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A global dataset of experimental agricultural management on soil carbon accrual, its synergies and trade-offs

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Maintaining and enhancing soil organic carbon (SOC) in agricultural soils is proposed as a key practice to mitigate climate change. While there is agreement on the co-benefits of SOC accrual on other agroecosystem services, its potential trade-offs in terms of greenhouse gas emissions and nutrient losses are still under debate. We present a global dataset compiling the results of 232 articles that experimentally compare the effects of agricultural management practices with a potential to preserve or enhance SOC against conventional practices. The dataset reports 570 experimental effects of practices to minimise soil disturbance, diversify cropping systems, or increase organic inputs in 254 experiments across 38 countries. The dataset further reports the qualitative (positive, neutral or negative) effects of these management practices on SOC accrual, crop yield, and other response variables related to soil structure, soil biota, CO_2 and N_2O emissions, and nitrogen and phosphorus losses. This dataset helps understanding the synergies and trade-offs of SOC accrual practices with other ecosystem services, detect current knowledge gaps, and guide future agricultural policies.

Background & Summary

Maintaining and enhancing soil organic carbon (SOC) stocks is currently on the scientific and political agenda as a mechanism to adapt to, and mitigate, climate change[1,2]. In agricultural soils, management practices aiming at SOC preservation and/or accrual include: 1. Minimising soil disturbance by reducing or eliminating tillage, 2. Diversifying cropping systems in space or time, either using cropping elements (e.g., crop rotations, cover crops, intercropping) or non-cropping elements (e.g., tree or shrub hedgerows, flower strips, either within or around the field), and 3. Increasing organic inputs to soil by retaining crop residues or incorporating other organic residues[3–6]. SOC accrual can have synergies with many other agroecosystem services, including the maintenance or improvement of soil structure and the preservation or stimulation of biodiversity, but may come at the cost of increased greenhouse gas (GHG) emissions and nutrient losses[7–10]. Results in the literature, however, are inconsistent and show context dependencies. We performed a systematic literature synthesis to review whether agricultural management practices aiming at SOC preservation and/or accrual show synergies with

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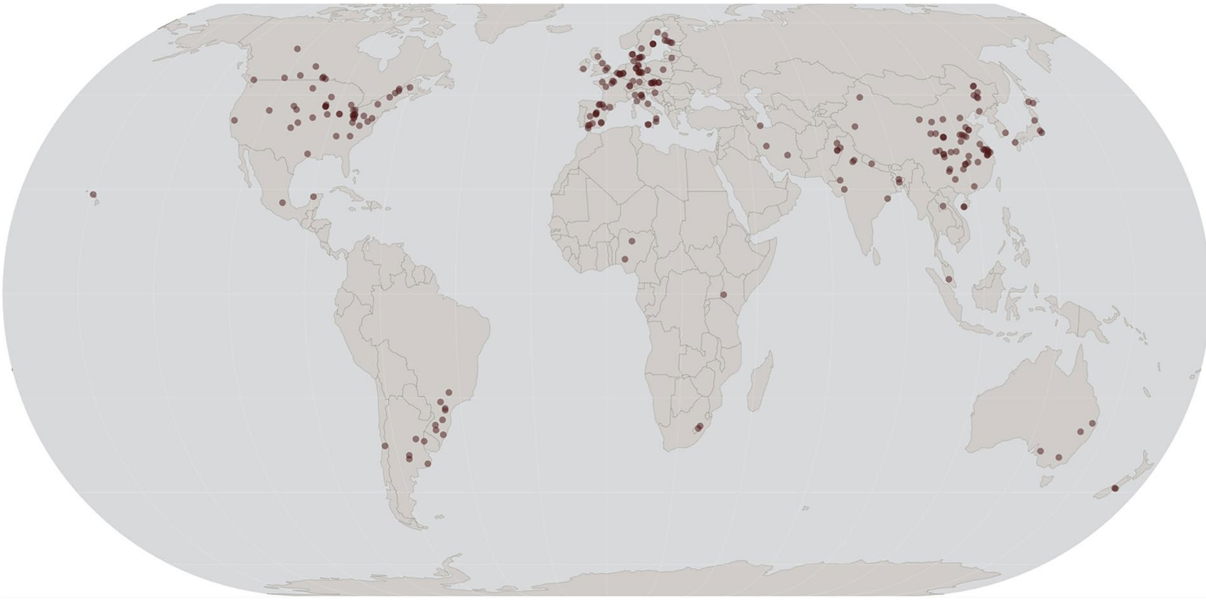

Fig. 1 Geographic distribution of the 239 experimental sites assessing the effects of agricultural management practices aiming at SOC accrual against conventional practices, reported in 232 articles. Map produced with Geo Point Plotter https://dwtkns.com/pointplotter/.

other agroecosystem services, including the maintenance of soil structure, the preservation of soil biodiversity, and trade-offs with climate regulation services including GHG (CO_2 and N_2O) emissions, and nutrient (N and P) losses. We also addressed whether such synergies and trade-offs vary across pedoclimatic regions and amplify with time since the adoption of target management practices. We followed the steps of a systematic literature synthesis, including the formulation of research questions and the design of a review protocol to define eligibility criteria for data inclusion or exclusion, search terms, as well as data selection, extraction and synthesis[11].

In this paper, we present a global dataset based on results from agricultural experiments worldwide, established since 1846 and having a mean duration of 10 years. Data were extracted from 232 articles published between 1991 and 2021, which altogether reported 570 experimental effects. The articles covered 254 experiments located at 239 sites in 38 countries (Fig. 1). The dataset includes (i) general information on the articles; (ii) general information on the experimental sites, soil properties and climate conditions; (iii) general agricultural management practices (fertilisation, weeding, etc); (iv) experimental management practices aiming at SOC preservation/accrual, (v) qualitative responses in terms of SOC accrual, crop yield, soil structure, soil biota, GHG emissions, and nutrient losses of target management practices against conventional practices.

Methods

Definition of eligibility criteria and search terms. We established the eligibility criteria following the Population-Intervention-Control-Outcome (PICO) framework[12]. We searched for published articles on agricultural systems in mineral soils that experimentally compare management practices aimed at SOC accrual and conventional practices. Articles had to include quantitative measurements of SOC accrual, synergies and/or trade-offs (Table 1).

We defined the search terms and combination of Booleans related to three types of management practices and five types of response variables (Table 2). Search terms were reviewed by co-authors specialised in soil science and soil biology and further fine-tuned through systematic searches in Web of Science (WoS) using an iterative procedure as follows. We performed literature searches in WoS Core Collection using the search terms defined within each category of management practices and response variables separately. Our initial strategy was to use combinations of search terms that maximise the number of records retrieved. After each search, we randomly screened the abstracts of several articles to evaluate the extent to which they matched our scope. This process led us to redefine the search terms, generally making them more stringent to discard unrelated articles.

We performed the systematic literature search using the search terms in Table 2 in WoS Core Collection as of 13 April 2021. We carried out several combined searches, each one including terms for:

1. A management practice, either related to minimising soil disturbance, diversifying cropping systems, or increasing organic inputs,
2. A response variable related to SOC accrual, which was used in all searches to guarantee that studies included a quantitative measurement of SOC or SOM content, and
3. Another response variable, either related to the synergies of SOC accrual, i.e. soil structural or biological parameters, or to the trade-offs of SOC accrual, i.e. GHG emissions or nutrient losses.

Inclusion Criteria	Description
POPULATION: Published research on agricultural systems in mineral soils	We included articles in English that reported replicated agricultural experiments with and without management practices aiming at SOC accrual, published in any year and any location around the world. We focused on arable lands, grasslands, as well as agrosilvicultural, silvopastoral, and agrosilvopastoral systems. We excluded forest soils, as well as tree crops grown for timber, fibre, or biomass. We focused on mineral soils, thus excluding organic soils (i.e. soils in peatlands, wetlands or classified as Histosols). Experiments could be of any time length and spatial scale.
INTERVENTION: Agricultural systems with management practices aiming at SOC accrual	Articles had to experimentally test the effects of one or more of the following agricultural practices separately: • Minimise soil disturbance: adoption of reduced or no tillage practices, • Diversify cropping systems through: (i) Increasing crop diversity: use of intercropping, crop rotations, cover crops, catch crops or forage crops; (ii) Increasing non-crop diversity: plantation of flower strips, tree, shrub or grass hedgerows or isles either within or around the fields, or use of practices to increase landscape complexity, • Increase organic matter inputs: landspreading or application of organic residues - such as manure, compost, biochar - retention of crop residues, or inoculation of beneficial microorganisms. In cases of articles reporting multiple experiments, multiple practices or more than one level of a single practice, we extracted data for each treatment separately.
CONTROL: Agricultural systems with conventional practices	Control refers to conventional practices as compared to the SOC-enhancing practices but otherwise under the same management and experimental conditions: • Conventional inversion tillage, • No intercropping, monocultures or less diverse rotations, no cover crops, no catch crops, or no forage crops, • No flower strips or hedgerows, no practices to increase landscape complexity, • No use of organic amendments, no crop residue retention, no inoculants.
OUTCOME: Quantitative measures of SOC accrual, its potential synergies and trade-offs	Articles had to include quantitative data on soil organic carbon (SOC) or soil organic matter (SOM) stock, content or sequestration rate, as well as quantitative data for at least one of the other response variables of interest: • Soil structure parameters: porosity, compaction, aggregation, and/or water content, • Biological soil parameters: biomass and/or diversity of groups of fauna and/or microbiota, • CO_2 or N_2O emissions: determined as field or laboratory fluxes, or balances, • N or P losses: leaching, runoff, crop uptake, or change in soil content.

Table 1. PICO framework that describes the criteria for article inclusion.

Combined searches retrieved 1,216 articles. We exported all records from WoS, detected duplicated records (i.e. articles that were retrieved in more than one search) using the *intersect* function in the base package for R v 4.0.5[13]. After removing 445 duplicated reports, we retained 771 articles. The selection process is reported in the PRISMA diagram[14] (Fig. 2).

Data selection and extraction. Among the 771 references obtained, we were able to retrieve 769 articles and further assessed them for eligibility using expert judgement rather than automatic tools. This led us to exclude 539 records (70% of the original articles retrieved) based on general aspects (i.e. language other than English, only abstract available; 21 articles excluded), the type of article (review, opinion papers; 159 articles excluded), a focus on non-soil habitats (29 articles excluded), forest soils (9 articles excluded), organic soils (6 articles excluded), or experimental designs not matching our criteria (e.g. lack of replication, lack of control, lack of statistical analysis, assessment practices other than those targeted here, etc.; 315 articles excluded). The remaining 232 full-text articles that met all criteria were used in our synthesis[15–246]. For each article, we extracted information and coded it systematically in an Excel file using predefined contents (see detailed description in the section Data Records). Extracted information was related to the environmental characteristics, experimental design, and agricultural management practices assayed in the studies, and to their effects on the selected response variables. Table 3 summarises all the fields contained in the database, which are further detailed in Supplementary Table 1.

Data Records

The data are accessible in the Zenodo repository, available at https://zenodo.org/communities/trace-soils/[247]. An Excel file (TRACE-Soils_GlobalDatasetSOCAccrual.xlsx) with different sheets is provided:

1. The sheet 'Readme' presents the contact information of the authors, research project and funding source,
2. The sheet 'Original Articles' contains the list of 771 non-duplicate articles retrieved from WoS, with coded information on the reasons for exclusion of 539 articles. Here, all articles coded as 'INCL' constitute the list of 232 articles retained to perform the literature synthesis,
3. The sheet 'Metadata' contains descriptive information for all data available in the sheet 'Database', including the nature of the data (text, number, categorical), a detailed description of the variable, and whether the variable is based on predefined contents available in the 'Drop Down Lists' sheet. All fields coded in Table 3 and Supplementary Table 1 are described in the 'Metadata' sheet,
4. The sheet 'Database' contains all data extracted from 232 articles used to perform the literature synthesis (see details on the structure of this sheet below),
5. The sheet 'Drop Down Lists' contains the predefined content of all categorical variables in the database.

In the 'Database' sheet, data in each row correspond to an experimental comparison between a management practice aiming at SOC accrual and the corresponding control. When an article reported several management practices, one row was filled per treatment. Since only one management practice is recorded in each row, the interactive effects of minimising soil disturbance, diversifying cropping systems, and increasing organic inputs are not considered. The columns in the database are structured into different sections (summarised in Table 3 and Supplementary Table 1), which are described below.

Search terms related to agricultural management practices	# Records
Minimise soil disturbance: no-till* OR no-plo* OR zero-till* OR zero-plo* OR low-till* OR low-plo* OR direct-drill* OR direct-seed* OR minimum-till* OR minimum-plo* OR reduced-till* OR reduced-plo* OR conservation-till* OR conservation-plo* OR chisel* OR stubble-till* OR stubble-plo* OR mulch-till* OR mulch-plo* OR ridge-till* OR ridge-plo* OR strip-till* OR strip-plo* OR harrow*	27,029
Diversify cropping systems:	
Increase crop diversity: crop-diver* OR (intercrop* OR inter-crop*) OR (interrow* OR inter-row*) OR cover-crop* OR crop-rotation OR crop-association OR catch-crop* OR succession-planting OR winter-crop* OR forage-crop* OR fodder-crop* OR agroforestry	41,788
Increase non-crop diversity: divers* AND (hedge* OR flower*-strip OR flower*-crop OR buffer-strip OR margin)	12,066
Increase OC inputs: compost* OR manure OR dung OR sludge OR biosolid OR slurry OR crop-residue OR vegetation-residue OR stubble-retention OR (mulch* NOT plastic) OR organic-amend* OR organic-fert* OR biochar OR digestate OR (inocul* AND ("AMF" OR mycorrh* OR "PGPR" OR plant-growth-promoting-bacteria))	264,706
Search terms related to SOC accrual, its synergies and trade-offs	
SOC: soil AND ("SOC" OR "TOC" OR organic-c* OR c-seq* OR carbon-seq* OR c-stock* OR carbon-stock*)	71,752
Soil structure: soil-structur* OR (soil AND (porosity OR pore-space OR pore-geometry OR pore-connectivity OR air-permeab* OR gas-diffusiv* OR hydraulic-conduct* OR bulk-density OR aggregat* OR penetration-resistance))	63,798
Soil biota: (soil OR rhizosph* OR edaph*) AND divers* AND (invertebrate OR *fauna OR protist OR nematode OR earthworm OR mite OR collembol* OR enchytr* OR arthropod OR insect OR myriapod OR tardigrad* OR microb* OR microorg* OR bacteria OR fung* OR mycorrh* OR "AMF" OR *nitrif*)	42,210
GHG emissions: (emission OR flux OR loss*) AND (CO2 OR carbon-dioxide OR N2O OR nitrous-oxide OR greenhouse-gas OR "GHG")	187,000
Nutrient losses: (leach* OR runoff OR run-off) AND (NO3 OR nitrate OR nitrogen OR ammonium OR phosphorus OR phosphate)	36,342

Table 2. Search terms related to agricultural management practices and response variables. The number of records retrieved in WoS in April 2021 for each set of search terms is given.

General information on the articles and experimental sites. *Article identifier*. The "Article_ID" section contains the article reference (authors, article title, journal title, journal volume, page numbers, year of publication) and the digital object identifier (doi).

Environment includes information on the country, climatic zone (Köppen classification), geographic coordinates, the type of cropping system, and the main crop studied in the experiment. The vast majority of experiments (93%) were performed on arable land, rather than permanent or temporary grasslands, agrosilvicultural, silvopastoral, or agrosilvopastoral lands. Most experiments (60%) had a single crop rather than crop rotations (40%). The most common crops were maize (27% of the experiments using one crop), rice (18%), wheat (15%), and other cereals (8%).

Experiment contains information on the name of the experimental site, spatial and temporal scale of the experiment, soil texture, soil pH, and sampling depth. Most experiments (79%) were performed on field plots. Experiments lasted from a few months to over 160 years, with an average duration of 10 years and a median of 5 years (Fig. 3). Soil properties were highly variable, both in terms of pH ranging from 4.5 to 8.8 (Fig. 3) and particle size distribution, with most soils having a silt loam (22%) or sandy loam texture (21%). Sampling depth was restricted to the upper 0–15 cm (69%) or 0–30 cm layers (28%) in most cases, with very few cases reporting data from subsurface soil horizons. If data from more than two soil layers were reported, results were coded in different rows.

Management includes descriptions of the main agricultural management practices of the experimental site. It includes data on N and P fertilisation types and rates. For the total 393 cases in which fertilisation was reported, 222 cases (56%) were based on inorganic fertilisation followed by the combined use of organic and mineral fertilisers (21%). Median fertilisation rates were ca. 150 kg N ha^{-1} yr^{-1} and 70 kg P ha^{-1} yr^{-1} (Fig. 3). The section also includes data for the type of irrigation, liming, type of pest and weed control, although most publications did not specify these practices.

Experimental management practices aiming at SOC accrual. **Minimise soil disturbance** summarises the experimental management practices related to the reduction of soil disturbance (minimum and no-tillage) compared to a control (standard tillage), which constituted 29% of all experimental practices found (Fig. 4). It includes information on the type of tillage practice applied "soil_dist1" and the specific implement used "soil_dist2" (e.g. chisel, disk, harrowing, strip tillage). Information on the use of glyphosate, till depth and crop residue retention are also provided.

Diversify cropping systems describes the experimental management practices related to the diversification of cropping systems, based on either cropping or non-cropping elements (12% of all practices). Diversification refers to the increase of crop types, either across time or space, through the use of cover crops, crop rotations, or intercropping (Fig. 4). The variable "div_crop1" indicates the type of diversification (e.g. use of cover crops), and "div_crop2" relates to the specific technique applied for each div_crop1 (e.g. legumes, grasses, brassicas, species mixtures, etc.). The type of experimental control used (e.g. monoculture, no cover crop) and the total number of crop species included both in the diversified treatment and the conventional practice are indicated. The second part reports experiments including diversification of non-cropping elements, which refers to the use of flower stripes, shrub or tree hedges, or vegetation islands either within or around the fields (Fig. 4).

Increase organic inputs includes data on articles aimed to increase organic matter inputs, which constituted the majority of the reports found (58%). The dataset specifies whether organic inputs were based on organic amendments, retaining crop residues, or inoculating beneficial microorganisms ("increase_om1"). Further, the specific residue applied ("increase_om2") and the type of control (e.g. no amendment, no residue retention, etc) are indicated.

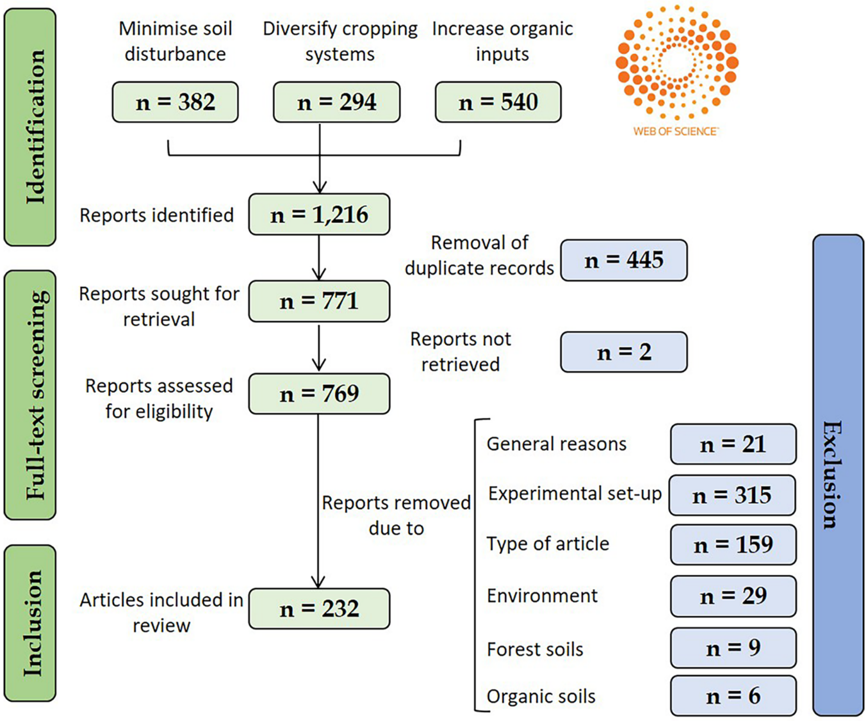

Fig. 2 PRISMA diagram[14] showing the workflow of article identification, screening, inclusion and exclusion. Numbers indicate the number of articles included (green boxes) or excluded (blue boxes) at each step.

Environmental and Management Description						
Article	**Environment**	**Experiment**	**Management**	**Minimise soil disturbance**	**Diversify cropping systems**	**Increase organic inputs**
Reference	country	exp_site	fertilisation_type	soil_dist1	div_crop1	increase_om1
doi	climatic_zone	exp_spatial_scale	N_fertilisation_rate	soil_dist2	div_crop2	increase_om2
	latitude	exp_time_scale	P_fertilisation_rate	till_depth	num_sps	increase_om_control
	longitude	soil_texture	P_2O_5_fertilisation_rate	crop_residue_retention	div_crop_control	
	cropping_system	soil_ph	liming	glyphosate	num_sps_control	
	main_crop	soil_depth	water_management	soil_dist_control	div_noncrop1	
			pest_control	till_depth_control	div_noncrop2	
			pest_control_appl	crop_res_ret_control	div_noncrop_control	
			weed_control			
			weed_control_appl			

SOC accrual, its synergies and trade-offs						
SOC accrual	**Crop yield**	**Soil structure**	**Soil biota**	**Soil biota**	**GHG emissions**	**Nutrient losses**
SOC_accrual_resp	crop_yield_resp	mechanics_resp	microb1_diversity_resp	fauna1_diversity_resp	CO_2_emission_resp	N_response
SOC_accrual_var	crop_yield_var	mechanics_var	microb1_diversity_var	fauna1_diversity_var	CO_2_emission_var	N_variable
		aggregation_resp	microb1_biomass_resp	fauna1_biomass_resp	N_2O_emission_resp	P_response
		aggregation_var	microb1_biomass_var	fauna1_biomass_var	N_2O_emission_var	P_variable
		water_resp	[]	[]		
		water_variable				
		porosity1_response				
		porosity1_variable[]				

Table 3. Information retrieved from the 232 articles included in the database. [] Indicates repetition as many times as necessary, 'resp' indicates response and 'var' indicates variable. A detailed version of this table is provided in Supplementary Table 1, and its contents are described in the Data Records section.

Response variables. For each response variable, we coded the qualitative response between a management practice aiming at SOC accrual and the control based on statistical comparisons reported in the original studies as follows: i) Increase, indicates a significant increase in the response variable in target versus conventional

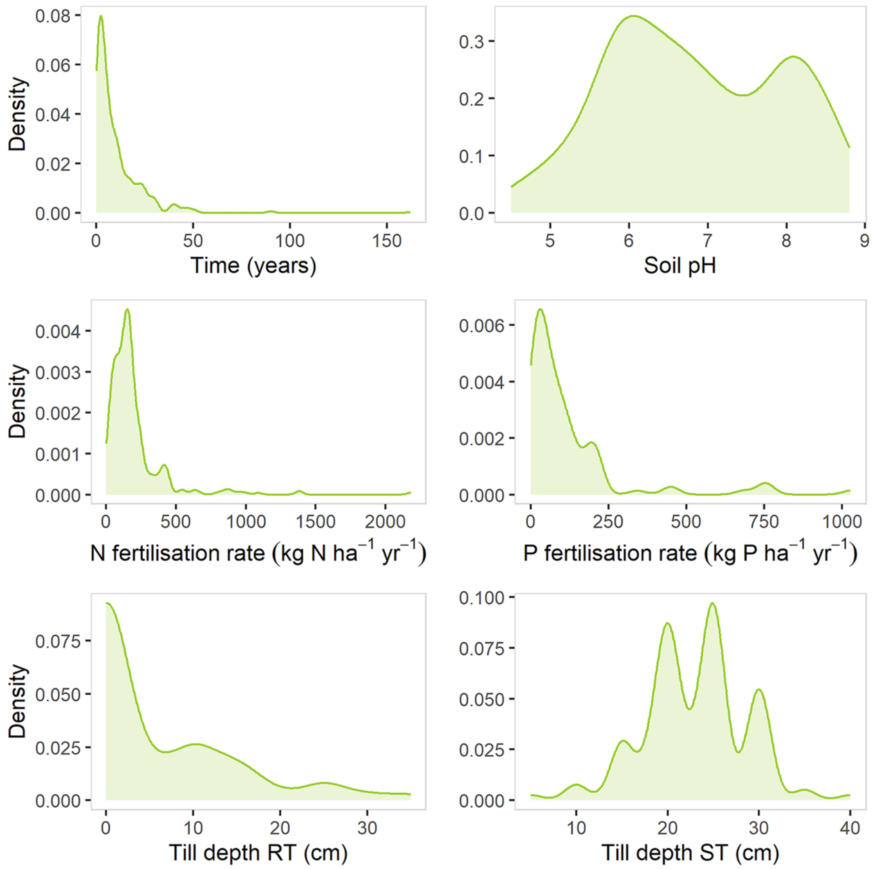

Fig. 3 Density plots showing the frequency distribution of a few parameters in the dataset, including the duration of the experiments, soil pH, nitrogen (N) and phosphorus (P) fertilisation rates, and tillage depth under reduced (RT, including minimum and no tillage) and standard tillage (ST) practices.

management practices; ii) Decrease, indicates a significant decrease in the response variable in target versus conventional management practices; iii) Neutral, indicates non-significant differences between target and conventional management. In some instances, responses are coded as: iv) 'non-reported', indicating that data are available but statistical tests were not performed in the original study, v) 'varying', indicating varying responses (e.g. across sampling times), or vi) 'change', indicating significant changes in specific categorical response variables (e.g. community structure of soil biota). Finally, we also registered the metrics used to quantify each response variable (e.g. for the variable 'water content' we specified whether it was measured as soil water content, infiltration, saturated or unsaturated hydraulic conductivity, or water retention).

SOC accrual and crop yield. The qualitative response of SOC accrual was coded as explained above. Most studies reported the change in SOC concentration (76%) or stocks (15%), whereas the remaining studies reported changes in SOM, SOC sequestration rates, among others. We also recorded the shifts in crop yield, although the number of cases reporting it was relatively low (139 out of 570 total study cases).

Synergies of SOC accrual includes responses of: (i) Soil structure, including soil mechanics (38% of study cases), aggregation and structure (28%), soil water and movement (24%), porosity and gas movement (17%); (ii) Soil biota, several groups of fauna and microbiota were coded, as well as their response in terms of biomass and diversity. While 40% of all study cases reported information on microbial groups, only 2% included information on soil fauna. When several groups of fauna, microorganisms, or several porosity properties were quantified in the same experiment, they were included as separate variables.

Trade-offs of SOC accrual includes responses of: (i) GHG (CO_2 and N_2O) emissions, most of which were fluxes measured in the field (45% of all cases for CO_2 and 63% for N_2O) or in the laboratory (50% and 33%, respectively), and (ii) Nutrient (N and P) losses, reported as N and P runoff and/or leaching (17% and 28% of all cases for N and P, respectively) or changes in soil content (77% and 63% for N and P, respectively).

Technical Validation

The careful application of the PICO framework[12] and the PRISMA guidelines[14] ensures the accuracy and reproducibility of our data collection from published peer-reviewed journals. Articles were randomly assigned to the co-authors, who all followed the same procedures for data extraction. To ensure homogeneity in data extraction, drop-down lists were generated and agreed upon for most of the variables in the database (except for variables

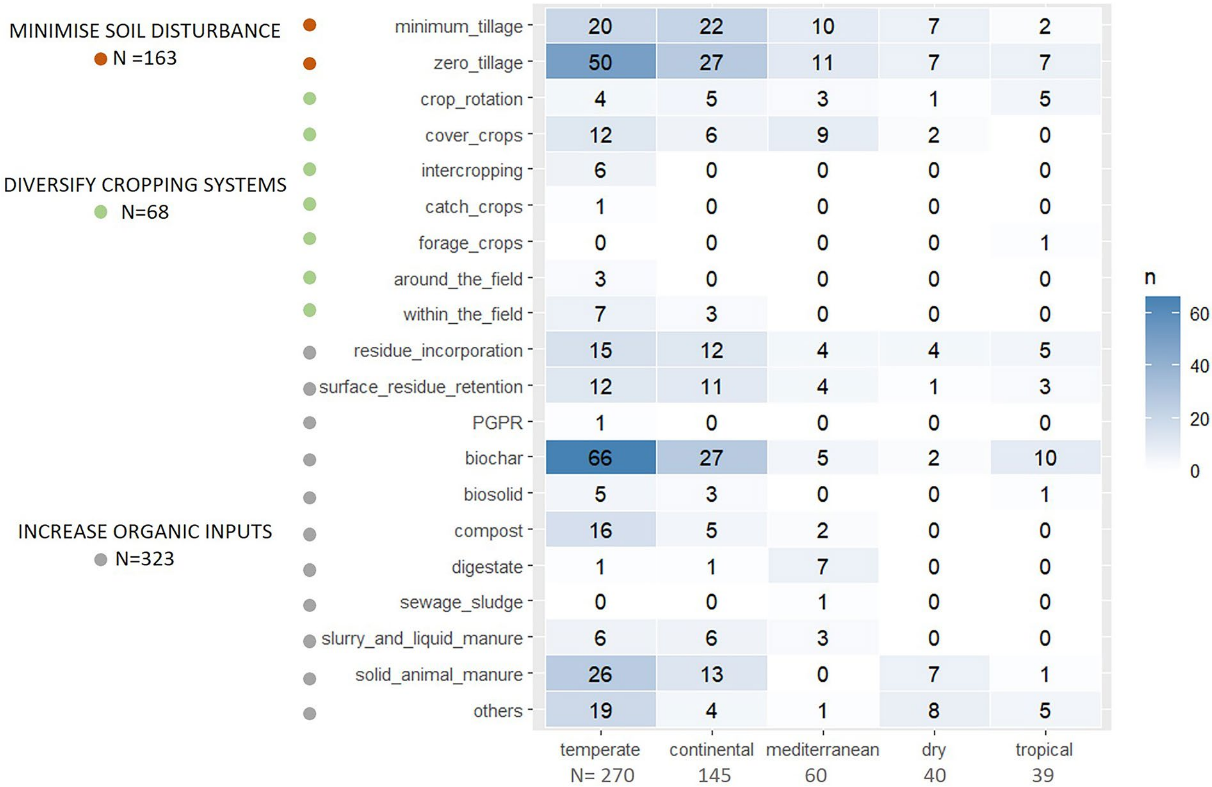

Fig. 4 Distribution of the counts of experimental effects recorded for specific management practices in the three categories targeted (minimising soil disturbance, diversifying cropping systems, increasing organic inputs) throughout five climatic zones. N indicates the number of experimental effects.

such as the duration of the field experiments or the geographic coordinates). The final version of the dataset was reviewed by two co-authors to further ensure the homogeneity of data extraction. Observational and experimental studies without enough replication ($n < 3$) or inappropriate statistics were discarded. Neutral responses (i.e. the statistically-checked absence of response) were reported to avoid the over-representation of significant effects. All qualitative data on SOC accrual, its potential synergies, and trade-offs, were extracted from numerical sources, checked for statistically-proven responses, and only then coded into the corresponding response categories (increase, neutral, decrease). We plotted the frequency distribution of the numeric variables, and returned to the original articles to verify any extreme values. Similarly, for categorical variables we built contingency tables of the counts for each factor level to check for possible errors.

Appropriate comprehension of the adoption of agricultural management techniques at the global scale requires data from different geographical, climatic, pedological and agronomical scenarios. Our dataset, however, is biased towards temperate areas and northern latitudes. Only 11% of our records are from Mediterranean climates, 7% from tropical areas, and 7% from dry regions (Fig. 4). As previously reported[248], our results reflect the current uneven distribution of publications in global science[249], and highlight the necessity to collectively support science in the Global South.

Usage Notes

This dataset represents an exhaustive exploration of the synergies and trade-offs of SOC accrual in mineral soils due to agricultural management practices at a global scale. We gathered the responses of synergies and trade-offs of SOC in a qualitative manner due to the broad coverage of management practices, response variables and geographic scope of our study. This exploratory database allows 1. developing a comprehensible understanding of the multiple effects of SOC accrual on other agroecosystem services maintaining a wide focus, and 2. detecting main knowledge gaps and future research needs. Further, the dataset can constitute the basis to identify the set of articles that can be useful to additionally address specific scientific questions using a quantitative (rather than qualitative) synthesis. This would require revisiting the articles to calculate the effect sizes of target versus conventional management practices. While such a quantitative approach would permit calculating the magnitude of the effects, it will necessarily narrow down the scope of the research questions and reduce the set of articles that allow answering them. Our dataset is especially useful to identify knowledge gaps and uncertainties in relation to the effects of SOC accrual on soil services. It can be used by scientists and decision makers to explore beneficial and detrimental side-effects of both general and specific agricultural practices at varying spatial scales and time frames. However, please note that the number of observations for certain combinations of management practices and responses, especially in certain climates or related to soil biota are low, suggesting that inferences of certain patterns should be done cautiously. Finally, our dataset can easily be updated when new information is available.

Code availability

Data visualisation was conducted using R v 4.4.1[13]. Scripts used with R programming language and additional related files to make the graphs presented in this paper are available at https://zenodo.org/communities/trace-soils/[247].

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Competing interests

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

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