evolve with climate (CP Managed, fixvar), had a smaller, although still significant effect on yields, but also very little effect on $E_{\text{LUC}}$. Thus, we conclude that realistic individual management interventions influencing crop productivity...
have only a small effect on $E_{\text{LUC}}$. The reason for these disparate effects is that the large harvested fraction of crops means that only a very small fraction of any changes in simulated productivity are propagated to the soil carbon pools. Only for a productivity increase of the order 100–200% as a result of the combined effect of multiple management actions (as seen, for instance, during the ‘green revolution’ since ca. 1960; Zeng et al. 2014), would changes in crop productivity have an effect on $E_{\text{LUC}}$ to rival that of e.g. residue management.

Fertilisation, which is not explicitly simulated here, is also highly important for crop productivity (Rosenzweig et al. 2014). For the purpose of assessing effects on the global carbon cycle, it is reasonable to assume that as nutrient availability represents a limitation on growth, it can be considered as analogous to water availability. On that basis, and considering the similar global distribution of areas of high levels of irrigation and of high fertiliser application rates (see Portmann et al. 2010, figure 4 and Elliott et al. 2014, figure 3), it is expected that, as a first order effect, variations in rates of crop fertilisation will have a similarly small influence on $E_{\text{LUC}}$, assuming that at least a minimum level of fertilisation is maintained to replace nutrient loss through harvest. We note, however, that we are unable to fully assess here all interactions and feedbacks of nitrogen with soil biogeochemistry, for instance, effects on the competitive balance between plants and soil microbes (Zaeule and Dalmon 2011). These limited effects of crop productivity on supra-annual CO$_2$ emissions are consistent with recent findings that although croplands are a large contributor to seasonal variations in [CO$_2$], their net annual effect on CO$_2$ fluxes at the global scale is minimal (Gray et al. 2014a, Zeng et al. 2014).

Environmental factors result in large regional variations in the timescale over which the soil legacy flux is realised (figure 3). Following conversion of natural vegetation to CPManaged, an e-folding timescale (time over which the fraction $1 - 1/e$ of the total soil legacy flux is realised) of ca. 10 years was simulated for tropical regions, but more than 100 years for the Northern boreal and temperate regions. Combined with the high carbon densities in boreal and temperate soils, these long-lasting losses of ecosystem carbon have the potential to dominate $E_{\text{LUC}}$ for as much as a century following a conversion to cropland. This strong legacy effect of land-use change on carbon fluxes is not seen in the ‘classic’ agriculture representations (figure 3). For GHarvest, a longer e-folding timescale, but a much smaller and more regionally-mixed response with regard to soil carbon stock change compared to CPManaged is simulated. The lack of tillage and smaller harvested fraction in GHarvest slows the response rate, and in some regions the increased carbon loss due to harvest does not outweigh the tendency for increased soil carbon accumulation under grassland alone (GnoHarvest) (Guo and Gifford 2002) (figure 3). Although currently most land conversions to agriculture occur in tropical and sub-tropical regions (Ciais et al. 2013), climate warming opens the possibility of expanding agriculture in northern regions, also as an adaptation to yield decreases elsewhere in the world (Rosenzweig et al. 2014). As the GHarvest treatment corresponds to that used for grazed pasture (Lindeskog et al. 2013), in many parts of the world sustainable levels of grazing are simulated to maintain soil carbon stocks similar to those that would exist under natural vegetation (figure 3, figure S1).

3.2. Model evaluation

The results herein imply that inclusions of harvest, grazing and tillage, are important for calculations of $E_{\text{LUC}}$ and hence the global carbon cycle. But how representative are these results? To test this, the modelled soil carbon response following cropland transition was compared with site-scale observations (figure S2). The responses were consistent in terms of direction, magnitude and speed, despite the model not being parameterised to specific site characteristics (supplementary information). Both the GnoHarvest and GHarvest Simulations performed much more poorly in comparison to the observations. The results herein (figure 3) were also consistent with a 42% decrease following forest to crop conversion and an 8% increase following forest to pasture conversion reported from meta-analysis (Guo and Gifford 2002). Failing to consider agricultural processes would not allow models to capture this differentiation in soil carbon stocks between conversion from forest to cropland and forest to pasture.

Over the last 50 years, $E_{\text{LUC}}$ from our CPManaged simulation compares well with bookkeeping studies, which implicitly capture at least part of the effect of agricultural processes through their use of observed cropland soil carbon densities (figure 1, see also Reick et al. 2010). In particular, the modelled 40.8 Pg soil carbon loss in CPManaged over 1850–2012 (figure 2) is consistent with bookkeeping estimates of 39 Pg C for the period 1850–2005 (Houghton 2010) and 35 Pg C for 1850–1992 (Reick et al. 2010), and highlights the importance of agricultural processes in leading to differences between bookkeeping-and DGVM/ESM calculations of $E_{\text{LUC}}$. A quantitative comparison between other global-scale process-based studies of $E_{\text{LUC}}$ is precluded by large differences in the representation of processes related to land-use change such as gross land-use transitions (Shevlakova et al. 2013) and wood harvest (Shevlakova et al. 2013, Stocker et al. 2014) (table S4), and uncertainties introduced by using different climate and/or land-cover input products. Qualitatively, our results for $E_{\text{LUC}}$ are comparable to previous process-based estimates, with the GnoHarvest results being at the lower end of literature values and the CPManaged simulations at the upper (figure 1, table S4).
3.3. Future projections and implications for carbon-cycle modelling

If crucial for the past, how important then is the representation of land-use change for assessment of the future terrestrial carbon cycle? We forced our model using climate projections from an ensemble of CMIP5 global climate models (Ciais et al. 2013), thus comparing a range of projected climate and [CO₂] futures, and effects of representing agriculture and management (methods). The effects of agriculture were relatively modest compared to those for past E_LUC (table 2). A strong forcing pathway (RCP 8.5, Moss et al 2010) resulted in E_LUC = 171 Pg C (ensemble range 144–215) over 2006–2100, but a difference between CPManaged and G_noHarvest of only 2 Pg C (−8–17). Under a moderate climate forcing pathway (RCP 2.6), the difference was 27 Pg C (26–28), out of a total E_LUC of 84 Pg C (82–94), suggesting that efforts to calculate the allowable level of anthropogenic carbon emissions consistent with limiting climate change to the RCP 2.6 pathway (Moss et al 2010, Jones et al 2013) may overestimate this level by up to ca. 10% (Jones et al 2013, calculate allowable emissions of 322 Pg C for 2006–2100 for RCP 2.6). The very small difference for RCP 8.5 arises because, under high [CO₂], unharvested tropical grasslands (G_noHarvest) no longer accumulate more soil carbon than the natural ecosystems they replace, due to a greater relative CO₂ fertilisation of tree productivity than of grass productivity (supplementary information).

The benefits of reforestation are enhanced in our CPManaged simulations, however. A reforestation land-use scenario (RCP 4.5) reverses the influence of agriculture on E_LUC (table 2), as croplands with strongly depleted soil carbon have more potential for carbon recovery in response to mitigation measures. Given the long timescale for soil carbon changes to occur, especially in middle and high latitudes where the RCP4.5 scenario projects most reforestation, further carbon uptake would be expected over a longer time horizon.

Overall, the effect of agricultural processes on E_LUC in the simulated future scenarios is relatively small compared to the historical period. This result stems from relatively conservative projections of future land-use change (Hurt et al 2011); between 1850 and 1960 the percentage of global ice-free land area used for agriculture increased from 10 to 33%, compared to a 5% change from 2006–2100 in RCP 8.5 (Hurt et al 2011). Because soil legacy fluxes are tied to the date of land conversion, and most land-use transitions to cropland in the RCP scenarios occur in the tropics where soil fluxes are smaller and relatively rapidly realised (see middle latitude regions, figure 3), these scenarios effectively minimise the influence of agricultural processes on E_LUC. Yet these scenarios are far from embracing the full uncertainty; less positive assumptions regarding technological development of crop yields would result in much larger rates of future land-use conversions (Hardacre et al 2013). Further, the disparate regional magnitude and e-folding time of the soil-carbon response means that the relation between the change in agricultural area and the influence of agricultural representation on E_LUC is strongly nonlinear (figure S5). This also implies that it is impossible to account for the effects of agriculture on the global carbon cycle using a simple scaling factor; explicit consideration of key agricultural processes is necessary.

As ESMs used for global climate projections in the CMIP5 model intercomparison effort represent vegetation using similar basic physical principles to LPJ-GUESS, but widely omit agricultural processes (Ciais et al 2013), we contend that the underestimation of E_LUC by up to 1.0 Pg C a⁻¹ (figure 1) identified herein will propagate directly into an overestimation in ESM calculations of terrestrial carbon uptake, S_T (S_T = S_L – E_LUC), although in those ESMs which simulate well or underestimate the magnitude of S_L it may also be symptomatic of an underestimation of S_L. It should further be noted that simulations herein do not include processes such as wood harvest, nor gross land-use transitions, which have recently been shown to substantially increase calculations of E_LUC in other models (Houghton et al 2012, Shevliakova et al 2013), implying that ESM estimations of E_LUC effects may be

|           | G_noHarvest | CPManaged |
|-----------|-------------|-----------|
| E_LUC     |             |           |
| E_LUC (E_noIS + E_LUC) | 9.1 | 12.1 |
| E_LUC (E_noIS + E_LUC) | 127.6 | 126.9 |
| E_LUC     | 169.3       | 170.8     |
| Δ[CO₂] (ppmv) | 63 | 63 |

Table 2. Historical and future components of the land-use flux as forced by an ensemble of GCM climates. Positive values indicate a flux to the atmosphere. Notation is as for figure 2. Units are Pg C. Change in [CO₂] due to the land-use emission is also shown.

| RCP 8.5 climate/ [CO₂] and land-use 2006–2100 | RCP 2.6 climate/ [CO₂], RCP 8.5 land-use 2006–2100 | RCP 8.5 climate/ [CO₂], RCP 4.5 land-use 2006–2100 |
|-----------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| E_LUC (G_noHarvest + CPManaged) | 32.6 | 31.8 | 20.1 | 20.4 | 15.7 | 13.6 |
| E_LUC (G_noHarvest + CPManaged) | 39.8 | 39.8 | 24.4 | 24.4 | 10.6 | 10.6 |
| E_LUC (G_noHarvest + CPManaged) | −7.2 | −8.0 | −4.3 | −4.0 | 5.1 | 3.0 |
| E_LUC (G_noHarvest + CPManaged) | 9.1 | 12.1 | −17.5 | 9.1 | 12.9 | −19.8 |
| E_LUC (G_noHarvest + CPManaged) | 127.6 | 126.9 | 54.6 | 54.7 | −12.3 | −12.1 |
| E_LUC (G_noHarvest + CPManaged) | 169.3 | 170.8 | 57.2 | 84.3 | 16.4 | −18.2 |
| Δ[CO₂] (ppmv) | 63 | 63 | 21 | 31 | 6 | −6 |
even larger than 1.0 Pg C a$^{-1}$. Combining results from LPJ-GUESS with a carbon budget model (supplementary information), we calculate that the inclusion of agricultural processes in calculation of $E_{\text{LUC}}$ results in the emission of 43 ppmv more CO$_2$ into the atmosphere from 1850 to 2012 than would otherwise be estimated, of which 27 ppmv would remain in the atmosphere in 2012. This may help explain the negative bias for [CO$_2$] shown by several ESMs in comparison to observations (Hoffman et al 2013), while in others, this missing agricultural emission may appear as an understimation of model-internal $S_C$ for which there are many candidate sink processes to explain the shortfall (Zaechle et al 2011, Erb et al 2013, Keenan et al 2013). The differences in [CO$_2$] for future scenarios (table 2) will have implications for the calculations of allowable anthropogenic emissions consistent with each of the RCP scenarios (Jones et al 2013). Our results also indicate the importance of considering the effects of harvest, grazing and tillage on soil carbon when calculating the climate impact of future land-use adaptation. Excluding agricultural processes from ESM calculations of $E_{\text{LUC}}$ means that the carbon-mitigation potential of reforestation may have been underestimated.

4. Conclusions

Crop and pasture land contain, by our simulation, 19% of the world’s terrestrial carbon stocks in 2012, totalling ca. 350 Pg C. The way in which humans affect these ecosystems has a substantial influence on simulations of historical land-use change emissions, and will continue to do so if future land-use change is large. The large committed soil legacy fluxes elicited by agriculture means past conversions to cropland may be a major contributor to $E_{\text{LUC}}$ for many decades. We find that the processes of key importance for $E_{\text{LUC}}$ and the supra-annual terrestrial carbon sink (harvest, grazing, tillage, residue management), are fundamentally different to the productivity-relevant processes recently identified to strongly influence the seasonal variability of $S_C$ (Gray et al 2014, Zeng et al 2014). These key processes also act towards a qualitatively unambiguous outcome; they reduce soil carbon stocks in agricultural land, and thereby increase $E_{\text{LUC}}$, relative to simulations in which these processes are excluded. Model simulations lacking these processes will therefore display a low bias in terms of the effect of agriculture on $E_{\text{LUC}}$. Exclusion of agricultural management in ESMs will thus inhibit attempts to correctly close the present and future carbon budget, and thus project future climate and carbon cycle feedbacks. We neglect here forcing from other agricultural-related gases such as N$_2$O and CH$_4$, and biophysical effects, which likely further amplify the importance of including a representation of managed systems in ESMs (Luyssaert et al 2014). Clearly agricultural processes are a key aspect of global carbon cycle and climate modelling.

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