

# Management induced changes of soil organic carbon on global croplands

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**Abstract.** Soil organic carbon (SOC) is one of largest carbon stocks on earth. It is three times larger than the biospheric pool and more than twice as big as the atmospheric pool, when looking into the first meter of the earth soil profile. Human cropping activities led and still lead to a depletion of SOC though, which 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 on the global scale. Here we create a spatial explicit data set for agricultural management on cropland, especially for crop residue and manure management, 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 SOC stock changes on mineral soils. We estimate that due to arable farming soils have lost over 37 GtOC of which 4 GtOC have been regained within the period 1975-2010. We show that, our results on global scale based on Tier 2 IPCC methodology 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 necessity to incorporate better management data in soil models.

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# 1 Introduction

Possible titles:

- How management changed soil organic carbon on global croplands
- Agricultural soil have lost 37 GtC topsoil carbon
- 5    – Linking agricultural management data to soil modeling – a global approach

Soil Organic Carbon (SOC), the amount of organic carbon stored through the earth's soil, is the largest terrestrial carbon pool, exceeding the carbon in the atmospheric and biospheric pools multiple times (Bathjes). As such, even small changes in drivers of SOC may thus lead to substantial shifts in earth carbon cycle and influence the amount of CO<sub>2</sub> in the atmosphere (ref. permafrost melting). The specific amount of carbon stored in the soil is however uncertain, with estimates ranging from 10 1500 to 2400 GtC for the first meter of the soil profile (Bathjes, 1996). The quality of SOC maps has markedly improved in recent decades, along with better understanding of the factors driving the global magnitude, distribution, and dynamics of SOC pools. Natural properties like climatic, biophysical, and landscape characteristics clearly play the most important roles in this regard.

Human intervention, including land cover change and land management, has however added a further driver to SOC change, 15 which alters terrestrial carbon pools in much shorter time scales and is likely one of the most dominant driver of SOC changes on managed land today. Recent studies identify the anthropogenic SOC debt for the first meter of the soil profile at around 116 GtC (Sanderman et al.), compared to previous estimates between 60-130 GtC (Lal, 2006). Other studies have focused more closely on spatially disaggregation of SOC changes via advanced digital soil mapping techniques (S-World; Stoorvogel 2, 2017) or better representation of biogeochemical processes within SOC dynamics (Hararuk, 20XX). While providing a 20 rough estimate of the order of magnitude of change, these studies lack a detailed consideration of land management, especial agricultural activities.

Field-scale models (ref. Daycent, RothC, Ecosse, C-Tool) are able to capture these land mangement impacts by using detailed information on crop yield levels, fertilizer inputs and various other on-farm activities. However, due to the lack of comprehensive global management data as input to these models, scaling up to the global extent remains a complex challenge.

25 Our study combines an spatially explicit estimate of agricultural management data on the global level with a 3-pool SOC model parametrized for global croplands. This allows us to estimate SOC stock change factors, as well as organic carbon flow dynamics within the agricultural system. We thereby consider change in SOC caused by historical land cover change as well as of different agricultural mangement practices, including residue recycling, manure amendments, irrigation, and tillage. We thereby provide the first global, spatially explicit SOC loss maps that consider detailed agricultural management.

30 This paper will first introduce in the methods section the basic concept of SOC dynamics as applied in this study. We continue with a detailed description of the global gridded management data used here, including crop production levels, residue recycling rates, manure amendments, and the adoption of irrigation and tillage practices. Lastly, we shortly refer to the concept of stock change factors as outlined in the Tier 1 approach of the IPCC guidelines. In our results section we focus on the SOC

dynamics of global croplands by (1) analysing the spatially explicit distribution and depletion of SOC from 1975 to 2010, (2) comparing the climate zone specific stock changes with default stock change factors from the IPCC Tier 1 approach and (3) quantify global agricultural carbon flows and stocks to compare the importance of various management aspects. Finally, we will discuss our findings – including their implications for SOC model development – and conclude with an outlook on the

5 ability of SOC management to mitigate climate change and contribute to negative greenhouse gas emissions.

## 2 Method

We compile calculations as open-source R packages available at [github.com/pik-piam/mrcommons](https://github.com/pik-piam/mrcommons) (management related functions) and [github.com/pik-piam/mrSOCbudget](https://github.com/pik-piam/mrSOCbudget) (soil dynamic related functions), which are both based on the MADRaT package (package citation?), a framework which aims to improve reproducibility and transparency in data processing. In the following chapter we outline the most important relationships and assumptions. Table 6.1 provides further information on corresponding code within the R packages.

### 2.1 SOC Stocks and Stock changes following the Tier 2 steady-state method

Following the tier 2 approach of the refinement of IPCC guidelines vol. 4 (IPCC (2019); short Tier 2 steady-state method) , we estimate soil organic carbon (SOC) stocks and their change over time for cropland on half-degree resolution from 1975 to 2010. We assume the current SOC state converges towards a steady state, which itself is 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 from and to an other land-use type represented as natural vegetation, (3) we estimate SOC stocks and changes 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

$$SOC^{eq} = \frac{C^{in}}{k} \quad \forall \quad i, t \quad (1)$$

with  $C^{in}$  being carbon inputs to the soil,  $k$  denoting the soil organic carbon decay rate; as well as  $i$  representing grid cell indices and  $t$  years. We use for our calculations the Tier 2 steady-state method, which assumes three soil carbon sub-pools (active, slow and passive) and interactions between them. Annual carbon inflow to each sub-pool and annual decay rates of each sub-pool are the key components to determining steady-state SOC stocks.

#### Carbon Inputs to the Soil

We account for different carbon input sources depending on the two land-use types we distinguish: croplands and natural vegetated land as representative for all other land use (see table 1). Carbon sources for cropland are recycled crop residues, below ground biomass of crops (for both see 2.2.2) and recycled manure (see 2.2.3); for natural vegetation litterfall (Schaphoff et al., 2018) is the only source of carbon inflow to the soil.

Following the IPCC carbon accounting methodology, carbon inputs are disaggregated into metabolic and structural components depending on their lignin and nitrogen content (see IPCC (2019)). For each component the sum of all carbon input sources is allocated to the respective SOC sub-pools via transfer coefficients. This implies that both the amount of carbon as well as its structural composition determine the effective inflow. Data sources for all considered carbon inputs as well as for lignin and nitrogen content can be found in table 1.

**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]
Natural vegetation	annual litterfall	LPJmL4 [4]	Nitrogen and lignin content of tree compartments used in CENTURY [4]

**SOC decay**

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 Tier 2 steady-state method we consider temperature (temp), water (wat), sand fraction (sf) and tillage (till) effects to account for spatial variation of decay rates. Thus

5  $k_{sub}$  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 2.2.5) and irrigation (see 2.2.4) practices on decay rates, whereas for natural vegetation, we assume rainfed and non-tilled conditions. Data sources as well as drivers considered for each land-use types are shown in table 2. To account for variations of decay rates within each grid cell due to different tillage

10 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]

### 2.1.2 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

$$5 \quad SOC_{lut,t*} = SOC_{lut,t-1} - \frac{SOC_{lut,t-1}}{A_{lut,t-1}} \cdot AR_{lut,t} + \frac{SOC_{!lut,t-1}}{A_{!lut,t-1}} \cdot AE_{lut,t} \quad \forall \quad sub, i \quad (3)$$

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 2.2.1.

### 2.1.3 Total SOC stocks and stock changes

- 10 Carbon stocks  $SOC$  for each sub-pool ( $sub$ ) converge towards the calculated steady-state stock  $SOC^{eq}$  for each land-use type ( $lut$ ), each sub-pool ( $sub$ ) and each annual time step ( $t$ ) like

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

Reformulating this equation, we obtain a massbalance equation as follows

$$SOC_t = SOC_{t-1} - \underbrace{SOC_{t-1} \cdot k_t \cdot 1a}_{\text{outflow}} + \underbrace{SOC_t^{eq} \cdot k_t \cdot 1a}_{\text{input (using equation (1))}} \quad \forall \quad lut, sub, i. \quad (5)$$

- 15 The global SOC stock for each time step can then be calculated via

$$SOC_t = \underbrace{\sum_i \sum_{lut} \sum_{sub} SOC_{lut,sub,t,i}}_{SOC_{t,i} - \text{total SOC stock within cell}} \quad (6)$$

$SOC_{lut,t,i}$  – land-use type specific SOC stock within cell

According to the IPCC guidelines SOC changes can be calculated as the difference of two (aufeinander folgenden) years (see Eq. 5.0A in (IPCC, 2019)). This however will also include naturally occurred changes due to climatic variance over time. For our study we will define the absolute and relative SOC changes in relation to a potential natural state  $SOC_{pnv}$  under the same

20 climatic conditions at time  $t$  in grid cell  $i$ , that is based on the natural vegetation SOC calculations as defined above without

accounting for land conversion from cropland at any time. The absolute changes  $\Delta SOC$  and relative changes  $F^{SCF}$  are thus given by

$$\Delta SOC_{t,i} = SOC_{t,i} - SOC_{pnv,t,i} \quad , \quad F_{t,i}^{SCF} = \frac{SOC_{t,i}}{SOC_{pnv,t,i}}. \quad (7)$$

Note that the absolute changes  $\Delta SOC$  can be also interpreted as cumulative SOC emissions or as SOC depth of mankind; whereas relative changes  $F^{SCF}$  can be denoted as stock change factors as defined within the IPCC guidelines of 2006 (IPCC, 2006).

#### 5 2.1.4 Initialisation of SOC pools

To initialize all SOC sub-pools we assume that cropped land as well as natural vegetation are in a steady state for the specific configuration present within the initialization year 1961. We assume after a spin-up period of 15 years reliable results start from 1975 and improve over time, since dependency on the initial conditions will decrease.

## 2.2 Agricultural management data on 0.5 degree resolution

We compile country-specific FAO production and cropland statistics (FAOSTAT, 2016) to a harmonized and consistent data set. The data is prepared in 5 year time steps from 1965 to 2010, which, together with the spin up phase, restricts our analysis to time span from 1975 to 2010. For all the following data, if not declared differently, we interpolate values linearly between the time steps and hold them constant before 1965.

### 2.2.1 Landuse and Landuse Change

Land-use patterns are based on the Land-Use Harmonization 2 (Hurt et al., 2020) 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 grid cell based on the country and year specific area harvested shares of FAOSTAT data (FAOSTAT, 2016) (see 6.2 for more details on the crop group mapping). Land-use transitions are calculated as net area differences of the land-use data on half-degree.

### 2.2.2 Crop and Crop Residues Production

#### Crop Production

Using half-degree yield data from LPJmL (Schaphoff et al., 2018) as well as half-degree cropland patterns (see 2.2.1) we compile crop group specific half-degree production patterns. We calibrate cellular yields with a country-level calibration factor for each crop group to meet historical FAOSTAT production (FAOSTAT, 2016). Note that by using physical cropland areas we account for multiple crop harvest events as well as for fallows.

#### Crop Residue Production

Crop residue production and management is based on a revised methodology of (Bodirsky et al., 2012) and key aspects are explained here given its central role for soil carbon modelling. Starting from harvested crop production ( $CP$ ) estimates and their respective harvested crop area ( $CA$ ), we estimate above-ground ( $AGR$ ) and below-ground ( $BGR$ ) residual biomass using crop group ( $cg$ ) specific harvest indices ( $HI$ ) and root:shoot ratios ( $RS$ ) as follows

$$\begin{aligned} AGR &= CP \cdot HI_{\text{slope}} + CA \cdot HI_{\text{intercept}} & \text{and} \\ BGR &= (CP + AGR) \cdot RS & \forall \quad cg, i, t. \end{aligned} \tag{8}$$

Following the IPCC guidelines, we split the harvest index into a yield and an area dependend fraction (IPCC, 2006). Note that deviating from (Bodirsky et al., 2012) we use harvested instead of physical crop area to account for increased residue biomass due to multiple cropping and decreased amounts on fallow land. We assume that all BGR are recycled to the soil, whereas AGR can be burned or harvested for other purposes such as feeding animals (?), fuel or for material use.

#### Burned Residues

A fixed share of the AGR 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 ( $< 1000 \frac{USD}{yr\ cap}$ ), 15% for high-



income ( $> 10000 \frac{USD}{yr\ cap}$ ) and linearly interpolate shares for all middle-income countries depending on their per-capita income. Depending on the crop group 80–90% of the residue carbon burned on the fields are lost within the combustion process (IPCC, 2006).

## 5 Residue Usage

We compile out of our 17 crop groups, three residue groups (straw, high-lignin and low-lignin residues) with additional demand for other purposes and one residue with no double use (see 6.3). Residue feed demand for five different livestock groups is based on country- and residue-group-specific feed baskets (see (?)), taking available AGR biomass as well as livestock productivity into account. We estimate, for low-income countries, a material-use share for straw residues of 5% and a fuel-share of 10% for all used residues groups in low-income countries. For high-income countries, no withdrawal for material or fuel use is assumed, and middle-income countries use shares are linearly interpolated based on per-capita income. The remaining AGR as well as all BGR are assumed to be recycled to the soil. We limit high recycling shares at  $10 \frac{tC}{ha}$  to correct for outliers.

### 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 6.4).

## 2.2.3 Livestock Distribution and Manure Excretion

We assume that manure is applied at its excretion place, leaving the livestock distribution the driving factor for the spatial pattern of manuring.

**Livestock Distribution** To disaggregate country level FAOSTAT livestock production values to the half-degree scale, we use the following rule-based assumptions, drawing from the approach of (Robinson et al., 2014), and uses feed basket assumptions based on a revised methodology from (?). We differentiate between ruminant and monogastric systems, as well as extensive and intensive systems. For ruminants, we assume that livestock is located where the production of feed occurs. We distinguish between grazed pasture, which is converted into livestock products from extensive systems; and all other (crop-based) feeds, which we consider to be consumed in intensive systems. For poultry, egg and monogastric meat production we use the per-capita income of the country to divide between intensive and extensive production systems. For low-income countries, we assume extensive production systems. We locate them according to the share of built-up areas based on the idea that these animals are held in subsistence or small-holder farming systems with a high labour per animal ratio. Intensive production associated with higher income countries, is distributed within a country using again share of crop-based feed production, assuming that feed availability is the most driving factor for livestock location.

**Manure Excretion, Storage and Recycling** Manure production and management is based on a revised methodology of (Bodirsky et al., 2012) and is presented here due to its central role in 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 originated 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, we adopt a share of 25% of crop residues in feed intake directly consumed and excreted on crop fields (stubble grazing), we do not consider any stubble grazing in high-income countries; middle-income countries see linearly interpolated 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 with livestock housing. 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 systems we compiled carbon loss rates partly depending on the nitrogen loss rates as specified in (Bodirsky et al., 2012) (see 6.5). We limit high application shares at  $10 \frac{\text{tC}}{\text{ha}}$  to correct for outliers.

#### **2.2.4 Irrigation**

We use irrigation area shares to modify the water effect on decomposition by weighting the irrigated and rainfed water factors based on these shares. The LUH2v2 data set provides irrigated fractions for their cropland subcategories. We apply aggregated area shares, leading to the same impact of irrigation on all of our crop groups. Moreover we assume the irrigation effect to be present for all 12 months of a year in grid cells, that has been marked as irrigated.

#### **2.2.5 Tillage**

To account for the distribution of tillage of the three tillage types specified by the IPCC - full tillage, reduced tillage and no tillage -, we assume that all natural land and pastures are not tilled, whereas annual crops are under full and perennials under reduced tillage. This rule is based on the approach of (Porwollik et al., 2018), but neglects the (less common) adoption of no-tillage farming on agricultural land.

### 2.3 SOC Stocks and Stock changes following Tier 1

- 5 Additionally to the tier 2 approach of the refinement of IPCC guidelines vol. 4 (IPCC, 2019) and the detailed analysis of management data coming with it, SOC changes can be estimated using the IPCC tier 1 approach of IPCC guidelines vol. 4 (IPCC (2006), IPCC (2019)). Here, stocks are calculated via stock change factors ( $F^{SCF}$ ) given by the IPCC for the topsoil (0-30 cm) and based on observational data.  $F^{SCF}$  are differentiated by different crop, management and input systems (here summarized under  $m$ ) reflecting different dynamics under changed in- and outflows without explicitly tracking these. Moreover
- 10  $F^{SCF}$  vary for different climatic zones ( $c$ ) specified by the IPCC (see 6.6). The actual SOC stocks as thus calculated based on a given reference SOC stock by

$$SOC_i^{\text{target}} = \sum_{c,m} T_{c,i} \cdot SOC^{\text{ref}} \cdot F_{c,m}^{SCF} \quad \forall \quad t, \quad (9)$$

with  $T_{c,i}$  being the translation matrix for grid cells  $i$  into corresponding climate zones  $c$ . For this analysis we use the default  $F^{SCF}$  from the Tier 1 method of (IPCC, 2006), and (IPCC, 2019) as a comparison and consistency check for our more detailed

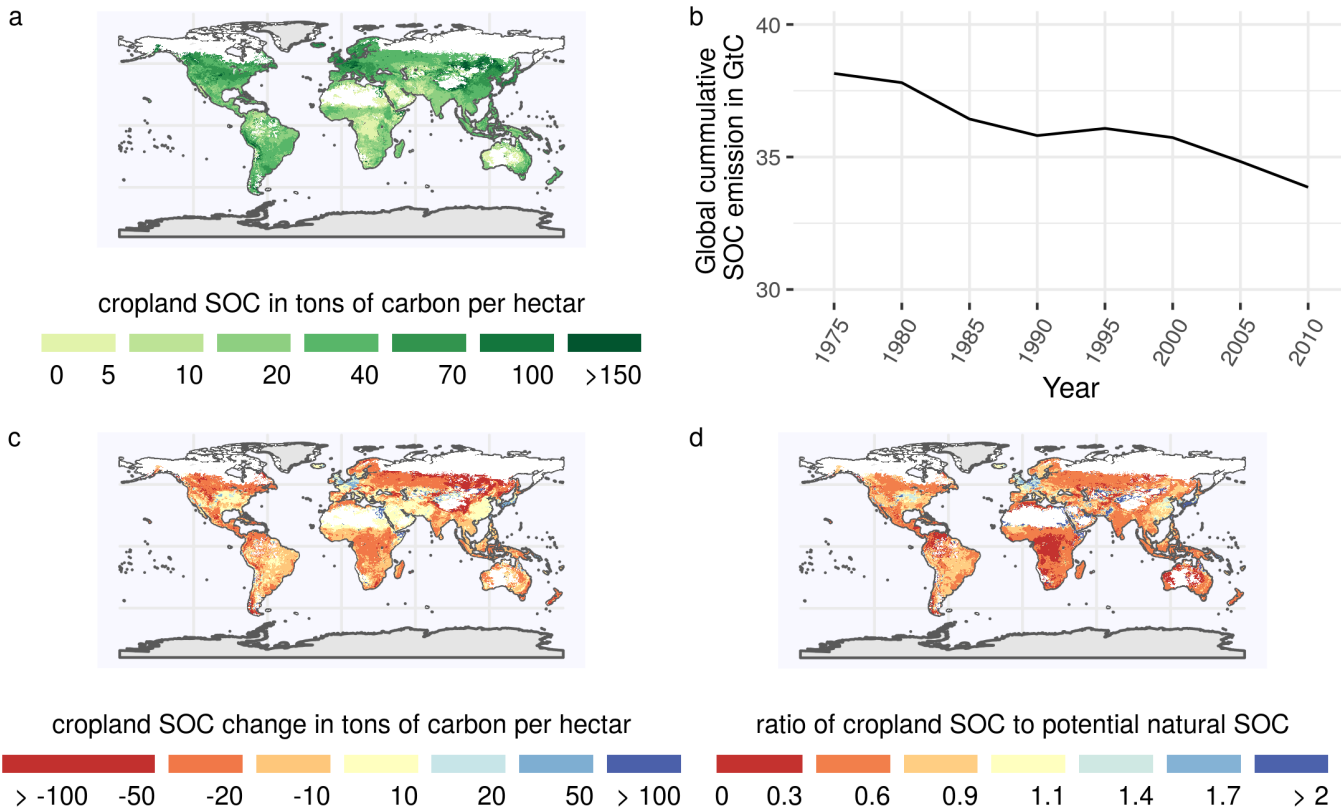
- 5 budget approach.

### 3 Results

We present simulation results of the SOC budget of the period from 1975 to 2010 mainly focusing on cropland areas. Detailed total global and regional results of the state of the worlds SOC in comparison to other estimates can be found in the supplement.

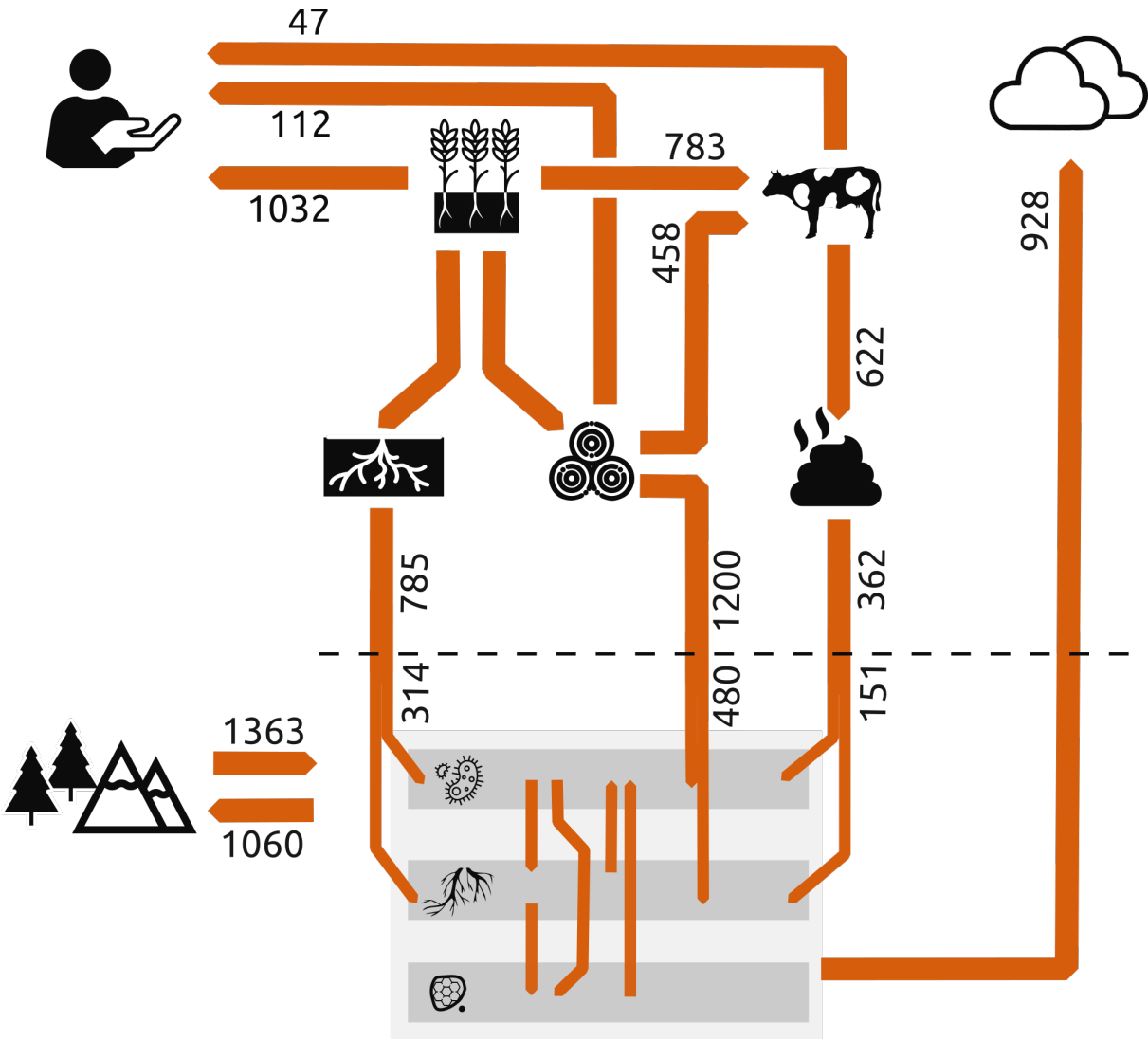
#### 3.1 SOC distribution and depletion

Figure



**Figure 1.** (a): Distribution of total global SOC stocks on cropland shows high carbon stocks in high yielding areas. (b): The SOC debt is decreasing over time, meaning net SOC gains on global croplands over the last decades (despite ongoing cropland expansion). (c)+(d): Absolute (c) and relative (d) SOC stocks compared to a potential natural state showing different hot spots of SOC dynamics. Whereas the absolute losses might be in temperate dry regions, relative losses are more prominent in tropical moist areas.

3.2 global agricultural carbon flows and stocks



**Figure 2.** Global carbon flows (small numbers) and stocks (bold numbers) within the agricultural system for the year 2010 (in MtC): Most important carbon sources on cropland are crop residues. Note the two numbers on carbon inputs to soil denote carbon applied to the field and carbon entering the soil (difference is decomposed before official counting as soil).

5   **3.3   comparison of stock changes factors**

Source	tropical.moist	tropical.dry	temperate.dry	temperate.moist
IPCC2006	0.48	0.58-0.64	0.80	0.69
IPCC2019	0.83	0.92	0.76-0.77	0.69-0.70
SOCbudget 1990	0.38	0.42	0.64	0.57
SOCbudget 2010	0.49	0.57	0.73	0.64

**Figure 3.**  $F^{SOC}$  in comparison to IPCC Tier 1 default factors: Stock change factors are in good agreement with the default values of the IPCC in general. For the tropical regions the assumptions changed notably from the guidelines in 2006 to the update in 2019, leaving our results in very good agreement with the old default assumptions. Default assumption are given under the assumption of medium input systems, which, considering the yield gap in mainly developing regions in the tropics, might be an overestimation and decrease  $F^{SOC}$  by additional 5-8 percent. Also: modelled  $F^{SOC}$  have increased for all climates over time .

## 4 Discussion

- The natural land representation and therefor also SOC initialization is lacking proper parametrization of both decay behaviour and natural input (e.g. nitrogen and lignin content of litterfall). As all results are valued against these potential natural SOC the absolute values and also the changes over time have to be used with caution. Especially in boreal zone and in very dry regions the natural land representation might be far off, due to the focus for the parametrization for cropped areas. The good agreement of the stock change factors  $F^{SCF}$  with the Tier 1 default values might serve as a hint that the natural land representation is not totally off. Boreal and very dry zone might be uncropped, leaving the results on SOC changes on cropland untouched from the bad boreal land representation.
- This study as the IPCC guidelines suggested has limited her focus to the first 30 cm of the soil profile, leaving changes in the subsoil unnoticed. Nevertheless studies (see Don on tillage) have shown, the subsoil to be a game changer in evaluating total SOC losses or gains for no-tillage systems. It has been argued that for intensively tilled soils, subsoil SOC is increasing due to the import of carbon rich topsoil to deeper soil layers. Following these argumentation SOC stocks in croplands might even be underestimated.
- As pointed out by Keel (2017), Smith (2019) the results might be highly sensitive to carbon input calculations more precisely 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:shoot 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. (In general the sensitivity to and the uncertainty of certain parameters might be very high.)

Smaller points and shortcomings:

- Fertilizer interaction is not included here by accounting for additional N supply that would alter C:N ratio of the carbon inputs. Tier 2 steady-state method is neglecting fertilizer application, however we would have fertilizer amounts at hand to include them, if proper representation of fertilizer within the method would be possible to add.
- 10 – Pasture dynamics are neglected and treated as natural vegetation, which might be – looking on pasture degradation due to overgrazing – oversimplified for some spots, but is inline with assumption on pasture SOC stocks done before (see Tier 1 IPCC). (Note that also manure excreted to pastures is neglected within these analysis, since we focus purely on cropland dynamics.)
- 15 – No tillage adaptaion is neglected on cropland due to less common adoption of no tillage and conservation agriculture. Pastures are assumed to be not tilled at all (propably only heavy managed pastures are tilled with some rotation)
- Irrigated areas are not crop specific and irrigation is not restricted to growing periods (since it is very complex to calculate average growing periods). Crop specific growing periods might be possible using LPJmL data.
- flooded rice area are not represented correctly as parameterization does not hold true for flooded conditions.
- Carbon displacement via leaching and erosion is neglected in this study.
- 20 – Non-net/Gross land use transitions are not tracked in this study.
- Within cropland we do not track croparea 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.
- 25 – The disaggregation of manure to uild-up areas (in the case of extensive monograstrics) is leeding to a lot of displaced manure (?) that is cut off
- It is known that there are mismatches between FAO statistics and LUH areas. As far as possibles there were harmonized within this study.
- “The Tier 2 method does not simulate C change but simply calculates an annual C stock change from the current C stock to the future steady-state soil C stock calculated based on current conditions.” Leading to the fact that our total stock results are highly uncertained.



## **5 Conclusions**

- 5 Outlook including perspective on mitigation (and soc enhancement in the future).

## **6 Appendix**

### **6.1 table on method subsections to functions within R packages**

### **6.2 table on mapping LUH2FAO2MAG**

### **6.3 kcr2kres mapping**

### **6.4 carbon 2 dry matter**

Litter is coming from LPJmL in carbon units - transformation with 0.44 is done twice reverting the effect of the transformation

### **6.5 closs in AWMS - Table**

### **5 6.6 map on climate zone used for SCF**

*Code and data availability.* Software code for paper and result preparation can be found under [www.github.com/k4rst3ns/](https://www.github.com/k4rst3ns/). Data used for the output can be found under .

*Author contributions.* Karstens wrote code and paper build on work of Bodirsky (and ). Bodirsky, and Popp revised paper.

*Competing interests.* The authors declare no competing interests.

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- 310