Historical Soil Organic Carbon Budget

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Abstract. SOC one of larges c sinks on earth (3 times larger biosphere pool). Agricultural management leads to a depletion of soil organic carbon. 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. We show that, our results on global scale based on Tier 2 IPCC methodolgy are in good agreement with Tier 1 default assumptions. We also find that SOC is very sensitive to management decision such as residue recycling indicating the nessessity to incorporated better management data in soil models.

1 Introduction

Within the last centuries the recognition of soil organic carbon (SOC) has developed from being a major source of agricultural carbon emissions towards a potentially large additional sink to offset other green house gas emissions and thus mitigate climate change. Whereas the extent of sink potential by SOC enhancement is highly debated (add refs), it is largely agreed upon that the SOC pool itself is the biggest terrestrial carbon pool, over topping the atmospheric and even more the biospheric carbon pool multiple times. Even small changes in SOC drivers might lead to substantial shifts in earth carbon cycled and influence the atmospheric CO2 concentration (ref. permafrost melting). The specific amount of carbon stored in the soil is uncertain though and estimates ranging from 1500 to 2400 GtC for the first meter of the soil profile (Bathjes, 1996).

Mapping the worlds SOC has been of great interest over the last decades and led to an increased quality of SOC maps as well as a even better understanding of factors driving magnitude, distribution and dynamics of SOC pools. It is undisputed that natural properties like climatic, biophysical and landscape characteristics play the most important role in this regard. These factors can not be easily altered by human intervention, leaving land cover, land use and land management changes the most important factors for SOC dynamics till dawn of civilization .

Recent studies identified the SOC debt of anthropogenic source at around 116 GtC (Sanderman et al.), which compares to older estimates of around 60-130 GtC (Lal, 2006). Other studies have focus more closely on spatially disaggregation SOC changes via advanced digital soil mapping techniques (S-World; Stoorvogel 2, 2017) or better representation of biogeochemcial processes within SOC dynamics (). Most of these studies doing cutting edge research in their field, but seem to lack proper representation of available information on land management.

On the other hand small-scale models (ref. Daycent, RothC, Ecosse, C-Tool) are able to represent fairly well SOC dynamics on field-scale driven by high quality management data on yield levels, fertilizer inputs and various other on farming activities. Due to the lack of proper, concise management data to feed these input demanding models on larger extends, it seems still very complex to scale them up to a global extent.

This study however wants to contribute filling the gap on impacts of agricultural management like yield levels, residue recycling, manure amendments, irrigation and tillage on SOC stocks of the worlds croplands. It is doing so by combining work on agricultural management data on global level with a robust but light weighted SOC model to estimate SOC stocks and stock change factors as well as OC flow dynamics within the agricultural system.

This is critically important since managing agricultural soil might be one of the few setscrew for humans to *naturally* combat climate change (ref. to natural climate solutions). Other *natural* options, which might be summarized by restoring potential natural stocks via renaturation of managed land, seem to be often limited due to increased pressure on the land systems for feed, food and energy demand of a growing and developing population on earth.

2 Method (50)

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

Following the tier 2 approach of the refinement of IPCC guidelines vol. 4 (IPCC (2019)), we estimate global land-use type specific soil organic carbon (SOC) stocks for cropland and natural vegetation on half-degree resolution from 1965 to 2010. We assume the actual SOC state converges towards a stable steady state, that itself is changing over time and space depending on biophysical, climatic and agronomic conditions. Therefore we conduct the following three steps within each yearly timestep: (1) We calculate annual land-use (sub-)type specific steady states and decay rates for SOC stocks, (2) We account for land conversion by transferring SOC between land-use types and (3) We estimate SOC stocks based on the stocks of the previous time period, the steady state stocks 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

$$SOC_t^{eq} = \frac{C_t^{\text{in}}}{k_t} \tag{1}$$

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. Annual carbon inflow to each sub-pool (see @ref(sec:carboninputs)) and annual decay rates (see @ref(sec:tier2)) of each sub-pool are still the key components to determining steady-state SOC stocks.

BB: I would include the t, also to show that the steady-state is time-dependent.

2.1.2 Carbon Inputs to the Soil

We account for different carbon input sources depending on the land-use type (see table @ref(tab:datasourceinputs)). Name here the inputs, and refer to the respective sections, dont just refer to the table. Following the IPCC methodology carbon inputs are disaggregated into metabolic and structural components depending on their lignin and nitrogen content (see @ref(ipcc_2019_2019)). For each component the sum over all carbon input sources is allocated to the respective SOC sub-pools via transfer coefficients. 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)

The sub-pool specific decay rates are influenced by climatic conditions, biophysical and biochemical soil properties as well as management factors that all vary over time (t) and space (i). Following the steady-state method of the refinement of the IPCC

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

land-use types BB: table header should be bold	source of carbon inputs	data source	nitrogen and lignin c
Cropland	residues	FAOSTAT, LPJmL4 [2, sec:residues]	default values given
	dead below ground biomass of crops	FAOSTAT, LPJmL4 [2, sec:residues]	default values given
	manure	FAOSTAT, Isabelle [2, sec:manure]	default values given
Natural vegetation	annual litterfall	LPJmL4 [4]	Nitrogen and lignin c compartments used i

guidelines vol. 4 (IPCC (2019)) for mineral soils we consider temperature (temp), water (wat), sand fraction (sf) and tillage (till) effects to account for spatial variation of decay rates. 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 distinguish the effect of different tillage (see @ref(#sec:tillage)) and irrigation (see @ref(#sec:irrigation)) practices on decay rates, whereas on 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 each grid cell due to 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), the respective share of the SOC stocks is reallocated. 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 calculated 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).

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

This equation can also be reformulated to a massbalance equation as follows:

$$SOC_t = SOC_{t-1} - k_t \cdot 1\text{a} + C^{\text{in}} \qquad \forall lut, sub, i. \tag{5}$$

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

$$SOC_t = \sum_i \underbrace{\sum_{lut} \overbrace{\sum_{sub} SOC_{lut,sub,t,i}}^{SOC_{lut,t,i} \text{ - land-use type specific SOC stock within cell}}}_{SOC_{t,i} \text{ - total SOC stock within cell}}. \tag{6}$$

2.1.6 Initialisation of SOC pools

To initialize all SOC sub-pools we assume that cropped land natural vegetation * steady-states or * spin up

2.2 Carbon Budget following Tier 1 (150)

Additionally to the tier 2 approach of the refinement of IPCC guidelines vol. 4 (IPCC (2019)), we also estimate SOC pools using the IPCC tier 1 approach of IPCC guidelines vol. 4 (IPCC (2006)) for comparison. Here, stocks are estimated via stock change factors given by the IPCC for the topsoil (0-30 cm) and based on a review of measurement data. The factors differentiate different crop and management systems reflecting different dynamics under changed in- and outflows without explicitly tracking these. The SOC stocks as thus calulated

$$SOC_{\text{target}} = \sum_{c,s,i} SOC_{\text{ref}_{c,s,i}} \cdot F_{\text{LU}_{c,s,i}} \cdot F_{\text{MG}_{c,s,i}} \cdot F_{\text{I}_{c,s,i}} \cdot A_{c,s,i} \tag{7}$$

<!- also include an equation here –> <!- even if there are just “copied” out of te guidelines so to say? –> <!- more details will follow - how deep to go? –>

2.3 Agricultural management data on 0.5 degrees (50)

Agricultural management data is estimated using the R library moinput ([cite git link]), which compiles country-specific FAO production and cropland statistics ((**?**)) to a comprehensive and constistent data suite. BB: Isnt the whole calculation based on R libraries? The data is prepared in 5 year time steps from 1965 to 2010, which also restricts our analysis to this time span. For all the following data, if not declared differently, we interpolate values linearly between the time steps and hold it constant before the first time step from 1961 to 1965. BB: too short for a spin-up, so dont use this word. Maybe also just ignore this detail.

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 (c3ann, c3per, c4ann, c4per, c3nfx) of LUH2 into our 17 crop groups, applying the relative shares for each gridcell based on the country and year specific area harvested shares of FAOSTAT data ((**?**)) (see @ref(append:Table_luh2fao2mag) for more details on the crop type mapping). 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)

2.3.3 Crop Production

Using half-degree yield data from LPJmL ((**?**)) as well as half-degree cropland patterns (see @ref(#sec:landuse)) we compile crop group specific half-degree production patterns. We calibrate cellular yields with one country-level calibration factor for each crop group to meet historical FAOSTAT production ((**?**)). Note that by using physical cropland areas we account for multiple crop harvest events as well as for fallows.

2.3.4 Crop Residue Production

Crop residue production and management is based on a revised methodology of ((**?**)) 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. BB: One new thing is here that we use a doublecropping factor to account for lower harvest indices of multicropping vs a very high single-cropped yield

2.3.5 Burned Residues

A fixed share of the ag residues is assumed to be burned on field depending 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 interpolate shares for all middle-income countries depending on their per-capita income. Depending on the crop type 80–90% of the residue carbon burned on the fields are lost within the combustion process ((IPCC, 2006)).

2.3.6 Residue Usage

We compile out of our 17 crop groups, three used residue groups (straw, high-lignin and low-lignin residues) with additional demand for other purposes and one residues with no double use (see @ref(append:Table_kcr2kres)).

Residue feed demand for five different livestock groups is based on country- and residue-group-specific feed basekts (see (**?**)) taking available ag residual biomass as well as livestock productivity into account.

We estimate a material-use share for the straw residues group of 5% and a fuel-share of 10% for all used residues groups in low income countries according to worldbank definitions ($< 1000 \frac{USD}{yr}$). For high-income ($> 10000 \frac{USD}{yr}$ no withdrawl for material or fuel use is assumend, leaving middle-income countries with linearly interpolate shares depending on their per-capita income.

The remaining ag residues as well as all bg residues are assumend to be recycled to the soil. We cut high recycling shares per hectar at the 95%-percentile to corrected for outliers.

2.3.7 Pasture Production

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. BB: Oh, does that mean we assume that only the pasture grows that is being eaten? Thats not too much, is it? Maybe ask Isabelle for a better solution (e.g. direct pasture yields from LPJmL). And then the "pasture production" is just the part being removed by grazing. Does the IPCC specifiy something in respect to pastures?

2.3.8 Dry Matter to Carbon Transformation

To transform dry matter estimates into carbon, we compiled crop-group and plant part specific carbon to dry matter (c:dm) ratios (see @ref(append:Table_c2dm)) (**?**).

2.3.9 Livestock Distribution and Manure Excretion (300)

2.3.10 Livestock Distribution

To disaggregate country level FAOSTAT livestock production values to half-degree pattern, we use the following rule based assumptions which were inspired by the approach of (**?**) and uses feed basket assumptions based on a revised methodology of **?**. We differentiate ruminant and monogastric systems, as well as extensive and an intensive systems. For ruminants, we use the country-level shares of gras within the feed baskets to split up pasture-fed, extensive systems from the rather intensive crop-fed livestock. For extensive dairy and ruminant meat production we estimate, that livestock is located in proximity to pastures and rangelands and distribute manure excretion proportional to pasture production of all half-degree gridcell of a country. Intensive dairy and ruminant meat production is assumend to be located proportinal to crop production to have short transport distances for feed stuff.

BB: What does not become clear to me: Do the extensive cows only eat pasture, and the intensive one only crops? Does that in the end mean we just redistirbute grazed pasture to pastures and crop-based feed to croplands proportional to production? Or is there more to it?

For poultry, egg and monogastric meat production we use the per-capita income of the country to divide into intensive and extensive production systems. For low-income countries according to worldbank definitions (<1000 USD/yr), we assume extensive production systems. We locate them according to built-up areas shares based on the idea that these animals are held in households, subsistence or small-holder farming systems with a high labour per animal ratio. Intensive production is distributed within a country using the crop production share, assuming that feed availability is the most driving factor for livestock location.

2.3.11 Manure Excretion, Storage and Recycling

Manure production and management is based on a revised methodology of ((**?**)) and will be explained in key aspects again due to its central role for soil carbon modelling. Based on the gridded livestock distribution we calculate excretions by estimating the nitrogen balance of the livestock system on the basis of comprehensive livestock feed baskets ((**?**)), assuming that all nitrogen in protein feed intake, minus the nitrogen in the slaughter mass, is excreted. Carbon in excreted manure is estimated by applying fixed C:N ratios (given by ((IPCC, 2019)). Depending on the feed system we assume manure to be handled in four different ways: All manure orginated from pasture feed intake is excreted directly to pastures and rangelands (pasture grazing), deducting manure collected as fuel. Manure fuel shares are estimated using IPCC default values (**?**). Whereas for low-income countries according to worldbank definitions (<1000 USD/yr), we adopt a share of 25% of crop residues in feed intake directly consumend and excreted on crop fields (stubble grazing), we do not consider any stubble grazing in high-income countries ($> 10000 \frac{USD}{yr}$, leaving middle-income countries with linearly interpolate shares depending on their per-capita income. For all other feed items we assume the manure to be stored in animal waste management systems associated to animal houses. To estimate the carbon actually recycled to the soil, we account for carbon losses during storage and recycling shares in different animal waste management and grazing systems. Whereas we assume no losses for pasture and stubble grazing, we consider that the manure collected as fuel is not recycled. For manure stored in different animal waste management system we compiled carbon loss rates partly depending on the nitrogen loss rates as specified in (**?**) (see @ref(append:Table_clossAWMS))).

2.3.12 Irrigation (100)

BB: Where does the irrigated area come from? Simple growing period calculations together with irrigation shares of LUH2v2 are used to estimate water effects on decay rates.

2.3.13 Tillage (100)

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

Table 3. SCF compared to potential natural state

	tropical_moist	tropical_dry	temperate_dry	temperate_moist
1965	0.25	0.33	0.55	0.48
1970	0.29	0.36	0.56	0.50
1975	0.32	0.38	0.57	0.51
1980	0.34	0.38	0.56	0.53
1985	0.36	0.40	0.60	0.56
1990	0.38	0.42	0.63	0.58
1995	0.40	0.45	0.63	0.59
2000	0.42	0.47	0.64	0.60
2005	0.45	0.54	0.69	0.65
2010	0.50	0.58	0.73	0.67

Table 4. SCF compared to actual natural state

	tropical_moist	tropical_dry	temperate_dry	temperate_moist
1965	0.25	0.33	0.55	0.48
1970	0.29	0.36	0.56	0.50
1975	0.32	0.38	0.57	0.51
1980	0.34	0.38	0.56	0.53
1985	0.36	0.40	0.60	0.56
1990	0.38	0.42	0.63	0.58
1995	0.40	0.45	0.63	0.59
2000	0.42	0.47	0.64	0.60
2005	0.45	0.54	0.69	0.65
2010	0.50	0.58	0.74	0.68

3 Results

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par(mar = c(4, 4, 0.1, 0.1))
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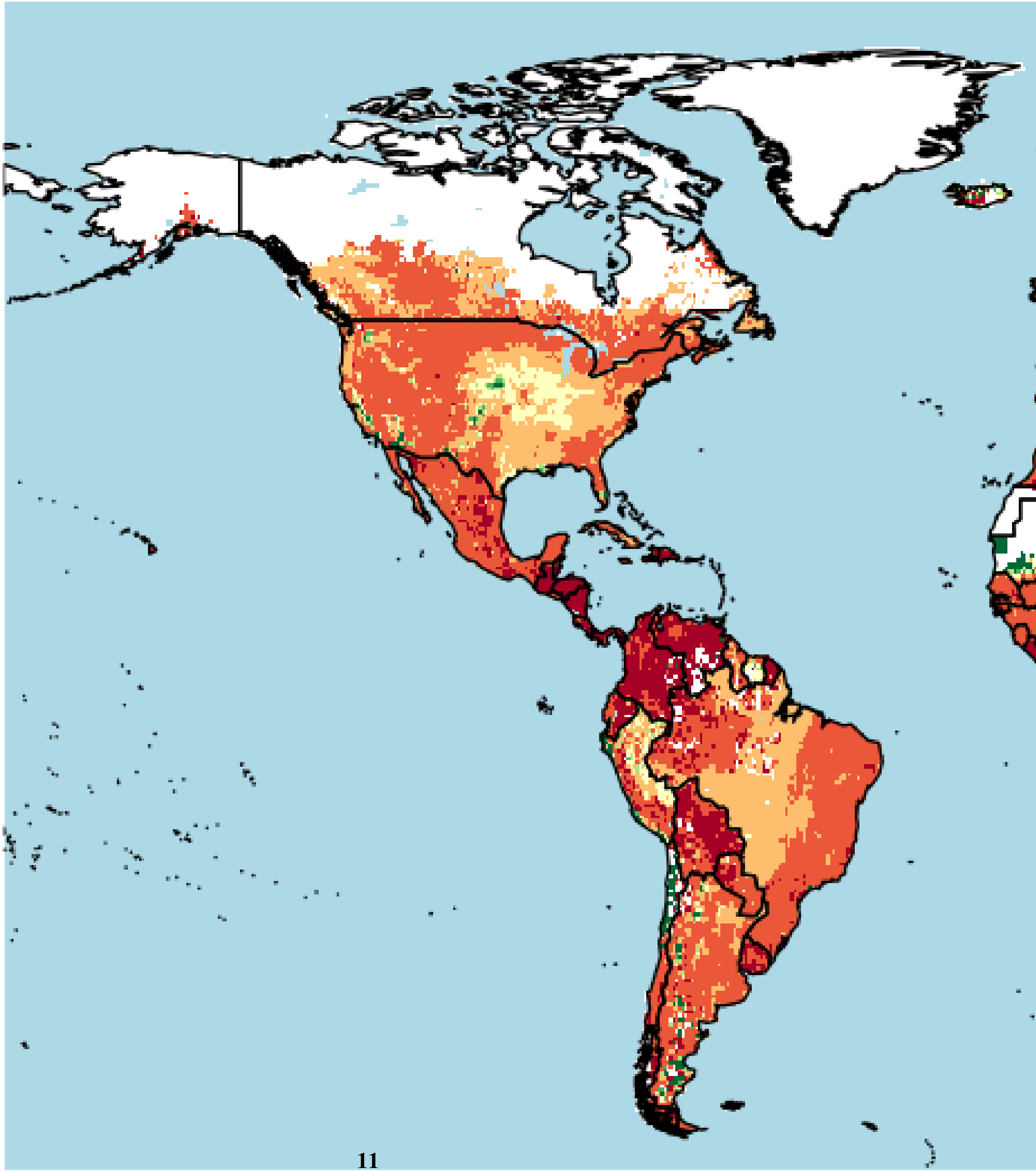
C_share on



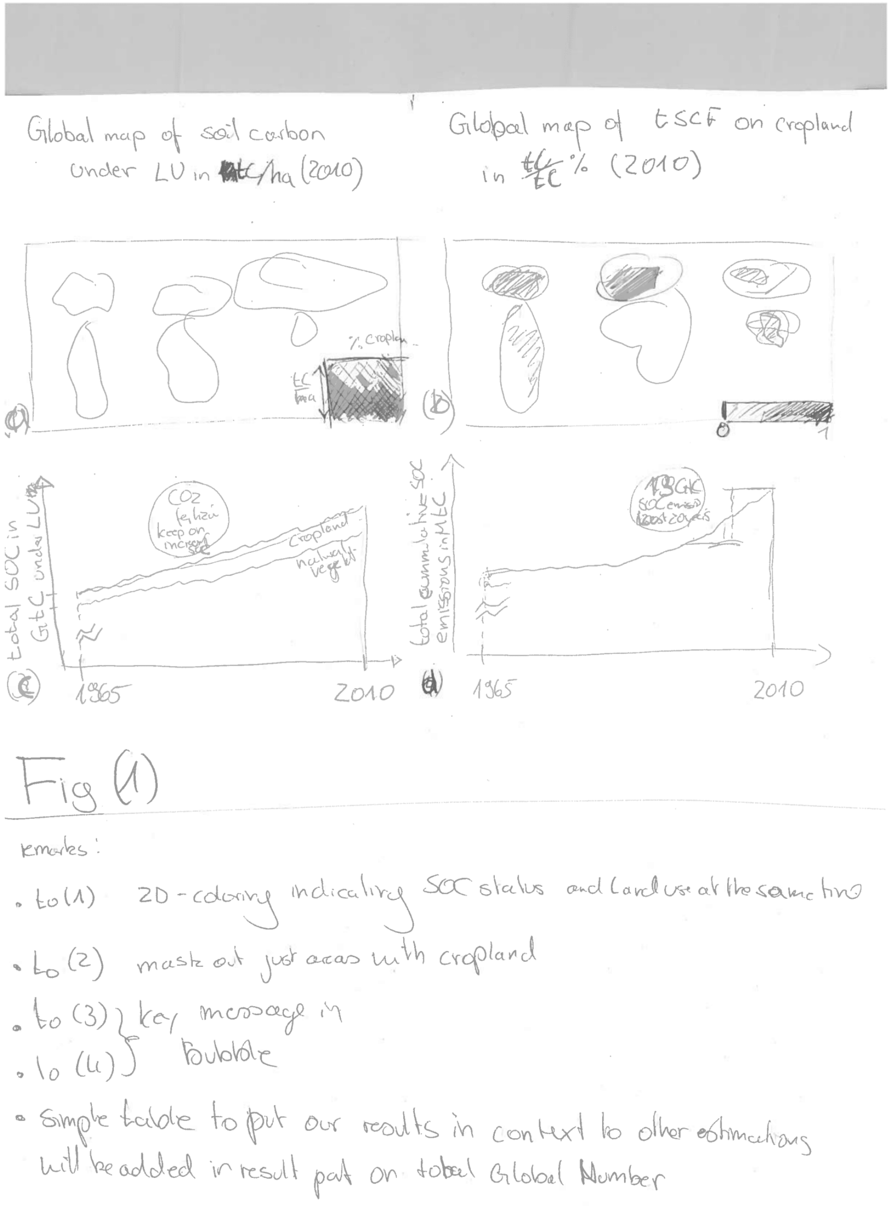


Figure 2. two column figure

	SCF - Tier 2 $\frac{tC}{tC}$ (%)	SCF - Tier 1 $\frac{tC}{tC}$ (%)
temperate dry	0.81 (*)	0.92
temperate moist	0.87 ( )	0.85
tropical dry	0.60 ( )	0.70
tropical moist	0.50 ( )	0.62

Fig 3. Comparison of stock change factors

(*) maybe including sensitivity analysis of Tier 2 approach here

remarks:

- if there are big mismatches (not clear so far), add a fig. (4) that adress the problem of "missing" carbon in the budget to come closer to Tier 1 approach values

Figure 3. two column figure

Soil related carbon flows in agricultural system 2010 (1985)
in MtC

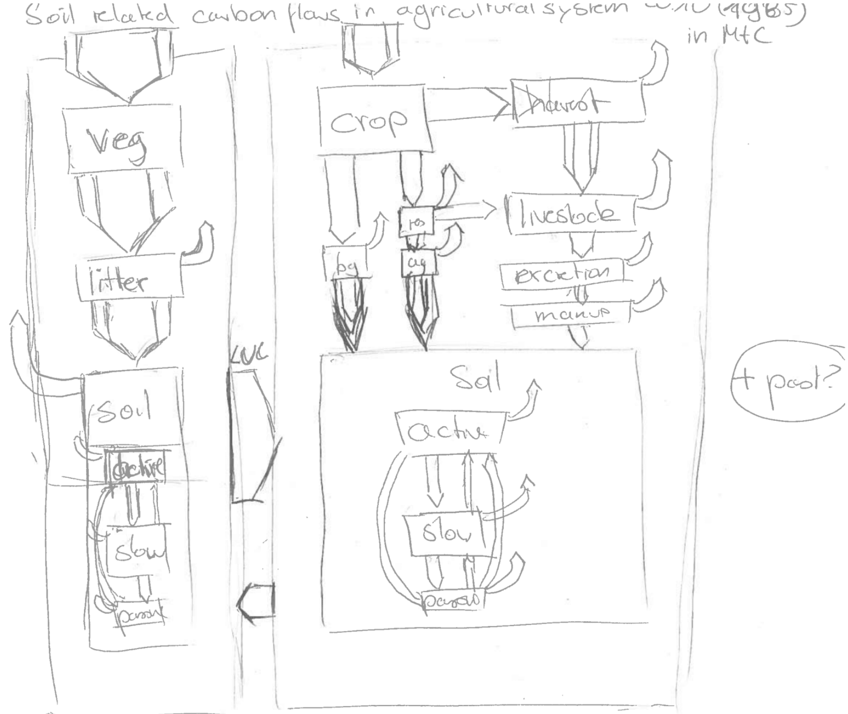


Fig (2)

remarks

- maybe including both data for 2010 and 1986 or 1965 (as in Benni Nitrogen Budget Paper)
- if pasture budget will be included explicitly has to be decided later (depending on ~~LPJml~~ additional LPJmL data that Susanne has to ~~be~~ provided)

Figure 4. two column figure

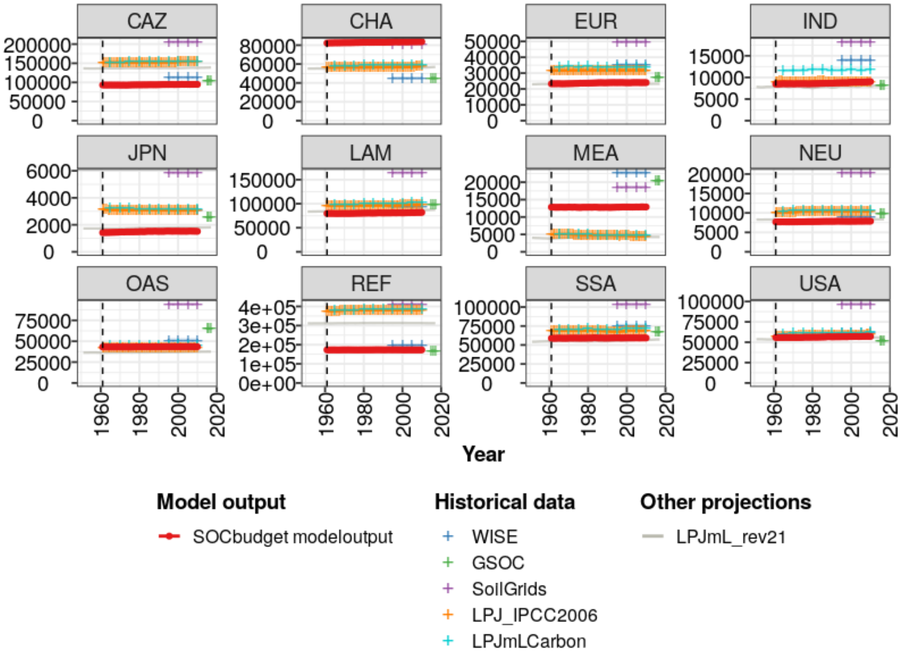


Figure 5. two column figure

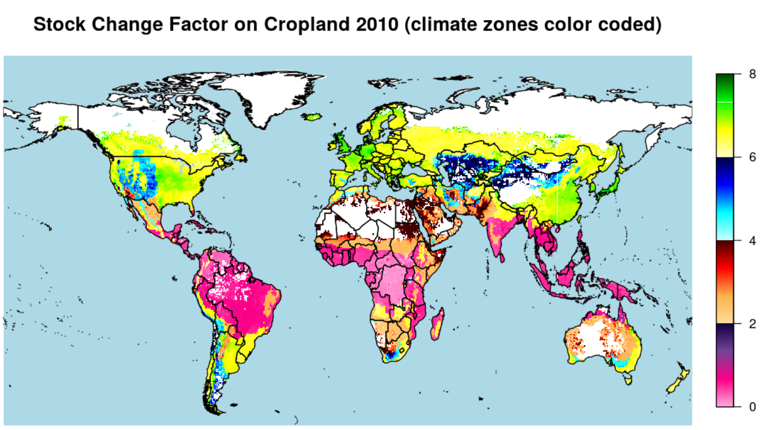


Figure 6. one column figure

Table 5. Steady state SCF compared to actual natural state

	tropical_moist	tropical_dry	temperate_dry	temperate_moist
1965	0.22	0.32	0.53	0.47
1970	0.24	0.46	0.52	0.53
1975	0.25	0.51	0.69	0.55
1980	0.26	0.45	0.68	0.63
1985	0.29	0.57	0.90	0.87
1990	0.31	0.60	0.90	0.87
1995	0.35	0.62	0.85	0.72
2000	0.37	0.67	0.85	0.78
2005	0.41	0.78	1.05	0.91
2010	0.47	0.83	1.30	0.95

4 Discussion

Big points:

- SOC initialization is bad (Task: find a better representation)
- natural land representation is lacking proper parametrization of natural input (n, lg content of litterfall) (–> ask Christop again)
- boreal zone and dry regions are not well represented (maybe because of the bad parameterization of the soil model for natural soils)
- As pointed out by Keel (2017), Smith (2019) the results might be highly sensitive to carbon input calculations more precisly to below and above ground residue carbon estimates derived from harvested quantities. It has been questioned, that below ground residues might increase with a fixed root:shot ratio (maybe specifically in high end farming systems (?)). Following this argumentation SOC results shown in this study might especially in high-yielding farming system (europe etc.) overestimate actual SOC stocks.
- fertilizer interaction (–> ask LPJmLer again)
- diaggregation of manure with urban area is leeding to a lot of displaced manure (?) that is cut off
- mismatches between FAO/LUH

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

The conclusion goes here. You can modify the section name with `\conclusions[modified heading if necessary]`.

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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References

IPCC: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Tech. rep., 2006.

IPCC: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories — IPCC, Tech. rep., https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/, 2019.