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LETTER

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

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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_{LUC}) versus the biospheric carbon uptake (S_L; $S_T = S_L - E_{LUC}$). One key aspect of the interplay of E_{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_{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_{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):

$$S_T = S_L - E_{LUC} = E_{FF} - S_O - \frac{d[CO_2]}{dt}\delta_{CO_2},$$

where $[CO_2]$ is the atmospheric CO_2 mixing ratio, S_O is the oceanic CO_2 sink, E_{FF} is anthropogenic fossil fuel and cement emissions and δ_{CO2} 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 use change (E_{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_{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_T 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_{LUC}, then that implies that 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_T 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 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) (Ciais et al 2013). Thus far, the importance of agricultural processes for E_{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 historical and future E_{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_{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_{LUC} using a detailed treatment of crops and pasture, and their management ($CP_{Managed}$). 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 ($G_{noHarvest}$), as often used in previous calculations of E_{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 ($G_{Harvest}$) (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 $G_{noHarvest}$ and $G_{Harvest}$ simulations, with 50% of above-ground biomass removed and oxidised each year in $G_{Harvest}$ (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 $CP_{Managed}$ 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 $CP_{Managed}$ simulations following Chatskikh et al (2009), to account for the effects of tillage. Pasture in $CP_{Managed}$ simulations was represented as for $G_{Harvest}$. 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 [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

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	[CO_2]	Land-use	Land-use data	No. Sims.	Purpose[a]
Historical comparisons									
A1	1850-2012	$G_{noHarvest}$, $G_{Harvest}$, $CP_{Managed}$, $CP_{Managed,notill}$, $CP_{Managed,noresr}$, $CP_{Managed,noirr}$, $CP_{Managed,fixvar}$, $CP_{Managed,mostprod}$	Transient	CRU	Transient	Transient	HYDE	8	$E_{LUC,2} = NBP_{A1} - NBP_{A2}$ $E_{LUC,3} = NBP_{A1} - NBP_{A3}$ Calculate E_{LUC} including environmental change effects.
A2						Fixed at 1850		8	
A3		n/a				PNV	n/a	1	
B1		$G_{noHarvest}$, $G_{Harvest}$, $CP_{Managed}$, $CP_{Managed,notill}$, $CP_{Managed,noresr}$, $CP_{Managed,noirr}$	1965-1994, repeated		338 ppmv (1980)	Transient	HYDE	6	$E_{LUC,1b} = NBP_{B1} - NBP_{B2}$ Comparison with bookkeeping estimates of E_{LUC}.
B2						Fixed at 1850		6	
C1			1901-1930, repeated		285 ppmv (1850)	Transient		6	$E_{LUC,1a} = NBP_{C1} - NBP_{C2}$ Exclude environmental change effects on E_{LUC}.
C2						Fixed at 1850		6	
Future projections									
D1	1850-2100	$G_{noHarvest}$, $G_{Harvest}$, $CP_{Managed}$	Transient	GCM (all) Hist. + RCP 8.5	Transient Hist. + RCP 8.5	Transient	Hurtt Hist. + RCP 8.5	18	$E_{LUC,3}$, baseline strong climate/[CO_2] change projection.
D2				GCM (all)[b] Hist. + RCP 2.6	Transient Hist. + RCP 2.6			15	$E_{LUC,3}$, test effect of weak climate/[CO_2] change.
D3				GCM (MPI) Hist. + RCP 8.5	Transient Hist. + RCP 8.5		Hurtt Hist. + RCP 4.5	3	$E_{LUC,3}$, test effect of different LUC scenario (reforestation).
D4							Hurtt Hist. + RCP 6.0	3	$E_{LUC,3}$, test effect of different LUC scenario.
D5		n/a		GCM (all) Hist. + RCP 8.5		PNV	n/a	6	$E_{LUC,3}$ = (D1 | D3 | D4) - D5
D6				GCM (all)[b] Hist. + RCP 2.6	Transient Hist. + RCP 2.6			5	$E_{LUC,3}$ = D2 - D6
Idealised simulations									
E1	105 years	$G_{noHarvest}$, $G_{Harvest}$, $CP_{Managed}$	1901-1930, repeated	CRU	285 ppmv (1850)	Idealised	5 years PNV then 100 years agriculture	3	Identify response timescales of soil carbon pools to LUC.
E2					717 ppmv (2075)			3	Identify influence of high [CO_2] on soil C response to LUC.

[a] The subscript number next to E_{LUC} refers to the definition used. Please refer to the Supplementary Information for further explanation.

[b] MRI-CGCM3 data was not available for RCP 2.6 simulations.

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 E_{LUC} 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 [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. E_{LUC} calculations

Multiple methods exist in the literature for the calculation of E_{LUC}, 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, [CO_2] and land-use, with that from a baseline simulation that is entirely potential natural vegetation (PNV). This method (referred to as $E_{LUC,3}$ 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 1(c)), which are effectively conducted for fixed climate and [CO_2] (Houghton *et al* 2012), simulations are carried out for 1850–2012 with [CO_2] fixed at the 1980 mixing ratio (338 ppmv) and using detrended, repeated 1965–1994 CRU climate ($E_{LUC,1b}$). E_{LUC} 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

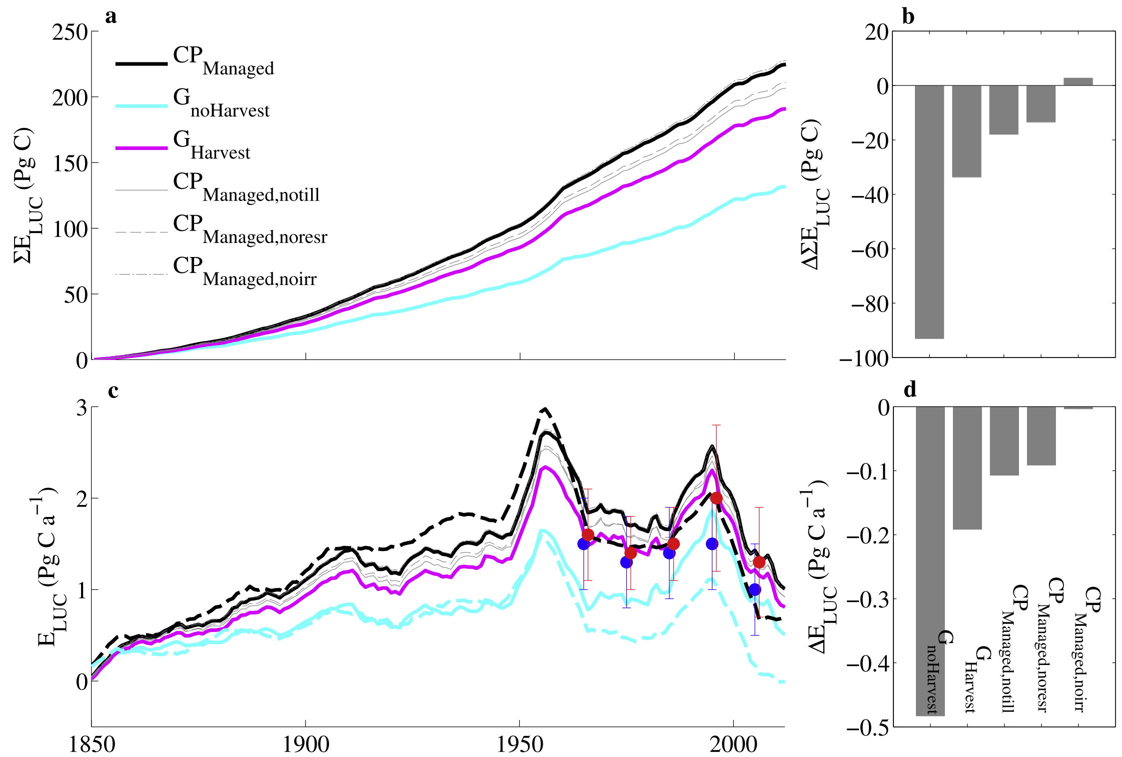

Figure 1. Land-use change emissions over the historical period (1850–2012) for several different levels of agricultural representation and management. Management simulations are based on the $CP_{Managed}$ simulation but with no tillage ($CP_{Managed,notill}$), no residue removal ($CP_{Managed,noresr}$), and no irrigation ($CP_{Managed,noirr}$). (a) Cumulative E_{LUC} since 1850 including emissions from land clearance and legacy soil fluxes, and the change in sink capacity (see methods and supplementary information). (b) Difference in cumulative E_{LUC} for the year 2012 between $CP_{Managed}$ and the various management options. (c) Annual E_{LUC} emissions (11 year running mean), thick dashed lines show E_{LUC} calculated including only emissions from land clearance and legacy soil fluxes, calculated in such a way as to be compatible with bookkeeping model estimates (Le Quéré *et al* 2014) (methods), whilst thick solid lines use E_{LUC} calculated as for (a). Blue dots and error bars show E_{LUC} as estimated from a bookkeeping model as part of the Global Carbon Project (Le Quéré *et al* 2014), whilst red dots and error bars show the mean and standard deviation of DGVM estimates from the same study. Dots and error bars represent values averaged over the decade on which they are centred. (d) Difference in mean 2003–2012 E_{LUC} between $CP_{Managed}$ and the various management options.

environmental change on E_{LUC}, simulations representing pre-industrial conditions were carried out with [CO_2] fixed at 285 ppmv, and climate as during the spin-up ($E_{LUC,1a}$). Using this combination of simulations with fixed and transient climate and land-use, it was possible to partition E_{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_{LUC} under different definitions, for comparison with previously published estimates, are presented in the supplementary information.

Further to the $G_{noHarvest}$, $G_{Harvest}$ and $CP_{Managed}$ simulations, additional management sensitivities were tested using the $CP_{Managed}$ set-up for the historical period: $CP_{Managed,notill}$ ignored increased soil respiration rates in croplands; $CP_{Managed,noresr}$ left all crop residues (excluding the harvested products) on the field, instead of 75% residue removal as in the standard simulation; $CP_{Managed,noirr}$ excluded irrigation of croplands; $CP_{Managed,mostprod}$ enforced the use of only the most productive crop at each location; $CP_{Managed,fixvar}$ 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 1901–1930 climate was used, and simulations were carried out both with [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) $G_{noHarvest}$, (b) $G_{Harvest}$, and (c) $CP_{Managed}$ (based on the most productive crop at each location).

3. Results and discussion

3.1. Historical land-use emissions

We find that the classic ($G_{noHarvest}$) 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 ($CP_{Managed}$; figure 1). Including simple harvest/grazing ($G_{Harvest}$) reduces this difference to 15%. To understand these emission differences we break down E_{LUC} into component fluxes broadly consistent with

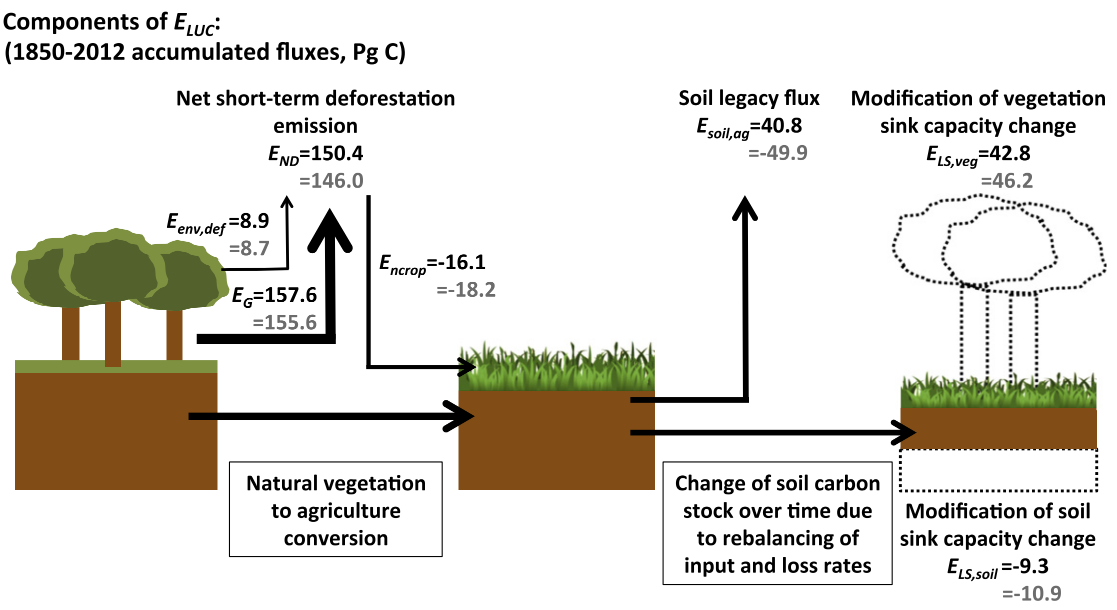

Figure 2. Decomposition of the land-use change flux, E_{LUC}, into component parts representing the gross land clearance flux (E_G), the additional gross land clearance flux due to environmental changes since the preindustrial period ($E_{env,def}$), the uptake of carbon in the biomass of new agricultural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

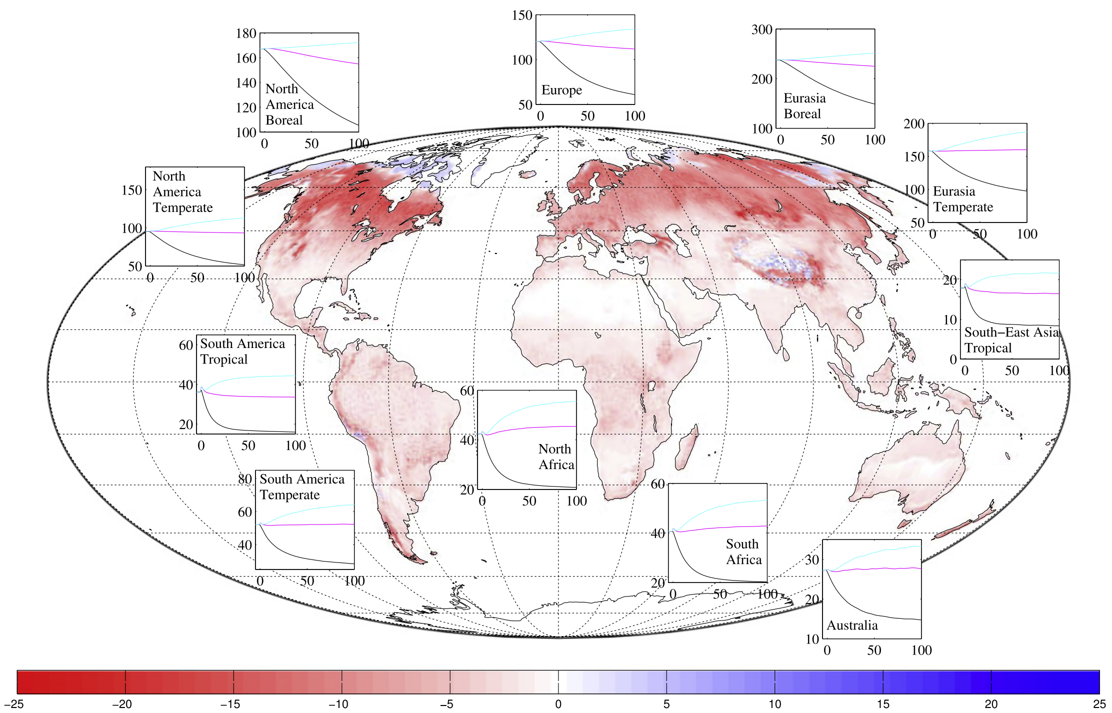

Figure 3. Change in soil carbon stocks (kg C m^{-2}), excluding litter, from natural vegetation to 100 years after a conversion to agriculture ($CP_{Managed}$, most productive crop chosen at each location) under constant climate and [CO_2]. Red shading indicates a decrease in soil carbon. Insets show the evolution of regional carbon stocks (Pg C) across this period for geographical regions enclosing vegetation of similar seasonal structure and carbon exchange ($CP_{Managed}$ in black, $G_{Harvest}$ in magenta, $G_{noHarvest}$ in cyan). Regional calculations were based upon the TransCom 3 regions (Gurney and Denning 2008).

Pongratz *et al* (2014) (figure 2; supplementary information). The net short-term deforestation emission (deforested biomass minus new crop/grass biomass) barely changes between $G_{noHarvest}$ and $CP_{Managed}$. Instead, most of the change in E_{LUC} induced by agricultural processes results from the soil legacy flux.

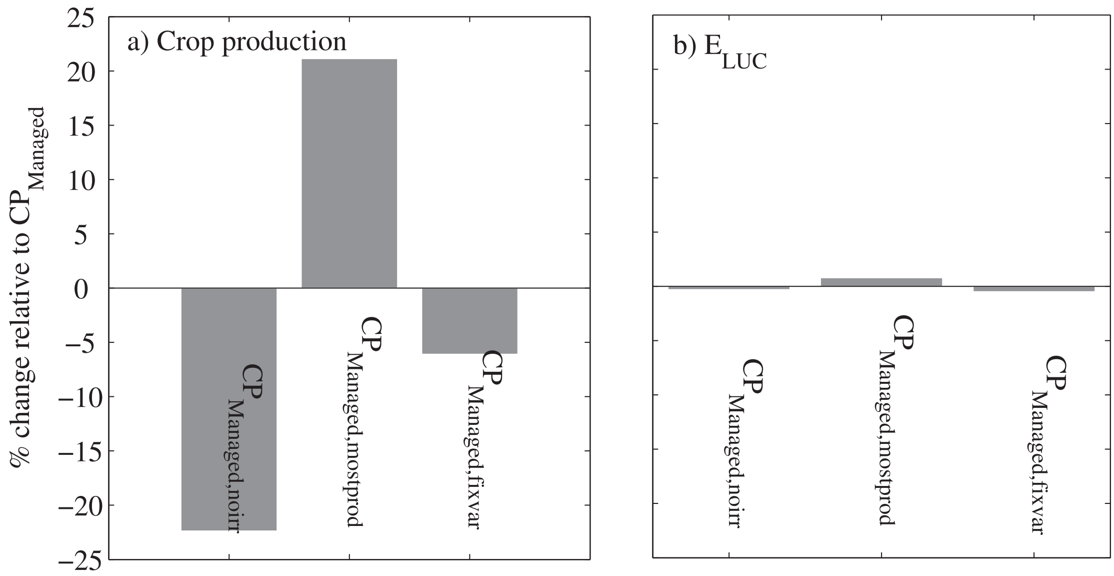

Figure 4. (a) Percentage change in simulated global crop production (2003–2012 mean), relative to the $CP_{Managed}$ simulation, for the no irrigation simulation ($CP_{Managed,noirr}$), the most productive crop choice simulation ($CP_{Managed,mostprod}$), and the simulation with no cultivar adaptation to climate after 1900 ($CP_{Managed,fixvar}$). (b) As for panel (a), except displaying percentage change in annual E_{LUC}. Panels (a) and (b) are presented at the same scale, in order to highlight the relative difference in importance of cropland management for the two variables.

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_{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 (Powlson *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_{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_{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_{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_{LUC}. Thus, we conclude that realistic individual management interventions influencing crop productivity have only a small effect on E_{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_{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_{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 (Zaehle and Dalmonech 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 $CP_{Managed}$, 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_{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 $G_{Harvest}$, a longer e-folding timescale, but a much smaller and more regionally-mixed response with regard to soil carbon stock change compared to $CP_{Managed}$ is simulated. The lack of tillage and smaller harvested fraction in $G_{Harvest}$ 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 ($G_{noHarvest}$) (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 $G_{Harvest}$ 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_{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 $G_{noHarvest}$ and $G_{Harvest}$ 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_{LUC} from our $CP_{Managed}$ 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 $CP_{Managed}$ 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 booking-keeping and DGVM/ESM calculations of E_{LUC}. A quantitative comparison between other global-scale process-based studies of E_{LUC} is precluded by large differences in the representation of processes related to land-use change such as gross land-use transitions (Shevliakova *et al* 2013) and wood harvest (Shevliakova *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_{LUC} are comparable to previous process-based estimates, with the $G_{noHarvest}$ results being at the lower end of literature values and the $CP_{Managed}$ simulations at the upper (figure 1, table S4).

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 $[CO_2]$ due to the land-use emission is also shown.

	RCP 8.5 climate/$[CO_2]$ and land-use 2006–2100		RCP 2.6 climate/$[CO_2]$, RCP 8.5 land-use 2006–2100		RCP 8.5 climate/$[CO_2]$, RCP 4.5 land-use 2006–2100	
	$G_{noHarvest}$	$CP_{Managed}$	$G_{noHarvest}$	$CP_{Managed}$	$G_{noHarvest}$	$CP_{Managed}$
E_{ND}	32.6	31.8	20.1	20.4	15.7	13.6
$E_G + E_{env,def}$	39.8	39.8	24.4	24.4	10.6	10.6
E_{ncrop}	−7.2	−8.0	−4.3	−4.0	5.1	3.0
E_{soil} ($E_{soil,ag} + E_{LS,soil}$)	9.1	12.1	−17.5	9.1	12.9	−19.8
$E_{LS,veg}$	127.6	126.9	54.6	54.7	−12.3	−12.1
E_{LUC}	169.3	170.8	57.2	84.3	16.4	−18.2
$\Delta[CO_2]$ (ppmv)	63	63	21	31	6	−6

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 $[CO_2]$ 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 $CP_{Managed}$ 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 $[CO_2]$, unharvested tropical grasslands ($G_{noHarvest}$) no longer accumulate more soil carbon than the natural ecosystems they replace, due to a greater relative CO_2 fertilisation of tree productivity than of grass productivity (supplementary information).

The benefits of reforestation are enhanced in our $CP_{Managed}$ 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 (Hurtt *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 (Hurtt *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_T 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 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_{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 underestimation of model-internal S_L, for which there are many candidate sink processes to explain the shortfall (Zaehle *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_{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_{LUC} for many decades. We find that the processes of key importance for E_{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_T (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_{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_{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_2O 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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