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GSOCS-LULCC: the Global Soil Organic Carbon Stock dataset after Land Use and Land Cover Change

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Abstract. The direction and magnitude of soil organic carbon stock (SOCS) change following land use and land cover change (LULCC) are highly uncertain, largely due to the lack of relevant global soil data. Great efforts have been made to build SOCS database at regional, national and even sub-continental scales following LULCC; however, a comprehensive and open-access global database has not yet been developed, hindering a deep understanding of LULCC impact on SOCS dynamics. In this

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study, we introduce a new global SOCS database for LULCC, compiled from 639 articles documented in the Web of Science through the end of 2023. Targeting five major land uses (cropland, grasslands, forest, plantation, and savanna), this database —named the Global Soil Organic Carbon Stock dataset after Land Use and Land Cover Change (GSOCS-LULCC)—include 1,206 sites with 5,982 records at various sampling depths. The database will enable users to assess the global impact of LULCC on SOCS dynamics and identify the factors that control SOCS changes for specific types of LULCC. The GSOCS-LULCC database is freely available from the Zenodo platform at https://doi.org/10.5281/zenodo.11183819 (Chen et al., 2024).

1 Introduction

Soil organic carbon (SOC) promotes influence extends to the physical, chemical, and biological properties of the soil, directly affecting soil fertility and crop yield. As the largest carbon (C) pool in terrestrial ecosystems (1,550 Pg), the storage of SOC is twice that of atmospheric C pool (760 Pg) and 2.8 times that of vegetation C pool (560 Pg) (Lal, 2004). Therefore, a subtle change in SOC pools can have a significant impact on global C cycling so as to impact greenhouse gas emissions and global climate change (Beillouin et al., 2022). Previous studies have shown that each type of soil has SOC carrying capacity, and the balance between carbon input and carbon outflow in the soil is disrupted by LULCC until a new balance is finally reached in a new ecosystem (Guo and Gifford, 2002; Emde et al., 2024). The change in SOC stock (SOCS) is directly influenced by the transformation of ecosystem types, which may lead to soil carbon pools serving as carbon sources or sinks. The changes in SOCS impacted by LULCC may be influenced by various factors such as climate conditions, soil physicochemical properties, land management, vegetation types, and land use history (Jobbágy and Jackson, 2000; Poeplau et al., 2011; Hong et al., 2020). However, previous studies have reported that SOC stocks exhibited a high vulnerability to land use and land cover change (LULCC) (e.g., Guo and Gifford, 2002; Smith, 2008; Don et al., 2011). The Global Carbon Budget 2023 has also revelled the persistent large uncertainty in the estimate of LULCC induced C emissions (Friedlingstein et al., 2023).

Despite the substantial data provided by existing research to understand SOCS dynamics following LULCC, a systematic and comprehensive database collection on SOCS changes remains absent. Consequently, establishing a spatial database to track the dynamic changes in global SOCS has become an urgent need for better understanding the long-term impact of LULCC on SOCS. This study aims to create a comprehensive, high-quality dynamic database of SOCS by synthesizing carefully selected literature data, thereby providing a scientific foundation for understanding and predicting SOCS cycling in response to global LULCC.

2 Soil data collection and harmonization

2.1 Literature search

We gathered relevant literature on SOCS changes resulting from LULCC, published in English academic journals up to December 31, 2023, using the Web of Science database. The literature search was performed using the following keywords:

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"TITLE: (land use change OR land use dynamic OR land use conversion OR land cover change OR land cover dynamic OR land cover conversion OR deforestation OR afforestation OR reforestation OR restoration OR plantation) AND TOPIC: (soil carbon OR soil organic carbon OR soil organic matter)" (Shuai et al., 2024).

In this study, we adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines proposed by Page et al. (2021) to identify and select relevant articles. The PRISMA framework consists of four phases: identification, screening, eligibility, and inclusion (Fig. 1). During the identification phase, a total of 9,930 articles were initially identified in the Web of Science, and 652 duplicate articles were removed prior to screening. Subsequently, 9,278 articles were screened based on their titles and abstracts, resulting in the exclusion of 4,756 irrelevant articles and 572 non-English articles. Following this, 3,950 articles were assessed for eligibility. From this group, 552 articles lacking temporal data post-LULCC, 764 articles without geographic coordinates, 1,619 articles missing data on SOC or SOCS before or after LULCC, and 406 articles that did not meet the required land use and cover types (cropland, grassland, natural forest, plantation) were removed. Ultimately, 639 articles were included in the final database, which comprises 1,206 sites and 5,982 records globally.

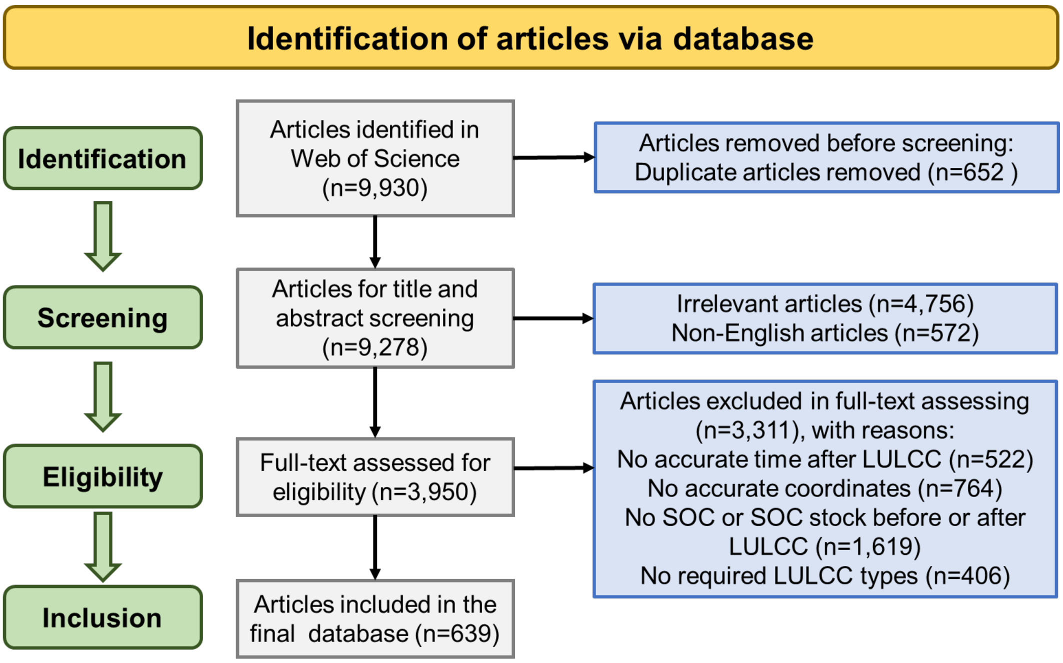

Figure 1 The PRISMA flow diagram for articles identification and selection.

2.2 Data extraction

From the selected 639 articles, we collected the following information: (1) Basic article information: publication year, author, title, and journal; (2) Study region information: country, specific study area, elevation, and coordinates (latitude and longitude); (3) Climate conditions: mean annual temperature (MAT), mean annual precipitation (MAP), potential evapotranspiration (PET), and aridity index (AI); (4) Soil sampling information: sampling replicates and sampling design (paired site, repeated

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sampling, chronosequence); (5) Time after LULCC; and (6) Soil characteristics: soil type, sampling depth, soil pH, and particle size fractions (clay, silt, sand) before LULCC, as well as soil bulk density before and after LULCC, and the average and standard deviation (or standard error) of SOC or SOCS before and after LULCC.

The required information was extracted from the text, tables, charts, and supplementary materials in the selected articles. The GetData software (http://getdata-graph-digitizer.com/) was utilized to extract relevant data when the information was presented in figures. Four main land use types were investigated: cropland, grassland, forest, and plantation. It is important to note that "forest" refers to natural or secondary forests without anthropogenic management.

2.3 Missing data gap-filling

Since not all required information was simultaneously available in the selected articles, we employed various approaches to fill in the gaps in the database for missing information, such as climate conditions, elevation, soil bulk density, pH, particle size fractions, and the standard deviation of SOC or SOCS. For climate conditions, mean annual precipitation (MAP) and mean annual temperature (MAT) were extracted from WorldClim Version 2.0 at a 1 km resolution (Fick and Hijmans, 2017). Potential evapotranspiration (PET) and the aridity index (AI) were obtained from the Global Aridity Index and Potential Evapotranspiration Climate Database v3, also at a 1 km resolution (Zomer and Trabucco, 2022). The elevation data were filled using the SRTM 90m Digital Elevation Database v4.1 (Jarvis et al., 2008). Soil pH and particle size fractions (clay, silt, and sand) were extracted from SoilGrids 2.0 at a 250 m resolution for six standard GlobalSoilMap depth intervals (0-5, 5-15, 15-30, 30-60, 60-100, and 100-200 cm) and subsequently harmonized to the corresponding depth intervals using numerical integration (Chen et al., 2022; Hengl et al., 2017; Poggio et al., 2021). For sites with SOC content but without bulk density (BD) data, we utilized a pedotransfer function developed by Tao et al. (2023), based on WoSIS data encompassing 78,913 layers from 16,248 profiles (Batjes et al., 2020).

$$BD = 0.32 + 1.30 \times e^{0.0089 \times SOM} \quad (1)$$

where BD is the bulk density (g cm^{-3}), SOM is the soil organic matter content (%) calculated as SOC×1.724.

Then, SOC content (g kg^{-1}) was converted to SOCS (t ha^{-1}) using the equation below:

$$\mathrm{SOCS} = \mathrm{SOC} \times \mathrm{BD} \times \mathrm{Thickness} \times 0.1 \quad (2)$$

where Thickness is the thickness of soil layer (cm), and 0.1 is the conversion factor for unit.

For sites lacking standard deviation or standard error for SOC or SOCS, we assigned a standard deviation equal to one-tenth of the mean, as suggested by previous studies (Jerabkova et al., 2011; Luo et al., 2006).

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3 Results

3.1 Spatial distribution of GSOCS-LULCC

Fig. 2 illustrates the spatial distribution of the 15 main types of land use and land cover change (LULCC) included in this database: cropland to forest (379 records), cropland to grassland (582 records), cropland to plantation (1,104 records), forest to cropland (795 records), forest to grassland (516 records), forest to plantation (695 records), grassland to cropland (562 records), grassland to forest (267 records), grassland to plantation (885 records), plantation to cropland (50 records), plantation to forest (16 records), plantation to grassland (19 records), savanna to cropland (39 records), savanna to plantation (61 records), and savanna to grassland (12 records). The initial land uses of grassland and forest were widely distributed, while initial cropland was primarily located in the United States, Europe, and China. Initial savanna land was only present in Africa and South America.

Fig. 3 presents the coverage of the GSOCS-LULCC dataset across biomes and the USDA soil texture triangle. The dataset covers nearly all biomes (except for tundra), with high density observed in temperate seasonal forests, tropical seasonal forests/savannas, and woodland/shrubland. The GSOCS-LULCC also exhibits comprehensive coverage of the USDA soil texture triangle, with a high density found in clay loam and loam textures.

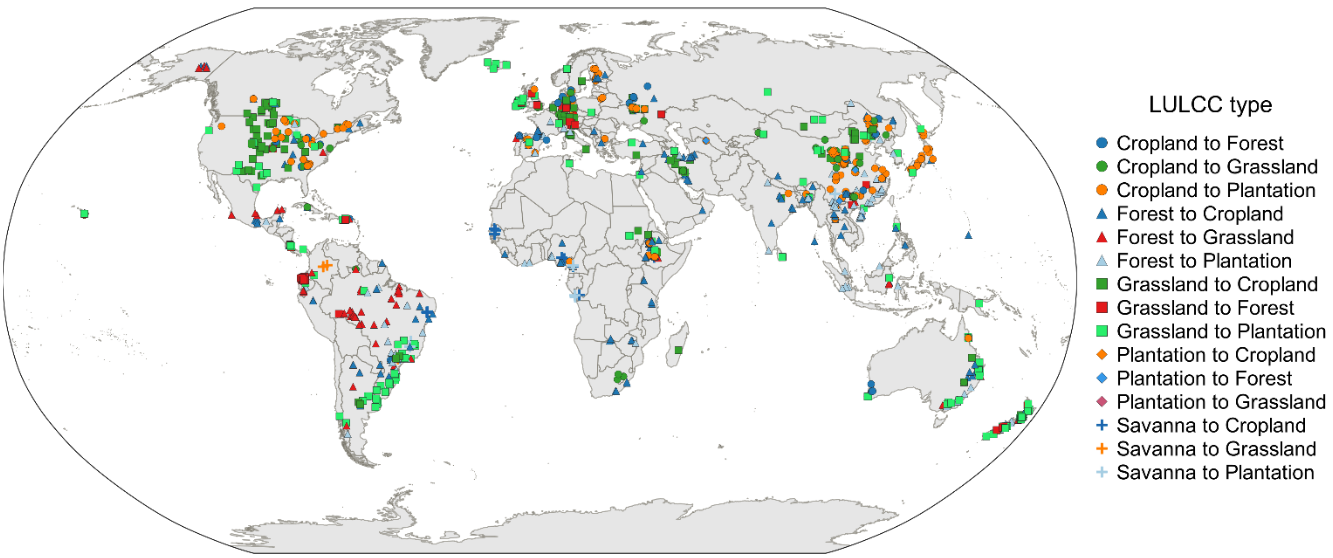

Figure 2 Spatial locations of study sites after five major types of LULCC: (a) cropland to others (circle); (b) forest to others (triangle); (c) grassland to others (square); (4) plantation to others (diamond); (5) savanna to others (cross).

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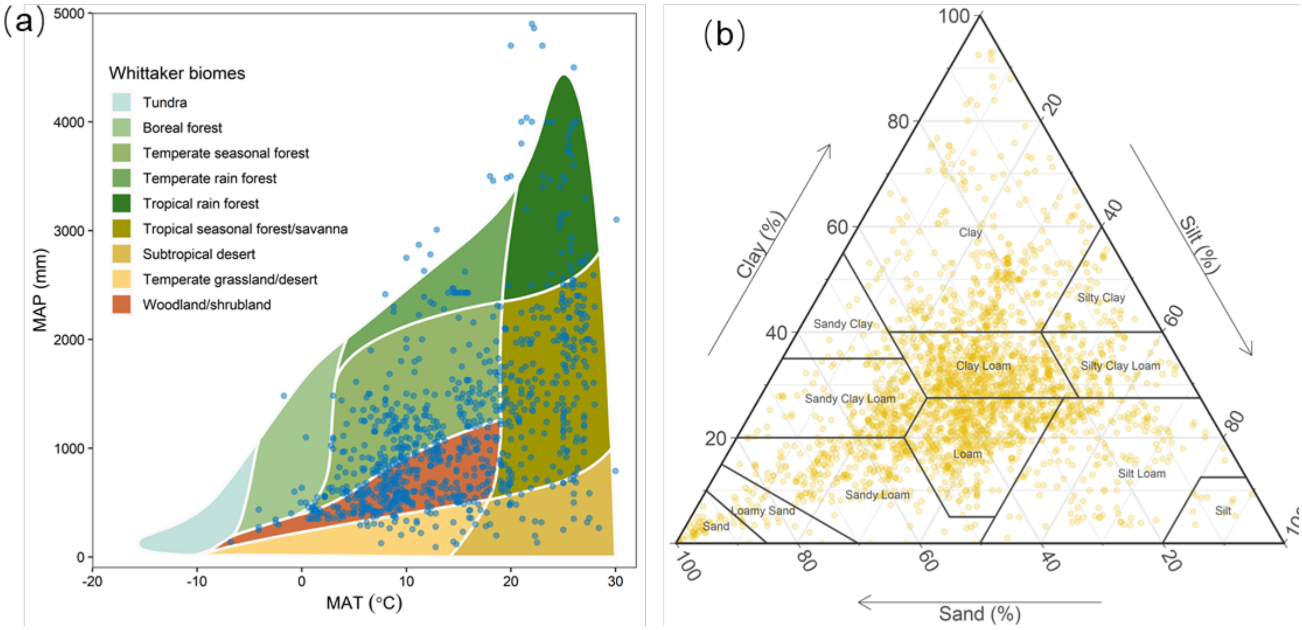

Figure 3 The coverages of GSOCS-LULCC on biomes (a) and USDA soil texture triangle (b).

3.2 The distribution of SOCS in GSOCS-LULCC

Figure illustrates the distribution of SOCS before and after LULCC in the GSOCS-LULCC dataset. The majority of soil samples exhibited SOCS below 50 t ha^{-1}, both before (79.2%) and after (81.9%) LULCC. The mean SOCS after LULCC was 31.52 t ha^{-1}, which was slightly lower than the mean SOCS before LULCC, recorded at 33.68 t ha^{-1}.

Figure 4b depicts the changes in SOCS across the 15 types of LULCC. Generally, SOCS increased when cropland was converted to forest, grassland, and plantation, with median values of 4.47 t ha^{-1}, 1.84 t ha^{-1}, and 2.20 t ha^{-1}, respectively. Conversely, SOCS significantly decreased when forest was converted to cropland (-7.00 t ha^{-1}) and to plantation (-3.48 t ha^{-1}), while limited change was observed for conversion to grassland (-0.21 t ha^{-1}). A notable decrease in SOCS was found when grassland was converted to cropland (-5.06 t ha^{-1}); however, there was no significant change observed for conversions to forest (-0.20 t ha^{-1}) and plantation (-0.07 t ha^{-1}). In the case of plantation, conversions to cropland (-2.86 t ha^{-1}) and grassland (-1.47 t ha^{-1}) resulted in decreases in SOCS, while a substantial increase was noted when it was converted to forest. Additionally, SOCS increased when savanna was changed to grassland (7.15 t ha^{-1}), but a slight decrease was observed for conversion to cropland (-1.13 t ha^{-1}), with no significant change noted for conversion to plantation (0.20 t ha^{-1}). It is important to highlight

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that mass correction is a critical step for accounting for SOCS changes on an area basis (Don et al., 2011), yet less than 20% (1,020 records) of the data in the GSOCS dataset have incorporated this procedure.

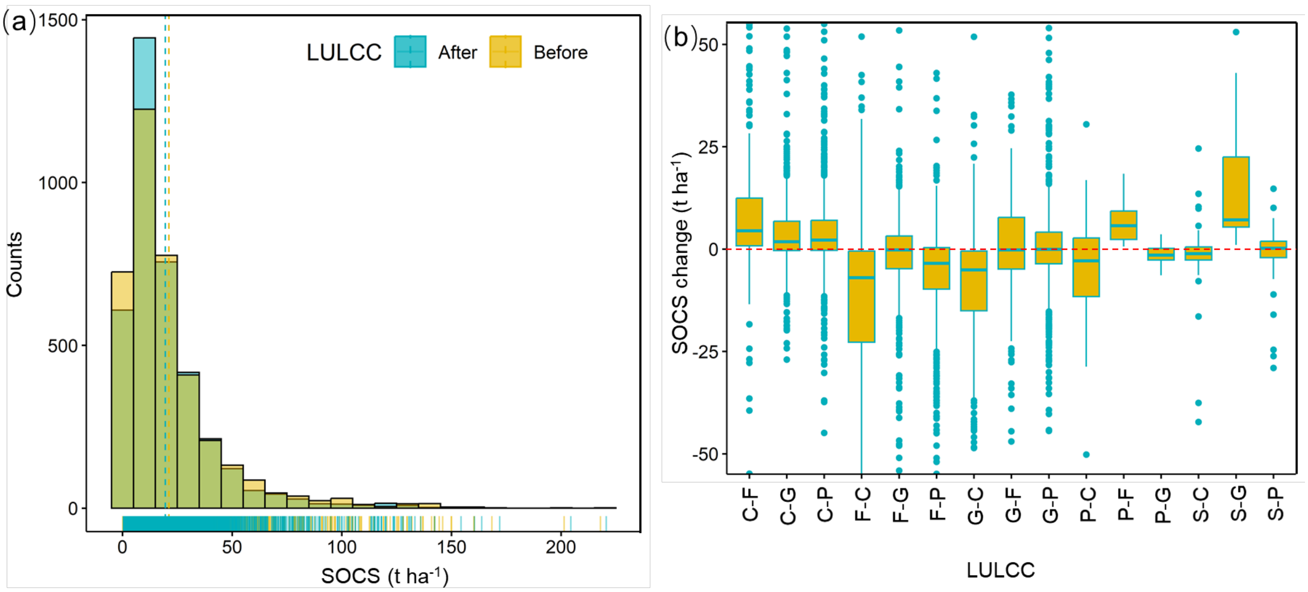

Figure 4 Histograms of SOCS (in t ha^{-1}) before and after LULCC recorded in the GSOCS-LULCC (a) and its change for each LULCC (b). The vertical dash lines (in a) show the mean of SOCS before and after LULCC, and the red horizontal dash line (in b) is at the 0. The abbreviations (in b) are listed below: C, cropland; F, forest; G, grassland; P, plantation; S, savanna.

3.3 The spatial distribution of SOCS changes after LULCC

The spatial distribution of SOCS changes following four types of LULCC (cropland to others, forest to others, grassland to others, and others) is presented in Fig. 5. When cropland was converted to other land use types (forest, grassland, and plantation), a gain in SOCS was commonly observed across the continents. Deforestation was widely reported on various continents, particularly in South Africa and Asia, resulting in significant losses of SOCS. The conversion from grassland to other land uses was also widespread globally, with a large number of observations reported from North America. The directions of SOCS change varied after LULCC in grassland areas. As shown in Figure 4(d), the data for other LULCC types were limited in spatial coverage globally, indicating that more efforts are needed to address this gap.

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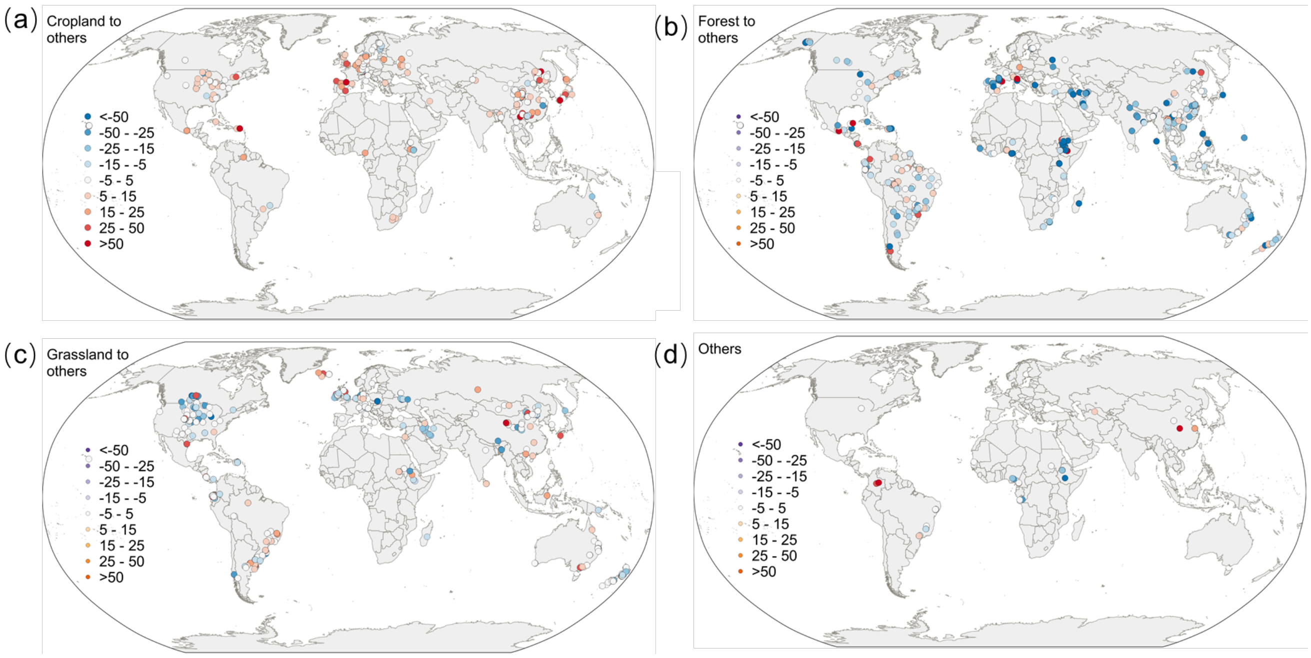

Figure 5 The spatial distribution of SOCS changes after LULCC with the classes from cropland to others (a), forest to others (b), grassland to others (c) and others (d, including plantation to others and savanna to others). Red and blue mean gain and loss of SOCS (in t ha^{-1}) after LULCC.

3.4 The time of LULCC and the maximum soil depth of interest

Fig. 6 displays the time since LULCC and the maximum soil depth of interest in the GSOCS-LULCC dataset. The dataset encompasses a wide range of time frames, from less than 5 years to over 100 years, with 71.33% of the samples representing a relatively short duration (< 30 years) after LULCC. This suggests a high level of uncertainty when assessing SOCS dynamics over extended periods. Additionally, it is noteworthy that more than two-thirds of the data focused on topsoil (⩽30 cm), while less than 2% of the data recorded measurements from depths greater than 100 cm. This highlights the need for further investigation into deeper soil profiles to achieve a more comprehensive evaluation of SOCS dynamics following LULCC.

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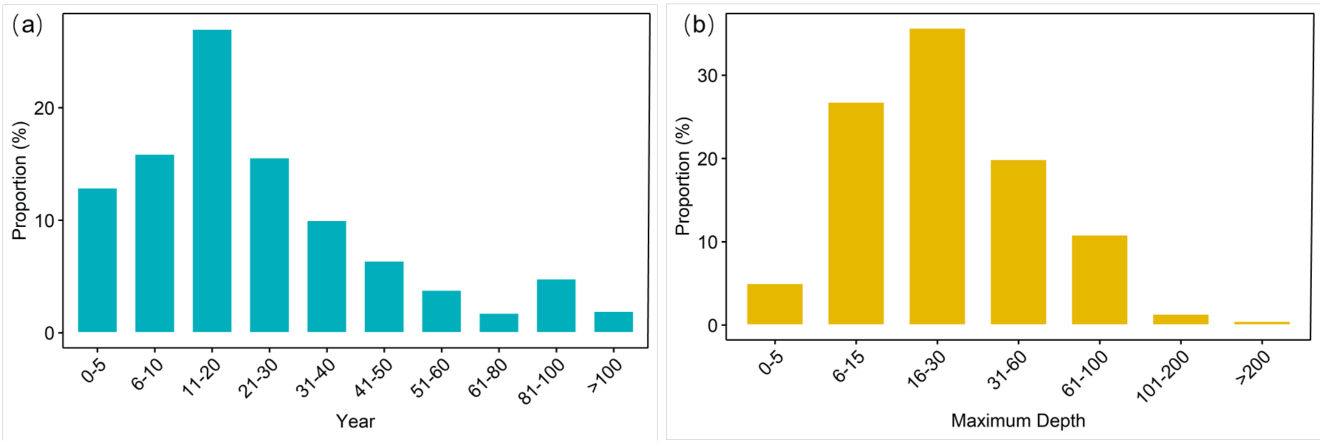

Figure 6 The time after LULCC (a) and the maximum soil depth (in cm) of interest (b) in the GSOCS-LULCC. The year is split into the intervals of 0-5, 6-10, 11-20, 21-30, 31-40, 41-50, 51-60, 61-80, 81-100 and >100. The maximum depth is classified into 0-5, 6-15, 16-30, 31-60, 61-100, 101-200 and >200 based on GlobalSoilMap specifications (Arrouays et al., 2014).

4 Data availability

The Global SOC Stock Dataset after Land Use and Land Cover Change (GSOCS-LULCC) present in this paper is available at https://doi.org/10.5281/zenodo.11183819 (Chen et al., 2024).

5 Conclusions

Covering major biomes and the USDA soil texture triangle, the GSOCS-LULCC consists of 1,206 sites with 5,982 records at multiple sampling depths globally. In addition to reporting SOCS before and after LULCC, this database includes various environmental covariates, such as additional soil information, relief, and climate factors that may influence SOCS changes over time. The establishment of this global database aims to enhance our understanding of the direction and magnitude of SOCS dynamics following LULCC, providing a scientific basis for evaluating historical SOCS fluxes caused by LULCC and supporting decision-making in sustainable land management.

We would like to emphasize that this database is just the beginning, with significant opportunities for expansion. Future versions of the GSOCS-LULCC will focus on the following aspects: (1) incorporating more datasets as relevant open-access databases become available; (2) expanding the records of soil characteristics, particularly biological indicators such as SOC fractions, soil respiration, and enzymes; (3) including more small-area but ecologically important LULCC types, such as

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peatlands and wetlands; and (4) designing strategies for collecting new soil data to capture long-term changes and deep soil profiles.

6 Author contributions

SC, QS, LD, YH, NW, and JX compiled the data. SC and QS performed the analysis and drafted the manuscript. DA, ZC, LD, YH, BH, YH, WJ, SL, ZL, YM., ACR-d-F, CS, YS, HT, NW, XW, YW, ZW, DX, JX, SY, XZ, YZ, PZ, and ZS validated the data, results, and revised the manuscript. SC acquired of the financial support. PZ and ZS supervised this work.

7 Competing interests

PZ is the member of the editorial board of journal Earth System Science Data.

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9 Disclaimer

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