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A systematic and critical review of long-term diachronic experiments on soil organic carbon dynamics in the Global South[☆]

Tchodjowiè P.I. Kpemoua[a,b,*], Issiakou A. Houssoukpevi[c,k,l], Kenji Fujisaki[c], Antoine Versini[d,e], Rémi Cardinael[h,i,j], Pierre Barré[f], Tiphaine Chevallier[g], Julia Le Noë[a]

[a] Institut des Sciences de l'Ecologie et de l'Environnement de Paris—Institut de Recherche pour le Développement (IRD), Sorbonne Université, 4 place Jussieu, 75252 Paris Cedex 05, France
[b] INRAE, UR 1138 Biogéochimie des Ecosystèmes Forestiers (BEF), Champenoux, France
[c] INRAE, Info&Sols, 45075 Orléans, France
[d] CIRAD, UPR78, Recyclage et risque, 01 Avenue Agropolis, 34398 Montpellier Cedex 5, France
[e] Recyclage et Risque, Univ Montpellier, CIRAD, Montpellier, France
[f] Laboratoire de Géologie, Ecole Normale Supérieure, CNRS, PSL University, IPSL, Paris 75005, France
[g] UMR Eco&Sols, University of Montpellier, CIRAD, Institut Agro Montpellier, INRAE, IRD, Montpellier, France
[h] AIDA, Univ Montpellier, CIRAD, Montpellier, France
[i] CIRAD, UPR AIDA, Harare, Zimbabwe
[j] Department of Plant Production Sciences and Technologies, University of Zimbabwe, Harare, Zimbabwe
[k] CIRAD, UMR ABSys, F-34398 Montpellier, France
[l] ABSys, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, Montpellier, France

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ABSTRACT

Soil organic carbon (SOC) sequestration is increasingly recognized as a key lever for mitigating greenhouse gas emissions. However, knowledge about SOC dynamics under various land management practices remains limited in the Global South. Long-term experiments (LTEs), combined with a diachronic soil sampling approach, i.e., based on repeated measurements over time, offer robust insights into how land use and management practices affect SOC sequestration and provide indispensable observations for reliable model calibration. This systematic review compiles 155 peer-reviewed diachronic studies conducted in the Global South, excluding China, corresponding to 174 LTEs lasting at least 5 years. Most LTEs are conducted on cropland (92%), while agroforestry, forest, and savannah are underrepresented. The most frequently studied practices are mineral fertilization (52%), mixed mineral and organic fertilization (37%) and tillage management (30%). The effects of these practices on SOC dynamics show trends similar to those observed in the Global North, i.e., positive effects of both mineral and organic fertilization and conservation tillage. However, these findings may be biased by limited geographical, pedoclimatic, and agricultural practices representativeness. Arid soils and dry climates are underrepresented in favor of subhumid and humid areas. India and Brazil alone account for two-thirds of LTEs studies, despite their contrasting farming systems, smallholder agriculture in India versus large-scale mechanized systems in Brazil. This hides the variability of farming systems in the Global South. In many African and Southeast Asian countries, mineral fertilizer rates applied in LTEs exceed national averages by 100 to 1000%, while low-input traditional systems, such as agroforestry or slash-and-burn are absent. These imbalances reflect a funding and publication dynamic that favors agricultural systems and practices that are already well documented. These biases also present major blind spots for SOC modeling and limit the applicability of current knowledge to diverse farming systems in the Global South. It is therefore essential to intensify and diversify LTEs research to better reflect local practices and underrepresented pedoclimatic conditions.

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* Corresponding author at: INRAE, UR 1138 Biogéochimie des Ecosystèmes Forestiers (BEF), Champenoux, France
E-mail address: israel.kpemoua@inrae.fr (T.P.I. Kpemoua).

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1. Introduction

Soil organic carbon (SOC) sequestration has potential to offset a small but significant part of global anthropogenic greenhouse gas (GHG) emissions (Jiménez and Lal, 2006; Friedlingstein et al., 2023). The global SOC pool is more than three times larger than the atmospheric carbon pool (Lal, 2018), therefore even a small increase in SOC can significantly reduce atmospheric CO_2 concentrations, making it a key component of global climate change mitigation efforts (Don et al., 2024). SOC sequestration refers to the process of transferring CO_2 from the atmosphere into the soil, through plant photosynthesis and subsequent plant residues and other organic solids input to the soils which are stored or retained in the soil as organic matter (Olson et al., 2014; Don et al., 2024). By contrast, SOC loss refers to a situation in which CO_2 release through soil respiration and erosion exceeds the carbon inputs from plants and manure. On a global scale, land use change is one of the main drivers of SOC balance (Wiesmeier et al., 2019; Ramesh et al., 2019). Sanderman et al. (2017), estimated that the conversion of natural ecosystems to croplands between 1960 and 2019 resulted in a net loss of SOC of approximately 116 Gt in the top two meters of the soil. In contrast, afforestation of croplands can partially restore these stocks (Laganière et al., 2010; Fonkeng et al., 2024), while best management practices for anthropized terrestrial ecosystems can also promote SOC sequestration (Minasny et al., 2017; Beillouin et al., 2023).

In addition to its role in climate change mitigation, SOC sequestration offers multiple co-benefits, including soil fertility enhancement, land restoration and food security, in accordance with the United Nations Sustainable Development Goals (Smith et al., 2021). These numerous ecosystem services provided by SOC are essential for human well-being, ecosystem balance, and biodiversity (Nielsen et al., 2011). Lal (2007) proposed six management strategies to enhance SOC storage: (1) minimal soil disturbance, (2) keeping a permanent vegetation cover, (3) intensifying nutrient recycling mechanisms, (4) establishing a positive nutrient balance, (5) enhancing biodiversity and (6) reducing water and nutrient losses. These management strategies are essential for turning soils into carbon sinks, but they are also highly generic. The success or failure of their actual application depends on several factors, including land cover, land use, land use history, management practices, topography, climate, and soil condition, which influence SOC dynamics (Luo et al., 2017; Liu et al., 2014; Poeplau et al., 2011).

To evaluate SOC dynamics and the role of its multiple drivers, experiments and observations over several years are essential as it takes years before any significant change in bulk SOC can be detected (Smith, 2004). These long-term monitoring approaches are time-intensive, costly and difficult to maintain. An alternative approach is space-for-time analysis, which assumes that the land use history of the plots is known: with a reference plot representing the SOC stocks in their initial state before treatment or land use change, and a plot that underwent treatment or land use change several years ago and has not undergone any changes since. For example, SOC stocks in grasslands can be compared to those in croplands within the same geographical area and same management history. This spatial difference is then used as a proxy for the temporal evolution of SOC stocks following land use conversion (Li et al., 2023). However, this approach can introduce significant bias and blind spots, as it necessarily misses the temporal dynamics of annual changes in SOC, which are generally small compared to spatial difference with the reference SOC stocks, while other confounding factors may further influence the assessments (Baker et al., 2007; Rumpel et al., 2018; Körschens et al., 2013; Le Noë et al., 2023; Costa Junior et al., 2013; Rakotovao et al., 2020). Assessing the evolution of SOC stocks over time is thus important to correctly estimate the potential of additional SOC storage in soils and evaluate management practices in terms of both SOC stock increase and sequestration potential (Bruni et al., 2021). To that end, long-term experiments (LTEs) and soil monitoring networks are essential, as they provide a fundamental empirical basis for identifying the controlling factors governing SOC dynamics, and help improve the accuracy of soil biogeochemical models (Campbell and Paustian, 2015; Le Noë et al., 2023; Garsia et al., 2023). Moreover, given the limited number of LTEs, modeling offers an opportunity to assess SOC stocks and their future trends at a much broader scale than field data alone would allow. The uncertainties of SOC dynamics can be reduced as new datasets emerge that can be used to initialize, validate and better constrain SOC models while refining the understanding of the various drivers of SOC dynamics, which can also be incorporated in model equations (Beillouin et al., 2022).

On a global scale, hundreds of long-term experiments have been conducted to assess the impact of various drivers on SOC stocks (Xu et al., 2019; Beillouin et al., 2023). However, long-term field studies relating to southern countries, excluding China, remain underrepresented in these global studies (Beillouin et al., 2022; Xu et al., 2019; Abbas et al., 2020; Garsia et al., 2023), despite the significant role of SOC in these regions in sustaining the terrestrial carbon sink and soil health (Friedlingstein et al., 2023). For example, tropical forests alone account for 20-25% of soil and vegetation carbon stocks worldwide (Dixon et al., 1994; Bonan, 2008; Poorter et al., 2015). Biogeochemical carbon models have been mostly developed in temperate regions, and remain largely unvalidated in the Global South, largely due to a lack of LTEs data (Garsia et al., 2023; Le Noë et al., 2023). Recent modeling studies using LTEs from sub-Saharan Africa reveal that soil organic matter decomposition and nitrogen dynamics are for instance not well represented, leading to important uncertainties in modeling SOC dynamics, even more in sandy soil (Couëdel et al., 2024, 2026). These authors suggest that having a larger diversity of LTEs from different pedoclimatic contexts in the tropics, together with a few key measured soil and plant parameters will largely improve modeling of SOC dynamics with soil-crop models in the region. Moreover, soil management practices are deeply shaped by socio-economic contexts and land tenure systems, which vary significantly not only between the so-called industrialized North and the newly or weakly industrialized South but also within these broad global categories themselves (Ouédraogo and Sorgho Millogo, 2007). Indeed, soil management in any given region is shaped by multiple interacting factors, including biophysical characteristics (soil properties, climate, and topography), socioeconomic drivers (agricultural practices, urbanization, and economic status), and political influences (land-use policies and governance structures) (Lamidi and Oyewusi, 2024; Oyewusi and Lamidi, 2024). The underrepresentation of the Global South in SOC research is further exacerbated by a lack of local data, appropriate technologies, and financial resources needed for effective SOC stock monitoring and evaluation of sequestration strategies (Paustian et al., 2016; Minasny et al., 2017). These limitations hamper the identification of optimal soil management practices that can improve carbon sequestration, strengthen agricultural resilience, and support biodiversity in diverse pedoclimatic and socio-economic contexts.

To overcome these challenges and specify the most critical research gaps, a comprehensive assessment of existing long-term field experiments measuring SOC stocks using a diachronic approach in the Global South is needed, considering the diversity and specificity of land use and management systems, as well as the diversity of pedoclimatic contexts (Feller and Beare, 1997; Lal, 2010). Such an assessment is key to identifying gaps in SOC stock monitoring, highlighting the most studied biophysical drivers and agricultural practices, and refining research priorities to better account for regional specificities.

In this context, the present research conducts an in-depth review focused on countries in the Global South, excluding China due to its distinct socio-economic and scientific context, characterized by research capacities and levels of investment that differ substantially from those of most other Global South countries, in order to ensure greater coherence and comparability among the studies analyzed. By doing so, this study aims to answer three fundamental and critical questions: (i) Which long-term SOC monitoring data are available in the Global South? (ii) What are the effects of different management practices on SOC sequestration across the diverse contexts of the Global South? (iii) Are retrieved studies representative of the diversity of pedoclimatic contexts and cropping systems of the Global South?

2. Materials and methods

2.1. Literature search and study selection

We conducted a systematic review based on a structured literature search to identify all peer-reviewed articles published in English, and in some cases in Portuguese, reporting measurement data for SOC, expressed either as concentration (g C kg^{-1} soil) or stock (t C ha^{-1}), on at least two separate dates taken at least 5 years apart. The search was done on March 11, 2024, through the academic database "Web of Science Core Collection". The following search string, including selected keywords, was used within the fields titles and abstracts: (("country 1" OR "Country 2" OR "country 3" OR … OR "country n" OR "South Africa" OR "East Africa" OR "West Africa" OR "Sub-saharan" OR "Sahel" OR "Central Africa" OR "Latin America" OR "South America" OR "Central America" OR "South Asia" OR "Southeast Asia" OR "Global South") AND ("Carbon" OR "SOC") AND ("Soil") AND ("Field" OR "Experiment" OR "Observ*" OR "Measur*" OR "Analys*") AND ("Temp*" OR "Evolu*" OR "Long" OR "Time*" OR "Change*"). The complete list of Global South countries considered in the research equation is: Afghanistan, Algeria, Angola, Argentina, Bangladesh, Belize, Benin, Bhutan, Bolivia, Botswana, Brazil, Burkina Faso, Burundi, Cambodia, Cameroon, Cape Verde, Central African Republic, Chad, Chile, Colombia, Comoros, Congo (Brazzaville), Congo (Democratic Republic), Costa Rica, Cuba, Djibouti, Dominican Republic, East Timor (Timor-Leste), Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Fiji, Gabon, Gambia, Ghana, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, India, Indonesia, Iran, Iraq, Ivory Coast (Côte d'Ivoire), Jamaica, Jordan, Kazakhstan, Kenya, Kiribati, Kyrgyzstan, Laos, Lebanon, Lesotho, Liberia, Madagascar, Malawi, Malaysia, Maldives, Mali, Mauritania, Mexico, Micronesia, Mongolia, Morocco, Mozambique, Myanmar, Namibia, Nepal, Nicaragua, Niger, Nigeria, Pakistan, Palestine, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Rwanda, Samoa, São Tomé and Príncipe, Senegal, Sierra Leone, Solomon Islands, Somalia, South Africa, South Sudan, Sri Lanka, Sudan, Suriname, Syria, Tajikistan, Tanzania, Thailand, Timor-Leste, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkmenistan, Tuvalu, Uganda, Uruguay, Uzbekistan, Vanuatu, Venezuela, Vietnam, Yemen, Zambia, Zimbabwe. No restrictions were applied to the date of publication, and all climatic zones were considered.

The initial literature search identified 3641 unique articles (Fig. 1). The first screening consisted in reading the abstracts of the articles and selecting potential articles based on the following keywords and expressions: "soil carbon", "SOC", "carbon", "SOC stocks", "long-term", "experiment", "changes", "decades", "pluriannual". This preliminary screening identified 452 articles. The retrieved articles were then examined for the following selection criteria to build the database: (i) The study must involve long-term field experimentation of at least 5 years apart; (ii) The stock or concentration of SOC at the start of the experiment (initial state) and at the end of the period examined (final state) must be available (diachronic approach). In the case where only soil organic matter (SOM) concentration was presented, SOC concentration was calculated using a coefficient of 0.58 (Pan et al., 2004); (iii) Exclusion of articles with SOC data estimated by remote sensing or modeling method or articles based on space-for-time studies (synchronic approach). According to these criteria, a total of 155 studies from 174 LTEs sites were included (Fig. 2), providing 1362 pairs of observations (initial and final) of SOC content and/or SOC stock. Data from the figures were extracted using the WebPlotDigitizer digitizing software (Burda et al., 2017; Kpemoua et al., 2022) to convert the data points into numerical values.

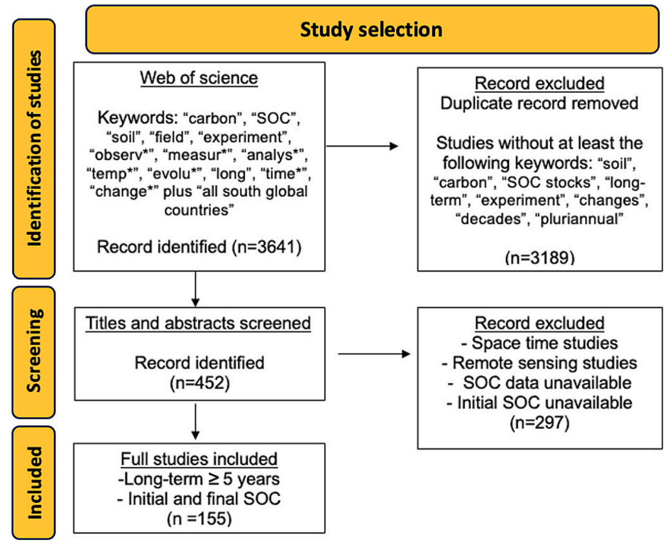

Fig. 1. Diagram describing the protocol used to search, identify and select publications in the present meta-analysis. "n" represents the total number of studies.

2.2. Database construction

All data from the 155 publications were compiled into an Excel file available in a data repository (Kpemoua et al., 2025). For each study site, we collected information on location, land use (forest, grassland, cropland, fallow, agroforestry, crop-livestock), soil tillage management (conventional tillage, minimum tillage, permanent beds or no-tillage), crop management (mineral fertilization rate, organic fertilization type and rate, mix of organic and mineral fertilization type and rate, crop rotation, crop diversification, etc.), climate (temperate, tropical, Mediterranean, mean temperature and precipitation when available), soil physicochemical characteristics (clay, silt, sand, pH, bulk density, soil type, N, C/N ratio and $CaCO_3$). The percentage of clay, silt and sand was used to determine soil texture classes based on the textural triangle. Soil texture classes were then grouped into three categories: coarse texture (sand and loamy sand), medium texture (loam, silty loam and clay loam) and fine texture (sandy clay loam, silty clay loam, clay loam, clay), according to the soil survey manual of the USDA (Canarini et al., 2017). Data on crop yields, carbon inputs via aboveground plant biomass or exogenous organic inputs were also collected each time this information was available. In situations where plant biomass inputs are expressed as dry matter, we use the calculation factor of 0.45 (Bolinder et al., 2007) to convert into tons of carbon. The exogenous organic matter inputs were also expressed in tons of carbon. In case several publications reported data from the same LTE but with different durations, the study presenting the longest duration was kept. If several publications reported exactly the same data, the first publication was kept. In studies where only SOC concentrations were reported, these were converted to SOC stock using bulk density measurements or estimates:

$$SOC\ stock\ \left(t\ C\ ha^{-1}\right) = SOCcontent\left(g\ C\ kg^{-1}\right)*Bulk\ density\ \left(g\ cm^{-3}\right) *Depth\ (cm)*0.1 \quad (1)$$

The coarse fraction (>2 mm) was not accounted for, as this information was not consistently reported across studies; however, this limitation is expected to have a limited effect given that the analysis focuses on relative changes in SOC stocks rather than absolute values.

Soil bulk density (BD) estimates are critical for calculations of SOC stock, but many studies did not measure it. We established an empirical relationship between soil BD and SOC content based on available data from our database, as SOC was the most consistently reported soil

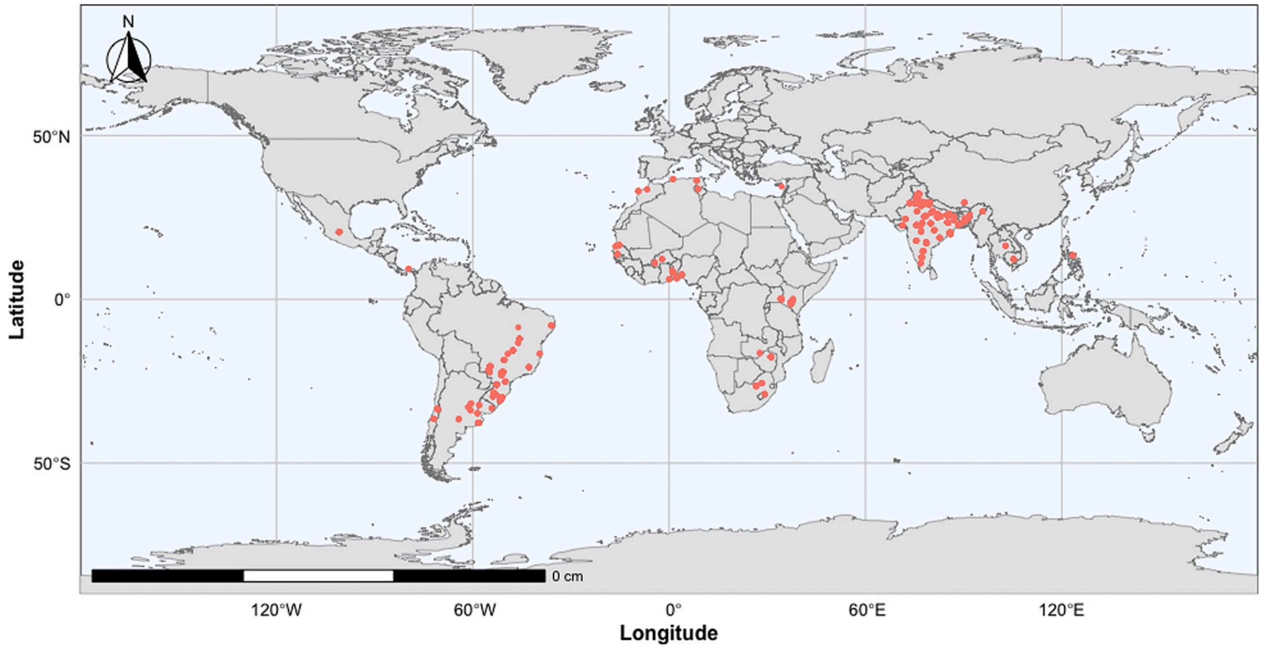

Fig. 2. Global distribution of the sites included in this meta-analysis. The points represent the geographical location of the sites based on the longitudes and latitudes collected in the studies.

property across studies, whereas texture-related variables required for alternative pedotransfer functions were frequently missing, making this SOC-based approach the most robust and consistent option for the present dataset (Fig. S2). The data used covered textural and even soil type variability within the entire database. The line is fitted to the function:

$$BD = 1.524 - 0.0132*SOC \quad (2)$$

($n = 254$, $R^2 = 0.41$, $p < 0.05$), and can be used to estimate bulk density of soils for which direct measurements have not been performed. This linear function is suitable to calculate missing soil bulk density as reported by previous studies (Manrique and Jones, 1991; Bernoux et al., 1998; Kobal et al., 2015; Sevastas et al., 2018). A total of 391 bulk density data points were estimated using this linear function, including 284 complete pairs of bulk density values and 107 additional estimates corresponding to either initial or final bulk density values only. The majority of SOC stocks were reported based on an equivalent volume method (90% of data), which multiplied the SOC concentration by bulk density at a fixed depth using Eq.1.

To quantify the annual SOC change rate at each site, we used the following equation:

$$SOC\ accrual\ rate\ \left(t\ C\ ha^{-1}\ yr^{-1}\right) = \frac{SOC_{final} - SOC_{initial}}{T} \quad (3)$$

$SOC_{initial}$ and SOC_{final} refer to the initial and final SOC stock of a given field experiment, and T is the duration of the field experiment (years). Differences in annualized SOC change rate (ΔSOC rate) between control (unfertilized and conventional tillage) and alternative practices (mineral fertilization, organic fertilization, organic+mineral fertilization, minimum tillage, no tillage and permanent beds) were calculated to assess the effect of the various practices tested compared to a reference situation:

$$\Delta SOC\ rate\ \left(t\ C\ ha^{-1}\ yr^{-1}\right) = \frac{\left(SOC_{final,practice} - SOC_{initial,practice}\right) - \left(SOC_{final,Control} - SOC_{initial,control}\right)}{T} \quad (4)$$

$SOC_{initial,practice}$ and $SOC_{final,practice}$ refer to the initial and final SOC stocks for fields with different alternative practices (mineral fertilization, organic fertilization, organic+mineral fertilization, minimum tillage, permanent beds, no-tillage). $SOC_{initial,control}$ and $SOC_{final,control}$ represent the initial and final SOC stock under control practices (unfertilized and conventional tillage), and T is the duration of a study (years). Only paired comparisons were considered, whereby each management practice was systematically compared to its corresponding control within the same experimental site. This approach was applied consistently across all studies, including multi-factorial experimental designs, ensuring that ΔSOC rates reflect alternative practices effects relative to site-specific controls and avoiding unpaired comparisons between different sites or studies. ΔSOC rate calculates SOC change relative to SOC stock with control practice as the baseline scenario. If SOC accrual rate is negative, there is a decrease of SOC stock in "final" compared to "initial" state. If ΔSOC rate is negative, there is a decrease of SOC stock in "practice" compared to "control", indicating in the latter case emissions of CO_2 to the atmosphere and in the former that practices are less favorable than control to sequester carbon.

For ΔSOC rate, soil depth adjustment is necessary because it directly affects the absolute amount of SOC change. Among the 1362 paired observations (initial and final), most studies reported SOC stock for the 0–15 ($n = 529$ paired observations), 0–20 ($n = 409$ paired observations), or 0–30 cm ($n = 162$ paired observations) depth increments. To facilitate comparison and analysis, we harmonized SOC stocks into several depth intervals (0-15, 0-20 and 0-30 cm). Soil profiles with similar depth ranges were grouped and recalculated to common depth intervals using proportional depth adjustment: profiles sampled at 0–10 cm (88 observations) and 0–12 cm (6 observations) were adjusted to 0–15 cm;

profiles of 0–17.5 cm (16 observations), 0–18 cm (4 observations), 0–23 cm (20 observations), and 0–25 cm (7 observations) were harmonized to 0–20 cm; and deeper profiles (0–40 cm: 38 observations; 0–50 cm: 8 observations; 0–60 cm: 22 observations; 0–100 cm: 51 observations) were harmonized to 0–30 cm. As we have no data for the intermediate layers (eg., 10-20 cm, 15-20 cm or 20-30 cm), especially for situations where reduced tillage or no-tillage is used, we have considered a homogeneous vertical distribution as a pragmatic approximation to adjust SOC stocks across comparable depth intervals. Overall, 260 data pairs were adjusted from the entire database, only 45 of them being either no- or reduced tillage.

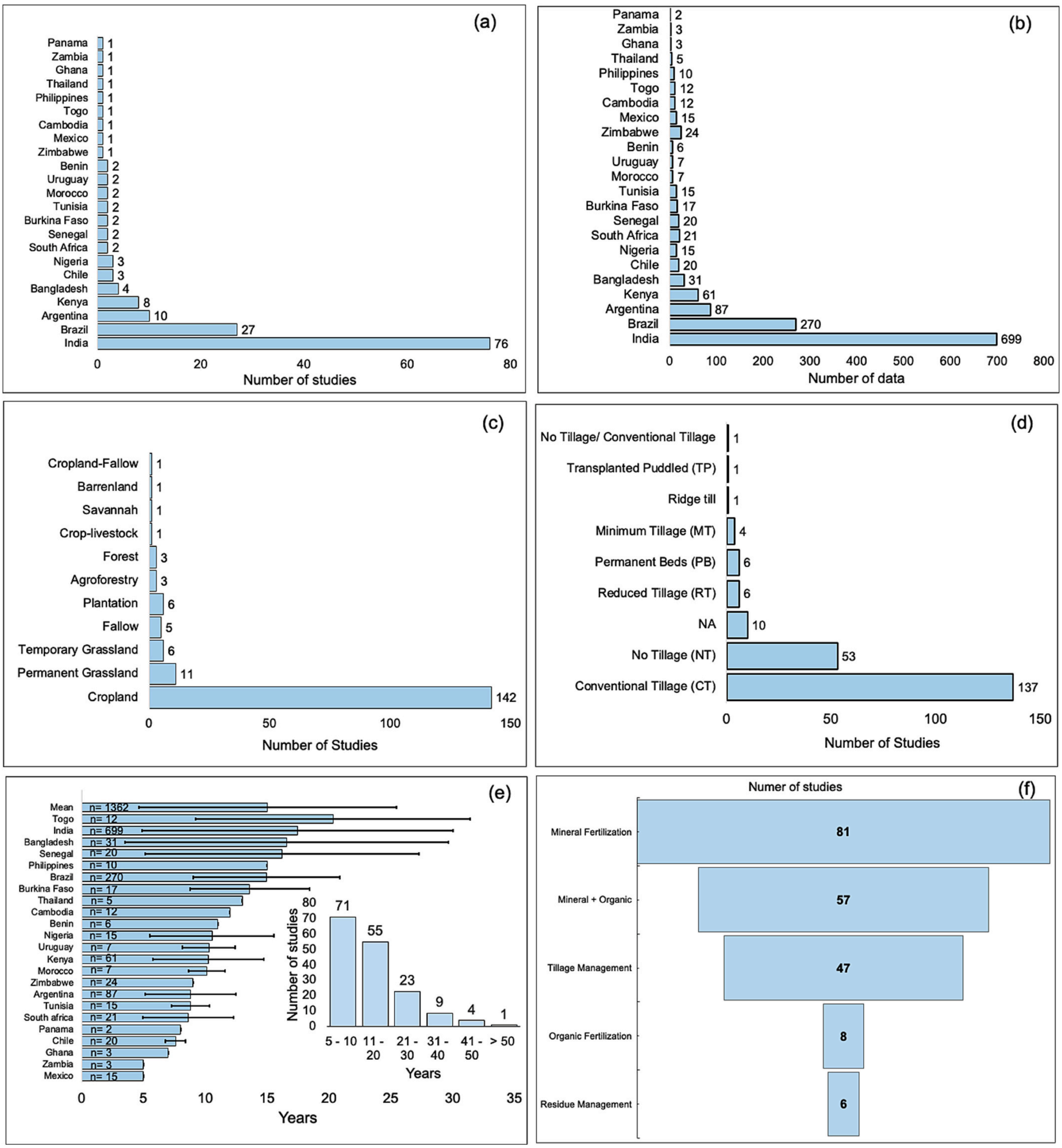

Fig. 3. Characteristics of long-term experiments within selected studies ($n = 155$). (a) Number of studies by country. (b) Number of paired observations by country. (c) Number of studies by land use. (d) Number of studies by tillage management. (e) Average duration of long-term experiments (years). The bars represent the average duration, and the standard deviation. (f) Number of studies focused on the different strategies: effects of mineral fertilization, organic fertilization or their combination (Mineral+Organic), tillage management and crop residue management.

2.3. Contextual and comparative data analysis

The spatial repartition of the observations collected in this study was evaluated according to two key pedoclimatic variables: soil types, based on the USDA classification which was the most found in the studies, and climatic zones, following the Köppen-Geiger system (Gibson et al., 2021). For each major region studied, Africa, Latin America and Asia, soil and climate maps were extracted from regional atlases of soil type and climate obtained from the European soil data centre (https://esdac.jrc.ec.europa.eu/). The maps were processed and segmented using ImageJ software to quantify the surface area represented by each soil and climate class in the regions concerned.

In addition, context-specific agricultural indicators have been extracted from the FAOSTAT database (https://www.fao.org/faostat/en/#home), focusing on the 2010 and 2020 census data. These include average farm size, the top five most cultivated crops per country (covering over 70% of the total cultivated area in most countries) and average fertilizer application rates, based on the most recent national agricultural censuses carried out under the auspices of the FAO. More specifically, data on average national doses of nitrogen (N), phosphorus (P) and potassium (K) per hectare per farm were used to calculate the percentage of fertilizer applied in long-term experiments compared to the average amount applied by farmers in each country. These pedoclimatic and agricultural variables are essential to assess the extent to which existing LTEs represent the real diversity of farming systems and environmental conditions in southern countries, and to identifying gaps or imbalances in the geographical and biophysical coverage of these experiments relative to real world contexts.

2.4. Statistical analysis

To assess the differences in ΔSOC rate among management practices, region, countries, soil profiles or textural class, we performed a non-parametric Kruskal-Wallis test, which is a rank-based alternative to ANOVA suitable for non-normally distributed data. If the Kruskal-Wallis test indicated significant differences ($p < 0.05$), we performed a Dunn post-hoc test with Bonferroni correction to identify which modality significantly differed from each other. All analyses and graphical representations were performed with the R software (R Core Team, 2020), *tidyverse* packages for data manipulation (Wickham et al., 2019), *ggplot2* (Wickham, 2016), and *ggmap* packages for data visualization. The world map was taken from a map database in R using packages ("*ggplot2*", "*rnaturalearth*", "*rnaturalearthdata*" and "*ggspatial*").

3. Results

3.1. Description of long-term experiments in the global south

The data reported by the long-term experiments (LTEs) database come from only 23 southern countries out of the 116 countries included in the publication search. The main contribution comes from India (76 studies, 49%), followed by Brazil (27 studies, 17%), Argentina (10 studies, 6%), and Kenya (8 studies, 5%). The duration of experiments ranges up to 109 years, with an average of 15 ± 10 years. Overall, 71 studies had experiments lasting 5–10 years, 55 studies spanned 11–20 years, 23 studies covered 21–30 years, 9 studies lasted 31–40 years, 4 studies extended 41–50 years, and only one study, located in India, exceeded 50 years (Fig. 3e). We find that all the studies were published after 1990 (Fig. S1). This result highlights the significant delay in research on SOC sequestration across countries in the Global South, where such studies remain limited and relatively recent. However, this pattern may be partly influenced by methodological constraints of the literature review, as some older studies published in French or other languages may not have been captured.

Regarding land cover, we found that 142 studies focused on cropland, compared with 11 studies on permanent grassland, 6 studies on temporary grassland, 6 studies on plantations and 5 studies on fallow land. Only one study evaluates crop-fallow rotation, barren land and crop-livestock. A very limited number of studies reports LTEs on forest ecosystems (3 studies), agroforestry (3 studies), and savannah (1 study) ecosystems (Fig. 3c). Our literature research also enabled us to identify the practices and cropping systems tested in the Global South. Overall, 81 studies involved mineral fertilization experiments, compared with 57 studies investigating both mineral and organic fertilization experiments, and 47 studies focused on experiments relating to the effect of tillage management, often combining plant cover or crop residues. Only 8 studies report organic fertilization experiments, where the effect of an organic amendment was compared with a situation in which no organic input was used (farmyard manure > green manure > crop residues > composts > slurry > others). Likewise, very few studies (6 studies) addressed the effect of removing or burning crop residues (Fig. 3f). A wide range of cropping systems can be identified, notably monocropping (52/155 studies), crop diversification including intercropping (7/155 studies) and crop rotation (96/155 studies). In the subset concerning crop diversification (i.e., intercropping and crop rotation), we recorded 63 studies with cereals-legumes rotations, 46 studies with cereals rotation and 4 studies with legumes rotation. Monocropping with maize (17 studies) and rice (17 studies) are also the most widespread monocropping systems reported in this study database. Excluding unfertilized control fields, mineral fertilization inputs ranged from 15 kg N ha^{-1} in Benin to 412 kg N ha^{-1} in Mexico, while phosphorus inputs varied from 15 kg P ha^{-1} in Benin to 140 kg P ha^{-1} in Chile, and potassium inputs from 15 kg K ha^{-1} in Benin to 151 kg K ha^{-1} in Brazil. Nitrogen inputs were generally higher than phosphorus and potassium inputs (Fig. S8a, b, c).

3.2. Effect of fertilization management on SOC in south LTEs

Our study reveals that fertilization, whether mineral, organic, or mixed, consistently promotes SOC sequestration compared to unfertilized controls across all regions (Fig. 4 and Fig. 6a). Unfertilized plots generally show carbon losses (-0.03 ± 0.04 t C ha^{-1} yr^{-1}), particularly pronounced in Africa (-0.53 ± 0.13 t C ha^{-1} yr^{-1}) and Asia (-0.03 ± 0.02 t C ha^{-1} yr^{-1}). In contrast, a modest carbon gain is observed in Latin America (0.15 ± 0.07 t C ha^{-1} yr^{-1}) (Fig. S3), likely attributable to the more frequent cultivation of leguminous crops, especially soybean in Brazil (Fig. S7b). Mineral fertilization alone contributes to an average SOC gain of 0.12 ± 0.01 t C ha^{-1} yr^{-1}, while organic fertilization leads to a higher sequestration rate of 0.47 ± 0.08 t C ha^{-1} yr^{-1}. The mixed application of organic and mineral sources achieves an intermediate but still significant rate of 0.35 ± 0.02 t C ha^{-1} yr^{-1}. Statistically, fertilization practices exert a significant effect on SOC accumulation ($p < 0.05$), with the hierarchy: Organic ≥ Organic + Mineral > Mineral > Unfertilized. In Asian LTEs, mineral fertilization yields the highest additional SOC rate (0.15 ± 0.01 t C ha^{-1} yr^{-1}), while LTEs in Africa and Latin America show more modest gains (0.03 ± 0.03 and 0.09 ± 0.05 t C ha^{-1} yr^{-1}, respectively). Organic fertilization shows strong and consistent benefits across all regions, particularly in Africa (0.59 ± 0.08 t C ha^{-1} yr^{-1}) and Asia (0.45 ± 0.10 t C ha^{-1} yr^{-1}). Similar patterns are observed for mixed fertilization (see Fig. S3).

When analyzing soil texture as a modulating factor, no clear linear relationship emerges between SOC sequestration rates and clay, silt, or sand content. A slight trend suggests higher gains in coarse-textured soils under mineral or mixed fertilization (Fig. S3). To further elucidate the mechanisms underlying SOC changes, we analyzed the relationship between carbon inputs and SOC sequestration rate (Fig. S5). Our results show a significant positive correlation between ΔSOC sequestration rate and ΔC input in the 0–20 cm ($R^2 = 0.16$; $p < 0.001$) and 0–30 cm ($R^2 = 0.38$; p < 0.001) soil layers. However, no significant correlation was observed in the 0–15 cm layer ($R^2 = 0.02$; $p > 0.05$). Residual analysis indicates that multiple complex interactions are at play, as no systematic pattern was detected.

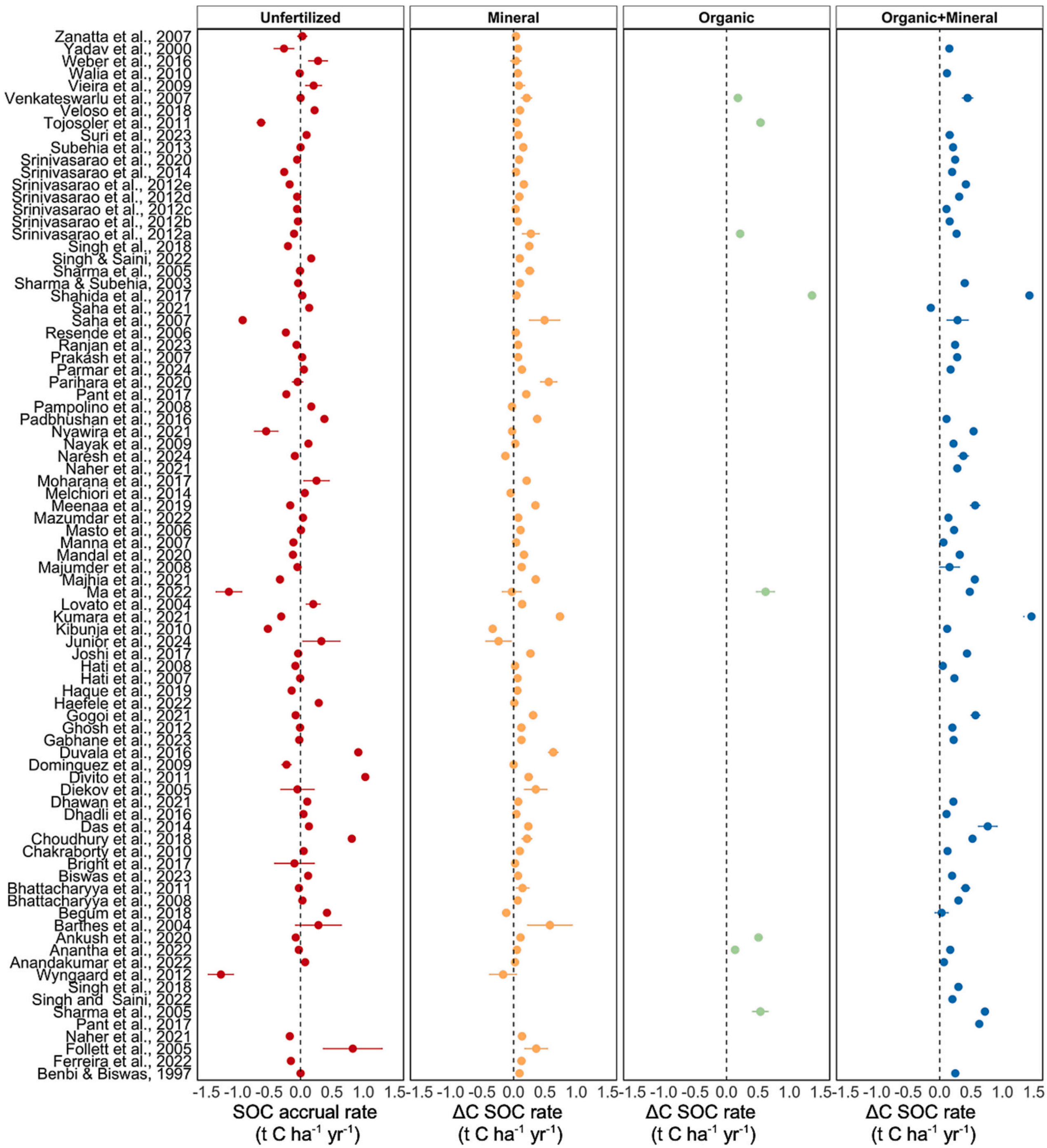

Fig. 4. SOC accrual rate of the control group without mineral fertilization (Unfertilized) and the ΔSOC rate (see eq. 2) which represent the effect of the fertilization treatment compared to the control treatment: Mineral fertilization, Organic fertilization or Organic+Mineral fertilization under different studies. Mean ± standard error. If SOC accrual rate is negative, there is a decrease of C-stock in "final" compared to "initial" state, indicating emissions of CO_2 to the atmosphere. If ΔSOC rate > 0, this indicates a positive effect of alternative practice on SOC sequestration.

3.3. *Effect of tillage management on SOC in south LTEs*

Tillage management plays a decisive role in SOC dynamics. We observed that conventional tillage (CT) on average leads to a net SOC loss (-0.12 ± 0.05 t C ha^{-1} yr^{-1}), while alternative tillage practices consistently lead to SOC gains: minimum tillage (MT) yields 0.35 ± 0.05 t C ha^{-1} yr^{-1}, no-tillage (NT) 0.43 ± 0.04 t C ha^{-1} yr^{-1}, and permanent beds (PB) 0.53 ± 0.07 t C ha^{-1} yr^{-1}. These trends are statistically significant (Fig. 5 and Fig. 6b; $p < 0.05$). The effectiveness of tillage alternatives also varies geographically. The CT results in a strong SOC loss in the LTEs in Africa (-0.54 ± 0.11 t C ha^{-1} yr^{-1}) and a modest carbon loss in Latin America (-0.07 ± 0.07 t C ha^{-1} yr^{-1}), while Asian LTEs unexpectedly show a slight gain (0.13 ± 0.05 t C ha^{-1} yr^{-1}), possibly due to interactions with local cropping systems or input levels (see Fig. S4). In contrast, alternative tillage practices yield consistent benefits in all regions. LTEs in Latin America exhibit particularly high SOC sequestration rates (MT: 0.31 ± 0.09; NT: 0.48 ± 0.05 t C ha^{-1} yr^{-1}), followed by LTEs in Africa and Asia. As with fertilization, soil texture does not show a significant linear relationship with SOC responses to tillage. While some coarse-textured soils appear more responsive under MT or NT, the effect

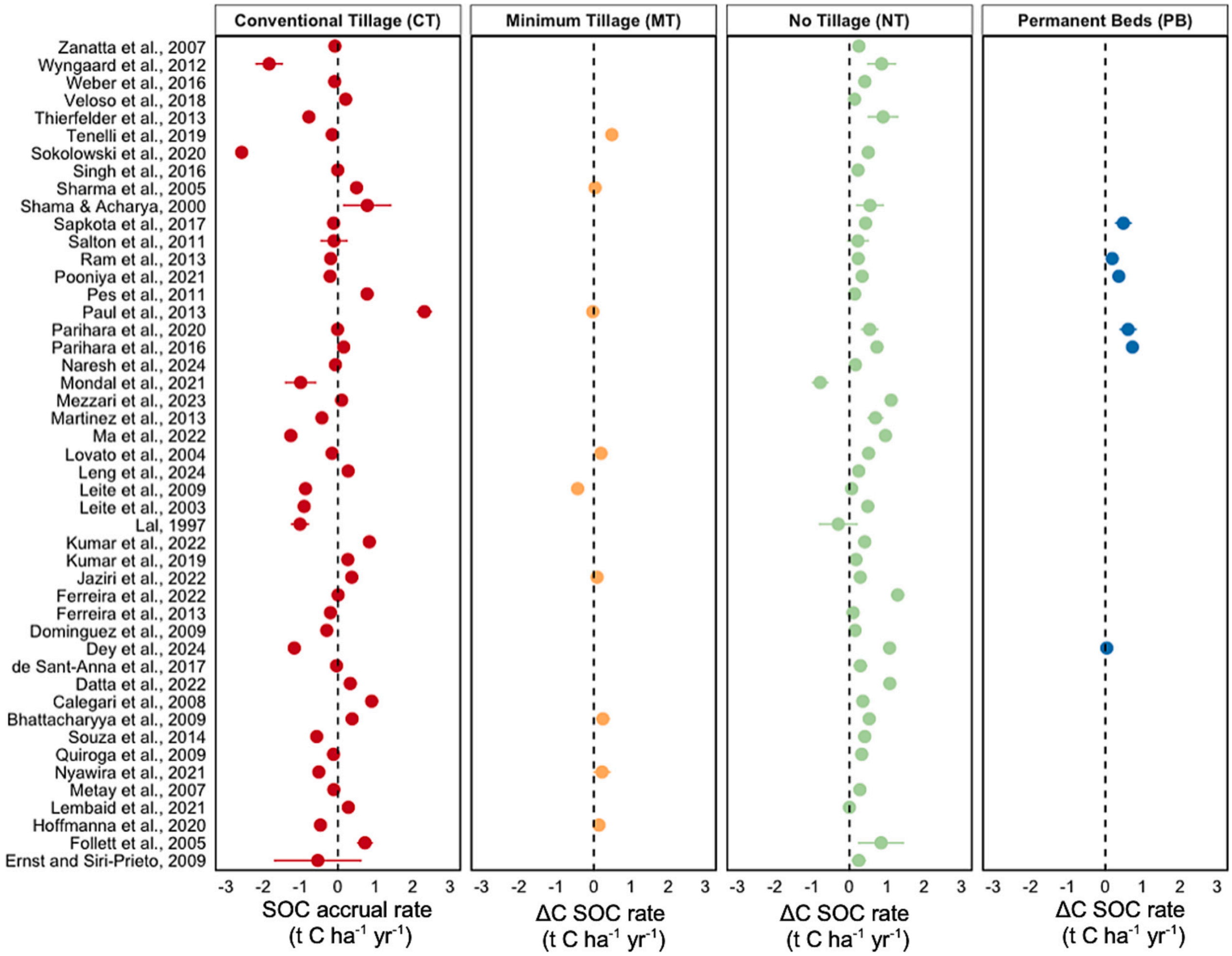

Fig. 5. SOC accrual rate of the control tillage (Conventional Tillage) and the ΔSOC rate which represent the tillage management effect: Minimum Tillage, No Tillage or Permanent Beds under different studies. Mean ± standard error. If SOC accrual rate is negative, there is a decrease of C-stock in "final" compared to "initial" state, indicating emissions of CO_2 to the atmosphere. If ΔSOC rate > 0, this indicates a positive effect of alternative practice on SOC sequestration.

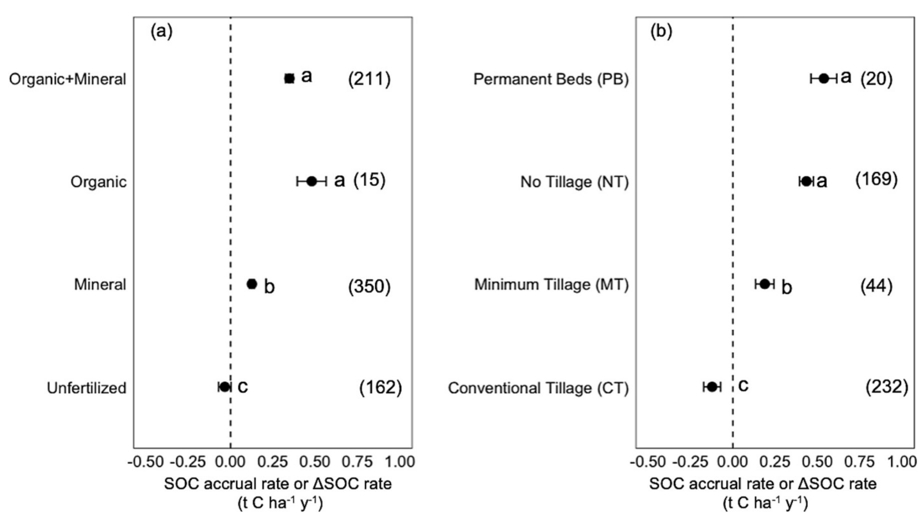

Fig. 6. (a) Mean effect of mineral, organic, organic +Mineral fertilization and (b) Mean effect of tillage practices on carbon sequestration rate (ΔC SOC rate) for all profiles together. Mean ± standard error. The number in brackets represents the number of data points. The letters represent significant differences at the 5% level between the modalities. The SOC accrual rate is calculated for the control treatments, namely the "unfertilized" and "conventional tillage" systems. When this rate is negative, it indicates a loss of carbon between the initial and final states of the control, thereby reflecting CO_2 emissions to the atmosphere. ΔSOC rate is calculated for alternative practices. If it is negative, it indicates a decrease in carbon stock under the "alternative practice" compared to "unfertilized" or "conventional tillage," reflecting a potential loss of carbon sequestration or an opportunity cost (Erb et al. 2022).

remains context-dependent.

4. Discussion

4.1. Are research and management practices in the south different to the north? Insights from LTEs

This study identified 174 LTEs sites, from 155 publications, which had analyzed the effects of management practices or land use on SOC dynamics using a diachronic approach. This number remains very limited when compared with Northern countries, particularly in Europe, where a long-standing tradition of long-term field experiments has resulted in a substantially larger and more diverse body of LTEs dedicated to soil carbon research. A recent inventory documented more than 616 long-term experiments (exceeding 20 years) conducted across 30 European countries, reflecting a structured and sustained research effort (Dönmez et al., 2022; Grosse et al., 2021; BonaResDatabase: https://tools.bonares.de/ltfe/). A more recent study identified 240 long-term diachronic experiments in Europe, lasting at least five years, of which only 91 LTEs (38%) provided data enabling the monitoring the evolution of SOC over time (Blanchy et al., 2024). Our study, by comparison, identified only 174 diachronic LTEs in the whole Global South, excluding China, with an average duration of approximately 15 years. This disparity is largely attributable to the substantial financial and human resources required to establish and maintain LTEs. In the Global North, such resources are often secured through strong public policies that support continuous, fundamental research carried out by universities, research institutions, or long-term experimental networks (Johnston and Poulton, 2018). Conversely, in many regions of the Global South, research investments are primarily allocated to short-term projects targeting urgent socio-economic issues such as food security and climate change adaptation (Tittonell and Giller, 2013; Vanlauwe et al., 2015). This difference in funding priorities partly explains the relative scarcity of LTEs. Nevertheless, alternative experimental approaches have emerged to respond to these constraints, in particular the synchronic approaches and chronosequences, although these can sometimes introduce considerable uncertainty (Rakotovao et al., 2020).

The predominance of LTEs on cropland is similar in southern and northern countries. Our study shows that 92% of the reviewed studies focus on LTEs established in cropland. This pattern is consistent with observations from Europe, where 82% of the 616 LTEs identified across 30 European countries are conducted in cropland (Dönmez et al., 2022; Grosse et al., 2021). This concentration reflects a research priority given to field crop systems, often to the detriment of other land uses such as grasslands (11% of LTEs), and more marginally, forests, agroforestry systems and fallow land, which together account for only 7% of LTEs. Yet, these systems play a central role in the functioning of ecosystems and carbon storage in many regions of the South and North. The most frequently studied management strategies in northern countries showed a clear over-representation of tillage-related practices (54% of LTEs), compared to those focusing on fertilization (22% of LTEs) (Dönmez et al., 2022), whereas in our study, mineral fertilization emerged as the dominant management practice (Fig. 3f). This disparity can be explained by the fact that in the South, LTEs are mainly geared towards immediate improvements in soil fertility and increased agricultural productivity. Conversely, research objectives in northern countries are geared towards long-term environmental sustainability, with growing interest in carbon sequestration, soil biodiversity preservation and greenhouse gas emission reduction (Smith et al., 2008; Sanderman et al., 2017). The adoption of no-tillage practices in the North is primarily driven by the need to mitigate soil erosion (Lahmar, 2010). In contrast, in many southern countries, the availability of labor enables manual weeding, thereby reducing the reliance on mechanized practices such as tillage. In this context, fertilization emerges as a more central management lever than tillage, reflecting priorities that differ from those observed in temperate regions. Although there are marked differences in research priorities and management strategies, the effects of the most common management practices on SOC sequestration are often comparable between North and South countries.

Mineral fertilization contributes to an average SOC gain of 0.12 ± 0.01 t C ha^{-1} yr^{-1}, while organic fertilization leads to a higher SOC sequestration rate of 0.47 ± 0.08 t C ha^{-1} yr^{-1} and the mixed application of organic and mineral sources achieves an intermediate rate of 0.35 ± 0.02 t C ha^{-1} yr^{-1}. Similar findings were reported by Pathak et al. (2011) at the national scale in India, where the mixed application of inorganic nutrients (NPK) and farmyard manure (FYM) sequestered SOC at a rate of 0.33 t C ha^{-1} yr^{-1}, compared to 0.16 t C ha^{-1} yr^{-1} with NPK alone. Many studies have certified that organic fertilization promotes SOC accumulation, but the results vary greatly. The global meta-analysis of Han et al. (2016), showed that SOC content increased by 36.2% with manure plus mineral fertilizer and 15.4% with mineral fertilizer alone. A synthesis study by Luo et al. (2018) found that the amount of SOC in organically amended soils was 38% higher than in mineral-fertilized soils. Our results are consistent with the previously cited studies and reinforce the broad consensus that organic fertilization is particularly effective in increasing SOC stocks (Maillard and Angers, 2014; Fujisaki et al., 2018; Jiang et al., 2018; Bai et al., 2023). Significant regional disparities have been observed. In the present study, LTEs in Asia reported the highest increases in SOC following mineral fertilization, with an average sequestration rate of 0.15 ± 0.01 t C $ha\text{-}^{1}$ $yr\text{-}^{1}$. This result is partly explained by the high representation of studies conducted in India, where the doses of mineral fertilizer applied are generally higher than in other regions of the South. In comparison, the effects reported in Africa (0.03 ± 0.03 t C $ha\text{-}^{1}$ $yr\text{-}^{1}$) and Latin America (0.09 ± 0.05 t C $ha\text{-}^{1}$ $yr\text{-}^{1}$) are much more modest. Furthermore, there is ongoing debate about the concept that soils with initially low SOC content have higher SOC sequestration potential (Rowe et al., 2016; Bai et al., 2023; Slessarev et al., 2023). In our database, initial SOC stocks in Asia were lower than those measured in Africa and Latin America, which could also explain their greater capacity to accumulate carbon, particularly when organic residue inputs increase with crops under mineral fertilization (see Fig. S10; Fig. S11). However, this study did not reveal any significant linear relationships between SOC sequestration rates and soil properties (clay, silt, sand, pH) or climate variables (mean annual temperature and rainfall). This finding aligns with previous research in tropical croplands (Fujisaki et al., 2018). However, categorizing soils by textural classes revealed a trend of greater SOC gains in coarse-textured soils under mineral or mixed fertilization (Fig. S3), consistent with Bai et al. (2023), who observed the highest relative SOC increases in coarse soils when manure was applied. While coarse-textured soils exhibit higher short-term SOC increases due to faster incorporation of organic amendments, their lower capacity for long-term stabilization raises questions about the persistence of this carbon. Moreover, most LTEs included in this study span less than two decades (88% of studies), suggesting that the observed effects primarily reflect short- to medium-term dynamics. Previous studies have shown that organic matter first accumulates in the coarse particulate organic matter fraction (Peltre, 2010; Paetsch et al., 2016), with significant stabilization in the fine (clay + silt) fraction occurring only after about 20 years, driven by biological processes (Kpemoua et al., 2024). However, it is important to note that these findings are based on a geographically unbalanced dataset, with a predominance of LTEs from just a few countries, notably India and Brazil. This concentration may limit the generalization of our results across the broader range of pedoclimatic, and land use contexts found in the Global South. Further studies are therefore needed to determine to what extent long-term organic inputs lead to a net increase in SOC stocks in coarse-textured soils in the long run, particularly in the Global South.

The results of our study confirm that higher carbon inputs generally lead to greater SOC stocks in 0-20 and 0-30 cm (Fig. S5). This finding is widely documented in the literature on SOC dynamics in croplands following changes in management practices (de Moraes Sá et al., 2015;

Hok et al., 2015; Maillard and Angers, 2014; Virto et al., 2012; Fujisaki et al., 2018). Across our dataset, carbon inputs were the strongest predictor of SOC accumulation rates, supporting the findings of Virto et al. (2012), who investigated the impact of no-tillage on carbon dynamics. Moreover, this effect partly depends on soil depth. The residual analysis did not reveal any significant influence of the pedoclimatic variables reported in the studies (e.g., pH, texture, altitude, temperature, precipitation), suggesting that SOC dynamics may be driven by complex interactions between management practices and other unaccounted factors not explored in this study, particularly in the 0–15 cm soil layer. In line with previous research at the global scales or in temperate regions of the Global North, these results underline the central role of organic carbon inputs, whether from exogenous organic matter, crop residues, or cover crops in enhancing long-term SOC sequestration (Maillard and Angers, 2014).

This study confirmed that tillage management also plays a decisive role in SOC dynamics in the Global South. We observed that the CT is associated with a net SOC loss, while alternative tillage practices consistently lead to SOC gains: CT < MT < NT ≤ PB. These trends are statistically significant (Fig. 6b; $p < 0.05$) and align with findings from global-scale studies (Freibauer et al., 2004; Haddaway et al., 2017). For instance, Haddaway et al. (2017) estimated long-term SOC gains of approximately 0.46 t C ha^{-1} yr^{-1} under NT, while Tang and Nan (2013), reported similar values for no-tillage with residue retention in China. The effectiveness of tillage alternatives also varies geographically. CT is associated with substantial losses of SOC in LTEs conducted in Africa (−0.54 ± 0.11 t C ha^{-1} yr^{-1}) and more moderate losses in Latin America (−0.07 ± 0.07 t C ha^{-1} yr^{-1}), whereas LTEs from Asia unexpectedly exhibit a slight SOC gain (0.13 ± 0.05 t C ha^{-1} yr^{-1}). This contrast likely reflects differences in cropping systems. Crop rotation systems dominate in Asia (75% of the dataset), mainly consisting of cereal–cereal and cereal–legume sequences. Latin America also shows a high proportion of crop rotations (70%), but with greater variability in management intensity. In contrast, monocropping is more prevalent in Africa, accounting for 67% of the dataset. In addition, rice-based systems represent a substantial share of the Asian dataset (45%) and are typically associated with residue incorporation and specific soil conditions that favor SOC accumulation. Higher nitrogen fertilization rates under CT in Asia (158 kg N ha^{-1} on average), compared with Latin America (108 kg N ha^{-1}) and Africa (55 kg N ha^{-1}), may further reinforce this pattern. In addition, alternative tillage practices yield consistent benefits in all regions. The enhanced SOC losses observed under CT systems may arise from the mechanical disruption of soil aggregates, which exposes previously protected organic matter to microbial decomposition (Jastrow et al., 1996; Six et al., 2000). This disturbance stimulates microbial activity, thereby accelerating the oxidation and mineralization of SOC (Six et al., 1999; Loke et al., 2012; Swanepoel et al., 2016). Apart from these results, an important methodological limitation needs to be highlighted when comparing SOC stocks at equivalent volumes: a decrease in tillage intensity is frequently accompanied by an increase in bulk density, which can lead to an overestimation of SOC stock. This potential bias is a confounding factor that needs to be considered when interpreting the results of meta-analyses. Several studies have also pointed out the existence of confounding factors in tillage research, namely the systematically higher carbon inputs in conservative agricultural systems with low or NT compared to CT systems (Virto et al., 2012; Autret et al., 2016). As with fertilization, soil texture does not show a significant linear relationship with SOC responses to tillage. While some coarse-textured soils appear more responsive under MT or NT, the effect remains context-dependent. In addition to the impact of management practices on carbon stocks, the LTEs identified in this study highlight a marked geographical concentration and significant pedoclimatic biases in the data collected.

4.2. Pedoclimatic bias of LTEs in the global south

The distribution of LTEs across the Global South revealed significant mismatches between the pedoclimatic diversity of each region and the

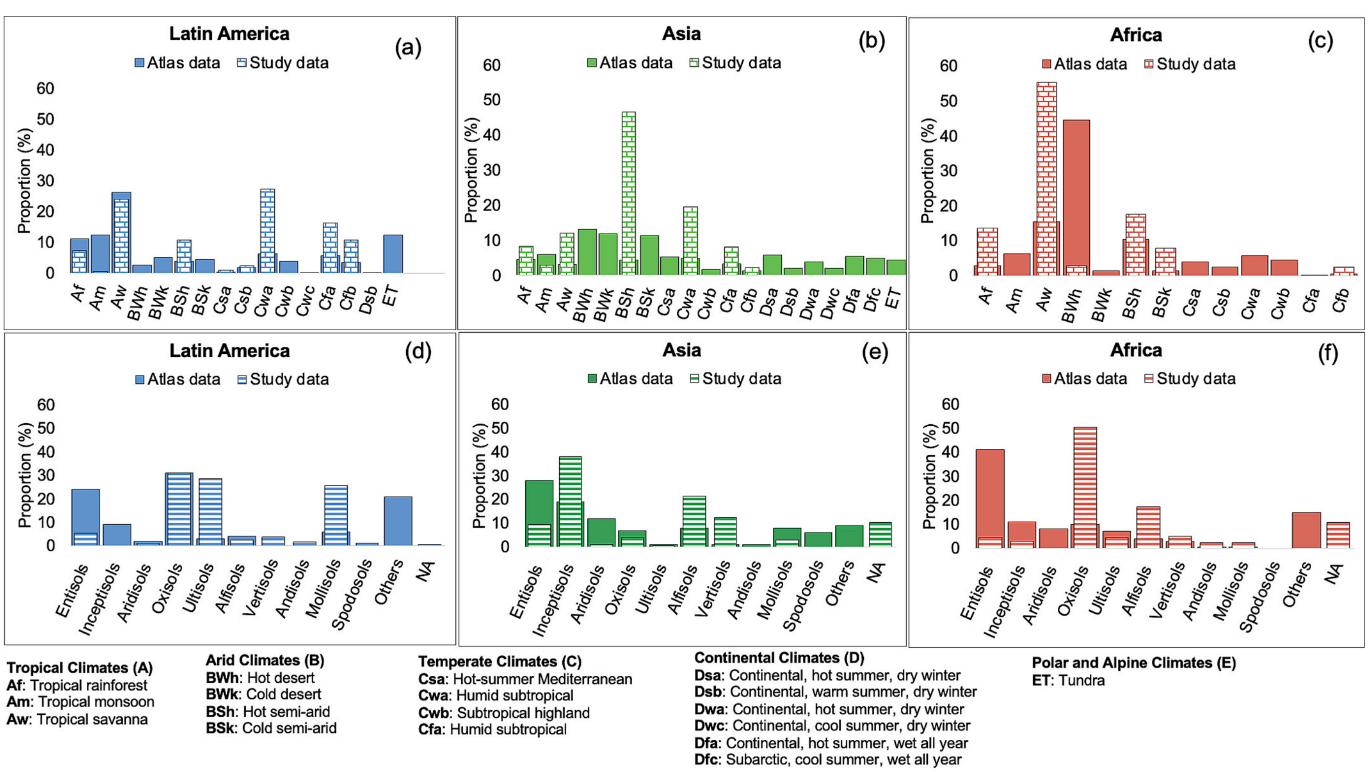

Fig. 7. Comparative distribution of soil types (USDA classification; Fig. 7 d,e,f) and climate (Köppen-Geiger classification; Fig. 7 a,b,c) in long-term experiments vs. regional atlas data (obtained from the European Soil Data Centre: https://esdac.jrc.ec.europa.eu/) across the Global South. Hatched bars refer to LTEs sites distribution, and unhatched bars show the distribution of all soils and climate for the respective regions.

conditions covered by LTEs (Fig. 7; Fig. S9). In Latin America, LTEs are mostly located in areas dominated by Oxisols, Mollisols, and Ultisols under humid tropical (Af) and subhumid (Aw, Cwa, Cfa, Cfb) climates. While the climatic coverage aligns relatively well with regional pedoclimatic maps, the soil types are biased: Mollisols and Ultisols are overrepresented, whereas Entisols are underrepresented and Inceptisols are entirely absent. In Asia, LTEs are predominantly situated in areas with Inceptisols, Alfisols, and Vertisols under semi-arid (BSh), tropical subhumid (Aw, Cwa, Cfa), and humid (Af) climates. This reflects a clear overrepresentation of semi-arid (BSh) and tropical subhumid (Cwa) climates. While Entisols are the most widespread soils in Southeast Asia, they are underrepresented in LTEs, in contrast to the overrepresentation of Inceptisols, Alfisols, and Vertisols. These discrepancies likely reflect the strong influence of India in the LTEs dataset, leading to a limited representation of Southeast Asia full pedoclimatic diversity.

In Africa, LTEs are mainly located in areas with Oxisols and Alfisols under tropical subhumid (Aw), humid (Af), and semi-arid (BSh, BSk) climates. This distribution results in a limited representation of hot arid climates (BWh), which cover large parts of the continent (e.g., the Sahara and Namib deserts as well as parts of the Sahel). However, these regions are generally not suitable for agricultural activities, except in specific contexts such as irrigated agriculture or oases, and their underrepresentation should therefore be interpreted in light of their limited contribution to rainfed agricultural production systems. Similarly, Entisols and Inceptisols, which are widespread across African landscapes, remain underrepresented, while Oxisols and Alfisols dominate the LTEs dataset. Notably, no LTEs were found on Aridisols, despite these soils are characteristic of arid and semi-arid regions. Overall, these patterns indicate that LTEs data do not fully capture the pedoclimatic variability of African agricultural context.

Similar bias also exists in the North and is not the exclusivity of the South. For instance, in Germany, LTEs show a significant bias in favor of dry climatic zones (CWBg), particularly around regions historically invested in agronomic research such as Berlin or the Bad Lauchstädt-Halle-Seehausen axis (Grosse et al., 2020). In addition, most LTEs sites in their study are located on medium to high quality soils, with low quality or poorly developed soils being largely under-represented. Although this uneven distribution partly reflects the history of research infrastructures in Germany, it limits the representativeness of the results obtained from these systems for all temperate agricultural systems. These pedoclimatic biases, observed in both North and South, highlight a structural imbalance in long-term experimental schemes worldwide. The recurrent under-representation of certain pedoclimatic contexts, notably arid zones and poor or degraded soils, compromises the generalisability of the knowledge produced and weakens the robustness of the SOC dynamics models based on these data. This makes it imperative to reimagine the spatial planning of future LTEs, incorporating better coverage of soil and climate gradients, in order to enhance their representativeness and relevance in meeting the global challenges of ecosystem sustainability and climate change mitigation.

4.3. Geographical bias and mismatch between agricultural practices tested in LTEs and local practices in the global south

The results of this study highlighted the predominance of some countries, particularly India and Brazil, which together account for 66% of the studies on LTEs and 71% of the total dataset (Fig. 2, Fig. 3a, b). Only a limited number of countries in the Global South (23 out of 116) have invested in research infrastructures and established LTEs sites, enabling the assessment of SOC stock changes through a diachronic approach. While India and Brazil offer a wide range of climatic and pedological conditions, their agricultural structures differ sharply and strongly shape the design and focus of LTEs. According to FAO data (FAOSTAT, 2025), in India, more than 75% of the cropped land is cultivated on farms under 5 ha, whereas in Brazil, 65% of cropped area occurred on farms ranging from 100 to over 2500 ha (Fig. S6). Such differences influence not only land-use management practices but also the types of treatments assessed in experiments. In India, the predominance of smallholder family farming is associated with a strong reliance on mineral fertilization in LTEs, with 68% of studies focusing on this practice. The nitrogen fertilizer application rates observed in these experiments are on average 44% higher than national per-farm averages reported by the FAO database (FAOSTAT, 2025). In contrast, tillage practices are less frequently represented in the LTEs in India, which likely reflects the predominance of smallholder family farming systems, where limited mechanization restricts the diversity and intensity of tillage practices, unlike in countries such as Brazil, where farming systems are larger in scale and more intensive. Given that the incorporation of residues is generally linked to tillage operations, this practice could also be indirectly limited. Conversely, in most African countries, the fertilizer application rates recorded in LTEs exceed national averages reported by the FAO by 100 to 1000% (Fig. 8).

This discrepancy clearly reflects a mismatch between locally practiced agriculture and the management strategies tested in experimental settings. Indeed, research projects conducted in Africa often replicate soil management models derived from very different agricultural contexts, such as those of India or Brazil, or the northern countries. These discrepancies are marked across most of the countries including in the present work, with exceptions in India, Bangladesh, Brazil and Uruguay, where experimental fertilizer doses are more comparable to actual practices. This divergence is most likely explained by strong economic constraints limiting access to inputs. In Africa, the cost of fertilizers is generally two to six times higher than in regions such as Europe, North America or Asia, which severely limits their accessibility to smallholders (Sanchez, 2002). Conversely, experimental plots usually benefit from secured resources and are designed to meet crop nutrient demands under optimal fertilization. Falconnier et al. (2023) showed that mineral and organic fertilizer resources and use are very limited in sub-Saharan Africa, especially in subhumid and semi-arid regions. In humid regions, slash-and-burn cultivation systems have been widely used as the primary method for managing soil fertility and weed control (Serrani et al., 2022). Similarly, in certain Southeast Asia such as Cambodia and Vietnam, agricultural systems are shaped by intercropping systems, use of slash-and-burn systems, and rice-based systems, which differ substantially from the large-scale soybean or intensive rice and cereal production systems dominant in Brazil and India (Carrière et al., 2019).

Regarding Brazilian LTEs, they are more focused on tillage management (60% of studies) and less on fertilization, reflecting its large-scale mechanized agricultural model and soybean-oriented cultivation, a nitrogen fixing legume. By contrast, in most of the countries included in the present review, the average farm size, according to the FAO data, remains below 10 or even 5 ha (Fig. S6), while tillage is one of the most investigated practices (Fig. 3f). As farm size often determines the requirement and capacity to implement tillage, it is very likely that tillage, as an agricultural practice, is over-represented in studies in the Global South compared to their actual implementation in real-world farms (Prestele et al., 2018). These biases partly stem from the current research funding landscape: to secure competitive grants, researchers typically build on an abundant existing literature, which is largely dominated by studies conducted in a few well-documented emerging countries (e.g., India, Brazil) or in the North. Investigating understudied agricultural systems is inherently more uncertain and therefore riskier. Furthermore, funding calls are frequently oriented towards “innovative” practices, reinforcing the tendency to prioritize certain management strategies over others that may be more representative of local farming realities but remain scientifically underexplored. Finally, we identified in this study five key crops most frequently studied in LTEs: maize, rice, wheat, soybeans, and beans (Fig. S7b). This result aligns with FAO (FAOSTAT, 2025) data on the five most widely cultivated crops in each country, which also lists maize, soybeans, rice, wheat, and beans as dominant crops (Fig. S7a), suggesting a strong alignment between research focus and agricultural importance.

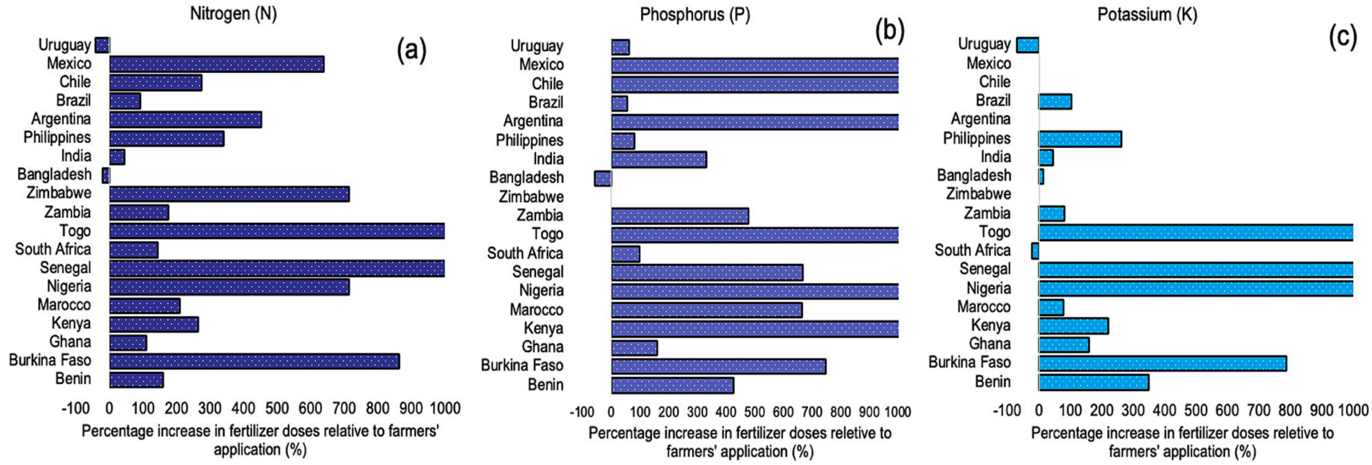

Fig. 8. The percentage of fertilizer applied in long-term experiments relative to the average amount per farmer in the individual countries, based on FAOSTAT data.

In summary, while India and Brazil span a wide range of climatic and pedological conditions, their environmental diversity does not adequately compensate for their limited socio-agronomic representativeness relative to the broader Global South. The experimental designs in both countries appear to mirror national agricultural systems and policy orientations, even if the causal link might not be direct. Indeed, both countries have followed distinct agricultural development paths shaped by major policy shifts, such as the Green Revolution in mostly smallholder farms in India (Pingali, 2012) and the large-scale intensification of commodity crop production in Brazil (Sparovek et al., 2019). These trajectories have led to highly mechanized agricultural systems integrated into global export markets in Brazil, and to subsistence-oriented but highly input-intensive- systems in India. In contrast, large areas of the Global South particularly in sub-Saharan Africa and southeast Asia are still dominated by low-inputs and low-mechanization subsistence-oriented, smallholder agriculture. These systems typically rely on agroforestry, legume crops, fallows and shifting cultivation (slash-and-burn) to maintain soil fertility (Van Vliet et al., 2012; Mertz et al., 2009). Despite supporting the livelihoods and food security of approximately 500 million people worldwide (FAO, 2017), the slash-and-burn agricultural models are completely absent from the LTEs datasets analyzed in this study. This lack of representation constitutes a major limitation not only for modeling SOC dynamics, but more broadly for soil sciences and related disciplines, as it excludes many widespread and environmentally vulnerable agricultural systems across large parts of the Global South (Metcalfe et al., 2025).

4.4. Limits of the study

Although we have constructed a database of diachronic LTEs at the scale of the Global South, this study still has some limitations. Firstly, our study did not incorporate land use history into the analysis, which can significantly affect SOC stabilization processes and therefore SOC stocks in managed landscapes (Sanderman et al., 2017). Another limitation concerns the bibliographic research strategy. We deliberately chose to use only the Web of Science database, as it is widely used by the scientific community and covers a broad range of disciplines. This choice aimed to ensure the scientific quality and reliability of selected publications. However, this choice may have led to the exclusion of relevant studies indexed in other databases. In addition, we restricted our review to open-access publications and those accessible through institutional subscriptions (e.g., Sorbonne University/AgroParisTech), primarily written in English and, to a lesser extent, in Portuguese, particularly for studies conducted in Brazil. This approach may have resulted in an underrepresentation of studies published in French, especially from non-anglophone African countries, where research outputs are often disseminated in local or regional journals that are not systematically indexed in major international databases. Furthermore, some relevant articles could not be included due to access restrictions, despite our efforts to contact the corresponding authors, most of whom did not respond. The limited accessibility of such publications therefore constitutes a potential source of bias in our dataset. Moreover, our search equation may have been too restrictive, and some relevant studies were not initially retrieved. To mitigate this limitation, additional articles were identified through backward citation tracking from studies retrieved via Web of Science and were included when they met the selection criteria. We also acknowledge that since we did our literature search, several other diachronic studies in LTEs have been published (Leng et al., 2024; Couëdel et al., 2026), and further work should consider using a dynamic or living review approach to keep the database up-to-date.

Another important limitation relates to the heterogeneity of methods used to determine SOC content across studies (e.g., dry combustion, Walkley-Black method). These methodological discrepancies may introduce uncertainty in SOC stock estimates. The lack of standardized reporting on soil sampling depth also represents a major barrier to data harmonization. For studies reporting SOC stocks at depths greater than 30 cm (e.g., 0–40, 0-50, 0–60, or 0–100 cm), data were aggregated into a 0–30 cm category. While this introduces some uncertainty, most SOC changes occur in the topsoil, and this approximation is expected to have a limited impact on ΔSOC estimates, particularly for relative comparisons between treatments. The adjustment of ΔSOC rates to standardized soil depths was performed using a proportional redistribution of SOC within the sampled soil profile when intermediate depth data were unavailable. This assumption does not reflect the actual vertical stratification of SOC, which generally decreases with depth, and may therefore introduce additional uncertainty, particularly when extrapolating from deeper profiles (e.g., 0–100 cm) to shallower ones (e.g., 0–30 cm). However, this source of uncertainty is expected to have a limited impact on our results, as confirmed by the sensitivity analysis (see Fig. S12), which does not indicate any significant effect of data harmonization on the main findings and conclusions of the study.

Another key limitation of this study concerns the estimation of BD for a subset of LTEs. Many LTEs reported SOC concentrations without corresponding BD measurements, requiring BD to be estimated for approximately one third of the dataset using an empirical linear relationship based on SOC content (Fig. S1). This relationship shows a relatively low explanatory power ($R^2 = 0.41$), which can introduce uncertainty into the resulting SOC stock estimates. Although the dataset used to derive this relationship included soils under different land uses, their representativeness across the wide range of soil types, management practices, and spatial scales covered in this synthesis remains limited.

Consequently, the use of estimated BD values may affect the accuracy of absolute carbon stock estimates and should be considered when interpreting cross-site comparisons. Calculating SOC stocks based on fixed-depth measurements rather than equivalent soil mass (ESM) can introduce an additional source of error. Indeed, several studies have shown that this methodological difference can lead to discrepancies of up to 6% in carbon stock estimates (Xu et al., 2019). Fixed-depth measurements do not account for changes in soil volume over time, a bias that may be particularly pronounced in long-term experiments, especially when tillage practices or organic input are involved.

Finally, the pedoclimatic data from our study were compared with those of the JRC atlas, which includes non-arable areas due to soil or climatic constraints. Therefore, the gap observed between this study data and the atlas should be considered with caution. For example, although sandy soils and arid climates are widespread in Africa, they are underrepresented in studies because many of these soils correspond to deserts unsuitable for agriculture.

5. Conclusion

This study provides an overview of 155 studies investigating SOC dynamics using a diachronic approach in the Global South, excluding China, highlighting both the value and limitations of LTEs in these regions. Our results show that the positive effects of fertilization and conservation tillage practices on SOC stocks follow the same trends as those observed in other meta-analyses and in the Global North, mainly through increased carbon inputs linked to higher yields or the maintenance of cover crops. However, this synthesis reveals significant biases and gaps. LTEs are heavily concentrated in India and Brazil, countries with more developed research infrastructures, leading to an over-representation of agricultural models specific to these countries. Many widely practiced agricultural systems in the Global South, such as intercropping or slash-and-burn agriculture, are scarcely studied, as are non-agricultural land uses (forests, savannah pastures). Furthermore, the pedoclimatic distribution of LTEs does not fully represent the diversity of climatic and soil zones present in these regions, limiting the representativeness of results at the regional scale and constitute major blind spots for the calibration and validation of SOC dynamic models, as well as for understanding the real impacts of local practices. It is therefore essential to intensify and diversify research efforts by establishing LTEs that better reflect the agricultural practices implemented by local populations and cover underrepresented pedoclimatic contexts. This study has assembled an unprecedented data set that could also serve as a valuable resource for modellers aiming to improve SOC projections in the Global South.

CRediT authorship contribution statement

Tchodjowiè P.I. Kpemoua: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Issiakou A. Houssoukpevi:** Writing – review & editing, Investigation. **Kenji Fujisaki:** Writing – review & editing, Investigation. **Antoine Versini:** Writing – review & editing, Investigation. **Rémi Cardinael:** Writing – review & editing. **Pierre Barré:** Writing – review & editing, Investigation. **Tiphaine Chevallier:** Writing – review & editing, Investigation. **Julia Le Noë:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2026.e01101.

Data availability

Research Link Provided

Dataverse A database of long-term experiments on soil organic carbon dynamics in the Global South (Original data)

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