Historical Soil Organic Carbon Budget

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Abstract. SOC one of larges c sinks on earth (3 times larger biospehre pool). Agricultural management leads to a depletion of soil organic crabon. However this depletion of soil organic carbon (SOC) pools are so far not well represented in global assessments of historic carbon emissions. While SOC models often represent well the biochemical processes that lead to the accumulation and decay of SOC, the management decisions driving these biophysical processes are still little investigated. Here we create a spatial explicit data set for crop residue and manure management on cropland based on global historic production (FAOSTAT) and land-use (LUH2) data and combine it with the IPCC Tier 2 approach to create a half-degree resolution soil organic carbon budget on mineral soils. We estimate that due to arable farming soils have lost over (?) GtOC of which (??) GtOC have been released within the period 1990-2010. Tier 2 IPCC methodolgy estimates higher soil organic carbon losses than Tier 1 methods, which may origin from . . . . We also find that SOC is very sensity to management decision such as residue recycling indicating the nessessity to incorporated better management data in soil models.

1 Introduction

Introduction text goes here. You can change the name of the section if neccessary using `\introduction[modified heading]`.

2 Method (50)

2.1 Carbon Stocks following (new) Tier 2 method (50)

We calculate annual land use type specific soil organic carbon stocks for cropland, pastures and natural vegetation on half-degree resolution for the period of 1965 to 2010 based on the following three steps: (1) Calculating the land use (sub-)type specific steady-states and decay rates for SOC stocks given the current biophysical, climatic and agronomic conditions, (2) accounting for land conversation effects by transferring SOC between land use types and (3) updating SOC stocks based on the previous stock, the steady-state and the decay rate.

2.1.1 Steady-state SOC stocks and decay rates

In a simple first order kinetic approach the steady-state soil organic carbon stocks SOC^{eq} are given by

$$SOC^{eq} = \frac{C^{\text{in}}}{k} \tag{1}$$

with C^{in} being carbon inputs to the soil and k denoting the soil organic carbon decay rate. We use for our calculations the steady-state method of the refinement of the IPCC guidelines vol. 4 (IPCC (2019)) for mineral soils, which assume three soil carbon sub-pools (active, slow and passive) and entangled dynamics between them. Carbon inflow to each sub-pool (see @ref(sec:carboninputs)) and decay rates (see @ref(sec:tier2)) of each sub-pool are still the key components to determining steady-state SOC stocks.

2.1.2 Carbon Inputs to the Soil

We account for different carbon inputs sources depending on the land use type (see table @ref(tab:datasourceinputs)). Following the IPCC methodology carbon inputs are disaggregated into different structural components depending on their lignin and nitrogen content (see @ref(ipcc_2019_2019)). For each structural components the sum over all carbon inputs sources is allocated to the respective SOC sub-pools. This implies that not only the amount of carbon, but also their structural composition is determining the effective inflow. Data sources for all considered carbon inputs as well as for lignin and nitrogen content can be found in table @ref(tab:datasourceinputs).

2.1.3 Soil Organic Carbon decay (300)

Decay rates are influenced by climatic conditions, biophysical and biochemical soil properties as well as management factors that vary over time (t) and space (i). Following the steady-state method of the refinement of the IPCC guidelines vol. 4 (IPCC (2019)) for mineral soils we consider temperature (temp), water (wat), sand fraction (sf) and tillage (till) effects to spatially

Table 1. Type and data sources for carbon inputs to different land use types

Land use types	source of carbon inputs	data source	nitrogen and lignin content
Cropland	residues	FAOSTAT, LPJmL4 [2, sec:residues]	default values given by [2]
	dead below ground biomass of crops	FAOSTAT, LPJmL4 [2, sec:residues]	default values given by [2]
	manure	FAOSTAT, Isabelle [2, sec:manure]	default values given by [2]
Pasture	annual litterfall	LPJmL4 [3]	default values given by [2]
	manure	FAOSTAT, Isabelle [2, sec:manure]	default values given by [2]
Natural vegetation	annual litterfall	LPJmL4 [4]	Nitrogen and lignin content of tree compartments used in CENTURY [4]

disaggregate default global decay rates. Since the three different SOC sub-pools represent different SOC characteristics, the global decay rates and the associated drivers differ. Thus k_{sub} is given by

$$\begin{aligned}
k_{active,t,i} &= k_{active} &&\cdot temp_{t,i} \cdot wat_{t,i} &&\cdot till_{t,i} \cdot sf_{t,i} \\
k_{slow,t,i} &= k_{slow} &&\cdot temp_{t,i} \cdot wat_{t,i} &&\cdot till_{t,i} \\
k_{passive,t,i} &= k_{passive} &&\cdot temp_{t,i} \cdot wat_{t,i}
\end{aligned} \tag{2}$$

For cropland we performed an assessment of tillage types and irrigation conditions, whereas on pastures and natural vegetation, we assume rainfed and non-tilled conditions. Data sources as well as considered effects for each land use types are shown in table @ref(tab:datasourcedecay). To account for variations of decay rates within grid cells based on different tillage and irrigation regimes, average rates based on area shares are calculated.

Table 2. Type and data sources for carbon inputs to different land use types

Land use types	type of decay driver	parameter use to represent driver	data source
all	Soil quality	Sand fraction of the first 0-30 cm	[SoilGrids]
	Mircobial activity	air temperature	[CRUp4.0]
	Water restriction	precipitation & potential evapotranspiration	[CRUp4.0]
Cropland (additionally)	Water restriction*	irrigation	[sec:irrigation]
	Soil disturbance	tillage	[sec:tillage]

2.1.4 SOC transfer between land use types

We calculate SOC stocks based on the area shares of land use types (lut) within the half-degree grid cells (i). If land is converted from one land use type into others (!lut), a respective share of the SOC stocks have to be reallocated as well. We account for land conversion at the beginning of each time step t by calculating a preliminary stock $SOC_{lut,t*}$ via

$$SOC_{lut,t*} = SOC_{lut,t-1} - \frac{SOC_{lut,t-1}}{A_{lut,t-1}} \cdot AR_{lut,t} + \frac{SOC_{!lut,t-1}}{A_{!lut,t-1}} \cdot AE_{lut,t} \qquad \forall sub, i \tag{3}$$

with A being the area, AR the area reduction and AE the area expansion for a given land use type lut. Note that $!lut$ denotes the sum over all other land use types, which decreases in the specific time step t. Data sources and methodology on land use states and changes are described in @ref(sec:landuse).

2.1.5 Total SOC stocks

Carbon stocks SOC for each sub-pool (sub) converge towards the calculate steady-state stock SOC^{eq} for each land-use types (lut), each sub-pool (sub) and each annual time step (t) as represented in equation @ref(eq:steadystate).

$$SOC_t = SOC_{t-1} + (SOC_t^{eq} - SOC_{t-1}) \cdot k_t \cdot 1\text{a} \qquad \forall lut, sub, i. \tag{4}$$

The global SOC stock for each time step can than be calculated via

$$SOC_t = \sum_i \underbrace{\sum_{lut} \overbrace{\sum_{sub} SOC_{lut,sub,t,i}}^{SOC_{lut,t,i} \text{ - land use type specific SOC stock within cell}}}_{SOC_{t,i} \text{ - total SOC stock within cell}}. \tag{5}$$

2.2 Carbon Budget following Tier 1 (150)

Following the tier 1 approach of the IPCC guidelines vol. 4 (IPCC (2006)), stocks are estimated via stock change factors given by the IPCC for the topsoil (0-30 cm) and based on measurement data and expert choice. The factors differentiate between different crop and management systems reflecting different dynamics under changed in- and outflows without explicitly tracking these. This method is used additionally to the Tier-2 approach to evaluate model accuracy.

2.3 Agricultural management data on 0.5 degrees (50)

2.3.1 Landuse and Landuse Change (150)

Land use patterns are based on the Land-Use Harmonization 2 (LUH2, (**?**)) data set, which we aggregate from quarter degree to half degree resolution. We disaggregate the five different cropland subcategories of LUH2 into our 17 crop groups, assuming relative shares for each gridcell based on the country and year specific area shares of FAOSTAT data ((**?**)). Land use transitions are calculated as net area differences of the land use data on half-degree.

2.3.2 Crop, Crop Residues and Pasture Production (300)

Using half-degree yield data from LPJmL ((**?**)) as well as half-degree cropland patterns (see @ref(#sec:landuse)) we compile crop functional type specific half-degree production patterns. We calibrate cellular yields with one country-level calibration factor for each crop-group to meet historical FAOSTAT production ((**?**)).

Crop residues production is based on a revised methodology as described in ((**?**)) and will be explained in key aspects again due to its central role for soil carbon modelling. Starting from crop production estimates of the harvested organs and their respective crop area, we estimate above-ground (ag) and below-ground (bg) residual biomass using yield-dependent harvest indices and shoot:root ratios. We assume that all bg residues are recycled to the soil, whereas ag residues can be burned or harvested for other purposes such as feeding animals ((**?**)), fuel or for material use.

A fixed share of the ag residues is assumed to be burned on field, which depends on the per-capita income of the country. Following (**?**)) we assume 25% burn share for low-income countries according to worldbank definitions ($< 1000\,\frac{USD}{yr}$), 15% for high-income ($> 10000\,\frac{USD}{yr}$ and linearly interpolated shares for all middle-income countries.

Residue demand for feed is based on regional livestock specific feed basekts (see (**?**)) taking available ag residual biomass as well as livestock production systems and thus again development state into account. Here we aggregate crop groups to residue groups based on their suitability as feed (see @ref(append:Table_kcr2kres)).

We estimated a material use share for the straw residues group of 5% and a fuel demand share demand of 10% in low income countries.

The remaining ag residues are assumend to be recycled to the soil.

Using livestock production statistics as well as feed mix assumptions as describted in ((**?**)) we estimating country specific pasture production. Following the same approach as for crop production we disaggregate and calibrate half-degree pasture production pattern from grass yields from LPJmL and pasture area and rangeland patterns ((see @ref(#sec:landuse))) to derive half-degree pasture production patterns.

To transform dry matter estimates into carbon, we compiled crop and residue group specific carbon to dry matter (c:dm) ratios (see appendix table X) [citations] for harvested organs and applied a universal c:dm ratio of 0.44 [LPJml???] for all above and below ground residue biomass as well as for grass biomass.

2.3.3 Livestock Distribution and Manure Excretion (300)

To disaggregate country level FAOSTAT livestock production values to half-degree pattern, we use the following rule based assumptions which was inspired by the approach of (**?**).

For poultry, egg and monogastric meat production we

– divide into intensive and extensiv eproduction systems based on a per-capita (explain rules in more detail)

– Based on the development state (thats not a fixed term) of a country, we devide poultry, egg and monogastric meat production into intensive and extensive systems.

– Extensive production is allocated to built-up area share within a country based on the assumption that these animals are held in households, subsistence or small-holder farming systems.

– Intensive production is distributed within a country using the crop production (excluding 2nd generation bioenergy crops) share, assuming that feed availability is the most driving factor for livestock location.

For dairy and ruminated meat production we split into pasture fed and non-pasture fed fractions based on the aggregated feed mix within a country (explain rules)

– Pasture fed animals are distributed to half-degree cells according to the pasture production shares of that cell within a country (not methodologically clear description).

– Non-pasture fed animals are distributed again using crop production (excluding 2nd generation bioenergy crops) shares (not clear, either).

We calculate excretions by first estimating the nitrogen balance of the livestock system ((**?**)) on the basis of comprehensive livestock feed baskets ([weindl]), assuming that all nitrogen in protein feed intake, minus the nitrogen in the slaugher mass, is excreted. Carbon in excreted manure is estimated by applying fixed C:N ratios (given by ((IPCC, 2019)). What about animal waste management losses?

2.3.4 Irrigation (100)

Simple growing period calculations together with irrigation shares of LUH2v2 are used (BB: you dont like d’s, on’t you) to estimate water effects on decay rates.

2.3.5 Tillage (100)

Tillage data sets of [Vera, others] together with rules are used to drive tillage effect on decay rates.

3 Results

4 Discussion

Shortcommings:

- Carbon displacement via leaching and erosion is neglected in this study.
- Non-net/Gross land use transitions are not tracked in this study.
- Within cropland we do not track area transitions, but rather look at statistical distributions of the crop functional types. Due to crop rotations and missing data on crop specific distributions, these transitions would be any way rather uncertain.

5 Conclusions

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Code and data availability. use this to add a statement when having data sets and software code available

Appendix A: Figures and tables in appendices

A1 Option 1

If you sorted all figures and tables into the sections of the text, please also sort the appendix figures and appendix tables into the respective appendix sections. They will be correctly named automatically.

A2 Option 2

If you put all figures after the reference list, please insert appendix tables and figures after the normal tables and figures.

`\appendixfigures` needs to be added in front of appendix figures `\appendixtables` needs to be added in front of appendix tables

Please add `\clearpage` between each table and/or figure. Further guidelines on figures and tables can be found below. Regarding figures and tables in appendices, the following two options are possible depending on your general handling of figures and tables in the manuscript environment: To rename them correctly to A1, A2, etc., please add the following commands in front of them:

Author contributions. Karstens wrote code and paper build on work of Bodirsky. Bodirsky and Popp revised paper.

Competing interests. The authors declare no competing interests.

Disclaimer. We like Copernicus.

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