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Meta-analysis of global soil data identifies robust indicators for short-term changes in soil organic carbon stock following land use change

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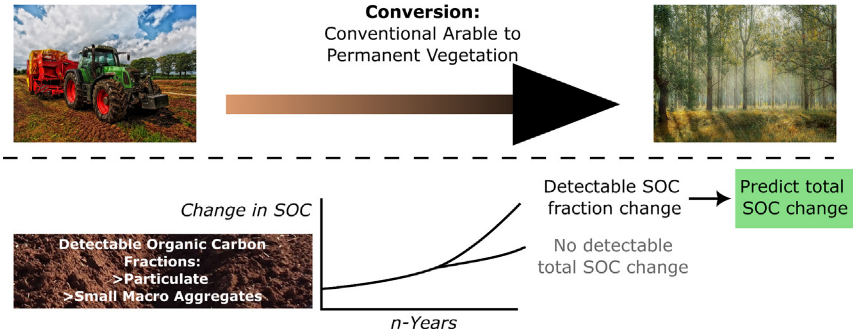
HIGHLIGHTS

- Arable land conversions significantly affect soil organic carbon (SOC) stock.
- Detecting short-term changes in SOC stock relevant to land managers is difficult.
- Global soil data was analyzed to identify early indicators of SOC stock changes.
- Particulate OC was the top candidate indicator of short-term changes in SOC stock.
- OC in macroaggregates was also a suitable indicator of SOC stock changes.

GRAPHICAL ABSTRACT



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ABSTRACT

The restoration of degraded lands and minimizing the degradation of productive lands are at the forefront of many environmental land management schemes around the world. A key indicator of soil productivity is soil organic carbon (SOC), which influences the provision of most soil ecosystem services. A major challenge in direct measurement of changes in SOC stock is that it is difficult to detect within a short timeframe relevant to land managers. In this study, we sought to identify suitable early indicators of changes in SOC stock and their drivers. A meta-analytical approach was used to synthesize global data on the impacts of arable land conversion to other uses on total SOC stock, 12 different SOC fractions and three soil structural properties. The conversion of arable lands to forests and grasslands accounted for 91 % of the available land use change datasets used for the meta-analysis and were mostly from Asia and Europe. Land use change from arable lands led to 50 % (32–68 %) mean increase in both labile (microbial biomass C and particulate organic C – POC) and passive (microaggregate, 53–250 μm diameter; and small macroaggregate, 250–2000 μm diameter) SOC fractions as well as soil structural stability. There was also 37 % (24–50 %) mean increase in total SOC stock in the experimental fields where the various SOC fractions were measured. Only the POC and the organic carbon stored in small macroaggregates had strong correlation with total SOC: our findings reveal these two SOC fractions were predominantly controlled by biomass input to the soil rather than climatic factors and are thus suitable candidate indicators of short-term changes in total SOC stock. Further field studies are recommended to validate the predictive power of the equations we developed in this study and the use of the SOC metrics under different land use change scenarios.

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Contents

1. Introduction

Soil degradation remains a serious threat to soil's capacity to deliver vital ecosystem services including climate change and flood mitigation, food production and water quality regulation (FAO and ITPS, 2015; Ferreira et al., 2022). Soil degradation is exacerbated through unsustainable land use practices particularly land use changes that involve the clearing of vegetation for agricultural production, urban infrastructural development, and intensification of agriculture on existing arable lands (Kopittke et al., 2019). It is well established that such land use changes alter important processes such as the carbon (C) and hydrological cycles that dictate the quantity of C that is stored or released from the soils and the amount of water that is absorbed and stored by the soils (Hong et al., 2021; Sun et al., 2018). These processes underlie many global environmental issues of great concern such as climate change and flooding (Sheil, 2018).

Soil organic carbon (SOC) stock and soil structure are often used as key indicators of the extent of soil degradation or improvement resulting from land use change (Obalum et al., 2017; Bünemann et al., 2018). This is because these two soil properties control most soil processes including nutrient and water cycling, gas exchange and biological activity (Rabot et al., 2018; Wiesmeier et al., 2019). Also, soil structure is strongly correlated with SOC stock because organic matter (OM) serves as the nucleus for the formation of stable soil aggregates, which in turns protects SOC from microbial decomposition and loss (Rabot et al., 2018). Natural and undisturbed ecosystems such as forests have high SOC stock with stable soil aggregates characterized by the predominance of large pores (e.g., >10 μm effective diameter) whereas intensively cultivated arable lands have relatively lower SOC and higher proportion of small pores (<10 μm effective diameter) with lower infiltration and hydraulic conductivity (Azizsoltani et al., 2019; Fernandez et al., 2019). Hence, changing land use from either natural ecosystem or intensive cultivation leads to changes in SOC and soil structure with consequential impacts on numerous soil functions such as greenhouse gas regulation, infiltration, drainage and erosion regulation (Veldkamp et al., 2020). For example, change to agricultural land use has significantly reduced SOC stocks by up to 116 Pg C globally (Sanderman et al., 2017) with annual carbon dioxide (CO_2) emissions estimated at 1.3 ± 0.7 Pg C for the 2007–2016 period (Le Quéré et al., 2017).

Addressing the negative consequences of land use change resulting in soil degradation requires minimizing the conversions of natural ecosystems to intensive uses and implementing measures to restore intensively cultivated lands to less disturbed natural conditions. However, this needs to be balanced with providing enough affordable food through sustainable land management practices. There are already ongoing efforts in different regions of the world to address soil degradation and achieve ecosystem benefits through natural regeneration of former agricultural lands to grasslands, shrublands and forests or deliberate planting of trees or grasses (Chazdon et al., 2020; Hu et al., 2021). These restoration measures lead to SOC accumulation (Deng et al., 2016) because they increase the capturing and storage of atmospheric CO_2 in biomass and soil (Shi et al., 2013), and reduce C loss via erosion (Deng et al., 2019). Restoration of arable lands has also been shown to improve soil structural properties which is evident in reported impacts on hydrological processes such as increased infiltration, and reduced surface runoff and erosion (Sun et al., 2018).

As many land restoration programmes (e.g., the AFR100 scheme in Africa and Environmental Land Management Scheme in the UK) are being implemented in different parts of the globe, including payment schemes and incentives for land managers based on environmental benefits, the need to reliably measure land management or land use change impacts on soils is a key priority. The challenge with direct measurement of changes in some soil properties especially SOC stock in the short-term of less than five years is that small changes in total SOC occur over a large background stock, making it difficult to detect within this timeframe (Smith, 2004; Lal, 2009). For example, changes in SOC stock associated with afforestation of former croplands have been shown to be significant after 30 years (Li et al., 2012; Bárcena et al., 2014) or at least 10 years (Deng et al., 2016; Chatterjee et al., 2018) with no changes detected below five years (Xiang et al., 2021). Farmers and other land managers may anticipate annual payments to sustain their land management efforts, hence, there is an urgent need to identify measures of SOC and structure that reflect both short- and long-term impacts of land restoration programmes.

There is a growing research focus on labile fractions of SOC (Table 1) such as microbial biomass C and particulate OC (POC) with shorter turnover time and more sensitivity to land use change than bulk SOC stock (Sierra et al., 2013; Gabarrón-Galeote et al., 2015; Zhong et al., 2021). These labile fractions of SOC may indicate whether the soil is losing or gaining C but do not provide absolute changes in SOC stock, and are measured via different approaches, including physical separation and chemical oxidation (Powlson and Neal, 2021). These various fractions of SOC have been proposed as early indicators of changes in SOC but it remains unclear which of the fractions reliably reflect changes in total SOC stock in both short- and long-term following land use change. As soil structure is very

Table 1
Classification of soil organic carbon (SOC) fractions recorded in the articles selected for this study.

Main group	Fractions	Properties/method of determination	Source
Density separated/dispersed organic carbon fractions	Particulate organic carbon (POC)	Carbon in organic materials retained in suspension and >0.05 mm effective diameter after soil dispersion in sodium hexametaphosphate solution.	Cambardella and Elliott, 1992
	Light organic carbon fraction (LFOC)	Organic carbon lighter than 1.7–1.8 g/cm^3 when suspended in a sodium iodide or sodium polytungstate solution.	Janzen et al., 1992; Steffens et al., 2009
	Heavy organic carbon fraction (HFOC)	Organic carbon heavier than 1.7–1.8 g/cm^3 when suspended in a sodium iodide or sodium polytungstate solution.	Steffens et al., 2009
Oxidizable organic carbon/organic carbon extractable with neutral-slightly alkaline solution	Potassium permanganate ($KMnO_4$) oxidizable organic carbon (POXC)	Organic carbon oxidized when treated with a solution of $KMnO_4$.	Weil et al., 2003
	Hot water extractable carbon (HWC)	Organic carbon in hot water soil extracts.	Ghani et al., 2003
Humic substances	Humic acid fraction (HAF)	Organic carbon in alkali (NaOH plus $Na_4P_2O_7$) soil extract that is not soluble in acid solution (e.g., H_2SO_4).	Baglieri et al., 2007
	Fulvic acid fraction (FAF)	Organic carbon in alkali (NaOH plus $Na_4P_2O_7$) soil extract that is soluble in acid solution (e.g., H_2SO_4).	Baglieri et al., 2007
Microbial-associated organic carbon fractions	Microbial biomass carbon (MBC)	Difference in K_2SO_4-extractable organic carbon between ethanol-free chloroform fumigated and unfumigated soils.	Vance et al., 1987
Organic carbon associated with soil aggregates	Silt and clay-sized organic carbon fraction (SCF)	Organic carbon in soil aggregates <53 μm in diameter.	Six et al., 2000a
	Microaggregate-occluded organic carbon (micAgg C)	Organic carbon in soil aggregates that are between 53 and 250 μm in diameter.	Six et al., 2000a
	Small macroaggregate-occluded organic carbon (smacAgg C)	Organic carbon in soil aggregates that are between 250 and 2000 μm in diameter.	Six et al., 2000a
	Large macroaggregate-occluded organic carbon (lmacAgg C)	Organic carbon in soil aggregates that are >2000 μm in diameter.	Six et al., 2000a

N.B. Only the SOC fractions that were recorded in the selected articles that met the inclusion criteria for this study were included in this table. Due to absence of data, the following other measures of SOC fractions are not described here: 1) chemical fractions (e.g., alkyl, aromatic and carboxyl C) based on Carbon-13 Nuclear Magnetic Resonance (NMR) spectroscopy, Fourier Transform Infrared (FTIR) spectroscopy, or Gas Chromatography-Mass Spectrometry (GC–MS); 2) thermal fractions distinguished based on resistance to thermal oxidation at temperatures 200–550 °C; and 3) microbial-associated CO_2 evolution in incubated soils.

sensitive to land use change and strongly correlates with SOC (Franco et al., 2020), structural properties such as aggregate stability and water storage and transmission capacities may also serve as reliable early indicators of changes in SOC stock. Identifying reliable SOC indicators will help to standardize approaches used by researchers to assess land use impacts on soils and simplify the complexities surrounding early detection of changes in SOC stock, which may then go onto to help landowners measure any changes in soils in shorter time periods.

While the identification of specific SOC fractions and soil structural properties that reflect soil C sequestration or loss is a crucial first step in overcoming reliable measurement challenges, it is also important to understand the drivers influencing such SOC indicators. Many factors including climate (Li et al., 2012), duration of land use (Qin et al., 2016), altitude (Cukor et al., 2017), previous land use type (Hou et al., 2019), dominant plant species (Hou et al., 2020) and the stage of soil development (Hüblová and Frouz, 2021) are known to moderate the impacts of land restoration measures on SOC stock and soil structural properties but the impacts of these factors on C fractions have not yet been synthesized. Using a legacy dataset, Luo et al. (2020) showed that SOC fractions from agricultural landscapes respond differently to land use conversions from croplands, with large variability in the response of each fraction due to factors including climate. This clearly indicates the need to account for environmental factors when assessing the impacts of land use change on not just long-term measures such as SOC stock but more dynamic C fractions.

To help in addressing the measurement challenges associated with the assessment of land restoration impacts on soils and better inform standard analysis protocols and policies, this study sought to:

1. Identify the SOC fractions (fractional SOC indicators) and soil structural properties that better reflect short-term changes in total SOC stock following the conversion of arable lands to other uses;
2. Identify specific land uses that lead to the most significant changes in fractional SOC indicators after conversion from arable use; and
3. Identify the specific climate and soil factors that moderate the responses of fractional SOC indicators to land conversion from arable use.

We hypothesized that: 1) SOC fractions associated with stable soil aggregates will be a better indicator of short-term land use change impacts on total SOC stock as these fractions are a function of various physical, chemical and biological soil processes; 2) converting arable lands to forest ecosystems either through deliberate planting of trees or natural regeneration will have the greatest impacts on SOC fractions; and 3) the response of SOC fractions to arable land conversions will be significantly moderated by temperature and precipitation.

2. Materials and methods

2.1. Selection, extraction and preparation of data

The data used for this study were obtained following a systematic literature review involving three main steps (Fig. S.1).

2.1.1. Step 1 – database searches

Literature searches for peer-reviewed journal articles were conducted in August 2021 using Web of Science (https://www.webofscience.com/wos/woscc/basic-search) and Google Scholar (https://scholar.google.co.uk/) databases. The precise search text strings used are shown in Table S.1 and contained keywords relating to land use change (e.g., "land use conversion") and soil properties/functions (e.g., "soil organic carbon") combined using Boolean operators. A total of 12,285 unique articles were obtained and screened.

2.1.2. Step 2 – article screening

The articles identified from database searches were independently screened manually by two of the authors using the following criteria for inclusion:

1) Field studies in which arable plots converted to other uses (land use change plots) were compared with adjacent arable plots that have not been converted to other uses at least in the past 30 years (control plots);
2) the nature of land use change was described and land use change duration was clearly specified;

3) control plots and land use change plots were comparable, i.e., they had similar broad environmental conditions such as climate and soil type;
4) land use change had been implemented for at least one year;
5) data on total SOC and a measure of SOC fraction and/or soil structure were reported for both land use change and control plots;
6) measurements of soil parameters were made at similar temporal and spatial scales;
7) the depth of soil samples was specified (this was needed for calculating SOC stock where necessary); and
8) The mean, sample sizes, and measures of variability such as standard deviation (SD), standard error (SE) or coefficient of variation (CV) were reported or could be extracted from the study.

Studies that compared conventional tillage/agriculture (as control) with minimum/no tillage or other forms of conservation agriculture such as the use of cover crops and organic manure were not included in this study because there are many recent review articles (e.g., Liu et al., 2021; Topa et al., 2021; Bohoussou et al., 2022; Das et al., 2022; He et al., 2022) that addressed the impacts of such agricultural land management changes on soils. Hence, the arable control used in this study refers to cultivated lands under crop production regardless of the intensity of tillage and the presence of conservation practices. The focus of the study was on the conversion of arable lands to other uses. Studies on organic soils such as peatlands were excluded as the response of organic soils to land use change differs from those of mineral soils. For example, afforestation of peatlands enhances the decomposition of SOC and its loss via CO_2 emission (Jovani-Sancho et al., 2021) whereas in mineral soils, afforestation increases SOC accumulation (Shi et al., 2013). Also, where multiple studies reported the same data from the same sites, we chose one of the studies with complete SOC and/or soil structure data and excluded others, except if they provided additional data or supporting environmental information about the site. Application of the inclusion criteria resulted in 69 articles (Table S.2) which reported data from 298 sites. The experimental sites were distributed across all continents apart from Antarctica and Oceania but were predominantly concentrated in eastern Asia and Europe (Fig. 1).

Step 3 – Data extraction. The following data were extracted for each site: total SOC, SOC fractions, soil structural properties (e.g., bulk density, aggregate stability, infiltration, hydraulic conductivity, water holding capacity), soil depth and clay content, location, duration of land use, latitude, longitude, altitude, mean annual precipitation (MAP), and mean annual temperature (MAT). Data were extracted directly from tables or texts in the selected articles, or indirectly from figures using WebPlot Digitizer (https://apps.automeris.io/wpd/). Only data for the last year of sampling were extracted from studies where sampling was conducted annually from the same site to maintain a key assumption of meta-analysis that studies must be independent. We considered different experimental sites sharing the same control site as independent observations. In studies where only SE was reported, these were converted to SD using the sample size (N). In five studies (7.2 % of selected studies) where measures of variability were not reported for some of the SOC fractions, we calculated average CV for all datasets for which measures of variability were reported and used the average CV for each SOC fraction to estimate the missing SDs. This was done separately for the control and experimental plots. Eight studies did not report latitude and longitude data, and these were estimated from https://www.findlatitudeandlongitude.com/searches/, based on the study site/location name. In studies where only SOC concentration was reported, these were converted to SOC stock using their bulk density values:

$$\text{SOC stock}\ (\text{Mg ha}^{-1}) = \text{SOC concentration}\ (\%) \times \text{Bulk density}\ (\text{g cm}^{-3}) \times \text{Depth}\ (\text{cm}) \quad (1)$$

Extracted data on SOC fractions were divided into groups based on the method of extraction and properties (Table 1) and data on soil structural properties were grouped into: 1) aggregate stability – based on mean weight diameter; 2) water transmission – mainly infiltration and hydraulic conductivity; and 3) water storage capacity – mainly plant available water capacity and water-holding capacity. MAT, MAP, latitude, soil clay content, soil depth and duration of land use change were categorized to better understand how they moderate the effects of land use change on SOC stock. Previous studies on land use change and land management (e.g., Laganiere et al., 2010; Bárcena et al., 2014; Deng et al., 2016; Eze et al., 2018) identified critical values of these factors where changes in their effects on soils occur. Based on the critical values, the moderating factors were categorized as follows. Three climatic zones were identified based on the latitudes where experiments were conducted: Tropics (0–23.5° N and S), Subtropics (24–40° N and S), and Temperate (41–66° N and S). MAT in °C was divided into six categories: <0.0, 0.0–5.0, 5.1–10.0,

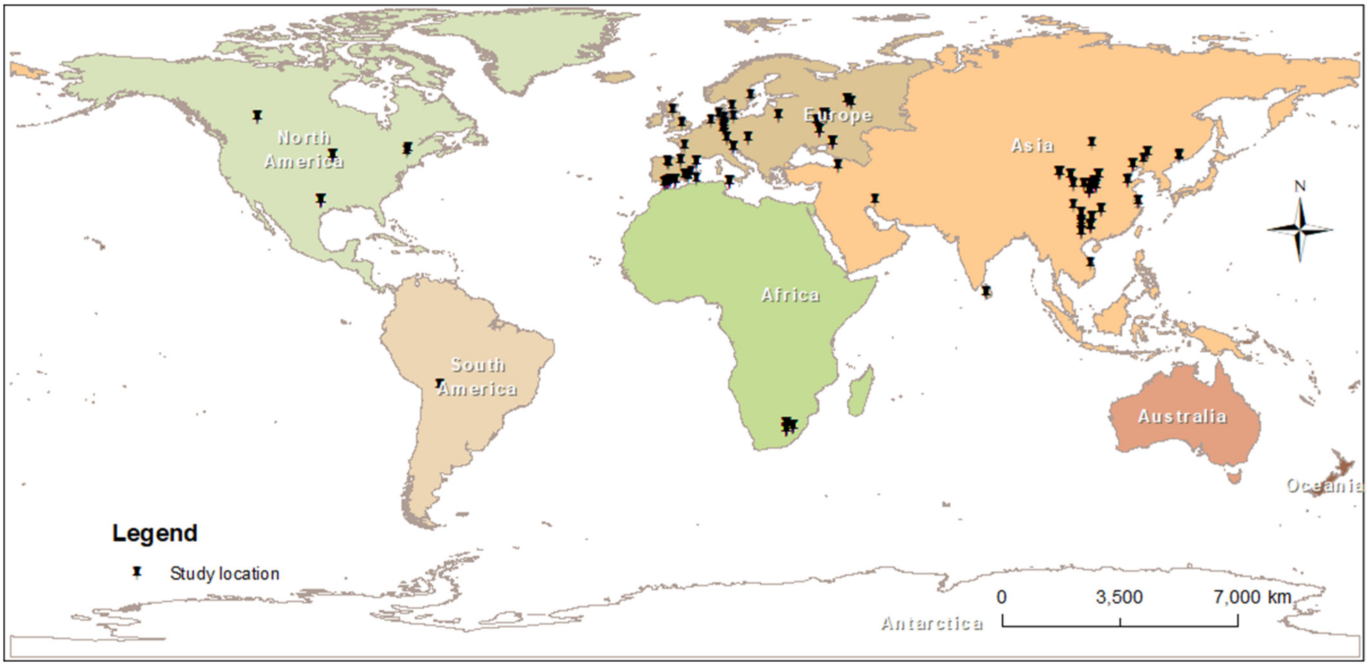


Fig. 1. Global distribution of the 298 study sites selected for data extraction and meta-analysis.

10.1–20.0 and 20.1–30.0 and > 30.0. MAP was grouped into dry (<600 mm), intermediate (600–1000 mm) and wet (>1000 mm) regimes. The clay content was used to categorize soils into sand (<20 % clay), loam (20–30 % clay) and clay (>30 % clay) textural classes. Maximum soil sampling depth was grouped into three: 0–20 cm, 0–40 cm, and 0–100 cm. The duration of arable land conversion was grouped into six periods: 1–5 years, 6–10 years, 11–30 years, 31–50 years, 51–100 years and >100 years.

2.2. Data analysis

The magnitude of the effect of land use change (effect size) on SOC and soil structural properties was estimated using the natural logarithm of the response ratio (RR) (Hedges et al., 1999), which is the ratio of the mean values of a given soil property between sites:

$$\text{Land use change effect size} = \ln\left(\frac{\text{Mean soil property in changed plot}}{\text{Mean soil property in control plot}}\right) \quad (2)$$

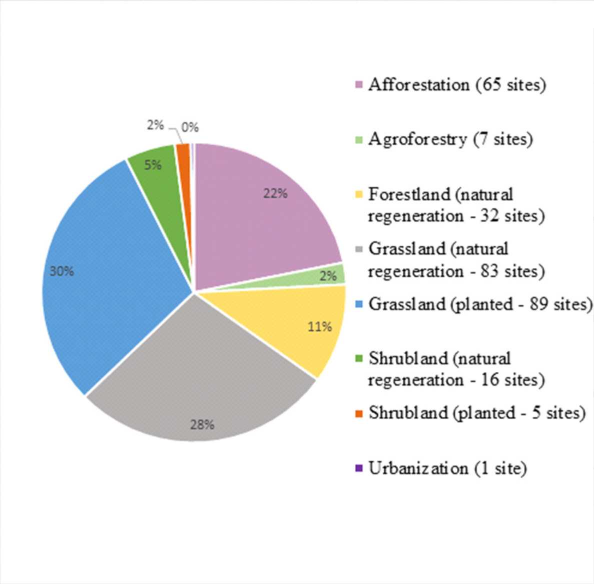
A negative effect size for any soil property means that land use change resulted in a reduction in that parameter whereas a positive effect size implies an increase. Effect size estimates were converted to percentage values using the equation:

$$\text{Percentage effect size} = (\exp(\text{Effect size}) - 1) \times 100 \quad (3)$$

The effect size and its corresponding variance for each site were calculated using the *metafor* package (Viechtbauer, 2010) in R (version 4.0.2). To aggregate the effect of land use change, average effect size and confidence intervals were calculated by fitting random effects models to the effect size and variance estimates for each soil property. This is a standard meta-analytical approach and was chosen because the sites from which data were extracted do not have identical characteristics, which introduced variability or heterogeneity that was treated as a random factor (Viechtbauer, 2010). To account for the heterogeneity, the following moderating factors – land use type, climate zone, MAT, MAP, soil clay content, duration of land use change and maximum soil sampling depth, were further included in the models, resulting in mixed-effects models. This helped to assess the influence of the moderating factors on the effects of land use changes. To diagnose for publication bias, funnel plot asymmetry was tested using the *regtest* function in R.

To identify the SOC fractions and/or soil structural properties that better reflect changes in total SOC stock following land use change, the following steps were taken. Firstly, the results of the effect size aggregation were examined to identify where significant effects of land use change on total SOC stock coincided with significant effects on SOC fraction or soil structural property. Pairs of total SOC stock – SOC fraction and total SOC stock – soil structural property that was significantly affected by land use change were identified and subjected to correlation analysis. The pairs of total SOC stock – SOC fraction and total SOC stock – soil structural property with statistically significant ($p < 0.05$) correlation coefficient of at least ±0.5 were identified and used to develop predictive regression models of total SOC stock. Pearson's product-moment correlation test was used for normally distributed data whereas Spearman's rank correlation test was used for non-normally distributed data. Shapiro-Wilk test was used to test the normality of data. It was not possible to generate a correlation matrix, perform multiple regression or any other factor analysis that combines all the SOC fractions, total SOC stock and soil structural properties because data for all these parameters were not all available for each site. All the 298 sites selected for data extraction had data on total SOC but differed in the type of SOC fraction or soil structural property data available. This meant that the sites with data on one type of SOC fraction did not all have data on other SOC fractions or soil structural properties. This resulted in the data being analyzed in pairs of total SOC and one type of SOC fraction or soil structural property.

Prior to model development, the datasets were split (using the *sample* function in R) into three: training dataset, calibration dataset and validation dataset, in a 60:20:20 proportion. The training datasets were used to build linear regression models (Model 1), which were fitted to the calibration datasets to predict total SOC. The predicted total SOC data were plotted against measured total SOC, and a regression line fitted through the plot (calibration plot). Model 1 was then divided by the slope of the calibration plot, resulting in the predictive model of total SOC (Model 2). Model 2 was fitted to the validation datasets and total SOC was predicted. The total SOC data predicted with the validation datasets were plotted against measured total SOC, and a regression line fitted through the plot (validation plot). The Root Mean Square Error (RMSE), Nash – Sutclifffe Efficiency (NSE) and Willmott Index of Agreement (*d*) were then used to assess the performance of Model 2 (the predictive model of SOC).



Land use description
Afforestation – land under tree plantation (single or multiple tree species)
Agroforestry – land under mixed tree-crop or tree-grass plantation
Forestland (natural regeneration) – abandoned or fallow land at an advanced stage of natural vegetation recovery and dominated by trees.
Grassland (natural regeneration) – abandoned or fallow land at an early stage of natural vegetation recovery and dominated by grass species. Ungrazed or grazed secondary vegetation.
Grassland (planted) – land under grass plantation which may be used as pasture and grazed by livestock e.g., cattle or sheep.
Shrubland (natural regeneration) –abandoned or fallow land at an intermediate stage of natural vegetation recovery and dominated by shrubs.
Shrubland (planted) – land under shrub plantation.
Urbanization – land that has been transformed to support the development of urban infrastructures such as buildings and roads.

Fig. 2. Types of land conversions from arable use (cultivated land under crop production) identified in the selected articles used in this study, their descriptions and number of sites from which data was extracted.

3. Results

The main land use changes identified in the research articles (with no publication bias; Table S.3) that met the selection criteria for this study were conversions of arable lands to agroforestry, forests, grasslands, shrublands and built-up environment (urbanization) (Fig. 2). The converted arable lands were predominantly under cereal cultivation (69 % of sites) with maize accounting for 74 % of the cereal sites (Fig. S.2). Conversion of arable lands to forests and grasslands accounted for 91 % of the land use changes, with more afforested lands than naturally regenerated forests, and about the same number of planted and naturally regenerated grasslands (Fig. 2). The land use change with the highest number of study sites was the conversion of arable to grassland whereas urbanization of arable lands had the least number of study sites (Fig. 2).

3.1. Response of SOC fractions, soil structural properties and total SOC to land use change

Overall, changing away from arable land use to agroforestry, forests, grasslands and shrublands, together, resulted in a significant ($p < 0.001$) increase in total SOC stock by an average of 40 % (34 % – 47 %) (Fig. 3; Table S.4). The greatest significant increases in total SOC stock occurred in forests (53–82 % increase) and shrublands (35–56 % increase). However, changes to agroforestry had no significant effects. Changes to urbanization also had no significant effects, although this was based on only one data point available for this study (Fig. 3; Table S.4).

In sites where land use change led to significant increases in total SOC stock, only the following five SOC fractions and two soil structural properties were significantly increased (Figs. 4 and 5): OC in microaggregate soil fractions (32 % [22–43 %]), OC in small macroaggregate soil fractions (34 % [18–52 %]), microbial biomass C (36 % [23–50 %]), fulvic acid C (65 % [39–97 %]), particulate OC (68 % [50–88 %]), water holding capacity (7 % [1–12 %]) and mean weight diameter (45 % [26–66 %]). Out of these seven soil parameters, only OC in small macroaggregate soil fractions (smacAgg C) and particulate OC (POC) had strong positive correlations (R = ± 0.5 or higher, $p < 0.001$) with total SOC stock (Fig. 6). Predictive models of total SOC stock developed based on these two SOC fractions with strong positive correlations showed good performance with very low values (<0.85) of Root Mean Square Error (RMSE), Nash – Sutclifffe Efficiency (NSE) and Willmott Index of Agreement (*d*) (Figs. 7 and 8). Combining POC and smacAgg C may offer a more reliable option for assessing SOC changes in the short term of less than five years when this has hitherto remained difficult to detect (Smith, 2004). Combining these two SOC fractions as key indicators of SOC change will provide information on the direction of SOC change and give insight into the nature of storage/sequestration. Using Eqs. (4) and (5) (Figs. 7 and 8), it is also possible to predict the magnitude of early changes in total SOC stock.

$$\text{SOC stock}\left(\text{Mg ha}^{-1}\right) = \left[0.056 + 0.34\left(\text{POC}\left(\text{Mg ha}^{-1}\right)\right)\right]/0.62 \tag{4}$$

$$\text{SOC stock}\left(\text{Mg ha}^{-1}\right) = \left[0.27 + 0.34\left(\text{smacAgg C}\left(\text{Mg ha}^{-1}\right)\right)\right]/0.64 \tag{5}$$

Further experimentations are, however, needed to verify the applicability of these equations under short term durations of less than five years and different land management and land use change scenarios. It may also be helpful where sufficient data is available to try and combine the two predictors in a single equation to see if the predictive power will increase thus further simplifying the process of estimating SOC changes.

3.2. Effects of specific arable land conversions on SOC fractions and the influence of environmental factors

On further analysis of the two SOC fractions (POC and smacAgg C) that correlated most strongly with total SOC, their responses to specific land use conversions namely afforestation, agroforestry, planted grassland, and naturally forests, grassland and shrubland differed (Table 2). All the land use changes (except urbanization with no available data) led to significant increases in POC, with afforestation and naturally regenerated shrubland causing >100 % increase. Only afforestation and establishment of grasslands led to significant increase in smacAgg C (Table 2).

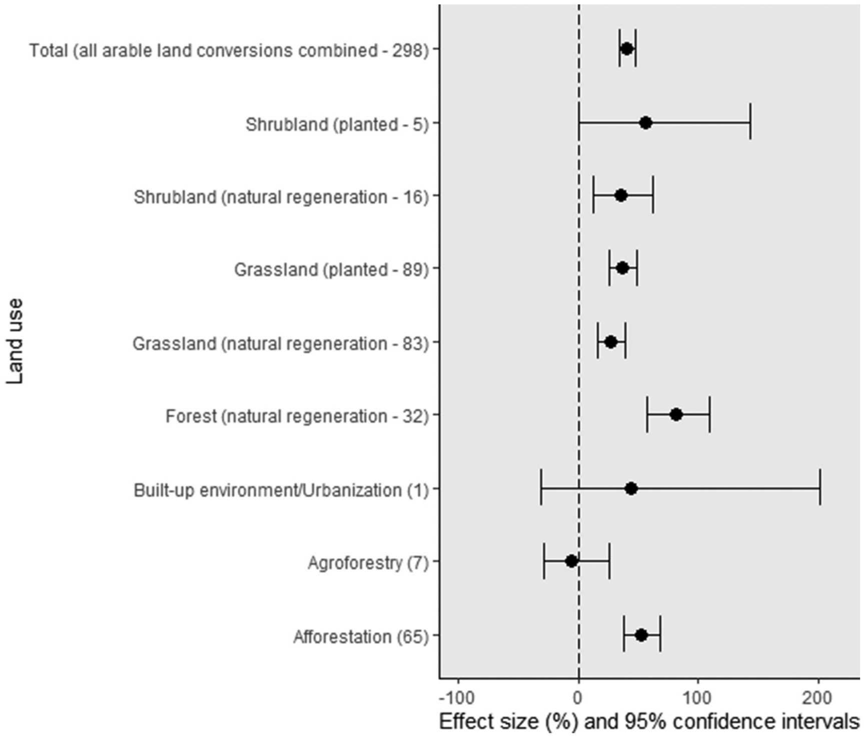


Fig. 3. Effects of arable land conversions on total SOC stock. There was no statistically significant effect on SOC stocks for all changes where the 95 % confidence intervals overlapped with zero.

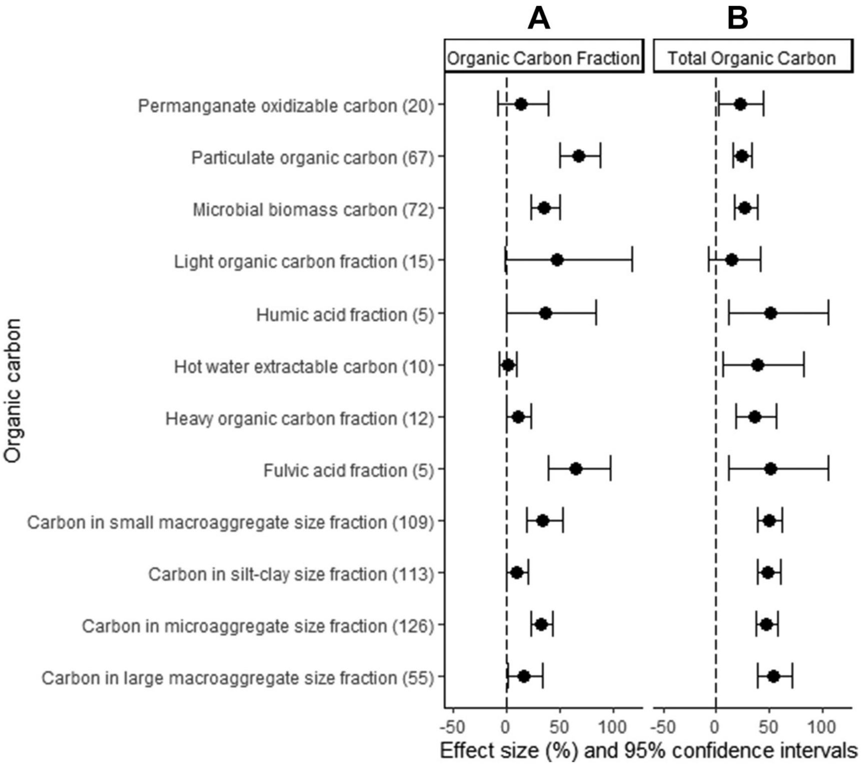


Fig. 4. Effects of all arable land conversions combined on SOC fractions (A) and total SOC (B) in sites where the SOC fractions were measured. There was no statistically significant effect on total SOC or its fractions where the 95 % confidence intervals overlapped with zero.

The impacts of land use changes on the two fractional SOC indicators differed depending on whether trees, grasses, or shrubs were planted or established through natural regeneration (Table 2). For POC, the land use change-induced increase was at least 50 % regardless of the method of establishing the vegetation. There was no significant effect of natural vegetation regeneration on the smacAgg C as only planted grassland and afforestation led to a significant increase.

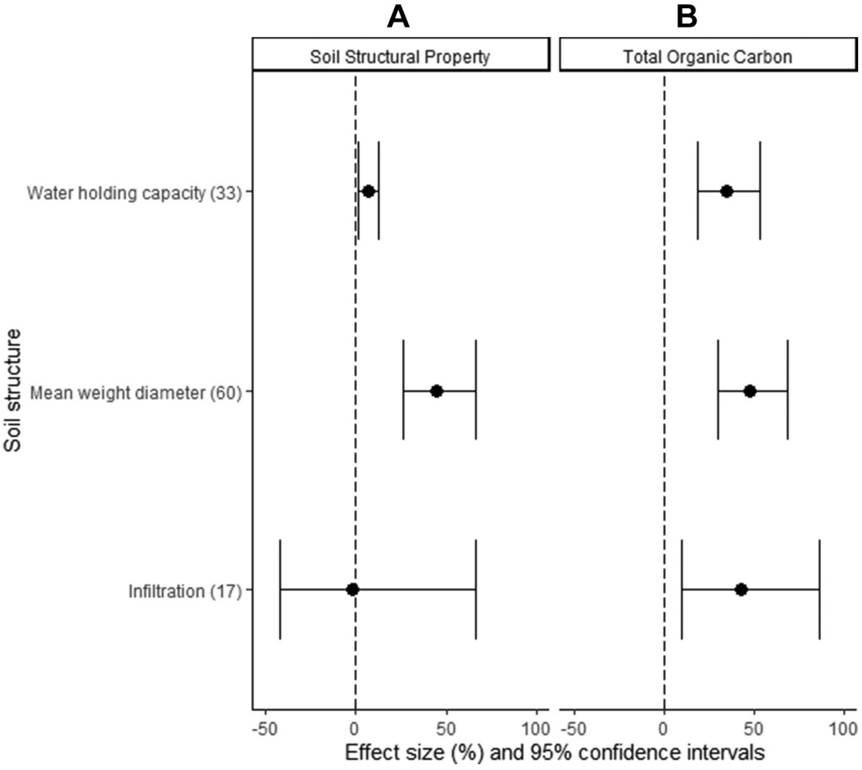


Fig. 5. Effects of all arable land conversions combined on soil structural properties (A) and total SOC (B) in sites where the soil structural properties were measured. There was no statistically significant effect on total SOC or soil structural properties where the 95 % confidence intervals overlapped with zero.

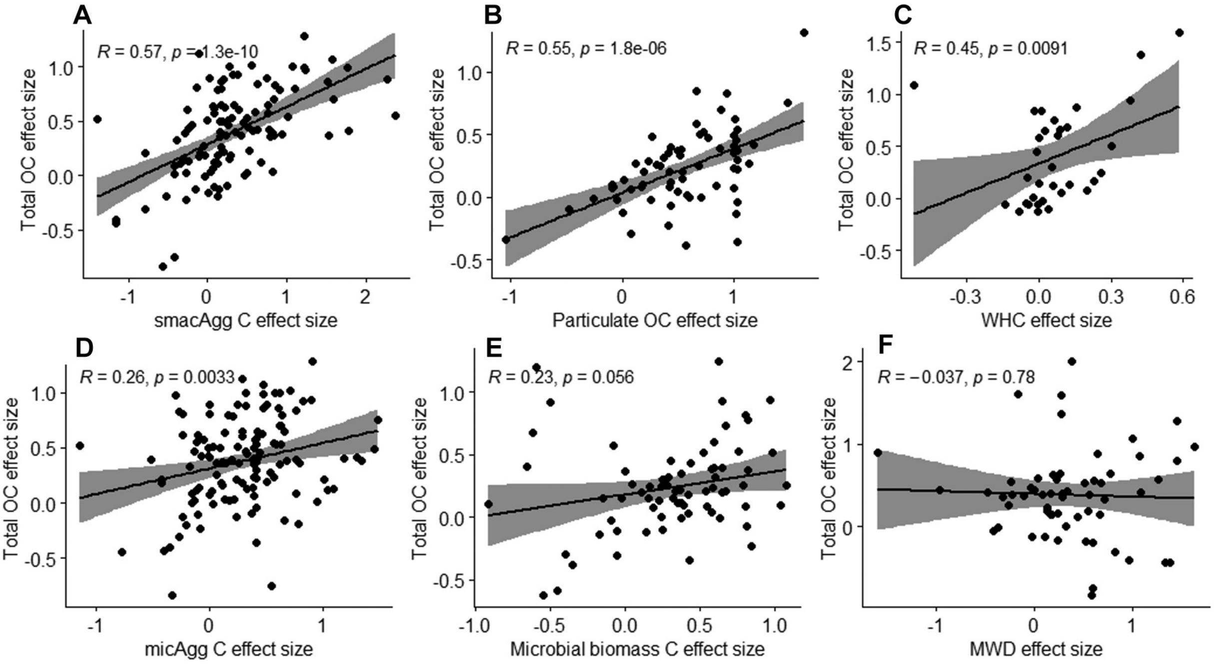
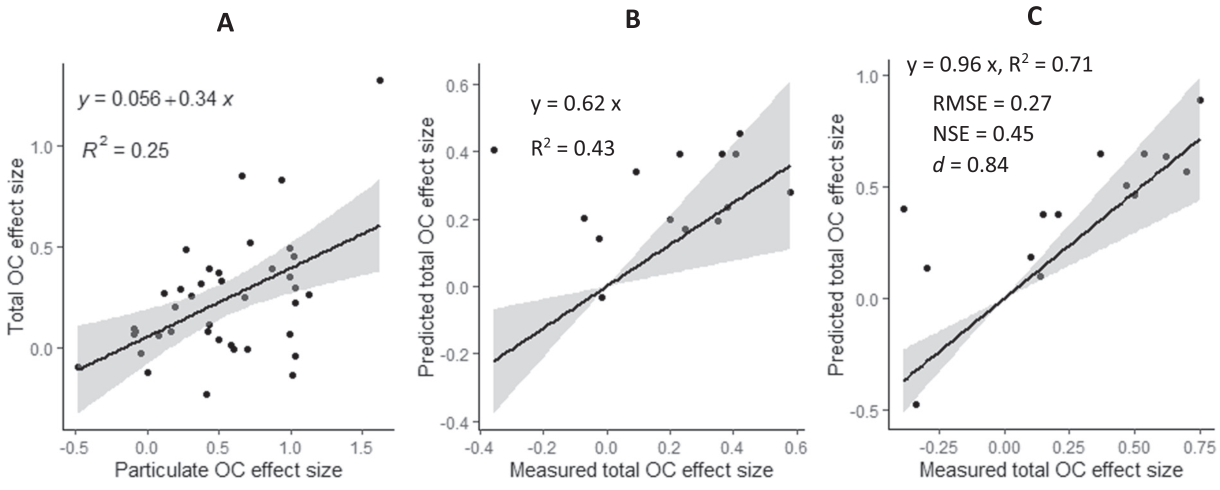


Fig. 6. Correlations between arable land conversion-induced changes in total soil organic carbon (OC) (*y*) and changes in other soil properties (x): A – OC in small macroaggregate soil fraction (smacAgg C); B – particulate OC; C – water holding capacity (WHC); D – OC in microaggregate soil fraction (micAgg C); E – microbial biomass C; F – mean weight diameter (MWD). R = correlation coefficient. Grey band represents the 95 % confidence interval for the regression line.

The influence of environmental factors on the effect size of land use change on SOC fractions depended on the type of SOC fraction and specific land use changes analyzed (Table 3). Under arable to agroforestry land use conversion, time was the only factor that influenced the response of POC, with significant increases occurring after 10 years of establishing agroforestry. In naturally regenerated forests, POC significantly increased at a relatively warm climate conditions of 10.1–20.0 °C MAT; whereas in naturally regenerated grasslands, a significant increase in POC occurred at a wide MAT range of 5.1–20.0 °C, across the Temperate and sub-Tropical regions, <30 % soil clay content and <1000 mm of MAP. The size of afforestation effects on smacAgg C was significantly influenced by only MAP with greatest increase occurring at an intermediate MAP of 600–1000 mm.

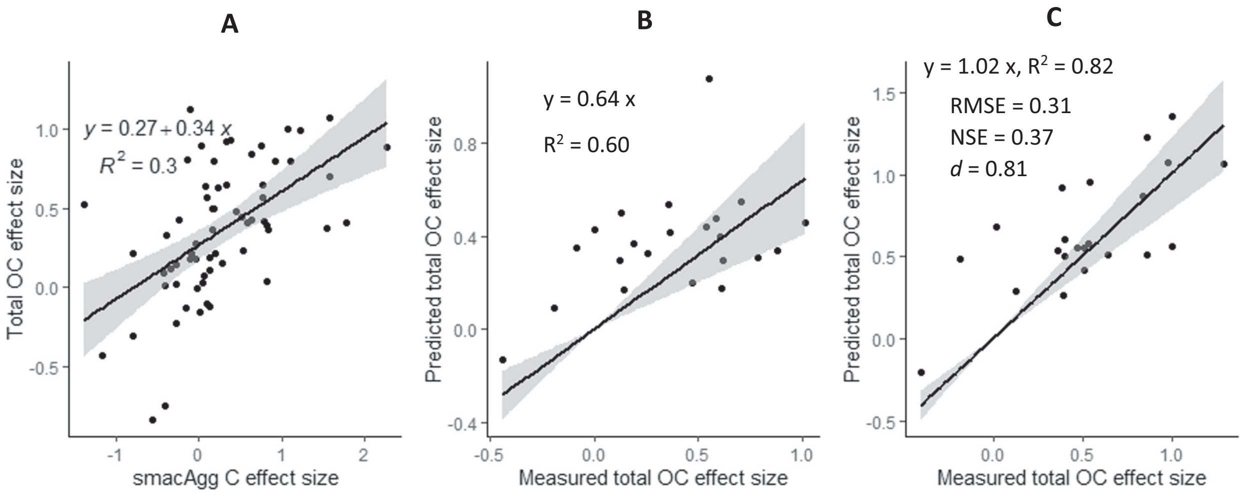


D

Predictive model

Total OC effect size = [0.056 + 0.34 (Particulate OC effect size)]/0.62

Fig. 7. Stages in the development of predictive model of total soil organic carbon (OC) changes using particulate OC. A – training model, B – model calibration, C – model validation, and D – the predictive model. RMSE = root mean square error, NSE = Nash – Sutclifffe Efficiency, *d* = Willmott Index of Agreement. Grey band represents the 95 % confidence interval for the regression line.



D

Predictive model

Total OC effect size = [0.27 + 0.34 (smacAgg C effect size)]/0.64

Fig. 8. Stages in the development of predictive model of total soil organic carbon (OC) changes using OC occluded in small soil macro-aggregates (smacAgg C). A – training model, B – model calibration, C – model validation, and D – the predictive model. RMSE = root mean square error, NSE = Nash – Sutclifffe Efficiency, *d* = Willmott Index of Agreement. Grey band represents the 95 % confidence interval for the regression line.

4. Discussion

4.1. Suitable indicators of changes in total SOC stock

This study revealed that converting arable lands to agroforestry, forests, grasslands or shrublands either through deliberate planting or natural regeneration led to a significant OC build up (+40 %) in the soil within an average of 23 years (10–35 years) after land use change (Fig. 3; Tables S.4 and S.5). This reaffirms findings in earlier studies such as Smith et al. (2016) who reported a global SOC gain of 18–53 % following the conversion of croplands to forests and grasslands.

We showed that arable land conversion increased not only total SOC stock but various SOC fractions. However, out of the many SOC fractions and soil structural properties commonly analyzed and particularly the ones investigated in this study, only POC and smacAgg C proved useful to estimate changes in total SOC stock in response to the conversion of arable lands to other uses. This is partly consistent with our first hypothesis and suggests that POC and smacAgg C can serve as suitable indicators of total SOC response to land management and land use changes. This finding is of particular interest considering that soil POC and mineral-associated OC respond differently to environmental and management changes because their pathways of protection differ (e.g., Rocci et al., 2021).

POC is present in the soil mainly as free plant materials (biomass) with high monosaccharide content and susceptibility to microbial decomposition (Llorente et al., 2017) whereas smacAgg C is held within stable soil macroaggregates limiting access to microbial and enzymatic processes

Table 2
Effects of arable land conversions on SOC fractions.

SOC fraction	Type of land use change (number of datasets)	Effect size (%)	LCI (%)	UCI (%)	*p*-Value
Particulate organic carbon	Afforestation (12)	113.93	62.01	182.50	**<0.001**
	Agroforestry (6)	52.56	7.17	117.17	**0.019**
	Grassland (planted; 28)	50.95	25.91	81.00	**<0.001**
	Naturally regenerated forestland (6)	62.73	10.21	140.27	**0.014**
	Naturally regenerated grassland (12)	65.58	28.13	113.96	**<0.001**
	Naturally regenerated shrubland (3)	140.68	43.65	303.30	**0.001**
	Total (67)	68.07	49.93	88.40	**<0.001**
Carbon in microaggregate size fraction	Afforestation (35)	29.93	12.23	50.43	**0.001**
	Agroforestry (1)	−34.01	−72.25	56.94	0.347
	Grassland (planted; 49)	23.81	9.86	39.54	**0.001**
	Naturally regenerated forestland (8)	74.79	27.71	139.19	**0.001**
	Naturally regenerated grassland (19)	48.62	21.81	81.32	**<0.001**
	Naturally regenerated shrubland (11)	28.12	−1.33	66.36	0.063
	Shrubland (planted; 3)	62.26	1.11	160.39	**0.045**
	Total (126)	32.18	22.40	42.75	**<0.001**
Carbon in small macroaggregate size fraction	Afforestation (29)	102.97	61.85	154.52	**<0.001**
	Agroforestry (1)	−54.72	−86.04	46.84	0.187
	Grassland (planted; 43)	22.32	1.96	46.74	**0.030**
	Naturally regenerated forestland (8)	13.43	−26.21	74.37	0.566
	Naturally regenerated grassland (16)	25.12	−7.96	70.08	0.153
	Naturally regenerated shrubland (9)	−23.75	−49.04	14.10	0.187
	Shrubland (planted; 3)	66.75	−16.47	232.84	0.147
	Total (109)	34.06	18.25	52.00	**<0.001**

SOC = soil organic carbon, LCI = lower confidence interval, UCI = upper confidence interval.

Table 3
Influence of multiple environmental factors and time on the impacts of arable land conversion on SOC fractions.

SOC fraction	Type of land use change	Influencing factor	Factor levels (n)	Effect size (%)	LCI (%)	UCI (%)	p-value
Particulate organic carbon	Agroforestry	Duration	1–5 years (3)	1.40	−35.94	60.51	0.953
			6–10 years (1)	76.84	−22.62	304.14	0.176
			11–30 years (2)	191.04	56.93	439.78	**0.001**
	Naturally regenerated forestland	Mean annual temperature	5.1–10.0 °C (2)	28.21	−35.45	154.64	0.478
			10.1–20.0 °C (4)	95.01	9.17	248.41	**0.024**
	Naturally regenerated grassland	Climate zone	Subtropics (5)	61.74	8.07	142.08	**0.019**
			Temperate (7)	68.12	23.90	128.14	**0.001**
		Mean annual precipitation	Dry (8)	57.90	18.20	110.92	**0.002**
			Intermediate (3)	94.99	13.78	234.18	**0.015**
			Wet (1)	68.25	−35.25	337.23	0.286
		Mean annual temperature	5.1–10.0 °C (8)	58.09	19.82	108.59	**0.001**
			10.1–20.0 °C (4)	88.76	19.85	197.25	**0.006**
		Soil texture	Loam (3)	75.29	4.56	193.88	**0.033**
			Sand (9)	63.20	24.05	114.71	**0.001**
Organic carbon in microaggregate soil fraction	Afforestation	Duration	1–5 years (5)	−17.65	−42.13	17.16	0.280
			6–10 years (6)	20.62	−14.60	70.37	0.287
			11–30 years (14)	46.80	18.05	82.58	**0.001**
			31–50 years (7)	31.31	−5.78	83.00	0.108
			51–100 years (1)	148.90	9.75	464.52	**0.029**
			>100 years (2)	56.42	−8.17	166.47	0.100
		Depth	0–20 (27)	33.78	12.16	59.55	**0.001**
			0–40 (8)	19.28	−11.84	61.40	0.253
	Grassland	Duration	1–5 years (6)	1.09	−20.04	27.80	0.928
			6–10 years (11)	21.03	2.57	42.80	**0.024**
			11–30 years (26)	27.25	13.84	42.25	**<0.001**
			31–50 years (5)	24.66	−3.43	60.93	0.091
			51–100 years (1)	146.87	39.01	338.42	**0.002**
		Depth	0–20 (43)	20.62	10.37	31.82	**<0.001**
			0–40 (6)	47.99	16.95	87.27	**0.001**
Organic carbon in small macroaggregate soil fraction	Afforestation	Mean annual precipitation	Dry (6)	48.32	−23.49	187.57	0.243
			Intermediate (16)	156.90	71.60	284.55	**<0.001**
			Wet (7)	57.93	−15.27	194.35	0.150

SOC = soil organic carbon, LCI = lower confidence interval, UCI = upper confidence interval, n = number of datasets.

(Blanco-Canqui and Lal, 2004). This has led to the historical use of POC as a measure of the "labile" or "active" SOC fraction (Cambardella and Elliott, 1992) with higher turnover times than smacAgg C, which is a more "passive" SOC that is important for long term soil C storage (Guo et al., 2020) and climate change mitigation (Beillouin et al., 2022). Despite the different turnover times of POC and smacAgg C, their changes reflect the response of the total SOC stock to land use change. Although this may be surprising, both POC and smacAgg C have been shown to be particularly responsive to land use changes (Arevalo et al., 2009; Poeplau and Don, 2013). Compared to many other "labile" SOC fractions such as POXC (Skjemstad et al., 2006) and dissolved OC (Trigalet et al., 2016), POC is more responsive to rapid changes in total SOC stock due to land use change. Like POC, smacAgg C is relatively more responsive to land use changes than some other C fractions associated with soil mineral surfaces (Arevalo et al., 2009).

Over 99 % of the land use change data used in this study (Fig. 2) were changes from arable to a more permanent vegetation cover such as grassland or forest, which are known to increase biomass input to the soil. Under these conditions of high biomass input, the possible reasons for rapid changes in POC are two-fold. The first being that the addition of biomass to these less disturbed soils lead to direct increase in POC, unlike in cultivated lands where added biomass gets oxidized very quickly (Trigalet et al., 2016; Zhang et al., 2020a). Secondly, due to the ease of microbial access to POC, any changes in the soil microbial environment due to land use change affect POC (Li et al., 2017). The response of smacAgg C to land use change can also be linked to biological activity including biomass input, which stimulates the formation of soil macroaggregates and C occlusion within them (Kong et al., 2005). Land use change alters the vegetation dynamics in an ecosystem, which influences biomass input and soil macroaggregation (Novara et al., 2013). Rapid formation of soil macroaggregates has been observed in former croplands planted with tress and those allowed to regenerate for 3–8 years, a timescale that is too short for large detectable gains in SOC (Liu et al., 2020; Rong et al., 2020). In other similar studies (e.g., Jiang et al., 2019; Yao et al., 2019; Zhang et al., 2020b), the accumulation of SOC due to revegetation of former arable lands have been mainly due to increase in smacAgg C. Although more stable than POC, the smacAgg C is a relatively dynamic SOC pool susceptible to rapid changes in biological processes of OC occlusion (Novara et al., 2013) and its transfer to other C pools (Del Galdo et al., 2003), hence its high response to land use change.

In terms of rapid response alone, one may be tempted to argue that there are other more sensitive SOC fractions such as microbial biomarkers (e.g., lipids) that can serve as early indicators of total SOC change as they tend to increase even before SOC gain is detected (Shao et al., 2019). We have not investigated these likely early indicators because of lack of data and the extent to which changes in them help to predict changes in total SOC stock remains unknown. One likely challenge with the use of microbial biomarkers to predict changes in total SOC is that they only provide indirect estimate of plant derived C which accounts for >50 % of OC in soil aggregates (Angst et al., 2021). Nonetheless, microbial biomarkers are useful as they give insight into microbial processes in soil C dynamics and can complement the use of POC and smacAgg C, which give a more direct estimate of SOC stock. Another advantage of using POC and smacAgg C as SOC indicators is the ease of isolation using simple techniques that have been around for over three decades (Fig. S.3). POC is generally isolated by dispersing soil in a dispersant such as sodium hexametaphosphate and passing the suspension through a 53 μm sieve (Cambardella and Elliott, 1992). Similarly, smacAgg C is isolated by slaking a sample of soil in water and passing this successively through a 2000 μm and a 250 μm sieves (Cambardella and Elliott, 1993). The relative ease of determining these SOC fractions, may reduce the costs associated with their determination. This will make it more affordable for land managers, who are sometimes required under environmental land management or carbon credit schemes to show proof of environmental outcomes such as C gains in the short term for payments purposes (Juutinen et al., 2018).

4.2. Moderators of fractional SOC response to land use change

The type of arable land conversion is an important determinant of the magnitude and direction of changes in SOC stock resulting from such land use change. Consistent with our second hypothesis, the restoration of arable lands via afforestation had the greatest positive impacts on SOC stock compared to other land cover types such as pastures/grasslands (Laganiere et al., 2010) where negative (Shi et al., 2013), non-significant positive (Gosling et al., 2017) and significant positive (Deng et al., 2016) impacts have been recorded. In our study, the responses of the two SOC fractional indicators – POC and smacAgg C followed similar pattern, with afforestation leading to >100 % increase in each of these fractions.

This relatively higher impact of afforestation on the fractional SOC indicators is attributable to higher afforestation-induced biomass input to the soil than other land uses. The type of vegetation affects the level of organic inputs to the soil and SOC pools (Eclesia et al., 2012; Canedoli et al., 2020) and this has been shown to be high under forest ecosystems (Fujii et al., 2020). Under low biomass input and SOC stock, OC tends to be predominantly stored in association with silt and clay soil fractions (Cotrufo et al., 2019). This fraction saturates under high biomass inputs and additional C then accumulates as POC (Cotrufo et al., 2019), which further serves as a binding agent and nucleus for the formation of macroaggregates (Witzgall et al., 2021) thereby increasing smacAgg C.

In this study, the level of biomass accumulation appears to be the dominant factor influencing the responses of POC and smacAgg C to the conversion of arable lands to other uses. This is because the influence of environmental factors including temperature and precipitation was small and not similar across the different land use types. For example, only precipitation influenced smacAgg C with significant impacts at an intermediate MAP of 600–1000 mm, and none of the environmental factors we assessed had any significant influence on POC in afforested lands where the largest increase in these SOC fractions occurred. A study in a boreal forest ecosystem has also shown the greater influence of increasing plant biomass in the soil layer on SOC than warming (Lim et al., 2019). Although these findings suggest greater impacts of biomass, they do not imply that environmental factors should be ignored in assessing fractional SOC response to land use change. It is a common knowledge that environmental variables influence the growth of living organisms including vegetation that determine the amount of biomass entering the soil. Our study suggests that under optimum or similar environmental conditions, e.g., MAT of 6–19 °C across forests and grasslands (Table 3), differences in vegetation play a dominant role in controlling the amount of biomass entering the soil and the subsequent partitioning of SOC into different pools.

Further studies are required to improve understanding of the dynamics of SOC distribution into the two fractional pools identified in this study – POC and smacAgg C. One key area that is still not fully understood is the turnover of smacAgg C under different scenarios of arable land conversion to other uses. A conceptual model of smacAgg C formation has long been proposed based on the idea that fresh organic residues in soil induces macroaggregate formation as they serve as energy source for microbes (Six et al., 2000b). Disturbances such as tillage disrupts these macroaggregates, leading to loss of SOC (Hati et al., 2021). Where such disturbances are not present or minimized such as in afforested or agroforestry sites, which characterize many ongoing land restoration schemes, it becomes less clear whether smacAgg C continues to accumulate in response to increasing biomass addition and at what rate.

4.3. Uncertainties and limitations

As this study shows, there was very little data from the southern hemisphere (Fig. 1) and SOC data from urban soils converted from arable systems are lacking (Fig. 2), highlighting the need for further studies in these areas. There are also a few other aspects of this study that would allow increased accuracy in the future once the data becomes available. For example, it would be more accurate to predict short term (less than five years) changes in total SOC stock with data across this time frame. However, the availability of short-term data on SOC change was very limited ($n = 6$ for POC and $n = 11$ for smacAgg C) making this insufficient for model development. The models of SOC changes in this study were therefore developed from land use change data across longer periods.

It is known that dominant plant species can influence the response of soils to land use change (Hou et al., 2020), but this potential influence was not assessed in this study. This is because the majority (69 %) of the converted arable lands (used as control) were under cereal cultivation with maize accounting for 74 % of the cereal sites. Also, in 16 % of the sites, the type of crops grown were not specified in the research articles reviewed in this study, which made it impossible to conduct crop-specific study. Further research is needed to try and understand how specific arable land conversions to both specific and broad land uses such as agroforestry, forests, grasslands, shrublands and built-up environment affect soil C dynamics.

The response of SOC stock to land use changes is known to vary by soil depth (Hou et al., 2020). In SOC studies, depth is commonly stratified such that the lower part of one soil layer marks the beginning of another layer (e.g., 0–15 cm, 15–30 cm, 30–60 cm, etc.). In this study, the maximum soil sampling depth (e.g., 0–10 cm, 0–20 cm, 0–30 cm, etc.) was used instead of actual soil layers to reflect the type of data available, and the accuracy of predictions may be increased once more accurate soil depth data accrue. Addressing these research gaps and limitations will help to better understand the impacts of land restoration schemes and inform implementation strategies for achieving maximum benefits.

4.4. Implications for management

It is very important but currently challenging to detect short-term changes in total SOC, and this study shows that labile fractions of SOC can be used as good indicators of short-term changes in total SOC stock. This is good news in terms of land management for two key reasons. Firstly, this provides a potential short-term measure of changes in soil carbon. This means that researchers and regulating agencies will be better equipped to monitor the short-term impact of various land use changes on soil carbon. This will produce evidence on which land use changes potentially sequester the largest amount of carbon on short term. Secondly, the use of these measures will empower farmers and other land managers, especially those participating in environmental land management schemes, to understand and evidence better the short term changes in carbon stocks in their soils. Together this will allow both government agencies and land-owners to align and enact land use changes that best sequester carbon on the short term, which given the accelerating climate crisis is absolutely key to understand.

5. Conclusion

SOC is an important indicator of soil productivity or degradation but the detection of SOC changes in the short term remains a challenge. Many “labile” fractions of SOC that change more rapidly in response to changing land management or land use have been proposed as early indicators of changes in SOC stock. In this study, we showed that not all these proposed fractions are suitable indicators. We identified POC – a “labile” SOC fraction and smacAgg C – a more passive SOC fraction as suitable indicators of changes in total SOC stock. These two fractions were strongly correlated with total SOC stock under arable land conversion to agroforestry, forests, grasslands and shrublands. This study reaffirms the importance of macroaggregation in OC accumulation in soil and revealed its potential for use as a marker for changes in SOC stock. Equations relating fractional SOC pools to total SOC stock were developed, which require testing and validation in land use change experiments. The dynamics of OC storage and turnover in soil macroaggregates will also benefit from further studies to help inform appropriated management practices within land use change projects.

CRediT authorship contribution statement

Samuel Eze: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Matthew Magilton:** Writing – review & editing.

Daniel Magnone: Methodology, Writing – review & editing. **Sandra Varga:** Writing – review & editing. **Iain Gould:** Writing – review & editing. **Theresa G. Mercer:** Writing – review & editing. **Matthew R. Goddard:** Funding acquisition, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

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.scitotenv.2022.160484.

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