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Grain legumes and dryland cereals contribute to carbon sequestration in the drylands of Africa and South Asia

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ABSTRACT

Grain legumes and drylands cereals including chickpea (*Cicer arietinum*), common bean (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*), groundnut (*Arachis hypogaea*), lentil (*Lens culinaris*), pigeon pea (*Cajanus cajan*), soybean (*Glycine max*), finger millet (*Eleusine coracana*), pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*) are the leading sources of food grain in drylands of Africa and South Asia. These crops can help smallholder agriculture to become more resilient, productive, and profitable, but their quantitative impact on carbon sequestration is unknown. The aim of this review study was to quantify their contribution to carbon sequestration across the drylands of Africa and South Asia based on 437 publications with 1319 observations in studies conducted across 32 countries. Cropping systems with grain legumes showed the greatest increase in soil organic carbon (SOC) concentrations, while cereals (and pigeon pea) gave the largest amount of aboveground carbon stock (>2 Mg C ha^{-1}). Estimated carbon stock in post-harvest residues of these crops was 1.51 ± 0.05 Mg C ha^{-1} in Africa and 2.29 ± 0.10 Mg C ha^{-1} in South Asia. These crops produced more aboveground carbon, and significantly increased SOC, when grown as intercrops. Soils with low initial SOC (<1%) and high clay content (>32%) showed the greatest potential for carbon sequestration when cropped with grain legumes and dryland cereals. This study is the first of its kind to provide evidence that grain legumes and drylands cereals improve carbon sequestration across Africa and South Asia.

1. Introduction

Subsistence agriculture is the main livelihood for millions of households in Africa and South Asia, where smallholder farms (<2 ha) account for over 30% of the food produced (Herrero et al., 2017). However, yields in Africa and South Asia are still below potential levels (Godfray and Garnett, 2014), so the vast majority of smallholder communities continue to experience poverty and food insecurity. The situation is worsened by climate change, which has put smallholder communities at risk and reinforced poverty and vulnerability (Knox et al., 2012). One way to spur economic growth and help populations in Africa and South Asia escape poverty is by transforming agriculture (AGRA, 2017; Gassner et al., 2019), e.g., through intensification. However, it is important that this intensification involves crops and cropping

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systems that can enhance soil organic carbon (SOC) content.

Grain legumes and dryland cereals (GLDC) such as sorghum and millets are important crops grown by millions of smallholder farmers in the drylands of Africa and South Asia (AGRA, 2017, 2013; Rao et al., 2016). These crops dominate the current debate on sustainable intensification of smallholder agriculture and play a critical role in food security and economic growth (CGIAR, 2017; Montpellier, 2013). Growing GLDC under smallholder conditions is envisioned to create synergies that can make agriculture more resilient, productive, and profitable (CGIAR, 2017). Recent reviews indicate that integration of both legumes and cereals into farming systems can improve soil health (Snapp et al., 2021), reduce weeds, increase productivity (Franke et al., 2018; Smith et al., 2016), reduce greenhouse gas emission (Jensen et al., 2012) and enhance SOC content (Powlson et al., 2011a). On the contrary, growing single crops continuously has several shortcomings, e.g., it reduces biodiversity, degrades the soil, increases the risk of diseases and pests outbreak, and increases economic risk of farmers (Montpellier, 2013). Sustainable intensification of smallholder farming is crucial to increase productivity and resilience of farms.

Increasing soil carbon levels has become part of the global agenda for climate change mitigation and adaptation, following the launch of three high-level initiatives: the 4 per 1000 initiative, the Koronivia initiative on agriculture, and the recarbonization of soils initiative (Amelung et al., 2020; FAO, 2019). A major way to accumulate SOC is to increase the amount of organic inputs into the soil. This can be achieved by in situ management of crop residues and application of organic amendments such as manure, compost, biochar, biosolids, anaerobic digestates. Organic amendments such as manure application greatly increase soil carbon levels (Bolinder et al., 2020; Gross and Glaser, 2021). On the other hand, biomass transfer and unsustainable use of crop residues are associated with leakages and negate the notion that effective carbon sequestration can occur, without a concurrent reduction in SOC, in locations where composting materials are obtained (Amelung et al., 2020; Powlson et al., 2011b). Therefore, in situ management of organic inputs represents the most effective and sustainable way to accumulate SOC and is primarily achieved by increasing production of above and below-ground biomass or by using green manure. Actual in situ accumulation of carbon can be influenced by crop type, which limits the amount and quality of residues that can be produced in an area (Hijbeek et al., 2019; Jansson et al., 2021), and by climate conditions, soil characteristics, and the way in which the crop is managed within a farming system (Lal, 2011).

A number of systematic reviews and meta-analyses have evaluated carbon sequestration in agricultural soils, focusing on different land management practices (Bai et al., 2019; Beillouin et al., 2022; Corbeels et al., 2019; Das et al., 2021; Haddaway et al., 2017) or on the effect of crop residues, manures, and nitrogen (N) fertilization (Bolinder et al., 2020; Gross and Glaser, 2021; Han et al., 2016; Liu et al., 2014; Lu, 2020). These reviews have provided some insights into the dynamics of SOC in cropland, but there are limitations and knowledge gaps that need to be addressed. One limitation is that existing reviews do not provide information about the type of crops responsible for the changes in SOC. Another limitation is that most reviews are based on observations from Europe, the Americas, and Oceania, with the majority of observations from Africa and South Asia being overlooked. Africa and South Asia have common challenges that differ from those in other regions, e.g., both regions have extensive areas of cropland on low carbon density soils (Zomer et al., 2017) and large tracts of degraded land or land at risk of degradation (Nkonya et al., 2016). In addition, farming systems in Africa and South Asia are still transitioning from extensive to intensive agriculture (AGRA, 2017; Rao et al., 2016) and are being severely affected by ongoing climate change (Knox et al., 2012).

The potential of GLDCs to increase carbon sequestration in the drylands of Africa and South Asia has not been comprehensively reviewed. Further, the conditions in which these crops enhance carbon sequestration in farming systems have not been identified. Therefore, the main objectives of this study were to: (1) quantify changes in SOC under GLDC grown under different soil and management conditions in Africa and South Asia; (2) quantify changes in aboveground carbon when farmers adopt improved varieties of GLDC, and (3) identify drivers of SOC sequestration in cropping systems with GLDC compared with systems without GLDC.

2. Methods

2.1. Choice of crop

Among the grain legumes, chickpea (*Cicer arietinum* L.), cowpea (*Vigna unguiculata* (L.) Walp.), pigeon pea (*Cajanus cajan* (L) Millsp.), groundnut (*Arachis hypogaea* L.), lentil (*Lens culinaris* Medik.), soybean (*Glycine max* (L.) Merr.) and common bean (*Phaseolus vulgaris* L.) were chosen for this analysis. The dryland cereals chosen for this analysis were sorghum (*Sorghum bicolor* (L.) Moench.), pearl millet (*Pennisetum glaucum* (L.) R.Br.), and finger millet *Eleusine coracana* Gaertn.). These crops were specifically selected because they have been identified by the CGIAR Research Program on GLDC (CGIAR, 2017) as critical for transforming agriculture in Africa, South Asia, and other regions where poverty, malnutrition, soil degradation and impacts of climate change are most severe (Kuyah et al., 2022). They are also among the most important crops grown by millions of smallholder farmers in the drylands of Africa and South Asia (AGRA, 2017, 2013; Rao et al., 2016).

2.2. Literature search

The primary studies reviewed in this study were located by searching three bibliographic databases (Web of Science, SCOPUS, and ProQuest) using a set of search strings (Table S1 in Supplementary material (SM)). The search strings included: (1) 10 priority crops, including their common name, scientific name and synonym/s, (2) indicators of the outcomes of adopting GLDC, (3) study scale, i.e., farm, field, or plot (excluding greenhouse or pot experiments), and (4) the region/country where the study was conducted. Including study area terms limited the number of search results but also captured studies that did not explicitly refer to Africa or South Asia. The reference lists in the publications retrieved were checked for relevant studies that were not captured by the search strings.

2.3. Selection criteria and screening of publications

A study was included when it fulfilled all three of the following criteria: (i) published in a peer reviewed journal, book chapter, or peer-reviewed proceedings, (ii) original experimental or observational study conducted in farmers' fields or on a research station in Africa or South Asia, and (iii) reported quantitative data on aboveground carbon or SOC in a cropping system that included at least one of the selected GLDC crops. Pot or greenhouse experiments, laboratory studies, modelling studies and reviews (narrative, systematic reviews, meta-analyses) were excluded. Total number of publications found, potential papers retained after reading the title and abstract and number of relevant papers from which data were extracted are shown in Fig. 1. Duplicate references were removed. The titles and abstracts of retrieved articles were examined to remove irrelevant literature. Finally, full texts were appraised and the data therein were extracted. Double screening was conducted on a subset (~10%) of the publications retrieved to check agreement (on selection criteria) between assessors.

2.4. Data retrieval and classification

A total of 437 publications with 1319 observations met the selection criteria (SM 2), of which 250 were from Africa and 187 from South Asia. Fifty studies came from areas outside drylands, while the majority (90%) came from areas that can be broadly classified as drylands in Africa and

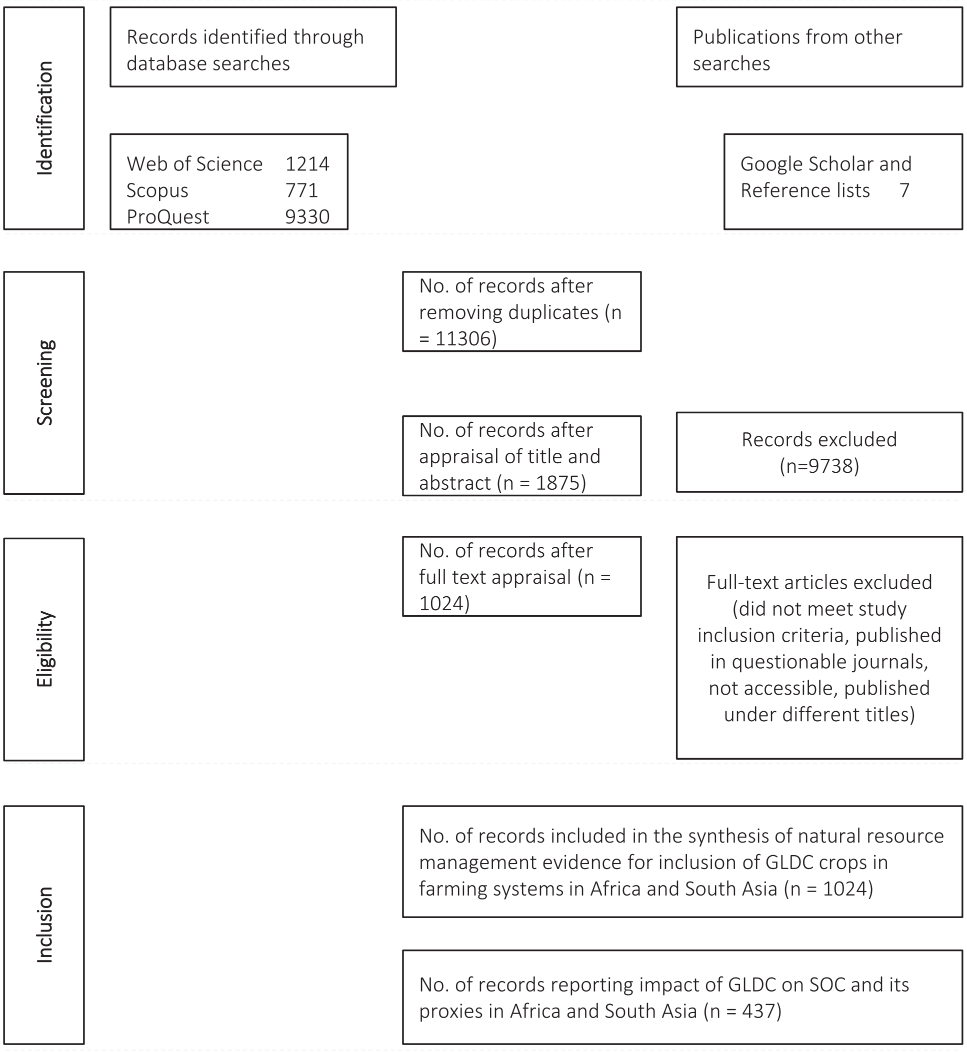

Fig. 1. Flow diagram illustrating the selection procedure, publications obtained in the literature search, and the screening process. (adapted from Kuyah et al., 2022).

South Asia. Fig. 2 shows their locations on a map the global distribution of drylands developed by FAO, ITPS (2021). The FAO and ITPS map combines the three different maps, namely, (1) the UNEP-World Conservation Monitoring Centre (UNEP-WCMC) map (Sörensen (2007); (2) the CGIAR Consortium for Spatial Information (CGIAR-CSI) map (Trabucco and Zomer, 2018); and (3) the World Terrestrial Ecosystems

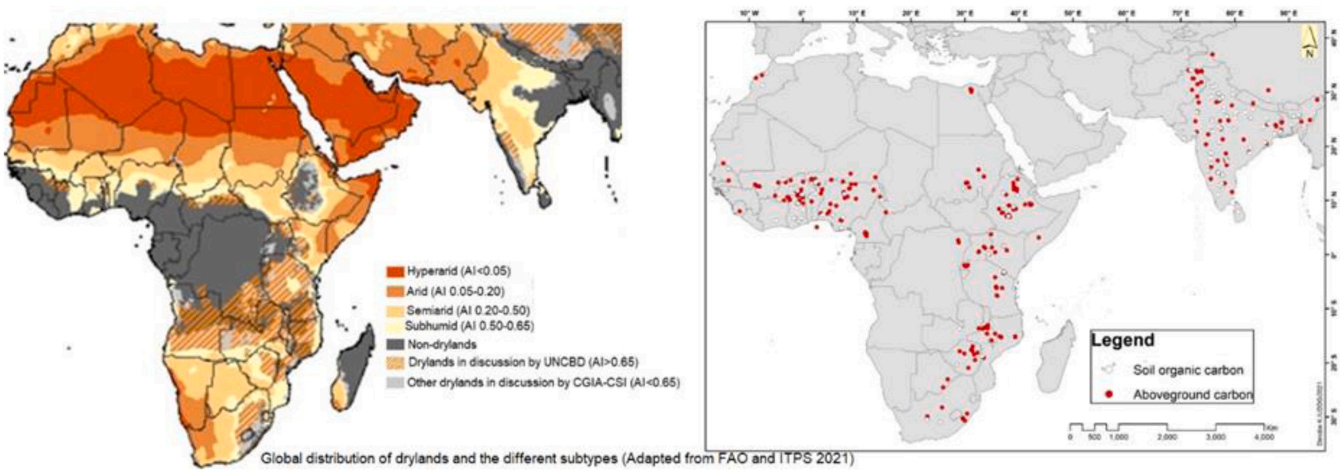

Fig. 2. Spatial distribution of published studies reporting soil organic carbon and aboveground carbon levels in cropping systems with dryland cereals (finger millet, pearl millet, sorghum) and grain legumes (chickpea, common bean, cowpea, lentil, pigeon pea, soybean) in the drylands of Africa and South Asia.

platform, Nature Conservancy, and USGS USGS-ESRI map (Sayre et al., 2020). Although the definition of drylands is still evolving, the United Nations Convention on Biological Diversity (UNCBD) defines drylands as areas ranging from hyper-arid to humid that are functionally connected (Sorensen, 2007). Following this logic, the dataset are representative of drylands.

Information extracted from the selected publications included bibliographic information (author and year), study location (continent, country, study site, and geographical coordinates), site characteristics (elevation, clay content, soil texture class, initial SOC, and depth to which soil samples were collected), climate conditions (mean annual rainfall), soil type, cropping system (continuous monocropping, intercropping, crop rotation and agroforestry), the GLDC species, fertilizer type (N, phosphorus (P)) and level, organic amendments, water regime (rain-fed or irrigation), and residue management (retained or removed). Mean values were recorded from data reported in tables and within the text, or extracted from figures using WebPlotDigitizer (Rohatgi, 2020). In addition, sample size (i.e., number of replicates or any other sample size recorded) was extracted. Missing rainfall data (total precipitation) were extracted from the SamSamWater Climate Tool (SamSamWater Foundation, 2018).

Soil type reported in the USDA or other classification systems were converted into the World Reference Base (WRB) system through *pro-parte* matching using the legends of the International Union of Soil Scientists (IUSS Working Group WRB, 2015). Soils were grouped into three broad texture classes (sandy, loam, clay), based on the fractions of sand, silt, and clay reported in the publications reviewed. These categories correspond to coarse-textured (<20% clay), medium-textured (20–32% clay) and fine-textured (>32% clay) soils, respectively. Initial SOC concentrations reported in each publication were divided into three groups as < 1%, 1–1.5% and > 1.5% to facilitate statistical analysis using SOC as a categorical variable.

2.5. Response variables relevant to carbon sequestration

Aboveground biomass carbon stocks and SOC concentrations were used as the response variables in the analysis because they are the most important measures of carbon storage in terrestrial ecosystems. Aboveground biomass carbon was assumed to consist of all carbon in plant biomass including straw, stover, and other postharvest residues excluding root biomass. Post-harvest residues were considered to refer to dry matter when a publication explicitly reported that samples were oven-dried to constant weight (with the term dry matter used interchangeably with biomass to refer to mass of plant material in dehydrated state). Grain biomass was not included in aboveground carbon as it was generally reported separately and is removed from the field. Dry matter values were converted to aboveground biomass carbon using the IPCC default carbon fraction of 47% for annual crops (IPCC, 2019).

Amount of biomass carbon that could be added to the soil was estimated as the sum of carbon in aboveground residues and carbon in belowground parts, including carbon in root biomass and rhizo-deposited carbon (Bolinder et al., 2007). The carbon input without residues was estimated by assuming that only 80% of residues leave the field (Bolinder et al., 2007) because a large proportion is often left behind as stubble, chaff and uncollected straw (Powlson et al., 2011a). Carbon in root biomass was calculated from aboveground carbon using root-to-shoot ratios reported in the literature. Carbon in rhizo-deposits was estimated from carbon in root tissues assuming that 65% of carbon in roots is released through exudation and sloughing of root hairs and fine roots during growth (Bolinder et al., 2007).

Data on SOC concentrations (%) were obtained from publications that reported SOC in the topsoil (0–30 cm depth), i.e. the layer in which SOC is most strongly influenced by management practices such as ploughing and input from crop roots. This soil depth is also recommended for national carbon accounting (IPCC, 2019). In the primary studies, sampling depths varied within the 0–30 cm profile, but in the majority of the publications (64) the 0–15 cm soil depth was covered while in 4, 30 and 18 publications, 0–10 cm, 0–20 cm and 0–30 cm soil depth were covered, respectively. It was assumed that different maximum sampling depths within the 0–30 cm layer did not affect SOC trends in qualitative since the meta-analysis was based on a relative effect measure. The concentrations of SOC in the topsoil layer were extracted as reported in each study and then converted to a percentage (by weight). SOC concentrations were used for comparisons in the meta-analysis because it is a more direct measure that is not influenced by soil volume and bulk density estimations (Aguilera et al., 2013). Bulk density was reported in only 48 publications and displayed such large variations that it was not possible to estimate missing bulk densities from regression of reported bulk density and SOC concentrations, as done in other studies. In addition, bulk densities were mostly reported for the treatment group, while values for the control group were missing. Therefore, SOC concentrations were not converted to weight of carbon per unit area (Mg ha^{-1}) as that would have over- or under-estimated soil carbon stock.

2.6. Independent observations and subgroup analysis

The following restrictions were applied to avoid non-independence of observations when a study reported multiple outcomes arising from several treatments, repeated measurements, multiple species, or different locations (Borenstein et al., 2009; Koricheva et al., 2013). Observations within a study were assumed to provide independent estimates of the effect if they were recorded at different locations (study sites) or if the experiments were conducted in different years (growing seasons) or involved different crop species. Where a study reported multiple values because of different fertilizer doses or different amounts of manure application, all the levels were entered in the database but only the recommended rate was selected to constitute an independent observation in the analysis. Where a study reported different tillage practices, residue management, or water regime, the effect sizes were calculated from data collected in the same group. A mean was calculated when a study reported multiple results for comparisons involving several varieties or cultivars. However, when a study reported both improved and local varieties, results for both varieties were selected and used to compare changes in aboveground carbon or SOC when farmers shifted from local to improved varieties. When multiple publications reported results on the same study (site) over different years, data were extracted only from the publication reporting the latest observations. When a study reported data on the same crop grown in more than one season or year, initial measurement and measurement at the end of the experiment, or the measurement in the first and the final year, was taken as the control and treatment value for SOC, respectively.

2.7. Statistical analysis

The response ratio (RR) was used as the effect size metric to facilitate statistical analysis as it measures the effect size of a treatment over that of the control group and is an appropriate metric for outcomes across studies that use different measurement procedures (Hedges et al., 1999). Here, RR was calculated as the ratio of the response variable (e.g., SOC) found on farms with GLDC and the corresponding value in the control (i.e., farms without GLDC). Logarithmic transformation is necessary to normalize RR values (Hedges et al., 1999), so the natural logarithm of RR (*lnRR*) was used to estimate the effect of GLDCs on SOC concentrations or aboveground biomass carbon stocks. Mean effect size and bias-corrected 95% confidence intervals (CI) were calculated with bootstrapping with (10,000 iterations), using the boot package in the R programming language 4.0.0 (R Core Team, 2020). The *lnRR* estimates were then back-transformed to the arithmetic domain to facilitate interpretation where: $RR = 1$ indicates the same response in the treatment and control, $RR > 1$ indicates that SOC was higher in the treatment compared to the control, and $RR < 1$ indicates that the effect of the treatment was lower than that of the control. The means of subgroups were considered to differ significantly if their 95% CI did not overlap. Estimated means ± standard error are presented in all cases.

Two types of comparisons, i.e. “before vs after” and “with vs without”, were used for subgroups that had a minimum of three publications with 12 observations. The first type of comparison involved comparison of SOC before and after inclusion of GLDC in the cropping system for publications that reported SOC values at the start of the experiment (initial SOC content) and the end of the experiment. The second type involved comparison of SOC in cropping systems with GLDC and in systems without GLDC for publications that reported SOC values. Here the treatment group included a GLDC and the control group was a crop other than GLDC. Subgroup analyses were performed using soil type, soil texture group, initial SOC, cropping system, crop species, and combinations of crops (i.e., grain legumes, dryland cereal, other cereals [maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), tef (*Eragrostis tef* (Zucc.) Trotter)]) as predictors to assess whether outcomes of GLDC integration differed for different combinations. Linear mixed effects models were used to test for significant effects of the selected predictors on aboveground biomass carbon and SOC. Ordinary least square regression and locally weighted scatterplot smoothing (LOESS) were used to explore the relationship between aboveground carbon and SOC (SM 3). In the regression analyses, the Johnson-Neyman technique (White, 2003) was followed when testing for equality of variances, slopes and intercepts. All statistical analyses were carried out in R 4.0.0 (R Core Team, 2020) with the package lme4.

3. Results

3.1. Aboveground biomass carbon contributions of sorghum, millet, and grain legumes

Synthesis of data from 437 publications on the drylands of Africa and south Asia showed that cropping systems with GLDC on average yield 1.76 ± 0.05 Mg C ha^{-1} in post-harvest aboveground residues (Fig. 1). This amount varied significantly with region, soil type, and cropping system (Fig. 3). Significantly higher aboveground carbon stocks were recorded in South Asia (2.29 ± 0.05 Mg C ha^{-1}) than in Africa (1.51 ± 0.05 Mg C ha^{-1}). Aboveground carbon stocks were also higher in studies located on Andosols and Luvisols than in those on Arenosols, Plinthosols, or Fluvisols (Fig. 3). There was greater uncertainty in aboveground carbon stocks on Cambisols than on the other soils. GLDC contributed the greatest amount of aboveground carbon in intercropping, followed by continuous sole cropping, and crop rotation (Fig. 3). The lowest amount of aboveground carbon was contributed by GLDCs in agroforestry systems.

Sorghum, millets, and pigeon pea gave the greatest amount of aboveground carbon stocks in both regions, while chickpea gave the lowest amount in Africa and lentil gave the lowest amount in South Asia (Table 1). Aboveground carbon stocks in pigeon pea were twice that in all other crops except finger millet and sorghum. In Africa, the total carbon potentially available for addition to the soil ranged from 1.24 ± 0.18 Mg ha^{-1} in chickpea to 5.36 ± 0.83 Mg ha^{-1} in finger millet when residues were retained in the field and from 0.45 ± 0.19 Mg ha^{-1} in soybean to 2.18 ± 0.79 Mg ha^{-1} in finger millet when residues were removed (Table 1). The corresponding amounts in South Asia ranged from 0.99 ± 0.22 Mg ha^{-1} in lentil to 4.60 ± 0.42 Mg ha^{-1} in sorghum when residues were retained and 0.41 ± 0.13 Mg ha^{-1} in lentil to 2.11 ± 0.65 Mg ha^{-1} in sorghum when residues were removed from the field (Table 1).

3.2. Soil organic carbon concentrations in cropping systems with GLDC

Across cropping systems with GLDCs, the estiamted SOC concentrations was 0.76 ± 0.04% (Fig. 4). The average SOC concentration in Africa (0.96 ± 0.06%) was significantly higher than that in South Asia (0.58 ± 0.04%) (Fig. 4). Soil organic carbon concentrations were significantly higher on Ferralsols than the other soil types (Fig. 4). This matched with the initial SOC concentrations reported in the primary studies; that sites located on Ferralsols (1.30%) and Ultisols (1.14%) had higher SOC compared to sites located on Arenosols (0.39%), Cambisols (0.61%), Lixisols (0.58%), Luvisols (0.58%), or Vertisols (0.64%). When

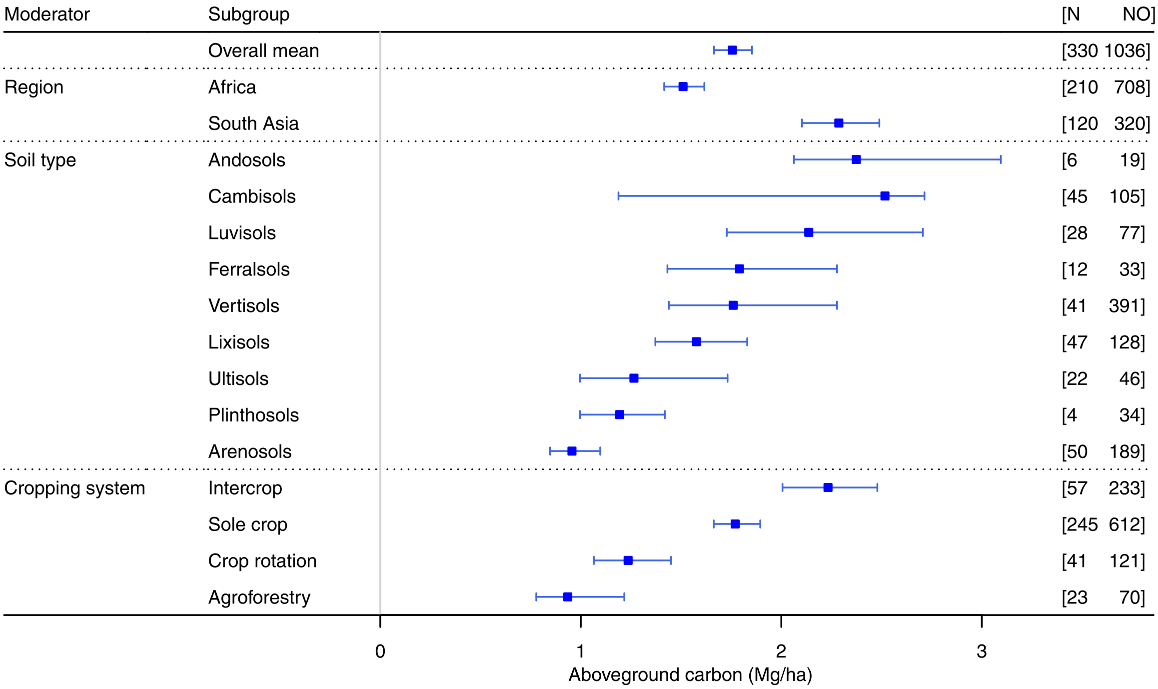

Fig. 3. Variation in aboveground carbon stocks in farms and fields with grain legumes and dryland cereals in Africa and south Asia according to region, soil type and cropping system. Squares and horizontal bars represent mean and 95% confidence intervals, respectively. Number of publications [N] and number of paired observations [NO] in each class are shown in brackets.

Table 1
Aboveground biomass carbon (mean±standard error), belowground biomass carbon and the amount of carbon stock (Mg C ha^{-1} harvest^{-1}) potentially available for addition to the soil in the drylands of Africa and South Asia. N = number of publications that included the crop, NO = number of paired observations where the crop was reported.

Region	Priority crop	Aboveground carbon	Belowground carbon		Available crop carbon input		N	NO	Root-to-shoot ratio (reference)
			Carbon in root biomass	Carbon in rhizo-deposits	Residues retained	Residues removed			
Africa	Chickpea	0.91 ± 0.13	0.20 ± 0.03	0.12 ± 0.02	1.24 ± 0.18	0.51 ± 0.19	7	21	0.22 (Gan et al., 2009)
	Common bean	1.42 ± 0.15	0.33 ± 0.03	0.21 ± 0.02	1.95 ± 0.20	0.82 ± 0.29	20	48	0.23 (De Costa et al., 1997)
	Cowpea	0.98 ± 0.08	0.27 ± 0.02	0.17 ± 0.01	1.42 ± 0.12	0.63 ± 0.20	48	139	0.27 (Laberge et al., 2011),
	Finger millet	3.98 ± 0.62	0.84 ± 0.13	0.54 ± 0.08	5.36 ± 0.83	2.18 ± 0.74	3	11	0.21 (Krishna and Reddy, 2021)
	Groundnut	1.36 ± 0.16	0.20 ± 0.02	0.13 ± 0.02	1.69 ± 0.20	0.61 ± 0.26	25	64	0.15 (Shridhar Rao et al., 2012)
	Lentil	0.94 ± 0.01	0.21 ± 0.00	0.13 ± 0.00	1.28 ± 0.01	0.53 ± 0.19	1	2	0.22 (Gan et al., 2009)
	Pearl millet	1.33 ± 0.09	0.41 ± 0.03	0.27 ± 0.02	2.01 ± 0.14	0.94 ± 0.28	48	142	0.31 (Brück et al., 2003)
	Pigeon pea	2.21 ± 0.38	0.46 ± 0.08	0.30 ± 0.05	2.98 ± 0.51	1.21 ± 0.44	13	30	0.21 (Rao and Itto 1998)
	Sorghum	2.10 ± 0.15	0.61 ± 0.04	0.40 ± 0.03	3.22 ± 0.21	1.43 ± 0.44	50	111	0.22–0.36 (Ghosh et al., 2004; Ramesh et al., 2005)
	Soybean	1.00 ± 0.09	0.15 ± 0.01	0.10 ± 0.01	1.25 ± 0.11	0.45 ± 0.19	56	77	0.15 (Ramesh et al., 2005)
South Asia	Chickpea	1.20 ± 0.15	0.26 ± 0.03	0.17 ± 0.02	1.63 ± 0.20	0.67 ± 0.25	24	39	0.22 (Gan et al., 2009)
	Common bean	2.46 ± 0.58	0.57 ± 0.13	0.37 ± 0.09	3.40 ± 0.80	1.43 ± 0.49	4	7	0.23 (De Costa et al., 1997)
	Cowpea	1.88 ± 0.37	0.51 ± 0.10	0.33 ± 0.06	2.72 ± 0.53	1.22 ± 0.43	13	29	0.27 (Laberge et al., 2011)
	Finger millet	1.18 ± 0.32	0.25 ± 0.07	0.16 ± 0.04	1.59 ± 0.43	0.65 ± 0.23	5	9	0.21 (Krishna and Reddy, 2021)
	Groundnut	1.64 ± 0.16	0.25 ± 0.02	0.16 ± 0.02	2.05 ± 0.20	0.74 ± 0.32	21	44	0.15 (Shridhar Rao et al., 2012)
	Lentil	0.73 ± 0.16	0.16 ± 0.04	0.10 ± 0.02	0.99 ± 0.22	0.41 ± 0.13	4	5	0.22 (Gan et al., 2009)
	Pearl millet	2.91 ± 0.25	0.90 ± 0.08	0.59 ± 0.05	4.40 ± 0.37	2.07 ± 0.63	8	38	0.31 (Brück et al., 2003)
	Pigeon pea	2.75 ± 0.34	0.58 ± 0.07	0.37 ± 0.05	3.70 ± 0.46	1.50 ± 0.54	9	23	0.21 (Rao and Itto 1998)
	Sorghum	3.11 ± 0.28	0.90 ± 0.08	0.59 ± 0.05	4.60 ± 0.42	2.11 ± 0.65	28	56	0.22–0.36 (Ghosh et al., 2004; Ramesh et al., 2005)
	Soybean	2.12 ± 0.30	0.32 ± 0.05	0.21 ± 0.03	2.65 ± 0.38	0.95 ± 0.41	26	46	0.15 (Ramesh et al., 2005)

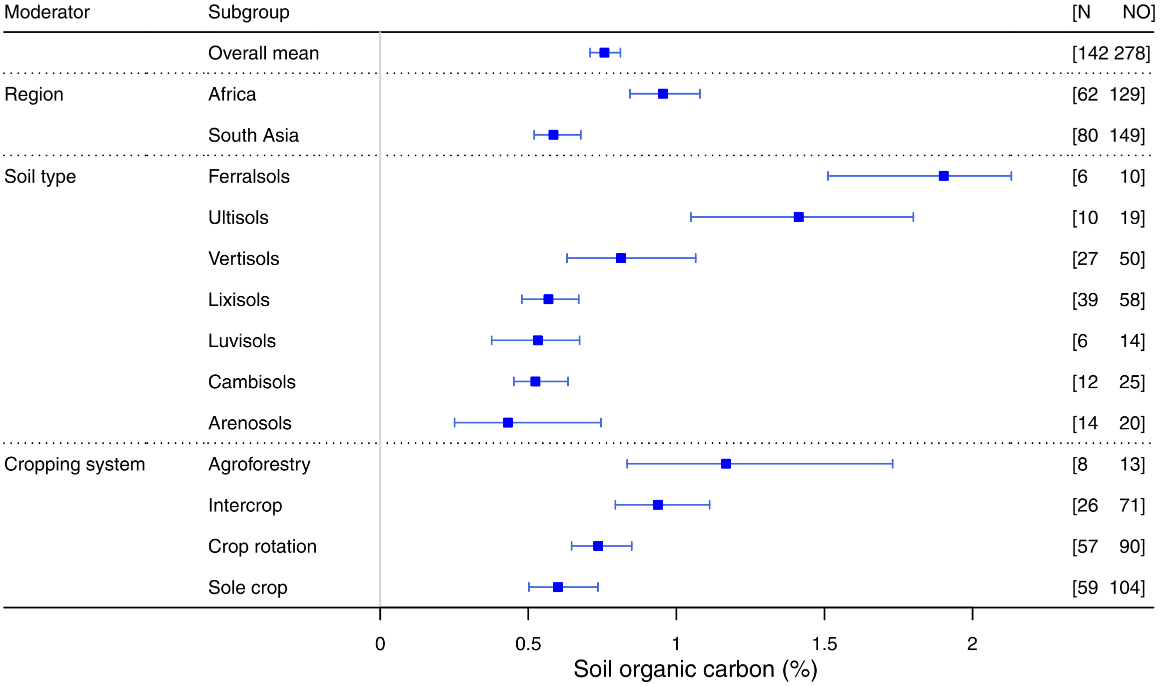

Fig. 4. Soil organic carbon concentrations at 0–30 cm depth on farms or fields with grain legumes and dryland cereals in Africa and South Asia. Squares and horizontal bars represent mean and 95% confidence intervals, respectively. Number of publications [N] and number of paired observations [NO] in each class are shown in brackets.

cropping systems were compared, SOC concentrations were significantly higher in agroforestry and intercropping than in continuous sole cropping (Fig. 4). The highest SOC concentration was recorded in systems including legumes, while the lowest SOC was in cropping systems consisting solely of cereals.

3.3. *Effect of cropping system, crop combination and variety on aboveground carbon stocks*

A total of 59 publications with 182 paired observations fulfilled the selection criteria for comparing changes in aboveground carbon stocks when sorghum, millet, or grain legumes were grown in different cropping systems or crop combinations. Among these, 14 publications with

29 observations had reported changes in aboveground carbon stocks when farmers shifted from traditional to improved varieties of chickpea, common bean, cowpea, pearl millet, sorghum, or soybean.

Growing sorghum, millets, or grain legumes as intercrops (RR: 1.44, 95% CI: 1.34, 1.56) or in rotations (RR: 1.04, 95% CI: 1.00, 1.11) significantly increased aboveground carbon stocks compared to continuous sole cropping, with the increase being much greater in intercrops (44%) than in crop rotations (12%). When different combinations were evaluated, intercropping grain legumes (main crop) with dryland cereals or other cereals (maize, wheat, rice) gave the greatest increase (>50%) in aboveground carbon stocks (Fig. 5; Table S2 in SM). Surprisingly, growing dryland cereals in agroforestry increased aboveground carbon by 24%, while growing grain legumes in agroforestry did not have a significant impact (RR: 0.79, 95% CI: 0.424, 1.27). Growing dryland cereals in rotation with grain legumes increased aboveground biomass by 27%. However, there were no significant differences between the different crop combinations. Aboveground carbon stocks (not including the grain) decreased by 40% when farmers shifted from local to improved varieties (Fig. 5).

3.4. *Effect of soil characteristics on changes in SOC concentrations*

A total of 81 publications (with 144 paired observations) had reported data on SOC concentrations at the start of the experiment (initial SOC concentrations) and the end of the experiment (final SOC concentrations), allowing evaluation of changes in SOC caused by inclusion of sorghum, millet, or any of the grain legumes. The studies concerned were conducted over a period ranging from 1.9 to 47 years, with a median of 7 years. Inclusion of GLDC in cropping systems gave a general trend for increased SOC relative to initial SOC concentrations although not statistically significant at the prescribed level of confidence. Within the dataset, there were more observations of an increase in SOC concentrations (59%; n = 108) compared to those of a decrease (41%). SOC increases did not significantly differ between Africa (RR: 1.02; 95% CI = [0.94, 0.10]) and South Asia (RR: 1.07, 95% CI = [0.95, 1.20]).

Across regions, inclusion of GLDC significantly increased SOC concentrations on Ferralsols and Vertisols, but decreased SOC concentrations on Lixisols and Luvisols (Fig. 6). The effect was not significant for Cambisols and Arenosols, but showed a near significant positive trend for Ultisols. Inclusion of GLDC in cropping systems increased SOC concentrations on clay soils, but did not significantly affect loam and sandy soils (Fig. 6). However, the effect of GLDC did not vary significantly with soil texture groups. There was a significant increase in SOC concentrations at sites where initial SOC content was below 1% but a decrease in soils that contained more than 1.5% SOC (RR=0.73) at the start of the experiments (Fig. 6). The confidence intervals were wider on soils with initial SOC > 1.5%, suggesting higher variation due to small sample size. Soils that had moderate initial SOC concentrations (1–1.5%) showed a non-significant change at the end of the experiments (Fig. 6).

3.5. *Effect of cropping system and crop combination on SOC concentrations*

Soil organic carbon concentrations were significantly higher after intercropping but there was no significant differences between initial and final SOC concentrations when sorghum, millet and grain legumes were included in crop rotations, or were the continuous sole crop (Fig. 7). Differences between intercropping, crop rotations, and sole cropping were also not significant. SOC concentrations significantly increased in cropping systems involving pigeon pea, chickpea and soybean, but declined under sorghum (Fig. 7). Cropping systems involving pearl millet did not have a significant effect on SOC.

A total of 42 publications (80 paired observations) reported SOC levels on farms with and without GLDC in different crop combinations. The overall mean effect size (RR=1.54, 95% CI: [1.44, 1.63]) was significantly greater than 1, suggesting that SOC concentrations was higher in systems that included sorghum, millet, or any of the grain legumes than in systems which did not. Planting grain legumes as

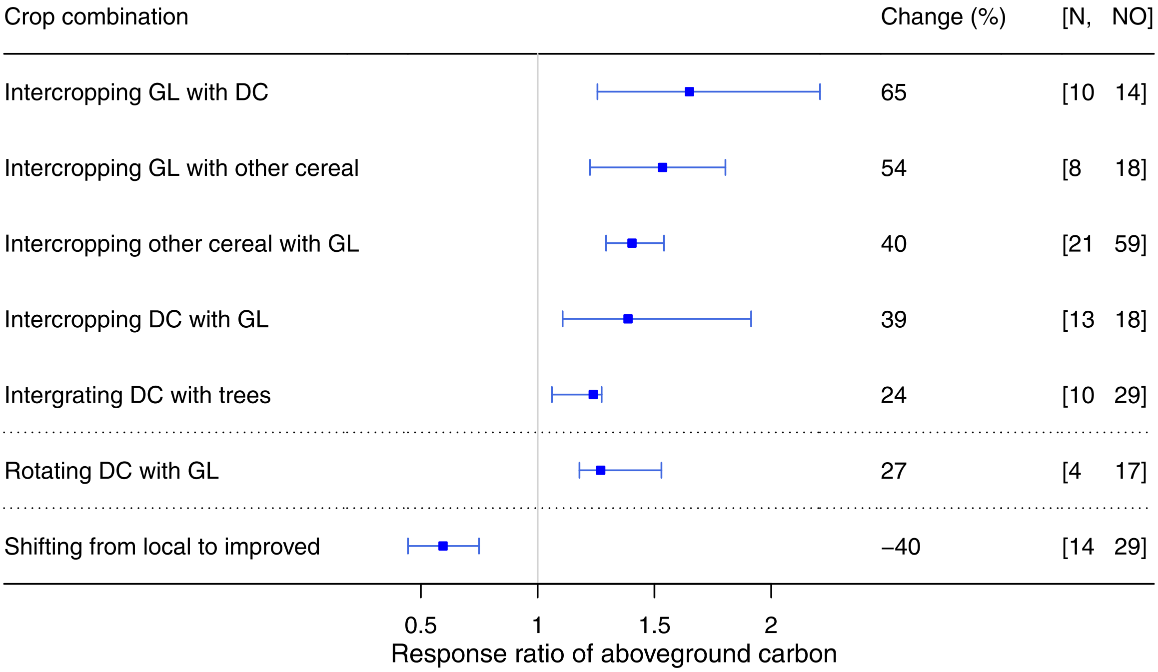

Fig. 5. Changes in aboveground carbon under different crop combinations and varieties. Squares and horizontal bars represent mean and 95% confidence intervals, respectively. Number of publications [N] and number of paired observations [NO] in each class are shown in brackets. The different crop combinations are intercropping grain legumes (GL: common bean, cowpea, groundnut, pigeon pea, soybean) with dryland cereals (DC: sorghum, finger millet, pearl millet); intercropping GL (common bean, cowpea, groundnut, soybean) with other cereals (maize, wheat); intercropping other cereals (maize, rice, wheat) with GL (common bean, cowpea, groundnut, pigeon pea, soybean); intercropping DC (finger millet, pearl millet, sorghum) with GL (common bean, cowpea, groundnut, pigeon pea, soybean); combining DC (pearl millet, sorghum) with trees; and rotating DC (pearl millet, sorghum) with GL (cowpea).

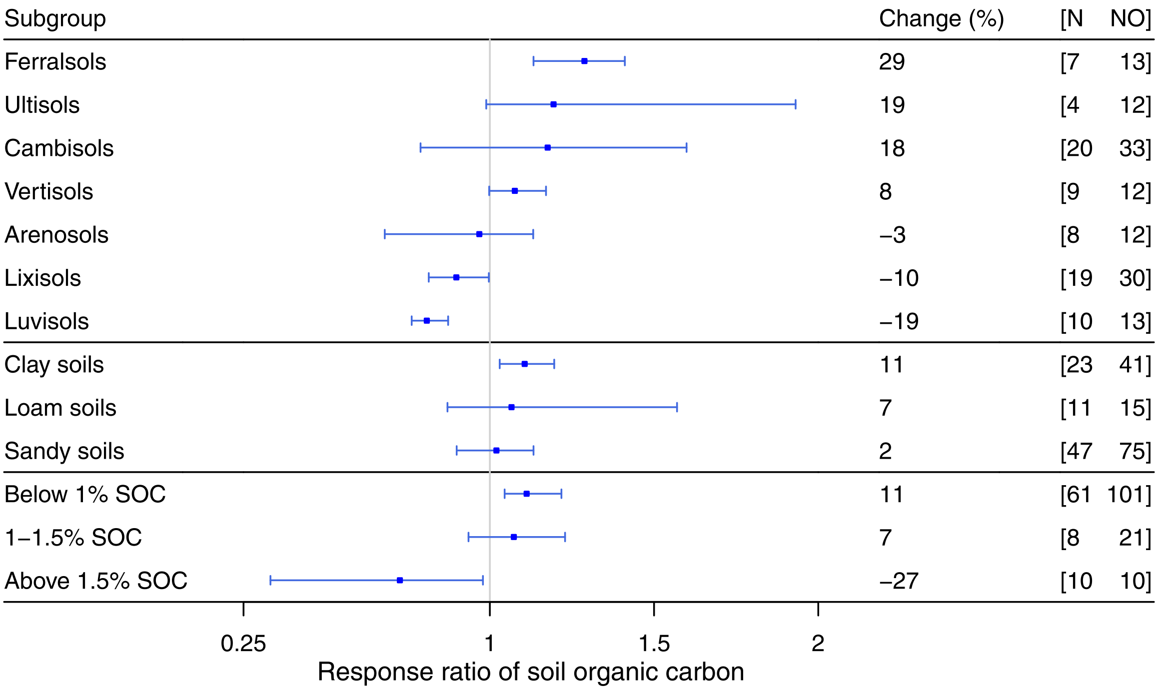

Fig. 6. Changes in soil organic carbon (SOC) concentrations in different soil types, and soil texture groups, and initial SOC concentration in studies comparing SOC at the start and end of the experiment. Squares and horizontal bars represent mean and 95% confidence intervals, respectively. Number of publications [N] and number of paired observations [NO] in each class are shown in brackets.

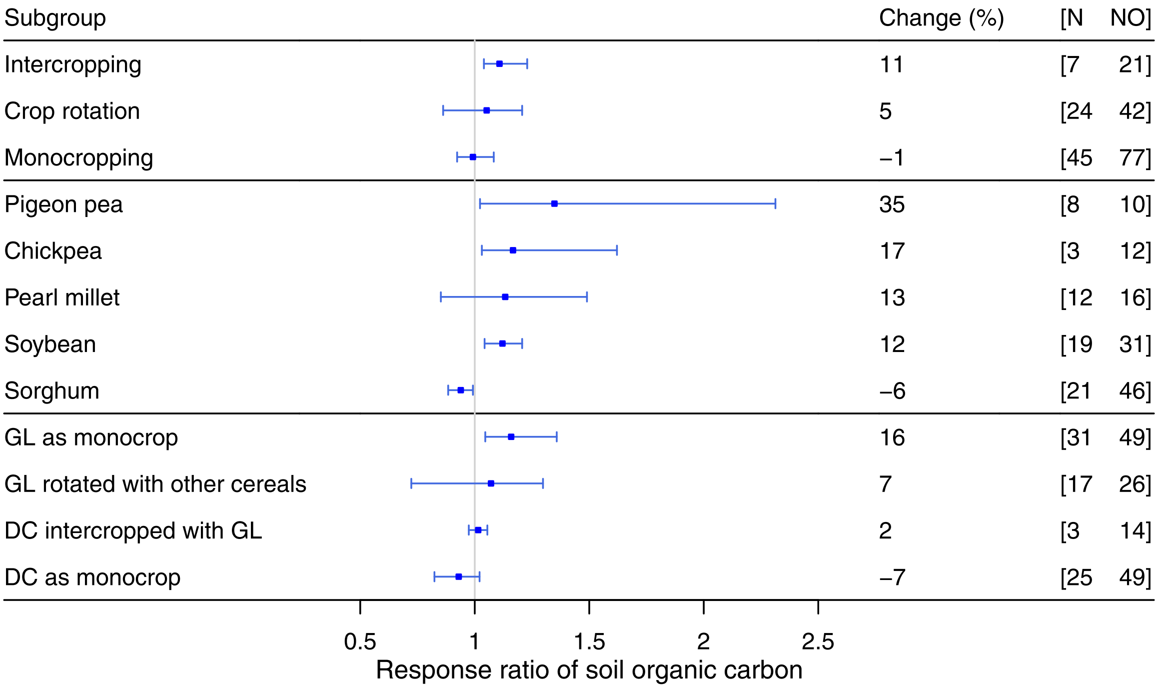

Fig. 7. Changes in soil organic carbon (SOC) concentrations in different cropping systems, crop species, and crop combinations in studies reporting SOC content at the start and end of the experiment. Squares and horizontal bars represent mean and 95% confidence limits, respectively. Number of publications [N] and number of paired observations [NO] in each class are shown in brackets. Crop combination are grain legumes (GL: chickpea, common bean, cowpea, groundnut, lentil, pigeon pea, soybean) as monocrop, GL (chickpea, cowpea, soybean, lentil) rotated with other cereals (maize, rice, wheat), dryland cereals (DC) as monocrops (sorghum, pearl millet), and DC (finger millet, pearl millet, sorghum) intercropped with GL (cowpea, chickpea, groundnut). Monocrop refers to continuous sole crop.

companion crops to other cereals (maize, wheat, rice) as the main crop increased SOC concentrations by 27% compared to monocropping with the other cereals. Similarly, planting grain legumes on land previously under other cereals significantly increased SOC concentrations (by 25%) relative to continuous sole cropping with other cereals. There were insufficient data to evaluate the effect of intercropping dryland cereals with trees, of intercropping grain legumes with other crops (cassava, cotton, green grams, Guinea grass, isabgol, menthol mint, mustard, Napier grass, safflower, sunflower) or of intercropping grain legumes with other cereals.

3.6. Drivers of aboveground carbon and SOC concentrations

In the subset regression analyses, clay content, N fertilizer, P fertilizer, water regime, and crop species were retained as significant moderators for aboveground carbon. Annual rainfall, soil type, clay content, and initial SOC concentrations were retained for SOC concentrations (Table 2). The regression analyses showed that aboveground carbon stocks and SOC varied most significantly among the variables used, explaining 37% and 38% of the variance, respectively.

Regression analysis showed that aboveground carbon and SOC increased together in all conditions represented in the dataset (SM). Aboveground carbon increased with SOC concentration regardless of soil texture. Aboveground carbon also increased with increases in SOC concentration across cropping systems. However, it was difficult to assign cause and effect relationships (e.g., aboveground carbon drives SOC concentration or SOC concentration drives aboveground carbon).

4. Discussion

The amount of crop biomass carbon available as input to soil was large and varied depending on the type of crop (legume or cereal), crop species, cropping system, and residue management. Differences in biomass carbon quantities between crops can be attributed to differences in growth habit, management or climate conditions, which limit the quantity of residues available as input to soils. Cereals and pigeon pea yielded the largest amount of aboveground carbon stocks (>2 Mg ha^{-1}). Depending on the variety, pigeon pea is a biennial or perennial crop with a long growing period that allows it to accumulate more carbon than other legumes. The low aboveground carbon stocks recorded in systems with cowpea could be due to soil and climate conditions. Cowpea and finger millet are tolerant to drought and are often grown in arid and semi-arid areas, where biomass production is low. Even though the quantity of aboveground residues available for return to the soil may be large, the actual amount of plant carbon added to the soil depends on whether residues are retained or removed from the field for different uses (e.g., feed, fuel). The amount of carbon inputs via roots may be higher than estimated in this study, since recent evidence shows that living root inputs are more efficient in forming SOC (Sokol et al., 2019). These inputs also act as the primary pathway of carbon incorporation in mineral soil, and are retained for longer than litter inputs (Fulton-Smith and Cotrufo, 2019; Puget and Drinkwater, 2001; Sokol et al., 2019).

Aboveground carbon stocks greatly increased when GLDCs were included as intercrops. Intercrops produce more biomass per unit area because of complementarity between components (Brooker et al., 2015), as evidenced by the combined biomass yield from the component crops. This accounted for about 50% of the increase in aboveground carbon in studies in the dataset. Intercropping increases resource use efficiency if the component crops utilizes resources at different times or depths within the soil profile (Duchene et al., 2017). The present analysis indicated that aboveground carbon stocks were depressed under agroforestry. However, the data only included the carbon concentrations in GLDC components, which was most likely affected by competition with the trees or a smaller population of the annual crop compared with in monoculture. Improved varieties of GLDC yielded smaller amounts of aboveground carbon, suggesting that breeding which focuses solely on grain yield can create a tradeoff between food production and agricultural carbon sequestration (Jansson et al., 2021). However, improved varieties produce large amounts of residues when the harvest index is not changed in the process of breeding (Johnson et al., 2006).

This analysis has established that SOC is increased using GLDCs in clay soils and in soils with low initial SOC (<1%). These findings are in agreement with a meta-analysis on the response of manure applications on SOC reported Gross and Glaser (2021). This suggests that soils with a high clay content accumulate SOC more rapidly than sandy soils. Sandy soils have limited capacity to stabilize organic compounds (Blanco-Canqui and Lal, 2004) and have low productivity due to limited capacity to retain nutrients or water. On the other hand, clay soils can protect SOC from breakdown by soil microbes through formation of aggregates or humification of SOC (Blanco-Canqui and Lal, 2004; Lal, 2004). Clay content can also indirectly affect SOC accumulation by retaining soil moisture, thereby increasing plant productivity (Franzluebbers et al., 1996). The negative relationship between carbon sequestration and initial SOC was probably because SOC accumulates rapidly when initial SOC content is below the soil carbon saturation level. This suggests that efforts aimed at increasing soil carbon sequestration should prioritize regions with low SOC content and can be expected to be most effective on clay soils.

Soil organic carbon concentrations increased relative to the initial SOC concentration when GLDC were grown as intercrops and in crop rotations. Intercropping and crop rotation are measures commonly used to raise cropping intensity in smallholder systems (Duchene et al., 2017; Franke et al., 2018; Godfray and Garnett, 2014). Both these measures can enhance carbon sequestration in soils by: increasing the amount of aboveground residues available to be returned to the soil (McDaniel et al., 2014; Tiemann et al., 2015); increasing carbon input from roots through e.g., production of more root biomass or exudates (Cong et al., 2015); introducing plants containing carbon compounds that may be more resistant to microbial metabolism (Tiemann et al., 2015); or improving the ability of soil microbial communities to rapidly process plant residues and protect them in soil aggregates (Tiemann et al., 2015). The effects of cropping systems on carbon sequestration are modified by the type of crop, tillage, and soil characteristics at the site

Table 2
Results of regression analysis on subsets of on soil, climate, and management parameters to choose the most significant moderators.

	Fixed effects		Random effects			R^2 (%)	
	Estimate± SE	p-value	σ^2Continent	σ^2Sites	σ^2Rsd	Marginal	Conditional
Aboveground carbon							
(Intercept)	1.19 ± 0.59	0.05	2.06	0.04	2.92	19.91	53.50
Soil type	-0.01 ± 0.02	0.6429					
Clay content	**0.02 ± 0.006**	**0.00453**					
N fertilizer	**0.01 ± 0.003**	**0.00300**					
P fertilizer	**0.03 ± 0.005**	**< 0.001**					
Water regime	**-0.73 ± 0.24**	**0.00262**					
Main crop	**0.05 ± 0.02**	**0.01668**					
Soil organic carbon							
(Intercept)	0.23 ± 0.16	0.023	0.00	0.00	0.32	37.75	37.75
Annual rainfall	**0.00 ± 0.00**	**< 0.001**					
Soil type	**-0.03 ± 0.01**	**< 0.001**					
Clay content	**0.01 ± 0.001**	**< 0.001**					
Initial SOC	**0.60 ± 0.06**	**< 0.001**					
P fertilizer	-0.00 ± 0.001	0.53367					
Water regime	-0.05 ± 0.06	0.3816					
Main crop	-0.00 ± 0.002	0.88389					

(Blanco-Canqui and Lal, 2004).

The greatest increase in SOC concentration was found in systems including legumes (especially pigeon pea), while systems including cereals showed a decline in SOC concentration (sorghum) or no effect (pearl millet). This shows that beyond the productivity and health benefits reported in the literature, legumes have a positive impact on carbon storage, which helps to increasing the robustness of cropping systems and mitigate climate change. Primary studies attribute higher soil carbon in systems with legumes to high-quality residues that promote microbial growth efficiency and aggregation (Blanco-Canqui and Lal, 2004; Drinkwater et al., 1998; McDaniel et al., 2014), production of large quantities of biomass by legume crop, e.g., pigeon pea (Abdurahman et al., 1998), improved biomass production of the subsequent crop in rotations (Franke et al., 2018), release of carbon in exudates in the root zone (Tiemann et al., 2015), or increasing N and P use efficiency of cereal crops (Franke et al., 2018; Ndayisaba et al., 2021). The low SOC concentration under some legumes, primarily those growing under semi-arid conditions, indicates an impact of limited biomass inputs, which may be more due to low and/or irregular rainfall rather than low potential of the legume species for biomass accumulation.

A number of limitations and gaps were identified in the dataset that can restrict the inferences possible from our analyses. First, in this review we quantified aboveground carbon and SOC concentrations in publications that investigated these attributes on farms or fields with GLDC in Africa and South Asia, thus the findings, reflect work in studies published in peer-reviewed literature, and not necessarily what farmers grow. Second, few publications in the dataset reported aboveground carbon for both improved and local varieties, and no publication reported SOC specified under both local and improved varieties. This makes it difficult to assess changes in SOC concentration when farmers change from local to improved varieties of GLDC, or the conditions under which GLDC offers the greatest carbon benefits. Third, a host of additional factors (e.g., tillage, organic amendment, elevation, slope, climate, pH) influence the amount of carbon added to the soil or changes in SOC, and these factors were rarely reported or not systematically reported in the studies in the dataset. Other details not reported in most publications were soil bulk density, sampling depth, previous land use, variance metrics and, in some studies, sample size. Fourth, methods for reporting SOC were not standardized, with only a few studies providing data on SOC before adopting GLDC. In this review, initial SOC information was inferred from initial soil properties reported in the methods section of published papers. Fifth, evidence reported in grey literature was not included in the review, because of the complexity of locating and assessing scientific evidence in grey literature, so we may have missed some information.

5. Conclusion

This comprehensive review showed that grain legumes and dryland cereals can make a significant contribution to carbon sequestration in smallholder agriculture, with up to 5.36 Mg C ha^{-1} harvest^{-1} potentially being returned to the soil through aboveground biomass. However, the actual quantity returned to the soil may be lower because of the various competing needs for crop residues such as livestock feed, fuel, mushroom cultivation and other uses. The review also showed that dryland cereals have greater potential for aboveground carbon inputs, while legumes contribute more to SOC. It is also concluded that intercropping or crop rotation with legumes increases soil carbon sequestration more than monocropping. Crop type and N and P fertilizer emerged as the major drivers of aboveground carbon, while SOC concentration was driven by soil type, clay content, and initial SOC concentrations. Although complex interactions may control carbon sequestration in smallholder agricultures, the overall effects of GLDC are positive. These findings have implications for policies and incentives targeting smallholder farmers.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests, There is no conflict of interest.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108583.

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