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Grain legumes and dryland cereals for enhancing carbon sequestration in semi-arid and sub-humid agro-ecologies of Africa and South Asia

Shem Kuyah, Tarirai Muoni, Jules Bayala, Pierre Chopin, A Sigrun Dahlin, Karl Hughes, Mattias Jonsson, Shalander Kumar, Weldesemayat Sileshi, Kangbeni Dimobe, Ingrid Öborn

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Front cover image: Sorghum-Pigeon pea intercropping system

Credit: PS Rao

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Abstract

Sorghum, millets (pearl and finger millet) and grain legumes (chickpea, common bean, cowpea, lentils, pigeon pea and soybean), collectively referred to as GLDC under the CGIAR research program on Grain Legumes and Dryland Cereals, are commonly grown, eaten and traded by small holder farmers in Africa and South Asia. These crops contribute to food and nutritional security, environmental sustainability, and economic growth in the region. However, their possible contribution to carbon sequestration through biomass production and accumulation of soil organic carbon (SOC) is not known. To find out more about their contribution, and how to increase SOC, this study reviewed the evidence of carbon sequestration in farming systems that integrate GLDC in Africa and South Asia. A total of 437 publications reporting SOC and its proxies across 32 countries in Africa (N=250 studies) and South Asia (N=187) were identified as sources of evidence for carbon sequestration. Among these, 179 publications provided appropriate control groups for evaluating changes in aboveground carbon when GLDC were integrated under intercrop (n=38), crop rotation (n=8) or agroforestry (n=13), or when improved varieties of GLDC were compared with local varieties (n=14). A further 81 publications compared SOC content at the start and the end of the experiment while 43 publications compared SOC between farms growing GLDC and those which did not. Aboveground carbon of GLDC was found to be 1.51±0.05 Mg/ha in Africa and 2.29±0.10 Mg/ha in South Asia. Absolute SOC concentration in the topsoil (0-30 cm) was 0.96±0.06% in Africa and 0.58±0.04 in South Asia. It was observed that GLDC produced more aboveground carbon and significantly increased SOC when grown as intercrops and in crop rotations. The increase, however, depended on the species and whether the crop was a legume or a cereal. The largest amount of aboveground carbon (>2 Mg/ha) was found in cereals (and pigeon pea) while the largest increase in SOC was found in farming systems that included legumes. Aboveground carbon of improved varieties of GLDC was lower compared to local varieties. Soils which had low initial (<1%) SOC but high clay content (>32%) showed the greatest potential for carbon sequestration when GLDC were grown. Among the GLDC crops, pigeon pea which is a perennial grain legume showed the highest biomass production and carbon sequestration in the soil when integrated into farming systems in Africa and South Asia. Findings from this study underscore the importance of aboveground residues in regulating the addition of carbon to the soil, and the role of legumes in the enhancement of SOC.

Acronyms

CGIAR	Consultative Group for International Agricultural Research
CI	Confidence interval
CO_2	Carbon dioxide
GHG	Greenhouse gas
GLDC	Grain legumes and dryland cereals
ICRAF	The International Center for Research in Agroforestry
ICRISAT	The International Crops Research Institute for the Semi-Arid Tropics
IITA	The International Institute of Tropical Agriculture
IPCC	Intergovernmental Panel on Climate Change
NRM	Natural resource management
RR	Response ratio
SOC	Soil organic carbon
SOM	Soil organic matter
WUR	Wageningen University and Research

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1. Introduction

1.1 Grain legumes and dryland cereals in smallholder agriculture

Subsistence agriculture is the main source of livelihood for millions of households in Africa and South Asia, where small farms (<2 ha) account for about 30% of the food produced (Herrero et al. 2017). Agriculture is also the sector expected to help people escape from poverty (Gassner et al. 2019) and spur economic growth in these regions (AGRA 2017). However, the impact of climate change has put smallholders at risk and reinforced poverty and vulnerability. Climate change alters rainfall patterns, resulting in potential changes in soil moisture balance (Knox et al. 2012). Carbon in soils affected this way mineralizes more quickly which is beneficial for yields but will degrade the soil in the long run, leading to smaller yields and dramatic impact on food production. High temperatures may affect soil carbon by limiting water availability, and reduce the rate of photosynthesis. Intensification of the regions' agriculture is among the efforts employed to increase agricultural production and incomes for smallholder farmers (Godfray and Garnett 2014; AGRA 2017). It is vital that this intensification focuses on crops and cropping systems that enhance soil organic carbon (SOC).

Cereals and legumes form an important component of crop production in Africa and South Asia (AGRA 2013), where they dominate the debate on sustainable intensification (Godfray and Garnett 2014; Franke et al. 2018a; Snapp et al. 2021). Their role in food security and economic growth is of critical importance, although farm yields in smallholder systems fall below their potential (Godfray and Garnett 2014). Low yields are generally attributed to low soil fertility and a host of factors that are aggravated by climate change. The CGIAR Research Program on Grain Legumes (chickpea, cowpea, pigeon pea, groundnut, lentil, soybean) and Dryland Cereals (sorghum, pearl and finger millet) has identified these crops as capable of transforming smallholder agriculture to become resilient, productive and sustainable (CGIAR 2017). When grown under common agro-ecological conditions, sorghum, millets and the grain legumes listed above (hereafter GLDC) create synergies that can help reduce poverty, improve food and nutritional security and enhance ecosystem services (CGIAR 2017).

The benefits of individual GLDC have been well-documented in literature. All GLDC crops are highly nutritious and diversify the diets of many families. They also provide fodder and feedstock in mixed crop-livestock farming systems. Existing systematic reviews document the importance of specific GLDC crops for sustainable intensification, suggesting improved soil health (Snapp et al. 2021), reduced weeds and increased productivity (Smith et al. 2016; Franke et al. 2018a), reduction of greenhouse gas (GHG) emission (Jensen et al. 2012) and enhancement of soil organic carbon (Powlson et al. 2011). The yields, profits and household welfare provided by GLDC crops have also been documented (Katovich et al. 2020). However, the potential for GLDC to increase carbon sequestration in African and South Asian farming systems has not been synthesized comprehensively. Further, it is not known under which climate, soil type or soil textures do the GLDC enhance carbon sequestration in farming systems in Africa and South Asia.

1.2 Soil carbon sequestration

One of the ways in which GLDC can transform and increase agricultural production is through enhanced carbon sequestration. Soil carbon sequestration is a process by which carbon dioxide (CO_2) is removed from the atmosphere and stored in the soil as SOC. There are several pathways through which carbon sequestered via photosynthesis contributes to the build-up of SOC in croplands (Figure 1). Atmospheric carbon that gets fixed into plant biomass through photosynthesis is transferred to the soil when the remains of roots and shoots decompose and form humus. It can also get transferred into the soil when living roots release organic substances into the rhizosphere in a process called rhizodeposition. Some of the carbon is released back to the atmosphere through root respiration and microbial decomposition of organic matter; and the balance between these processes determines the long-term SOC content. The amount of SOC in soils is therefore related to carbon input through residue retention or incorporation, below ground root biomass and rhizodeposition; with higher inputs producing higher SOC levels up to saturation level. This implies that farming approaches which increase biomass production may also increase carbon input in the soil, and eventually lead to larger SOC stocks.

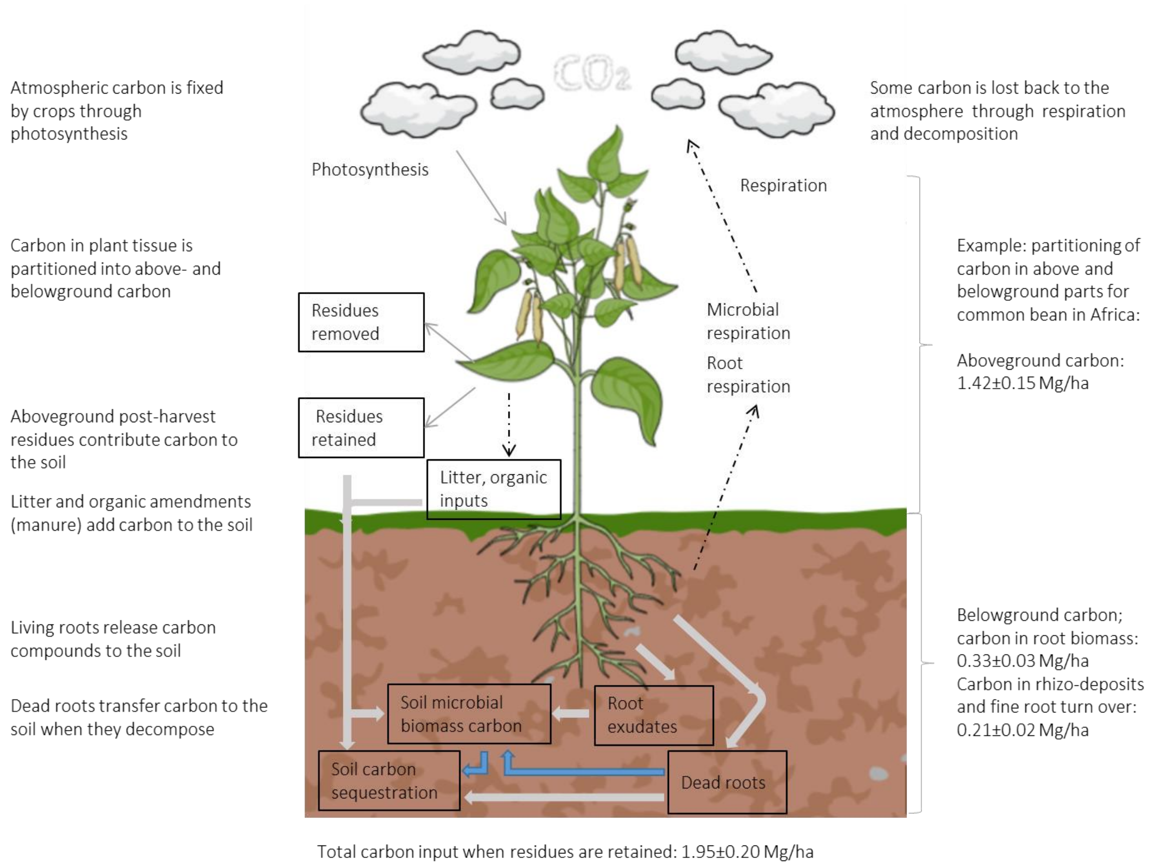

Figure 1. This figure denotes pathways through which carbon sequestered via photosynthesis contributes to build-up of soil organic carbon. Values of carbon are based on estimates of above- and belowground biomass determined for common bean in Africa in this study, assuming 47% carbon fraction in dry matter (IPCC 2019) and 65% carbon in root exudates (Bolinder et al. 2007).

The addition of SOC in the soil via plant residues may also be due to the fact that after harvesting agricultural crops, the residues are returned to the soil as mulch. Residue return is recommended as an effective means of improving overall soil health through accumulation of organic matter (Liu et al. 2014), and may increase crop yield, improve water use efficiency and prevent emission of GHG from burning residues (Lu 2020). On the other hand, residue removal reduces the amount of carbon entering the soil and can contribute to loss of carbon due to soil erosion. However, residues removed from cropland and fed to animals or used as animal bedding are indirectly returned to the field as manure or compost. Roots contribute much of the carbon added to the soil where little aboveground biomass is retained or returned to the cropland. The input of carbon from plant residues and rhizodeposition is greatly influenced by net primary productivity. This fact suggests that enhanced growth resulting from variety improvement, application of fertilizers, irrigation or addition of organic manure can increase carbon sequestration.

1.3 Objectives of this study

The aim of this study was to assess evidence of carbon sequestration in farming systems that include GLDC in Africa and South Asia. Specifically, the study (1) quantified the amount of aboveground carbon and SOC concentration in farming systems with GLDC, (2) determined changes in aboveground carbon or SOC when farmers adopted GLDC or moved from GLDC to other crops, and (3) determined changes in aboveground carbon when farmers changed from local to improved varieties of GLDC. The study also explored (4) variations of aboveground carbon and SOC under different crops types, regions, soil and climate conditions, and management practices. Major gaps in the evidence base are discussed.

2 Methods

2.1 Search strategy

A comprehensive search was conducted on three bibliographic databases to obtain published literature on studies that investigated the presence of GLDC in farming systems in Africa and South Asia. The search string was wider (Table 1) and included evidence of GLDC on indicators of natural resource management (i.e., land and water management, environmental quality, biodiversity, and system resilience). The search string consisted of (1) ten priority crops, including their common names, scientific names, and synonyms, (2) indicators of outcomes of adopting GLDC, (3) scale at which the study is conducted i.e., farm or field scale (excluding greenhouse or pot experiment), and (4) the region/country where the study was conducted. Including the study area terms limited the number of search results returned yet captured data that does not explicitly refer to the region (Africa or South Asia) where the study was conducted.

Table 1. List of search terms (Web of Science syntax) used to retrieve publications indexed in Web of Science: core collection, ProQuest and SCOPUS. Timespan = all years; language = English and French. Further refinements were applied to limit search results to countries in Africa and South Asia, exclude irrelevant subject area and exclude magazines and other grey literature.

Category	Terms for topic search (TS=)
Crops	(Ground$nut* OR "*Arachis hypogaea*" OR pea$nut* OR soy$bean* OR soya$bean* OR "soja bean*" OR "*Glycine max*" OR pigeon$pea* OR "*Cajanus cajan*" OR "red gram" OR lentil* OR "*Lens culinaris*" OR "*Lens esculenta*" OR cowpea* OR "*Vigna unguiculata*" OR "black-eyed pea" OR "chick$pea*" OR "*Cicer arietinum*" OR "common bean" OR "French bean" OR "*Phaseolus vulgaris*" OR sorghum OR "guinea corn" OR "great millet" OR "Indian millet" OR "*Sorghum bicolor*" OR "finger millet" OR "African millet" OR "*Eleusine coracana*" OR "spiked millet" OR "pearl millet" OR "*Pennisetum glaucum*" OR "*Pennisetum typhoides*")
AND	
Outcome	(Yield OR biomass OR "dry matter" OR grain OR "land equivalent ratio" OR "soil moisture" OR "soil water content" OR infiltration OR "soil erosion" OR "soil loss" OR "run off" OR "organic matter" OR "soil organic carbon" OR "soil carbon" OR "bulk density" OR "carbon sequestration" OR "aggregate stability" OR "soil respiration" OR "soil fertility" OR "green manure" OR "total nitrogen" OR "total soil nitrogen" OR "total phosphorus" OR "Olsen phosphorus" OR "extractable phosphorus" OR "available phosphorus" OR "rainfall use efficiency" OR "water use efficiency" OR "nutrient use efficiency" OR "nitrogen fixation" OR "greenhouse gas" OR "nitrous oxide emission" OR "carbon dioxide emission" OR "carbon emission" OR biodiversity OR "microbial biomass" OR macrofauna OR "macro organism" OR "arbuscular mycorrhizal fungi" OR "weed control" OR "pest control")
AND	

Scale	(Agriculture* OR “agricultural system*” OR farm* OR field* OR plot*)
AND	
Location of study	(Africa OR Algeria OR Angola OR Benin OR Botswana OR “Burkina Faso” OR Burundi OR Cameroon OR “Cape Verde” OR “Central African Republic” OR Chad OR Comoros OR “Congo Brazzaville” OR “Democratic Republic of Congo” OR DRC OR “Côte d'Ivoire” OR Djibouti OR Egypt OR “Equatorial Guinea” OR Eritrea OR Ethiopia OR Gabon OR Gambia OR Ghana OR Guinea OR “Guinea-Bissau” OR Kenya OR Lesotho OR Liberia OR Libya OR Madagascar OR Malawi OR Mali OR Mauritania OR Mauritius OR Morocco OR Mozambique OR Namibia OR Niger OR Nigeria OR Rwanda OR Reunion OR “Sao Tome and Principe” OR Senegal OR Seychelles OR “Sierra Leone” OR Somalia OR South Africa OR South Sudan OR Sudan OR Swaziland OR Tanzania OR Togo OR Tunisia OR Uganda OR “Western Sahara” OR Zambia OR Zimbabwe OR “South Asia” OR Afghanistan OR India OR Pakistan OR Bangladesh OR “Sri Lanka” OR Nepal OR Bhutan OR Maldives OR Myanmar OR Burma)

2.2 Selection and screening of publications

The total number of publications found from each database or other searches, potential papers selected after reading the title and abstract and the number of relevant papers from which data was extracted are indicated in Figure 2. A three-step process was used to filter papers: (1) removal of duplicate references from the three databases and other sources; (2) examination of abstracts and titles of retrieved articles to remove irrelevant literature such as patents, periodicals, studies on medical topics, genetics, molecular biology, pollination, nutrition and biochemical analysis, (3) appraisal of the full text to examine studies that met the selection criteria and concurrently extract data. A pre-established criterion was used to select publications for inclusion in the study, selecting only publications that reported: (1) the outcome of growing any of the GLDC crops in Africa or South Asia, (2) original experimental or observational study conducted at field or farm scale, and (3) quantitative and qualitative data on carbon sequestration and its proxies. Pot and greenhouse experiments, laboratory studies and meta-analysis were excluded. Modeling studies and reviews were included when they presented eligible empirical data.

Double screening was conducted on a subset (919) of the publications obtained to check agreement (on selection criteria) between assessors. During the double screening, two assessors independently screened the title and abstract of each publication to identify potential papers. Any publication for which there was a doubt about its relevance was referred to another assessor for a second opinion. Publications that met the inclusion criteria based on screening the title and abstract were obtained and used in full text appraisal. Selected publications were given a unique identification number and data therein was extracted into a Microsoft Excel spreadsheet. Care was taken to ensure that the same data was not extracted twice from multiple sources, for example, from a conference paper, thesis, and an article in a journal or a review paper. Publications that were excluded at each stage and the respective reasons are documented in Figure 2.

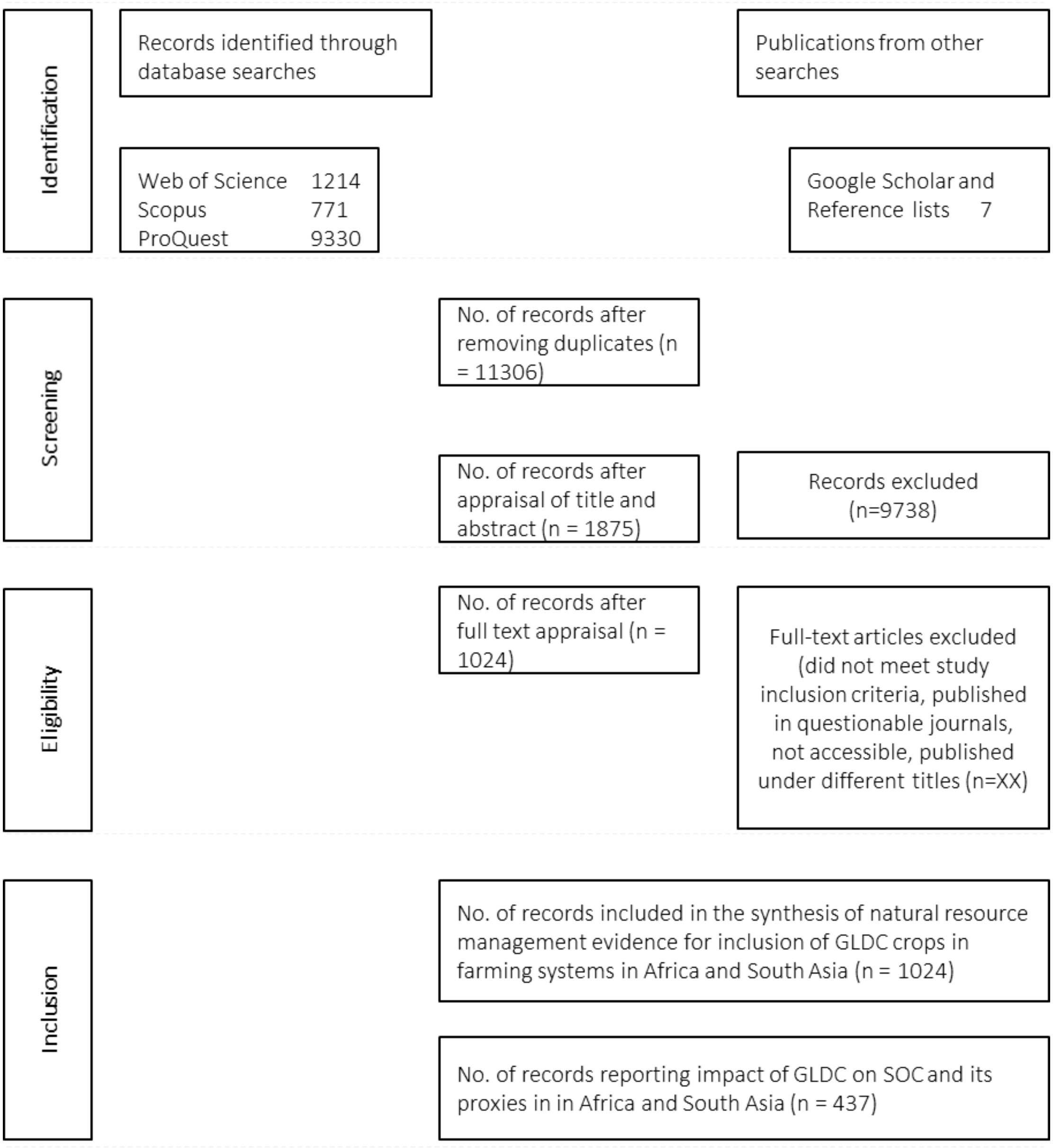

Figure 2. Illustration of results from literature search and screening of records retrieved from bibliographic databases. A total of 437 publications were used for an in-depth review of indicators aligned to sequestering carbon in farming systems that include grain legumes and dryland cereals in South Asia and Africa. Publications in journals that appear on Cabell's Blacklist (https://www2.cabells.com/) were excluded.

2.3 Elements of the database

The type of information extracted from selected publications includes bibliographic information (e.g. author, year), year of experiment, study location (continent, country, study site and geographical coordinates), site characteristics (elevation, clay content, soil texture class, initial SOC and the depth to which soil samples were collected). Climatic conditions like rainfall – annual, seasonal or - during the growing period were also considered. The type of trial (on a farm or on a station), soil type, scale of investigation (field or farm), farming systems (continuous sole crop, intercrop, crop rotation and agroforestry), or the GLDC crop, cropping system, and tillage practices were taken into account. As were fertilizer (N or P) levels, organic amendments and whether the crops were grown under rain-fed conditions or irrigation, and residue management (whether it was retained or removed).

Quantitative information on means for treatment and control (when available) were recorded as reported in tables, within the text or extracted from figures using Web Plot Digitizer (Rohatgi 2020). Additionally, the sample size (i.e., number of replicates or any other sample size recorded) was extracted. Missing rainfall data was obtained through the SamSamWater Climate Tool (SamSamWater Foundation 2018).

Farming systems were categorized based on descriptions provided by the studies reviewed (Table 2). Soils reported under the USDA or other classification systems were re-classified following the international soil classification system for naming soils and creating legends for soil maps (IUSS Working Group WRB 2015). Inceptisols and Ultisols were, however, retained in the USDA soil taxonomy because: (1) Inceptisols were reported in many studies (45 publications with 81 datapoints) conducted across 50 sites, and (2) Ultisols were reported interchangeably as Nitisols (seven publications), Acrisols (13 publications), Alisols (one publication) and solely as Ultisols in five publications. The soils were further grouped into three broad texture categories i.e., sandy soil, loam soil and clay soil, based on the reported sand, silt and clay fractions. These categories represent coarse textured soils (<20% clay), medium textured soils (20-32% clay) and fine textured soils (>32% clay), respectively. Initial SOC was divided into three groups: >1.5%, 1.0–1.5%, and < 1.0%.

Table 2. This table denotes the reclassification of farming systems reported by the studies including grain legumes and dryland cereals in African and South Asia. The references are not exhaustive and refer to examples of studies that reported soil organic carbon or its proxies under agroforestry, crop rotation, intercrop and continuous sole crop.

Farming system	Description	Examples	Reference from database
Agroforestry	A land management system which incorporates trees and shrubs in the same land area used for crop or livestock production. Four types of agroforestry practices were referred to in the studies reviewed.	Parkland systems: Multipurpose trees scattered on farmlands, following farmer selection and protection. Farmers grow crops under the canopy of trees such as *Faidherbia albida*, *Parkiabiglobosa*, or *Vitellaria paradoxa*.	Kho et al. (2001), Bayala et al (2003), Sanou et al (2012)
		Alley cropping (hedgerow intercropping): planting of annual crops between widely spaced rows of trees or shrubs.	Droppelmann et al. (2000), Forster et al. (2013)
		Improved fallow: Land is rested from cultivation, during which fast-growing legume species are planted, e.g., to replenish soil fertility and provide products such as wood or fodder.	Chirwa et al. (2004), Gathumbi et al. (2004)
		Windbreaks: Trees are planted in one or more rows to provide shelter or protection from wind	Leihner et al. (1993), Michels et al. (1998)
Crop rotation	The planting of different crops successively on the same land.	Cereal-legume rotation, cereal-cereal rotation legume-legume rotation, and cereal or legume rotated with other crops e.g., mustards.	(Waddington and Karigwindi 2001; Forster et al. 2013)
Intercrop	Growing two or more crops at the same time and on the same piece of land.	Row intercrops: Growing two or more crops grown in the same field simultaneously with one or more of the crops grown in a distinct row arrangement.	Ghosh et al. (2004), Ramesh et al. (2005)
Continuous cropping	Growing one crop only during the cropping season.	Continuous sole crop (monocropping): growing the same crop as a pure stand in successive seasons.	Ghosh et al.(2005), Laberge et al. (2011)

2.4 Estimation of aboveground and soil organic carbon

The systematic literature search identified 437 publications (1319 observations) that reported the effect of GLDC on SOC and/or its proxies (carbon input from plant resides and rhizodeposition) in Africa and South Asia. These include 331 publications that reported carbon in aboveground residues and 144 publications that reported SOC in farming systems that included GLDC in Africa and South Asia. Aboveground carbon consists of all the carbon in the plant biomass i.e., straw, stover and other post-harvest residues (Appendix 1). Aboveground residues were considered dry matter when a publication explicitly reported that samples were oven-dried (65 or 75°C) to a constant weight. The term dry matter was used interchangeably with biomass to refer to the mass of the plant material in a dehydrated state. Consequently, 42 publications were excluded for their data of conversion of dry matter to aboveground carbon as they did not explicitly state how the weight of straw (27 publications), stover (11 publications), haulms (3 publications) and stubble (1 publication) was determined (Appendix 1). In addition, the biomass of grain was not included in aboveground carbon as this was reported separately and is taken off the field.

Data reported as or recalculated to dry matter was converted to aboveground carbon using the default fraction (47%) of carbon for crops documented by IPCC (2019). It is recommended to use crop specific data for these parameters where possible; because the actual percentage of carbon in residues varies for different crops. However, a quick review of the existing literature showed a general lack of data on carbon fractions for GLDC crops. Default values are recommended for converting dry matter to carbon content where crop specific data is not available (IPCC 2019).

The amount of biomass carbon potentially added to the soil was estimated as the sum of carbon in aboveground residues, carbon in root biomass and rhizo-deposited carbon (Bolinder et al. 2007). Carbon in roots was calculated from aboveground carbon using literature values of root-to-shoot ratios measured at maturity; lentils: 0.22 (Gan et al. 2009), chickpea: 0.22 (Gan et al. 2009), soybean: 0.15 (Ramesh et al. 2005), groundnut: 0.15 (Shridhar Rao et al. 2012), common bean: 0.23 (De Costa et al. 1997), pigeon pea: 0.21 (Rao and Itto 1998), cowpea: 0.27 (Laberge et al. 2011), pearl millet: 0.31 (Brück et al. 2003), finger millet: 0.21 (Krishna and Reddy 2021) and sorghum: mean (0.29) of 0.22 (Ghosh et al. 2004) and 0.36 (Ramesh et al. 2005). Rhizo-deposited carbon was estimated from carbon in root tissues assuming that 65% of carbon in roots is released through exudates and sloughing of root hairs and fine roots during growth (Bolinder et al. 2007).

Data on SOC concentration (%) was limited to studies that examined the parameter in the topsoil (0-30 cm depth). The 0-30 depth represents the zone where SOC is highly influenced by management practices and input from crop roots, and is acceptable for national carbon accounts (IPCC 2019). Data on the concentration of SOC in the top layer was extracted as reported in a study, then converted to percentage. Eight studies reported soil organic matter (SOM), which was converted to SOC by dividing it by 1.72, considering the units of SOM reported in the publication. However, very few studies reported SOC density (Mg/ha) or bulk density required to convert carbon concentration to carbon density and therefore the analyses in this study are based on SOC concentration (%).

2.5 Independent observations, subgroups and statistical analysis

Observations from the same study were considered as independent datapoints and included separately if they were from different locations (sites), seasons (year) or crop species. Recommended rates or common farmer practices were selected to constitute independent observations (datapoints). This was specifically done when a study reported data from multiple results because of different fertilizer levels, manure, tillage practices, residue management, rainfall or irrigation conditions, row patterns/proportions, sowings rates and plant densities. When a study reported multiple results for comparisons involving several varieties or cultivars, a mean was calculated and the number of varieties or cultivars was used as the new sample size. When a study reported both improved and local varieties, results for both types of varieties were selected and used to compare changes in aboveground carbon when farmers shifted from local to improved varieties. When multiple publications reported results on the same study (site) over different years, only data from the publication reporting the latest observation was extracted. When a study reported the data on the same crop grown in more than one season or year, the measurement at the start and end of the experiment was taken as the control and treatment mean (for SOC), respectively. Further adjustments were done during meta-analysis to evaluate under which conditions the crops affected aboveground carbon or SOC positively or negatively.

Subgroup analysis was conducted on soil type, soil texture group, initial SOC, cropping system, the crop and the combination of crops (i.e. grain legumes, dryland cereal, other cereals [maize, wheat, rice, tef] or other crops [cassava, cotton, green grams, Guinea grass, Isabgol, menthol mint, mustard, Napier grass, safflower and sunflower]), to assess whether outcomes of GLDC integration are different for different conditions.

The natural log-transformed response ratio (*lnRR*) was used as a measure of effect size to determine changes in aboveground carbon or SOC following inclusion of GLDC in farming systems. The *ln*RR was considered appropriate because it is scale-free and therefore allows comparison of the outcomes across studies that use different measurement procedures (Hedges et al. 1999). The *ln*RR was calculated using equation (1), where $\overline{x}_E$ and $\overline{x}_C$ are the means of the treatment and the control group for aboveground carbon and SOC (Hedges et al. 1999).

$$lnRR = ln(\overline{x}_E/\overline{x}_C) = \ln(\overline{x}_E) - \ln(\overline{x}_C) \qquad (1)$$

Bootstrapping methods were used to estimate 95% confidence intervals around means of aboveground carbon values, absolute SOC and *ln*RR for different categorical variables through the application of 10,000 iterations using the boot package in the R programming language 3.4.2 (R Core Team 2018). The values (*ln*RR) were back-transformed and presented as means and 95% CI of response ratios. The 95% CI shows the magnitude and direction of change in aboveground carbon and SOC under treatment compared to the control, where 95% CI is greater than one and suggests that SOC or its proxies significantly increased under GLDC compared to the control. The means of categories or subgroups are therefore significantly different from one another if their 95% CI does not overlap. The effects were significant when the 95% CI lies below (decrease) or above (increase) one. The percentage change was calculated from weighted *ln*RR using equation 2.

$$\text{Change (\%)} = 100 \times (\exp^{lnRR})-1 \qquad (2)$$

Because different comparators (control groups) were reported, changes in SOC were evaluated in two ways for different subgroups that met the minimum number of three studies and 12 observations. The first method compared SOC values before and after the inclusion of GLDC in farming systems. This category evaluated publications that reported SOC values at the start of the experiment (based on initial site characteristics) and SOC values at the end of the experiment. The second compared SOC values in farming systems with or without GLDC. This category evaluated publications that reported SOC values where the treatment group included a GLDC and a control group where no GLDC were grown.

3. Results

3.1 Distribution of the studies

A total of 437 publications reported data related to carbon sequestration. The studies were spread widely across 32 countries (Figure 3a) and covered large ranges of annual rainfall (10 to 3784 mm year^{-1}), elevation (2 to 2740 ma.s.l.), 15 different soil types, four farming systems and other management practices. Three studies were reported in book chapters; the rest (434) were reported in peer reviewed journal articles. Most of the studies were conducted at a field scale (65%); few studies (5%) were conducted at a farm scale while 30% of the publications did not report the size of plots used. The number of publications reporting studies on aboveground carbon or SOC in different countries is shown in Figure 3b. The highest number of studies were reported in India; which had 38% of all studies reviewed (n= 451). In Africa, the other countries where a high number of studies were reported are Niger (11%), Nigeria (7%) and Ethiopia (7%). These countries represent 89% (n=188) and 44% (n=251) of the studies reported in South Asia and Africa, respectively. Fourteen countries in Africa and three countries in South Asia were reported in less than five publications.

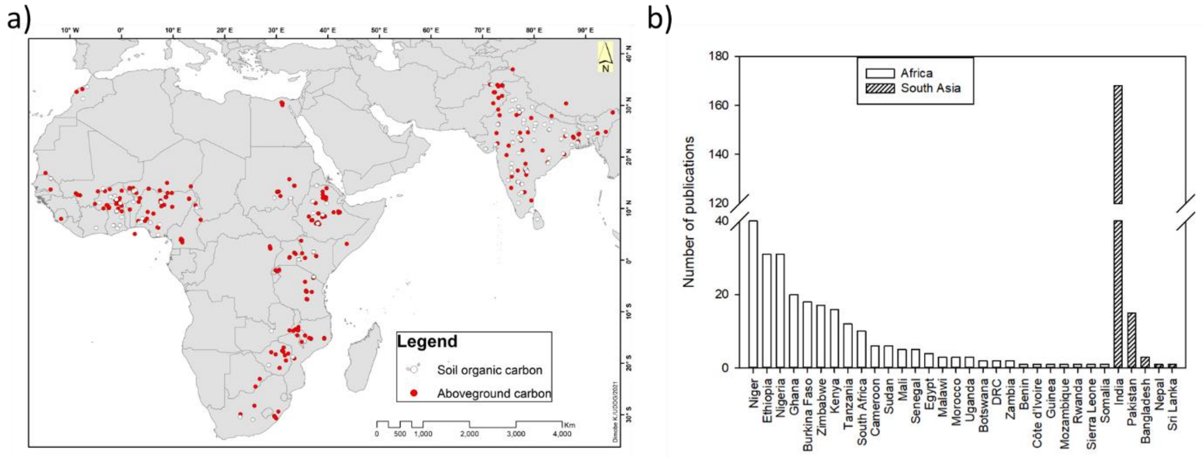

Figure 3. Location of studies that reported aboveground carbon (●) or soil organic carbon (○) in farming systems that had sorghum, millets or any of the grain legumes in Africa and South Asia (a); and the number of publications that reported aboveground carbon or soil organic carbon in Africa and South Asia (b).

Of the 142 publications reporting SOC, 80% were conducted on research stations while 20% were conducted on farmers' fields. Nearly all studies reported in India were conducted on research stations (91%, N=80). In Africa, 63% of the studies (N=62) were conducted on research stations while 37% were conducted on farmers' fields. Across the two regions, publications reviewed mostly reported GLDC under continuous sole crops (60%) and in fewer cases, in rotations (16%), as intercrops (19%) or in agroforestry systems (6%) (n= 484). A similar trend was observed in the regions where the crops were mainly integrated in farming systems as continuous sole crops in South Asia (63%) and in Africa (55%); and less in crop rotations (29%), and intercrops (15%) in South Asia; and crop rotations (17%) and intercrops (11%) in Africa. There was only one study in South Asia (India) where GLDC were integrated in agroforestry. Seventy-four percent of the publications referred to studies conducted on soils with low SOC (<1.0%), 16% on soils with medium SOC levels (1.0-1.5%) and 10% of studies were conducted on soils with high SOC (>1.5%).

Sorghum (21%) and pearl millet (19%) were the two leading GLDC reported for studies conducted in Africa. The next most mentioned GLDC in Africa were cowpea and soybean, reported in 17% and 13% of the studies reviewed. On the other hand, soybean and sorghum are the leading crops for studies conducted in South Asia, reported in 17% and 13% of the studies reviewed. There were also studies where aboveground carbon or SOC resulted from of a combination of two GLDC or a GLDC and a non-GLDC. Six such combinations (maize/cowpea, maize/soybean, sorghum/cowpea, sorghum/groundnut, sorghum/soybean and wheat/lentil) showed results and were effective for studies conducted in Africa; while South Asia had 32 such combinations. It is important to note that this is what is reported in research and may not represent what farmers have on their farms.

3.2. Aboveground carbon stocks in farming systems with GLDC

Farming systems with GLDC stock an average of 1.76±0.05 Mg/ha of plant carbon in aboveground residues. However, this value varies significantly with regions. Studies reported significantly more aboveground carbon in South Asia (2.29± 0.05 Mg/ha) than in Africa (1.51±0.05 Mg/ha) (Figure 4). Estimates of carbon in aboveground residues and the respective 95% confidence interval (CI) for the different moderators are presented in Appendix 2 for data aggregated across regions. Aboveground carbon varied among soil types, with significantly higher amounts in Andosols, Inceptisols and Luvisols than in Arenosols, Plinthosols and Fluvisols (Figure 4). When cropping systems were compared, aboveground carbon was significantly higher in intercrops, followed by continuous sole crops (Figure 4). The lowest amount of aboveground carbon was found in agroforestry systems (0.94±0.10 Mg/ha); however, the biomass of trees was not included for agroforestry treatments because this was not reported. Differences between aboveground carbon in crop rotations and agroforestry systems were not significant.

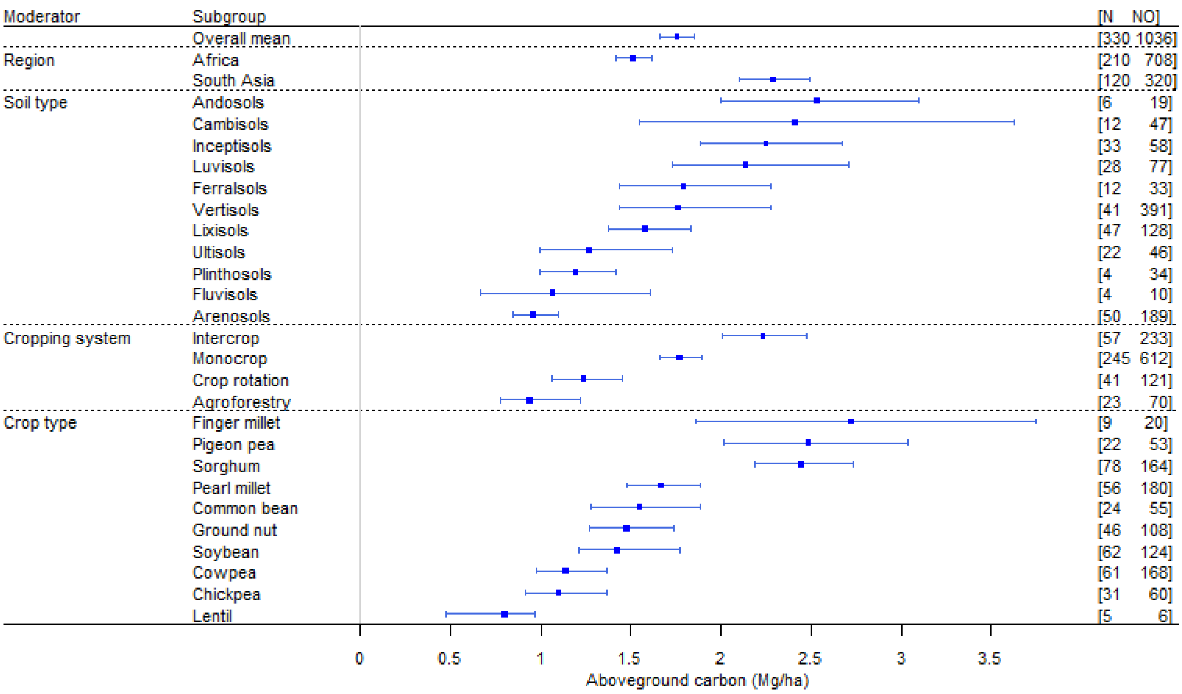

Figure 4. Aboveground carbon in farming systems including grain legumes and dryland cereals in Africa and South Asia. The vertices represent the 95% confidence limits of the estimate. Numbers within brackets indicate the number of publications [N] and number of observations [NO]. Differences among subgroups in each category are significant when the CI does not overlap.

When GLDC were grown as main crops, much of the aboveground carbon was associated with farming systems that had finger millet, pigeon pea and sorghum (Figure 4). A similar trend was observed for data disaggregated across regions, except that pearl millet had the second largest amount of aboveground carbon after sorghum in South Asia (Figure 5; Table 3). The lowest amount of aboveground carbon was found in lentils, which were also reported in only five publications with six datapoints (Figure 4). The amount of aboveground carbon that could be added to the soil ranged from 1.24±0.18 Mg/ha in cowpea to 5.36±0.83 Mg/ha in finger millet when residues were retained in the field; and from 0.45±0.19 Mg/ha in soybean to 2.18±0.79 Mg/ha in finger millet when residues were removed in Africa (Table 3). In South Asia, potential carbon added ranged from 0.99±0.22 Mg/ha in lentils to 4.60±0.42 Mg/ha in sorghum when residues were retained and from 0.41±0.13 Mg/ha in lentils to 2.11±0.65 Mg/ha in sorghum when residues were removed from the field (Table 3).

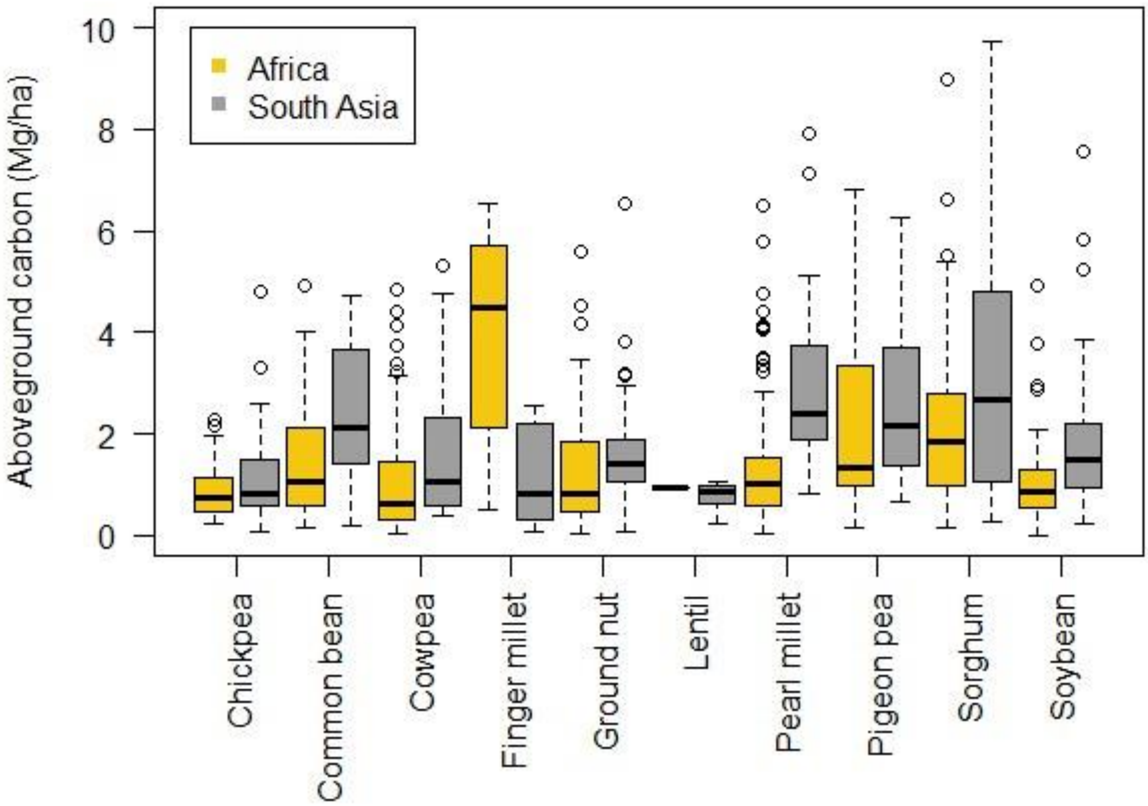

Figure 5. Aboveground carbon in farming systems associated with different crops by region.

Table 2. Aboveground carbon (mean±standard error, and 95% confidence interval [CI]), belowground carbon (carbon in root biomass and rhizo-deposits) and total carbon (Mg/ha) potentially available for addition to the soil in Africa and South Asia. N refers to the number of publications that mentioned the crop while NO refers to the number of independent observations (datapoints) where the crop was mentioned.

Region	Priority crop	Aboveground carbon[b]	95% CI, [0.25, 0.725]	Carbon in root biomass	Carbon in rhizo-deposits[c]	Potential carbon input[d]		N	NO
						Residues retained	Residues removed		
a) Africa	Chickpea	0.91±0.13	[0.69, 1.23]	0.20±0.03	0.12±0.02	1.24±0.18	0.51±0.19	7	21
	Common bean	1.42±0.15	[1.16, 1.73]	0.33±0.03	0.21±0.02	1.95±0.20	0.82±0.29	20	48
	Cowpea	0.98±0.08	[0.84, 1.15]	0.27±0.02	0.17±0.01	1.42±0.12	0.63±0.20	48	139
	Finger millet	3.98±0.62	[2.65, 5.06]	0.84±0.13	0.54±0.08	5.36±0.83	2.18±0.74	3	11
	Groundnut	1.36±0.16	[1.08, 1.71]	0.20±0.02	0.13±0.02	1.69±0.20	0.61±0.26	25	64
	Lentil	0.94±0.01	[0.93, 0.94]	0.21±0.00	0.13±0.00	1.28±0.01	0.53±0.19	1	2
	Pearl millet	1.33±0.09	[1.16, 1.54]	0.41±0.03	0.27±0.02	2.01±0.14	0.94±0.28	48	142
	Pigeon pea	2.21±0.38	[1.55, 3.06]	0.46±0.08	0.30±0.05	2.98±0.51	1.21±0.44	13	30
	Sorghum	2.10±0.15	[1.84, 2.42]	0.61±0.04	0.40±0.03	3.22±0.21	1.43±0.44	50	111
	Soybean	1.00±0.09	[0.86, 1.23]	0.15±0.01	0.10±0.01	1.25±0.11	0.45±0.19	56	77
b) South Asia	Chickpea	1.20±0.15	[0.96, 1.57]	0.26±0.03	0.17±0.02	1.63±0.20	0.67±0.25	24	39
	Common bean	2.46±0.58	[1.35, 3.62]	0.57±0.13	0.37±0.09	3.40±0.80	1.43±0.49	4	7
	Cowpea	1.88±0.37	[1.34, 2.91]	0.51±0.10	0.33±0.06	2.72±0.53	1.22±0.43	13	29
	Finger millet	1.18±0.32	[0.61, 1.86]	0.25±0.07	0.16±0.04	1.59±0.43	0.65±0.23	5	9
	Groundnut	1.64±0.16	[1.39, 2.05]	0.25±0.02	0.16±0.02	2.05±0.20	0.74±0.32	21	44
	Lentil	0.73±0.16	[0.33, 0.98]	0.16±0.04	0.10±0.02	0.99±0.22	0.41±0.13	4	5
	Pearl millet	2.91±0.25	[2.50, 3.49]	0.90±0.08	0.59±0.05	4.40±0.37	2.07±0.63	8	38
	Pigeon pea	2.75±0.34	[2.13, 3.47]	0.58±0.07	0.37±0.05	3.70±0.46	1.50±0.54	9	23
	Sorghum	3.11±0.28	[2.59, 3.71]	0.90±0.08	0.59±0.05	4.60±0.42	2.11±0.65	28	56
	Soybean	2.12±0.30	[1.68, 2.94]	0.32±0.05	0.21±0.03	2.65±0.38	0.95±0.41	26	46

[a]Aboveground carbon was estimated from post-harvest residues, assuming a carbon content of 47% in dry matter (IPCC 2019).
[b]Carbon in roots was estimated from aboveground resides using root-to-shoot ratios from literature (see section 2.4 for values and references).
[c]Carbon in rhizodeposits was estimated from carbon in roots, assuming that 65% of all carbon allocated in roots is released as sap exudates and during sloughing of root hairs and fine roots during the growing season (Bolinder et al. 2007).
[d]Carbon input was estimated as the sum of carbon in aboveground residues, belowground carbon and root extra carbon.

Across the two regions, there was a trend towards a decrease in aboveground carbon with time within field studies covering several years, although the differences were not significant. Average aboveground carbon decreased from 1.76±0.06 Mg/ha, 95% CI = [1.68, 1.92] in the first year to 1.75±0.08 Mg/ha, 95% CI = [1.60, 1.92]) and 1.44±0.15 Mg/ha, 95% CI = [1.19, 1.79] in the second and third year of the experiments, respectively. There was also a non-significant trend towards higher aboveground carbon when residues were retained (1.40±0.11 Mg/ha, 95% CI = [1.21, 1.67]) compared to when residues were removed from the field (1.15±0.16 Mg/ha, 95% CI = [0.88, 1.53]). When growing conditions (water regime: irrigated or rain fed) were considered, aboveground carbon was significantly higher under irrigated conditions (2.72±0.2 Mg/ha, 95% CI = [2.37, 3.15]) compared to purely rain fed conditions (1.71±0.09 Mg/ha, 95% CI = [1.55, 1.91]).

3.3. Absolute SOC concentration in farming systems with GLDC

The amount (mean ±SE) of SOC concentration under farming systems with GLDC across the regions was 0.76±0.04%. Unlike aboveground carbon (Figure 4), there was significantly higher SOC concentration in Africa (0.96±0.06%) than in South Asia (0.58±0.04) (Figure 6). Soil organic carbon in studies located on Ferralsols and Ultisols were significantly higher than the rest of the soil types (Figure 6). On average, initial SOC of sites located on Ferralsols (1.30%) and Ultisols (1.40%) was higher than that of sites located on Arenosols (0.39%), Cambisols (0.56%), Inceptisols (0.65%), Lixisols (0.58%), Luvisols (0.58%) and Vertisols (0.64%). When farming systems were compared, SOC was significantly higher in agroforestry and in intercrops than in continuous sole crop (Figure 6). Soils under common bean and pigeon pea had significantly higher SOC concentration than all other crops except lentil (Figure 6; Figure 7); soil under soybean had significantly higher SOC than sorghum, pearl and finger millet (Figure 6).

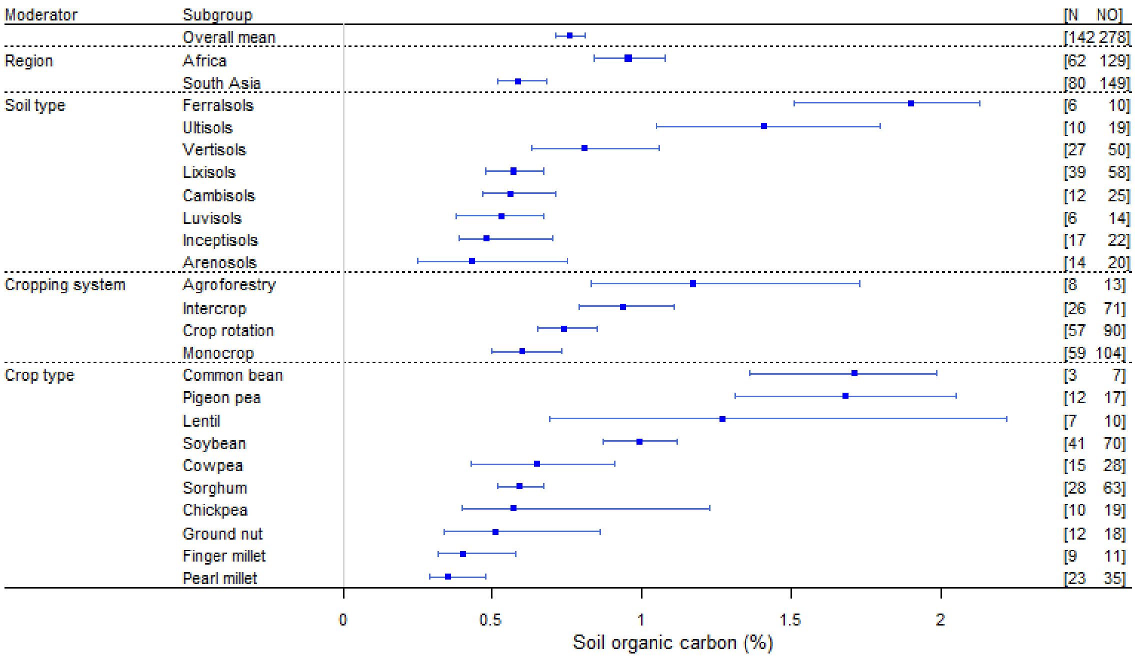

Figure 6.Soil organic carbon concentration at 0-30 cm depth on farms or fields including grain legumes and dryland cereals in Africa and South Asia. The vertices represent the 95% confidence limits of the estimate. Numbers within brackets indicate the number of publications [N] and number of observations [NO]. Differences among subgroups in each category are significant when the CI do not overlap.

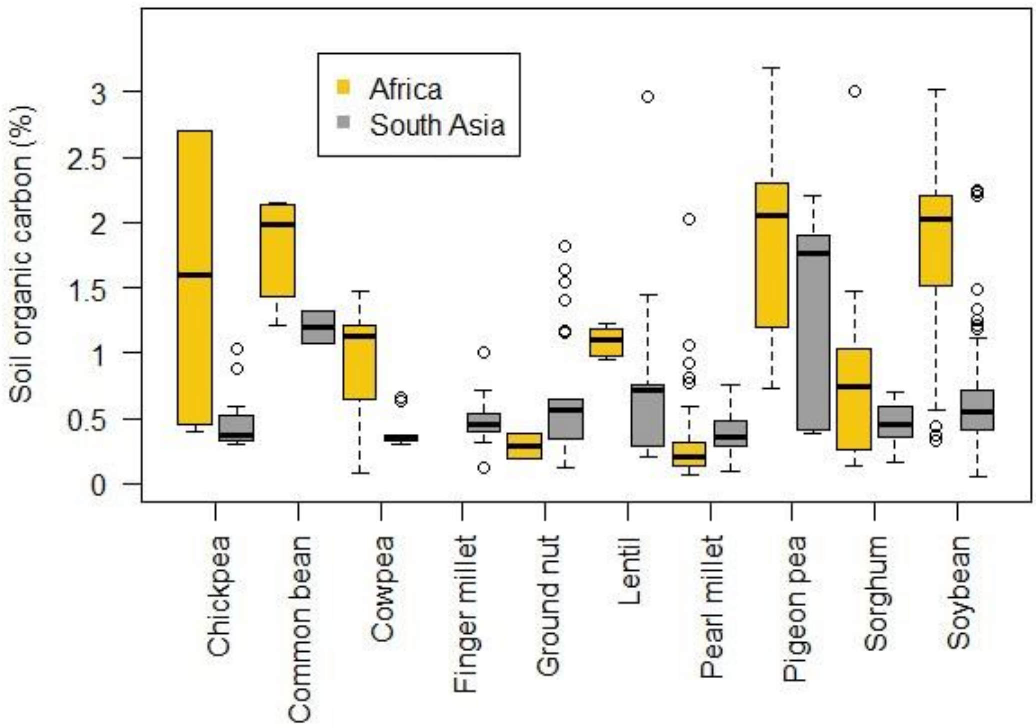

Figure 7. Soil organic carbon concentration in farming systems associated with different crops by region.

3.4 Changes in aboveground carbon due to presence of GLDC

Fifty-nine publications with 182 paired observations fulfilled the selection criteria for evaluating changes in aboveground carbon due to the presence of GLDC. Inclusion of GLDC in farming systems significantly increased aboveground carbon, both in Africa: (RR: 1.02, 95% CI = [1.00, 1.05]) and in South Asia (RR: 1.27, 95% CI = [1.16, 1.40]). The increase was largest in South Asia (27%) and marginal in Africa (2%). Changes in aboveground carbon were positive and significant when GLDC were grown as intercrops or rotations but not in agroforestry (Figure 8). Intercropping GLDC increased aboveground carbon by 44% on average while growing them in rotation increased it by 4% (Figure 8).

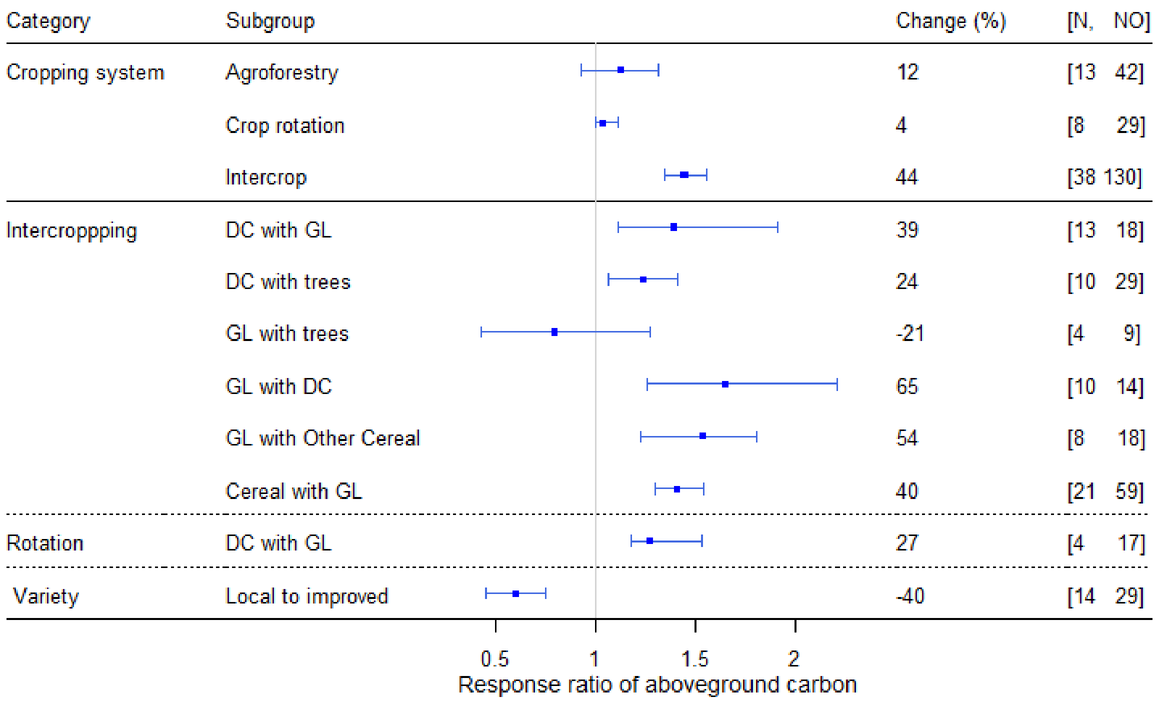

Figure 8. Variations in response ratios (RR) of aboveground carbon with cropping systems and crop combinations. The different crop combinations are intercropping or rotating dryland cereal (DC: sorghum, finger millet, pearl millet) with grain legumes (GL: chickpea, common bean, cowpea, lentil pigeon pea or soybean), or trees or other cereals (maize, wheat, rice, oat or tef) or vice versa; and changing from local to improved varieties of GLDC. The vertices represent the 95% confidence limits of RR. The grey line indicates the RR = 1 and represents the same response in treatment and control. Significant changes are indicated when the 95% confidence intervals lie below (decrease) or above (increase) the grey line. Negative values under "change (%)" represent a decrease while positive values represent an increase relative to initials SOC content at the start of the experiment. Numbers within brackets indicate the number of publications [N] and number of observations [NO].

When different combinations were evaluated, planting dryland cereals or other cereals (maize, wheat, rice and tef) as companion crops for grain legumes resulted in a more than 50% increase in aboveground carbon. On the contrary, planting grain legumes as a companion crop in dryland cereals or other cereals resulted in a 40% increase in aboveground carbon. Surprisingly, growing dryland cereals (C4 plants) in agroforestry increased aboveground carbon by 24% (Figure 8). Growing dryland cereals in rotation with grain legumes resulted in a 27% increase in the aboveground biomass. There were no significant differences among different combinations. Fourteen publications with 29 observations reported the presence of aboveground carbon when farmers changed from traditional to improved varieties of chickpea, common bean, cowpea, soybean, pearl millet and sorghum. Aboveground carbon was depressed (-40%) when farmers shifted from local to improved varieties (Figure 8).

3.5 Changes in SOC concentration due to presence of GLDC

3.5.1 Comparing SOC at the start and end of the experiment

Eighty-one publications with 144 paired observations reported data on SOC content at the start (initial SOC content) and at the end of the experiment (final SOC content), allowing for evaluation of changes in SOC due to inclusion of GLDC in farming systems. Across different climate and soil conditions and agronomic practices, the inclusion of GLDC in farming systems showed a non-significant trend towards higher SOC concentration (RR: 1.04; 95% CI= [0.94, 1.12]). The proportion of observations that showed an increase for the combined data were more (59%; n=108) than those that showed a decrease (41%). Although the differences were not statistically significant when the two regions were compared, the trend towards increased SOC was generally stronger in South Asia (RR: 1.07, 95% CI = [0.95, 1.20]) than in Africa (RR: 1.02; 95% CI = [0.94, 0.10]).

Soil organic carbon significantly increased in response to GLDC under Cambisols and Ferralsols, but decreased under Lixisols and Luvisols (Figure 9). Inclusion of GLDC did not have a significant effect in Ultisols, Vertisols, Arenosols and Inceptisols. Inclusion of GLDC in farming systems increased SOC under clay soils but did not have a significant effect under loam and sandy soils (Figure 9). SOC significantly increased where the initial SOC was below 1% (RR=1.11) but decreased in soils than had more than 1.5% SOC (RR=0.73) at the start of experiments (Figure 9). Soils that had moderate SOC (between 1 and 1.5%) at the start of experiment only showed a non-significant trend towards higher SOC (RR=1.07) at the end of the experiment (Figure 9).

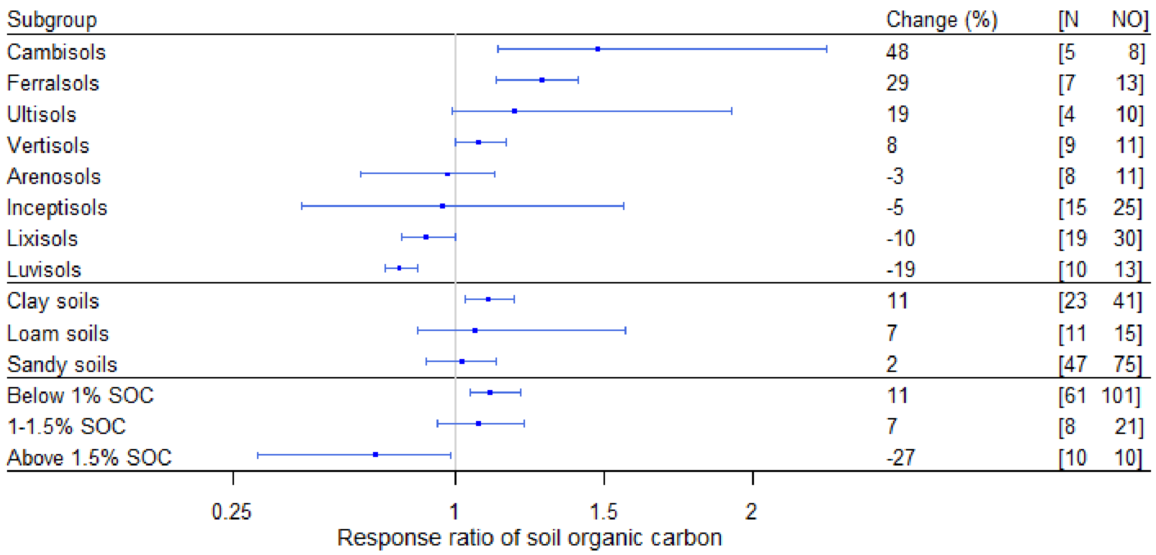

Figure 9.Variations in response ratios (RR) of soil organic carbon concentration (SOC) to GLDC with soil type, soil texture group and initial SOC for studies comparing initial and final SOC or SOC at the start and end of the experiment. The vertices represent the 95% confidence limits of RR. The grey line indicates the RR = 1 and represent same response in the treatment and control. Significant changes are indicated when the 95% confidence intervals lie below (decrease) or above (increase) the grey line. Negative values under "change (%)" represent a decrease while positive values represent an increase, relative to initial SOC content at the start of the experiment. Numbers within brackets indicate the number of publications [N] and number of observations [NO].

At the end of the experiment, SOC was significantly higher under intercropping, but did not show significant differences between initial and final SOC content when GLDC were included under crop rotation or monocrops (Figure 10). Differences between cropping systems were not significant. When individual GLDC were compared, SOC was significantly higher at the end of the experiment compared to initial values under pigeon pea, chickpea and soybean, but lower under sorghum and finger millet (Figure 10). There were no significant differences on SOC under different crops except between pigeon pea and sorghum (Figure 10).

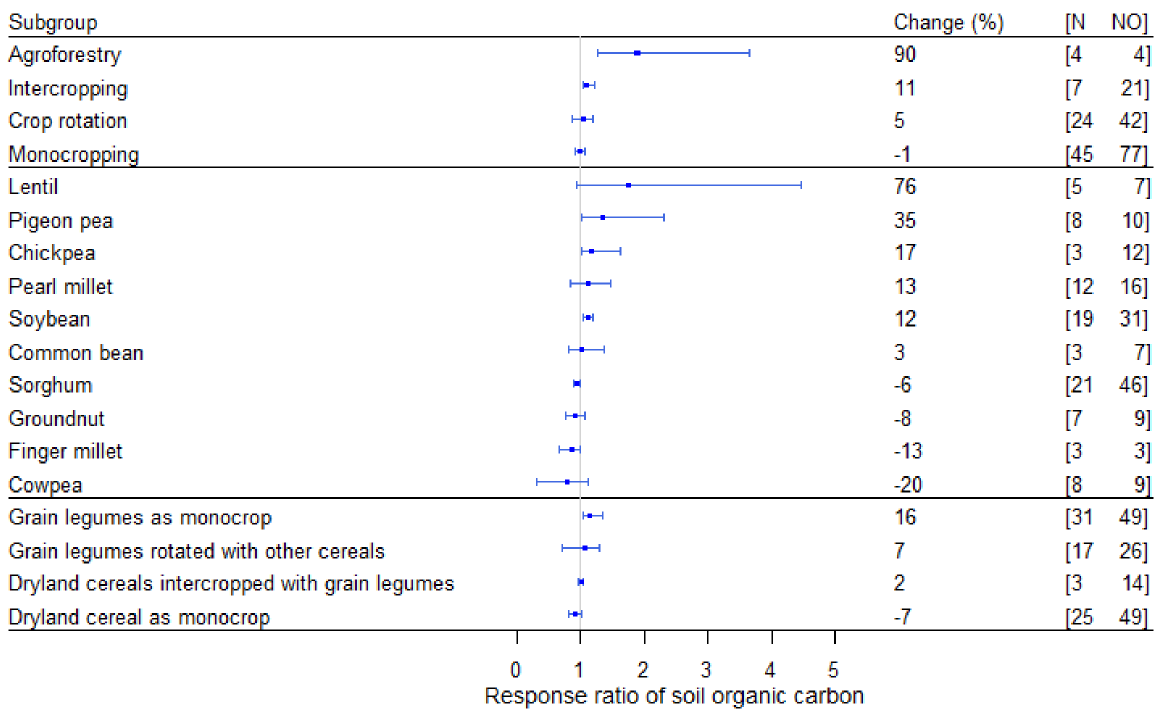

Figure 10.Variations in response ratios (RR) of soil organic carbon concentration (SOC) with soil cropping systems, the crop and the combination of crops for studies comparing initial and final SOC content or SOC at the start and end of the experiment. Other cereals are rice, maize, tef and wheat; other crops are cotton, green grams, menthol mint, safflower and sunflower. The vertices represent the 95% confidence limits of RR. The grey line indicates the RR = 1, i.e. where responses in the treatment and control are the same. Significant reductions or increases are indicated when the 95% confidence intervals lie below or above the grey line, respectively. Negative values under "change (%)" represent a decrease while positive values represent an increase, relative to SOC at the start of the experiment. Numbers within brackets indicate the number of publications [N] and number of observations [NO].

3.5.2 Comparing SOC in farming systems with and without GLDC

Forty-two publications with 80 paired observations reported listed different combinations of GLDC that facilitated the evaluation of changes in SOC in farming systems which included GLDC compared to those that did not. The overall mean effect size (RR=1.54, 95% CI: [1.44, 1.63]) was greater than one, suggesting that SOC was higher in farming systems which included GLDC than in those that did not. The effect size and corresponding percentage change of different combinations are presented in Figure 11. Planting grain legumes as companion crops where other cereals (maize, wheat, tef or rice) or other crops (cassava, castor, Guinea grass, menthol mint, Napier grass or sacred basil) were the main crops that significantly increased SOC by 27% and 9% respectively, compared to monocrops of other cereals or other crops (Figure 11). Similarly, it was found that planting grain legumes on land that was previously under other cereals significantly increased SOC by 25% while planting other cereals in plants that had grain legumes increased SOC by 18% (Figure 11). On the contrary, intercropping other cereals as companion crops in farming systems where grain legumes were the main crops; or intercropping grain legumes as companion crops in farming systems with dryland cereals as main crops did not show significant differences compared to monocrops of the main crop (Figure 11). Planting dryland cereals in agroforestry systems significantly increased SOC (by 15%) compared to growing dryland cereals alone (Figure 11).

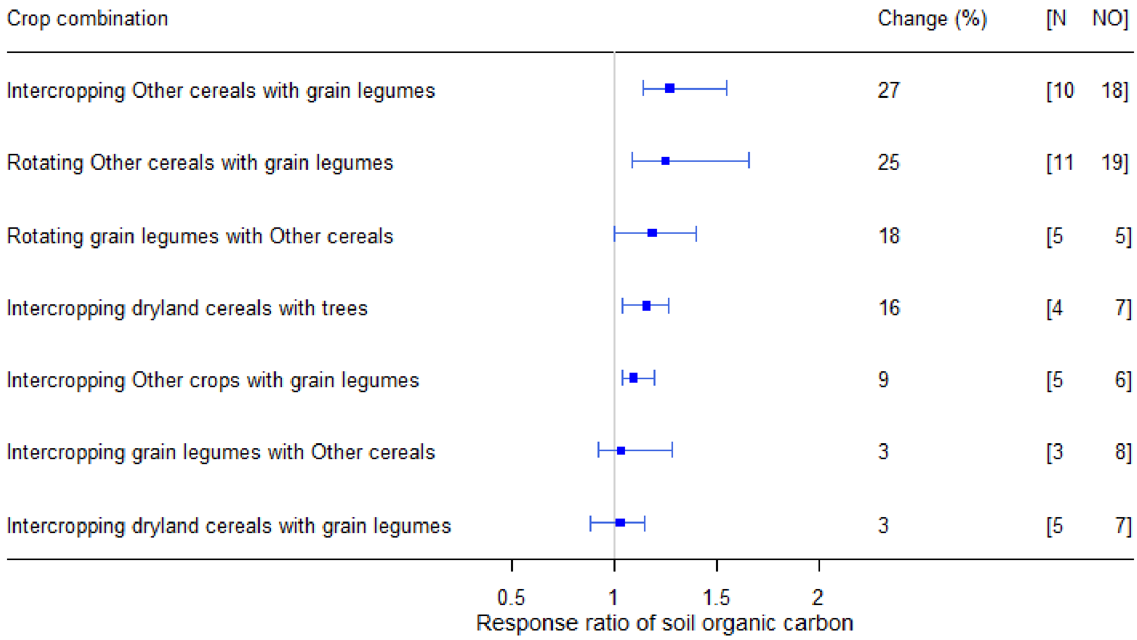

Figure 11.This figure shows variations in response ratios (RR) of soil organic carbon concentration with crop combinations for studies comparing farms or fields with GLDC and those without these crops. The cereals planted are rice, maize, tef and wheat; Other crops planted are cassava, castor, Guinea grass, menthol mint, Napier grass and sacred basil. The vertices represent the 95 % confidence limits of RR. The grey line indicates the RR = 1, i.e. where responses in the treatment and control are the same. Significant reductions or increases are indicated when the 95% confidence intervals lie below or above the grey line, respectively. Negative values under "change (%)" represent a decrease while positive values represent an increase, relative to the control group. Numbers within brackets indicate the number of publications [N] and number of observations [NO].

4. Discussion

The results show the potential of sorghum, millets and grain legumes to enhance carbon sequestration in farming systems in Africa and South Asia, and the opportunities to develop several pathways to increase carbon sequestration in a large number of countries. No studies were found in 32 out of the 64 countries admissible for selection. This difference represents a gap in research, considering that the studies included the period from 1975 to 2020. The fewer studies in some countries suggests moderate research effort. It is also possible that only few studies in these countries met the selection criteria, or publications on the subject are in languages other than English and French. Studies conducted in South Asia were concentrated in India, a country known for intensive cereal production, and one of the top five countries that account for over half the cereal production in the world.

The amount of plant carbon potentially available for input to the soil is large and varied depending on the crop (species), type of crop (legume or cereal) and cropping system. Differences in quantities between crops are attributed to differences in growth habits or climatic conditions, which limit the amount of residues that can be realized by the crop. Cereals and pigeon pea (woody perennial) had the largest amount of aboveground carbon (>2 Mg ha^{-1}). Pigeon pea is a multipurpose crop with long growing periods that allows it to accumulate more carbon compared to other legumes (Bayala et al. 2018, 2020). Low aboveground carbon under cowpea could be associated to growing conditions. Cowpea and finger millet are tolerant to drought and are often grown in arid and semi-arid areas where biomass production is low (Odeny 2007). The results underscore the importance of considering the growth habits of the crop for rotation or intercropping to maximize carbon sequestration.

The quantity of aboveground residues available for return to the soil is large, although the actual amount of plant carbon that can be added to the soil depends on whether residues are returned or removed from the field. Residue retention increases carbon sequestration by raising the quantity of carbon added to the soil from post-harvest residues and can in turn improve crop productivity (Johnson et al. 2006; Liu et al. 2014). On the contrary, residue removal lowers carbon inputs into the soil, and tilts the equilibrium towards net loss (Raffa et al. 2015; Bolinder et al. 2020; Lu 2020). In terms of climate mitigation, *in situ* accumulation of plant residues represents a net gain since atmospheric carbon is added to the soil without reduction in soil carbon where residues are obtained. However, residue retention is not common in Africa, where crop residues are needed for feed and fuel. Land preparation in Africa also involves the burning of gathered residues every year at the onset of the rainy season. Such practices reduce the biomass to be returned to the soil and also kill the soil communities that contribute to decomposition and aggregate formation.

Aboveground carbon was greatly increased when GLDC were integrated as intercrops but depressed under agroforestry. Intercrops produce more biomass per unit area because of the combined harvest from the component crops, which accounted for about 50% increase in aboveground carbon in this study; and because of complementarity / facilitation among components (Brooker et al. 2015). The latter is due to reduced competition and increased resource use efficiency among crops that utilize resources at different times or at varied depths within the soil profile (Duchene et al. 2017). Crops grown under agroforestry had low aboveground carbon because of competition with trees or a smaller population of the companion crop compared to monoculture (Kuyah et al. 2019). Studies that compare carbon sequestration under improved and local varieties were few, and indicated that improved varieties of GLDC produced less biomass carbon compared to local varieties. This suggests that high yielding varieties which produce more grain may have fewer residues that remain after harvesting. This presents a tradeoff between productivity and agricultural carbon sequestration. Carbon input from such varieties may to a larger extent come from root biomass, especially where improved varieties are bred to withstand drought. Much of the comparison between local and improved varieties has focused on yield, with indication that improved grain yields have low residue biomass. However, improved varieties produce large amounts of residues when the harvest index (ratio of grain to total plant mass aboveground) is not changed in the process of breeding (Johnson et al. 2006). The dearth of data makes it difficult to determine varieties (local or improved) with greater capacity for carbon sequestration.

Absolute SOC concentration in farms and fields where GLDC were grown in Africa (0.96±0.04) and in South Asia (0.58±0.06%) is low, and corresponds to characteristic low SOC levels in the regions (Lal 2004, 2008). Low soil carbon content in these regions is attributed to continuous low input, extractive agriculture in Africa and severe soil degradation and excessive tillage in South Asia (Lal 2004). Degraded soils have low biomass production, low input use efficiency and therefore lower amounts of crop residue are returned to the soil. Estimates of SOC in both regions are lower than the general threshold (1.74% carbon or 3% organic matter) that is considered critical for supporting crop production in low input agriculture on tropical soils (Musinguzi et al. 2016). SOC concentrations close to 1.74% were only found in farming systems that included legumes i.e. common bean (1.71±0.16%) and pigeon pea (1.68±0.19%). Based on SOC concentration, Musinguzi et al.(2016) broadly classified soils (in Uganda, Africa) as low fertility (<1.2%), medium fertility (1.2-1.7%) and high fertility (>1.7%). GLDC are therefore grown on soils that are low in soil fertility, as revealed also by the majority (74%) of publications that referred to studies conducted on soils with <1% SOC.

GLDC increased SOC when grown under intercrops and crop rotation, relative to the initial SOC content. Intercropping and crop rotation are leading measures used to raise cropping intensity in smallholder systems in Africa and South Asia (Godfray and Garnett 2014; Duchene et al. 2017; Franke et al. 2018b; King and Blesh 2018). They can enhance soil carbon sequestration by increasing the amount of aboveground residues that can be returned to the soils (McDaniel et al. 2014; Tiemann et al. 2015). These measures can also increase carbon input from roots e.g. through production of more root biomass or exudates (Cong et al. 2015). Introduction of plants which may have carbon compounds that are more resistant to microbial metabolism, or by improving the ability of soil microbial communities to rapidly process plant residues and protect them in aggregates can also enhance soil carbon sequestration(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 (Blanco-Canqui and Lal 2004).

The greatest increase in SOC was found in systems including legumes (pigeon pea, chickpea and soybean) while systems including cereals showed a decline in SOC (sorghum) or no effect (pearl millet). The use of grain legumes as companion crops in cereals (dryland and other cereals) increased SOC relative to initial SOC content. It also increased SOC in the intercrop/subsequent crop relative to the cereal monoculture or continuous sole cropping. Similarly, SOC increased significantly under legume monocrops but decreased under cereal monocrops, when the final SOC was compared to the initial SOC content in respective monocultures. Primary studies attribute higher soil carbon in systems with legumes to high quality residues that promote microbial growth efficiency and aggregation (Drinkwater et al. 1998; Blanco-Canqui and Lal 2004; McDaniel et al. 2014). Other reasons for higher soil carbon include production of large quantities of biomass in some legumes e.g. pigeon pea (Abdurahman et al. 1998), improved biomass production of the subsequent crop in rotations (Franke et al. 2018b), increased release of carbon in exudates in the root zone (Tiemann et al. 2015) or increasing nitrogen and phosphorus use efficiency of cereal crops (Franke et al. 2018b; Ndayisaba et al. 2021). High SOC increase under pigeon pea is attributed to its capacity to take up more carbon and to transfer substantial amounts of it to the soil via roots and litter fall (Bayala et al. 2018, 2020). Pigeon pea has extensive and deep root systems which increase belowground biomass and carbon storage at deeper soil profiles where it is locked and protected from disturbance and weather fluctuation. Low SOC under some legumes can be attributed to limited biomass input from the legume, and probably the chemical composition of the inputs (Tiemann et al. 2015).

Soil organic carbon significantly increased on clay soils and soils with low initial SOC (<1%) but decreased in soils with high (>1.5%) SOC. This is consistent with existing literature: a positive relationship between SOC and clay content and a negative relationship between carbon sequestration and initial SOC (Blanco-Canqui and Lal 2004; Lal 2004; Jagadamma and Lal 2010). A recent meta-analysis reported comparable results: higher SOC increase in clay soils compared to sandy soils (Gross and Glaser 2021). Increasing SOC with increase in clay content suggest that soils with high clay content accrued SOC more rapidly than sandy soils. Sandy soil has limited capacity to stabilize organic compounds (Blanco-Canqui and Lal 2004), and low productivity (equal to low carbon inputs) due to limited capacity to retain nutrients or water (Nkurunziza et al. 2019). On the contrary, clay soil has the capacity to protect SOC from breakdown by soil microbes through the formation of aggregates or humification of SOC (Blanco-Canqui and Lal 2004; Lal 2004). Clay content can also affect accumulation of SOC indirectly by retaining soil moisture thereby increasing plant productivity (Franzluebbers et al. 1996). The negative relationship between carbon sequestration and initial SOC is explained thus: SOC accumulates rapidly where initial SOC content is far from its saturation level. A similar trend was found in a meta-analysis by Gross and Glaser (2021), where the large increase in SOC occurred on soils with initial SOC lower than 1%. This suggests that efforts aimed to increase soil carbon sequestration should prioritize regions with low SOC content.

5. Conclusion

The results show the potential of sorghum, millets and grain legumes to enhance carbon sequestration in farming systems in Africa and South Asia, and therefore improve soil quality and mitigate climate change. The quantity of aboveground residues available for return to the soil is large. This is critical in Africa and South Asia, where low SOC is a key constraint for crop production. The large amount of carbon linked to aboveground residues suggest that residue return can play an important role in maintaining or increasing carbon stocks in farming systems, especially where there is no addition of organic amendments. However, the volume of residues added to the soil might be less than the amount quantified in this study because of competing needs for livestock feed, fuel and other uses. The results suggest cropping intensity holds much promise for increasing the amount of soil carbon in farming systems with GLDC. It was also proven that soils which have low carbon concentration but high clay content have the greatest potential for carbon sequestration when cropped with GLDC. The type of crop has significant influence on the amount of carbon sequestered in agricultural systems. Finally, this study found differences in aboveground carbon and SOC concentration among dryland cereals and grain legumes. Comparing dry matter production revealed that cereals (finger and pearl millet, and sorghum) and pigeon pea had the largest potential for aboveground carbon (>2 Mg/ha); legumes on the other hand, had the greatest influence on SOC concentration. In conclusion, the integration of GLDC in farming systems has the potential to contribute to climate mitigation and increased productivity through increased carbon sequestration.

Study limitations

This working paper is based on carbon in aboveground residues and SOC concentration in publications that reported on GLDC crops in Africa and South Asia. The results reflect what has been published and may not exactly represent what farmers grow. Even though aboveground residues provide significant carbon input, there are a host of factors (e.g. tillage, organic amendment, elevation, slope, pH etc.) that influence the amount of carbon added to the soil. These factors were either rarely or not systematically reported. Other information not reported in most publications was bulk density, previous land uses, variance metrics, and in some studies, sample size. Methods for reporting SOC were also not standardized, with only a few studies providing data on SOC before the adoption of GLDC. In this study, initial SOC information is inferred from initial soil properties reported in the methods. These limitations make it difficult to evaluate conditions under which the GLDC offer the greatest carbon benefits. Identifying conditions under which GLDC can make positive contributions requires analyses that include these factors. There were a few publications that reported aboveground carbon under improved and local varieties, and no publication reported SOC under the two varieties. This makes it difficult to assess what happens to SOC when farmers change from local to improved varieties of GLDC. Evidence reported in grey literature was not captured in this review because of the difficulty of locating and reviewing scientific evidence in this area. This is literature that is often unpublished research or publications not available through normal channels; or publications such as mainstream databases. The brief period of this review did not have scope for a comprehensive appraisal of grey literature.

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Appendices

Appendix 1. Aboveground carbon and soil carbon groups reported in publications reviewed for studies conducted in Africa and South Asia.

Carbon pool used for analysis	Reported carbon class or proxy for soil organic carbon	No. of studies
Aboveground carbon	Dry matter/aboveground biomass	193
	Fodder (dry)	19
	Aboveground residues (stalk, stover, straw, stubble, haulm) yield	165*
	Green manure (dry)	2
Soil organic carbon	Annual carbon input from residues	6
	Soil organic carbon	132
	Soil organic matter	9
	Soil carbon stocks	10
*42 publications did not specify how the weight of aboveground residues reported were determined, and therefore not considered as dry matter for estimation of aboveground carbon in this review.		

Appendix 2. Estimates (mean ± standard error [SE} and 95% confidence interval [CI]) of aboveground carbon (Mg/ha) in farming systems with grain legumes and dryland cereals in Africa and South Asia. N is the number of publications while NO is the number of observations.

Category	Subgroup	Mean±SE	0.25 CI	0.975 CI	N	NO
Overall mean	Overall mean	1.76±0.05	1.66	1.85	330	1036
Region	Africa	1.51±0.05	1.42	1.62	210	708
	South Asia	2.29±0.10	2.10	2.49	120	328
Type of trial	On farm	1.56±0.07	1.43	1.71	98	354
	On station	1.83±0.06	1.72	1.96	238	682
Soil type	Andosols	2.41±0.51	1.55	3.62	6	19
	Arenosols	0.96±0.06	0.85	1.10	50	189
	Cambisols	2.53±0.28	2.00	3.10	12	47
	Ferralsols	1.79±0.21	1.43	2.28	12	33
	Fluvisols	1.06±0.23	0.67	1.61	4	10
	Inceptisols	2.25±0.20	1.89	2.67	33	58
	Lixisols	1.58±0.12	1.37	1.83	47	128
	Luvisols	2.14±0.24	1.73	2.71	28	77
	Plinthosols	1.19±0.11	1.00	1.42	4	34
	Ultisols	1.26±0.18	1.00	1.73	22	46
	Vertisols	1.76±0.21	1.44	2.28	41	391
Cropping system	Agroforestry	0.94±0.10	0.78	1.22	23	70
	Crop rotation	1.24±0.10	1.07	1.45	41	121
	Intercrop	2.23±0.12	2.01	2.48	57	233
	Monocrop	1.77±0.06	1.66	1.90	245	612
Crop type	Chickpea	1.10±0.11	0.91	1.37	31	60
	Common bean	1.55±0.15	1.28	1.88	24	55
	Cowpea	1.14±0.10	0.98	1.37	61	168
	Finger millet	2.72±0.48	1.86	3.75	9	20
	Groundnut	1.47±0.12	1.27	1.74	46	108
	Lentil	0.80±0.12	0.48	0.97	5	6
	Pearl millet	1.66±0.10	1.48	1.89	56	180
	Pigeon pea	2.48±0.26	2.02	3.03	22	53
	Sorghum	2.44±0.14	2.19	2.74	78	164
	Soybean	1.42±0.13	1.21	1.77	62	124
Year of experiment	One	1.79±0.06	1.68	1.92	323	626
	Two	1.75±0.08	1.60	1.92	161	309
	Three	1.44±0.15	1.19	1.79	54	81
Water regime	Irrigated	2.72±0.20	2.37	3.15	68	157
	Rain fed	1.71±0.09	1.55	1.91	99	306
Residue management	Removed	1.15±0.16	0.88	1.53	25	61
	Retained	1.40±0.11	1.21	1.67	48	128

Appendix 3. Estimates (mean ± standard error [SE} and 95% confidence interval [CI]) of absolute soil organic carbon in farming systems with grain legumes and dryland cereals in Africa and South Asia. N is the number of publication while NO is the number of observations.

Category	Subgroup	Mean±SE	0.25 CI	0.975 CI	N	NO
Overall mean	Overall mean	0.76±0.04	0.71	0.81	142	278
Region	Africa	0.96±0.06	0.84	1.08	62	129
	South Asia	0.58±0.04	0.52	0.68	80	149
Type of trial	On farm	0.84±0.07	0.71	0.98	30	76
	On station	0.72±0.04	0.64	0.81	113	202
Soil type	Arenosols	0.43±0.12	0.25	0.75	14	20
	Cambisols	0.56±0.06	0.47	0.71	12	25
	Ferralsols	1.90±0.15	1.51	2.13	6	10
	Inceptisols	0.48±0.07	0.39	0.70	17	22
	Lixisols	0.57±0.05	0.48	0.67	39	58
	Luvisols	0.53±0.08	0.38	0.67	6	14
	Ultisols	1.41±0.19	1.05	1.80	10	19
	Vertisols	0.81±0.11	0.63	1.06	27	50
Cropping system	Agroforestry	1.17±0.22	0.83	1.73	8	13
	Crop rotation	0.74±0.05	0.65	0.85	57	90
	Intercrop	0.94±0.08	0.79	1.11	26	71
	Sole cropping	0.60±0.06	0.50	0.73	59	104
Crop type	Chickpea	0.57±0.165	0.40	1.23	10	19
	Common bean	1.71±0.16	1.36	1.99	3	7
	Cowpea	0.65±0.12	0.43	0.91	15	28
	Finger millet	0.40±0.06	0.32	0.58	9	11
	Groundnut	0.51±0.12	0.34	0.86	12	18
	Lentil	1.27±0.41	0.69	2.22	7	10
	Pearl millet	0.35±0.04	0.29	0.48	23	35
	Pigeon pea	1.68±0.19	1.31	2.05	12	17
	Sorghum	0.59±0.04	0.52	0.67	28	63
	Soybean	0.99±0.06	0.87	1.12	41	70
Year of experiment	One	0.74±0.04	0.67	0.83	135	217
	Two	0.79±0.08	0.64	0.97	7	7
	Three	0.77±0.22	0.42	1.36	28	47
Water regime	Irrigated	0.68±0.11	0.45	0.94	21	46
	Rain fed	0.68±0.06	0.57	0.82	47	98
Residue management	Removed	0.70±0.12	0.49	0.98	14	28
	Retained	0.69±0.07	0.57	0.85	42	54

Appendix 4 References of the systematic review

The list denotes publications from which data on soil organic carbon (SOC) or its proxies (aboveground biomass, soil organic matter or carbon stocks) was extracted for the review. The review yielded 437 publications spread across 32 countries in Africa and South Asia. The publications reported absolute quantities and/or changes aboveground carbon/SOC when dryland cereals (sorghum, finger or pearl millets) or grain legumes (chickpea, common bean, cowpea, lentils, pigeon pea or soybean) were integrated in farming systems in Africa and South Asia.

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The CGIAR Research Program on Grain Legumes and Dryland Cereals (CRP-GLDC) brings together research on seven legumes (chickpea, cowpea, pigeon pea, groundnut, lentil, soybean and common bean) and three cereals (pearl millet, finger millet and sorghum) to deliver improved livelihoods and nutrition by prioritizing demand driven innovations to increase production and market opportunities along value chains.
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