Geoderma 443 (2024) 116831

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Inorganic carbon is overlooked in global soil carbon research: A bibliometric analysis

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A R T I C L E I N F O

Handling Editor: C. Rumpel

Keywords:
Bibliometric analysis
Soil inorganic carbon
Soil organic carbon
Climate change
CO_2 emission
Carbon stocks
Carbon sequestration

A B S T R A C T

Soils are a major player in the global carbon (C) cycle and climate change by functioning as a sink or a source of atmospheric carbon dioxide (CO_2). The largest terrestrial C reservoir in soils comprises two main pools: organic (SOC) and inorganic C (SIC), each having distinct fates and functions but with a large disparity in global research attention. This study quantified global soil C research trends and the proportional focus on SOC and SIC pools based on a bibliometric analysis and raise the importance of SIC pools fully underrepresented in research, applications, and modeling. Studies on soil C pools started in 1905 and has produced over 47,000 publications (>1.7 million citations). Although the global C stocks down to 2 m depth are nearly the same for SOC and SIC, the research has dominantly examined SOC (>96 % of publications and citations) with a minimal share on SIC (<4%). Approximately 40 % of the soil C research was related to climate change. Despite poor coverage and publications, the climate change-related research impact (citations per document) of SIC studies was higher than that of SOC. Mineral associated organic carbon, machine learning, soil health, and biochar were the recent top trend topics for SOC research (2020–2023), whereas digital soil mapping, soil properties, soil acidification, and calcite were recent top trend topics for SIC. SOC research was contributed by 151 countries compared to 88 for SIC. As assessed by publications, soil C research was mainly concentrated in a few countries, with only 9 countries accounting for 70 % of the research. China and the USA were the major producers (45 %), collaborators (37 %), and funders of soil C research. SIC is a long-lived soil C pool with a turnover rate (leaching and recrystallization) of more than 1000 years in natural ecosystems, but intensive agricultural practices have accelerated SIC losses, making SIC an important player in global C cycle and climate change. The lack of attention and investment towards SIC research could jeopardize the ongoing efforts to mitigate climate change impacts to meet the 1.5–2.0 °C targets under the Paris Climate Agreement of 2015. This bibliographic study calls to expand the research focus on SIC and including SIC fluxes in C budgets and models, without which the representation of the global C cycle is incomplete.

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https://doi.org/10.1016/j.geoderma.2024.116831
Received 14 September 2023; Received in revised form 23 January 2024; Accepted 19 February 2024
Available online 29 February 2024

1. Introduction

Soils are the largest reservoir of terrestrial carbon (C) and comprise two distinct pools: soil organic C (SOC) and soil inorganic C (SIC). The estimated global SOC stock is 1500–1600 Pg (Pg = 10^{15} g) at 1 m depth and 2376–2456 Pg at 2 m depth (Fig. 1; Batjes, 1996; Monger and Gallegos, 2000; Lal, 2004a; Batjes and Sombroek, 1997). The wide range for SIC stock (695–1738 Pg at 1 m depth and 2255 Pg down to 2 m) (Fig. 1; Eswaran et al., 1995; Batjes, 1996) reflects uncertainties, due to lack of research on SIC. Importantly, even small changes in either the stocks and fluxes of both C pools can markedly impact the atmospheric carbon dioxide (CO_2) concentration, global warming, and the governmental ambitions to achieve the net zero under the Paris Climate Agreement (Nottingham et al., 2020).

Inorganic C as soil carbonate (2255 Pg C down to 2 m depth) and as bicarbonate in groundwater (1400 Pg C) together surpass SOC (2400 Pg C) as the largest terrestrial C pool (Fig. 1; Monger et al., 2015). The global SIC pool is primarily distributed across arid and semi-arid regions, accounting for 90 % of the total C stock in these regions (Filippi et al., 2021). Carbonate-containing soils account for approximately 50 % of the Earth's ice-free land area and approximately 9 billion hectares of arable land worldwide (Marschner, 1995; Lal, 2009). Generally, SOC and SIC are inversely related (Lal et al., 2021). In humid regions, SOC is higher than SIC. Arid regions account for an estimated 78 % of the global SIC, semiarid for 14 %, and humid regions less than 1 % (Eswaran et al., 2000).

Organic C is a vital component of healthy soils due to its crucial role in nutrient cycling, physical and chemical soil properties, as well as positive impact on microbial functions. This organic C is a major player in global climate change because of its dual roles as sink or source of atmospheric CO_2 depending on soil management, plant biomass input, land use, and climatic conditions. Extensive work over decades has deepened our understanding of the dynamics, turnover rate, sequestration potential, and the main processes of SOC losses and sequestration. Historically, soils have lost an estimated 40 to 116 Pg SOC through cultivation (Houghton, 1999; Houghton et al., 1999; Schimel, 1995; Lal, 1999; Sanderman et al., 2017), whereas land use change during the 1990 s alone emitted 1.6 ± 0.8 Pg C yr^{-1} CO_2 to the atmosphere from SOC mineralization (Schimel et al., 2001; IPCC, 2001).

As almost all cropped soils have lost a large portion (~25 %) of their pre-cultivation SOC (Lal, 2004b), global croplands may theoretically represent a large potential terrestrial sink for C by adopting efficient management practices or change back to (semi)natural ecosystems. SOC sequestration in a technically feasible manner can remove 0.8–1.5 Pg C yr^{-1} from the atmosphere (Fuss et al., 2018), indicating the substantial potential of SOC to offset anthropogenic climate forcing. Accordingly, several global initiatives have been launched to discuss and to increase SOC stocks as a potential solution to mitigate climate change: 4 per 1000 initiative (https://4p1000.org), RECSOIL (https://www.fao.org/global-soil-partnership/areas-of-work/recarbonization-of-global-soils), Koronivia joint work on agriculture (https://www.fao.org/koronivia), REDD + project (https://www.fao.org/redd/overview/en/), European Soil Strategy, and some others. Despite some well-known examples of SOC accumulation and C sequestration in long-term field experiments, soils around the world are continuously losing organic C and are likely to do so over the next few decades at minimum. Therefore, we do not see any real chance to fulfill the 4-per-1000 initiative (Van Groenigen et al., 2017; de Vries, 2018).

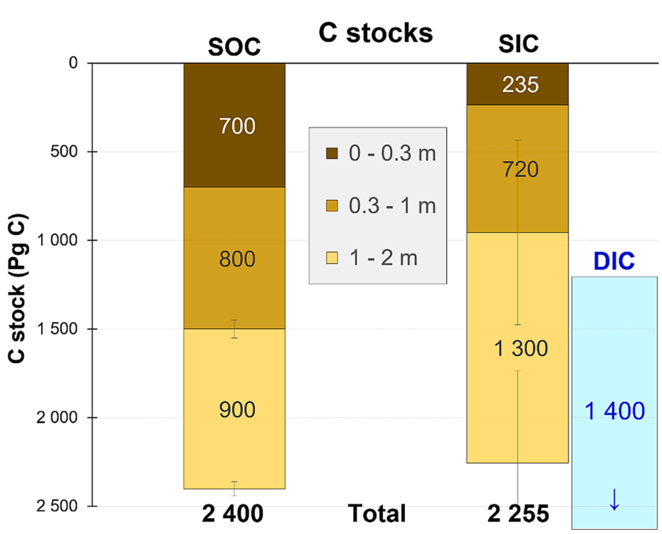

Fig. 1. The global soil organic (SOC) and inorganic carbon (SIC) stocks down to 2.0 m depth as well as dissolved inorganic carbon (DIC) (includes also inorganic C in groundwater). Whiskers: uncertainties of various estimations. Note that the DIC is not included in the common estimations of the SIC stocks, whereas dissolved organic carbon (DOC) is always included and therefore, DOC is not presented separately.

The SIC pool is larger than the atmospheric CO_2 pool or terrestrial plant biomass C. It is often assumed that SIC changes very slowly over geological time scales because its contribution to biological cycles is much lower than SOC (Schlesinger, 1985). Many recent studies, however, report that SIC is far from stable and can be vulnerable to land use changes and intensive crop production, soil acidification, and water flow and recharge – processes that can reduce and even deplete SIC stocks within a few decades (Khokhlova and Myakshina, 2018; Raza et al., 2020; Raza et al., 2021; Kim et al., 2020; Zamanian et al., 2018). Even SIC stocks deeper than 7 m are vulnerable to loss through agricultural practices (Kim et al., 2020). At a global scale, the dissolution of SIC by nitrogen (N) fertilization-induced acidification is releasing 7.5 Tg C yr^{-1} as CO_2 (Zamanian et al., 2018; Zamanian and Kuzyakov, 2019). Soil acidification is ameliorated by adding SIC as lime, which itself is considerable source of C losses of 270 Tg C yr^{-1} (Zamanian et al., 2018) and projected to reach 820 Tg C yr^{-1} in 2050 (Zamanian et al., 2021). A similar SIC amount may also be lost as bicarbonate ions from soils to the water system, representing a terrestrial-aquatic instead of terrestrial-atmospheric transfer. These SIC losses in the form of CO_2 emissions and bicarbonate ions (HCO_3^-) are irreversible losses, which cannot be fulfilled, if released Ca^{2+} is leached with e.g. NO_3^-. Therefore, SIC losses have irreversible and unpredictable implications for soil health, food security and climate amelioration (Wang et al., 2021; Raza et al., 2021). SIC stocks may increase solely in the presence of Ca^{2+} by CO_2 fixation leading to pedogenic carbonate formation, which can be more stable than newly sequestered SOC (Golubtsov et al., 2021; An et al., 2019; Dang et al., 2022; Liu et al., 2023). Oxalotrophic bacteria can also increase SIC stocks by producing carbonates during oxidation of ubiquitous oxalate through a process called oxalate-carbonate pathway (Syed et al., 2020; Rowley et al., 2017). Despite these processes are known *per se*, their relevance for SIC formation is completely unknown, but is probably of minor importance. Soil inorganic C is a major player in the global C cycle and climate change, whose contributions are mainly by releasing CO_2 in the atmosphere, that must be understood to achieve mitigation goals related to global land use and climate change.

There is a considerable disparity in the level of global research attention dedicated to SOC and SIC. Although several studies have generally indicated that SIC is an overlooked C pool, but it remains unclear how much specifically SIC is understudied in global soil C research. The differences in the contributions of SOC and SIC pools in global soil C research remain to be quantified.

The bibliometrics method has been widely applied to build knowledge atlases of soil and natural science research (Yan et al., 2022; Huang et al., 2020). Bibliometrics systematically reviews the relevant research history of specific scientific fields, conducts detailed analyses of research status, identifies research gaps, provides international cooperation networks between countries, institutions, and authors, and also detects future research directions in specific fields. This approach therefore offers benchmarking of research and can identify future research directions and opportunities for cross-discipline collaborations. We conducted a bibliometric analysis to answer four questions: (1) What are the historical changes in global research on soil C, and in the relative focus on SOC and SIC pools? (2) What proportion of SOC and SIC research is focused on climate change? (3) Which countries, institutions and funding agencies lead in SOC and SIC research? (4) What are the main research areas and topic trends for both C pools?

2. Materials and methods

2.1. Bibliometric analysis

A complete and robust overview of the progress in soil C pools research was quantified through bibliometric analysis of the data extracted from the Web of Science Core Collection. We are aware that papers published in early 20th century and in languages other than English may not be included in the Web of Science records. The analysis focused on comparing the research involving SOC and SIC pools, including research on climate change. For this purpose, the data search was divided into the four following categories (Fig. S1): (i) SOC research, (ii) SOC research focused on climate change, (iii) SIC research, and (iv) SIC research focused on climate change. Total soil C pools research was quantified as the sum of SOC and SIC research, and the total soil C research focused on climate change was calculated likewise. Climate change studies were identified as those that specifically examined greenhouse gas losses and C sequestration through all possible pathways. These studies were collectively referred to as "climate change studies.".

2.2. Developing queries and performing data search

The bibliometric search was performed using a combination of search terms considering all databases from the Web of Science® - Clarivate Analytics platform (https://webofknowledge.com/). The search terms consisted of rigorously identifying all possible keywords to ensure the maximum possible coverage of soil C research. The keywords were connected with Boolean Operators to build a query, which was finally used for the search in the database. An independent query was used for each data search, and a total of four queries were built (details about all queries are available in Supplementary Material).

For all queries, the search was performed within the "Topic Field," which includes the "Title," "Abstract," and "Keywords Plus®" of each record. The soil C studies were characterized through publication trends, citation rates, and the number of citations publication^{-1}. The data search for all the queries was performed on 13 January 2024. Full records of the data were downloaded as plain text files from the Web of Science Core Collection. The individual files were combined together through Biblioshiny, a graphical user interface (GUI) tool integrated with the Bibliometrix package in R (Aria & Cuccurullo, 2017).

2.3. Quality checks to remove unnecessary records

The bibliometric data were screened using four quality checks to isolate relevant publications (Fig. S2): (i) duplicates removal: we identified several duplicate publications, which were removed after verification based on title, abstract, and author names; (ii) language filter: this study focused only on English language publications, and publications in other languages were removed, (iii) year 2024: publications for 2024 were removed, (iv) publication types: only those publications such as article, proceedings paper, review article, early access and data paper were retained, because these are commonly considered as primary research or scholarly works. All other publication types such as book chapter, retracted publication (withdrawn due to errors or misconduct), book, correction (errata/corrigenda to previously published articles), editorial material (opinion pieces), letter (short communications), abstract (usually not complete research), news item (non-scholarly news reports), and note (brief communications) were removed as they many not represent original research or meet the inclusion criteria for this study. After exclusion of all filtered publications, the remaining publications were exported in BIB, CSV, and RIS formats for further analysis. The same procedure was adopted for all four queries, details of which are available in Supplementary Material. A total of 47,899 publications were finalized for analysis.

2.4. Data analysis and visualization

Initial data were processed by using the 'Analyzing Results' tool from the Web of Science® platform. However, in-depth data analysis was performed through Biblioshiny with help from MS Excel, MS Access, Power BI, BiblioAnalytics, and an online visualization platform (https://flourish.studio/). Biblioshiny provides an interactive and user-friendly interface for performing bibliometric analysis using the functionalities offered by the Bibliometrix package. Bibliometrix provides a comprehensive set of functions and methods for extracting, analyzing, and visualizing bibliometric data. VOSviewer is a freely available software that is used to create bibliometric maps. These maps allow a visual assessment of collaboration networks (e.g., countries, institutions, and authors) and help to identify research fields or topics that have received most attention from researchers (e.g., most used author-selected keywords) (Romanelli et al., 2018). The global maps showing research productivity by countries were prepared in ArcMap.

2.5. Calculations

The contributions of countries, institutions, and funding agencies to global C research were analyzed for their focus on SOC versus SIC pools. Research collaboration among countries, main research areas, relationship between research topics, topic trends, and the thematic evolution of keywords were also assessed. The annual and the total publications for SOC and SIC pools were calculated by adding up all the publications for each year and across all years, respectively. The research productivity of countries and institutions was calculated based on the affiliations of the authors in the papers. In cases where a paper has authors from multiple countries, or an author has multiple affiliations, one publication was counted for each author's affiliated country. Similarly, all the funding agencies acknowledged in the paper was credited with one publication. If a paper has measured both organic and inorganic C, one publication was counted for both SOC and SIC pools. The collaboration between countries was quantified based on the affiliations of a paper comprising two or more authors from different countries. For instance, a paper has 3 authors from three countries, one paper was counted as collaboration for each pair of countries.

3. Results

3.1. Historical changes in global C research and the contributions of SOC and SIC pools

The (known) published research on soil C started in 1905 with the first English-language publication on SIC, and the first SOC publication following six years later in 1911. Between 1905 and 2023 a total of 47,899 papers were published on soil C pools (SOC, SIC) (Fig. S3), with a dominating (96 %) share by SOC relative to SIC (<4%). The average annual SOC publication rate remained at < 6 publications yr^{-1} until 1990, followed by a strong shift in SOC research afterwards (Fig. 2). Out of 46,080 SOC publications, 64 % were published within the last decade (2014–2023). Over the course of 119 years (1905–2023), only 1819 SIC papers were published, with only 48 out of those being published until 1990 (0.5 publications yr^{-1}). SIC publications in the last decade (2014–2023) increased by 74 % compared to the previous decade (2004–2013). However, this increase in SIC publications is still only half the rate at which SOC publications increased (163 %) during the similar time period.

Soil C studies had > 1,780,000 citations during 1905–2023 (Fig. S2). The temporal distribution of citations followed the same trend as that of publications, initially very low (<3%) during 1905–1990 (citations: 49,481, citation rate: 575 yr^{-1}) and increasing exponentially during 1991–2023 (citations: > 1,732,000, citation rate: 52,501 yr^{-1}) (Fig. 2). SOC studies contributed 96 % of the total citations, with only a 4 % share

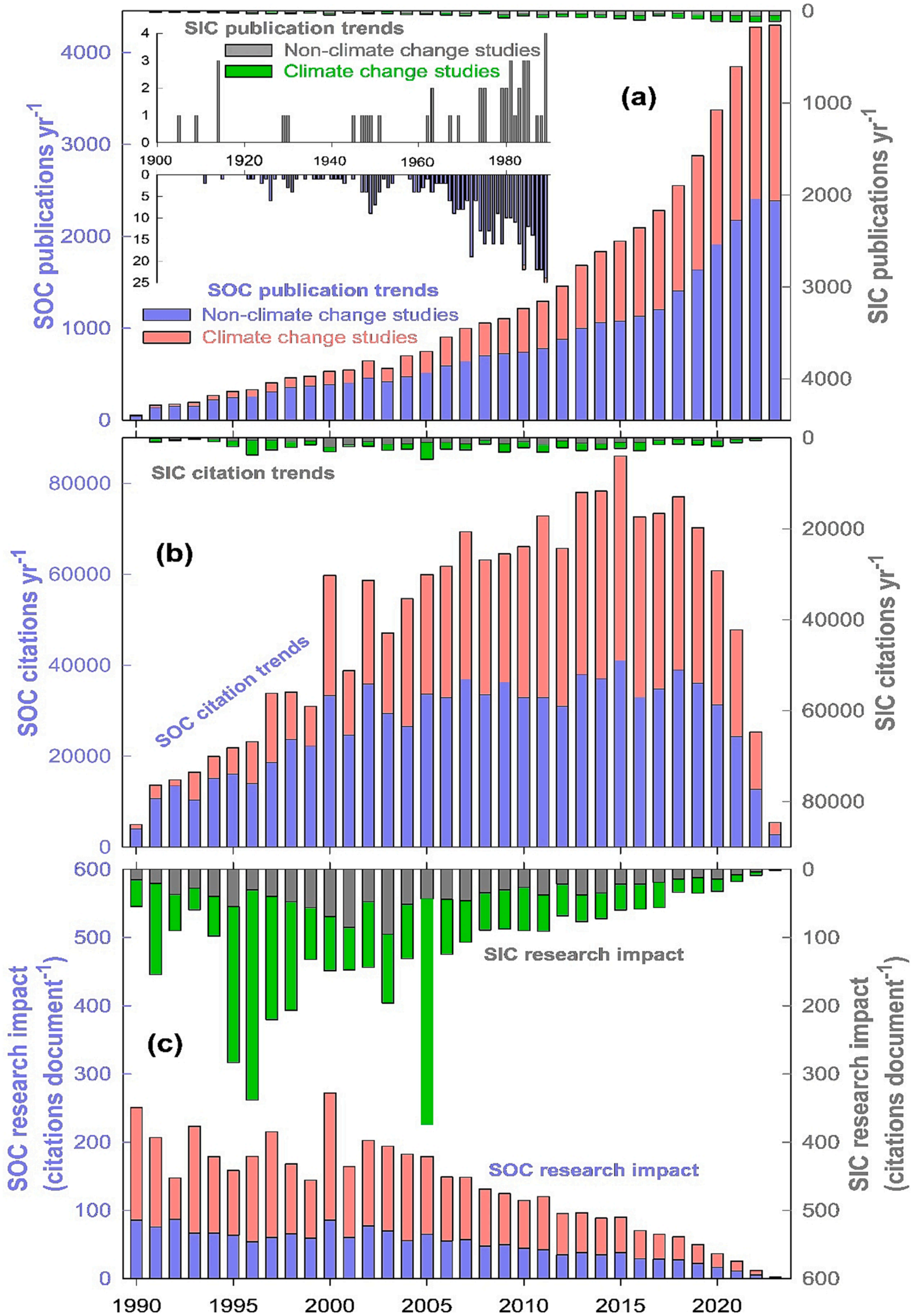

Fig. 2. Historical changes in the global C research (1905–2021) publications (a), citations (b), and research impact (c) by SOC (blue and red bars) and SIC (grey and green bars) pools. The subfigures within the panel (a) show publication trends from 1905 to 1989. Light red and green colors on top of vertical stacked bars: SOC and SIC publications and citations related to climate change. Blue and grey colored section of the bars: non-climate change publications and citations. Note that the fewer citations in recent years is because of the short time frame for newer publications to accumulate citations.

by SIC. The total SIC citations were 69,275, with only 4 % cited during 1905–1990 and 96 % during 1991–2023. The average citation rate was 2211 yr^{-1} during 1994–2003, increasing by 22 % during 2004–2013 but most recently decreasing by 42 % in 2014–2023 (Fig. 2).

The annual average research impact (RI = citations/publications) for SOC was 159 citations $publication^{-1}$, over 6-fold greater than the 25 citations $publication^{-1}$ for SIC during 1905–2023 (Fig. 2). Importantly, the substantially higher SOC RI was due to one methodological paper (Walkley & Black, 1934) that was cited 13,388 times. Excluding this paper, the research impact for SOC was 41 $publication^{-1}$. The research impact during 1994–2003 was high (SOC: 79 citations $publication^{-1}$, SIC: 82 citations $publication^{-1}$) and decreased by approximately 21–33 % during 2004–2013, followed by a substantial decrease of more than 61 % in the last decade (2014–2023; SOC: 25 citations $publication^{-1}$, SIC: 19 citations $publication^{-1}$). The decline in recent citations reflects the time lag in citations accumulating for newly published papers.

3.2. Global trends in soil C research focusing on climate change

The research on SOC and SIC in relation to climate change started in 1984 and 1990, respectively (Fig. 2). Soil C research on climate change has produced a total of 19,008 publications, which constitutes 40 % of the total global soil C research, with a 96 % contribution (18,204 publications) by SOC, but 4 % by SIC (804 publications). The growth in SOC-climate change research had a slow start with on average less than 50 publications yr^{-1} during 1984–2001, increased to 294 publications yr^{-1} by 2010, and in the last decade exceeded 1200 publications yr^{-1} (2014–2023). The SIC-climate change relationship received far less attention, averaging 9 publications yr^{-1} for nearly two decades (1990–2007). The publication rate increased slightly in the later years, with 47 publications yr^{-1} published in the last decade (2014–2023).

Soil C studies related to climate change were cited > 809,000 times during 1984–2023 (Fig. 2), making up about 45 % of the total combined citations by both C pools. Over 95 % of these citations were contributed by SOC-climate change studies, with less than a 5 % share by SIC-climate change studies. The average citation rate during 1984–2003 for SOC was 7310 citations yr^{-1}, which increased approximately 3-fold in the next decade (2004–2013) but decreased by 5 % in the current decade (2014–2023) (Fig. 2). The average citation rate for SIC studies was 937 yr^{-1} during 1990–2003 and increased by 69 % in the next decade, followed by a 43 % decrease in the last decade (2014–2023).

The average RI of soil C studies focused on climate change studies was 23 % higher than studies focused on other topics. Notably, the RI of SIC-climate change studies was 6 % higher than SOC-climate change studies, and 291 % higher than non-climate change SIC studies during 1990–2023. The RI for SOC-climate change studies was 51 % higher than SOC non-climate change studies during 1984–2023.

3.3. Contribution of countries to SOC and SIC research

Global soil C research is concentrated in a few countries, with only 9 countries publishing 70 % of soil C research (Fig. 3). China and the USA combined have produced 45 % of the global soil C research, with a 27 % (39,087 publications) share from China and 18 % from USA (25,685 publications). Germany (6 %), Australia (4 %), India (4 %), Brazil (4 %), France (3 %), United Kingdom (3 %), and Canada (3 %) are secondary contributors. The same countries contributed the most in citations, with major contributions from USA (30 %), China (17 %), and Germany (8 %). Studies from Netherlands and the USA had the highest RI (20 citations $publication^{-1}$), followed by the United Kingdom, Germany, Denmark, and Israel. Mostly, similar countries contributed the most for SOC and SOC-climate change studies (Fig. 3, Fig. S4; S5).

The USA was the leader in SIC research, producing 31 % of publications and 51 % of citations, followed by China (21 % publications), Germany (5 % publications), United Kingdom (4 % publications), and India (4 % publications) (Fig. 3). The RI of SIC studies was highest for

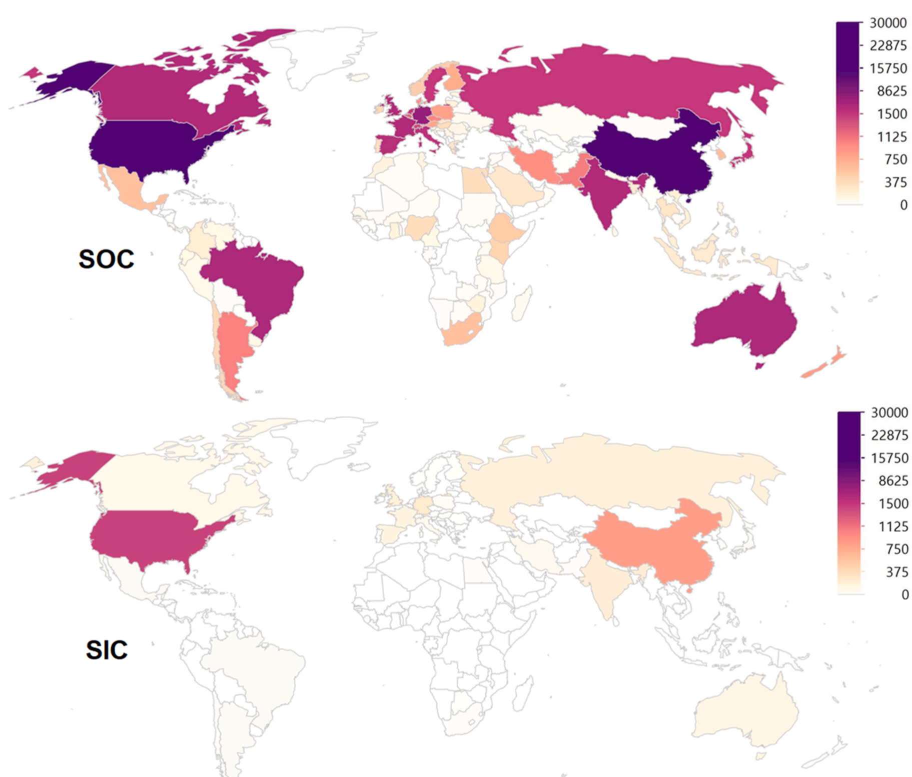

Fig. 3. Contributions of countries to SOC (top) and SIC (bottom) publications. The numbers on the scales represent the number of publications by each country. United States and China contributed the most in publications.

The Netherlands (75 citations publication^{-1}, and this despite very low SIC containing soils there), Israel, Greece, New Zealand, and the USA (Fig. 4). China and the USA combined contributed 60 % of the SIC-climate change research and 68 % of citations, and The Netherlands was at the top for RI (122 citations publication^{-1}) (Fig. S4; S5).

3.4. Collaboration among countries for SOC and SIC research

The degree of collaboration among countries for SOC research far exceeded that of SIC research (Fig. 5). Each of the top 12 collaborative countries collaborated with more than 80 countries for SOC research, while the leading country (USA) in SIC research collaborated with 58 countries. China and the USA produced 36 % of the global collaborative research for SOC and 48 % for SIC and were also the top collaborative countries for research focused on climate change (Fig. S6). Germany, France, and the United Kingdom were also among the top 5 collaborative countries for soil C research.

3.5. Contribution of global institutions in SOC and SIC research

More than 4500 institutions participated in SOC research, with 15 % of publications and 14% of citations produced by 10 institutions (Table 1). Institutions from the USA and China were the leaders for SOC and SIC research focused on climate change (Table S1), and the Chinese Academy of Sciences alone contributed 6 % of global SOC research. The research impact of SOC studies was greatest for institutions from the USA. The number of institutions involved in SIC research was 3.6-fold less than that in SOC. The top 10 SIC research producing institutions contributed 13 % of global publications and 15 % of citations, with 4 % publications alone from the Chinese Academy of Sciences (Table 1). Five of the top 10 institutions were from the USA and had a higher research impact (65 citations publication^{-1}) than other countries (21 citations publication^{-1}).

3.6. Top funding agencies leading SOC and SIC research

Global SOC research was funded by more than 20,000 agencies, and a major share in publications (31 %) and citations (38 %) was contributed by the top 10 funding agencies (Table 2). Seven out of the top 10 funders were from China and the USA. The National Natural Science Foundation of China produced 11 % of global SOC research, whereas the National Science Foundation of the USA contributed 5 % of SOC research but had greatest research impact (80 citations publication^{-1}). We found similar trends for SOC-climate change research (Table S2). SIC research was supported by approximately 1000 reported funders, about 20-fold less than for SOC. About 40 % of SIC research and 50 % of citations were contributed by the top 10 funding agencies (Table 2). Funding agencies from China and the USA dominated in supporting SIC research. The National Science Foundation of the USA funded the greatest number of publications and citations, whereas the studies funded by the UK's National Environment Research Council had the greatest research impact. SIC research focused on climate change was also dominantly funded by China and the USA (Table S2).

4. SOC and SIC major research topics, emerging research trends, and their evolution

4.1. Research topics analysis based on keywords

Global SOC and SIC research were highlighted by ~ 45,000 and ~ 3000 keywords, respectively (Fig. 6). Soil organic carbon and soil organic matter were the most dominant keywords used for SOC research, followed by carbon sequestration, climate change, and soil. All the keywords covered the main drivers and processes causing changes in SOC dynamics in the environment, starting from management practices such as tillage, land use, and fertilization; to negative consequences such as CO_2 emissions, global warming, soil erosion; and benefits such as climate change mitigation by increases in C sequestration through

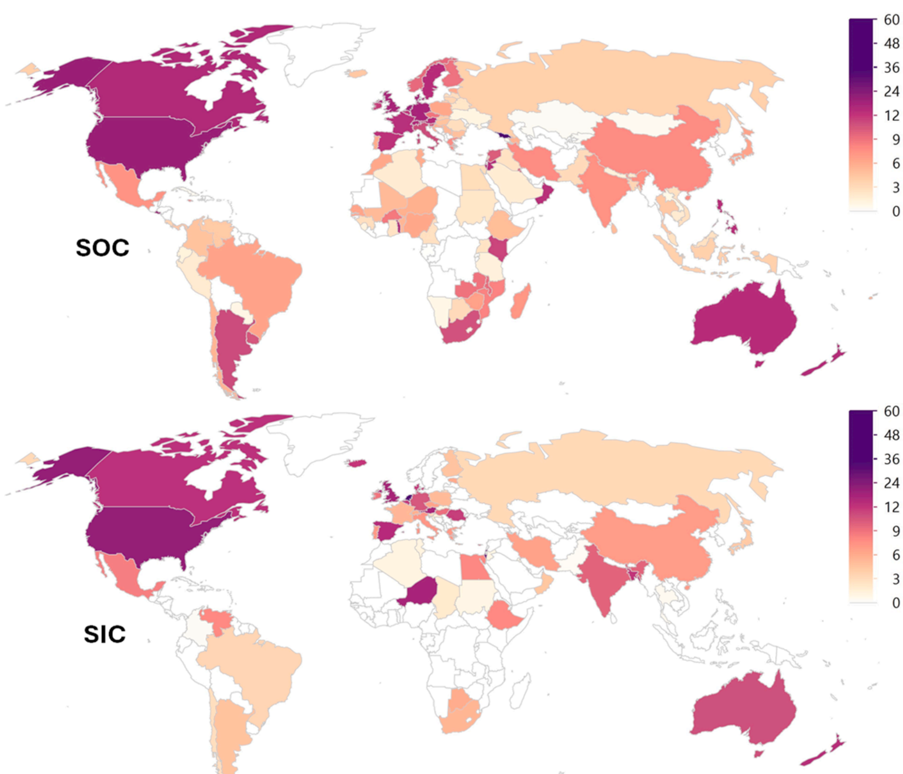

Fig. 4. Research impact (number of citations per paper) of SOC (top) and SIC (bottom) publications by countries.

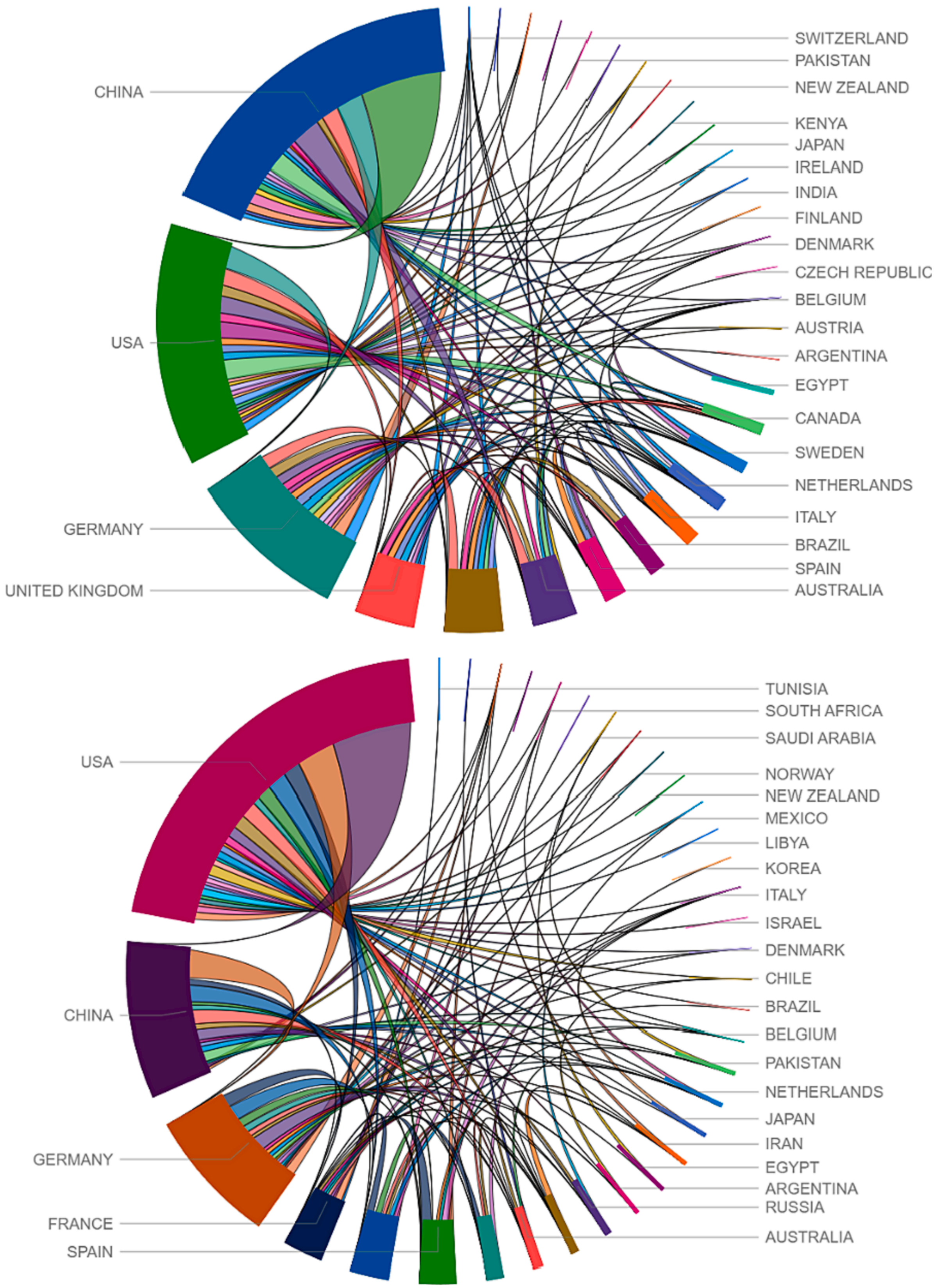

Fig. 5. Global share in collaboration by countries for SOC (top) and SIC (bottom) research. The figure shows results for the top 100 collaborations between countries that has produced maximum publications.

Table 1
Top institutions by publication productivity for soil organic (SOC) and inorganic carbon (SIC) research.

SOC Research Trends Institution	Country	FPY*	TP*	TC*	RI*
Chinese Academy of Sciences	China	1992	9813	276,125	28
United States Department of Agriculture	USA	1981	2406	140,171	58
University of Chinese Academy of Sciences	China	2002	2149	53,649	25
Indian Council of Agricultural Research	India	1974	1975	37,424	19
INRAE	France	1988	1776	94,348	53
Northwest A&F University	China	2002	1536	39,416	26
University of California System	USA	1977	1445	128,636	89
Centre National De La Recherche Scientifique	France	1986	1442	74,268	52
United States Department of Energy	USA	1990	1218	83,383	68
Ministry of Agriculture & Rural Affairs	China	2005	1131	25,070	22
SIC Research Trends Institution	**Country**	**FPY**	**TP**	**TC**	**RI**
Chinese Academy of Sciences	China	1996	299	8462	28
University of California System	USA	1979	117	8128	69
Russian Academy of Sciences	Russia	1998	92	1033	11
Centre National De La Recherche Scientifique	France	1994	76	1952	26
Northwest A&F University	China	1996	59	1354	23
University of Chinese Academy of Sciences	China	2006	55	1025	19
University of Arizona	USA	1979	51	3641	71
United States Department of Agriculture	USA	1993	51	1788	35
University of Texas System	USA	1996	50	1216	24
University System of Ohio	USA	1994	49	6177	126

[*] FPY: First publication year, TP: Total publications, TC: Total citations, RI: Research impact.

Table 2
Top funding agencies in soil organic (SOC) and inorganic carbon (SIC) publication productivity.

Funding Agency	SOC Research Trends Country	FPY*	TP*	TC*	RI*
National Natural Science Foundation	China	2006	8755	207,882	24
National Science Foundation	USA	2005	3847	308,318	80
Chinese Academy of Sciences	China	2008	2995	98,479	33
National Key Research & Development Program	China	2009	2664	54,151	20
United States Department of Agriculture	USA	2006	1607	61,863	38
Department of Energy	USA	2008	1251	85,811	69
Natural Environment Research Council	UK	2005	1002	55,829	56
German Research Foundation	Germany	2008	910	33,598	37
National Basic Research Program	China	2008	887	38,309	43
European Union	Europe	2007	757	35,759	47
Funding Agency	**SIC Research Trends Country**	**FPY**	**TP**	**TC**	**RI**
National Science Foundation	USA	1990	489	19,718	40
National Natural Science Foundation	China	2008	288	6786	24
Chinese Academy of Sciences	China	2009	82	2871	35
National Key Research & Development Program	China	2014	65	1176	18
Natural Environment Research Council	UK	2007	52	2620	50
German Research Foundation	Germany	2009	49	1581	32
National Basic Research Program	China	2008	48	2039	42
Geological Society of America	USA	2008	40	1560	39
Russian Foundation for Basic Research	Russia	2010	29	324	11
Fundamental Research Funds for Central Universities	China	2014	26	487	19

FPY: First publication year, TP: Total publications, TC: Total citations, RI: Research impact.

biochar, afforestation, and changes in microbial composition and activity. The most frequently used keywords for SIC research were pedogenic carbonate, soil organic carbon, stable isotopes, paleoclimate, carbon isotopes, and carbon sequestration.

We analyzed the relationship among keywords through a structural map, which distributes the keywords in two dimensions and keywords with greater similarity were clustered together (Fig. 7). Clusters indicated three main topics for SOC research: (i) nutrients (N, P), (ii) agricultural practices (fertilization, crop) and soil conditions (aggregates, moisture, quality) effects on SOC, climate change and C sequestration, (iii) changes in heavy metals and humic substances through mineralization and sorption. SIC research was also clustered into three main topics: (i) soil carbon storage and sequestration and their linkages with pH and acidification, (ii) weathering, carbon isotopes, and pedogenic carbonate and their linkages with climate and organic matter, (iv) paleoelevation and paleoaltimetry relationship with oxygen and clumped isotopes. A similar distribution of keywords was determined for soil C studies focused on climate change (Fig. S7).

4.2. Soil C pools trend topics and thematic evolution of keywords with time

The timeline visualization regarding the trend topics of SOC research showed strong changes over time (Fig. 8). The top SOC research topics during 2011–2017 were sorption, mineralization, nitrogen, organic matter, and carbon cycle. The recent (2017–2023) trend topics are C sequestration, soil properties, biochar, machine learning, and mineral-associated organic C. SIC trend topics were loess, paleosol, carbon isotopes, paleoelevation, and pedogenic carbonate during 2011–2016, and most recently focused on weathering, calcite, acidification, soil properties and digital soil mapping.

5. Discussion

5.1. Global soil carbon research and contributions by countries

Global C research has accelerated and expanded greatly over the years, with strong increases in the number of publications, citations, and their impact (citations publication^{-1}), especially since 1990 (Fig. 2). The large interest in soil C research globally is driven by its strong linkages with multiple challenges the world is facing such as food security, soil health, and climate change. Global soil C research is led by a handful of countries, with 9 countries publishing 70 % of soil C research (Fig. 3). The top contributors are China, USA, Germany, Australia, Brazil, France, India, Canada, and United Kingdom (Fig. 3). Most of these countries are economically strong and have a large network of well-established universities and research institutions nationwide and worldwide. This facilitates knowledge sharing, joint research projects, and cross-fertilization of ideas, further propelling research efforts. Additionally, these countries have large land area comprising diverse ecosystems and soil types, thus providing scientists with a rich research landscape for studying C dynamics depending on soil and climate conditions, as well as land use. However, the heavy reliance on only a few nations creates an imbalance in knowledge dissemination and technological advancements, leading to a lack of understanding of local problems in various regions. This calls for encouraging contributions in soil C research from all countries to effectively mitigate carbon-related climate crisis and develop local solutions.

Approximately 40 % of published research on soil C focused on climate change and such studies had a greater RI (citations publication^{-1}) than studies focusing on non-climate change issues (Fig. 2). The RI for SOC-climate change studies was 51 % greater than SOC non-climate change studies during 1984–2023. The RI for SIC-climate change

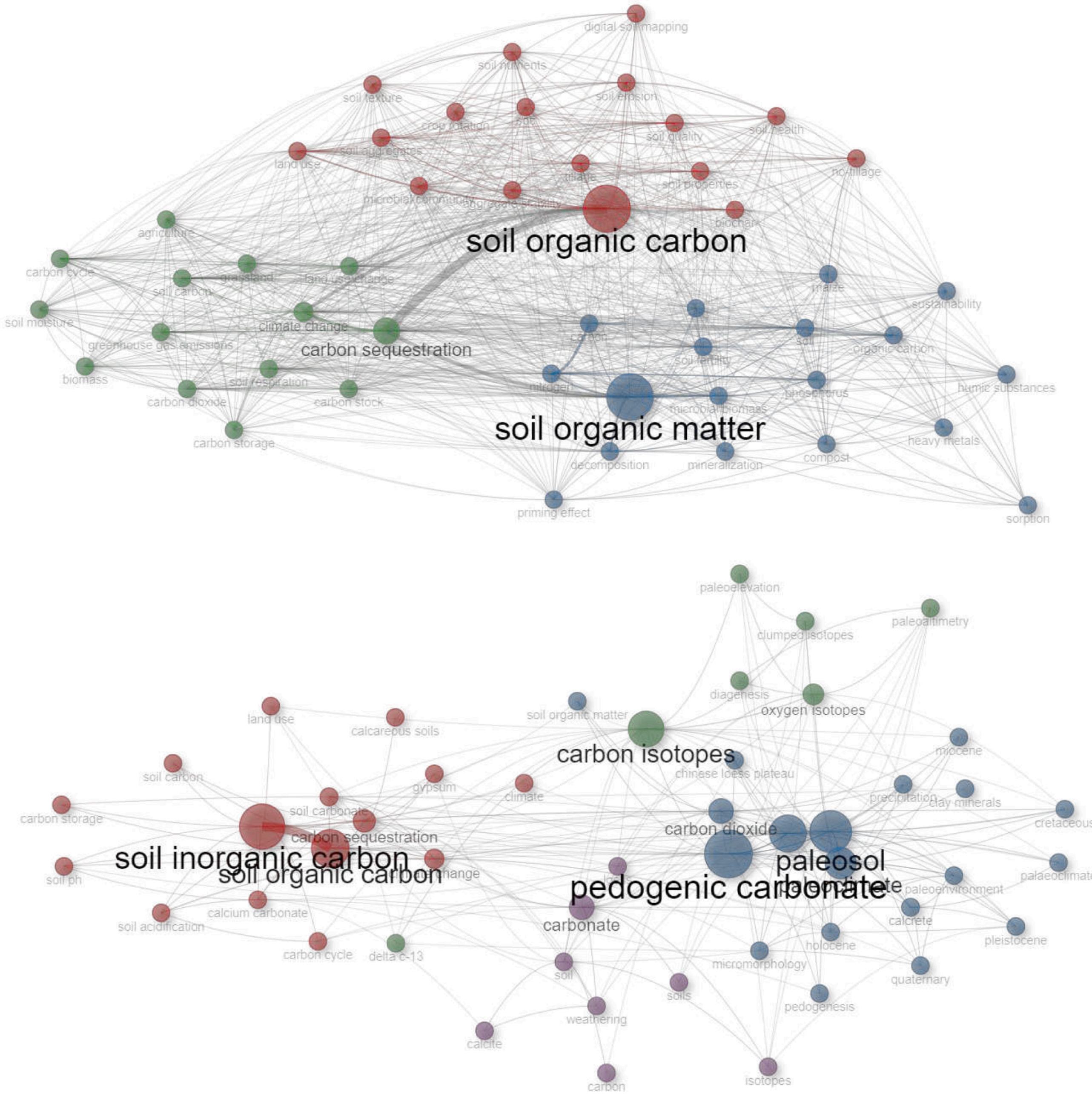

Fig. 6. Co-occurrence network of the most frequently used keywords to represent SOC (top) and SIC (bottom) research. Only the top 50 keywords are shown in the figure. The greater size of the text and of circles indicates keywords with a higher frequency of usage.

studies was 291 % higher than SIC non-climate change studies (1990–2023). The increasing focus of soil C studies on climate change is driven by the immense potential soils possess for both accelerating and mitigating climate change. The C losses from soils extend beyond national boundaries due to the long-range transport and global distribution of greenhouse gases. This means that all countries will face the consequences of global warming and air pollution regardless of individual emissions – which is why climate change is a uniquely global issue. Since soil C stocks and their drivers varies between countries due to variable soil types and environmental conditions, the trade-offs on soil C can strongly differ for an individual country (Scharlemann et al., 2014). Effectively reducing soil CO_2 emissions and increasing C sequestration at a global scale therefore require a site- and country-specific management of C fluxes. This, in turn, demands investment into soil C research by each country (Carlson et al., 2017). Additionally, the individual contributions of soil C trade-offs by each country can be summarized to build an accurate global C cycle map, which can guide policymakers and researchers on developing region-specific policies for climate-smart agriculture. This underscores the importance of further expansion in the international cooperation and collaboration on soil C research in addressing the challenges of climate change. The exploration of C sequestration in soils as a potential solution to mitigate greenhouse gas emissions is widely recognized and several global initiatives have been launched to support the increase of soil C stocks, with a predominant focus on SOC (Rumpel et al., 2018; Jungkunst et al., 2022).

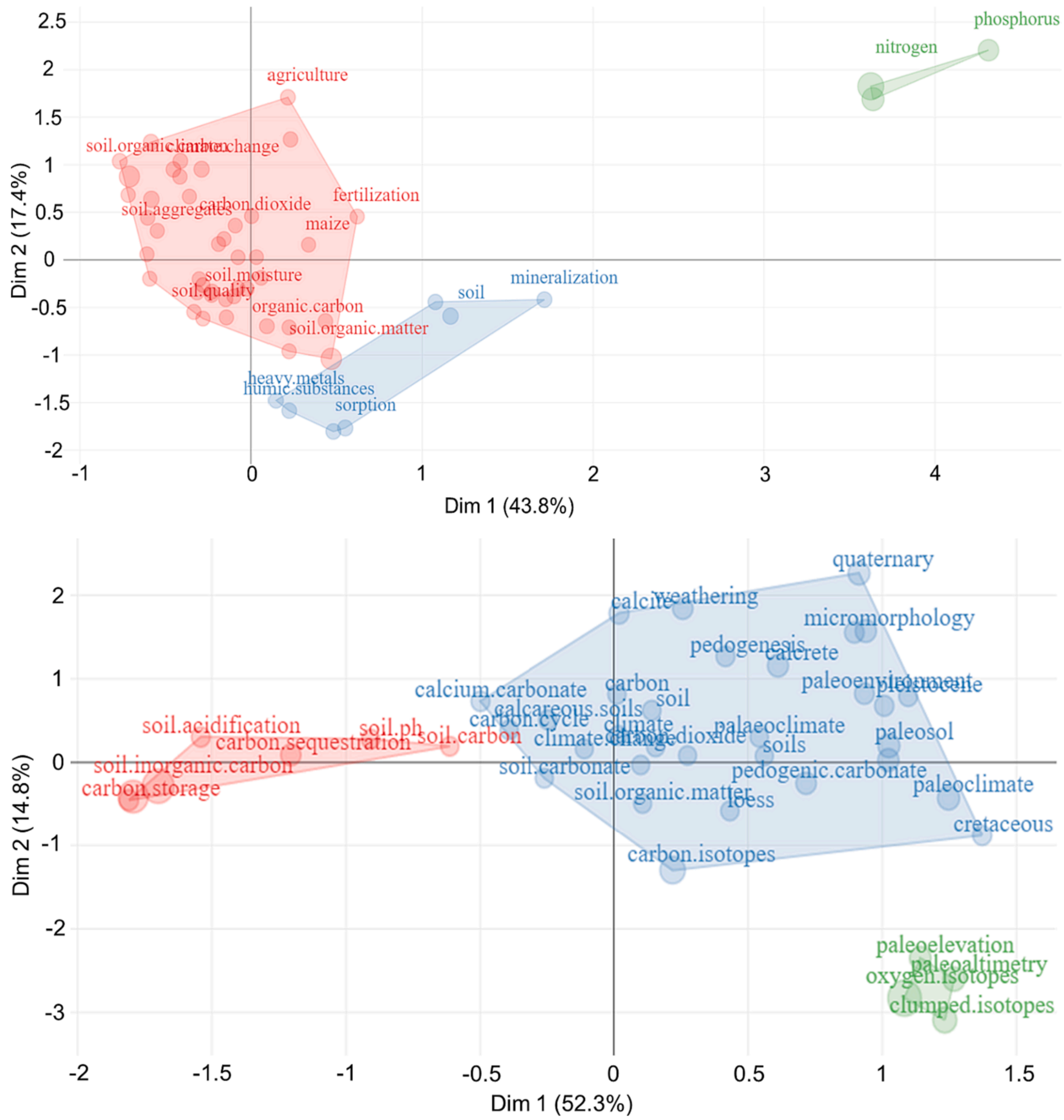

Fig. 7. Conceptual structural map with two dimensions showing the distribution of keywords for SOC (top) and SIC (bottom) research. Keywords with greater similarity are closer in proximity.

5.2. *Soil organic versus inorganic carbon research dynamics*

Global C research has largely prioritized SOC (96 % publications) with a minimal focus on SIC (4 %) (Fig. 2; Fig. S2). SOC draws global attention because it is considered to be a responsive C pool driving C fluxes within a short period and responds rapidly to agricultural practices and land use changes. SOC research has advanced on many fronts, particularly compared with SIC: (i) our understanding of global SOC stocks and their potential to mitigate climate change has greatly improved (Fu et al., 2021; Smith, 2012), (ii) knowledge of the factors governing belowground C processes such as root C input (Pausch and Kuzyakov, 2018), microbial and enzyme activities, the composition of SOC pools and their contribution to C losses and sequestration has increased (Liu and Greaver, 2010), (iii) SOC trade-offs under changing climatic scenarios, soil types, and agricultural management practices have been evaluated (Munoz-Rojas et al., 2013; Jiang et al., 2014; Khoklova and Myakshina, 2018), (iv) progress on applying remote sensing as a tool to quickly monitor SOC stocks in the topsoil on large scale has increased, although much remains to be done to establish its efficacy (Angelopoulou et al., 2019), and (v) several models have been developed to estimate and/or predict SOC fluxes under a variety of soil, vegetation, and climatic conditions (Campbell and Paustian, 2015). Looking ahead, SOC research is projected to increase, which is expected to propel global research to new heights, leading to advancements and innovations to understand and address complex soil and climate issues associated with SOC.

The SIC pool – which is approximately three times larger than the atmospheric C pool, i.e., CO_2 –is an overlooked player in the C cycle over human lifetime scales. That C pool has drawn limited attention from the scientific community, with only a 4 % contribution to global soil C research (Fig. S2). Even with few publications, the research impact of SIC studies was higher than that of SOC by 7 % for climate change research (Fig. S2). The negligible research attention on SIC is mainly based on the old assumption that it is stable, with a mean residence time of millennia, and less sensitive to agricultural practices and land use changes at least within the human timescale (Sanderman, 2012). SIC stability is considered to extend up to or over 85,000 years, and its turnover rate is considered to be 70- to 400-fold lower compared to that of SOC (Schlesinger, 1985; Bughio et al., 2016; Kuzyakov et al., 2006). SIC exchange with the atmosphere was estimated at approximately 1.0–5.0 g C m^{-2} yr^{-1} in desert soils (Schlesinger and Bernhardt, 2013). Based on these estimates it was believed that SIC plays a limited role in

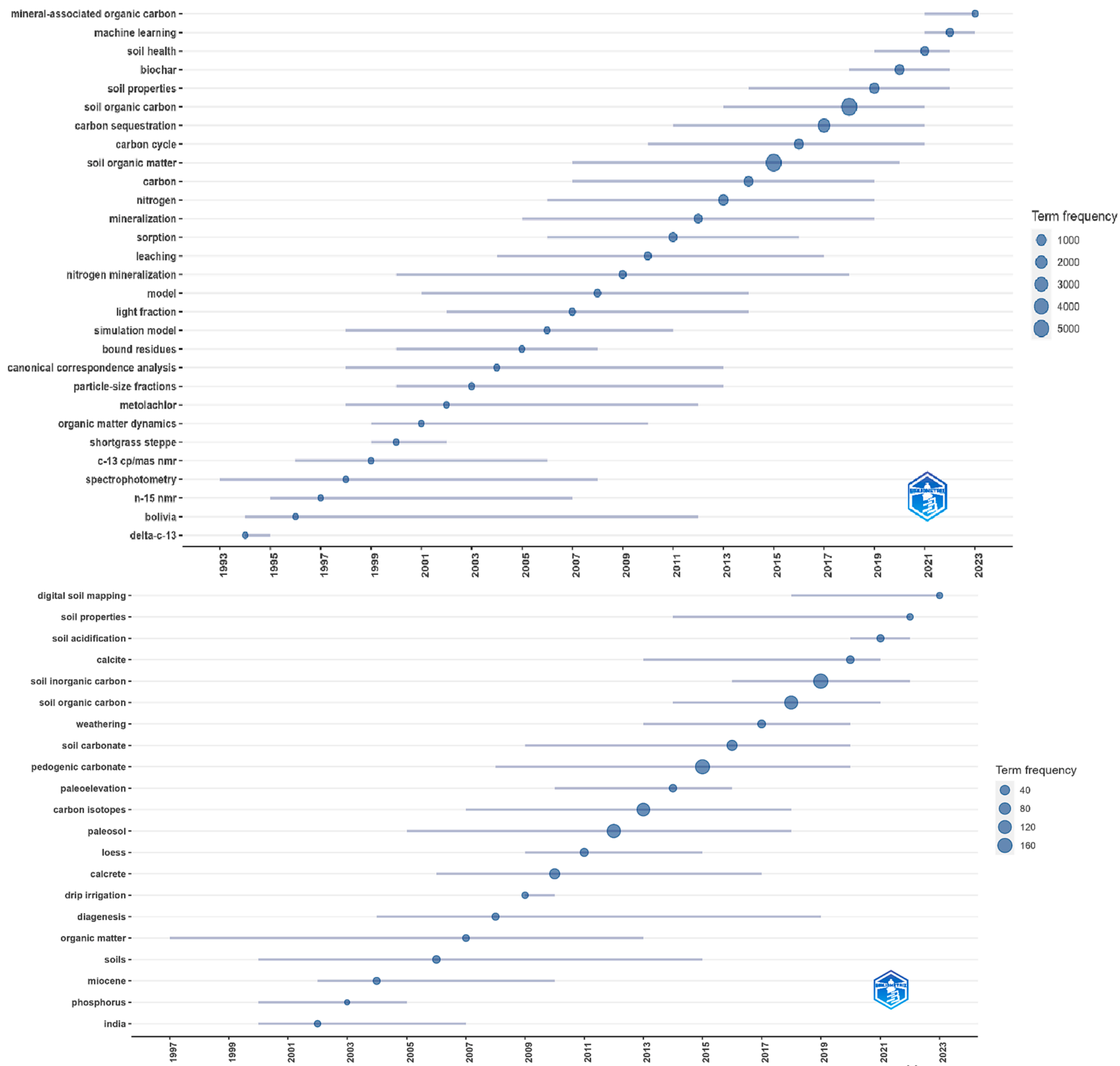

Fig. 8. Trends in the topics of SOC (top) and SIC (bottom) research. The graph illustrates clusters of the publications related to SOC and SIC research from left to right and the publication years at the bottom. The graph arranges the topics vertically, highlighting the most recent at the top and the oldest at the bottom.

the global C cycle and, consequently, the contributions of SIC to climate change and C sequestration were disregarded. However, this high SIC stability and the assumed negligible contribution of SIC to the global C cycle is true only in natural ecosystems and for fully developed soils – in which the SIC stock is at a steady state equilibrium. Rhizosphere acidification leads to carbonate dissolution and recrystallization of carbonate-containing soil parent material (Kuzyakov et al., 2006) as well as to partial leaching losses of Ca^{2+} and to CO_2 emissions (Gocke et al., 2012). This situation is strongly accelerated under intensive crop production, particularly under high N fertilization (Raza et al., 2021).

Intensive agricultural practices of fertilization and irrigation, along with land use changes, can strongly change inorganic C stocks within years or decades (not millennia). Soil acidification driven by high N fertilization has decreased inorganic C stocks within years at global and regional scales (Zamanian et al., 2018; Raza et al., 2020). In the longest continuous field experiment in the world, established in 1843 at Rothamsted, United Kingdom (Bolton, 1972; Poulton, 1996), the topsoil originally contained approximately 5 % carbonate (0.6 % carbonate-C) and had a pH value of approximately 8. By the 1940 s, $CaCO_3$ was entirely lost from N-fertilized plots, which was then followed by a rapid decline in pH value.

Inorganic C losses are also accelerated by a positive water balance (precipitation > potential evapotranspiration), leading to a shift of surface SIC either at depth or to other areas through runoff and erosion. Inorganic C losses from cultivated soils can be up to 10-fold more rapid than those from soils not under cultivation, mainly because cultivated soils are fertilized and irrigated, which accelerates SIC losses through carbonate dissolution and Ca^{2+} leaching (Magaritz and Amiel, 1981). SOC exchanges with the atmosphere occur cyclically, and its contents can increase through effective management practices (Raza et al., 2021).

Once lost, however, SIC stocks cannot recover within the human lifetime scale because the formation of pedogenic carbonate requires the availability of cations such as Ca^{2+} and Mg^{2+} combining with bicarbonate ions (HCO_3^-) under favorable climatic conditions (precipitation < potential evapotranspiration) (An et al., 2019; Dang et al., 2022; Liu et al., 2023). This makes SIC an irrecoverable C source (Zamanian et al., 2021). Like SOC, there is a need for research to recognize the contributions and feedback of SIC, without which any progress in achieving mitigation goals of global climate changes might be slower. Understanding SIC dynamics depending on different land- systems and evolving climate scenarios including local temperature and precipitation patterns is crucial for developing sustainable C management strategies. The integration of techniques like the use of models, artificial intelligence, machine learning, hyperspectral and computed tomography X-ray imaging, and remote sensing will advance our understanding of SIC dynamics from small scale at the aggregate level to large-scale at country, continent, and global level.

6. Conclusions

Soil C research has been predominantly focused on SOC, with minimal attention given to SIC. Contributions from countries, institutions and funding agencies, as well as collaboration among countries for SIC research was much lower than for SOC. More than half of the documented soil C research (64 % SOC, 51 % SIC) was published only in the last decade (2014–2023). A notable 40 % share of soil C publications was dedicated to investigating the implications of soil C in the context of climate change. Despite limited contributions, studies on the impact of SIC on climate change have had a research impact (citations per publication) that is 6 % higher than that of SOC. Neglecting SIC precludes a comprehensive understanding of the global C cycle that hinders the development of effective climate change mitigation strategies. To gain a comprehensive understanding of the global C cycle and to develop effective climate mitigation policies, it is imperative to expand research efforts to include SIC.

Competing interests

The authors declare no competing interests.

CRediT authorship contribution statement

Sajjad Raza: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Annie Irshad:** Data curation, Formal analysis, Visualization, Writing – review & editing. **Andrew Margenot:** Investigation, Writing – review & editing. **Kazem Zamanian:** Writing – review & editing. **Nan Li:** Visualization. **Sami Ullah:** Writing – review & editing. **Khalid Mehmood:** Conceptualization, Methodology. **Muhammad Ajmal Khan:** Conceptualization, Data curation, Formal analysis, Methodology. **Nadeem Siddique:** Data curation, Formal analysis. **Jianbin Zhou:** Writing – review & editing. **Sacha J. Mooney:** Funding acquisition, Writing – review & editing. **Irina Kurganova:** Funding acquisition, Writing – review & editing. **Xiaoning Zhao:** Conceptualization, Funding acquisition, Writing – review & editing. **Yakov Kuzyakov:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Supervision, Validation, Visualization, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Acknowledgements

S.R. was supported by National Natural Science Foundation of China (42150410386). S.R. and S.J.M. were funded by Biotechnology and Biological Sciences Research Council (BBSRC) project Delivering Sustainable Wheat (DSW) (BB/X011003/1). X.Z. was supported by Xinjiang Tian Chi Specially-Appointed Professor Project; Jiangsu Provincial Science and Technology Innovation Special Fund Project of Carbon Emission Peak and Carbon Neutralization (frontier and basis) (BK20220016) and Jiangsu Specially-Appointed Professor Project (R2020T29). Y.K was supported by the RUDN University Strategic Academic Leadership Program. I.K. was supported by the West-Siberian Interregional Science and Education Centers Project No. 89-DON (1), and the Project CarboRus (075-15-2021-610).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2024.116831.

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