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ORIGINAL ARTICLE

Exports and inputs of organic carbon on agricultural soils in Germany

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Abstract The quantity and quality of organic carbon (C_{org}) input drive soil C_{org} stocks and thus fertility and climate mitigation potential of soils. To estimate fluxes of C_{org} as net primary production (NPP), exports, and inputs on German arable and grassland soils, we used field management data surveyed within the Agricultural Soil Inventory (n = 27.404 cases of sites multiplied by years). Further, we refined the concept of yield-based C_{org} allocation coefficients and delivered a new regionalized method applicable for agricultural soils in Central Europe. Mean total NPP calculated for arable and grassland soils was 6.9 ± 2.3 and 5.9 ± 2.9 Mg C_{org} ha^{-1} yr^{-1}, respectively, of which approximately half was exported. On average, total C_{org} input calculated did not differ between arable (3.7 ± 1.8 Mg ha^{-1} yr^{-1}) and grassland soils (3.7 ± 1.3 Mg ha^{-1} yr^{-1}) but C_{org} sources were different: Grasslands received 1.4 times more C_{org} from root material than arable soils and we suggest that this difference in quality rather than quantity drives differences in soil C_{org} stocks between land use systems. On arable soils, side products were exported in 43% of the site * years. Cover crops were cultivated in 11% of site * years and contributed on average 3% of the mean annual total NPP. Across arable crops, total NPP drove C_{org} input ($R^2 = 0.47$) stronger than organic fertilization ($R^2 = 0.11$). Thus, maximizing plant growth enhances C_{org} input to soil. Our results are reliable estimates of management related C_{org} fluxes on agricultural soils in Germany.

Keywords Carbon sequestration · Manure · Net primary productivity · Carbon balance · Net biome productivity

Introduction

The content or stock of soil organic carbon (SOC) in agricultural soils is regarded as the key parameter

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sustaining soil fertility and health. Moreover, the carbon (C) cycle of agricultural systems plays a role in climate change mitigation: since the more C is stored as organic C (C_{org}) in the soil and the longer it is stored for, the less it contributes to climate change as the major greenhouse gas CO_2 (Minasny et al. 2017). It is widely acknowledged that farming practices can influence SOC levels to a certain extent (Freibauer et al. 2004). On field scale, SOC stocks are strongly correlated with the amount of C_{org} input, which is the almost exclusive source of SOC (Kätterer et al. 2012). However, on a national scale, there are very few data available on the amount of C_{org} input to agricultural soils.

The quantity, and also the quality, of organic inputs play an important role in SOC build-up and dynamics. For example, recent studies suggested that root- and manure-derived C_{org} has stronger effects on SOC stocks than straw-derived C_{org} (Kätterer et al. 2011; Rasse et al. 2005). Both the quantity and quality (e.g. C_{org} to nitrogen ratio of organic material) of C_{org} input to soil are controlled by the farmer through the choice of crop rotation, amount and type of mineral and organic fertilizers applied, and harvest residue management. The farmer also determines total net primary production (NPP_{tot}; Mg C_{org} ha^{-1} yr^{-1}), the fraction of NPP that is harvested as the main product, and the amount of C_{org} ultimately returned to the soil. There are five main pathways of C_{org} input to agricultural soils, governed by: (1) type and amount of aboveground harvest residues if left in the field, stubbles always remaining in the field or mulch if left in the field, (2) type and amount of organic fertilizers applied, (3) type and amount of excreta produced by grazing animals, (4) cover crops used for green manure, and (5) belowground biomass as dead roots and rhizodeposition. This implies that agricultural soils have C-sink potential and that implementation of certain management practices could help mitigate climate change (Minasny et al. 2017).

To understand, predict, and report SOC stock changes in agricultural systems, information on management and related C_{org} fluxes from and to the soil is of critical importance. In addition, knowledge on the regional distribution of harvest exports and inputs of C_{org} to soil is required for development of climate-smart and sustainable solutions in agriculture. However, field-specific data are often not available at national scales preventing 'C_{org} management' from being closely linked to SOC dynamics. The absolute magnitude of the major management-related annual fluxes of C_{org} on agricultural soils, i.e. NPP_{tot}, C_{org} export from the site, and C_{org} input from external sources are generally not well quantified. Estimates of C_{org} input to soil, e.g. when modeling SOC dynamics within the context of greenhouse gas reporting, are thus often derived from national or regional agricultural yield statistics (Andren et al. 2008). These statistics are than combined with plant-specific harvest indices and C_{org} allocation coefficients which are published for the major crops, forages (wheat, barley, oat, triticale, oil seed rape, grain maize, silage maize, potato, sugar beet, mustard, some legumes) and grasslands (Bolinder et al. 2007, 2015; Gan et al. 2009). Manure application rates can be roughly estimated from the number of animals reported in a specific region, while harvest residue management is not given in agricultural yield statistics. However, residue management is somewhat important for C_{org} input to soil since some harvest residues are removed from the field, e.g., for bioenergy provision and some are left in situ.

Apart from obvious uncertainties in agricultural activity data, another major source of uncertainty is the use of C_{org} allocation coefficients and harvest indices derived from global reviews. However, C_{org} allocation coefficients are needed to convert yield data into root- and shoot-derived C_{org} input. Keel et al. (2017) and Riggers et al. (2019) demonstrated that the choice of allocation coefficients used for C_{org} input estimation strongly influences the SOC trends modeled. Region-specific up-to-date allocation coefficients and harvest indices are required to minimize this source of error. So far, region-specific allocation coefficients are not applied for estimates of C_{org} input although validated values for, e.g., crop-specific harvest indices are available.

The specific aims of this study were to

(1) establish a sound method for estimation of mean annual NPP_{tot}, C_{org} inputs, and C_{org} exports from arable and grassland sites under Central European environmental conditions.
(2) quantify and compare mean annual NPP_{tot}, C_{org} inputs and C_{org} exports across land use systems in Germany.
(3) determine the spatial distribution of C_{org} input and its sources in Germany.

Data from the first German Agricultural Soil Inventory were used in the analysis. These comprised 10 years of management data, including crop type, yield, fertilization practices, harvest residue management, field operations, and other key variables such as livestock density, for each of 3104 arable and grassland sites surveyed within the Agricultural Soil Inventory. Based on this 'first-hand' dataset and on regional harvest indices, we estimated NPP_{tot} on arable and grassland sites, total C_{org} export via harvest of main products, and sources of C_{org} input across Germany.

Materials and methods

Database of agronomic and grassland management

The German Agricultural Soil Inventory collected samples of soils under agricultural land use in a 8 km × 8 km grid across Germany (Jacobs et al. 2018) accompanied by collection of arable and permanent grassland management data through a questionnaire sent to the farmers on whose sites soil sampling was performed. Thereby, for the definition of 'permanent grassland' (referred to as 'grassland' in the following), we referred to the one used in agricultural practice where a grassland is permanent after five years of continuous grassland use. Farmers were asked to record type of crop rotation, fresh matter yield of the main product, harvest residues management regimes, cover crops management regimes, and the amount and type of organic fertilizers used. For grassland sites, farmers were asked to record dry matter yield, number of cuts per year, mulching, amount and type of organic fertilizers used, and number and species of grazing animals. If possible, farmers were supposed to deliver the respective data on the previous decade of management, if possible. However, in the present analysis, we had to exclude some records (site * years) from the data set due to incomplete information especially on (1) crops and cover crops indicated as 'unknown' or 'unspecified' (n = 79 and 247, respectively), (2) data entries with no information on harvest residues management (n = 485), (3) data entries on use of organic fertilizer that did not state the amount or type (n = 45), and (4) data entries on pastures with no information on grazing animals or farm's livestock (n = 631). This left 2097 arable sites and 718 grassland sites for the evaluation. These values were multiplied by the site-specific management years, and thus a total of 19,987 arable site * years and 7417 grassland site * years in the period 2001–2016 were evaluated as cases in the present study. If not stated otherwise, results are shown as mean of site * years.

Method's development: Organic carbon allocation coefficients for arable crops grown under Central European conditions

Based on crop-specific harvest indices and on a set of coefficients of C_{org} allocation among crop compartments taken from the literature, we derived C_{org} allocation factors specific for cultivation conditions in Central Europe in order to estimate annual C_{org} input ($Mg\ C_{org}\ ha^{-1}\ yr^{-1}$) to soil based on yield information. The concept of C_{org} allocation, as described in detail by Bolinder et al. (2007), is based on the assumption that the sum of C_{org} within all plant compartments equals NPP_{tot} ($Mg\ C_{org}\ ha^{-1}\ yr^{-1}$) and that all C_{org} allocation factors add up to 1.

For arable crops, we applied the following five, crop-specific C_{org} allocation factors (CA_x):

$$CA_{MP} + CA_{HR} + CA_{ST} + CA_{R} + CA_{RD} = 1 \tag{1}$$

where MP is the main product, HR is the harvest residues, ST is stubbles as the part of HR always remaining in the field, R is dead roots, and RD is rhizodeposition.

We calculated the C_{org} allocation factors for arable main products, harvest residues, and stubbles based on C_{org} content, dry matter content, harvest index, and a stubble index for arable crops obtained in a literature search prioritizing German references (Table 1). The selection criteria for the search were, in descending order: (1) agricultural management representative of commercial farming in Germany, (2) factors quotable, and (3) factors consistent with each other. We generally took the mean value when more than one value was available. There are generally no data available specifically for cultivars used in organic agriculture although it is known that the physiology, and thus C_{org} allocation, of these cultivars differs from that of cultivars used in conventional agriculture. In this study, only 5% of the arable sites evaluated were under organic management and we ignored this

Table 1 Harvest index (HI = yield of main product/(yield of main product + biomass of harvest residues)), dry matter (DM; (Mg DM Mg^{-1} fresh matter^{-1})), and organic carbon content (C; (Mg C Mg^{-1} DM^{-1}) of main product harvested (MP) and aboveground harvest residues (HR) (C of stubbles (ST) was suggested to be the same than of HR), index for the amount of HR remaining in the field as stubble (stubble index = SI) when HR were exported, and allocation coefficients for organic carbon (CA) within crops (R = roots, RD = rhizodeposition) calculated as described in the text

Crop	DM_{MP} (Mg Mg^{-1})	C_{MP} (Mg Mg^{-1})	C_{HR} (Mg Mg^{-1})	HI	SI	CA_{MP}	CA_{HR}	CA_{ST}	CA_R	CA_{RD}[14]	Comments, suggestions made
Winter wheat	0.86[1]	0.46[3]	0.46[2,3,4,5,6]	0.55[1,2]	0.15[9]	0.417	0.284	0.050	0.190[9,10,11]	0.059	
Winter barley	0.86[1]	0.47[3,5]	0.46[2,3,4,5,6]	0.57[1,2]	0.15[9]	0.444	0.279	0.049	0.174[9,10]	0.054	
Spring barley	0.86[1]	0.46[3]	0.46[2,3,4,5]	0.57[1,2]	0.15[9]	0.422	0.268	0.047	0.200	0.062	CA_R: mean of all cereals
Winter rye	0.86[1]	0.47[3,5]	0.47[2,3,4]	0.53[1]	0.15[9]	0.404	0.308	0.054	0.178	0.055	CA_R: mean of all winter cereals
Winter triticale	0.86[1]	0.45[5]	0.46[2,5]	0.53[1]	0.15[9]	0.421	0.326	0.058	0.149[9]	0.046	
Oat	0.86[1]	0.46	0.45[2,5,6]	0.48[1]	0.15[9]	0.312	0.288	0.051	0.267[9,10]	0.083	C_{MP}: as spring barley
Other winter cereals	0.86	0.46	0.46	0.55	0.15[9]	0.423	0.292	0.052	0.178	0.055	mean of all winter cereals
Other spring cereals	0.86[1]	0.46	0.46	0.57	0.15[9]	0.422	0.268	0.047	0.200	0.062	HI, DM_{MP}, C_{MP}, C_{HR}: as spring barley; CA_R: mean of all cereals
Corn, sweet corn	0.86[1,2]	0.48[5]	0.43[2,6]	0.50[1,2]	0.10[9]	0.396	0.315	0.035	0.194[9,10]	0.060	
Silage maize, sorghum	0.31[1,7,8]	0.43[2,6]		1	0.05[9]	0.772	0	0.039	0.145[9]	0.045	HI = 1 for total biomass harvest
Clover (whole plant)	0.20[1,8]	0.41[5]		1	0.25[9]	0.455	0	0.114	0.329[9,10]	0.102	HI = 1 for total biomass harvest; in ref[10] ‘stem’ is equal the MP; CA_R, CA_{RD}: for annual cultivation only, otherwise see text
Clover (seeds)	0.91[1]	0.47[6]		0.11[1]	0.15	0.063	0.430	0.076	0.329[9,10]	0.102	C_{MP}: value for ‘herbaceous and agricultural biomass’; SI: as cereals; CA_R, CA_{RD}: for annual cultivation only, otherwise see text
Fodder and vegetable legumes (grains)	0.86[1]	0.47[6]	0.45[2,5]	0.47[1,2]	0.10[9]	0.380	0.321	0.040	0.166[9,11]	0.052	C_{MP} = value for ‘herbaceous and agricultural biomass’; CA_R, CA_{RD}: for annual cultivation only, otherwise see text
Fodder legumes (whole plant)	0.20[1,2]	0.46[2,4,5,6]		1.00	0.25[9]	0.455	0.000	0.114	0.329[9,10]	0.102	HI = 1 for total biomass harvest; CA_{MP}: in[10] ‘stem’ is equal the MP; CA_R, CA_{RD}: for annual cultivation only, otherwise see text
Oilseed rape	0.91[1]	0.63[3]	0.47[2,3,4,6]	0.38[1,2]	0.15	0.320	0.332	0.059	0.222[11]	0.069	SI: as cereals
Potatoes	0.22[1]	0.47[6]	0.47[6]	0.83[1]	0.00	0.798	0.160	0.000	0.033[10,12]	0.010	C_{MP}, C_{HR}: value for ‘herbaceous and agricultural biomass’; SI = 0 for root crop harvest
Sugar beet	0.23[1]	0.45[5]	0.41[2,9]	0.81[17]	0.00	0.788	0.169	0.000	0.033[10,12]	0.010	SI = 0 for root crop harvest
Fodder beet	0.12[1]	0.45[5]	0.41	0.76[1,17]	0.00	0.744	0.221	0.000	0.033	0.010	C_{HR}, CA_R: as sugar beet; SI = 0 for root crop harvest

Table 1 continued

Crop	DM_{MP} (Mg Mg^{-1})	C_{MP} (Mg Mg^{-1})	C_{HR} (Mg Mg^{-1})	HI	SI	CA_{MP}	CA_{HR}	CA_{ST}	CA_R	CA_{RD}[14]	Comments, suggestions made
Grass with legumes (whole plant)	0.20[1,8]	0.40[7]		1	0.15[9]	0.303	0.000	0.045	0.498[9]	0.154	HI = 1 for total biomass harvest; CA_R, CA_{RD}: for annual cultivation only, otherwise see text
Grass without legumes (whole plant)	0.20[1]	0.45[4,5,7]		1	0.15[9]	0.533	0.000	0.080	0.295[9,10]	0.092	HI = 1 for total biomass harvest; CA_{MP}: in[10] ‘stem’ is equal the MP; CA_R, CA_{RD}: for annual cultivation only, otherwise see text
Strawberries	0.10[8]	0.47[6]	0.47[6]	0.50	0	0.302	0.302	0.000	0.302	0.094	HI = own suggestion; C_{MP}, C_{HR} = value for ‘herbaceous and agricultural biomass’; SI = 0 for no stubble occurrence; CA_{MP}: own suggestion as 66% of biomass is aboveground with HI = 0.5; CA_R: own estimation as 33% of biomass is belowground
Asparagus	0.10[8]	0.47[6]		1	0	0.957	0.000	0.000	0.033	0.010	HI = 1 for total biomass harvest; C_{MP}: value for ‘herbaceous and agricultural biomass’; SI = 0 for root crop harvest; CA_R: mean of potatoes and sugar beet
White cabbage & ‘other vegetables’	0.13[7]	0.51[7]	0.43[2]	0.60[13]	0	0.450	0.246	0.000	0.232[15,16]	0.072	SI = 0 for no stubble occurrence; CA_R: mean value of turnip rape, fodder cabbage, swede, turnip, fodder radish as ‘vegetable-like’ cover crops
Red cabbage	0.13[7]	0.51[7]	0.43[2]	0.54[13]	0	0.409	0.287	0.000	0.232[15,16]	0.072	SI = 0 for no stubble occurrence; CA_R: mean value of turnip rape, fodder cabbage, swede, turnip, fodder radish as ‘vegetable-like’ cover crops
Green cabbage	0.13[7]	0.51[7]	0.43[2]	0.74[13]	0	0.536	0.160	0.000	0.232[15,16]	0.072	SI = 0 for no stubble occurrence; CA_R: mean value of turnip rape, fodder cabbage, swede, turnip, fodder radish as ‘vegetable-like’ cover crops
Broccoli	0.13[7]	0.51[7]	0.43[2]	0.56[13]	0	0.421	0.276	0.000	0.232[15,16]	0.072	SI = 0 for no stubble occurrence; CA_R: mean value of turnip rape, fodder cabbage, swede, turnip, fodder radish as ‘vegetable-like’ cover crops
Cauliflower	0.13[7]	0.51[7]	0.43[2]	0.63[13]	0	0.468	0.228	0.000	0.232[15,16]	0.072	SI = 0 for no stubble occurrence; CA_R: mean value of turnip rape, fodder cabbage, swede, turnip, fodder radish as ‘vegetable-like’ cover crops

Table 1 continued

Crop	DM_{MP} (Mg Mg^{-1})	C_{MP} (Mg Mg^{-1})	C_{HR} (Mg Mg^{-1})	HI	SI	CA_{MP}	CA_{HR}	CA_{ST}	CA_R	CA_{RD}[14]	Comments, suggestions made
Carrot	0.13[7]	0.51[7]	0.43[2]	0.86[13]	0	0.842	0.115	0.000	0.033	0.010	SI = 0 for no stubble occurrence; CA_R: mean of potatoes and sugar beet
Beetroot	0.13[7]	0.51[7]	0.43[2]	0.77[13]	0	0.769	0.188	0.000	0.033	0.010	SI = 0 for no stubble occurrence; CA_R: mean of potatoes and sugar beet
Small radish	0.13[7]	0.51[7]	0.43[2]	0.88[13]	0	0.855	0.102	0.000	0.033	0.010	SI = 0 for no stubble occurrence; CA_R: mean of potatoes and sugar beet
Radish	0.13[7]	0.51[7]	0.43[2]	0.79[13]	[13]	0.779	0.178	0.000	0.033	0.010	SI = 0 for no stubble occurrence; CA_R: mean of potatoes and sugar beet
Onion	0.13[7]	0.51[7]	0.43[2]	0.80[13]	0	0.789	0.168	0.000	0.033	0.010	SI = 0 for no stubble occurrence; CA_R: mean of potatoes and sugar beet
Celeriac	0.13[7]	0.51[7]	0.43[2]	0.83[13]	0	0.817	0.140	0.000	0.232[15,16]	0.072	SI = 0 for no stubble occurrence; CA_R: mean value of turnip rape, fodder cabbage, swede, turnip, fodder radish as ‘vegetable-like’ cover crops
Cucumber	0.13[7]	0.51[7]	0.43[2]	0.72[13]	0	0.522	0.174	0.000	0.232[15,16]	0.072	SI = 0 for no stubble occurrence; CA_R: mean value of turnip rape, fodder cabbage, swede, turnip, fodder radish as ‘vegetable-like’ cover crops
Pumpkin	0.13[7]	0.51[7]	0.43[2]	0.67[13]	0	0.490	0.206	0.000	0.232[15,16]	0.072	SI = 0 for no stubble occurrence; CA_R: mean value of turnip rape, fodder cabbage, swede, turnip, fodder radish as ‘vegetable-like’ cover crops
Salad	0.13[7]	0.51[7]	0.43[2]	0.82[13]	0	0.585	0.111	0.000	0.232[15,16]	0.072	SI = 0 for no stubble occurrence; CA_R: mean value of turnip rape, fodder cabbage, swede, turnip, fodder radish as ‘vegetable-like’ cover crops
Spinach	0.13[7]	0.51[7]	0.43[2]	0.75[13]	0	0.543	0.153	0.000	0.232[15,16]	0.072	SI = 0 for no stubble occurrence; CA_R: mean value of turnip rape, fodder cabbage, swede, turnip, fodder radish as ‘vegetable-like’ cover crops
Herbs	0.20	0.47[6]		1	0.25	0.483	0.000	0.121	0.302	0.094	HI = 1 for total biomass harvest; DM_{MP}: as grass without legumes; C_{MP}: value for ‘herbaceous and agricultural biomass’; SI: as fodder legumes (whole plant); CA_{MP}: own suggestion as 66% of biomass is aboveground with an HI of 1; CA_R: own suggestion as 33% of biomass is belowground; CA_R, CA_{RD}: for annual cultivation only, otherwise see text

Table 1 continued

Crop	DM_{MP} (Mg Mg^{-1})	C_{MP} (Mg Mg^{-1})	C_{HR} (Mg Mg^{-1})	HI	SI	CA_{MP}	CA_{HR}	CA_{ST}	CA_{R}	CA_{RD}[14]	Comments, suggestions made
Cereal silage (whole plant)	0.35[1]	0.47		1	0.05	0.702	0.000	0.035	0.200	0.062	HI = 1 for total biomass harvest; C_{MP}: as winter rye; SI: as silage maize; CA_{R}: mean of all cereals
Grass without legumes (seeds)	0.86[1]	0.47[6]	0.45[4,5,7]	0.11[1]	0.15	0.072	0.460	0.081	0.295	0.092	C_{MP} = value for ‘herbaceous and agricultural biomass’; SI: as cereals; CA_{R}: as grass without legumes (whole plant); CA_{R}, CA_{RD}: for annual cultivation only, otherwise see text
Sunflower & ‘other’ oil crops	0.91[1]	0.52[5]	0.44[5]	0.33[1]	0.15	0.264	0.379	0.067	0.222	0.069	SI: as cereals; CA_{R}: as oilseed rape
Linseed	0.91[1]	0.52[5]	0.44[5]	0.40[1]	0.15	0.313	0.337	0.059	0.222	0.069	SI: as cereals; CA_{R}: as oilseed rape
Tobacco	0.20	0.47[6]	0.47[6]	0.67	0.00	0.466	0.230	0.000	0.232	0.072	HI: mean of vegetables; DM_{MP}: as harvest residues of sugar beet; SI = 0 for no stubble occurrence; CA_{R}: as aboveground vegetables
Hemp	0.40[1]	0.47[6]		1	0.05	0.772	0.000	0.039	0.145	0.045	HI = 1 for total biomass harvest; SI, CA_{R}: as silage maize
Fallow	0.20	0.45		1	0.15	0.533	0.000	0.080	0.295	0.092	As grass without legumes (whole plant); not to be interpreted as bare fallow but as years of non-cultivation during which soil is covered by (volunteer) grass which is not harvested

[1] Anonymous (2017), [2] Franko et al. (2011), [3] Obernberger et al. (2006), [4] Nordin (1994), [5] BIOS Bioenergiesysteme GmbH (2018), [6] Vassilev et al. (2010), [7] Rynk et al. (1992), [8] Zorn et al. (2007), [9] Bolinder et al. (2007), [10] Li et al. (1997), [11] Gan et al. (2009), [12] Bolinder et al. (2015), [13] Feller et al. (2011), [14] Pausch and Kuzyakov (2018), [15] Nordrhein-Westfalen (2015), [16] Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL) (2009), [17] Laufer et al. (2016)

circumstance and applied the mean values we found to all records.

The C_{org} allocation factor of the main product (CA_{MP}) was calculated as:

$$CA_{MP} = \frac{A{-}MP * DM_{MP} * C_{MP}}{NPP_{tot}} \tag{2}$$

where A-MP is the fresh matter yield of the main product of an arable crop (Mg ha^{-1} yr^{-1}), DM_{MP} is its dry matter content (Mg Mg^{-1}), C_{MP} is the C_{org} content (Mg Mg^{-1} dry $matter^{-1}$) (Table 1), and NPP_{tot} (Mg C_{org} ha^{-1} yr^{-1}) was calculated as described below.

The C_{org} allocation factor of harvest residues (CA_{HR}) was calculated as:

$$CA_{HR} = \frac{A{-}MP * \frac{DM_{MP}}{HI} * (1 - HI) * C_{HR} * (1 - SI)}{NPP_{tot}} \tag{3}$$

where A-MP is the fresh matter yield of the MP of an arable crop (Mg ha^{-1} yr^{-1}), DM_{MP} is its dry matter content (Mg Mg^{-1}), HI is the harvest index, C_{HR} is the C_{org} content of harvest residues (Mg Mg^{-1} dry $matter^{-1}$), SI is the stubble index as the proportion of HR always remaining in the field as stubbles and therefore supposed to be calculated as a separate compartment of the crop (for crops for which MP is total aboveground biomass harvested, it is a proportion of MP) (Table 1), and NPP_{tot} (Mg C_{org} ha^{-1} yr^{-1}) was calculated as described below.

The C_{org} allocation factor for stubbles (CA_{ST}) was calculated as:

$$CA_{ST} = \frac{A{-}MP * \frac{DM_{MP}}{HI}(1 - HI) * SI * C_{HR}}{NPP_{tot}} \tag{4}$$

where A-MP is the fresh matter yield of the main product of an arable crop (Mg ha^{-1} yr^{-1}), DM_{MP} is its dry matter content (Mg Mg^{-1}), HI is the harvest index, C_{HR} is the C_{org} content of the harvest residues (Mg Mg^{-1} dry $matter^{-1}$), SI is the stubble index assuming that stubbles have the same C_{org} content as harvest residues (Table 1); NPP_{tot} (Mg C_{org} ha^{-1} yr^{-1}) was calculated as described below.

To develop the C_{org} allocation factor for roots, we used crop-specific constant ratios of aboveground NPP (NPP_{above}) to belowground NPP (NPP_{below}) allocation empirically derived from different studies following the general concept of C_{org} allocation (Table 1). We applied the NPP_{above}: NPP_{below} ratio to NPP_{above} (see below) although there are recent findings that at least wheat has rather a fixed than a yield-dependent NPP_{below} (Taghizadeh-Toosi et al. 2016). However, these results were not proven for the broad spectra of arable crops we evaluated here and thus we used the conventional concept of C_{org} allocation based on findings of Bolinder et al. (2007).

To derive the C_{org} allocation factor for rhizodeposition, we used a recent values published in a review by Pausch and Kuzyakov (2018) who concluded that rhizodeposition is 0.31 * root-C_{org} for most arable crops. The term rhizodeposition as used here is equal to the net rhizodeposition defined by Pausch and Kuzyakov (2018) as the part of C_{org} remaining longer in soil since it is not mineralized by soil organisms immediately after being released into the soil.

Calculation of annual net primary production on arable sites

For arable crops, calculations of annual NPP_{tot} (Mg C_{org} ha^{-1} yr^{-1}) for each site * year was based on the fresh matter yield of the respective main product, which in most cases (79% of site * years evaluated) was recorded by the farmer. Missing values were replaced as accurately as possible by statistical values in a three-step procedure: (1) If available, the year-specific yield of the main product at site-specific NUTS3 level (Landkreis) was used; (2) otherwise, the year-specific mean value of the respective Federal State was used; (3) if still not available, a statistical mean of Germany was used or a rough estimate was made (Graf et al. 2005; Kuratrorium für Technik und Bauwesen in der Landwirtschaft (KTBL) 2009; Landwirtschaftskammer Niedersachsen 2007, 2014, Statistisches Bundesamt (Destatis) 2003–2018, Technologie- und Förderzentrum (TFZ) im Kompetenzzentrum Nachwachsende Rohstoffe 2007). The statistical values of yield of the main product were adjusted to the yield level of the specific farm: For each farm and crop, a 'recorded:statistical' factor was calculated when the respective yield was recorded at least for 2 years; otherwise, the factor was calculated as the mean factor across all crops recorded. If no records were available, no adjustment was made.

If a record indicated that an arable crop was not harvested and all biomass was tilled into the soil, as done for fallow (unharvested grass; 3% of the site * years evaluated) or after extreme weather events

(0.3% of the site * years evaluated), the yield of the main product was set as zero. However, in further calculations, e.g. NPP_{above}, we needed an equivalent to the potential yield and estimated it as being about 50% of a default fresh matter yield (own suggestions as a rough estimate based on Graf et al. 2005; Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL) 2009; Landwirtschaftskammer Niedersachsen 2007, 2014; Statistisches Bundesamt (Destatis) 2003–2018; Technologie- und Förderzentrum (TFZ) im Kompetenzzentrum Nachwachsende Rohstoffe 2007): fallow: 15 Mg fresh matter ha^{-1}, grass: 15 Mg fresh matter ha^{-1}, winter rye: 2.5 Mg fresh matter ha^{-1}, clover (whole plant): 17.5 Mg fresh matter ha^{-1}, grass with legumes (whole plant): 17.5 Mg fresh matter ha^{-1}, fodder legumes (whole plant): 17.5 Mg fresh matter ha^{-1}, winter wheat: 4 Mg fresh matter ha^{-1}, fodder legumes (grains): 1.5 Mg fresh matter ha^{-1}, grass without legumes (grains): 0.5 fresh matter Mg ha^{-1}, winter oilseed rape: 18 Mg fresh matter ha^{-1}.

On arable sites, NPP_{tot} comprised all aboveground and belowground biomass compartments of the main crop and the cover crop. For perennial cultivation of grass, legumes, and herbs, NPP_{below} was calculated as for permanent grasslands (see below) except in the last year of the cultivation period. For cover crops, yield and belowground biomass were not recorded, and were thus estimated based on a literature search and a default C_{org} content of 0.47 Mg Mg^{-1} dry $matter^{-1}$ ('herbaceous and agricultural biomass' in Vassilev et al. (2010)) to obtain NPP_{above} and NPP_{below} for cover crops (Table S1). Rhizodeposition by cover crops was set at 0.31 * root-C_{org} (Pausch and Kuzyakov 2018).

The annual NPP_{tot} (Mg C_{org} ha^{-1} yr^{-1}) on arable sites (A-NPP_{tot}) was calculated as the sum of NPP_{above} and NPP_{below} of the main product and the cover crop (CC-) (Eq. 5). For A-NPP_{above} and A-NPP_{below}, C_{org} allocation factors were applied to the fresh matter yield (Eqs. 6, 7).:

$$A{-}NPP_{tot} = A{-}NPP_{above} + A{-}NPP_{below} + CC{-}NPP_{above} + CC{-}NPP_{below} \tag{5}$$

$$A{-}NPP_{above} = (A{-}MP * DM_{MP} * C_{MP}) + \left(A{-}MP * DM_{MP} * \frac{C_{MP}}{CA_{MP}} * CA_{HR}\right) + \left(A{-}MP * DM_{MP} * \frac{C_{MP}}{CA_{MP}} * CA_{ST}\right) \tag{6}$$

$$A{-}NPP_{below} = \left(A{-}MP * DM_{MP} * \frac{C_{MP}}{CA_{MP}} * CA_{R}\right) + \left(A{-}MP * DM_{MP} * \frac{C_{MP}}{CA_{MP}} * CA_{RD}\right) \tag{7}$$

where A-MP is the fresh matter yield of the main product of an arable crop (Mg ha^{-1} yr^{-1}), DM_{MP} is its dry matter content (Mg Mg^{-1}), C_{MP} is its C_{org} content (Mg Mg^{-1} dry $matter^{-1}$), CA_{MP} is the C_{org} allocation factor of the main product, CA_{HR} is the C_{org} allocation factor of the harvest residues, CA_{ST} is the C_{org} allocation factor of the stubbles, C_{AR} is the C_{org} allocation factor of the roots, and CA_{RD} is the C_{org} allocation factor of the rhizodeposition (Table 1).

Calculation of annual net primary production of grassland sites

For grassland sites, annual NPP_{tot} (Mg C_{org} ha^{-1} yr^{-1}) was again based on the 'yield', which was also recorded in the questionnaire. Three different types of grassland were distinguished and we developed specific approaches to fill gaps in yield data and to estimate NPP_{above} for these grassland types: meadows (grassland mown), pastures (grassland grazed) and mown pastures (grassland grazed and mown).

Missing yield data for meadows (42% of site * years recorded) were replaced with statistical values, in the same way as for arable crops, to derive the amount of biomass exported. However, for meadows, the average values obtained from NUTS3 statistics did not distinguish between different management intensities. The biomass exported from meadows is correlated to the number of cuts per year which is also an indicator for management intensity. Wendland et al. (2018), representing the agricultural extension service in Bavaria, published a linear relationship ($y = 16.2 + 25$; $R^2 = 0.99$) for intensively managed meadows for the use of official fertilization recommendations. Based on these long term experiences, we adjusted the statistical values as follows: We assumed that the statistical grassland yield values reflect a common number of cuts, which we set equal to the country-wide average number of cuts (2.66) recorded in the Agricultural Soil Inventory database. We then adjusted the statistical grassland main product by the number of cuts recorded using specific factors (Table S2), based on a linear relationship between yield and number of cuts derived from field observation (Wendland et al. 2018). Thus, for meadows with two or fewer cuts, we reduced the statistical yield, while for meadows with of three or more cuts we increased it.

For pastures, yield data recorded were assumed to be an estimate of total uptake by grazing animals, which we refer to as grassland main product taken-up. When no yield for pastures was recorded, biomass uptake was calculated from recorded livestock units grazing on the site and mean biomass uptake values for all cattle specimen used in the German National Inventory Report (Rösemann et al. 2017). This was the case for 23% of all site * years recorded for pastures. Missing data on livestock units grazing were replaced by dividing the number, species, and days of animals grazing recorded for the entire farm by the total pasture area recorded for the farm. This was the case for 71% of all site * years recorded for pastures. The major assumption in this approach was that grazing animals were equally distributed over the total pasture area of the farm. Default values used to calculate species-specific grassland main product taken up are given in Table S3.

For mown pastures, the yield recorded was divided into main product yield and biomass taken up in the following way and as a rough approximation (for details, see Table S4): If one cut was performed, it accounted for 25% of the total yield, two cuts accounted for 50%, and more than two cuts accounted for 75% of the yield, while the rest was assigned to biomass taken up. When the yield was not recorded for mown pastures, we calculated the biomass taken up as described for pastures and multiplied the number of cuts recorded by 1.7 Mg dry matter ha^{-1} as the best estimate of yield, based on the equation given above. This was the case for 38% of the records evaluated for pastures.

If not stated otherwise, we assumed that a record indicating mulching was one cut of 1.7 Mg dry matter ha^{-1} remaining in the field.

The calculation of annual $\mathrm{NPP}_{\mathrm{above}}$ on grassland sites (G-$\mathrm{NPP}_{\mathrm{above}}$; Mg $\mathrm{C}_{\mathrm{org}}$ ha^{-1} yr^{-1}) was the sum of all grassland biomass grown on the site (for exact calculation, see Table S4):

$$G{-}NPP_{above} = \left(G{-}MP + G{-}MP_{up} + MU\right) * 1.215 * 0.45 \tag{8}$$

where G-MP is the dry matter yield of the main product of the grassland site (Mg ha^{-1} yr^{-1}), G-$\mathrm{MP}_{\mathrm{up}}$ is the biomass taken up by animals (Mg ha^{-1} yr^{-1}), MU is the biomass mulched (Mg ha^{-1} yr^{-1}), the factor 1.215 represents the part of biomass that grows each year after the last cut or before/after grazing period of animals which is about 30% of the biomass measured as G-MP or G-$\mathrm{MP}_{\mathrm{up}}$ or MU (Christensen et al. 2009) and of which 50% decays within the year evaluated (Poeplau 2016), and 0.45 is the $\mathrm{C}_{\mathrm{org}}$ content (Mg Mg^{-1} dry matter^{-1}) of the aboveground biomass (Bolinder et al. 2007).

Grassland specimen were lately proven to be extremely variable in the ratio of $\mathrm{NPP}_{\mathrm{above}}$ to $\mathrm{NPP}_{\mathrm{below}}$ (also known as ‘root:shoot ratio’) with increasing values due to management intensity, especially due to fertilization (Ammann et al. 2009; Cong et al. 2019; Poeplau 2016; Sochorová et al. 2016). Meanwhile, the studies cited showed that belowground biomass of grassland specimen was rather unaffected by management. In accordance to that, an earlier study (Poeplau et al. 2018), in which seven different long-term fertilized grassland experiments in Germany were sampled, we statistically proved that $\mathrm{NPP}_{\mathrm{below}}$ was unaffected by fertilization and site. The average root-$\mathrm{C}_{\mathrm{org}}$ stock to a depth of 100 cm in that study was 3.38 ± 1.15 Mg $\mathrm{C}_{\mathrm{org}}$ ha^{-1}. Within the dataset used for the present study, the entire range of fertilization intensity was represented and the application of $\mathrm{C}_{\mathrm{org}}$ allocation as a ratio of $\mathrm{NPP}_{\mathrm{above}}$ to $\mathrm{NPP}_{\mathrm{below}}$ would have caused large errors. Thus, we made use of our data published in Poeplau et al. (2018) and established a fixed and yield-independent value to estimate $\mathrm{NPP}_{\mathrm{below}}$ as it appeared advisable according to latest publications. Based on the root-$\mathrm{C}_{\mathrm{org}}$ stock of 3.38 Mg $\mathrm{C}_{\mathrm{org}}$ ha^{-1} found by Poeplau et al. (2018), we assumed an average annual root turnover of 50% (Gill and Jackson 2000) and an additional 31% of annual root-$\mathrm{C}_{\mathrm{org}}$ produced being allocated belowground as rhizodeposition (Pausch and Kuzyakov 2018). The grassland's NPP_{below} was thus fixed to 2.2 Mg C_{org} ha^{-1} yr^{-1}, assuming that the assessment of root biomass to a depth of 100 cm approximately captured the total root biomass.

Calculation of annual carbon export from arable land and grassland

For arable sites, total annual C_{org} export (Mg C_{org} ha^{-1} yr^{-1}) occurs via the main product harvested, harvest residues when exported as side products, and cover crops when harvested for fodder or energy use. If a record indicated that a main product was not harvested and all biomass was tilled into the soil, as done for fallow (grass unharvested) or after extreme weather events, C_{org} export was set to zero. Information on whether harvest residues and/or cover crops were exported from the field was retrieved from the farmer questionnaire. If the use of a cover crop was not recorded, it was assumed here that its biomass was not exported, since this is estimated to be applied in $> 80\%$ of cases.

Total annual C_{org} export from arable sites (A-EX_{tot}; Mg C_{org} ha^{-1} yr^{-1}) was calculated as the sum of C_{org} export via main product, harvest residues and cover crops (CC-) harvested (Eq. 9). For export via main product and harvest residues, C_{org} allocation factors were applied to NPP_{tot} of the arable site (Eqs. 10, 11). For cover crops which were exported from the site it was suggested that export accounts for 75% of the biomass only (Bolinder et al. 2007) (Eq. 12).

$$A{-}EX_{tot} = A{-}EX_{MP} + A{-}EX_{HR} + CC{-}EX \tag{9}$$

$$A{-}EX_{MP} = A{-}NPP_{tot} * CA_{MP} \tag{10}$$

$$A{-}EX_{HR} = A{-}NPP_{tot} * CA_{HR} \tag{11}$$

$$CC{-}EX = CC{-}NPP_{above} * 0.75 \tag{12}$$

where A-EX_{MP} is the C_{org} export via the arable main crop (Mg C_{org} ha^{-1} yr^{-1}), A-EX_{HR} is the C_{org} export of the harvest residues as side products (Mg C_{org} ha^{-1} yr^{-1}), CC-EX is the C_{org} export via the cover crop harvested (Mg C_{org} ha^{-1} yr^{-1}), A-NPP_{tot} is the NPP_{tot} of the arable site (Mg C_{org} ha^{-1} yr^{-1}), CA_{MP} is the C_{org} allocation factor of the main product, CA_{HR} is the C_{org} allocation factor of the harvest residue, CC-NPP_{above} is the NPP_{above} of the cover crop (Mg C_{org} ha^{-1} yr^{-1}), and 0.75 is the factor for the part of CC-biomass exported.

For grassland sites, the total annual C_{org} export (G-EX_{tot}; Mg C_{org} ha^{-1} yr^{-1}) occurs via the yield as the main product on meadows and mown pastures, and via biomass uptake as the main product on pastures and mown pastures. It was calculated as:

$$G{-}EX_{tot} = \left(G{-}MP + G{-}MP_{up}\right) * 0.45 \tag{13}$$

where G-MP is the dry matter yield of the main product of the grassland site (Mg ha^{-1} yr^{-1}), G-MP_{up} is the biomass taken up by animals (Mg ha^{-1} yr^{-1}), 0.45 is the C_{org} content (Mg Mg^{-1} dry $matter^{-1}$) of aboveground biomass (Bolinder et al. 2007).

Calculation of plant-derived annual carbon inputs on arable and grassland soils

On arable sites, the plant-derived annual C_{org} input to soil (Mg C_{org} ha^{-1} yr^{-1}) occurs via harvest residues if left in the field (as recorded in the questionnaire), stubbles which always remain in the field, roots, rhizodeposition, and cover crops. For this study, it was not differentiated in which soil depth the C_{org} was incorporated by tillage since the focus was rather on the amount of C_{org} left on the site. If a cover crop was recorded as being exported, it was assumed that 25% of its NPP_{above} was left in the field as stubbles (Bolinder et al. 2007).

The total C_{org} input to arable soils (A-IN_{tot}; Mg C_{org} ha^{-1} yr^{-1}) was calculated as (although sources of plant-derived C_{org} input are shown separately):

$$A{-}IN_{tot} = \left(A{-}NPP_{tot} - A{-}EX_{tot}\right) \tag{14}$$

where A-NPP_{tot} is the NPP_{tot} of the arable site (Mg C_{org} ha^{-1} yr^{-1}) and A-EX_{tot} is the C_{org} export from the site (Mg C_{org} ha^{-1} yr^{-1}).

On grassland sites, the plant-derived annual C_{org} input to soil occurs via mulch, decaying aboveground, and belowground residues of the main product. Decaying aboveground residues were suggested to comprise 50% of the biomass produced that was not harvested or grazed (Poeplau 2016). The C_{org} input from decaying belowground residues (roots and rhizodeposition) was equal to NPP_{below} (2.2 Mg C_{org} ha^{-1} yr^{-1}). This was based on the notion that in a mature permanent grassland, annual root biomass growth and turnover are in a steady state.

The annual C_{org} input to grassland soils (G-IN_{tot}; Mg C_{org} ha^{-1} yr^{-1}) was calculated as:

$$G{-}IN_{tot} = [MU * 0.45] + [(G{-}NPP_{above} - G{-}EX_{tot} - (MU * 0.45)) * 0.5] + 2.22 \quad (15)$$

where MU is the dry matter biomass mulched (Mg ha^{-1} yr^{-1}), 0.45 is the C_{org} content (Mg Mg^{-1} dry $matter^{-1}$) of aboveground biomass (Bolinder et al. 2007), G-NPP_{above} is the NPP_{above} of the grassland site (Mg C_{org} ha^{-1} yr^{-1}), G-EX_{tot} is the C_{org} export from the grassland site (Mg C_{org} ha^{-1} yr^{-1}), 0.5 is the factor respecting the 50% biomass decaying (see above), and 2.22 Mg C_{org} ha^{-1} yr^{-1} is the C_{org} input from decaying belowground residues (see above).

Calculation of annual carbon inputs via organic fertilizers and grazing animal excreta

For arable and grassland sites, the annual C_{org} input via organic fertilizers (FER_{org}-IN; Mg C_{org} ha^{-1} yr^{-1}) was calculated according to information recorded in the questionnaire:

$$FER_{org}{-}IN = FER_{org} * DM_{FER} * C_{FER} \quad (16)$$

where FER_{org} is the fresh matter amount of the specific organic fertilizer applied (Mg ha^{-1} yr^{-1}) where a density of 1 Mg m^{-3} was assumed for all liquid organic fertilizers, DM_{FER} is its dry matter content (Mg Mg^{-1}), CF_{FER} is its C_{org} content (Mg Mg^{-1} dry $matter^{-1}$) which both were obtained in a broad literature search (Table S5).

To estimate the annual C_{org} input to soil from animal excreta on pastures and mown pastures, the number and species of animals on the site were multiplied by excretion rates expected for species, as estimated by Rösemann et al. (2017) (Table S3). When the respective information was not recorded, missing data were replaced by dividing the number and species of animals grazing on the entire farm (as given in all cases) by the amount of grassland grazed on the farm.

The annual C_{org} input to the soil via grazing animals excreta (FER_{ani}-IN; Mg C_{org} ha^{-1} yr^{-1}) was calculated as:

$$FER_{ani} - IN = FER_{ani} * C_{FER} \quad (17)$$

where FER_{an} is the dry matter amount of grazing animals excreta (Mg ha^{-1} yr^{-1}) and C_{FER} is its C_{org} content (Mg Mg^{-1} dry $matter^{-1}$; Table S5).

Results

Net primary production on and export of organic carbon from arable and grassland sites

The majority of crops cultivated on German arable soils between 2001 and 2015 were winter wheat, silage maize, oil seed rape, and winter barley which were cultivated in 65% of all arable site * years evaluated (Table 2). Carbon fixation as mean annual NPP_{tot} by main crops and cover crops on arable sites was 6.9 ± 2.3 Mg C_{org} ha^{-1} yr^{-1} (Fig. 1). The values of the main crops' NPP_{above} and NPP_{below} were specific for each crop type (Table 2). On average, 74.9 ± 9.7% of NPP_{tot} on arable sites was in aboveground biomass while 25.1 ± 9.7% was allocated to roots and rhizodeposition of main crops and cover crops. Cover crops contributed 3 ± 10% of NPP_{tot} and were grown in 11% of all arable site * years evaluated. They were most often cultivated after cereals (winter barley, summer barley, winter triticale, winter rye, winter wheat) or were associated with silage maize cultivation. In this group of main crops, cover crops were grown on an average of 16% of all site * years evaluated (Table S6). Mean annual total C_{org} export from arable sites via harvest of main product, harvest residues exported as side product and cover crops was 3.7 ± 1.8 Mg C_{org} ha^{-1} yr^{-1} (Table 2, Fig. 1), of which 0.4 ± 0.8 Mg C_{org} ha^{-1} yr^{-1} was in side products, such as straw. Harvest residues were exported as side product in 43% of all arable site * years evaluated (Table S6).

On grasslands, mean annual NPP_{tot} was 5.9 ± 2.9 Mg C_{org} ha^{-1} yr^{-1}, which was on average lower than on arable sites (Fig. 1). However, NPP_{below} of grassland sites, which was estimated with a fixed value of 2.2 Mg C_{org} ha^{-1} yr^{-1}, contributed to a larger share (average 43 ± 14% of NPP_{tot}) to NPP_{tot} than on arable sites. Mean annual C_{org} export was 3.0 ± 2.3 Mg C_{org} ha^{-1} yr^{-1} (Fig. 1) of which 1.9 ± 1.4 Mg C_{org} ha^{-1} yr^{-1} was via cutting of meadows and mown pastures and 1.1 ± 2.2 Mg C_{org} ha^{-1} yr^{-1} was taken up by grazing animals. Meadows

Table 2 Share of main crops cultivated of annual fluxes of organic carbon (C_{org}; Mg C_{org} ha^{-1} yr^{-1}) as net primary production (NPP) for main crops (total and belowground) and cover crops, C_{org} export via main product and via harvest residues exported as side products, and plant-derived C_{org} input; values are the mean and standard deviation (SD) calculated from the multiplication of sites and years (site * years) recorded within the German Agricultural Soil Inventory and are given for crops with a minimum share of 1% across all records

Crop	Share of site * years (%)	NPP						C_{org} export				C_{org} input			
		Main crop (NPP_{total})		Main crop ($NPP_{belowground}$)		Cover crop		Main product		Side product		Fertilizer		Total	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Arable															
Winter wheat	26.4	7.2	1.4	1.8	0.4	0.3	0.9	3	0.6	0.8	1.0	0.3	0.7	4	1.6
Silage maize	14.1	7.7	1.7	1.5	0.3	0.3	1	5.9	1.3	0	0	1.2	1	3.2	1.4
Oil seed rape	12.2	6.8	1.5	2.0	0.4	0.1	0.4	2.2	0.5	0.1	0.3	0.3	0.6	4.9	1.3
Winter barley	11.9	6.1	1.3	1.4	0.3	0.6	1.1	2.7	0.6	0.8	0.9	0.4	0.8	3.5	1.6
Winter rye	5.9	4.7	1.8	1.1	0.4	0.4	1	1.9	0.7	0.8	0.8	0.3	0.7	2.7	1.6
Summer barley	4	4.8	1.1	1.3	0.3	0.5	1.1	2	0.5	0.5	0.6	0.3	0.6	3	1.4
Sugar beet	3.9	8.7	1.6	0.4	0.1	0.2	0.7	6.9	1.3	0	0.1	0.6	1.4	2.6	1.6
Grain maize	3.7	10.4	2.7	2.7	0.7	0.1	0.4	4.1	1.1	0.1	0.7	0.5	0.7	6.8	1.8
Winter triticale	3.3	5.5	1.5	1.1	0.3	0.5	1.1	2.3	0.6	1	0.9	0.4	0.6	3.2	1.7
Fallow[1]	3	3.6	0.4	2.1	0.4	0	0.2	1.3	0	0	0	0	0	3.7	0.4
Potato	2.2	5.4	1.3	0.2	0.1	0.2	0.8	4.3	1	0	0	0.4	0.7	1.7	1.1
Grass without legumes (whole plant)	1.4	5.7	2.2	2.5	0.6	0.1	0.5	3	1.5	0	0	0.7	0.8	3.4	1.3
Summer oat	1.4	5.8	1.8	2.0	0.6	0.2	0.8	1.8	0.6	0.9	0.9	0.5	0.8	3.8	1.6
Grain legumes	1.1	3.5	1.8	0.7	0.4	0.3	0.8	1.3	0.7	0	0.1	0.2	0.7	2.6	1.6
Grass with legumes (whole plant)	1.1	5.3	2.1	2.6	1.3	0.1	0.4	2.3	1.1	0	0	0.7	0.9	3.7	1.7
Other crops	4.3	4.9	1.8	1.8	0.7	0.3	0.7	2.3	0.9	0.2	0.3	0.4	0.6	3.2	1.3
Average		6.6	2.1	1.6	0.4	0.3	0.9	3.2	1.7	1.1	1.1	0.5	0.8	3.7	1.8
Grassland															
Meadow	44.5	5.6	1.4			–	–	2.8	1.2	0.0	0.0	0.7	0.9	3.5	1.0
Mown pasture	40.3	6.4	3.3			–	–	3.4	2.7	0.0	0.0	1.0	1.0	4.0	1.4
Pasture	15.2	5.6	4.3			–	–	2.7	3.5	0.0	0.0	0.7	0.8	3.5	1.5
Average		5.9	2.9			–	–	3.0	2.4	0.0	0.0	0.8	1.0	3.7	1.3

[1] 'Fallow' is not to be interpreted as bare fallow but as years of non-cultivation during which soil is covered by (volunteer) grass which is not harvested

mown up to six times per year were the prevailing management type on grasslands (44% of all grassland site * years evaluated), while pastures used only for grazing represented 15% of all grassland site * years evaluated (Table 2).

Carbon inputs to agricultural soils

Total mean annual C_{org} input to soils did not differ between arable (3.7 ± 1.8 Mg C_{org} ha^{-1} yr^{-1}) and grassland sites (3.7 ± 1.3 Mg C_{org} ha^{-1} yr^{-1}) (Fig. 2). Across all arable crops, NPP_{tot} ($R^2 = 0.47$), rather than C_{org} input via organic fertilizer ($R^2 = 0.11$)

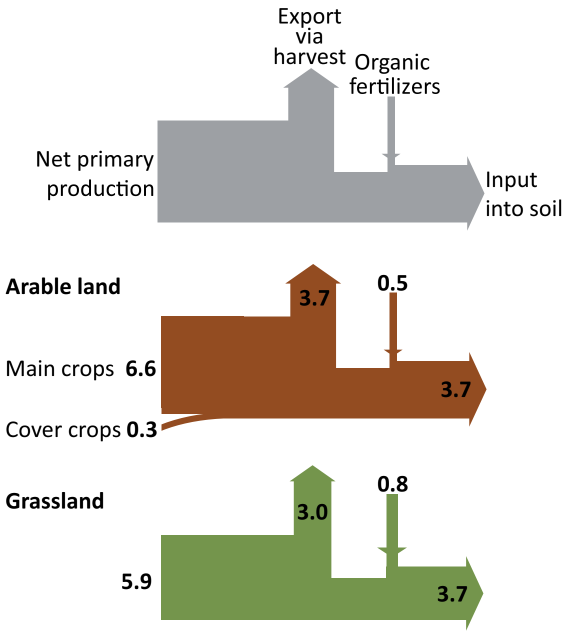

Fig. 1 Mean fluxes of organic carbon (C_{org}, Mg C_{org} ha^{-1} yr^{-1}) on agricultural soils in Germany calculated for the multiplication of sites and years recorded within the German Agricultural Soil Inventory (arable: n = 19,987; grassland: n = 7417); for grassland soils, harvest includes biomass uptake of animals and fertilizers include excreta of animals

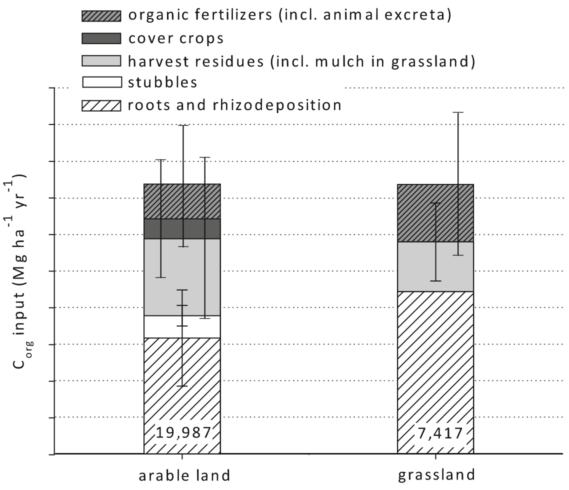

Fig. 2 Sources of mean annual input of organic carbon (C_{org}) to arable and grassland soils calculated for the multiplication of sites and years recorded within the German Agricultural Soil Inventory; mean value and standard deviation. C_{org} input via roots and rhizodeposition in grassland estimated as a fixed value (see text for details) of 2.2 Mg ha^{-1} yr^{-1} and therefore shown without standard deviation

or C_{org} export (R^2 = 0.03), was the main driver of total C_{org} input to the soil (Figure S1).

The largest proportion (83 ± 23%; 3.0 ± 1.5 Mg C_{org} ha^{-1} yr^{-1}; Fig. 2) of total mean annual C_{org} input to arable soils was via above- and belowground plant material of the main crop with 1.6 ± 0.7 Mg C_{org} ha^{-1} yr^{-1} from roots and rhizodeposition, 0.3 ± 0.1 Mg C_{org} ha^{-1} yr^{-1} from stubbles, and 1.1 ± 1.1 Mg C_{org} ha^{-1} yr^{-1} from harvest residues left in the field. Cover crops accounted for 5 ± 15% of the total mean annual C_{org} input to soil with on average 0.3 ± 0.8 Mg C_{org} ha^{-1} yr^{-1}. Organic fertilizers accounted for 12 ± 18% of the total mean annual C_{org} input to arable soils with 0.5 ± 0.8 Mg C_{org} ha^{-1} yr^{-1}. They were applied on 71% of all arable sites and in 43% of all site * years evaluated and derived mainly (94%) from animals (including biogas digestates). Among arable crops, the highest average C_{org} input was found for grain maize cultivation, due to very high average NPP_{tot} (10.4 ± 2.7 Mg C_{org} ha^{-1} yr^{-1}) and a low portion of C_{org} export via harvest (40%, Table 2). The lowest C_{org} input (lower quantile = 1%) was found for potato cultivation (1.1 ± 0.3 Mg C_{org} ha^{-1} yr^{-1}) mainly due to its high harvest index of 0.83. Sites with very high C_{org} input (> 7.6 Mg C_{org} ha^{-1} yr^{-1}) (upper quantile = 99%) had a regular cover crop cultivation and/or were fertilized with compost and/or manure.

As found for arable soils, the largest proportion of total mean annual C_{org} input to grassland soils was again via plant biomass (83 ± 15% or 2.9 ± 0.5 Mg C_{org} ha^{-1} yr^{-1}) (Fig. 2) of which the fixed value of 2.2 Mg C_{org} ha^{-1} yr^{-1} deriving from roots and rhizodeposition had the largest share. The remaining 0.7 ± 0.5 Mg C_{org} ha^{-1} yr^{-1} derived from aboveground residues and mulching. Mulching of grassland was recorded for 2% of all grassland site * years evaluated. Organic fertilizers accounted for 17 ± 15% of total mean annual C_{org} input to grassland soils with 0.8 ± 1.0 Mg C_{org} ha^{-1} yr^{-1}. They were distributed on 81% of grassland sites and in 45% of all grassland site * years evaluated. This high number reflects the fact that excreta from grazing animals were considered here as organic fertilizers. Meadows received organic fertilizers in 51% of all grassland site * years evaluated. There were only two cases where organic fertilizers did not derive from animals (sewage sludge, potato processing sludge). Sites with low C_{org} input (< 2.3 Mg C_{org} ha^{-1} yr^{-1}) (lower

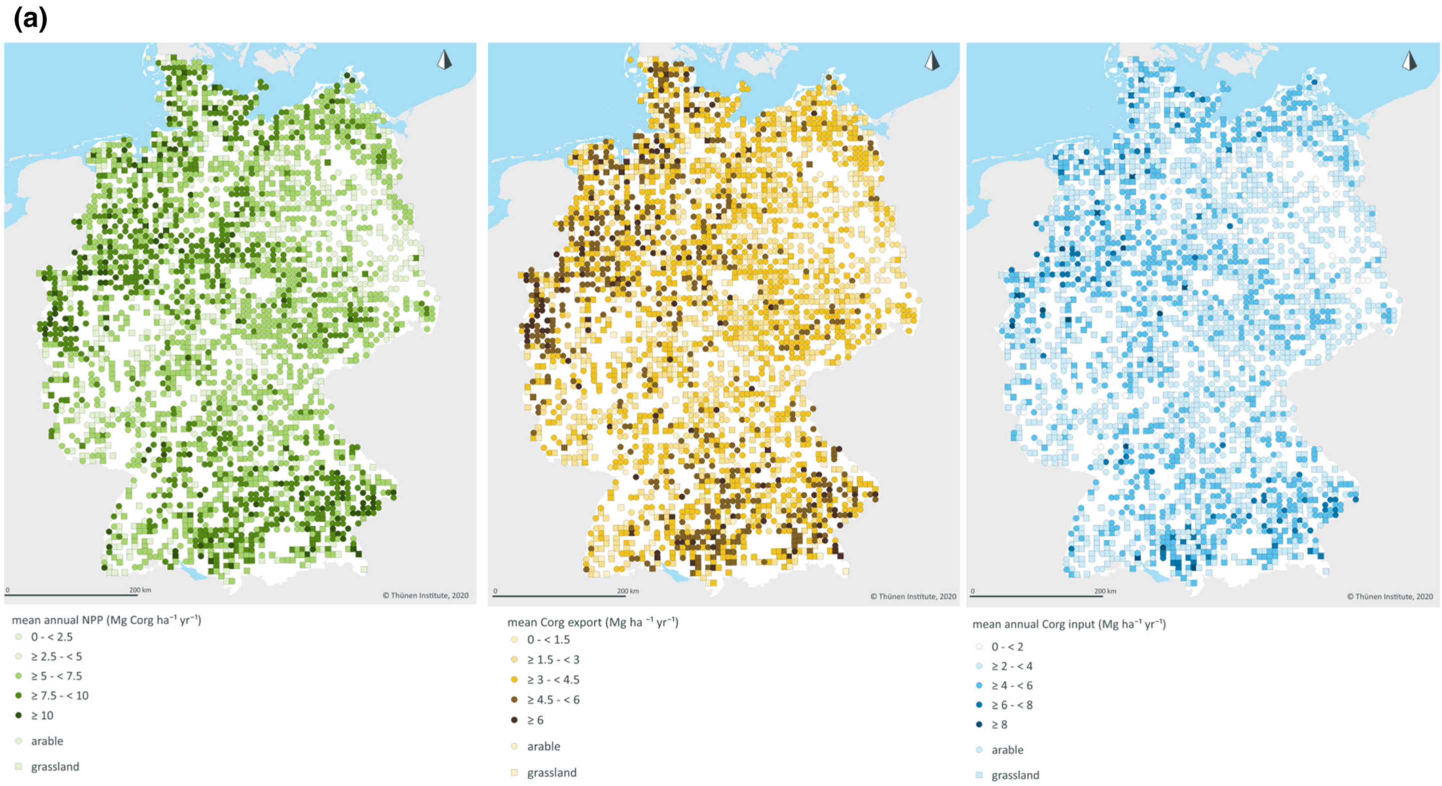

Fig. 3 **a** Annual total net primary production, organic carbon (C_{org}) export, and total C_{org} input, and **b** C_{org} input via cover crops and organic fertilizers of animals' origin to arable (n = 2097) and grassland (n = 718) soils in Germany, calculated as mean value of sites sampled within the German Agricultural Soil Inventory

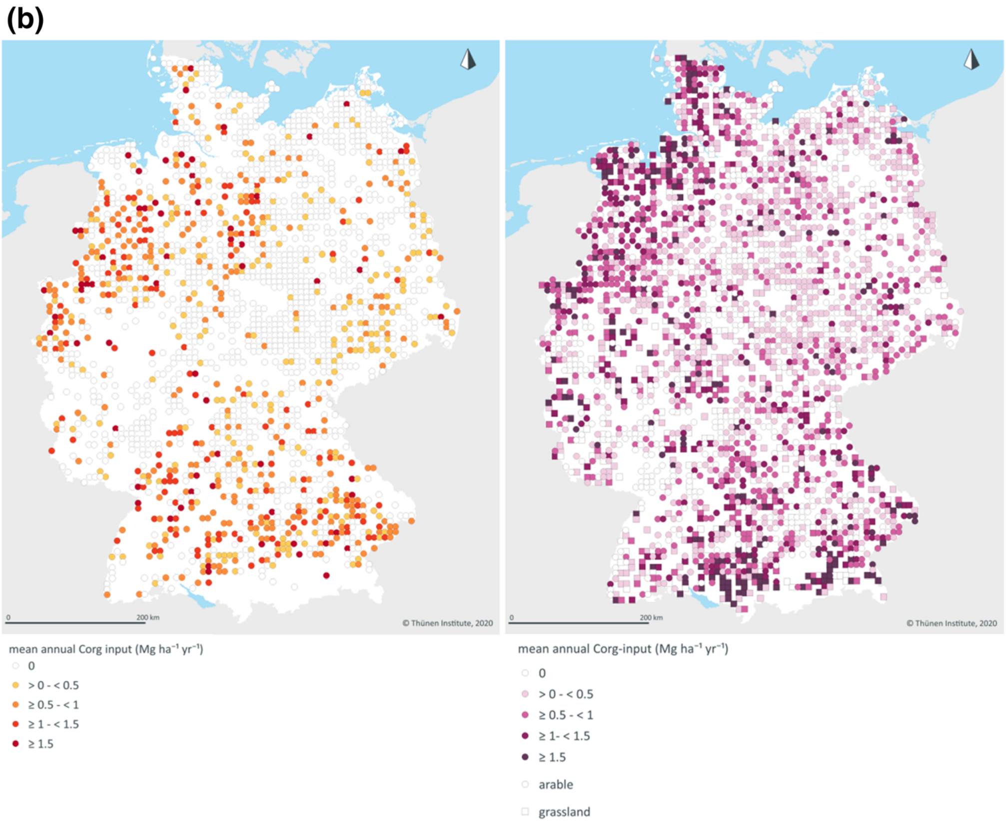

Fig. 3 continued

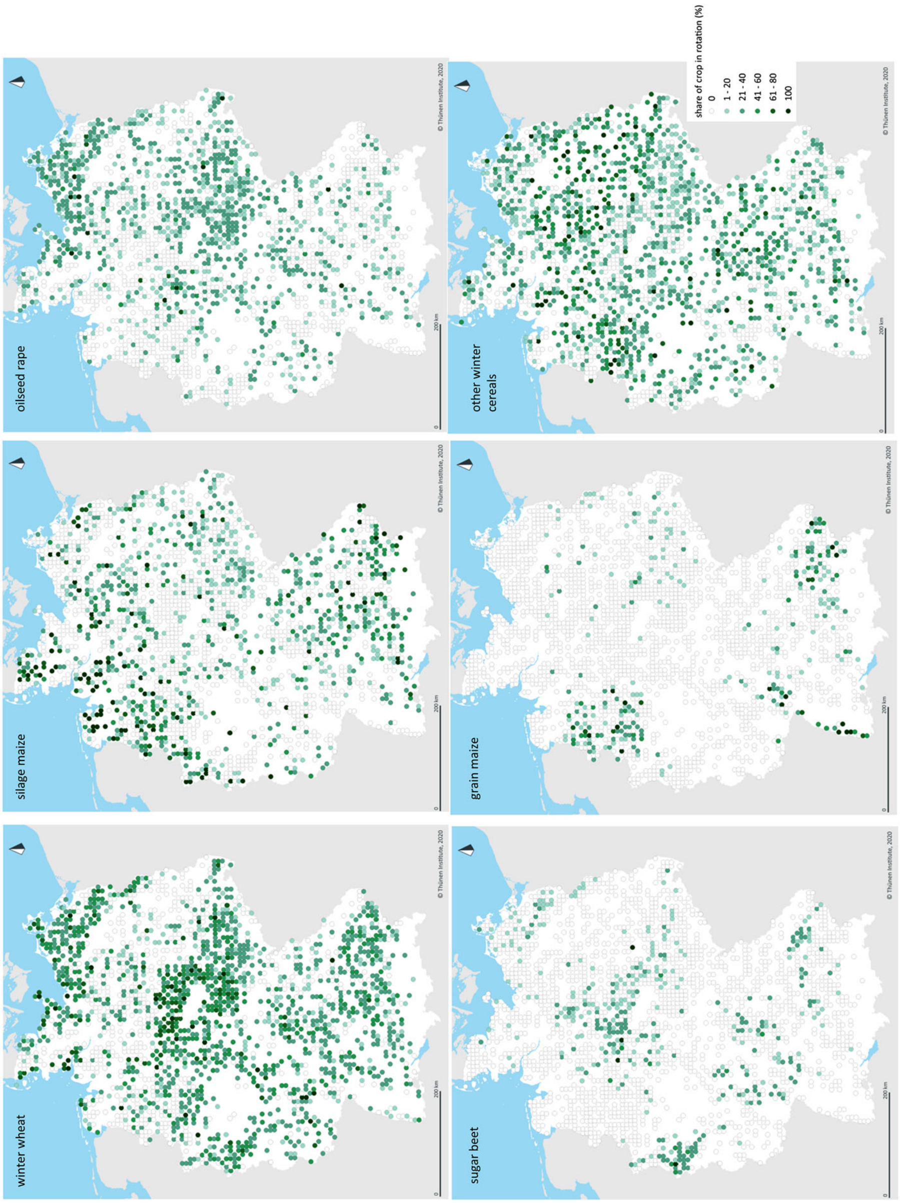

Fig. 4 Spatial distribution of crop cultivation on arable land in Germany, shown as proportion of the specific crop in the crop rotation, calculated for sites sampled within the German Agricultural Soil Inventory

quantile = 1%) were characterized by low yield level and no organic fertilization. Sites with a high C_{org} input (> 7.6 Mg C_{org} ha^{-1} yr^{-1}) (upper quantile = 99%) were pastures with high animal grazing density or received a large amount of organic fertilizer and/or had a high yield level expressed as high number of cuts per year.

Spatial distribution of net primary production and inputs and exports of organic carbon

The highest NPP_{tot} and C_{org} export values were obtained for north-west and south-east Germany (Fig. 3a). Figure 4 shows the spatial distribution of the crops most often cultivated, i.e., winter wheat, silage maize, oilseed rape, sugar beet, grain maize, and other winter cereals. Each of the crops is preferentially grown in certain areas, which partly explains the spatial pattern of NPP_{tot} found in this study. In particular, the distribution of silage maize cultivation explains the high values of NPP_{tot} and C_{org} export in north-west and south-east Germany. The C_{org} input from cover crops was also highest in these areas (Fig. 3b), most likely driven by high precipitation (mean annual precipitation of, e.g., 910 mm in Bavaria in contrast to the German average of 771 mm; mean values of 1881–2019 of Deutscher Wetterdienst 2020) and the specific crop rotation (maize-dominated). North-west and south-east Germany are also areas of high livestock density, explaining the high amounts of C_{org} input via organic fertilizers (Fig. 3b). Regions with the most fertile soils, such as the young moraine soils of north-east Germany and the central German chernosem area, were dominated by the cultivation of winter wheat and oilseed rape. In these regions, the major source of C_{org} input to soil was harvest residues left in the field. In the central German chernosem area in particular, but also in large parts of eastern Germany, cover crops did not play any role in the crop rotation. This can be explained by the lower annual precipitation, e.g., with an average of 566 mm and 600 mm in Brandenburg and Mecklenburg-Western Pomerania (mean values of 1881–2019 of Deutscher Wetterdienst 2020). Moreover, crop rotations in those areas are winter crop-dominated.

Finally, C_{org} input was more regionally variable and site-specific than C assimilation by plants, estimated here as NPP_{tot}. However, the pattern of NPP_{tot} was still visible in the map showing the spatial distribution of C_{org} input (Fig. 3a), confirming NPP_{tot} as a strong driver for C_{org} input.

Discussion

More than half of carbon assimilated is exported from German agricultural soils

Based on our method, mean annual NPP_{tot} on arable sites in Germany was estimated 6.9 Mg C_{org} ha^{-1} yr^{-1} and was slightly higher than on grasslands (5.9 Mg C_{org} ha^{-1} yr^{-1}) despite the fact that grasslands are characterized by permanent vegetation cover and, thus, potentially maximized C-assimilation. This is well in line with global estimates of NPP_{tot}. Using the earth surface model LPJ, Haberl et al. (2007) estimated mean annual global NPP_{tot} of 6.1 Mg C_{org} ha^{-1} yr^{-1} on arable land and 4.9 Mg C_{org} ha^{-1} yr^{-1} on grazing land. The higher values we obtained in the present study might be due to intensive management regime in German agriculture and to generally fertile and relatively young soils. Management, e.g. fertilization, and differences in pedoclimatic site properties are the most important drivers for the differences in NPP_{tot} between arable land and grassland. Grasslands in Germany are characterized by a range of management intensities, from unmanaged to intensively managed, whereas arable sites are mostly intensively managed and fertilized. Further, a large proportion of permanent grasslands in Germany are established in conditions that do not favor cultivation of arable crops, e.g., on wet soils in floodplains, shallow and stony soils, and colder mountainous regions.

On average, 53% of the NPP_{tot} on arable sites was found to be exported each year. Of this exported C_{org} portion, 11% was in harvest residues which were exported as side products. This fact was strongly crop-dependent: Aboveground biomass of crops dedicated for forage or energy production, e.g. silage maize, does not deliver any side products, while harvest residues of cash crops other than cereals, such as oilseed rape, sugar beet or potatoes, are completely left on the site (Table S6). Among all cereals, 40% of all arable site * years evaluated, which is equivalent to 42% of all cereal straw biomass (not shown), was recorded with an export of straw as side product. This value is somewhat larger than the 27–38% estimated in a review on biomass potentials in Germany by Brosowski et al. (2016). Of the C_{org} portion exported, only 15% ended up in organic fertilizers returned to arable soils as C_{org} input. This is comparable to other estimates for Europe showing 47% of NPP_{tot} being exported via harvest of arable crops and 10% of NPP_{tot} being returned as organic fertilizers (Schulze et al. 2009). German grasslands are characterized by high productivity and a relatively high portion of NPP_{tot} being exported (51%). At European scale, it was estimated that only 37% of grassland NPP_{tot} is exported via harvest (Schulze et al. 2009), which underlines the high intensity of German grassland usage. Of the C_{org} portion exported, 27% ended up in organic fertilizers (including animal excreta) returned to grassland soils as a C_{org} input. On a global scale, Haberl et al. (2007) estimated that the proportion of NPP_{tot} harvested was 83% on arable land and 19% on grazing land. This indicates that C_{org} export via harvest is subject to uncertainties and strongly region-specific.

Total organic carbon inputs into soils do not differ between land use systems

The C_{org} input to arable soils estimated by our method was slightly higher (3.7 Mg ha^{-1} yr^{-1}) than estimated for Swedish arable soils: Andren et al. (2008) estimated C_{org} inputs in a range of 3.3 Mg C_{org} ha^{-1} yr^{-1} in the south of Sweden to 2.6 Mg C_{org} ha^{-1} yr^{-1} in the north. Considering the climate advantages for crop cultivation in Germany compared to Sweden, C_{org} inputs estimated in the present study were comprehensible. Across arable crops, we found that C_{org} input to soil was strongly driven by NPP_{tot}, while neither input as organic fertilizer nor C_{org} export correlated with C_{org} input. Thus, in the context of increasing SOC stocks for climate change mitigation, maximizing NPP_{tot}, e.g., by cover crop cultivation, has a considerable potential to increase C_{org} input to soils.

We found no difference between mean annual C_{org} input to arable soils (3.7 Mg C_{org} ha^{-1} yr^{-1}) and to grassland soils (3.7 Mg C_{org} ha^{-1} yr^{-1}). This was surprising, since SOC stock measured in the top 0–30 cm layer on the sites evaluated here was on average 1.4 times higher in mineral soils under grassland (89 ± 36 Mg C_{org} ha^{-1}) than under arable use (62 ± 30 Mg C_{org} ha^{-1}; for details see Jacobs et al. 2018). This difference was often explained by the reduced physical disturbance (tillage) of grassland soils which enhances SOC storage (Six et al. 2000) on the one hand and by higher C_{org} inputs to grassland soils (Hu et al. 2019) on the other hand. However, the type of C_{org} serving as C_{org} input varies considerably between the two land use systems. The C_{org} input to grassland soils was dominated by root-derived C_{org} and the proportion was on average 1.4 times higher in the grassland than in the arable soils. This is in line with Pausch and Kuzyakov (2018) who reported that annual crops allocate less C_{org} belowground (21%) than grassland specimen (33%). However, it needs to be noted that we used a fixed value for root-derived C_{org} in grasslands (see below). Root-derived C_{org} was reported to contribute more to SOC stabilization as shoot-derived C_{org} for various reasons including higher chemical recalcitrance, physical protection by aggregates (Rasse et al. 2005 and papers cited therein) and microbial C-use efficiency (Sokol and Bradford 2019). For example, Kätterer et al. (2011) reported a 2.3 times higher stabilization rate of roots compared with shoots in a Swedish long-term field experiment. Further, in our study, C_{org} input to soil via organic fertilizers (mainly animal manure) was 1.6 times higher on grassland than on arable sites. Manure was also reported to build up SOC at a higher rate than fresh aboveground harvest residues, e.g. straw, (Kätterer et al. 2011) since the labile C_{org} fraction is preferentially decomposed and already lost during gut passage and storage of manure. Straw was found to have a retention rate of about 10% or less (Lemke et al. 2010), while manure often reached retention rates of up to 30% (Kätterer et al. 2011) with a global average of 12% (Maillard and Angers 2014).

An adapted method for estimation of organic carbon inputs to soils in Central Europe

The C_{org} input estimation method we developed is a revised version of allocation coefficients previously published (Bolinder et al. 2007; Gan et al. 2009; Li et al. 1997) adapted to regional conditions. For arable sites, we used regional harvest indices and the latest findings on rhizodeposition (Pausch and Kuzyakov 2018). However, recent studies claim that appyling yield-dependent ratios of NPP_{above} to NPP_{below} in C_{org} input estimation methods might be an oversimplification.

Such findings were clear and reliable for grassland specimen for which several independent studies showed that NPP_{below} is not a function of NPP_{above} in managed grasslands (Ammann et al. 2009; Cong et al. 2019; Poeplau et al. 2018; Sochorová et al. 2016) and that the ratio of NPP_{above} to NPP_{below} can vary greatly upon management intensity and yield. Thus, the application of a yield-dependent ratio of NPP_{above} to NPP_{below} would most likely cause large errors for the estimation of NPP_{below} (Poeplau 2016). This was supported by a recent publication of Taghizadeh-Toosi et al. (2020) who also claimed that using a fixed value for belowground C_{org} input in leys improved SOC model simulations for several long-term field experiments compared to the application of a fixed ratio of NPP_{above} to NPP_{below} for the estimation of belowground C_{org} inputs. Thus, for grassland sites, we made a fundamental change regarding the conventional estimation of belowground C_{org} input based on a ratio of NPP_{above} to NPP_{below}: We adopted the assumption of a fixed value for NPP_{below} and made use of a large German dataset of a related study of Poeplau et al. (2018). Based on these results, we assumed a fixed average root-derived C_{org} input of 2.2 Mg C_{org} ha^{-1} yr^{-1}. This value is supported by Ammann et al. (2009) who measured root C_{org} stocks of 2.3 and 2.1 Mg C_{org} ha^{-1} in intensively and extensively managed Swiss grassland, respectively.

For arable crops, recent findings are less profound: It was shown in two Swiss and one British field trial that maize and wheat have a much stronger aboveground than belowground response to fertilization (Hirte et al. 2018; Taghizadeh-Toosi et al. 2016) and a fixed root-C_{org} input value was regarded more robust for wheat (Taghizadeh-Toosi et al. 2016). However, at this current point of research, it is impossible to deduce reliable values replacing conventional C_{org} allocation coefficients by fixed root-C_{org} input for arable crops. Such values are not available for the majority of crops but crop types differ strongly in physiology. Thus, we decided to stick to the conventional assumption well proven by Bolinder et al. (2007) and provided regionally sound mean values of NPP_{below} (equal root-C_{org} input) as a starting point for future research. A SOC modeling study on German arable long-term monitoring sites using five different C_{org} input estimation methods (Riggers et al. 2019) supported this procedure: C_{org} input estimated by the here presented regional approach led to lower model errors than the original one of Bolinder et al. (2007). This is most likely because the latter summarized studies mainly from North America. To summarize, the C_{org} inputs we calculated for German arable and grassland soils can be regarded as most reliable.

The size and representativeness of the dataset used in this study to estimate management related C_{org} fluxes on German agricultural soils make it unique. Yield data are usually available on strongly aggregated scales or for certain crops only or they are gained from experimental sites that do not reflect commercial agriculture. Field-scale fertilization or residue management data are scarcely available at all. Here, we took the opportunity to comprehensively analyze a decade-long dataset obtained directly from about 1% of all German farmers through a questionnaire. Due to this unique dataset and the region-specific method we developed, the present study delivered the first robust estimates of C-assimilation (NPP_{tot}) and C_{org} inputs and exports from German agricultural soils. Anyway, results are subject to two sources of uncertainty: one related to the dataset as such and the other related to assumptions used in the method. We hold that the priority for improvement of the method is to continue with crop- and site-specific quantification of root biomass in arable land and grasslands, as critical component of total plant-derived C_{org} input to soils.

Conclusions

Our study revealed that maximizing plant productivity, measured as NPP, has the greatest potential to maximize C_{org} inputs to soil and thus SOC stocks in agriculture. Any decrease in plant productivity, e.g. due to climate change induced droughts, threatens current SOC stocks. Surprisingly, total C_{org} inputs did not vary between grasslands and croplands, suggesting that large differences in SOC stocks usually observed between both land use types cannot be explained by differences in total C_{org} inputs. Quality and allocation of C_{org} input matter and point toward a pivotal role of roots for building SOC. A more profound understanding of the stabilization rates and pathways of various C_{org} input sources is thus necessary. We recommend using the method and data presented here for Central European agricultural soils as it complies the up-to-date data sources available for this region. Yet, more field studies are needed to further improve C_{org} input estimates. For example, the role of different pedoclimatic regions as well as cultivars on allocation coefficients and C_{org} input estimates are widely neglected to date. The latter might be especially relevant for comparisons between organic and conventional farms, since organic agriculture uses with different cultivars. The role of breeding on allocation coefficients and, thus, root derived C_{org} input is poorly understood. The C_{org} input to soil is a large C-flux that is directly controlled by agricultural management. All efforts to maintain or increase SOC stocks can only be successful when we understand the effects of agricultural management of this flux in detail.

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