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Historical and future carbon emissions from croplands

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Abstract

We examine past and future carbon emissions from global croplands, considering land-use change, changes in crop productivity, tillage practices, and residue removal. We find that emissions over the historical period are sensitive to the assumed productivity of arable land that is not planted in a given year and the assumed fraction of soil carbon that is released during land conversion. The role of this “other” arable land, both at present and over the historical period, is not well understood and should be examined further. The carbon balance of croplands over 21st century depends on changes in management practices, particularly the adoption of conservation tillage and the potential removal of residue for use as energy feedstocks. We find that croplands will not become large carbon sinks in the future, however, unless most crop residue is left on fields. Given the relatively low carbon “penalty” incurred by removal, residue use for energy feedstocks may be the preferred option.

1 Introduction

Human-induced changes in land-use are a major contributor to atmospheric increases in carbon dioxide, although the magnitude of past land-use change emissions is deeply uncertain (Houghton, 2010). The transformation of landscapes to croplands has long been recognized as a major component of land-use change emissions (Houghton et al., 1983). Spatially explicit estimates of historical cropland extent (Ramankutty and Foley, 1999; Goldewijk et al., 2011) have been used for a number of years now to examine the impact of historical cropland on the earth system. Different estimates of land-use change over time (Jain and Yang, 2005) and different assumptions for forest carbon density (Smith and Rothwell, 2013) both impact estimates of emissions due to past land-use change. Earth-system models are now being used to examine the impacts of past and future land-use change (Pongratz et al., 2009; Shevliakova et al., 2009), some using the same dataset for past and future land-use transitions that we use here (Hurtt et al., 2011).

In this work, we examine the global role of carbon cycling in croplands after conversion to agricultural use has occurred. We consider the influence of residue removal and changes in cropping practices such as no- or low-till. We examine here the net change in cropland carbon stocks, excluding emissions that occur as part of land-use conversion. These are, therefore, the changes that would be measured over time in established croplands.

To examine the past and future role of croplands we conduct a series of sensitivity experiments using a simple global model with regional detail that self-consistently treats carbon flows within ecosystems and under land-use change (Smith and Rothwell, 2013). The model, and extensions added in this work to better capture cropland dynamics, are described in the next section. We follow with a discussion of quantitative results, ending with conclusions regarding the role of croplands in global carbon cycle.

2 Methodology

2.1 Carbon-cycle model

We use the G-Carbon global terrestrial carbon-cycle model (Smith and Rothwell, 2013). This model is designed to examine past and future global changes in terrestrial carbon stocks by tracking carbon flows within ecosystems using a first order kinetic representation with three carbon pools (vegetation, litter, soil), 50 yr age cohorts for secondary forests, wood product flows, and carbon flows associated with land-use changes. The model is run for 14 world regions with 12 ecosystems/land-use types in each region. All carbon pools are started in an equilibrium state, except for peatlands (Smith and Rothwell, 2013), and the model is run from 1500 to 2100.

While there are many more complex models of soil and crop carbon, these often have large data requirements and are more difficult to use for long-term and global analyses.

The use of a relatively simple representation of carbon flows allows exploration of long-term dynamics under a variety of different assumptions.

We focus on the data and assumptions for the representation of cropland in this section. Cropland in each region is represented as one aggregate land-use with soil carbon characterized by fast, slow, and passive carbon pools. Carbon flows are represented by the following equations.

$$\mathrm{NPP}_{\mathrm{eff}} = \mathrm{NPP} - C_{\mathrm{crop}} \tag{1}$$

$$\frac{\mathrm{d}C_{\mathrm{fast}}}{\mathrm{d}t} = a^{\mathrm{res}}_{\mathrm{remain}}\mathrm{NPP}_{\mathrm{eff}} - \frac{C_{\mathrm{fast}}}{\tau_{\mathrm{fast}}} - f_{\mathrm{fast}}(\mathrm{LUC}) \tag{2}$$

$$\frac{\mathrm{d}C_{\mathrm{slow}}}{\mathrm{d}t} = a^{s}_{\mathrm{fast}}\frac{C_{\mathrm{fast}}}{\tau_{\mathrm{fast}}} - \frac{C_{\mathrm{slow}}}{\tau_{\mathrm{slow}}} - f_{\mathrm{slow}}(\mathrm{LUC}) \tag{3}$$

$$\frac{\mathrm{d}C_{\mathrm{passive}}}{\mathrm{d}t} = a^{p}_{\mathrm{slow}}\frac{C_{\mathrm{slow}}}{\tau_{\mathrm{slow}}} - \frac{C_{\mathrm{passive}}}{\tau_{\mathrm{passive}}} - f_{\mathrm{passive}}(\mathrm{LUC}) \tag{4}$$

The effective Net Primary Productivity, $\mathrm{NPP}_{\mathrm{eff}}$, is the cropland NPP minus the carbon in harvested products, which are assumed to be removed and re-emitted to the atmosphere. The a coefficients represent the fraction of the turnover from each pool that is not oxidized over a year and flows into the next carbon pool. We assume that, in equilibrium, the size of the slow and passive carbon pools are equal (Izaurralde et al., 2001). The fast carbon pool was assumed to have a turnover timescale (τ) of 1.5 yr in the US, and scaled with the regional grassland mean residence time from Smith and Rothwell (2013) for other regions. 30 % of residue is assumed to flow to the fast soil pool each year, 40 % of the fast soil pool to flow to the slow pool, and 13 % of the slow pool flows to the passive pool. These parameters were chosen so that the mean residence time is about 60 yr in the US and Canada, with a turnover time for the slow soil pool of 500–600 yr. Turnover timescale are calibrated such that total equilibrium slow + passive cropland soil carbon contents in 2000 are the regional values estimated in Thomson et al. (2008) using data from Batjes (2002). Turnover times in other regions vary as expected, with faster turnover times in tropical regions, particularly for the slow soil pool (Table S1, Supplement).

Cropland soil carbon in the discussions below refers to the sum of the four carbon pools, or $C_{\text{total}} = C_{\text{fast}} + C_{\text{slow}} + C_{\text{passive}}$.

2.2 Cropland net primary productivity

A key aspect of this model is the incorporation of changes in crop productivity increases over time. Data from the UN Food and Agriculture Organization from 1961 through 2005, and other historical sources for previous years, were used to estimate net crop productivity. We follow the general procedures of Lobell and Hicke (2002), accounting for changes in harvest index over time drawing from Hay and Porter (2006) and Sinclair (1998) as described in Smith and Rothwell (2013), and summarized in the Supplement. Data collection previous to 1962 was focused on a few key years (1961, 1950, 1940, 1900, 1870) and the largest countries in each region in order to capture the major historical changes in crop productivity with a manageable data collection and processing effort. Our goal was to construct a reasonable representation of regional trends over time. There are substantial uncertainties in these data as well as data gaps that could potentially be improved by further work.

Table 1 shows the estimated effective crop NPP, which is the amount of above- and below-ground residue available as potential input to the soil. In OECD regions crop production and harvested area data are generally available from at least 1900, while for developing regions data is generally only available after 1940. Values after 2005 represent scenario results from the GCAM RCP4.5 scenario (Thomson et al., 2011).

These trends represent changes in crop mix as well as productivity increases. Effective NPP can decrease due to changes in crop mix, even though productivity might increase for specific crops over the same time period. The effect of the “green revolution” can be seen in many regions over the 20th century as an increase in net available residue (Fig. S3, Supplement). As a consequence, between 1940 through 2005 effective NPP increased by at least 0.1 kgC m^{-2} in almost every region and by 0.3 kgC m^{-2}

in Latin America and South East Asia (Table 1). Note that this effect on residue production was damped somewhat by the historical increase in harvest index, which results in grain yield increasing without increasing overall biomass by the same amount.

In addition to the changes in aggregate crop productivity quantified above, the fraction of cropland actually planted in crops, and then harvested, also can change over time. Total cropland area, as reported in FAO and global data sets used for environmental modeling, represents arable land. The definition of arable land is not necessarily consistent across regions, but is, broadly speaking, land classified as cropland, but not land necessarily planted in crops in a given year. For this paper we distinguish, therefore, between land from which crops are harvested in a given year (e.g., as reported by FAO), and “other arable” land, which is the difference between total reported cropland and land on which a crop harvest takes place.

Using the data sources above, we estimated the total harvested area over time in each region (Tables S2 and S3, Supplement). Subtracting this value from total cropland from the HYDE dataset, as used in Hurtt et al. (2011), gives an estimate for “other arable land”, that is land that from which a crop was not harvested in a given year (Table 2). This fraction is larger than 20 % in most regions, and larger than 33 % in 6–13 regions, depending on the year. We estimate that the fraction of cropland that is not harvested has decreased slightly from 1940 to 2005, although confidence in these figures is low. The estimates here for earlier years could be biased low due to incomplete data on crop harvest areas. Data on fodder crops, for example, is often absent from the historical compilations examined for this work. One reason for a long-term decrease in the amount of unplanted cropland might be the more widespread use of fallow rotations before the widespread use of commercial fertilizer. These estimates are limited by the available data and in some cases appear to have some biases. It is unlikely, for example, that there was no fallow rotation in Eastern Europe or Japan in the early 20th century, although this does not have a large impact on global results since cropped areas in these regions are a small portion of the global total.

The nature and magnitude of this “other” arable land on a global level is uncertain, as detailed accounts of land-use at this level of detail are not available globally. Comparing with more detailed data available for the US (US Census of agricultural land 1990; Table S3, Supplement), for example, shows that this other arable land appears to be composed of a combination of land used for pasture and grazing (but not classified as permanent pasture), land planted but not harvested (e.g. crop failure), cover crops, land set aside as conservation reserve, and land in fallow or simply left idle.

Globally, we estimate “other arable” land to have increased from 450 million Ha in 1950 to 520 million ha in 2005. The amount of this other arable land declines thereafter in the GCAM RCP4.5 scenario as cropland (including dedicated biofuels) expands over the 21st century. This estimate compares well with the estimate of abandoned agricultural lands of 385–472 million Ha by Campbell et al. (2008), although we note that these are estimates of somewhat different quantities.

Aggregate cropland NPP in each region is taken to be the sum of the effective NPP from harvested cropland plus the assumed NPP for other arable land. In the central case, the NPP from other arable land is taken to be equal to the average value for grassland in the same region. This implicitly assumes that these areas are highly productive when not in use for growing crops. This also is broadly consistent with some of this other arable land being used for fodder crops. The impact of this assumption is addressed in sensitivity tests described in the next section.

2.3 Sensitivity tests

We will examine the role of croplands within the global carbon-cycle by estimating net emissions from croplands while varying a number of uncertain parameters. In these sensitivity tests we will examine the impact of: changing cropland NPP over time, residue removal, assumptions about the productivity of “other arable” land, and the impact of the adoption of no-till agricultural practices. To keep the interpretation of results straightforward, we generally apply altered assumptions for all time periods, or over the 21st century in the case of no-till. While a more realistic scenario might use changing assumptions over time, we wish here to examine the impact of these uncertain assumptions in order to determine which areas might be useful topics for future research.

The sensitivity tests discussed in this work are summarized in Table 3. We consider different levels of above-ground residue removal. Residue can be removed by burning of residue while still on fields (Yevich and Logan, 2003) or removal of residue for use as fuel (Fernandes et al., 2007), construction material, or fodder. Note that we do not explicitly consider the impact of residue removal on erosion or nutrient balance, which will also impact carbon stocks (Gregg and Izaurralde, 2010). These sensitivity tests, however, will provide an estimate of the importance of residue removal relative to other uncertainties.

As discussed above, the characteristics of “other arable land” are uncertain. Our central assumption, that the productivity of this land is equal to grassland, may be overly optimistic if for example, if land that is lying fallow due to nutrient depletion from crop harvest has lower productivity, or if arable land that is not being used to produce crops is inherently less productive than lands chosen to plant crops. An alternative scenario is considered where the NPP of other arable land is taken to be half that of grassland in the same region.

We also consider a strawman scenario where cropland NPP is taken to be constant over time. While this is not a realistic scenario, this might be a simplifying assumption made in some global models.

Finally, in many areas of the world significant areas of cropland, particularly grain and soybean crops, are now managed using conservation tillage practices such as low and no-till (Derpsch et al., 2010). In the two initial sensitivity cases we assume that no-till practices are applied to 25 and 50 % of harvested area phased in from 2000 to 2020. Following Six and Jastrow (2012), we assume that the turnover timescale of the slow carbon pool is increased by 50 % for lands under no-till, noting that these gains may not be applicable to all cropping systems (Hermle et al., 2008).

2.4 Carbon loss under conversion to cropland

On conversion from native ecosystems to cropland, the previous vegetation is removed and soil is generally physically mixed. As a result, a significant portion of the carbon previously in the soil is oxidized and released to the atmosphere. Literature reviews find that about 30 % of soil carbon is lost to the atmosphere within a few years of the land-use transition, which we take as our central assumption, although a range of values were also found (Murty et al., 2002; Guo and Gifford, 2002; Luo et al., 2010; Don et al., 2011). This initial rapid loss of carbon is modeled as an instantaneous loss upon land-use conversion and is not included in the results for LUC emissions below, which focus on the longer-term changes in cropland carbon pools.

This amount of carbon lost on conversion is uncertain, however, due to difficulties in finding matching conditions pre-and post-conversion, differences in measurement protocols between studies, and regional differences in soil conditions. In addition, for much of the period under consideration here, we are concerned with conversions that occurred up to 1–3 centuries ago, where both conversion practices and, perhaps more importantly, cropping practices could have been different than those practiced today.

If, as modeled here (Eqs. 1–3), cropland soil contents approach the same equilibrium state regardless of the land-use conversion process, then assumptions about the amount of carbon lost during conversion will not change the total carbon release, but will change the distribution of emissions over time. The slow and passive carbon pools have timescales substantially longer than a few years. This implies that if the cropland soil carbon contents after conversion to cropland are not in equilibrium with the values implied by agricultural practices at the time of emission, then a slow transition toward some equilibrium state will take place.

In general, particularly for cropped areas before the 20th century, cropland NPP is less than that of most natural ecosystems, which implies a substantially lower equilibrium carbon density for cropland. Even with a significant portion of carbon lost during the land-use change transition, croplands could be a net source of emissions to the atmosphere for long after the transition. Over time, particularly with the generally decreased soil turnover time due to annual tillage, as compared to native ecosystems, cropland soil carbon values would come closer to values that are in equilibrium with crop carbon inputs and net emissions from cropped lands would slow.

Global cropland emissions, measured after land-conversion, vary by up to $\pm 30\,\mathrm{Gt\,C\,yr^{-1}}$ if the fraction of carbon released during conversion to cropland is varied from 20 to 40 % (Fig. 1). If a larger (smaller) fraction of soil carbon is lost upon conversion to cropland then there will be lower (higher) residual land-use change emissions from croplands over time. The impact of changes in the assumed carbon release is largest in the 1960s at $\pm 30\,\mathrm{Gt\,C\,yr^{-1}}$ and decreases to $\pm 15\,\mathrm{Gt\,C\,yr^{-1}}$ in 2050 and $\pm 8\,\mathrm{Gt\,C\,yr^{-1}}$ in 2100 as land-use conversion rates slow in the 21st century under the RCP4.5 future land-use scenario and as cropland soil carbon contents begin to converge toward the same equilibrium values.

Here we have assumed that soil carbon remaining after the initial conversion event is partitioned evenly between the slow and passive carbon pools. We implicitly assume that the same timescale applies to both equilibrium cropland carbon dynamics and any remaining carbon inherited from a land-use conversion event. It is unclear if these simplifying assumptions are fully applicable, but these appear to be reasonable first order approximations.

Assumptions for the initial amount of carbon lost upon land conversion has a long-term impact on cropland carbon content and net carbon balance. Given the diversity of past and present land-conversion practices and physical context (soil type, rainfall, pre-existing vegetation type) better constraints on land-use carbon dynamics would likely entail substantial effort.

3 Results

Figure 2 shows net land-use change emissions from croplands under the sensitivity assumptions discussed above. These values represent the net change in cropland carbon pools, primarily soil carbon, excluding emissions that occur as part of land-use conversion. In other words, these are the values that would be measured over time in in established croplands.

The central case has a net global release of 18 GtC from croplands over 1800 and 2000. These emissions are dominated by residual emissions from conversion of carbon-rich native ecosystems to croplands in the Canada, the US, and the Former Soviet Union (Fig. S1, Supplement). Note that these figures do not include the initial release of carbon, for example from above-ground vegetation, as part of the land-use change process (Sect. 2.4).

In the central case, global croplands are a net sink of carbon by 2000. There is a large increase in the cropland sink from 2000 to 2005, which is largely due to increasing cropland NPP in several regions over this time period. The central case has a net uptake of 6 GtC over the 21st century (Table 4), with large uptake levels in South East Asia, India, and Latin America (Fig. S1, Supplement).

We find that the assumed productivity of other arable land, that is land not harvested in a given year, has a large impact on historical cropland emissions. Emissions over the last two centuries increase by 7 GtC if other arable land is assumed to have only half the productivity of grassland. The impact of the assumptions for other arable land diminish in the 21st century because the land-use scenario used here shifts more of this land to either active use as cropland or into other land uses.

We also examined an alternative case, where other arable land was assumed to have the same productivity of cropland. The result was very similar for the historical period, since before the late 20th century, cropland productivity was much lower than that of natural ecosystems. This assumption, however, over-estimates cropland carbon uptake in the 21st century given the large assumed increases in cropland NPP in the scenario used here.

It is also useful to consider the implications of other simplistic treatments of cropland. Smith and Rothwell (2013) found that treating cropland as grassland underestimates historical emissions. We find here that if cropland NPP is taken to be constant over all time at our estimated year 2000 values, then historical emissions will be underestimated by 2 GtC. A much larger impact is seen on 21st century emissions, however, where emissions are over-estimated by 10 GtC. This is due to both the assumed future increases in crop NPP in the 21st century and also the long-term impacts of 20th century NPP increases that have not been fully realized in terms of soil carbon stock changes.

Removal of 25 % of above-ground residue increases net historical emissions from cropland by 2 GtC, and increases emissions over the 21st century by 4 GtC. The impact of residue removal is larger in the future due to both an increased scale of agricultural output and the assumption that harvest index values do not increase significantly in the 21st century, which means that the assumed NPP increases translate directly to increases in residue production and potential carbon inputs into the soil. The impact of residue removal on cropland carbon emissions in this model is linear with the amount of residue removed.

In contrast to residue removal, increased implementation of no-till agricultural practices over the 21st century will increase soil carbon sequestration, with an additional 3 GtC stored in agricultural soils if 25 % of land is converted to no-till practices.

In terms of annual rates of cropland carbon flows, differences in residue removal (0 or 25 %) and other arable land productivity assumptions (as grassland or half of grassland) result in a global cropland carbon release ranging from 90 to 180 MtC in 1960. By 2000 these differing assumptions range from a net uptake of 20 MtC yr^{-1} to a net release of 90 MtC yr^{-1}. The range is still substantial by 2050, but all combinations of these assumptions lead to a net uptake ranging from 20 to 90 MtC yr^{-1}.

Interaction between residue removal and no-till

Given the opposing effects of residue removal and no-till agricultural practices we now focus on the combination of these two effects. The impact of 25 % residue removal combined with 50 % no-till adoption nearly cancel when averaged over the 21st century (Table 4).

To put these stylized scenarios into context, Yevich and Logan (2003) estimate that, around 2000, 500 MtC of crop residues were burned on fields or as fuel. This is 30 % of our estimated year 2000 above ground residue. Derpsch et al. (2010) estimated that adoption of no- or occasional-till practices has been increasing steadily and now has been adopted on 111 million Hectares of cropland, which is 11 % of global harvested land in 2000.

One motivation for removing crop residue is for use as a low-carbon fuel. In many modeling systems (e.g. Luckow et al., 2010), residue removal is considered carbon neutral. In terms of overall carbon balance, the removal of residue has only a small “carbon penalty”, with increased land-use change emissions that ranged from 10 % of the carbon content of the residue removed early in the 21st century to 4 % late in the 21st century as the system has come closer to equilibrium (Fig. 3). This is comparable in magnitude to the results found in a detailed modeling study of residue removal in the US (Gregg and Izaurralde, 2010). Note, however, that we did not consider the impact of residue removal on crop productivity or carbon loss through erosion that would likely increase this value. As also found above, the impact of residue removal is slightly larger, in relative terms, under no-till than under conventional tillage.

Under 50 % no-till and no residue removal, the maximum global uptake is 160 MtC yr^{-1} in 2020. This is similar to the maximum values found in Thomson et al. (2008). Residue removal reduces this value, however, with 2020 uptake under 50 % no-till adoption equal to 100 and 30 and 90 MtC yr^{-1} with 25 and 50 % residue removal, respectively. Maximum uptake rates for no-till adoption are, therefore, only achievable if most crop residue is left on fields.

The interaction between residue removal and the adoption of no-till practices is slightly non-linear with respect to non-till adoption. As compared to the case with no residue removal, 25 % removal resulted in 2050 (2100) global carbon emissions from cropland that were emissions are 43 (21) MTC yr^{-1} higher under conventional tillage, 47 (23) MTC yr^{-1} higher under 25 % no-till, and 50 (26) MTC yr^{-1} higher under 50 %

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no till. The relative impact of residue removal was, as expected, independent of the assumptions for other arable land productivity.

Finally, in Fig. 4, we consider the consequences of a stylized scenario where global crop residue removal increases from an assumed value of 25 % up to 2005, to 50 or 75 % in 2050. Shown are net global cropland carbon emissions under four management practices ranging from conventional tillage to 75 % adoption of no-till. If 50 % of cropland residue is removed then 50 % application of no-till would be required for a neutral global cropland carbon balance by the end of the century. If 75 % of residue were removed, however, even under a 75 % application of no-till practices global cropland would be a net source of carbon to the atmosphere through most of the 21st century.

4 Conclusions

A simple model of regional and global terrestrial carbon-dynamics has been used to examine long-term cropland carbon including changes in land-use, crop productivity, and changes in management practices. We find that cropland carbon balance is sensitive to a number of input assumptions that are either not well constrained or not included in most current global models. We find that a key assumption impacting historical estimates of cropland carbon balance is the assumed productivity of land that is classified as cropland, but from which crops are not harvested in a given year. Better characterization of lands classified as cropland, both at present and in the past, is therefore needed to reduce this uncertainty. Cropland emissions as defined here are 7–10 % of global land-use change emissions as found in Smith and Rothwell (2013).

Assumptions about historical changes in residue removal have only a modest impact on historical carbon uptake, which indicates that our neglect of likely varying rates of residue removal in the past may not substantially alter these results. Residue removal has a somewhat larger impact on future cropland carbon stocks and should be considered in future scenarios. Under a 4.5 $\mathrm{W\,m^{-2}}$ stabilization scenario using the release version of the Global Change Assessment Model (GCAM) version 3.1 (available at http://www.globalchange.umd.edu/models/gcam/download/), for example, nearly 80 % of total crop residue is removed for use as biomass feedstock (Luckow et al., 2010). These larger amounts of residue removal occur mid to late 21st century where higher crop productivity is assumed to allow substantial bio-energy supply from residues while allowing sufficient residue retention for erosion control (Gregg and Smith, 2010).

We find that the widespread future adoption of no-till practices must be coupled with residue removal at these rates in order to reduce the impact of residue removal on cropland carbon balance. Overall, we find that at the large rates of residue removal seen in future scenarios, global croplands become a net carbon source. While agricultural carbon sequestration can be a non-trivial component of future carbon abatement policies (Thomson et al., 2008), large amounts of agricultural carbon sequestration are not consistent with the large amount of residue removed in some future scenarios. Given the relatively low “carbon penalty” associated with residue removal (e.g. Fig. 3), residue removal for use as an energy feedstock may have more value than additional carbon in agricultural soils. However, local soil characteristics need to be taken into account in order to limit impacts on erosion and crop yield (Gregg and Izaurralde, 2010).

The range of historical assumptions considered here result in an approximately 100 $\mathrm{MtC\,yr^{-1}}$ spread in 20th century emissions from cropland, and a somewhat larger spread of emissions over the early 21st century under large-scale changes in cropland management such as application of low-till practices or large-scale residue removal as an energy feedstock (Fig. 2). This results in a cumulative difference in cropland carbon emissions of 10 GtC over 1800–2000 and 18 GtC over the 21st century. These uncertainties are smaller, on a global scale, than the largest sensitivities found by Smith and Rothwell (2013). These are comparable, for example, to the change in emissions due to the use of lower tropical forest carbon densities (Smith and Rothwell, 2013; Table 6). Treating cropland as a grassland results in a large bias in historical emission estimates of 50 GtC over 1850–2000, larger than any of the effects seen here.

More detailed data characterizing current and historical cropland would enable improved estimates of cropland carbon balance. Cropland area that has been in long-term use as pasture, for example, might be better represented as land-use change rather than has part of cropland. Historical reconstructions of cropland also differ greatly and further research on this topic is clearly of great importance. We did not consider here the application of manure or other management techniques that might increase cropland soil carbon. The potential importance of South Asian areas for future cropland carbon uptake indicates that the applicability of the simple model used here for tropical cropping systems should be further investigated.

Data from this work are available from the author and will be archived at CDIAC.

Supplementary material related to this article is available online at http://www.earth-syst-dynam-discuss.net/5/1/2014/esdd-5-1-2014-supplement.pdf.

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References

Batjes, N.: Soil parameter estimates for the soil types of the world for use in global and regional modeling, ISRIC Report 2002/02c, available at: http://www.isric.orgS, International Food Policy Research Institute (IFPRI) and International Soil Reference and Information Centre (ISRIC), Wageningen, 46 pp., 2002.

Campbell, J. E., Lobell, D. B., Genova, R. C., and Field, C. B.: The global potential of bioenergy on abandoned agriculture lands, Environ. Sci. Technol., 42, 5791–5794, 2008.

Derpsch, R., Friedrich, T., Kassam, A., and Hongwen, L.: Current status of adoption of no-till farming in the worls and some of its main benefits, Int. J. Agric. Biol. Eng., 3, 1–22, 2010.

Don, A., Schumacher, J., and Freibauer, A.: Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis, Global Change Biol., 17, 1658–1670, 2011.

Fernandes, S. D., Trautmann, N. M., Streets, D. G., Roden, C. A., and Bond, T. C.: Global biofuel use, 1850–2000, Global Biogeochem. Cy., 21, GB2019, doi:10.1029/2006GB002836, 2007.

Goldewijk, K. K., Beusen, A., van Drecht, G., and de Vos, M.: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years, Global Ecol. Biogeogr., 20, 73–86, 2011.

Gregg, J. S. and Izaurralde, R. C.: Effect of crop residue harvest on long-term crop yield, soil erosion and nutrient balance: trade-offs for a sustainable bioenergy feedstock, Adv. Biochem. Eng. Biot., 1, 69–83, 2010.

Gregg, J. S. and Smith, S. J.: Energy from residue biomass, Mitig. Adapt. Strat. Global Change, 15, 241–262, doi:10.1007/s11027-010-9215-4, 2010.

Guo, L. B. and Gifford, R. M.: Soil carbon stocks and land use change: a meta analysis, Global Change Biol., 8, 345–360, 2002.

Hay, R. K. M. and Porter, J. R.: The Physiology of Crop Yield, 2nd edn., Blackwell Publishing, Oxford 314 pp., doi:10.1017/S0014479707005595, 2006.

Hermle, S., Anken, T., Leifeld, J., and Weisskopf, P.: The effect of the tillage system on soil organic carbon content under moist, cold-temperate conditions, Soil Till. Res., 98, 94–105, 2008.

Houghton, R. A.: How well do we know the flux of CO_2 from land-use change?, Tellus B, 62, 337–351, 2010.

Houghton, R. A., Hobbie, J. E., Melillo, J. M., Moore, B., Peterson, B. J., Shaver, G. R., and Woodwell, G. M.: Changes in the carbon content of terrestrial biota and soils between 1860 and 1980 – a net release of CO_2 to the atmosphere, Ecol. Monogr., 53, 235–262, 1983.

Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P., and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100, 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Climate Change, 109, 117–161, 2011.

Izaurralde, R. C., McGill, W. B., Robertson, J. A., Juma, N. G., and Thurston, J. J.: Carbon balance of the Breton classical plots over half a century, Soil Sci. Soc. Am. J., 65, 431–441, 2001.

Jain, A. K. and Yang, X. J.: Modeling the effects of two different land cover change data sets on the carbon stocks of plants and soils in concert with CO_2 and climate change, Global Biogeochem. Cy., 19, GB2015, doi:10.1029/2004GB002349, 2005.

Lobell, D. B., Hicke, J. A., Asner, G. P., Field, C. B., Tucker, C. J., and Los, S. O.: Satellite estimates of productivity and light use efficiency in United States agriculture, 1982–98, Global Change Biol., 8, 722–735, 2002.

Luckow, P., Wise, M. A., Dooley, J. J., and Kim, S. H.: Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO_2 concentration limit scenarios, Int. J. Greenh. Gas Con., 4, 865–877, 2010.

Luo, Z. K., Wang, E. L., and Sun, O. J.: Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: a review and synthesis, Geoderma, 155, 211–223, 2010.

Murty, D.„ Kirschbaum, M. U. F., McMurtrie, R. E., and McGilvray, A.: Does conversion of forest to agricultural land change soil carbon and nitrogen? a review of the literature, Global Change Biol., 8, 105–123, 2002.

Pongratz, J., Reick, C. H., Raddatz, T., and Claussen, M.: Effects of anthropogenic land cover change on the carbon cycle of the last millennium, Global Biogeochem. Cy., 23, GB4001, doi:10.1029/2009GB003488, 2009.

Ramankutty, N. and Foley, J. A.: Estimating historical changes in global land cover: croplands from 1700 to 1992, Global Biogeochem. Cy., 13, 997–1027, 1999.

Shevliakova, E., Pacala, S. W., Malyshev, S., Hurtt, G. C., Milly, P. C. D., Caspersen, J. P., Sentman, L. T., Fisk, J. P., Wirth, C., and Crevoisier, C.: Carbon cycling under 300 years of land use change: importance of the secondary vegetation sink, Global Biogeochem. Cy., 23, GB2022, doi:10.1029/2007GB003176, 2009.

Sinclair, T. R.: Historical changes in harvest index and crop nitrogen accumulation, Crop Sci., 38, 638–643, 1998.

Six, J. and Jastrow, J. D.: Soil organic matter turnover, in: Encyclopedia of Soil Science, edited by: Lal, R., Marcel Dekker, New York, 936–942, 2002.

Smith, S. J. and Rothwell, A.: Carbon density and anthropogenic land-use influences on net land-use change emissions, Biogeosciences, 10, 6323–6337, doi:10.5194/bg-10-6323-2013, 2013.

Thomson, A. M., Izaurralde, R. C., Smith, S. J., and Clarke, L. E.: Integrated estimates of global terrestrial carbon sequestration, Global Environ. Change, 18, 192–203, 2008.

Yevich, R. and Logan, J. A.: An assessment of biofuel use and burning of agricultural waste in the developing world, Global Biogeochem. Cy., 17, 1095, doi:10.1029/2002GB001952, 2003.

Table 1. Effective crop NPP over time for harvested cropland by region ($\mathrm{kg\,C\,m^{-2}}$), which is the total above- and below-ground crop NPP minus the amount removed in grain. Data after 2005 are model projections from the GCAM RCP4.5 scenario. Where data are not available for early years (e.g. before 1940), the value from the earliest available year is used.

	Africa	Australia & NZ	Canada	China	Eastern Europe	Fmr Soviet Union	India	Japan	Korea	Latin America	Middle East	Southeast Asia	USA	Western Europe
1870			0.11										0.09	0.15
1900			0.13		0.11	0.06	0.19	0.45					0.10	0.16
1940	0.06	0.07	0.19	0.29	0.12	0.08	0.14	0.56	0.50	0.12	0.10	0.23	0.12	0.17
1950	0.08	0.12	0.18	0.22	0.10	0.08	0.11	0.50	0.50	0.20	0.11	0.20	0.13	0.17
1962	0.10	0.13	0.12	0.18	0.13	0.08	0.14	0.55	0.54	0.21	0.09	0.21	0.15	0.18
1970	0.10	0.13	0.15	0.24	0.17	0.11	0.16	0.60	0.55	0.24	0.10	0.22	0.18	0.21
1980	0.12	0.13	0.17	0.31	0.20	0.12	0.17	0.55	0.68	0.27	0.10	0.27	0.20	0.24
1990	0.13	0.16	0.17	0.38	0.21	0.14	0.23	0.61	0.75	0.31	0.12	0.33	0.23	0.27
2000	0.14	0.21	0.19	0.42	0.20	0.11	0.28	0.54	0.66	0.35	0.14	0.41	0.25	0.31
2005	**0.15**	**0.19**	**0.21**	**0.42**	**0.21**	**0.15**	**0.30**	**0.53**	**0.59**	**0.40**	**0.18**	**0.49**	**0.27**	**0.30**
2020	0.23	0.25	0.22	0.48	0.22	0.16	0.38	0.53	0.59	0.55	0.19	0.65	0.29	0.33
2035	0.27	0.25	0.27	0.46	0.21	0.18	0.47	0.51	0.58	0.58	0.22	0.80	0.29	0.35
2050	0.28	0.26	0.29	0.44	0.20	0.20	0.51	0.46	0.57	0.59	0.22	0.82	0.28	0.36
2065	0.28	0.27	0.30	0.44	0.20	0.20	0.50	0.43	0.57	0.60	0.22	0.82	0.30	0.37
2080	0.28	0.28	0.32	0.46	0.20	0.19	0.48	0.43	0.58	0.60	0.22	0.81	0.32	0.38
2095	0.28	0.29	0.33	0.48	0.21	0.19	0.48	0.45	0.60	0.60	0.23	0.82	0.33	0.39
2100	0.29	0.29	0.34	0.48	0.21	0.19	0.47	0.45	0.61	0.60	0.23	0.82	0.34	0.40

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Table 2. Fraction total cropland that is harvested in a given year. Data after 2005 are model projections from the GCAM RCP4.5 scenario. Where data are not available for early years (e.g. before 1940), the value from the earliest available year is used.

	Fraction of total cropland that is Harvested													
	Africa	Australia & NZ	Canada	China	Eastern Europe	Fmr Soviet Union	India	Japan	Korea	Latin America	Middle East	Southeast Asia	USA	Western Europe
1870			0.23										0.53	
1900			0.26		1.00	0.70		1.00					0.62	0.86
1940	0.51	0.32	0.44	0.49	1.00	0.74	0.54	1.00	0.54	0.54	0.23	0.54	0.59	0.74
1950	0.70	0.28	0.42	0.74	1.00	0.66	0.60	1.00	0.61	0.48	0.42	0.60	0.59	0.66
1962	0.58	0.29	0.39	0.92	0.95	0.75	0.63	0.93	0.72	0.54	0.43	0.57	0.56	0.65
1970	0.64	0.31	0.41	0.92	0.89	0.72	0.64	0.76	0.75	0.54	0.51	0.61	0.56	0.67
1980	0.60	0.38	0.49	0.97	0.88	0.74	0.67	0.70	0.68	0.55	0.61	0.66	0.68	0.74
1990	0.70	0.33	0.54	0.81	0.90	0.69	0.70	0.60	0.64	0.58	0.72	0.67	0.59	0.80
2000	0.73	0.38	0.51	0.77	0.86	0.62	0.69	0.64	0.70	0.59	0.73	0.69	0.65	0.80
2005	**0.72**	**0.38**	**0.51**	**0.76**	**0.86**	**0.55**	**0.69**	**0.66**	**0.74**	**0.60**	**0.71**	**0.69**	**0.67**	**0.79**
2020	0.80	0.46	0.72	0.80	0.88	0.65	0.75	0.68	0.77	0.68	0.76	0.76	0.71	0.81
2035	0.85	0.60	0.81	0.89	0.92	0.78	0.80	0.73	0.80	0.78	0.83	0.83	0.82	0.86
2050	0.87	0.64	0.83	0.92	0.94	0.79	0.84	0.79	0.84	0.81	0.87	0.87	0.87	0.91
2065	0.87	0.64	0.82	0.93	0.95	0.80	0.85	0.83	0.87	0.82	0.87	0.88	0.88	0.92
2080	0.87	0.63	0.81	0.93	0.95	0.79	0.86	0.85	0.88	0.82	0.87	0.88	0.88	0.92
2095	0.86	0.62	0.80	0.92	0.95	0.78	0.86	0.84	0.88	0.81	0.87	0.88	0.87	0.92
2100	0.86	0.62	0.80	0.92	0.95	0.78	0.86	0.84	0.88	0.81	0.87	0.88	0.87	0.92

Table 3. Summary of the sensitivity tests.

Sensitivity case	Description
Default	No residue removal and conventional tillage for all years. NPP in other arable land equal to that of grassland for that region. Cropland NPP changes over time as described in the text.
25 % Residue Removal	25 % of above-ground residue is assumed to be removed for other purposes (fuel, construction, burned on fields, etc.).
50–75 % Residue Removal	As above with removal of 50 or 75 % of above-ground residue.
Lower NPP in Other Arable Land	The productivity of other arable land is assumed to have half the NPP of grassland (half the value in the central case).
Constant NPP	Aggregate cropland NPP is taken to be constant at year 2000 values.
25 % no-till	25 % of harvested crop area is assumed to be managed using no-till practices by 2020.
50–75 % no-till	As above with 50 or 75 % of harvested crop area under no-till.

Table 4. Total carbon emissions from croplands under the central scenario (MtC yr^{-1}) along with the difference from the central scenario for the sensitivity tests discussed in the text.

Cropland Carbon Emissions		
	1800–2000	2000–2100
Central Scenario Emissions (MtC)		
	18 000	−5300
Difference from central (MtC)		
Constant Cropland NPP	−2100	10 100
Lower NPP Other Arable	6800	−1500
25 % No-till	0	−2700
50 % No-till	0	−5200
25 % Residue Removal	1900	4100
25 %-notill_25 %ResRemove	1900	1600
50 %-notill_25 %ResRemove	1900	−570
50 % Residue Removal	3900	8200
25 %-notill_50 %ResRemove	3900	6000
50 %-notill_50 %ResRemove	3900	4000
75 %-res-removal	5800	12 300

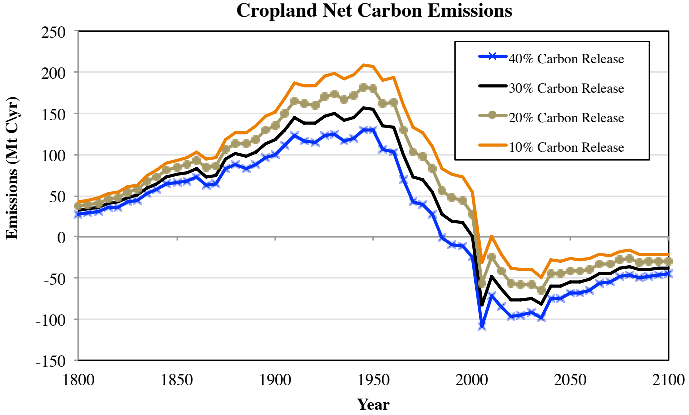

Fig. 1. Sensitivity of cropland carbon emissions to the assumed fraction of carbon in the native ecosystem that is released during land-use conversion.

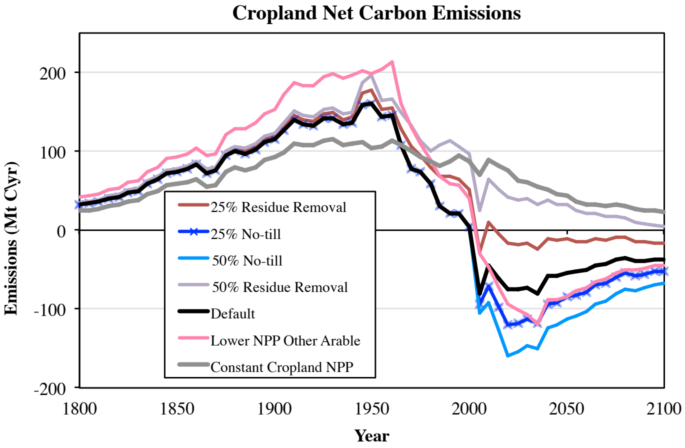

Fig. 2. Net carbon emissions from cropland over time by region. The Default case assumes conventional tillage and no residue removal.

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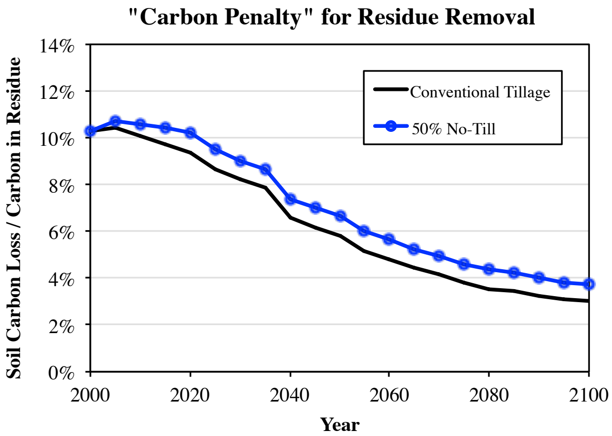

Fig. 3. Increase in carbon emissions from cropland due to 25 % residue removal divided by the carbon content of the removed residue for both conventional tillage and 50 % adoption of no-till practices.

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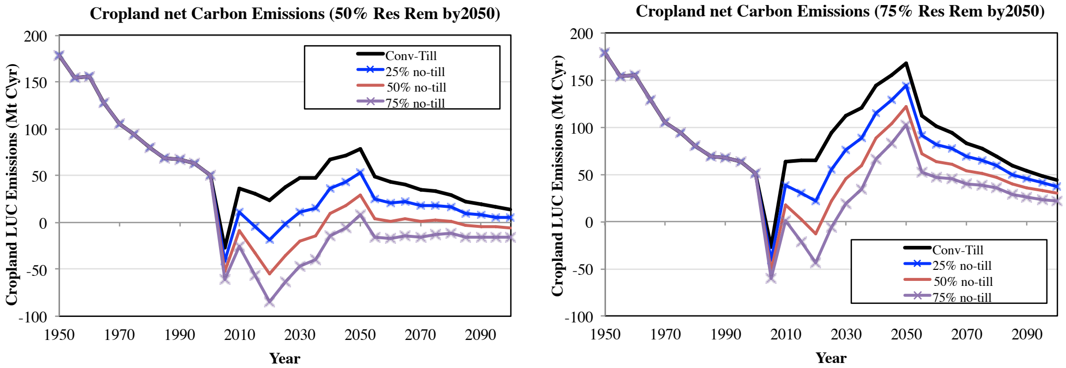

Fig. 4. Net carbon emissions from global cropland under two stylized future scenarios. 25 % of residue is assumed to be removed until 2005 in both cases, and linearly increased to either 50 % (left panel) or 75 % in (right panel) by 2050.