Enhanced top soil carbon stocks under organic farming

Andreas Gattinger[a,1], Adrian Muller[a], Matthias Haeni[a,b], Colin Skinner[a], Andreas Fliessbach[a], Nina Buchmann[b], Paul Mäder[a], Matthias Stolze[a], Pete Smith[c], Nadia El-Hage Scialabba[d], and Urs Niggli[a]

[a]Research Institute of Organic Agriculture, 5070 Frick, Switzerland; [b]Institute of Agricultural Sciences, Eidgenössische Technische Hochschule Zurich, 8092 Zurich, Switzerland; [c]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen AB24 3UU, Scotland; and [d]Natural Resources Management and Environment Department, Food and Agriculture Organization of the United Nations, 00153 Rome, Italy

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It has been suggested that conversion to organic farming contributes to soil carbon sequestration, but until now a comprehensive quantitative assessment has been lacking. Therefore, datasets from 74 studies from pairwise comparisons of organic vs. nonorganic farming systems were subjected to metaanalysis to identify differences in soil organic carbon (SOC). We found significant differences and higher values for organically farmed soils of 0.18 ± 0.06% points (mean ± 95% confidence interval) for SOC concentrations, 3.50 ± 1.08 Mg C ha^{-1} for stocks, and 0.45 ± 0.21 Mg C ha^{-1} y^{-1} for sequestration rates compared with nonorganic management. Metaregression did not deliver clear results on drivers, but differences in external C inputs and crop rotations seemed important. Restricting the analysis to zero net input organic systems and retaining only the datasets with highest data quality (measured soil bulk densities and external C and N inputs), the mean difference in SOC stocks between the farming systems was still significant (1.98 ± 1.50 Mg C ha^{-1}), whereas the difference in sequestration rates became insignificant (0.07 ± 0.08 Mg C ha^{-1} y^{-1}). Analyzing zero net input systems for all data without this quality requirement revealed significant, positive differences in SOC concentrations and stocks (0.13 ± 0.09% points and 2.16 ± 1.65 Mg C ha^{-1}, respectively) and insignificant differences for sequestration rates (0.27 ± 0.37 Mg C ha^{-1} y^{-1}). The data mainly cover top soil and temperate zones, whereas only few data from tropical regions and subsoil horizons exist. Summarizing, this study shows that organic farming has the potential to accumulate soil carbon.

climate change | soil quality | agricultural systems

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Soil carbon sequestration at a global scale is considered the mechanism responsible for the greatest mitigation potential within the agricultural sector, with an estimated 90% contribution to the potential of what is technically feasible (1, 2). However, global soil carbon stocks of agricultural land have decreased historically and continue to decline (3). Thus, improved agronomic practices that could lead to reduced carbon losses or even increased soil carbon storage are highly desired. This includes improved crop varieties, extending crop rotations, notably those with grass–clover or forage legume leys that allocate more carbon below- ground, avoiding or reducing use of bare (unplanted) fallow (4), and the application of organic fertilizer such as compost or waste products from livestock husbandry in the form of slurry or stacked manure (5). Although these practices are not common in current modern agriculture, they are core practices of organic agriculture, where crop production relies in large part on closed nutrient cycles by returning plant residues and manures from livestock back to the land and/or by integrating perennial plants, mainly grass–clover mixtures, into the system. It is therefore hypothesized that the adoption of organic agriculture will lead to a reduction in soil carbon losses or even to higher soil carbon concentrations and net carbon sequestration over time (6). Introducing organic farming is considered an interesting and sustainable option for greenhouse gas (GHG) mitigation in agriculture. In contrast to the adoption of single GHG mitigation practices, organic farming as a systems approach provides many other cobenefits, such as adaptation to climate change, biodiversity and soil conservation, and the improvement of rural livelihood at the same time (7).

Although there is some evidence that soil carbon concentrations are higher in soils managed organically than in those from integrated or conventional (nonorganic) farming (6, 8–10), other studies have not found such differences (11, 12). Because of these inconsistent findings, advantages and disadvantages of the organic farming system vs. integrated or conventional production are hotly debated (11, 13). A drawback of existing reviews on soil organic carbon (SOC) in organic vs. nonorganic management is that they are either narrative (10) or based on a limited number of datasets, often do not account for data quality differences, and do not control for potential confounding drivers (9, 14). Thus, there is a need for a systematic, globally explorative literature review/synthesis on soil carbon datasets from pairwise organic vs. nonorganic farming system comparisons and a systematic quantitative analysis of SOC concentrations, stocks and sequestration rates that accounts for data quality, and potential confounding factors such as climatic conditions, soil characteristics, or the quantity of external nutrient inputs.

In this study, we aim to close this knowledge gap by conducting a metaanalysis of published data on the responses of SOC to conversion from conventional (= nonorganic) to organic farming management in pairwise comparisons. The objectives were to test whether adoption of organic farming resulted in (*i*) an increase in overall SOC concentration, (*ii*) an increase in overall SOC stocks, and (*iii*) higher SOC accumulation over time (= C sequestration rates) compared with nonorganic management. Using metaregression, we also analyzed how climatic conditions (rainfall and temperature), soil characteristics (clay concentration), duration of contrasting farming management, external C and N inputs, and land use type (arable, grassland, vegetable, orchard/viticulture farming) modulated the responses of SOC to the adoption of organic farming practices.

Results

General Results. The literature review yielded 74 eligible independent studies reporting SOC concentrations, of which 29 reported also SOC stocks (Table 1). Among them, 20 studies also reported baseline SOC data, which enabled the calculation of SOC sequestration rates. The vast majority of studies included in the database were published in peer-reviewed scientific journals.

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[1]To whom correspondence should be addressed. E-mail: andreas.gattinger@fibl.org.

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Table 1. Overview of the obtained publications matching the search and eligibility criteria

Criterion	SOC concentration	SOC stocks	C sequestration
Type of publications			
Scientific journals	70 publications	26 publications	18* publications
Dissertations/books chapters/proceedings	4 publications	3 publications	2* publications
Type of comparisons			
Plot scale	26 publications	23 publications	19 publications
Farm scale	48 publications	16 publications	1 publications
Coverage of land use types	Full coverage	Full coverage	Only arable and vegetables
Coverage of climatic zones	6 of 8 (except boreal and arid)	5 of 8	6 of 8
Coverage of continents[†]	5 of 6 (except Africa)	5 of 6 (except Africa)	5 of 6 (except Africa)
Sampling depth (top–bottom) (cm)	Mean: 2.4–18.4/median: 0–15.0	Mean: 1.8–19.4/median: 0–15.0	Mean: 0.8–22.5/median: 0–20.0
For all SOC datasets		Mean: 1.8–19.0/median: 0–15	
Experimental duration (y)	Mean: 13.2/median: 8.0	Mean: 16.1/median: 10.0	Mean: 12.5/median: 11.0
For all SOC datasets		Mean: 14.4/median: 10.0	

SOC concentrations, stocks, and C sequestration rates are the three effect-sizes in this metaanalysis.

*Of 20 publications on SOC sequestration, 11 report measured bulk densities, for the other 9 bulk densities were estimated.

[†]Continents except Antarctica.

The observation period of the eligible farming system comparisons for the total dataset was 3–70 y (mean: 14.4 y; median: 10.0 y), and the soil horizon sampled encompassed the layer from 1.8 to 19.0 cm (median: 0–15 cm). Not all studies started sampling from 0 cm, but depth increments and total sampling depths were identical within comparative pairs (Table 1 provides further details on duration and sampling depths).

SOC concentration and stock data from farming system comparisons existed for all investigated land use types (i.e., arable, grassland, vegetable, orchard/viticulture farming), whereas sequestration rates were only available for arable and vegetable land use. The SOC dataset covered all climatic zones typical for agricultural production (Fig. S1 shows the localization of the comparative trials). We are not aware of organic vs. nonorganic farming management comparisons under boreal or arid climates. All three effect sizes contained data from all continents except for Africa and Antarctica. There are ongoing field trials comparing organic vs. nonorganic production in Kenya (vegetables), India (cotton), and Bolivia (cocoa), but published SOC datasets are not yet available (15).

Differences Among Farming Systems. Metaanalyses of all three effect sizes revealed significantly higher SOC concentrations, SOC stocks, and C sequestration rates in soils under organic compared with nonorganic farming management. In organically managed soils, SOC concentrations were 0.18 ± 0.06% points (mean ± 95% confidence interval) higher (Fig. 1*A*; dataset category I, 200 comparisons), SOC stocks were 3.50 ± 1.08 Mg C ha^{-1} higher (Fig. 1*B*; dataset category I, 204 comparisons), and sequestration rates were 0.45 ± 0.21 Mg C ha^{-1} y^{-1} higher (Fig. 1*C*; dataset category I, 41 comparisons) than in nonorganically managed soils. These differences were all highly significant at $P < 0.0001$ and were rather conservative estimates because we removed five to nine outliers that would have biased the differences between farming systems considerably upward, although not greatly influencing significance levels. Removing these outliers thus reduces the risk of overestimating the effects of organic farming and provides a conservative analysis of the differences between systems. In all analyses, SOC stocks were derived from bulk densities and SOC concentrations, although not all bulk density values had been measured. Thus, we analyzed differences in SOC stocks and sequestration rates separately for a subset of studies that reported measured bulk densities. SOC stocks for this subset were 3.60 ± 1.45 Mg C ha^{-1} higher ($P < 0.0001$; Fig. 1*B*; dataset category III, 93 comparisons), and sequestration rates were 0.30 ± 0.14 Mg C ha^{-1} y^{-1} higher ($P <$ 0.0001; Fig. 1*C*; dataset category III, 32 comparisons) for organic vs. nonorganic management. Soil bulk densities were found to be lower for the organic practice (Dataset S1), thus the observed increase in SOC stocks in organically managed soils resulted from SOC enrichment and not from soil compaction.

Because soil carbon sequestration is time dependent owing to the phenomenon of "sink saturation" (16), we also performed a metaanalysis with our dataset grouped according to duration of farming system comparison (up to 10 y, 10–20 y, more than 20 y). Our results show this time dependency with the highest difference in sequestration rates for the first 10 years of organic management. Differences in sequestration rates are significant for the duration up to 10 y and 10–20 y, whereas differences in concentrations and stocks were always significant. Detailed results from these analyses are displayed in Dataset S1.

Although these data clearly showed that organic management increased SOC, it is often criticized that increased SOC stocks originate from massive imports of organic matter taken from elsewhere (13, 17, 18). To examine the potential impact of imported organic matter, we analyzed a subset of studies representing organic farming systems with zero net input separately. These represent mixed livestock–crop production farms with forage crops in the crop rotation, such that the livestock can be fed entirely from fodder produced on-farm. In such systems, no import of organic matter occurs. On the other hand, these systems could also be stockless farms that import organic matter from elsewhere but to an extent that is supported by their own systems' productivity. For our analysis, the cutoff for a zero net input system was set at an amount of organic fertilizers applied to the trials that corresponds to the manure amount from 1.0 (European) livestock unit (LU) ha^{-1}. This is lower than the maximum stocking rates that we consider to reflect a zero net input system. Adopting this conservative threshold, we may neglect some studies that actually represent zero net input systems, but we can be sure that we have excluded all organic systems with net inputs. For nontemperate zones, a conservative threshold for zero net input systems could even be lower. Because only one study from nontemperate zones showed values below 1.0 LU (it reported 0.9 LU), the use of this threshold is adequate for our data set. In this subset, SOC concentrations were 0.13 ± 0.09% points higher ($P < 0.001$; Fig. 1*A*; dataset category II, 60 comparisons), SOC stocks were 2.16 ± 1.65 Mg C ha^{-1} higher ($P < 0.01$; Fig. 1*B*; dataset category II, 60 comparisons), and C sequestration rates were no longer significantly different from nonorganically managed soils (0.27 ± 0.37 Mg C ha^{-1} y^{-1}, $P > 0.1$; Fig. 1*C*; dataset category II, 19 comparisons). Identifying whether the organic treatment in a comparison corresponded to a zero net input system required data on external C and N inputs. Measured external C and N inputs had been

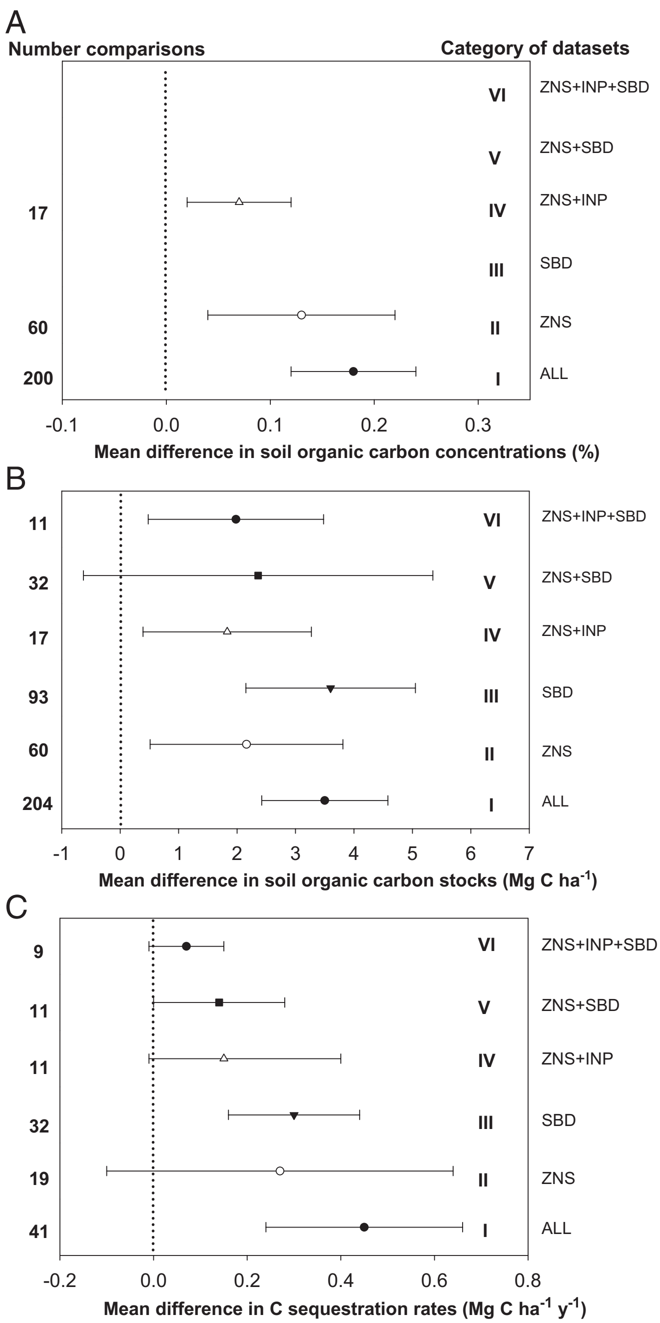

Fig. 1. Mean difference in (*A*) SOC concentrations, (*B*) SOC stocks, and (*C*) C sequestration rates of soils under organic vs. nonorganic management, grouped according to different dataset categories after removal of outliers. Category I: total dataset (ALL); II: dataset containing only those studies in which the organic treatment is ≤1.0 ELU ha^{-1}, the threshold for zero net input systems (ZNS); III: dataset containing only those studies reporting measured soil bulk densities (SBD); IV: dataset containing only those studies in which the organic treatment is ≤1.0 ELU ha^{-1} and in which measured data of external annual C inputs were reported (ZNS+INP); V: dataset containing only those studies in which the organic treatment is ≤1.0 ELU ha^{-1} and in which measured data of soil bulk densities were reported (ZNS+SBD); VI: dataset containing only those studies in which the organic treatment is ≤1.0 ELU ha^{-1} and in which measured data of external annual C inputs and soil bulk densities were reported (ZNS+INP+SBD). Categories III, V, and VI are not reported for SOC concentrations, because the restriction on measured bulk densities is not relevant for the quality of the SOC concentration values. Horizontal bars show the 95% confidence interval. Numbers of comparisons are displayed for each dataset category along the *y* axis.

reported for only a few studies. For the other studies, they were calculated from reported rates of manure and compost using standard C and N concentrations. An analysis of only those zero net input systems that reported external C and N inputs in detail showed that SOC concentrations of organically managed soils were 0.07 ± 0.05% points higher ($P < 0.01$; Fig. 1*A*; dataset category IV, 17 comparisons) and SOC stocks were 1.83 ± 1.44 Mg C ha^{-1} higher ($P < 0.01$; Fig. 1*B*; dataset category IV, 17 comparisons) compared with nonorganically managed soils. No difference in C sequestration rates between both systems could be determined from this dataset (0.16 ± 0.25 Mg C ha^{-1} y^{-1}, $P > 0.1$; Fig. 1*C*; dataset category IV, 12 comparisons). However, taking only the subset also reporting measured bulk densities for the zero net input system trials led to SOC stocks that were not significantly higher under organic management (2.36 ± 2.99 Mg C ha^{-1}; Fig. 1*B*; dataset category V, 32 comparisons), whereas C sequestration rates were 0.14 ± 0.14 Mg C ha^{-1} y^{-1} higher ($P < 0.05$; Fig. 1*C*; dataset category V, 11 comparisons) compared with nonorganic management. Taking all three conditions (measured inputs, measured bulk densities and zero net input systems), finally, led to SOC stocks that were 1.98 ± 1.50 Mg C ha^{-1} higher under organic management ($P < 0.01$; Fig. 1*B*; dataset category VI, 11 comparisons) and sequestration rates that were 0.07 ± 0.08 Mg C ha^{-1} y^{-1} higher ($P < 0.05$; Fig. 1*C*; dataset category V, 9 comparisons). These analyses suggest that organically managed systems have higher SOC levels, both when using the full dataset or the various subsets of zero net input systems only, or when using subsets of improved data quality only, by exclusively retaining those comparisons with directly measured data.

Factors Influencing Changes in Soil Organic Carbon. The organic and nonorganic farming systems covered in the trials varied considerably with respect to the amount of farmyard manures applied and the composition of crop rotations, potentially influencing the observed differences in SOC stocks and C sequestration rates. Furthermore, climatic and soil conditions as well as the land use types may influence the observed SOC differences. Thus, we used a metaregression to identify the importance of potential driving variables on observed SOC differences.

On the basis of these metaregressions (detailed results are given in Dataset S1; further details on the regressions are provided in *Methods*), significant results were found for SOC concentrations and stocks but not for C sequestration rates. We thus only display the corresponding tables for SOC concentrations and stocks (Dataset S1). The estimated parameters, their significance levels, and how those change between the different models and data subsets (*SI Methods*, Dataset S1) suggested that differences in external C inputs, clay concentrations, mean annual precipitation, and mean annual temperature did influence differences in SOC concentrations and stocks. Presence of the same crop rotation in both systems, and land use may also be influential. As expected, the sign of the influence of external C inputs is positive, and the sign of the influence of the same crop rotations is negative. External N inputs and forage legumes in organic systems seem unimportant. However, for all of these variables, more data are necessary before conclusive impacts can be determined, and our findings are thus-far indicative at best.

Discussion

Limitations of the Dataset. The compiled database is to the best of our knowledge the largest for comparing of SOC in organic vs. nonorganic farming systems. However, there are some few limitations concerning the significance and the transferability of our results.

A first limitation is that less than 50% of all studies that qualified for our database reported SOC stocks or provided soil bulk densities to calculate stocks. This is because the majority of the farming system comparisons were originally designed to investigate the influence of agricultural management practices on agronomic performance, such as plant dry matter production, grain yields, and other agronomic properties (13). However, SOC concentration is more often reported in these studies, because it is considered a key indicator for soil quality, but C concentrations alone are not sufficient to assess the C sink potential.

Another important limitation is the lack of data from the start of the respective experiment (baseline). However, without a proper baseline, it is impossible to determine whether a measured difference in SOC between two treatments after a certain period is actually caused by the treatment or whether it has already been present at the beginning. In the current database, SOC stock data at time point zero could be obtained from only 20 studies, of which nine only reported initial SOC concentrations but no bulk density. For these nine studies, SOC stocks were calculated on the basis of bulk density values that were estimated according to Post and Kwon (2000) (19).

Moreover, the average soil sampling depth of the studies in our database included the thickness of a typical tillage layer of 20 cm soil depth. This soil depth covers almost the entire cultivation horizon of an agricultural soil, but it can be assumed that a substantial part of SOC will not be considered (20) and may lead to misinterpretation of management effects (21). This is particularly significant in the view that in deeper soil horizons SOC may be more conserved (22). It has been showed in farming systems of the DOK (bio-dynamic D, bio-organic O, and conventional K) farming systems trial in Switzerland with rotations comprising 2 y of deep rooting grass–clover leys (= forage legumes) in the crop rotation, that 64% of the total SOC stocks were deposited in the horizons at 20–80 cm soil depth (23). In our dataset, 28% of the nonorganic and 47% of the organic treatments comprised forage legumes and thus likely produce a significant farming system effect on subsoil SOC. This, however, is not reflected in the current dataset, because subsoil samples under forage legumes in the crop rotation are scarce (compare the nonsignificant results of the metaregression for this variable).

Finally, our database showed a rather unbalanced coverage of climatic regions and continents. Of the 74 studies reporting SOC from farming system comparisons, 60 are obtained from three developed continents—North America, Europe, and Australia/New Zealand. We have found only five eligible studies from the Asian continent, and none from Africa (most recent state of the database: 15.04.2012). However, for Sub-Saharan Africa (SSA) for instance, where soil resources are scarce and severely degraded, organic farming might be a promising approach for sustaining agricultural production. In this region a substantial reduction in precipitation has already been observed (24), and the projected increase in human population between 2008 and 2050 will be from 364 million to 595 million (25). The large population of resource-poor and small-size land holders can neither afford the use of chemical fertilizers and other input, nor are they sure of their effectiveness (25). For such regions, low external input systems such as organic farming can offer a long-term solution, but it remains unclear whether a SOC gain crucial for the build-up of soil fertility and resilience will really result from its adoption in SSA and comparable regions in the developing world. Therefore, data from field comparisons is much needed for these regions.

More Carbon in Organically Managed Soils? The metaanalysis of the three effects sizes "SOC concentration," "SOC stocks," and "C sequestration rates" indicated the presence of significantly more carbon in organically managed top soils. Our results showed that organic farming practice lead to SOC stocks in the upper 20 cm of soil over a period of *ca.* 14 y that are 3.50 ± 1.08 Mg C ha^{-1} higher in organic than in nonorganic systems. Considering those studies with the highest precision of data quality (measured C and N inputs and bulk densities) containing zero net input organic systems only, this difference is reduced, but still significant and positive at 1.98 ± 1.50 Mg C ha^{-1}. No comparison of these numbers with earlier results from review articles is possible, because the results presented here go beyond whatever has been published on SOC under organic and nonorganic management to date: in previous narrative reviews and/or semiquantitative approaches, only SOC concentrations were considered (6, 10, 13, 14).

The observed differences in SOC concentrations, stocks, and C sequestration rates seem to be influenced by the amount of external annual C inputs. This is indicated by the regression results and also by the lower differences reported for zero net input systems. These C inputs are from organic fertilizer mainly in the form of stacked manure, slurry, or compost, which are either produced on the farm or imported into the farm; both are possible within the organic regulations (e.g., European Union regulation 837/2007). On average, 0.29 Mg and 1.20 Mg external C inputs ha^{-1} y^{-1} were applied to nonorganically and organically managed soils, respectively (Dataset S1). We used the variable "external C inputs" instead of the "total C inputs" for metaregression, because we have data on external C inputs for 57 of 74 studies, whereas only six studies provided data on total C inputs derived from plant residues and organic fertilizers. For these six studies, the mean total annual C input was 4.23 and 4.86 Mg C ha^{-1} for nonorganic and organic farming systems, respectively.

The observed differences in external C inputs between farming systems reflect the situation in modern agriculture whereby an increased specialization of farming enterprises in many developed countries led to a separation into livestock and crop production (26), with the consequence that manure (mostly as slurry from livestock) is disposed of rather than recycled. In contrast, organic farms show a more pronounced integration of livestock into the farming system (27). First, the above-ground biomass of forage legumes in organic crop rotations feed the farm animals, whose manure is brought back to the land; and second, the below-ground biomass of forage legumes contributes to soil fertility build-up. A higher percentage of forage legumes in organic cropping than in nonorganic cropping systems was also found in our dataset. The higher C inputs are thus system-intrinsic to organic agriculture and are not a phenomenon of a biased comparison between organic and conventional farming, as argued elsewhere (13). The analysis of the subset of zero net input farms is important in the context of this discussion: it shows that, also under these conditions, increased SOC levels are observed under organic farming.

Carbon Sequestration Within Organic Farming Systems? The presence of a positive difference in SOC concentrations, stocks, and C sequestration rates between organic and nonorganic systems does not reveal whether this change goes along with a net carbon gain due to conversion from conventional to organic farming or whether it rather reflects a reduced carbon loss if compared with the nonorganic treatment. Averaging the differences between initial and final SOC stocks for studies in which such data were available and accounting for the study duration led to a slight carbon gain of 0.090 Mg C ha^{-1} y^{-1} for nonorganic and a carbon gain of 0.55 Mg C ha^{-1} y^{-1} for organic treatments. Hence, the result of the metaanalysis for the mean differences in C sequestration, 0.45 ± 1.05 Mg C ha^{-1} y^{-1}, between organic and nonorganic farming can be considered as net sequestration in the top soil. Leifeld and Fuhrer (13) found in their review an average annual increase of the SOC concentration in organic systems by 2.2%, whereas in conventional systems, SOC did not change significantly. Freibauer et al. (4) estimated a C sequestration potential of organic farming in Europe of 0–500 kg ha^{-1} y^{-1} (more than 50% uncertainty) using calculations based on the combination of single practices such as extensification, improved rotations, residue incorporation, and manure use, but excluding zero and reduced tillage.

Furthermore, the data show that carbon sequestration follows sink saturation dynamics (compare Dataset S1). SOC concentrations and stocks show increasing differences between farming systems for longer trial durations. This increase is largest in the early years of the comparisons and then attenuates. These dynamics also suggest that differences in sequestration rates quoted on a "per-year" basis arise from differences in trial duration. For unbiased assessment of differences in soil carbon sequestration between farming systems, stocks and concentrations at the beginning and the end of a trial need to be reported and expressed relative to the trial duration.

Soil Carbon Sequestration in Organic Farming in a Wider Context. We close this discussion by putting our results in the wider context of global climate change mitigation and life-cycle analysis. First, an estimate of the maximum technical mitigation potential from soil C sequestration by switching to organic agriculture can be gained by applying the average difference in sequestration rates for net zero input systems (0.27 Mg C ha^{-1} y^{-1}) to the current global arable land area, and to European or US arable area only, thus accounting for the bias of the data for these regions (data and calculations for this paragraph are given in Dataset S1). This results in 0.37 Gt C sequestered per year globally (0.03 Gt C in Europe, 0.04 Gt C in the United States), thus offsetting 3% of current total GHG emissions (2.3% for Europe, 2.3% for the United States), or 25% of total current agricultural emissions (23% for Europe, 36% for the United States), and equaling approximately 25% of the annual technical agricultural mitigation potential, as identified elsewhere (2). The cumulative mitigation till 2030 would contribute 13% to the cumulative reductions that would be necessary until 2030 to stay on the path to reach the two-degree goal by 2100 [56 Gt C globally from 2010 till 2030, according to the RCP2.6 scenario (28)]. We emphasize that this estimate represents the maximum technical potential because (*i*) it is unclear how much conventionally farmed cropland already receives organic material, and (*ii*) our calculations do not account for economic and market aspects.

Further, the estimation of carbon sequestration alone does not equate to climate change mitigation because (*i*) offsetting emissions with sequestration only buys time and does not negate the need for emission reduction, and (*ii*) soil-derived N_2O emissions, production emissions of different fertilizers, and energy-related emissions from farm machinery and irrigation, as well as emissions from livestock and manure, need to be accounted for in a life-cycle analysis. We have focused on the differences in SOC sequestration between organic and conventional production. Schader et al. (29) provide a review on the relative performance of organic agriculture regarding other aspects, such as, for example, energy use and emissions in the livestock sector.

Conclusions

Metaanalysis from the farming systems database compiled for this study confirms higher SOC concentrations and stocks in top soils under organic farming. Second, SOC differences seemed to be mainly influenced by elements of mixed farming (livestock plus crop production), such as organic matter recycling and forage legumes in the crop rotation. It is therefore likely that SOC concentrations and stocks under modern agriculture could be improved if these measures were adopted. These measures are intrinsic to organic agriculture but can in principle be applied in any agricultural production system. Further research is required to underpin the observed findings for the entire soil profile and for developing regions (e.g., SSA) where no data from farming systems comparisons are available.

Methods

Additional details on the data and methods can be found in the *SI Methods*.

Data Sources. We collected data from pairwise comparisons on organic and nonorganic farming systems from peer-reviewed research papers that reported measured data on SOC concentrations, SOC stocks, and C sequestration rates. SOC concentrations describe the organic carbon concentration on a weight by weight basis, SOC stocks on a weight by area basis, and C sequestration rates on weight by area and elapsed time since conversion. The majority of the collected research papers were published in scientific journals, but we also included eligible studies from conference proceedings, book chapters, and dissertations to enlarge the dataset, because those contributions also undergo a peer-review process. In a few cases the authors were contacted for further information/data on their farming system comparison (Dataset S1).

All studies were based on farming system comparisons in which the organic practice was exclusively defined as organic by the respective authors. The term nonorganic was applied in the present article to a range of modern management systems that are defined as conventional or integrated, and as such, its exact meaning varied across studies. We used the term nonorganic for any farming system that relied on the use of synthetic nitrogen fertilizer and chemical plant protection means.

We used the following qualifying criteria to include studies: (*i*) the relevant organic farming principles were applied for at least 3 consecutive years. This is in agreement with the European Union legislation on organic farming (EC) Nr. 834/2007 and the organic farming directives in most countries worldwide; (*ii*) pairwise farming system comparisons: organic and nonorganic farming management was performed under the same pedo-climatic conditions (e.g., temperature, precipitation, soil texture, and soil type). In the studies in which SOC concentration but no SOC stock data were reported (because of missing bulk densities), SOC stocks were calculated according to the formulas below to increase the number of studies reporting SOC stocks and C sequestration. SOC stocks (Mg C ha^{-1}) in the corresponding soil layer were calculated as:

$$SOC_{stock} = BD \times SOC_{conc} \times D. \quad [1]$$

where *BD* is soil bulk density (Mg m^{-3}), and *D* is the thickness of the soil layer (m). For nine studies, *BD* was not available at the beginning and the end of the observation period and was estimated according to Post and Kwon (19):

$$BD = \frac{100}{\left(\frac{OM_{conc}}{0.244}\right) + \left(\frac{100 - OM_{conc}}{1.64}\right)}. \quad [2]$$

where 0.244 is the bulk density of soil organic matter, 1.64 the bulk density of soil mineral matter, and OM_{conc} the concentration of soil organic matter (%), which was estimated according to Nelson and Sommer (30):

$$OM_{conc} = 1.72 \times SOC_{conc}. \quad [3]$$

Livestock Stocking Density as a Proxy for Organic Fertilization Intensity. Only a few studies reported exact values on total annual C inputs, because most of the farming system comparisons were initiated to study the agronomic performance rather than soil carbon dynamics. Additionally, information on whether harvest residues were left on the field is scarce. In contrast, the external annual N inputs from organic fertilizer were reported more often in the used datasets. On the basis of the external annual organic N inputs (N fixation is excluded owing to lack of data), we calculated the animal stocking density as European livestock units (ELU) ha^{-1}, assuming a dairy cow (3,000 L milk, without additional concentrated feedstuffs) (31) produces 77 kg N in the form of organic compounds (32). From this, external annual C inputs were calculated using standard factors (32). This approach was used as a proxy to assess whether the amount of manure applied could have been produced theoretically at the respective organic farm, thus allowing for identification of comparisons that represented zero net input organic systems. We further validated our assumptions on zero net input systems by assessing yield data for the comparisons in which external inputs correspond to $\leq$1.0 ELU ha^{-1}. Yield data were available for four studies of this category only, but the results justify that the amount of farmyard manure applied is supported by the productivity of the relevant organic farming systems and that those thus indeed represent zero net input systems.

Data Analysis. For each farming system comparison, the mean in SOC concentration, SOC stock, and C sequestration rate under organic (x_{ORG}) and nonorganic ($x_{non\text{-}ORG}$) management was used to calculate the three effect sizes of interest, namely the mean differences (*MD*) in SOC as influenced by the farming system:

$$MD = x_{ORG} - x_{non\text{-}ORG}. \quad [4]$$

We extracted the mean, SD, or significance level (*P* value) and sample size (*n*) of SOC data in each experiment for weighing the response of SOC change by

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variation (SD) and sample sizes (*n*). Where we could neither extract nor calculate SD from SEs, we reassigned the SD as 1/10 of the mean (33). This was the case for approximately half of the SOC concentration and for a third of the stock data. In fact, SD for measured SOC data were always below 1/10 of the mean SOC concentrations and SOC stocks (Dataset S1). A random-effects metaanalysis was performed using the restricted maximum likelihood estimator using the Knapp-Hartung adjustment to account for the uncertainty in the estimate of (residual) heterogeneity (34–37). Datasets were analyzed with R Statistical Software using the "metafor" package (37) to calculate the effect sizes and their significance levels (Dataset S1).

Metaregression. To investigate potential driver variables of the observed SOC differences, we used a mixed-effects metaregression. This was also run in R using the "metafor" package (37).

We tested a general model, whereby differences in external C and N inputs influence differences in SOC between the farming systems, and whereby a range of other parameters also influences these differences. These additional parameters were mean annual temperature and mean annual precipitation levels; differences in clay concentrations; one variable for the same crop rotation in the organic and nonorganic trials and one for the absence of forage legumes in the conventional system while being present in the organic one; the duration of the farming system comparison; and variables for land use types ("arable," "grassland," "vegetables," and "orchards," where "arable" is the baseline for comparison).

Nonindependent Data. Eighty-seven comparisons analyzed belonged to sets of dependent comparisons that referred to the same conventional baseline for several organic treatments, to the same organic treatment for several conventional baselines, or (e.g., in the DOK trial: bio-dynamic D, bio-organic O, and conventional K) (12) where two organic treatments ("organic" and "bio-dynamic") are compared with two conventional baselines ("conventional with farmyard manure" and "conventional without farmyard manure"), resulting in four nonindependent comparisons). We accounted for this by also analyzing the data on aggregate level for these cases (i.e., by averaging over the conventional and/or organic treatments per study), as recommended by Borenstein et al. (38). This reduced the number of observations by replacing the 87 comparisons with 30 aggregates. The results of such aggregated metaanalysis without control variables exhibited largely the same significance levels as the original results, although the values of SOC differences were usually about 10% higher for all three effect sizes. We do not provide further details on this aspect, because we chose to report the more conservative results from the analysis on the level of single comparisons.

Global Mitigation Potential. Arable land areas are taken from the FAOSTAT database (http://faostat.fao.org/). We focus on arable land, because sequestration rates are not available for grasslands in our dataset. Given that the median duration of all trials is 8 y, the average sequestration rate of 0.27 Mg C ha^{-1} y^{-1} allows the cumulative mitigation from 2010 up to 2030 (~2012+2*8) from such a switch to be estimated. It should also be noted that the difference in sequestration rates for net zero input systems used was not significant.

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Supporting Information

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SI Methods

Data Sources. Further selection criteria for including a study comparing SOC in organic vs. nonorganic systems were the following: (*i*) availability of field comparisons (i.e., from plots managed organically and conventionally in the same field or in close vicinity, thus ensuring equal external conditions besides management as far as possible); (*ii*) the data provided values for SOC concentrations, SOC stocks, or C sequestration rates or information that allowed us to calculate these values (SOC concentrations, measured bulk density, sampling depth, and duration of farming system comparison).

The data ideally also included clear, logical reference to agricultural land use types (arable, grassland, vegetable (excluding greenhouse cultivation), horticulture/viticulture); reported pedoclimatic conditions (mean annual temperature, mean annual precipitation, and clay concentration); reported inclusion/exclusion of green manures (e.g., grass–clover leys); and included information on whether there have been annual external inputs (e.g., slurry or compost) and on further characteristics of the experimental sites (e.g., regarding crop rotations) (Dataset S1).

To assess differences in SOC between farming systems, ideally, the SOC stocks at the beginning and at the end of the reporting period should be known. This then allows identifying differences in SOC stocks while accounting for differences already present at the beginning. Thus, average C sequestration rates can be derived and compared by dividing the increase in soil carbon stocks over the reporting period by the length of this period. Only few studies provided all this information, and we therefore decided to also assess differences in soil C stocks and concentrations from studies in which the baseline values were not known. This provided further information, although we could not identify how much of the difference between farming systems may be due to soil carbon values being different right from the beginning. Thus, results derived from such SOC concentration and stock comparisons are less reliable, but given the fact that all data considered originated from pairwise system comparisons including controlled field trials, baseline differences in SOC concentrations and stocks among the different plots of one comparison were expected to be negligible. Results from these analyses may thus not be able to provide accurate numbers, but robust trends can still be identified.

In some cases, more than one study reported SOC results from a particular experiment. We reported only SOC data from the study covering the longest period but included additional information concerning field activities from studies reporting on the same experiment but for shorter periods (Dataset S1). In 11 studies, information about the duration of the nonorganic farming practice was not available. In these cases we assumed that the duration of the nonorganic practice was the same as for the organic management.

In the present study, soil depth was not adjusted to account for changes in bulk density with conversion to organic agriculture unless the authors of the original data had already done so. We think such an adjustment might be meaningful when effects in land use changes (e.g., from forest to grassland, or arable to grassland) were studied, which was not the focus of the present article. In two of 209 comparisons, the sampled soil depths varied slightly within comparative pairs. SOC corrections to uniform soil depths were not performed because these two adjustments had no significant effect on the difference in SOC.

Data Analysis. Besides performing the random-effects metaanalysis using the restricted maximum likelihood estimator using the Knapp-Hartung adjustment, we also tested results with the empirical Bayes method, which gave very similar results (1, 2). We also recalculated without the Knapp and Hartung adjustment. As expected, this resulted in smaller confidence intervals and correspondingly higher significance levels. Differences affected significance levels for some calculations only and by at most one order of magnitude. Outliers were identified via their Cook's distance and the diagonal elements of the hat matrix (and the other criteria provided by the "influence" function of the "metafor" package). We then asked what caused them to be outliers. Frequent causes were very high external C inputs and SOC changes. In the full dataset, five to nine outlying comparisons out of 209 were deleted for the three effect size measures. In the subsets, the number of outliers was lower and for some analysis even zero.

Metaregression. Analysis was again done with the restricted maximum likelihood estimator with the Knapp and Hartung adjustment and also checked with the empirical Bayes estimator (with Knapp and Hartung adjustment). Results between these methods did not differ much, and omitting the Knapp and Hartung adjustment had similar effects as described above for the metaanalysis (i.e., slightly increasing significance levels for some analyses). Outliers were also identified as described above. Outliers were often linked to very high external C inputs or SOC changes. This also explained why the full dataset including outliers showed significant results for the influence of external C and N inputs on the effect sizes, whereas these effects disappeared after having removed the few outliers. Removing these outliers is thus crucial for unbiased results.

We ran the regressions for the full dataset (after having deleted outliers), for the subset of the data representing zero net input systems only, for the subset of highest data quality (i.e., reporting measured external inputs and bulk densities), and for combinations of these conditions. Because of missing values in many variables, running the full model considerably reduced the number of studies retained. Thus, we also ran two reduced models. In the first, the difference in clay concentrations was omitted, because this variable had many missing values, and nonmissing values were mainly zero, with some big differences reported for others. In the second, only external C and N inputs were retained. The changes in significance levels and values when running these restricted models (compare Dataset S1) showed that conclusions should only be drawn very cautiously. Additionally, when reducing the full dataset to subsets of zero net input systems, respectively improved data quality, significance levels changed considerably, often resulting in only insignificant results remaining. Because of these problems, we do not draw any statistical inference from these regressions. We only use the results as indication of which factors may be influential and which may rather not. This is also in line with our understanding of metaanalysis as a powerful tool of descriptive rather than inferential data analysis.

Nonindependent Data. Aggregation of nonindependent data leads to a considerable loss of information (3, 4), whereas the dependence on the level of single comparisons mainly results in some underestimation of variances without greatly affecting mean values. This is the result of the double-counting of identical treatments or baseline data, which basically leads to an overestimation of sample sizes by also double-counting them. The metaregressions on aggregated level showed few and mainly weakly significant results because of the reduced number of observations. Owing to the descriptive and indicative character of such metaregressions, we did not further analyze these results or compare them with the metaregression on the level of single comparisons.

Nonindependent data were an issue in 25 studies. In 16 studies, more than one treatment qualified for the definition "nonorganic." These treatments were named conventional, integrated, low-input, or no-till management in the original studies. In these cases additional pairs were formed (e.g., "organic vs. conventional" and "organic vs. integrated"). In nine studies, more than one treatment qualified for the definition of organic. In these cases, additional pairs were formed (e.g., "organic vs. conventional" and "bio-dynamic vs. conventional").

Global Mitigation Potential. Because projected crop areas in 2030 are likely to be somewhat higher than today, our estimates are conservative regarding this. RCP2.6 is the representative concentration pathway scenario with radiative forcing of 2.6 W m^{-2} by 2100, which is necessary to reach the 2° goal. It corresponds to cumulative emission reductions of 70% by 2100, respectively annual emission reductions of 95% in 2100, for which the baseline is the IMAGE 2.4 B2 scenario, which represents a medium development in population, income, energy, and land use. The main emission reductions in the RCP2.6 scenario are incurred between 2020 and 2060 (5). The cumulative emissions reductions until 2030 under RCP2.6 used here are approximate numbers, derived from the information given by van Vuuren et al. (5). We point out that the RCP2.6 scenario has a land use module, and the effects of switching to organic production should ideally be assessed by implementing this in this land use model, because it will affect other sectors and modules in the model. These numbers for the mitigation potential from SOC sequestration represent the maximum unconstrained technical potential and are not equivalent to realizable economic or market potentials (6).

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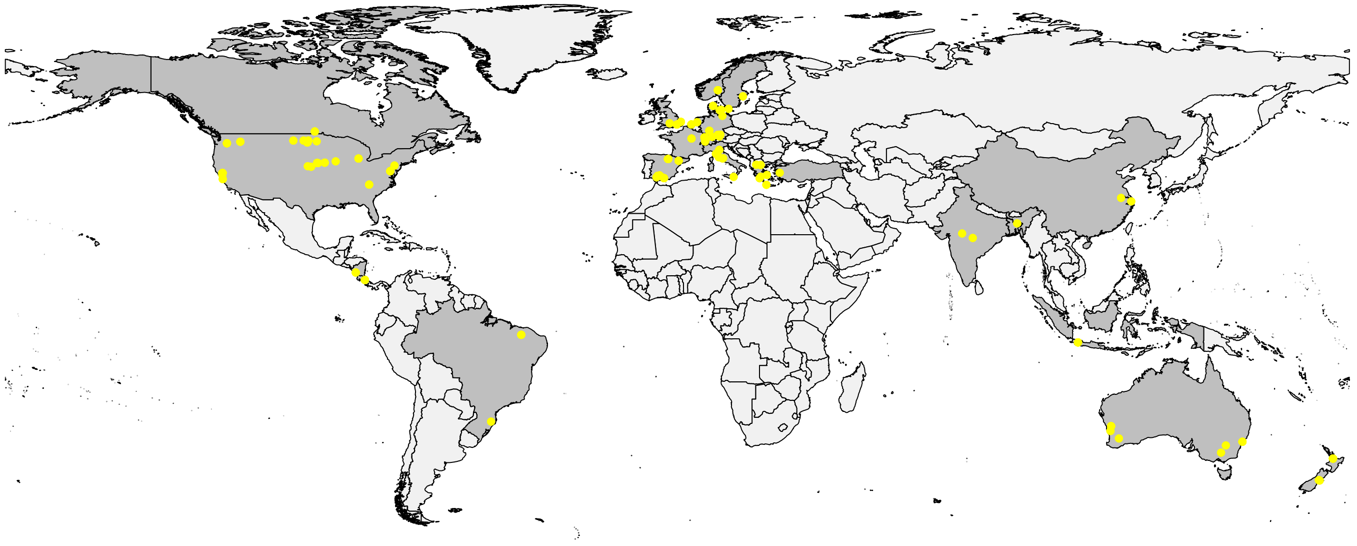

Fig. S1. Map showing the locations of the comparative trials that were included in the metaanalysis. Countries where comparative trials were performed are highlighted in dark gray; yellow dots mark the exact positions of the trials.

Dataset S1. Overview of the dataset with the (*i*) main variables, (*ii*) references, (*iii*) results of the metaregression, (*iv*) results of the metaanalysis:SOC differences over time, and (*v*) data and calculations for the assessment of the global mitigation potential

Dataset S1