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Soil organic carbon stocks potentially at risk of decline with organic farming expansion

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Organic farming is often considered a strategy that increases croplands' soil organic carbon (SOC) stock. However, organic farms currently occupy only a small fraction of cropland, and it is unclear how the full-scale expansion of organic farming will impact soil carbon inputs and SOC stocks. Here we use a spatially explicit biogeochemical model to show that the complete conversion of global cropland to organic farming without the use of cover crops and plant residue (normative scenario) will result in a 40% reduction of global soil carbon input and 9% decline in SOC stock. An optimal organic scenario that supports widespread cover cropping and enhanced residue recycling will reduce global soil carbon input by 31%, and SOC can be preserved after 20 yr following conversion to organic farming. These results suggest that expanding organic farming might reduce the potential for soil carbon sequestration unless appropriate farming practices are implemented.

The agricultural sector is responsible for 23% of global anthropogenic greenhouse gas (GHG) emissions worldwide[1], but there is an opportunity for mitigation of climate change through carbon sequestration in agricultural soils. While arable lands have lost up to half of their organic carbon stocks since the industrial revolution, agricultural practices could help increase soil organic carbon stocks by increasing carbon inputs to soils or by reducing soil carbon mineralization[2].

Organic farming is often proposed as a way to increase soil organic carbon (SOC) stocks[3]. Meta-analyses of field experiments have shown that organically managed cropland soils have, on average, higher SOC stocks (+3.5 t C ha^{-1}) and soil carbon sequestration rate (+0.45 t C ha^{-1} yr^{-1}) than conventional (that is, non-organic) ones[4,5]. These results are largely explained by higher soil carbon inputs in organic systems through both enhanced manure application rates and the use of more complex crop rotations with higher frequency of temporary pastures and cover crops[6]. However, concerns have been raised that these positive effects of organic farming may result from carbon transfers from other ecosystems through manure and compost inputs, so that there may be no net change in carbon stocks over the whole land area[7]. Accounting for these lateral carbon transfers and capturing their effects are therefore essential for obtaining accurate estimates of the potential of organic farming to sustain global SOC stocks.

Organic farming occupies less than 2% of the global utilized agricultural area (UAA)[8]. Evidence provided by meta-analyses therefore reflects situations where organic materials, such as animal manure or compost, are readily available for fertilization of organically managed soils. In contrast, the expansion of organic farming might trigger competition for fertilizing resources, possibly resulting in a reduction of potential for soil carbon inputs and soil carbon sequestration. A recent study has shown that organic farming upscaling to 100% of the UAA would lead to a 56% crop yield reduction due to severe nitrogen (N) limitation[9]—a large drop compared with the 20–30% yield reduction previously reported in organic farming field experiments[10,11]. This drop is mostly due to the ban on synthetic N fertilizers in organic guidelines that reduces both the range and the amount of N fertilization resources, with large consequences for soil fertilization—a result confirmed by recent studies highlighting N fertilization limitation when organic farming is upscaled[12–14]. Expansion of organic farming is thus likely to have major consequences for soil carbon inputs from crop residues and fertilizing materials, potentially resulting in large changes in SOC stocks.

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Capturing these systemic feedbacks is key to accurately estimating soil carbon inputs in scenarios of large-scale organic farming. We addressed these knowledge gaps by combining (1) GOANIM, a spatially explicit model simulating cropland N cycle, crop productivity and livestock populations under scenarios of large organic farming expansion[9] with (2) RothC, a model simulating carbon dynamics in soils[15,16]. We used GOANIM outputs about livestock manure and crop residue production to estimate carbon fluxes between croplands, grasslands and livestock, and to estimate soil carbon inputs (SCI) in scenarios of large organic farming expansion for croplands. We then used the estimated SCI as an input to RothC to simulate the changes in SOC stocks under different time horizons. We assessed different scenarios combining (1) variations in organic farming practices (for example, cover cropping, use of conventional manure on organic croplands, residue recycling) and (2) variations in the level of organic farming expansion globally, each compared with a baseline scenario of no changes in current agricultural practices.

Although all organic regulations share a ban on synthetic fertilizers, organic farming encompasses a diverse set of farming practices depending on regional regulations, farming contexts and markets[17]. In particular, organic farmers may adopt cropping practices that are known to improve soil carbon sequestration (for example, cover cropping, extensive crop residues recycling, diversified crop rotations including pasture). We captured this variability in cropping practices by considering both (1) a normative organic scenario in which organic farming is restricted to the ban on synthetic fertilizers, some differences in crop rotations, no cover crops and a redistribution of livestock population compared to conventional farming and (2) an optimal organic scenario that may favour carbon inputs to cropland soils mostly through extensive cover cropping and enhanced residue recycling. Note that the assumptions related to the normative scenario were well aligned with those of a previous study about organic farming expansion that resulted in drastic reductions of global cropland production and livestock population in a fully organically managed world, with a large shift towards ruminant animal species[9]. In contrast, the optimal scenario was well aligned with observational data that show that covering soils with catch and cover crops is a common practice that many organic farmers implement[6,7]. We hypothesized that in the normative organic scenario, both soil carbon inputs and SOC stocks would be negatively affected by a global transition to organic farming, whereas those negative effects can be partly ameliorated when additional cropping practices are considered, as in the optimal organic scenario. Hereafter, we first focus on results from a hypothetical 100% conversion of cropland areas to organic farming and second, we analyse scenarios with an intermediate level of organic farming expansion. The scenarios are exploratory, and the primary goal of our modelling exercise is to explore whether, how and where SOC stocks could be at risk of decline under organic farming expansion.

Reduction of SOC inputs

Globally, we found a 40 and 31% reduction in the total SCI to croplands for the normative and optimal organic scenarios, respectively (Table 1). Such massive drop in SCI is primarily due to (1) 39 and 29% reduction in plant-based residues returned to the soil (−1 Pg C yr^{-1} and −0.7 Pg C yr^{-1}), followed by (2) a 68% reduction in farmyard manure application rate (−0.11 Pg C yr^{-1}) in both 100% organic scenarios compared to the baseline. In the normative organic scenario, the reduction in plant-based residues returns is mainly due to a 51% reduction in annual crop dry matter production, partially attenuated by increased frequency of temporary rotational pastures, resulting in an overall 47% reduction of cropland biomass production (Supplementary Table 1). The reduction in manure application rate is mainly due to a 66% reduction in the global livestock population, as well as changes in animal types and in the regional distribution of livestock populations. In the optimal organic scenario, the additional 0.25 Pg C yr^{-1} carbon inputs compared to the normative organic scenario is explained at 83% by additional SCI from the use of cover crops on organically managed croplands (+0.21 Pg C yr^{-1} or +0.07 t C ha^{-1} yr^{-1} on average when expressed on a per area basis).

Table 1 | Global SCI (Pg C yr^{-1}) for croplands under both 100% organic scenarios and the baseline

		Plant-based residues	Manure	Total
Baseline		2.50	0.22	2.72
100% organic scenario	Normative	1.51	0.11	1.62
	Optimal	1.77	0.11	1.87
Ratio organic/baseline	Normative	0.61	0.48	0.60
	Optimal	0.71	0.48	0.69

These global changes in soil carbon inputs mask large variations among world regions (Fig. 1). In some specific regions such as Central Africa or Russia, soil carbon inputs are increased in the normative 100% organic scenario compared to the baseline. This is explained by higher inputs of plant-based residues (Extended Data Fig. 1) due to (1) high manure application rates that help to sustain high crop yields in organic farming (Extended Data Fig. 1) and (2) high share of carbon fixing crops, such as temporary pastures, in organic rotations[6,18]. Note that in other regions such as Northern Brazil, the increase in plant-based residues resulting from more frequent carbon fixing crops in organic rotations is offset by a drop in farmyard manure application, resulting in reduced soil carbon inputs to cropland soils. In the optimal 100% organic scenario, the additional soil carbon inputs from cover crops are in some cases (for example, Central Canada, Eastern Europe or Southern Russia; Fig. 1b) sufficient to compensate for the reduction of soil carbon inputs due to a drop in crop production resulting from the ban on synthetic fertilizers (Extended Data Fig. 1).

Changes in SOC stocks

In the normative scenario, the transition to 100% organic farming would result in a 9, 13 and 18% SOC stock reduction in croplands after 20, 50 and 100 yr, respectively, compared to the baseline (Table 2). This reduction would represent an overall loss of −6.8 Pg C from croplands in the first 20 yr after that transition and a mean loss of 0.23 t C ha^{-1} yr^{-1}. However, a transition to 100% organic farming in the optimal scenario would result in the conservation or slight increase in cropland SOC stock. In particular, cropland SOC stocks would slightly increase by 0.3 Pg C 20 yr after the transition to organic farming, leading to an average storage of 0.01 t C ha^{-1} yr^{-1}.

Again, these global results mask spatial variations among world regions (Fig. 2). In the normative scenario, cropland SOC stocks increase in some regions (such as central Africa), while they decrease in others (such as India and Mexico) (Fig. 2b)—a result largely explained by regional variations in soil carbon inputs (Fig. 1a). In the optimal scenario, some of these latter regions (such as India) would experience an increase in cropland SOC stocks. These regions are marked by high potential of additional SOC stocks per hectare due to cover cropping (Fig. 3). This positive effect of cover crops in the optimal scenario is due to (1) an additional soil carbon input of +0.07 t C ha^{-1} yr^{-1} on average on global cropland soils and (2) a ground covering effect that reduces soil carbon mineralization. Both effects result in an additional global mean increase in cropland SOC of +0.47 t C ha^{-1} yr^{-1} over the first 20 yr following conversion to organic farming.

In the normative scenario, SOC stocks declined drastically in the first 20 yr after transitioning to organic farming (−0.5% ha^{-1} and yr^{-1} on average), whereas the SOC reduction slowed down thereafter (−0.2% ha^{-1} and yr^{-1} on average) (Extended Data Fig. 2). This rapid decline in the first 20 yr followed by slower loss after 20 yr is frequently observed in field studies[19].

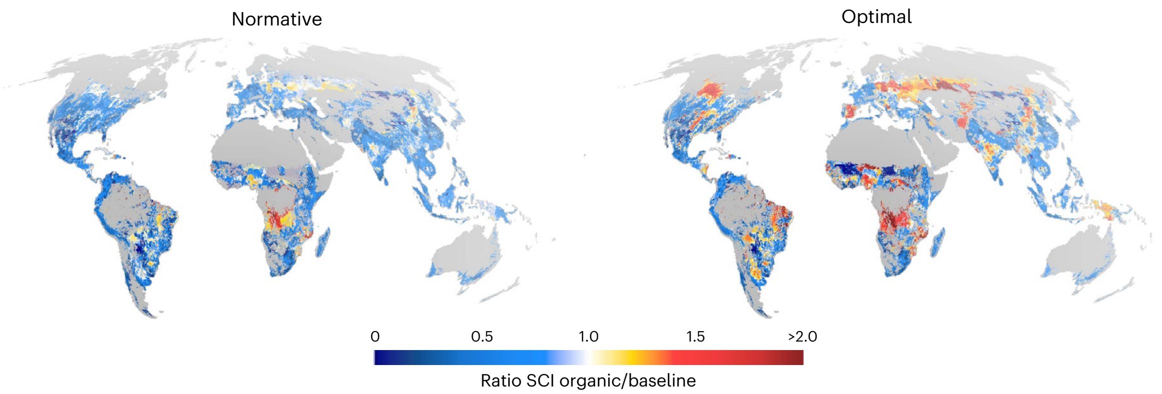

Fig. 1 | Annual organic-to-baseline ratios of soil total carbon inputs. Normative (left) and optimal (right) 100% organic scenario.

Table 2 | Global changes in SOC stocks (PgC) in croplands after 20, 50 and 100 yr following conversion to organic farming

		Global SOC stocks (PgC)		
		20 yr	50 yr	100 yr
Baseline		75.7		
100% organic scenario	Normative	68.9	65.5	62.3
	Optimal	76.1	77.1	78.5
Ratio organic/baseline	Normative	0.91	0.87	0.82
	Optimal	1.00	1.02	1.04
Difference organic−baseline ($tC\,ha^{-1}yr^{-1}$)	Normative	−0.23	−0.23	−0.18
	Optimal	0.01	0.03	0.04

Ratios and differences between the organic and the baseline are indicated.

Intermediate scenarios of organic farming expansion

Because converting the entire agricultural area to organic farming is a drastic thought experiment, we also explored more realistic scenarios of intermediate conversion to organic farming. In these intermediate scenarios, manure surplus from conventional farming systems, that is, conventional manure that is in excess compared with conventional cropland N requirements, is applied on organically farmed lands. Therefore, we introduced two variants of our normative and optimal organic scenarios by considering (1) the application of or (2) a ban on conventional manure surplus in organically managed lands.

We found that in situations without conventional manure application, changes in global SOC stocks in croplands were linearly correlated with increasing share of the UAA under organic farming. This linear relationship was strongly negative in the normative organic scenarios, reflecting that expanding normative organic systems would put SOC stocks in global croplands at risk. In contrast, the slightly positive relationship between global SOC stocks and share of UAA under organic farming in the optimal organic scenarios suggests that sustaining expansion of diversified organic systems would help to protect SOC stocks (Fig. 4a).

Using conventional manure surplus as an additional external source of organic fertilizing material on organically managed croplands—a practice often implemented by organic farmers[20,21]—would make SOC stocks nonlinearly correlated with the share of the global UAA under organic farming (Fig. 4a). In both the normative and optimal organic scenarios, applying conventional manure would help to increase global SOC stocks as well as SOC sequestration rates (Fig. 4a,b). Transferring animal manure from conventional to organic systems increases SOC stocks in organically managed lands through both direct effects (via the application of additional soil carbon input to organic soils) and indirect effects (by alleviating at least partly their often-reported N deficiency[9–11], thereby boosting organic crop yields with positive feedback on crop residue returns to soils). Some regions (such as the United Kingdom, Northern India and Northern China) would see their cropland SOC stocks increasing compared to the baseline in both the normative and optimal scenarios (Fig. 4c). In these same regions, SOC stocks would decrease in a scenario with 20% of the UAA under organic farming without conventional manure application compared to the baseline. This regional effect is explained by the uneven geographic distribution of conventional manure surpluses at the global scale (Extended Data Fig. 3), with major consequences for soil carbon inputs. Interestingly, our results also show that SOC stocks in conventionally managed lands would remain constant with or without the use of conventional manure surplus on organically managed lands (Supplementary Table 2). This absence of an effect of transferring carbon from conventionally to organically managed lands is explained by the small share (less than 1%) of conventional manure surplus in the total soil carbon inputs in conventionally managed lands.

Achieving 20% of the global UAA under organic farming, although being far above the current 1.5% share of organic farming, is the most realistic of the situations we simulated. This yielded a global SOC stock decrease of −2% and −1% in the normative organic scenario without and with conventional manure, respectively, and an increase of +0.1% and +1% in the optimal organic scenario without and with conventional manure, respectively. This would translate to a $-0.118\ t\ C\ ha^{-1}\ yr^{-1}$ difference in SOC sequestration rate between organic and conventional farming (with conventional manure) in the normative organic scenario, whereas this difference would increase to $+0.124\ t\ C\ ha^{-1}\ yr^{-1}$ in the optimal organic scenario (Fig. 4b and Supplementary Table 2).

Discussion and conclusion

Contrary to what is sometimes claimed[22,23], our results suggest that global SOC stocks may be at risk of decline if organic farming expands, especially if the expansion occurs through normative organic farming systems. This would result from a drastic reduction in global SCI, mostly as crop residues and animal manure, due to large N deficiency, resulting in severe decline in crop production as well as a reduction in livestock populations[9]. In addition, our results show that SOC stocks could be conserved under the optimal organic scenarios via extensive cover cropping and enhanced residue recycling. Our findings contradict previous studies reporting strong carbon sequestration potential of organic farming based on field observations at the local scale[4]. These results highlight that soil carbon impacts of organic farming uptake

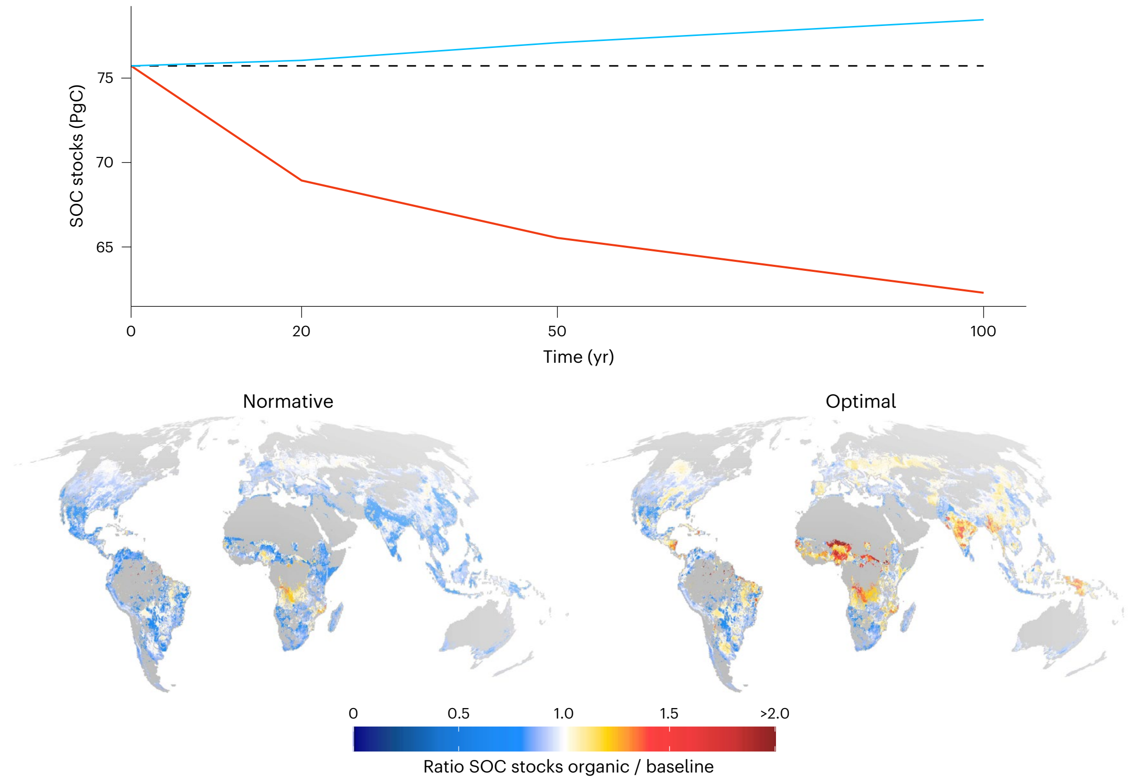

Fig. 2 | Global changes in SOC stocks and SOC stock ratios between the 100% organic scenarios and the baseline at 20 yr. Changes in global SOC stocks (Pg C) in croplands (top) and spatial distribution of ratios (bottom) are reported for the normative (red line) and optimal (blue line) 100% organic scenarios. The black dashed line represents the baseline's global SOC stocks for croplands.

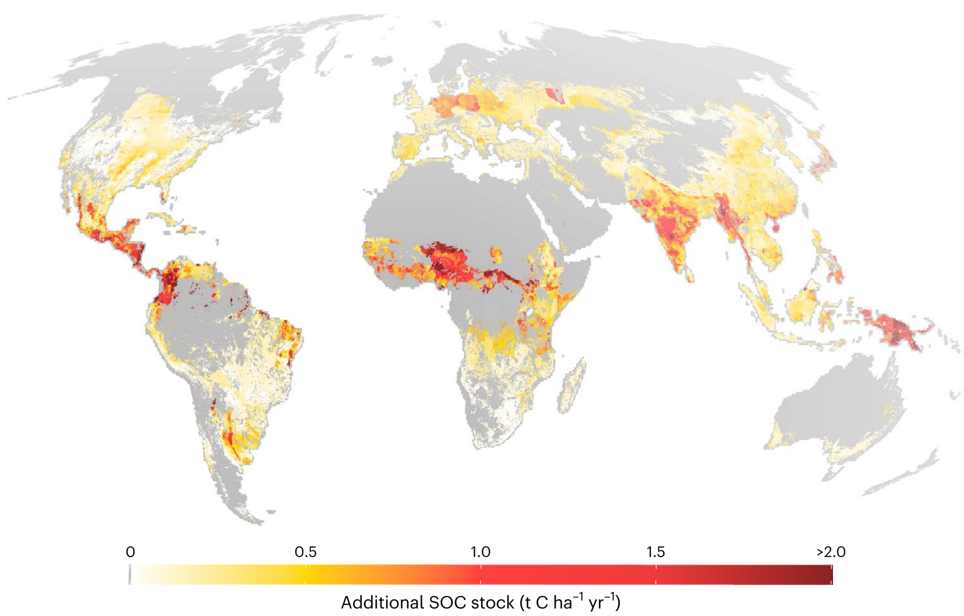

Fig. 3 | Additional SOC stocks per ha (t C ha^{-1} yr^{-1}) due to cover cropping in the optimal organic scenario compared to the normative organic scenario. The optimal organic scenario compared to the normative organic scenario.

cannot be assessed simply by extrapolation of local field observations without considering whole-system effects. The assessment of the impacts of expansion of organic farming systems needs to consider the systemic feedbacks that accompany organic farming expansion itself, in particular the availability of fertilizing resources and related effects on crop production[24,25].

Our results are, however, fairly well aligned with local reports on organic farming expansion. For instance, the N deficiency (and its resulting effects on crop biomass production) simulated by the GOANIM model here is consistent with local observations that N fertilizing resources may become scarce if organic farming expands widely, as recently highlighted in France[26], India[27] or Bhutan[28]. In addition, our

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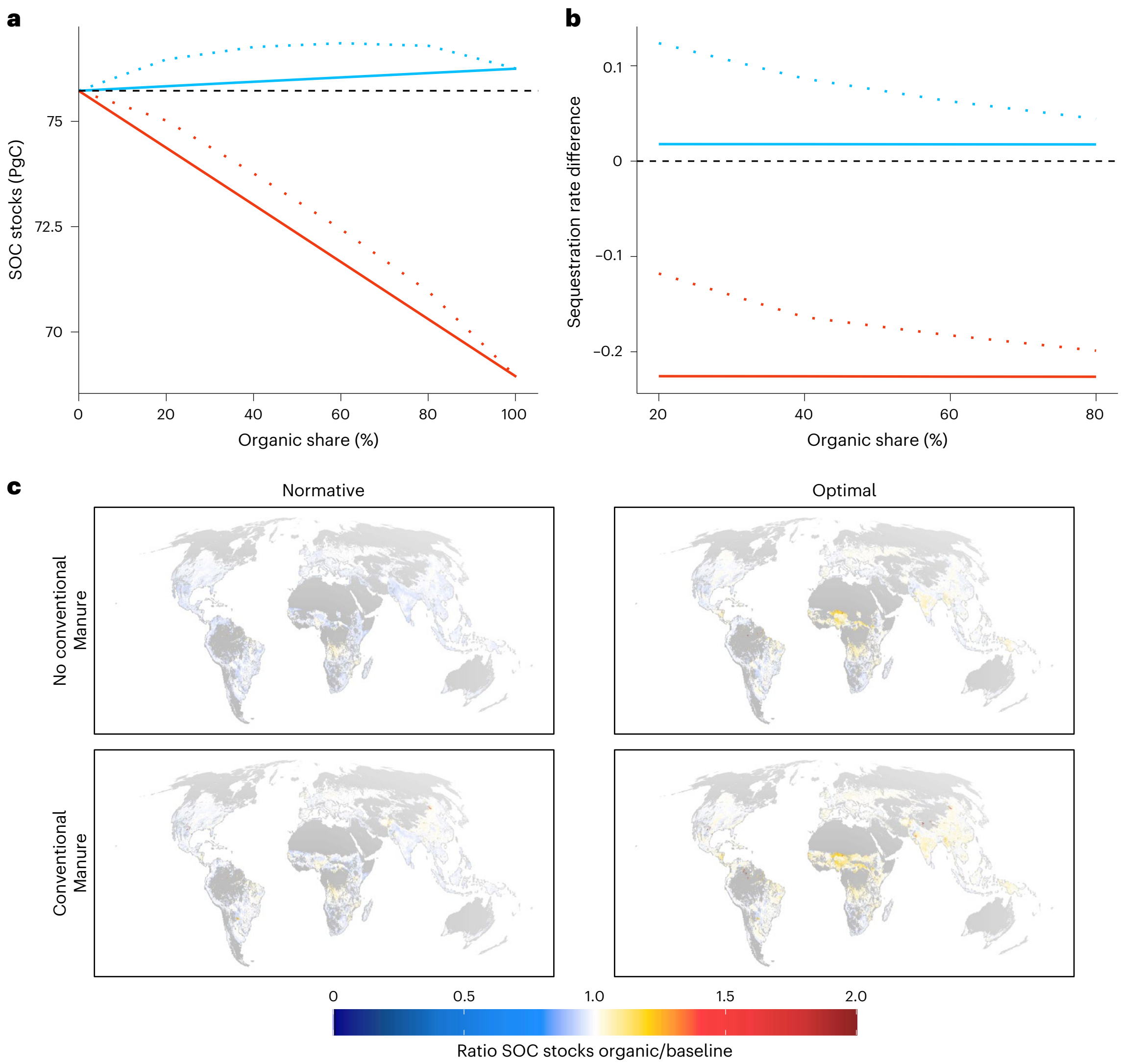

Fig. 4 | Evolution of global SOC stocks. a,b, The SOC (Pg C) at 20 yr (**a**) and the mean difference (organic minus baseline) in SOC sequestration rate (t C ha^{-1} yr^{-1}) over the first 20 yr (**b**), with maps of SOC stock ratios at 20 yr and with 20% of the global UAA under organic farming (**c**). In both upper panels, the red lines represent the normative organic scenario and the blue lines the optimal organic scenario. The dashed lines represent situations where conventional manure surpluses are applied on organically managed croplands, whereas the solid lines represent situations without conventional manure application.

results on limited SOC benefits from organic farming are consistent with findings from a recent meta-analysis that organic farming may not increase SOC stocks compared to conventional farming if there is no lateral carbon transfer from other agroecosystems[7]. Finally, our global estimates of 0.124 t C ha^{-1} yr^{-1} SOC sequestration rates in the optimal organic scenario and under 20% of the global UAA under organic farming are close to the 0.07–0.14 t C ha^{-1} yr^{-1} values reported from an extensive meta-analysis on SOC sequestration potential of organic farming when lateral carbon transfers are controlled[4].

Besides these global estimates, our results also show that a range of additional cropping practices could sustain or increase SOC stocks in organically managed croplands. In particular, we found that the extensive use of cover crops is key to increasing SOC stocks through both increases in SCI and reduction in SOC mineralization[29–31]. Estimating the real benefits that extensive use of cover crops could bring for SOC stocks in organic farming at the global scale is subject to many uncertainties, given the lack of precise information on (1) potential areas available for cover cropping, (2) spatially explicit species composition of the cover crops and (3) cover crop biomass potential production. However, the potential additional SOC stocks offered by cover crops that we found in our study (0.29 t C ha^{-1} yr^{-1}) is very similar to the 0.32 t C ha^{-1} yr^{-1} value reported in a recent meta-analysis[32].

Other practices such as agroforestry[33], enhanced circularity[34] and increased frequency of temporary N-fixing leys or cover crops in organic rotations[11] may have positive impacts on N resource conservation (by avoiding nitrate leaching), N supply to plants and SOC stocks. External fertilizing organic materials such as urban compost, green wastes, food industry by-products or eventually sewage sludge could also provide N to soils while providing additional soil carbon inputs. Modelling the benefits brought by this extensive set of additional cropping practices was beyond the scope of this study, but our results suggest that making organic farming more climate beneficial will require some of these additional practices.

Modelling variations in soil organic carbon stocks in different farming scenarios at the global scale has some limitations. In particular, SOC stocks were modelled using RothC, a model that has proved its potential to accurately simulate SOC changes at the local[35] and large[16] scales, but that requires some specific modelling assumptions. Among them, we had to assume that carbon stocks in the baseline are at equilibrium[16]. It is likely that this assumption does not always reflect the reality[36], which may have implications for our findings. However, we found evidence that the error brought by this assumption was negligible, with only 1% reduction in global cropland SOC stocks after 100 yr compared to the initial situation where SOC stocks were not considered at equilibrium in the baseline (see Extended Data Fig. 4). Another limitation may be related to the fact that soil organic carbon mineralization tracks nitrogen mineralization, which may sustain plant growth, a factor we did not consider in our study. This may lead to a slight overestimation of SOC stock reduction due to overestimation of the reduction in soil carbon inputs compared to the baseline, an effect that should be addressed in further analyses.

The estimates of global changes in SOC stocks in croplands provided by this study should be complemented by similar estimates for grasslands. Indeed, carbon transfers between grasslands and croplands through livestock grazing, manure collection and disposal on croplands, although probably minimal at the global scale, may affect local SOC stocks under grasslands, especially when livestock species and spatial distribution are modified in organic farming. However, we found that converting global agriculture to organic farming would result in small changes in grassland SOC stocks (see Extended Data Fig. 5). Additionally, the region with the biggest effects is India, where information on grasslands management is highly uncertain[37], calling for caution in interpreting the estimates of grassland SOC stocks.

Simulations were performed considering recent past climate. However, ongoing climate change is likely to affect (1) crop yields and livestock farming, with major consequences on soil carbon inputs to agricultural soils and (2) SOC mineralization through a series of processes that are soil temperature and moisture dependent. Accounting for these climate change effects would make sense to allow mitigation and adaptation to be explored together. However, modelling climate change effects on SOC stocks in organic farming would require a series of additional and disputable assumptions (about climate change effects on crop yields, cropping area spatial distribution, livestock farming and animal production[38]) and would probably result in increased uncertainties. More importantly, the literature critically lacks data about how climate change effects would differ in organic vs conventional farming[5]. Addressing these issues is necessary to derive accurate estimates of SOC stocks in organic farming under future climate.

This study provides information to estimate the potential of organic farming to reduce GHG emissions from agriculture. Our results provide an alternative estimate of changes in SOC stocks following conversion to organic farming, to those that upscale SOC stock differences on the basis of field observations[13,39]. Because organic farming expansion is also likely to affect methane and nitrous oxide emissions through a series of processes related to rice cultivation, animal husbandry, manure management and N fertilization, deriving accurate estimates for these emissions is much needed to complement the SOC stock change estimates provided in this study.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01721-5.

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Methods

The objective of this study was to estimate the potential impact of global organic farming expansion on SOC stocks. To do so, we used a modelling approach to estimate the SOC stock changes in scenarios of global organic farming expansion compared to the currently observed SOC stocks. Currently, organic farming occupies less than 2% of the global agricultural lands. Therefore, we consider that the currently observed SOC stocks are those observed under conventional farming, hereafter called the baseline. The modelling approach was based on two separate steps, as explained below.

First, we estimated the SCI in scenarios of large organic farming expansion and in the baseline for croplands in a spatially explicit way (5 arc-min resolution, that is, ~10 × 10 km at the equator). In both the organic scenarios and the baseline, we estimated the SCI as the sum of (1) the amount of carbon that is returned to agricultural lands as plant residues (crop-based and grass-based residues) and (2) the amount of carbon excreted by animals as farmyard manure (FYM) applied to lands after accounting for C losses during manure storage. The SCI estimates for organic farming scenarios were computed using outputs from the GOANIM model[9]. GOANIM is a spatially explicit (5 arc-min resolution) linear optimization model that simulates nitrogen flows to and from croplands and grasslands under scenarios of organic farming upscaling. GOANIM calculates cropland N budget and its effects on crop yield for 61 crop species. The optimizing module of GOANIM is designed to maximize food availability at the global scale (from both crop-based and animal-based products) by spatially optimizing the global livestock population and the N allocation from animal manure to the different considered crops. We used the latest version of GOANIM, accounting for (1) differences in feed rations and feed use efficiency between organic farming and conventional farming[40], (2) the 2019 refinement of the IPCC guidelines values on manure management and nitrogen losses (as direct nitrous oxide emissions, nitrate leaching and ammonia volatilization) and (3) representation of non-productive young animals. Further details about the GOANIM model can be found in ref. 9, especially about the case of Sub-Saharan Africa where drops in yields following the conversion to organic farming due to factors other than N limitation (for example, poor pest and weed control) were negligible. In addition, two organic farming scenarios were considered in this study: (1) a normative organic scenario in which organic farming is restricted to the ban on synthetic fertilizers, differences in the type of crop grown in crop rotations as reported in ref. 18, no cover crops and redesign of the global livestock population as reported in ref. 9 and (2) an optimal organic scenario that draws upon the normative scenario but with cover cropping implemented on 50% of the bare-soil periods between two cash crops (in organically managed lands), increased root–shoot ratio and enhanced plant-based residues recycling on croplands (see below for additional details on this optimal scenario).

Second, we used the estimated SCI from both organic scenarios as inputs to the RothC[15,16] model to estimate changes in SOC stocks over 0–30 cm soil depth in the context of large organic farming upscaling, considering only annual crops (which represents 45 of the 61 crops in GOANIM, thereby assuming no changes in carbon inputs to soils for perennial crops). RothC is a model that estimates soil organic carbon turnover in both croplands and grasslands according to SCI, soil covering, climate and soil properties. RothC considers four active soil organic carbon compartments: the resistant plant pool (RPM), the decomposable plant pool (DPM), the microbial pool (BIO) and the humic pool (HUM). An additional inert organic matter (IOM) pool is considered but is supposed to be constant over time in RothC; it is thus assumed to be unchanged in the organic scenarios vs in the baseline and is not included in the equations below. RothC estimates the carbon flows among the four active compartments as well as the amount of carbon mineralized from each compartment, with a monthly time step and through first-order kinetic equations. In this study, we used the continuous formulation of RothC[41] summarized in equation (1).

$$\mathrm{SOC}'(t) = \rho(t) * A \times \mathrm{SOC}(t) + B(t) \quad (1)$$

where SOC′(t) represents the derivative of SOC with respect of time, SOC(t) represents the SOC stocks at time t. A is a 4 × 4 matrix representing the mineralization and carbon flows among the four active soil organic carbon pools. ρ(t) is the decomposition rate modifier and depends on the climatic, edaphic and soil covering conditions. Note that soil covering affects SOC dynamics by reducing its mineralization rate in RothC. We assumed similar rates of soil organic carbon stabilization and mineralization in both the organic scenarios and the baseline—a rather conservative estimate due to lack of consistent data, despite preliminary evidence of more active carbon cycling in organically managed soils[42]. Spatially explicit climatic data were retrieved from the AgMERRA dataset[43] combined with the Penman equation to estimate potential evapotranspiration. Spatially explicit data on soil clay content were retrieved from the harmonized world soil database[44]. Finally, spatially explicit soil covering data for all crops considered were extracted from ref. 45. $B(t)$ represents the soil carbon inputs at time t and was estimated using equation (2):

$$B(t) = \Big[\begin{pmatrix} a_{\mathrm{dpm}} & a_{\mathrm{rpm}} & a_{\mathrm{bio}} & a_{\mathrm{hum}} \end{pmatrix}^{T}_{\mathrm{cropresidues}} \times (1 - \%\mathrm{FYM}) + \begin{pmatrix} a_{\mathrm{dpm}} & a_{\mathrm{rpm}} & a_{\mathrm{bio}} & a_{\mathrm{hum}} \end{pmatrix}^{T}_{\mathrm{farmyardmanure}} \times \%\mathrm{FYM}\Big] \times b_t \quad (2)$$

where a_{dpm}, a_{rpm}, a_{bio} and a_{hum} are four coefficients that define the proportions of the carbon inputs to soils attached to the four active soil organic carbon pools for both crop residues and farmyard manure. Here, a_{dpm}, a_{rpm}, a_{bio} and a_{hum} were parameterized as follows: (0.6,0.4,0,0) for crop-based residues, (0.4,0.6,0,0) for grass residues and (0.49,0.49,0,0.02) for farmyard manure. %FYM represents the share of farmyard manure in total SCI and b_t represents the total SCI at time t (in t C ha^{-1}).

SCI estimates

For both the organic scenarios and the baseline, we estimated the annual SCI using equation (3):

$$\mathrm{SCI} = \mathrm{AgC} \times \%\mathrm{Recycled} + \mathrm{BgC} + \mathrm{FYM}_{\mathrm{applied}} \quad (3)$$

where SCI represents the inputs of organic carbon to either cropland or grassland soils (in t C $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$). 'AgC' and 'BgC' (in t C $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$) are respectively the above and below-ground plant carbon biomass (the latter being estimated over the 0–30 cm soil depth). '%Recycled' represents the percentage of the 'AgC' that remains on field. In croplands, the '%Recycled' data were extracted from the GOANIM model[9]. In grasslands, '%Recycled' represents the non-grazed carbon share of the entire grassland biomass production. Finally, $\mathrm{FYM}_{\mathrm{applied}}$ (in t C ha^{-1}) is the carbon from farmyard manure applied to the cropland or grassland soils. We assumed that biomass quality and its related carbon stabilization and mineralization properties were similar in both the organic scenarios and the baseline due to inconsistent data in the literature[46]. We estimated AgC and BgC using equations (4) and (5):

$$\mathrm{AgC} = \mathrm{Yield} \times 0.5/\mathrm{HI} \quad (4)$$

$$\mathrm{BgC} = \mathrm{AgC} \times \mathrm{RS} \quad (5)$$

where HI and RS represent the crop-specific harvest index (unitless) and the root–shoot ratio (unitless), respectively, for each of the considered 45 crop species. Both HI and RS values were retrieved from refs. 47,48. 'Yield' refers to crop yields (in tons DM ha^{-1}) as retrieved from ref. 47 (for the baseline) or from the GOANIM model (for the organic scenarios)[9]. To convert the estimated dry matter production in C, we used a 0.5 coefficient value (in t C t^{-1} DM).

$\mathrm{FYM}_{\mathrm{applied}}$ was estimated using equations (6) and (7):

$$\mathrm{FYM_{applied}} = \frac{C_{ex} \times (1-\beta)}{\mathrm{HA}} \quad (6)$$

$$C_{ex} = \sum_a \mathrm{VS}_a \times \mathrm{Pop}_a \quad (7)$$

where C_{ex} (in t C yr^{-1}) is the total amount of carbon excreted by the livestock population as farmyard manure and HA is the total harvested area (ha). β represents the share of C_{ex} that is not applied to agricultural lands. In croplands, β represents the share of C_{ex} that is left on pasture during animal grazing, used for non-agricultural purposes (for example, as fuel) and is lost during the manure management process. In grasslands, β is the share of C_{ex} that is not left on pasture during animal grazing. β was estimated following the 2019 IPCC guidelines refinement[49]. The amount of carbon lost in the manure management process was estimated according to ref. 50. In equation (7), Pop_a is the livestock population (in heads) for each of the nine considered animal species a. VS (in t C $head^{-1}$ yr^{-1}) is the amount of volatile solid carbon excreted per animal and per year, and was estimated using equation 10.24 of the 2019 refinement of IPCC guidelines represented in equation (8):

$$\mathrm{VS} = \left[\mathrm{GrE} \times \left(1 - \frac{\mathrm{DE}}{100}\right) + (\mathrm{UE} \times \mathrm{GrE})\right] \times \left[\left(\frac{1-\mathrm{ASH}}{18.45}\right)\right] \quad (8)$$

where GrE is the gross energy intake (MJ d^{-1}), DE is the feed digestibility (%), UE is the urinary energy (% of GrE) and ASH is the ash content of the feed (% of DM). UE had a value of 0.02 for pigs and 0.04 for all other animals. In the organic scenario, the estimations of GrE, DE and ASH were made using the feed nutritional composition from feedipedia (feedipedia.org). In the baseline, we used data from ref. 51 to estimate DE and ASH, and used equation (9)[52] to estimate GrE:

$$\mathrm{GrE} = \mathrm{CP} \times 0.056 + \mathrm{Fat} \times 0.096 + (100 - \mathrm{CP} - \mathrm{Fat} - \mathrm{ASH}) \times 0.042 \quad (9)$$

where CP is the crude protein content of the ration (%), 'Fat' is the fat content of the ration (%) and ASH is the mean ash content of the ration (%). CP, Fat and Ash were retrieved from ref. 51.

We made sure that the VS excretion would remain in a range of 10 to 50% of the total C ingested by livestock animals[53]. This helped to close the carbon cycle within both the organic scenarios and the baseline, thereby avoiding any overestimation of soil carbon inputs.

SOC inputs in the optimal organic scenario

We designed the optimal organic scenario to estimate the benefits brought by a more carbon-oriented farming and to capture the potential effect of additional cropping practices on SOC stocks. On the basis of a preliminary sensitivity analysis of SCI and SOC stocks to various cropping parameters (see Supplementary Table 3), we built the optimal organic scenario on the assumption that the fraction of crop residues recycled on croplands (%Recycled) and RS would be increased. More precisely, we used equation (3) using modified %Recycled, AgC and BgC (hereafter called $\mathrm{AgC_{opt}}$ and $\mathrm{BgC_{opt}}$) values, with %Recycled being increased by 10% and $\mathrm{AgC_{opt}}$ and $\mathrm{BgC_{opt}}$ being estimated using equations (10–12):

$$\mathrm{Total} = \mathrm{Yield} \times 0.5 \times (1 + \mathrm{RS}) / \mathrm{HI} \quad (10)$$

$$\mathrm{AgC_{opt}} = \frac{\mathrm{Total}}{(1 + \mathrm{RS'})} \quad (11)$$

$$\mathrm{BgC_{opt}} = \mathrm{Total} - \mathrm{AgC_{opt}} \quad (12)$$

where 'Total' is the total carbon biomass produced. $\mathrm{AgC_{opt}}$ and $\mathrm{BgC_{opt}}$ are the total carbon in the above-ground and below-ground biomass in the optimal organic scenarios, respectively. Evidence shows that RS is up to twice higher for crops in conditions of low N availability compared with conditions of high N availability[54]. We estimated a modified RS' root–shoot ratio for situations of N availability in the optimal organic croplands using equation (13):

$$\begin{cases} \mathrm{if Yield} < \mathrm{Yield_{max}} \mathrm{then RS'} = \left(2 - \frac{\mathrm{Yield}}{\mathrm{Yield_{max}}}\right) \times \mathrm{RS} \\ \mathrm{if Yield} = \mathrm{Yield_{max}} \mathrm{then RS'} = \mathrm{RS} \end{cases} \quad (13)$$

where $\mathrm{Yield_{max}}$ is the crop-specific maximum attainable yield for organic farming (in t C ha^{-1}) as defined in the GOANIM model[9].

In addition, we also simulated extensive use of cover crops in the optimal organic scenario on the basis of the observed higher share of cover crops in organic crop rotations compared with conventional ones[6]. The use of cover crops is limited by agronomic and pedo-climatic conditions. On the basis of a previous meta-analysis on the extent of cover crops, we considered that cover cropping could be potentially applied on 50% of global croplands[32] where bare-soil periods exist between main cash crops. We estimated the additional SCI from cover crops using equation (14). Meanwhile, we assumed that there were no cover crops in the baseline.

$$\mathrm{SCI_{cc,\mathit{i},month}} = \frac{\frac{1.87}{\mathrm{GMBSP}} \times \mathrm{Yield_{plant,\mathit{i}}}}{\mathrm{Yield_{plant,world}}} \quad (14)$$

where $\mathrm{SCI_{cc,\mathit{i},month}}$ (in t C ha^{-1} $month^{-1}$) is the soil carbon input from cover crops in country i per month of cover cropping. The 1.87 value (in t C ha^{-1} yr^{-1}) is the global annual mean of soil carbon input from cover crops estimated by ref. 32. We divided this 1.87 value by the estimated global mean duration of the bare-soil period in the baseline (GMBSP, expressed in month). To account for the variability in cover cropping productivity among countries, driven by climatic and farming factors, we multiplied this global mean cover-cropping biomass production by the ratio of the country-specific mean yield ($\mathrm{Yield_{plant,\mathit{i}}}$) to the global mean yield ($\mathrm{Yield_{plant,world}}$) for the most productive crop species between wheat and maize in the country. Finally, for each of the considered grid cells, this monthly $\mathrm{SCI_{cc,\mathit{i},month}}$ was multiplied by the average bare-soil period (in months) between main cash crops, on the basis of sowing and harvesting dates retrieved from ref. 45.

Note that sharp differences in SCI for this optimal scenario may appear among countries in Fig. 1, such as between Spain and France. These differences are probably due to differences in climate. Because crop productivity is overall lower in Spain compared with France due to its more arid conditions, even small additional carbon inputs to soils from cover crops are likely to raise the SCI ratio above 1 in Spain. In contrast, because of higher crop productivity in France, much higher carbon provisioning is needed from cover crops to raise the SCI ratio above 1 in that country. The same holds true for several Sub-Saharan African countries. Other explanations lie in the data and model parameterization that we used in our simulations. Several parameters, such as the biomass productivity of cover crops, were in fact defined by country or climatic region. These effects are quite common in global databases, and they are in most cases an artefact from the interpolation of climate data.

RothC model parameterization

We used RothC assuming carbon pools to be at steady state in the baseline. This necessary assumption translates into a steady state assumption for climatic conditions and soil carbon inputs over the years for both the organic farming scenarios and the baseline. Although partly unrealistic, this assumption is consistent with the thought experiment of large organic farming expansion that we report in this study. To remain in line with this steady state assumption in the baseline, we first estimated the SCIs that are required to keep baseline SOC stocks at their current level (SCI_0) by using the method developed in ref. 41 and summarized in equation (15).

$$SCI_0 = (I_4 - F) \times SOC^* \quad (15)$$

where SCI_0 is the carbon input (in t C ha^{-1} yr^{-1}) required to maintain SOC stocks at their current level. F is a 4 × 4 matrix representing the mineralization and carbon flows among the four active soil organic carbon pools. F values depend on the climatic, edaphic and soil covering conditions. SOC^* is the current active (that is, not comprising the IOM pool) SOC stock that is assumed to be at equilibrium (in either croplands or grasslands), and I_4 is an identity matrix. Total SOC stocks were retrieved from the AEZEF dataset[55] that provides estimates of soil organic carbon stocks in the first 30 cm of topsoil for croplands per country and for 18 agroecological zones. SOC* was estimated after subtracting the IOM content, which was estimated using the equation in ref. 35.

To estimate the SCI in the organic farming scenarios (SCI_1), we corrected SCI_0 using the ratio of SCI_{org} to $SCI_{baseline}$ (RCI) as detailed in equation (16).

$$SCI_1 = SCI_0 \times RCI = \frac{SCI_0 \times SCI_{org}}{SCI_{baseline}} \quad (16)$$

where SCI_{org} and $SCI_{baseline}$ are the soil carbon inputs for the organic farming scenarios and the baseline, respectively, estimated using the methods presented in the previous sections. We used SCI_1 as input in the RothC model to estimate the changes in SOC stocks in the organic farming scenarios 20, 50 and 100 yr after a global conversion to this farming system using equation (1). We assumed constant climate data over the simulation periods. This assumption is disputable given current and future climate change, but it remains consistent with our thought experiment on exploring situations of drastic expansion of organic farming. Further studies that are beyond the scope of this Article would be needed to account for future climate scenarios. The estimated SCI_1 is expressed in t C ha^{-1} yr^{-1}, although RothC requires monthly data. We assumed that the annual soil carbon inputs were equally distributed among the 12 months of the year.

To account for the observed differences in crop rotations between organic and conventional farming[6], we ran RothC in the organic farming scenarios for each of the 45 considered crop species separately and then estimated a weighted mean of SOC stocks according to crop species harvested areas, as detailed in equation (17):

$$SOC_{t,mean} = \frac{\sum_i SOC_{t,i} \times HA_i}{HA_{total}} \quad (17)$$

where $SOC_{t,mean}$ is the weighted mean of SOC stocks at time t, $SOC_{t,i}$ is the SOC stock estimated by the run of RothC for each specific crop i, HA_i represents the harvested area of crop i in the organic farming scenarios and HA_{total} is the total harvested area (all crops considered). HA_i and HA_{total} were retrieved from ref. 18.

Limitations and uncertainties

Although the modelling foundations of our work are solid, its global extent requires a large set of input data that may come with some limitations. In particular, both the baseline and the organic scenarios required detailed, spatially explicit distribution of cropland areas, types of crop grown and crop yields. These data were derived from ref. 47 and Earthstat, and were centred circa year 2000. Many changes have occurred in agriculture during these past 20 yr (including expanding irrigation and changes in varieties) that may affect our simulations. However, to the best of our knowledge, these databases remain the most appropriate given their global extent, higher number of crop species considered, and data quality and cross-validation. Note that uncertainties and possible caveats may remain in these databases, for example about cropland areas in the island of Guinea or about grassland areas in India, as already mentioned.

Finally, several of our input data may be affected by some uncertainties. The complexity of the GOANIM and RothC models and limited knowledge about several aspects of input data make the quantification of these uncertainties very difficult. However, the SOC stocks we estimated were determined over long periods (20, 50 and 100 yr). Long term averages show reduced errors on estimated variables due to reduced aggregation effects by the input data, especially the climate data[56]. In addition, this study is based on the comparison of organic farming to a baseline, both of which are affected by the same errors and uncertainties. Therefore, concentrating the analysis on the ratios (or differences) of organic to conventional estimates helps to reduce errors and uncertainties.

Data availability

All data on crop areas, soil carbon inputs and soil organic carbon stocks for any of the scenarios and organic shares considered in this paper are available on a public repository[57].

Code availability

The model code for GOANIM is available in its most recent version at https://github.com/Pie90/GOANIM_public/, together with a full model documentation. All analyses were done using R x64 3.5.3. For RothC we used the 'cin_month' and 'runExplicitSol' functions from the RothC package to respectively estimate SCI_0 and SOC stock evolution across time.

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Author contributions

U.G., M.K., P.S., S.P. and T.N. designed the study; U.G. performed the modelling work with the help of P.B. for the GOANIM model and M.K., P.S. and M.M. for the RothC model. All authors were involved in the interpretation of results and contributed actively to writing and revising the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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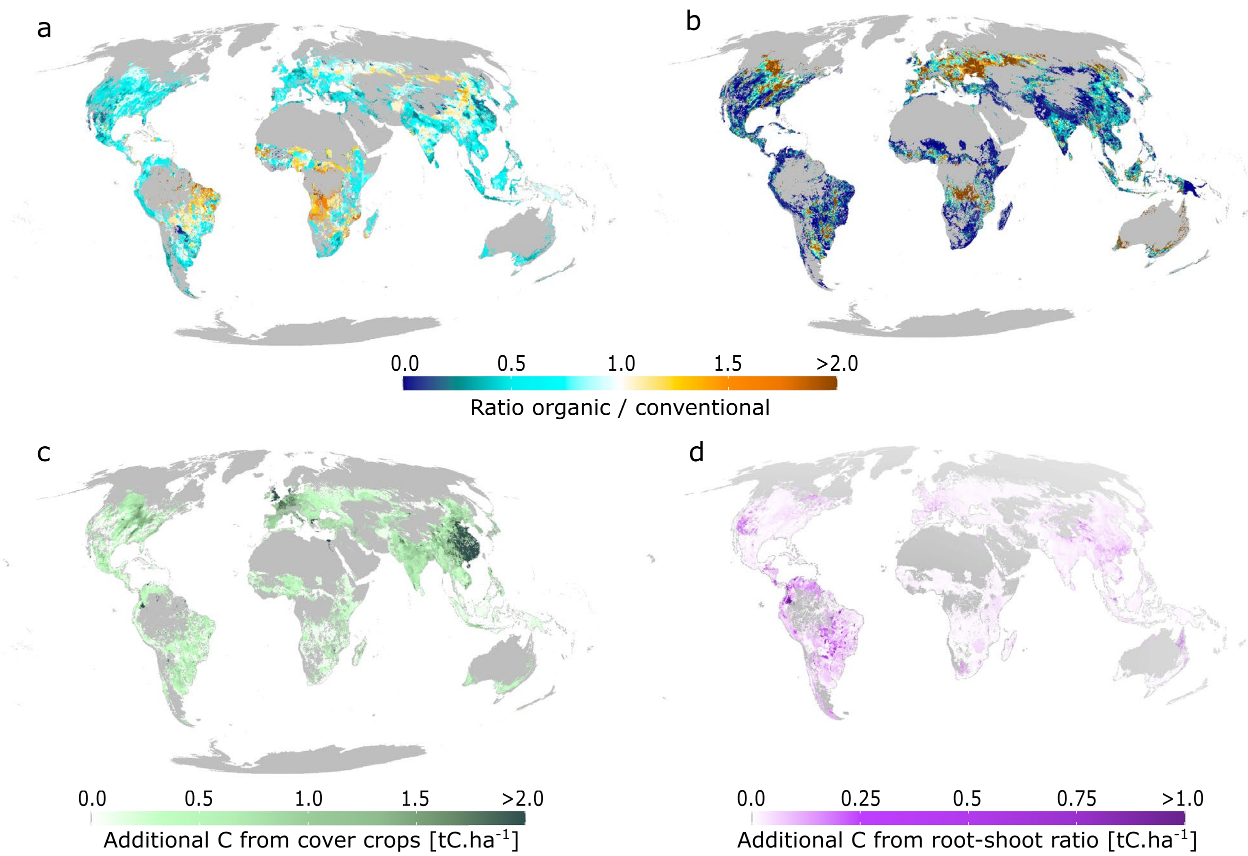

Extended Data Fig. 1 | Annual organic to baseline ratios of plant-based residues (a) and manure (b) carbon inputs (in both normative and optimal organic scenarios) and the additional carbon inputs from cover-crops (c) and from enhanced root/shoot ratio and residues recycling (d) in the optimal organic scenario.

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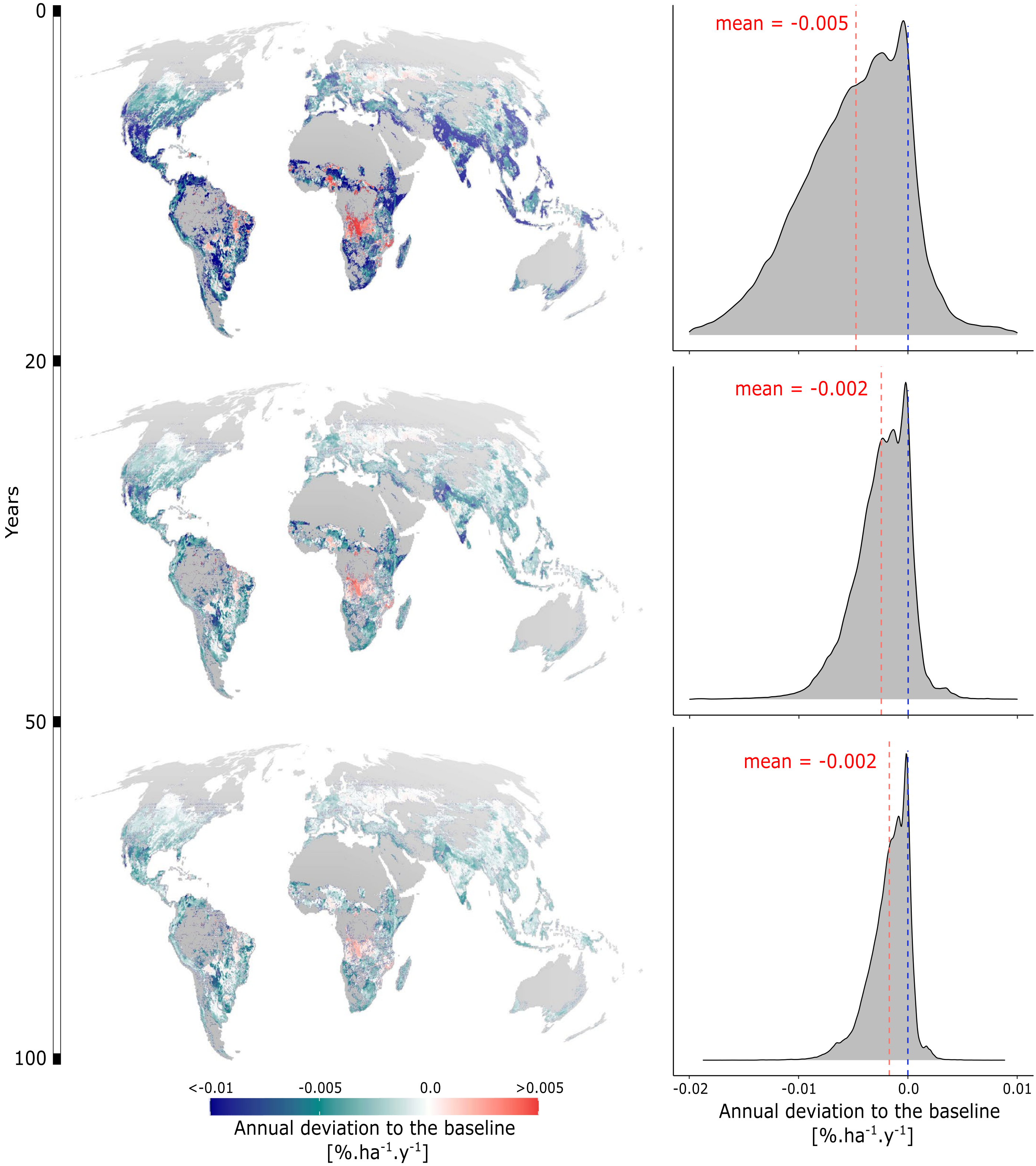

Extended Data Fig. 2 | Organic to baseline annual SOC stock change in global croplands (% per ha and per year) and in the normative organic scenario. Annual SOC stock change is reported as a map and a density curve for each period after global transition to organic farming (0–20 years, 20–50 years, 50–100 years). In the density curves, the red dashed lines indicate the estimated global mean of organic to baseline ratio of annual SOC stock change per ha, and the blue dashed lines indicate the value 1.

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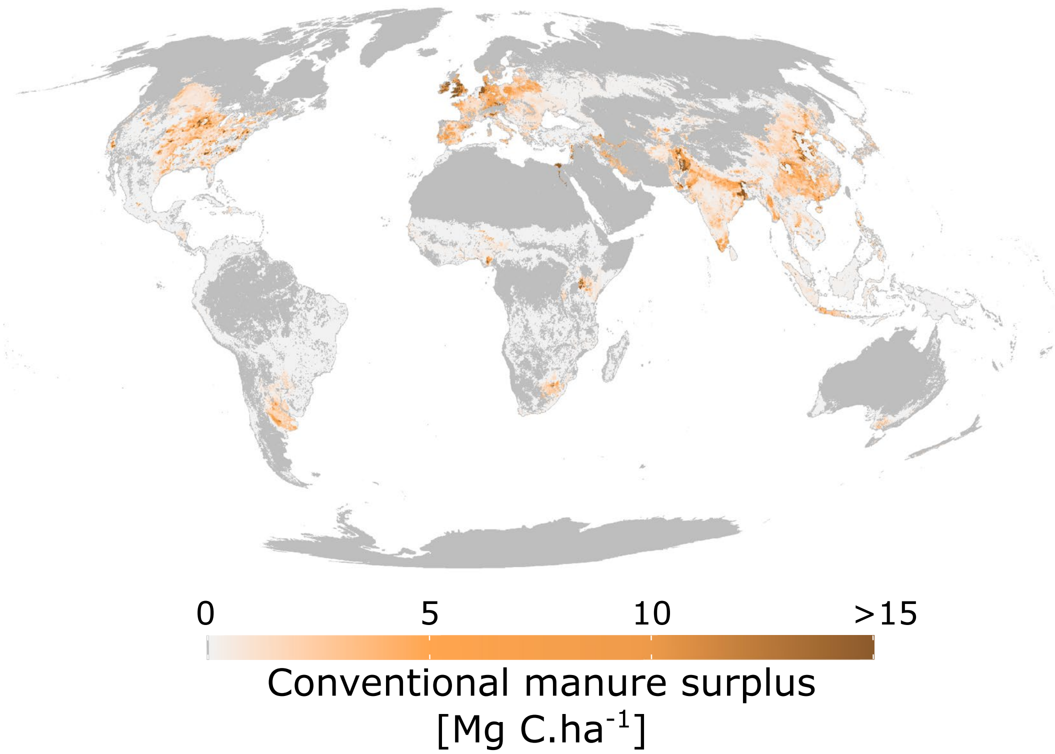

Extended Data Fig. 3 | Conventional manure surpluses available for organic croplands (Mg C.ha-1).

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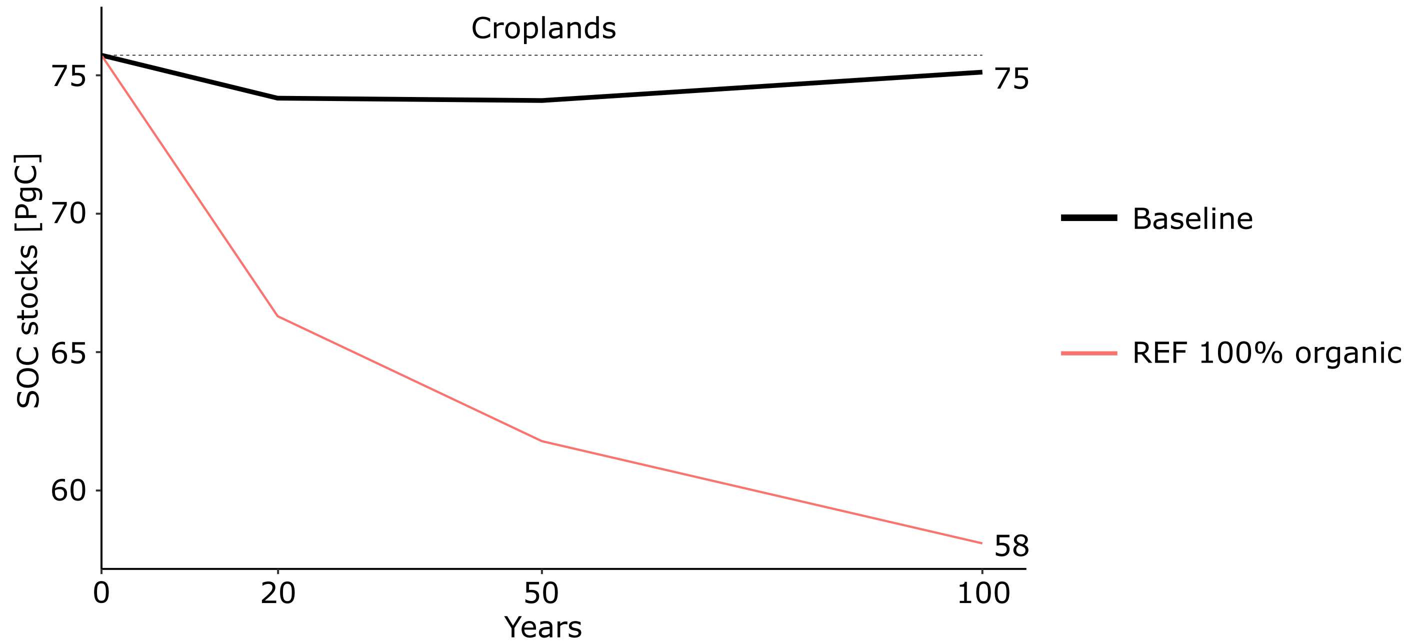

Extended Data Fig. 4 | Changes in global SOC stocks (PgC) over time using directly $SCI_{baseline}$ and SCI_{org} as inputs to the RothC model. Changes in global cropland SOC stocks are reported for the baseline (black line) and the normative organic scenario (red line). Values at the right end of each curve represent the SOC stocks after 100 years. The black dashed lines represent the current global SOC stock for croplands.

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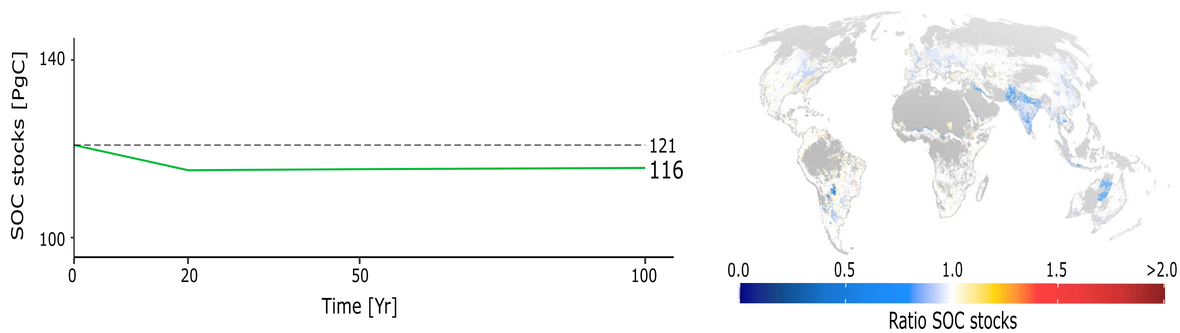

Extended Data Fig. 5 | Global changes in soil organic carbon (SOC) stocks (PgC) in grasslands over time, and maps of the SOC stock ratios between the 100% organic scenario and the baseline at 20 years. Changes in global SOC stocks in grasslands and spatial distribution are reported for the 100% normative organic scenario. The black dashed line represents the global SOC stocks for grasslands in the baseline.