Check for updates

Received: 3 February 2024 | Accepted: 15 May 2024 | Published online: 19 June 2024

DOI: 10.1002/csc2.21294

Crop Science

PLANT BREEDING REVIEW

Biomass allocation and carbon storage in the major cereal crops: A meta-analysis

Asande Ngidi[1] | Hussein Shimelis[1] | Vincent Chaplot[2,3] | Kwame Shamuyarira[4] | Sandiswa Figlan[5]

[1]African Centre for Crop Improvement, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Scottsville, South Africa

[2]Laboratory of Oceanography and Climate, Experiments and Numerical Approaches (LOCEAN), UMR 7159, IRD/C NRS/UPMC/MNHN, IPSL, Paris, France

[3]School of Agricultural, Earth & Environmental Sciences, University of KwaZulu-Natal, Scottsville, Republic of South Africa

[4]Faculty of Natural and Agricultural Sciences, University of the Free State, Bloemfontein, Republic of South Africa

[5]Department of Agriculture and Animal Health, University of South Africa, Florida, South Africa

Correspondence
Sandiswa Figlan, Department of Agriculture and Animal Health, University of South Africa, Florida, 1709, South Africa.
Email: figlas@unisa.ac.za

Assigned to Associate Editor Irwin L. Goldman.

Funding information
Water Research Commission, Grant/Award Number: C2020/2021-00646; African Centre for Crop Improvement (ACCI);

Abstract

Crop biomass is the reservoir of carbon (C), a valuable input to the soil, thus supporting the soil fauna and enhancing soil health. There are limited studies that compared the major cereal crops for C storage for regenerative agriculture and to optimize C sequestration strategies. The objective of this study was to quantify the extent of variation in biomass allocation and C storage between maize (*Zea mays* L.), sorghum (*Sorghum bicolor* [L.] Moench), and wheat (*Triticum aestivum* L.) for crop production, and C sequestration potential. The study used metadata from 40 global studies that reported on the allocation of plant biomass and C between roots and shoots of the major cereal crops. Key statistics were computed to determine the variability between genotypes for total plant biomass (Pb), shoot biomass (Sb), root biomass (Rb), root-to-shoot biomass ratio (Rb/Sb), total plant carbon content, shoot carbon content, root carbon content, total plant carbon stock (PCs), shoot carbon stock, root carbon stock, and root-to-shoot carbon stock ratio (RCs/SCs). Maize exhibited the highest variability for Pb (with a coefficient of variation [CV] of 31.2% and a mean of 4.2 ± 1.3 Mg ha^{-1} year^{-1}), followed by wheat (CV of 24.2% and a mean of 1.5 ± 0.4 Mg ha^{-1} year^{-1}) and sorghum (CV of 16.8% and a mean of 2.0 ± 0.8 Mg ha^{-1} year^{-1}), respectively. A similar trend was observed for PCs, with maize (CV of 40.1% and mean of 1.6 ± 0.7 Mg ha^{-1} year^{-1}) showing the highest total plant C stock variability, followed by wheat (24.4% and 0.2 ± 0.1 Mg ha^{-1} year^{-1}) and sorghum (16.3% and 0.9 ± 0.3 Mg ha^{-1} year^{-1}), respectively. Maize (with a CV of 24.4% and mean of 0.1 ± 0.03 Mg ha^{-1} year^{-1}) exhibited the highest variability for Rb/Sb, while wheat (30.92% and 0.2 ± 0.05 Mg ha^{-1} year^{-1}) exhibited the highest variability for RCs/SCs. Correlation analysis revealed the following significant associations: Pb and mean annual temperature (MAT) ($r = -0.47$), and Sb and

Abbreviations: MAP, mean annual precipitation; MAT, mean annual temperature; OC, organic carbon; OM, organic matter; Pb, total plant biomass; PCc, total plant carbon content; PCs, total plant carbon stock; R/S, root-to-shoot ratio; Rb, root biomass; Rb/Sb, root-to-shoot biomass ratio; RCc, root carbon content; RCs, root carbon stock; RCs/SCs, root-to-shoot carbon stock ratio; Sb, shoot biomass; SCc, shoot carbon content; SCs, shoot carbon stock; SOC, soil organic carbon.

University of South Africa (UNISA); French National Research Institute for Sustainable Development (IRD)

MAT ($r = -0.43$), and Pb and mean annual precipitation (MAP) ($r = -0.34$), and Sb and MAP ($r = -0.30$). Rb had a strong, significant positive correlation with MAT ($r = 0.72$) and MAP ($r = 0.85$). The meta-analysis revealed that maize and sorghum have the highest variability for Pb and plant carbon stocks, while wheat exhibited the highest variability for the below-ground biomass and carbon stocks. The data aided in crop selection and suggested that the best cultivars could be developed and identified for production and C sequestration potential for cultivation by farmers, land rehabilitation, and climate change mitigation.

1 | INTRODUCTION

Crop biomass is the main reservoir of organic carbon (OC) that supports soil fauna and enhances soil health while sequestrating atmospheric carbon. Soils constitute the greatest terrestrial pool of carbon (C) and store two to three times the C found in the atmosphere (Minasny et al., 2017). Soil carbon, which is found as part of organic matter (OM) within the soil, provides energy and nutrients for soil micro-organisms and is vital for ecosystem functioning, such as food production and climate regulation. However, due to the conversion of natural ecosystems to agricultural production, most of the original soil C has been lost to the atmosphere. Harvested crops export enormous amounts of nutrients from soils, thus leading to OM depletion (Chaplot & Smith, 2023). Abbas et al. (2020) estimated the total amount of C lost to the atmosphere during the 5 and 50 years in the tropical to amount to 20 Mg C ha^{-1} and 50 Mg C ha^{-1} for tropical and temperate regions, respectively. Therefore, C replacement and soil enrichment appear to be a credible strategy for rehabilitating denuded croplands and reducing the carbon buildup in the atmosphere (Daba & Dejene, 2018).

The atmosphere–plant–soil system is the most crucial part of the global C cycle, with about 17% of the 720 Gt atmospheric C stock flowing through it yearly (Jaradat, 2013). The assumption is that increasing soil C stocks would only require a slight increase in the flux of C from the atmosphere to plants and from plants to soils (Mathew et al., 2017). Plants capture atmospheric C through photosynthesis for assimilation and release OC into the soil through rhizodeposition and decomposition of plant residues such as leaves, stems, and roots (Abbas et al., 2020). Balesdent and Balabane (1996) indicated that most of the C released into the soil by plants comes from roots rather than shoots. Evidence from other studies (Cardinael et al., 2018; Hirte et al., 2021; Katterer et al., 2011) show that crops with higher root-to-shoot ratios (R/S) have up to 20% higher capacity to sequester carbon in soils than crops with low R/S. Furthermore, Lorenz and Lal (2014) observed that root-derived soil organic carbon (SOC) is 1.5–3.0 times higher than shoot-derived carbon. The reason for higher soil C sequestration by crops with high R/S is that roots are physically embedded in the soil, providing them with a more stable and secure environment while providing soil fauna with a high variety of sugars that feed soil micro-fauna whole cells, ultimately turning into soil organic matter (Kramer et al., 2012). In addition, soil provides a buffer against environmental factors, such as temperature fluctuations, moisture changes, and exposure to light, which enhances the decomposition of fresh above-ground OM (Buytaert et al., 2011).

Variation in total biomass and C and their allocation between roots and shoots have been observed among crop species in several studies (Gonzalez-Sanchez et al., 2012; Mathew et al., 2017). In a global meta-analysis, Mathew et al. (2017) reported that maize (*Zea mays* L.) had 11% and 32% higher shoot biomass (Sb) and shoot C stocks than sorghum (*Sorghum bicolor* [L.] Moench). Conversely, in Canada, Thivierge et al. (2016) reported higher Sb for sorghum (19 kg ha^{-1}) followed by maize (17.6 kg ha^{-1}) and pearl millet (13.40 kg ha^{-1}). However, crop production environments as affected by soil type, climate, and management practices also significantly influence biomass and C allocation. For instance, Kukal and Benbi (2009) reported that wheat (*Triticum aestivum* L.) allocated 55% C to shoots in manure-fertilized soils but allocated 45% C to the shoots in soils applied with inorganic fertilizers. Similarly, Amujoyegbe et al. (2007) reported an increase in root biomass (Rb) and root carbon stock (RCs) allocation in maize by 35% and sorghum by 18.2% in Nigeria when N application rate was increased. This information can be used to match crop types to land and inform on the best management practices to adopt to increase biomass allocation to the roots for land rehabilitation and climate change mitigation (Kellogg & Schware, 2019). Carbon allocation into crops differs not only between crop types and between land management systems but also between cultivars of a crop. Aquino et al. (2017) pointed out that the accumulation of carbon in maize shoots was 46% higher in a newly developed genotype USM Var 10 than in Crystal, which is the local variety.

Maize (*Zea mays* L.), sorghum (*Sorghum bicolor* [L.] Moench), and wheat (*Triticum aestivum* L.) are the major cereal crops in terms of grain production, food security, and marketing. Over two-thirds of the global cereal outputs are used for food for an estimated 35% of the world's population, and one-fifth is used to feed livestock (Grote et al., 2021). The global production of maize and wheat is approximately 1127 and 750 million tonnes annually, respectively (OECD/FAO, 2022). The global sorghum production amounts to an annual average of 58.87 million tonnes (OECD/FAO, 2022). The crops can be grown in a wide range of agroecologies, including diverse temperatures and latitudes, and land and soil types. Furthermore, sorghum can withstand high temperatures and extended periods of drought due to its deep root system to access soil moisture (Chen et al., 2020). Crop production in Africa has been challenged by drought stress, poor soil health, diseases, insect pests, and parasitic plants (Macauley & Ramadjita, 2015). Crops have high biomass production and can transfer atmospheric C to the soil over their life cycle, which can enhance the potential for carbon sequestration.

There are limited studies that compared the major cereal crops for C storage for regenerative agriculture and to optimize C sequestration strategies. Understanding the C input between roots and shoots allows for assessing options for enhancing soil C storage. There is a need to differentiate potential powerhouse crops with high biomass production that involve high C sequestration to guide plant breeding and crop production programs (Wegener et al., 2015). By integrating data collected from global studies, it would be possible to assess the variability in carbon allocation to shoots and roots among different crop cultivars. Hence, the objective of this paper is to integrate results from different studies worldwide to assess the variation in plant biomass production and C allocation of maize, sorghum, and wheat cultivars. Understanding the differences in biomass and carbon allocation between roots and shoots can help assess the capacity of the major cereal crops to sequester atmospheric C and screen crop types for carbon efficiency to enhance soil health and productivity and subsequently mitigate climate change.

Core Ideas

- There is sufficient genetic variation in maize, sorghum, and wheat cultivars for manipulation of biomass and carbon allocation.
- Root carbon is a major contributor to soil organic carbon.
- Above-ground biomass is important for atmospheric carbon sequestration.

2 | MATERIALS AND METHODS

2.1 | Study setup

Research articles published between 1980 and 2022, and reporting on plant biomass and carbon variables for shoots and roots were identified using Google Scholar, Scopus, and Web of Science. Keywords used to identify relevant articles were "carbon partition," "carbon allocation," "plant carbon sequestration," "root: shoot biomass carbon," "rhizodeposition," "plant/soil organic C stocks," "root and shoot carbon," "cereal," "maize," "sorghum," and "wheat." All relevant articles were entered into a Microsoft Excel database. Articles included in the database had to meet the following criteria: (i) they had to report on plant (both root and shoot) biomass, C stocks, and C content variables; (ii) they had to report on data for either maize, sorghum, or wheat cultivars; and (iii) they had to report on experiments conducted in the field rather than in pots or controlled environments. For articles reporting on multi-year experiments, each year was treated as a separate and independent experiment, while in the case of replicated values, a mean was calculated for each treatment to avoid duplication and bias. The final database (summarized in Table 1) consisted of 509 data points from 40 research articles, reporting on 133 variable genotypes of maize, sorghum, and wheat. Nine main variables, namely total plant biomass (Pb), Sb, Rb, total plant carbon content (PCc), shoot carbon content (SCc), root carbon content (RCc), total plant carbon stocks (PCs), shoot carbon stocks (SCs), and RCs were included in the final database. The observations in the final database were stratified using long-term climate variables (mean annual precipitation [MAP] and mean annual temperature [MAT]) and soil parameters (pH and texture). When climatic variables were not explicitly described in each article, data were retrieved from climate-data.org in 2021 for the location where the experiment was conducted. The soil texture was cited from journal articles or determined using a soil texture triangle according to Mutema et al. (2015) when proportions of sand, silt, and clay were reported. The soil pH derived from the research articles was converted using the $CaCl_2$ scale and averaged across the soil profile to allow comparison using standardized values between research articles.

2.2 | Biomass and C allocation variables

Definitions for Pb, Rb, Sb, root-to-shoot biomass ratio (Rb/Sb), PCc, SCc, RCc, PCs, SCs, RCs, and root-to-shoot carbon stock ratio (RCs/SCs) are summarized in Table 2. Soil properties (clay content, bulk density, and pH) are also described in Table 3. All the definitions used in the current study were exclusively for the purposes of the current analysis and are not intended to be used in other contexts. These definitions matched most of the studies, except for a few studies

TABLE 1 References included in databases with locations, crops, and climatic zones under which the studies were conducted.

Paper ID	Author and year	Crop	No. of tested genotypes	Country	Climate	Tillage
1	Amujoyegbe et al., 2007	Maize and sorghum	2	Nigeria	Sub-tropical	No tillage
2	Anderson, 1988	Maize	1	USA	Temperate	Conventional, minimum tillage, and no tillage
3	Aquino et al., 2017	Maize	2	Philippines	Tropical	Conventional
4	Bolinder et al., 1997	Wheat	8	Canada	Temperate	Conventional
5	Christiansen-Weniger et al., 1992	Wheat	3	Netherlands	Tropical	Conventional
6	Comin et al., 1999	Maize	2	Brazil	Tropical	Conventional
7	Das et al., 2016	Maize and Sorghum	2	USA	Temperate	No tillage
8	Figuero et al., 2018	Wheat	5	Australia	Tropical	Conventional
9	Gan et al., 2009	Wheat	1	Canada	Temperate	Conventional
10	Geng et al., 2006	Wheat	2	China	Sub-tropical	Conventional
11	Hebert et al., 2001	Maize	7	France	Temperate	Conventional
12	Hussein & Alva, 2014	Sorghum	1	Egypt	Tropical	Conventional
13	Mathew et al., 2019	Wheat	15	South Africa	Temperate	Conventional
14	Kanchikerimath & Singh, 2001	Maize	1	India	Sub-tropical	Conventional
15	Kaushik et al., 2005	Wheat	3	India	Tropical	Conventional
16	Khorramdel et al., 2013	Maize	1	Iran	sub-tropical	Conventional
17	Kundu et al., 2007	Wheat	1	India	Sub-tropical	Conventional
18	Liang et al., 2020	Maize	2	China	Temperate	Conventional
19	Liu et al., 2014	Maize	4	China	Temperate	No tillage
20	Martin & Kemp, 1980	Wheat	12	Australia	Temperate	Conventional
21	Meki et al., 2013	Sorghum	1	USA	Tropical	Conventional, minimum tillage, and no tillage
22	Meskelu et al., 2014	Maize	1	Ethiopia	Sub-tropical	Conventional
23	Montanez et al., 2012	Maize	2	Uruguay	Temperate	Conventional
24	Msongaleli et al., 2017	Sorghum	3	Tanzania	Tropical	Minimum tillage
25	Nguyen et al., 2019	Wheat	2	Australia	Tropical	Conventional
26	Promkhambut et al., 2010	Sorghum	4	United Kingdom	Tropical	Conventional
27	Sainju et al., 2005	Sorghum	1	USA	Temperate	No tillage
28	Schortemeyer et al., 1997	Maize	4	USA	Tropical	Conventional and minimum tillage
29	Shaheen & Hood-Nowotny, 2005	Wheat	4	Austria	Sub-tropical	Conventional
30	Shen et al., 2007	Wheat	1	China	Temperate	No tillage
31	Srinivasarao et al., 2012	Sorghum	1	India	Sub-tropical	Conventional
32	Teravest et al., 2015	Maize	1	Malawi	Tropical	No tillage
33	Thivierge et al., 2016	Maize and sorghum	2	Canada	Temperate	Minimum tillage
34	Van de Broek et al., 2020	Wheat	4	Switzerland	Tropical	Conventional
35	Wang et al., 2007	Wheat	3	China	Sub-tropical	Conventional
36	Wang et al., 2018	Maize	5	China	Temperate	No tillage
37	Xia et al., 2021	Maize	2	China	Temperate	Conventional
38	Xu et al., 2020	Maize	10	Belgium	Temperate	Conventional
39	Xu et al., 2020	Maize	10	Belgium	Temperate	Conventional
40	Zan et al., 2001	Maize	1	Canada	Temperate	Conventional

TABLE 2 Descriptions of biomass and carbon variables used in this study.

Variable	Symbol	Unit	Definition
Total plant biomass	Pb	Mg ha^{-1}	The total mass of root and shoot biomass of the crop.
Root biomass	Rb	Mg ha^{-1}	The mass of above-ground biomass (stems and leaves) of the crop.
Shoot biomass	Sb	Mg ha^{-1}	The mass of below-ground biomass of the crop, excluding harvestable components.
Total plant carbon content	PCc	g C kg^{-1}	The total concentration of carbon in the roots and shoots.
Shoot carbon content	SCc	g C kg^{-1}	Concentration of carbon in the shoots.
Root carbon content	RCc	g C kg^{-1}	Concentration of carbon in the roots.
Total plant carbon stock	PCs	Mg C ha^{-1}	The total quantity of carbon contained in the entire plant, as stated by the authors, or as the sum of root and shoot carbon stocks.
Shoot carbon stock	SCs	Mg C ha^{-1}	The total quantity of carbon in the shoot biomass as stated by the authors or calculated as shoot biomass multiplied by shoot carbon concentration.
Root carbon stock	RCs	Mg C ha^{-1}	The total quantity of carbon in the root biomass stated by authors or calculated as root biomass multiplied by root carbon concentration.
Root-to-shoot ratio of biomass	Rb/Sb		An expression of root biomass as a fraction of shoot biomass.
Root-to-shoot ratio of carbon stock	RCs/SCs		An expression of root carbon stocks as a fraction of shoot carbon stocks.

TABLE 3 Environmental factors and their categories.

Factor	Remarks	Categories	Symbol	Class
Soil pH	Soil pH as reported in the article	<5.5 6.5–7.5 >7.5	pH	Acidic Neutral Alkaline
Soil bulk density (g cm^{-3})	Average bulk density (BD) of soil profile	<1.5 >1.5	BD	Low High
Fertilizer application	Amount of fertilizer applied on the soil, as cited on the paper	N (kg/ha) P as P_2O_5 (kg/ha) K as K_2O (kg/ha)	NPK	Applied Nitrogen Applied Phosphate fertilizer. Potassium applied.
Climatic region	Based on the study site's average annual temperature and precipitation	Precipitation > 1000 mm Temperature >20˚C Precipitation 300–1000 mm Temperature 10–20˚C Precipitation <800 mm Temperature <10˚C	Hot and warm Warm and arid humid Cool and arid to moist	Tropical Sub-tropical Temperate
Soil texture	Soil texture based as cited on the paper or based on soil texture triangle	% Clay % Silt % Sand	Texture	Clay, Sand, Loam, Sandy clay, Sandy clay loam, loamy sand, clay loam, silt loam, etc.
Tillage	The mechanical manipulation of the soil for the goal of crop production.	No ploughing at all Targeted ploughing Deep ploughing	Tillage	No-tillage Minimum Conventional
Mulching	Covering of soil between plants with a layer of material (plastic)	Soil mulch Plastic mulch Organic mulch	Mulch	No mulch Half mulch Full mulch

where the authors did not separate roots from shoots. For the purpose of this study, all biomass was considered as Sb when no distinction was made between roots and shoots. In articles where plant biomass and plant carbon variables were not provided, they were derived by adding shoot and root variables for biomass and carbon, respectively. In instances where plant biomass, C stocks, and C content variables were not reported directly, estimates were obtained using harvest indices and

R/Ss reported in the experiment. Where the biomass and carbon variables were not explicitly stated in the paper, they were estimated using ratios according to the following formulae:

$$\mathrm{Rb} = \mathrm{Rb} : \mathrm{Sb} \times \mathrm{Sb} \quad (1)$$

$$\mathrm{Sb} = \mathrm{Rb} : \mathrm{Sb} \times \mathrm{Rb} \quad (2)$$

$$\mathrm{Pb} = \mathrm{Sb} + \mathrm{Rb} \quad (3)$$

$$\mathrm{PCc} = \frac{\mathrm{Pcs}}{\mathrm{Pb}} \times 100 \quad (4)$$

$$\mathrm{SCc} = \frac{\mathrm{Scs}}{\mathrm{Sb}} \times 100 \quad (5)$$

$$\mathrm{RCc} = \frac{\mathrm{Rcs}}{\mathrm{Sb}} \times 100 \quad (6)$$

Also, where the carbon variables were not stated, they were estimated according to Bar-On et al. (2018) using the following formulae:

$$\mathrm{SCs} = \mathrm{Sb} \times \mathrm{SCc} \quad (7)$$

$$\mathrm{RCs} = \mathrm{Rb} \times \mathrm{RCc} \quad (8)$$

$$\mathrm{PCs} = \mathrm{SCs} + \mathrm{RCs} \quad (9)$$

where Rb is the root biomass (Mg ha^{-1}), Sb is the shoot biomass (Mg ha^{-1}), Pb is the total plant biomass (Mg ha^{-1}), Rb/Sb is the root-to-shoot biomass ratio, RCc is the root carbon content (g C kg^{-1}), SCc is the shoot carbon content (g C kg^{-1}), PCc is the total plant carbon content (g C kg^{-1}), SCs is the shoot carbon stock (Mg C ha^{-1}), RCs is the root carbon stock (Mg C ha^{-1}), and PCs is the total plant carbon stock (Mg C ha^{-1}).

2.3 | Variability of biomass and carbon variables

Key statistics were computed to determine genotype variability based on plant and soil parameters. Standard deviations (SD) were calculated as a measure of variability between maize, sorghum, and wheat cultivars in Pb, Sb, Rb, Rb/Sb, PCc, SCc, RCc, PCs, SCs, RCs, and RCs/SCs. Variability was also expressed using the coefficient of variation (CV) as the ratio of the SD and the mean for each biomass, C content, and C stock variables.

2.4 | Data analyses

SDs were calculated using Genstat 18th edition (Payne et al., 2011) for each paper to measure the variability of cultivars in that location. Summary statistics were generated for SD of biomass allocation, C content, and C stocks using Genstat 18th edition (Payne et al., 2011), which were outlined by mean, median, minimum, maximum, first quartile (Q_1) and third quartile (Q_3), SD, CV, skewness, and kurtosis. Box plots were used to depict the variability of datasets based on SD obtained per individual site for the three crop types. Each boxplot recorded the outliers, minimum, maximum, median, mean, Q_1, and Q_3 values. Bar graphs showing the variability between crop cultivars expressed in percent of mean total biomass, C content, and C stocks were generated using Microsoft Excel 2016. Correlation coefficients (*r*), based on Spearman Rank correlations, were carried out using IBM SPSS statistics (Wagner III, 2019) to determine the magnitude of associations between variables. A biplot principal component analysis (PCA) was conducted using R statistical software (R Core Team, 2019) to show the multiple relationships of the variation for biomass allocation, C allocation, and C content with environmental factors.

3 | RESULTS

3.1 | Variation of plant biomass, carbon content, and C stocks of cereal cultivars

The variabilities for biomass, carbon content, and C stocks recorded at individual sites of maize, sorghum, and wheat are summarized in Tables 4–6. Maize with a mean plant biomass of 4.18 Mg ha^{-1} accumulated the highest value followed by sorghum (2.02 Mg ha^{-1}) and wheat (1.10 Mg ha^{-1}) (Table 4). All the crops showed a similar trend for biomass and C allocation variability in shoots and roots, with shoots showing higher variability than roots across crop types (Figure 1a,c). Wheat had the lowest variability in Sb than sorghum and maize but higher variability in Rb compared to sorghum, with mean variability in Sb and Rb of 1.11 and 0.51 Mg ha^{-1}, respectively. Maize showed great variability across plant and shoot variables, whereas sorghum showed more variability when compared to wheat. Wheat had the highest mean (0.13) variability in Rb/Sb, followed by maize (0.07) and sorghum (0.04).

Maize had the highest variability for PCc with the maximum variability of 37.42 g C kg^{-1} followed by wheat (6.63 g C kg^{-1}) and sorghum (2.24 g C kg^{-1}) (Table 5; Figure 1b). Wheat had the highest variability in SCc and sorghum had the highest variability in RCc with mean variability values of

TABLE 4 Summary statistics of biomass variables for maize, sorghum, and wheat.

	Pb (Mg ha^{-1})			Sb (Mg ha^{-1})			Rb (Mg ha^{-1})			Rb/Sb		
Statistics	**Maize**	**Sorghum**	**Wheat**	**Maize**	**Sorghum**	**Wheat**	**Maize**	**Sorghum**	**Wheat**	**Maize**	**Sorghum**	**Wheat**
No.	19	8	13	19	8	13	19	8	13	19	8	13
Mean	4.18	2.02	1.49	3.31	1.76	1.11	1.27	0.32	0.51	0.07	0.04	0.13
Median	1.51	0.85	1.22	1.43	0.68	0.87	0.38	0.13	0.40	0.02	0.04	0.10
Min.	0.06	0.04	0.11	0.04	0.03	0.06	0.02	0.01	0.04	0.00	0.001	0.03
Max.	20.48	6.73	6.48	14.47	5.34	3.85	11.03	1.39	1.86	0.57	0.25	0.44
Q1	0.91	0.49	0.49	0.67	0.25	0.35	0.14	0.04	0.26	0.001	0.02	0.04
Q3	4.56	3.08	1.84	4.40	3.05	1.68	0.85	0.30	0.60	0.08	0.10	0.18
SD	5.80	2.23	1.56	4.22	1.94	1.05	2.55	0.45	0.46	0.13	0.08	0.12
SEM	1.33	0.79	0.42	0.97	0.69	0.28	0.58	0.16	0.12	0.03	0.03	0.03
Variance	33.66	4.96	2.43	17.82	3.75	1.10	6.50	0.20	0.21	0.02	0.01	0.01
% CV	138.79	110.03	105.01	127.51	110.16	94.35	200.08	140.35	90.01	186.60	179.42	94.80
Skewness	2.03	1.08	2.19	1.81	0.82	1.23	3.06	1.63	1.75	3.22	1.90	1.13
Kurtosis	4.16	0.98	7.51	3.23	−0.64	1.73	11.71	3.99	4.79	13.66	5.81	1.63

Abbreviations: CV, coefficient of variation; Max., maximum; Min., minimum; No, number of values; Pb, total plant biomass; Q_1, first quartile; Q_3, third quartile; Rb, root biomass; Rb/Sb, root-to-shoot biomass ratio; Sb, shoot biomass; SD, standard deviation; SEM, standard error of mean.

TABLE 5 Summary statistics of carbon content variables for maize, sorghum, and wheat.

	PCc (g C kg^{-1})			SCc (g C kg^{-1})			RCc (g C kg^{-1})		
Statistics	**Maize**	**Sorghum**	**Wheat**	**Maize**	**Sorghum**	**Wheat**	**Maize**	**Sorghum**	**Wheat**
No.	19	8	13	19	8	13	19	8	13
Mean	2.30	0.52	0.95	0.10	0.30	0.58	0.12	1.19	0.64
Median	0.03	0.03	0.40	0.61	0.00	0.00	0.00	0.00	0.00
Min.	0.001	0.001	0.00	0.001	0.00	0.00	0.001	0.00	0.00
Max.	37.42	2.24	6.63	1.30	2.42	4.51	2.03	8.03	6.85
Q1	0.001	0.00	0.06	0.001	0.00	0.00	0.00	0.00	0.00
Q3	0.38	0.56	0.72	0.99	0.00	0.00	0.18	0.36	0.00
SD	8.32	0.84	1.68	0.32	0.80	1.43	0.45	2.63	1.81
SEM	1.91	0.30	0.45	0.07	0.28	0.38	0.30	0.93	0.48
Variance	69.24	0.71	2.83	0.10	0.64	2.04	0.21	6.93	3.27
% CV	361.86	161.96	177.88	307.62	264.57	246.73	388.74	222.00	281.94
Skewness	3.94	1.24	2.74	3.03	2.27	2.10	3.96	2.13	2.90
Kurtosis	18.54	0.79	10.06	10.86	8.00	4.33	18.63	7.20	10.97

Abbreviations: CV, coefficient of variation; Max, maximum; Min, minimum; No, number of values; PCc, total plant carbon content; Q_1, first quartile; Q_3, third quartile; RCc, root carbon content; SCc, shoot carbon content; SD, standard deviation; SEM, standard error of mean.

0.58 g C kg^{-1} and 0.64 g C kg^{-1}, respectively. There is very low variation for carbon content between cultivars with constant variables recorded as coefficient of variation and SD. Maize had the highest variability in PCs, ranging from 0.02 to 14.36 Mg C ha^{-1} with a mean variability value of 1.55 Mg C ha^{-1} followed by sorghum (0.83 Mg C ha^{-1}) (Table 6; Figure 1d). The variability in Rb and carbon stocks was low across all crop types compared to variability in shoot parts. Wheat had the highest mean (0.18) variability in RCs/SCs, followed by maize (0.06) and sorghum (0.05).

3.2 | Variability expressed in percent of mean biomass, C content, and C stocks

The variability between cultivars expressed in percent of mean plant biomass, carbon content, and C stocks are presented in Figure 2 and Table 7. Maize and wheat had higher variability expressed in the percent of mean Pb, Sb, and Rb (Figure 2a). Sorghum showed the lowest variability expressed in percent of mean Pb (16.82%), Sb (18.13%), and Rb (36.96%), respectively, compared to maize and wheat. The variability

TABLE 6 Summary statistics of carbon stock variables for maize, sorghum, and wheat.

	PCs (Mg C ha^{-1})			SCs (Mg C ha^{-1})			RCs (Mg C ha^{-1})			RCs/SCs		
Statistics	Maize	Sorghum	Wheat	Maize	Sorghum	Wheat	Maize	Sorghum	Wheat	Maize	Sorghum	Wheat
No.	19	8	13	19	8	13	19	8	13	19	8	13
Mean	1.55	0.85	0.21	0.82	0.73	0.12	0.29	0.16	0.11	0.06	0.05	0.18
Median	0.46	0.46	0.16	0.38	0.30	0.09	0.09	0.06	0.07	0.01	0.02	0.13
Min.	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.003	0.001	0.001	0.001	0.01
Max.	14.36	2.94	0.83	3.56	2.35	0.48	2.52	0.59	0.56	0.53	0.24	0.69
Q1	0.22	0.21	0.05	0.16	0.11	0.03	0.05	0.04	0.03	0.0002	0.00	0.01
Q3	1.22	1.25	0.27	1.08	1.24	0.12	0.19	0.27	0.12	0.07	0.05	0.29
SD	3.20	0.92	0.23	1.04	0.80	0.13	0.58	0.19	0.14	0.12	0.08	0.19
SEM	0.73	0.33	0.06	0.24	0.28	0.03	0.13	0.07	0.04	0.03	0.03	0.05
Variance	10.23	0.85	0.05	1.08	0.64	0.02	0.34	0.04	0.02	0.01	0.01	0.04
% CV	206.66	107.96	109.46	127.16	109.94	107.32	197.46	115.51	126.97	206.13	155.54	106.22
Skewness	3.39	1.26	1.55	1.80	0.94	1.60	3.07	1.24	2.48	3.26	1.83	1.24
Kurtosis	14.46	2.41	2.84	3.21	0.29	3.53	11.75	2.14	8.86	13.82	5.58	2.21

Abbreviations: CV, coefficient of variation; Max, maximum; Min, minimum; No, number of values; PCs, total plant carbon stock; Q_1, first quartile; Q_3, third quartile; RCs, root carbon stock; RCs/SCs, root-to-shoot carbon stock ratio; SCs, shoot carbon stock; SD, standard deviation; SEM, standard error of mean.

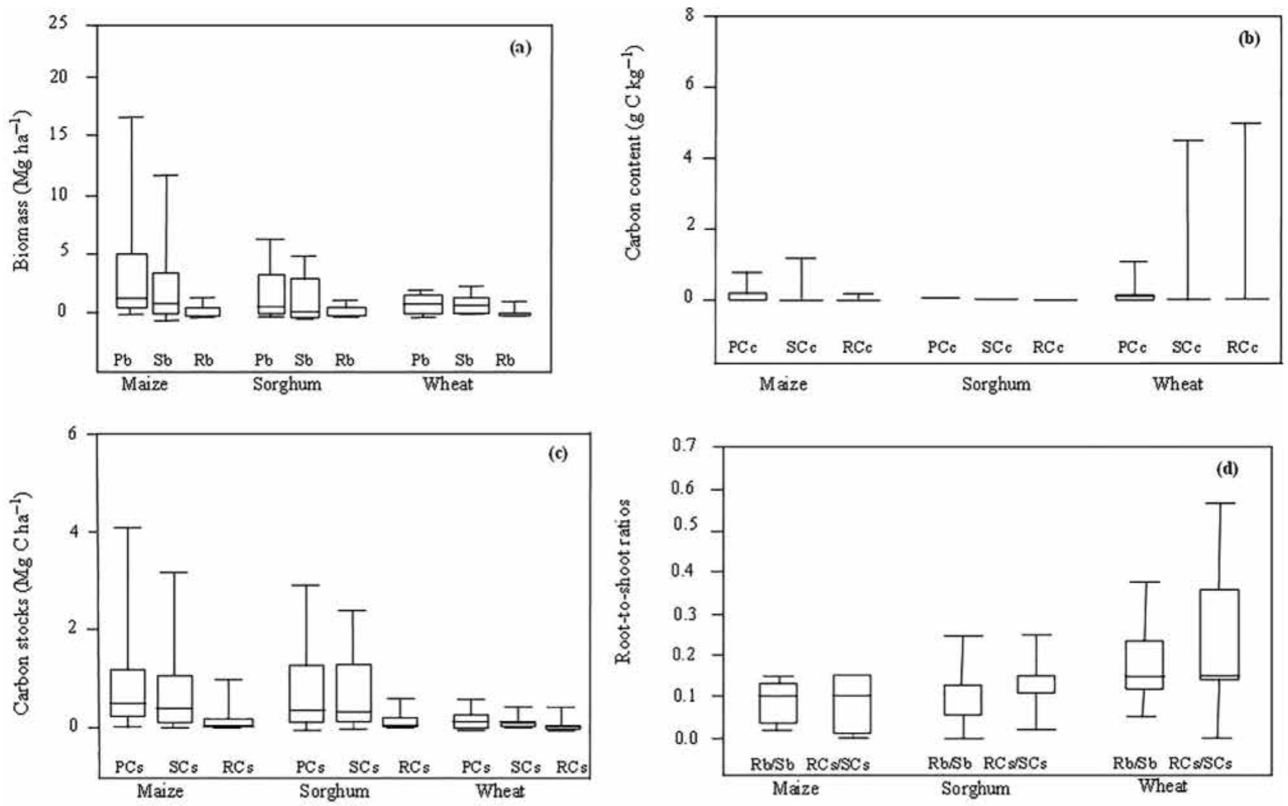

FIGURE 1 Variability between crop cultivars in total plant biomass (Pb), shoot biomass (Sb), and root biomass (Rb) (a); total plant carbon content (PCc), shoot carbon content (SCc), and root carbon content (RCc) (b); total plant carbon stock (PCs), shoot carbon stock (SCs), and root carbon stock (RCs) (c); root-to-shoot biomass ratio (Rb/Sb) and root-to-shoot carbon stocks ratio (RCs/SCs) (d) of maize, sorghum, and wheat. Each box plot presents the minimum, maximum, median, quartile 1 (25%), and quartile 3 (75%). See Table 2 for descriptions and units.

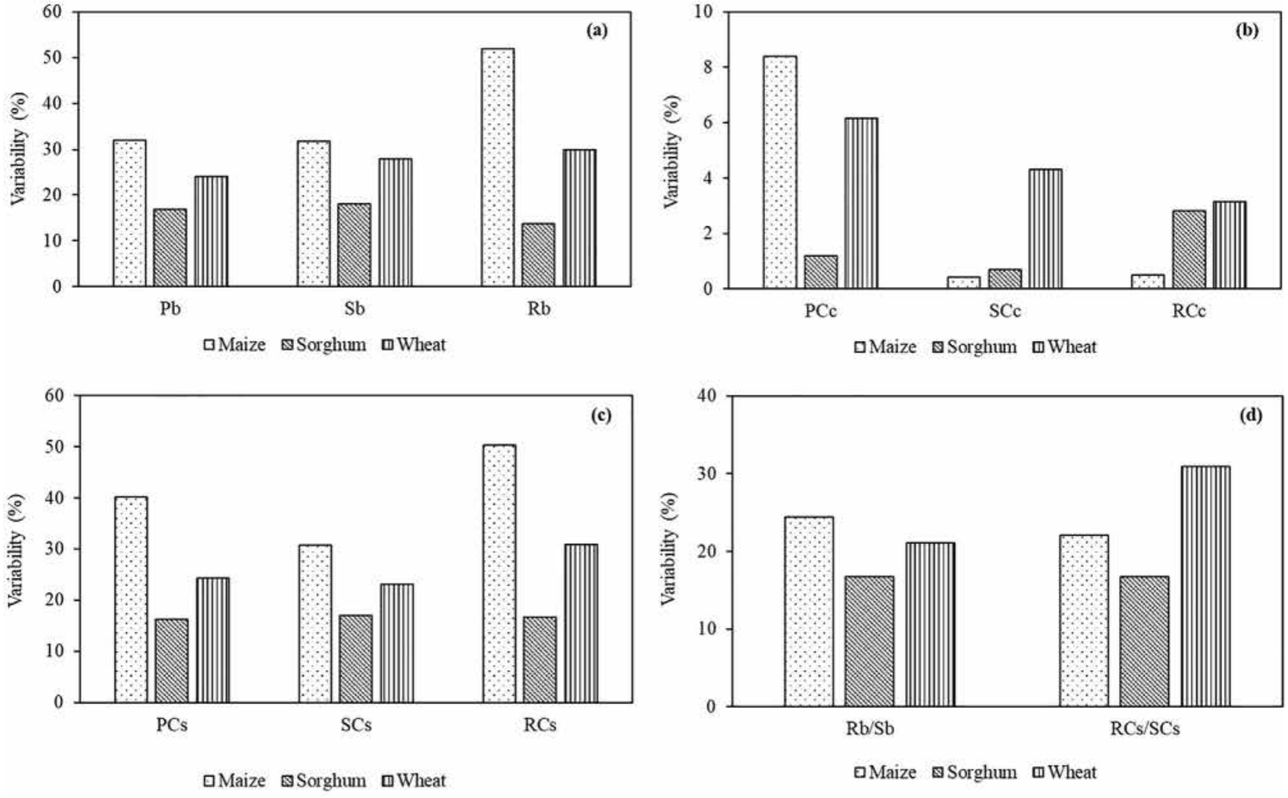

FIGURE 2 Variability between crop cultivars expressed in percent of mean total plant biomass (Pb), shoot biomass (Sb), and root biomass (Rb) (a); total plant carbon content (PCc), shoot carbon content (SCc), and root carbon content (RCc) (b); total plant carbon stock (PCs), shoot carbon stock (SCs), and root carbon stock (RCs) (c); root-to-shoot biomass ratio (Rb/Sb) and root-to-shoot carbon stocks ratio (RCs/SCs) (d) of maize, sorghum, and wheat. See Table 2 for descriptions and units.

TABLE 7 Mean variability, the standard deviation of variability, and percent of mean variability for plant biomass and carbon stocks for maize, sorghum, and wheat.

	Pb	Sb	Rb	Rb/Sb	PCc	SCc	RCc	PCs	SCs	RCs	RCs/SCs
Mean variability	——Mg ha^{-1}——				——g C kg^{-1}——			——Mg C ha^{-1}——			
Maize	4.18	3.31	1.27	0.07	2.3	0.1	0.42	1.55	0.82	0.29	0.06
Sorghum	2.02	1.76	0.32	0.04	0.52	0.30	1.19	0.85	0.73	0.16	0.05
Wheat	1.49	1.11	0.51	0.13	0.95	0.58	0.64	0.21	0.12	0.11	0.18
SD of variability											
Maize	5.80	4.22	2.55	0.13	8.32	0.32	0.45	3.20	1.04	0.58	0.12
Sorghum	2.23	1.94	0.45	0.08	0.84	0.80	2.63	0.92	0.80	0.19	0.08
Wheat	1.56	1.05	0.46	0.12	1.68	1.43	1.81	0.23	0.13	0.14	0.19
Coefficient of variation (%)											
Maize	31.89	31.78	51.97	24.38	8.39	0.42	0.51	40.13	30.76	50.38	22.02
Sorghum	16.82	18.13	13.64	16.79	1.19	0.69	2.82	16.30	17.03	16.76	16.76
Wheat	24.15	27.97	29.94	21.09	6.15	4.32	3.15	24.35	23.14	30.92	30.92

Note: See Table 2 for descriptions and units.

expressed in the percent of mean Sb in maize and wheat was greater than 27.97% and was twice the variability expressed in percent of mean Sb in sorghum. Maize had variability expressed in percent of mean Pb exceeding 31.89% compared to 24.15% of wheat.

Similar trends were observed for carbon content variables with maize excelling higher than the other crops. Maize (8.39%) had the highest variability expressed in percent of mean PCc, followed by wheat (6.15%) and sorghum (1.19%). Wheat amassed the highest variability expressed in percent

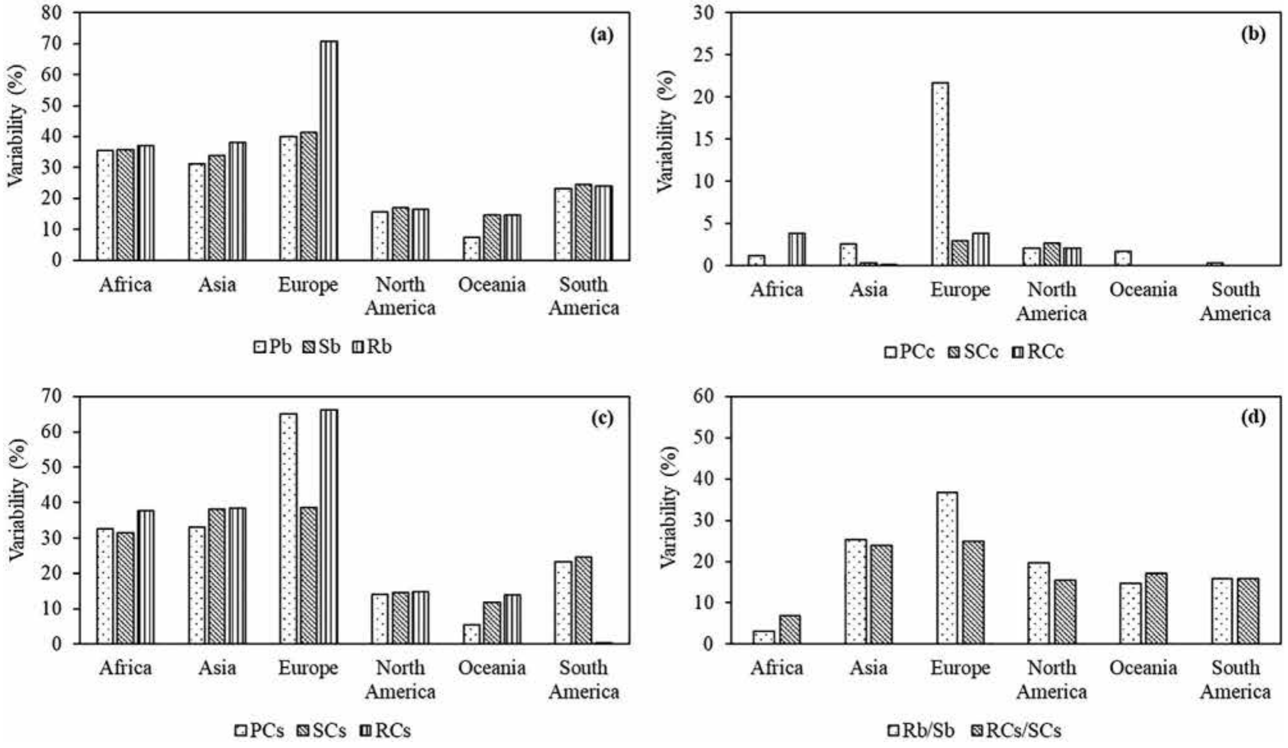

FIGURE 3 Variability between crop cultivars expressed in percent of mean total plant biomass (Pb), shoot biomass (Sb), and root biomass (Rb) (a); total plant carbon content (PCc), shoot carbon content (SCc), and root carbon content (RCc) (b); total plant carbon stock (PCs), shoot carbon stock (SCs), and root carbon stock (RCs) (c); root-to-shoot biomass ratio (Rb/Sb) and root-to-shoot carbon stocks ratio (RCs/SCs) (d) of maize, sorghum, and wheat for different continents. See Table 2 for descriptions and units.

of mean SCc and RCc (4.32% and 3.15%, respectively), followed by sorghum (0.69% and 2.82%, respectively) and maize (0.42% and 0.51%, respectively) (Figure 2b).

Maize exhibited higher variability expressed in percent of mean PCs, SCs, and RCs compared to sorghum and wheat with the values of 40.13%, 30.76%, and 50.38%, respectively. Sorghum had the lowest variability expressed in percent of mean carbon stocks for all variables measured (Figure 2c). Maize had the highest variability expressed in percent of mean Rb/Sb and wheat displayed the highest variability expressed in percent of mean RCs/SCs with values of 24.38% and 30.92%, respectively (Figure 2d).

3.3 | Global variability expressed in percent of mean plant biomass, C content, and C stocks

The variability between cultivars expressed in percent of mean plant biomass, C content, and C stocks for different continents are presented in Figure 3. Europe (Pb = 40.02%, Sb = 41.39%, and Rb = 70.74%) had the highest variability for all the biomass variables, followed by Africa (Pb = 35.46%, Sb = 35.81%, and Rb = 37.18%) and Asia (Pb = 31.18%, Sb = 33.9%, and Rb = 38.13%). The continents with the lowest variability expressed were South America, North America, and Oceania (Figure 3a) in descending order. Similar trends were observed for C content, with Europe continuing to excel for variability expressed in percent of mean C content for all the C content variables (Figure 3b).

Europe (PCs = 65.13%, SCs = 38.55%, and RCs = 66.22%) had the highest variability expressed in percent of mean C stocks for all the carbon variables, followed by Asia (PCs = 33.00%, SCs = 38.19%, and RCs = 38.31%) and Africa (PCs = 32.46%, SCs = 31.34%, and RCs = 37.82%) (Figure 3c). Europe exhibited the highest variability expressed in percent of mean Rb/Sb and RCs/SCs (36.73% and 24.84%, respectively) (Figure 3d).

3.4 | Associations between environmental factors and variabilities for biomass, C stocks, and carbon content

MAP and variability in Rb displayed the strongest significant positive correlation ($r = 0.85$, $p < 0.05$), suggesting a direct link between the two (Table 8). The variability in Pb and Sb significantly negatively correlated with both MAP and MAT. The variability in PCs and SCs followed the same trend but showed an insignificant correlation. MAT had the strongest significant positive correlation ($r = 0.72$, $p < 0.05$) with

TABLE 8 Correlations showing the relationship between variability in biomass, C variables, and environmental factors.

Plant variables	MAT	MAP
Pb	−0.47*	−0.34*
Sb	−0.43*	−0.30*
Rb	0.72*	0.85*
Rb/Sb	0.67	0.81*
PCc	0.58	0.73
SCc	0.39	0.57
RCc	0.49	0.66
PCs	−0.45	−0.31
SCs	−0.70	−0.63
RCs	0.60	0.76
RCs/SCs	0.65	0.80*

Note: See Table 2 for descriptions and units.
*Significance at $p \leq 0.05$.

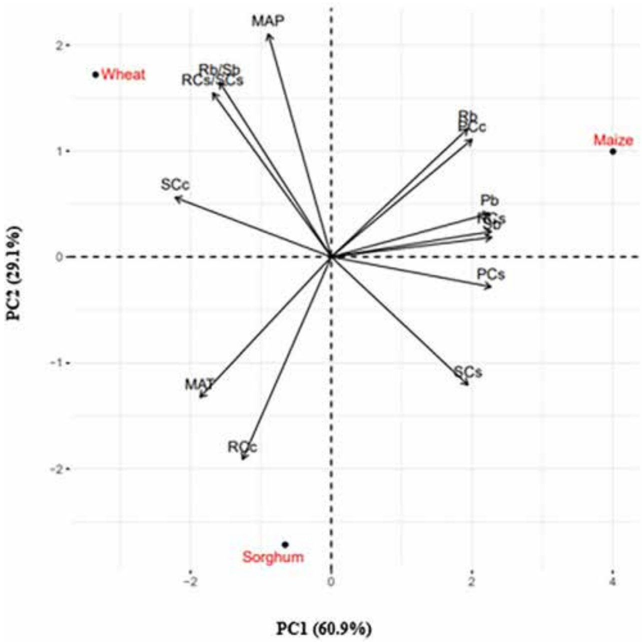

FIGURE 4 Principal component biplot displaying the relationship among the variability in plant biomass, C content, C stocks, and environmental factors in cultivars of maize, sorghum, and wheat. See Table 2 for descriptions and units. SCc, shoot carbon content; RCs, root carbon stock; RCs/SCs, root-to-shoot carbon stocks ratio; Rb/Sb, root-to-shoot biomass ratio; MAP, mean annual precipitation; Rb, root biomass; PCc, total plant carbon content; Pb, total plant biomass; PCs, total plant carbon stock; SCs, shoot carbon stock.

variability in Rb. MAP exhibited the strongest correlations with variability in Rb/Sb and RCs/SCs ($r = 0.80$ and $r = 0.80$, $p < 0.05$, respectively) compared to MAT. This trend was the same with variability in RCs. The variability in PCc, SCc, and RCc exhibited non-significant correlations with all the environmental factors.

3.5 | Principal component biplot for variability of biomass, C content, C stocks, and environmental factors

A biplot based on the PCA of variables relationship between the variation of biomass, carbon stock, carbon content, and environmental factors of different cereals is shown in Figure 4. The first and second principal components (PC1 and PC2) accounted for a total variation of 90%, with PC1 accounting for 60.9% of the variation while PC2 accounted for only 29.1%. The variability between cultivars in Pb, Rb, Sb, PCc, and RCs was strongly associated with PC1. On the other hand, PC2 was positively correlated with the variability in Rb/Sb, SCc, and RCs/SCs. The variability in PCs was associated with SCs and could thus be interpreted as an axis of carbon enrichment. Maize varieties were associated to PC1, while wheat varieties contributed more to PC2. Sorghum had a negative association with both PC1 and PC2. The first PC correlated with MAP, and PC2 was closely correlated with MAT on the negative coordinates. Several of the studied variables, including variability in Rb/Sb and RCs/SCs showed negative coordinates on Axis 2. Conversely, variability in Pb, Sb, and carbon stocks between cultivars increased as MAT decreased, and variability in SCc increased with increasing MAP.

4 | DISCUSSION

4.1 | Causes of variation in biomass allocation among crop types

The present study shows that different crop types exhibited significant variations in biomass allocation, agreeing with Monti et al. (2008) (Table 5). A higher amount of biomass was measured in maize compared to sorghum and wheat for all the plant variables, consistent with Ritchie et al. (1998) and Guzman and Al-kaisi (2010). Compared to other cereals, maize produces more biomass because it maximizes light absorption for synthesizing carbon assimilates that are used to drive biomass production (Stewart, 2013). Additionally, the C4 photosynthetic pathway in crops, such as maize and sorghum, is more efficient at utilizing carbon dioxide than the C3 crops such as wheat. This enables C4 species to photosynthesize more effectively, producing higher biomass (Sales et al., 2021). Furthermore, C4 species are better acclimated to high temperatures and droughts, typical in many regions where maize and sorghum are cultivated (Brown, 1999). These factors collectively contribute to the higher biomass accumulation observed in maize and sorghum than in wheat. Global maize improvement programs have achieved yield gains using traditional maize landraces and improved open-pollinated varieties (OPVs) or hybrid varieties. The result of maize improvement has thus been increased yield. Maize has higher hybrid vigor compared to sorghum or wheat, and new cultivars have been developed that generate more biomass than sorghum or wheat (Hiremath et al., 2013). Studies in maize conducted by Ibraheem and El-Ghareeb (2019) and Li et al. (2018) reported that F_1 hybrid of maize showed strong heterosis for agronomic traits and increased biomass compared to parents. These results are consistent with the ones reported by Singh et al. (2014), who indicated that crosses involving complementary inbred lines with different genetic compositions result in hybrid vigor, which produces superior phenotypes with higher yield, accelerated growth rate and development, improved biomass, better quality, and improved resistance to biotic and abiotic stress. This also explains the high variability in biomass variables in maize compared to other cereals. With landraces, OPVs, and commercial cultivars grown worldwide, wide variation in biomass production is expected in maize.

Wheat accumulated less biomass and C compared to maize and sorghum for all the biomass and C variables, and this may be due to the low plant stature (Figure 1a). The crop size of wheat is generally smaller than that of maize and sorghum. In addition, Theocharis et al. (2012) reported that one of the main environmental stressors that restricts wheat growth and photosynthetic output and lowers grain yield is low temperature. Wheat is mainly grown in temperate regions, and cold stress often extends the period of crop growth and lowers net photosynthetic rate and biomass accumulation (Li et al., 2015; Whaley et al., 2004; Yamori et al., 2014). Interestingly, wheat had higher Rb/Sb. However, the size of the wheat root systems remains lower than that of maize and sorghum, and as such, the latter two crops will contribute more to carbon sequestration than wheat.

Open-pollinated and landrace sorghum genotypes could produce comparable or higher biomass than maize. However, improved sorghum cultivars, such as hybrids, have shorter plant stature and reduced biomass than maize. Maize has undergone extensive genetic improvement efforts over the years, leading to the development of high-yielding varieties optimized for biomass production than sorghum (Gedil & Menkir, 2019). In contrast, sorghum has not been widely researched and bred, aiming to increase biomass yields (Hao et al., 2021). Therefore, sorghum possesses great untapped potential in breeding for biomass production. Sorghum breeding for ethanol production led to substantial genetic gains for biomass production (Pfeiffer et al., 2019). However, this has been limited to sweet stem sorghums, and the adoption of such varieties will not be beneficial to resource-poor farmers in drier areas where they depend on sorghum grain for food.

4.2 | Causes of variation in C accumulation and allocation among crop type

Sorghum had higher PCc and plant carbon stock than maize and wheat, making it a more efficient crop in increasing carbon fluxes from the atmosphere to the soil (Figure 1c,d). Its big and fibrous root system will ensure deeper C deposition in the soil which will be crucial for the long-term stability of SOC (Zuazo & Pleguezuelo, 2009). The large and deep root system of sorghum distinguishes its root architecture (Kell, 2011). According to Xiong et al. (2020), sorghum roots can reach soil depths of up to 2 m, whereas maize and wheat roots typically reach 1 m or less. Sorghum has deeper root system and deposits OM, including carbon, in deeper soil horizons. Because of its notable drought tolerance, sorghum develops deep roots as an adaptation strategy. Wheat and maize, on the other hand, have shallower root systems despite being sensitive to drought stress. Drought-stressed conditions can promote deeper root growth in sorghum (Chadalavada et al., 2021). The authors observed sorghum roots extending deeper during dry spells. Gautam et al. (2020) reported that sorghum produced 20% more aboveground biomass, which enhanced carbon inputs into the soil profile.

4.3 | Variations of plant biomass and carbon variables between crop type cultivars

The variation between cultivars in root and Sb could result from different specific allocation patterns caused by genetic variation between major cereal species. These patterns could be high Sb production in maize, deep root systems, and balanced allocation of shoot and Rb in sorghum and tillering in wheat (Irving, 2015). Maize had higher variability in Pb, Sb, and Rb between cultivars compared to sorghum and wheat (Figure 1a). Pittelkow et al. (2015) reported that the increase in biomass production from subtropical to tropical regions corresponds to increases in temperature and precipitation. These results are consistent with the ones reported in the current study as variability in Rb had the strongest, highest positive correlation with MAP and MAT (Table 8). Hence, lower precipitation limits Rb production in temperate and subtropical climates, whereas low temperatures further limit biomass production in temperate climates.

Sorghum also exhibited high variability in Pb, Sb, and Rb between cultivars than wheat. This is due to sorghum's genetic diversity. There is a wide range of stem biochemical compositions suitable for different end uses, such as bioenergy or fodder (Perrier et al., 2017). Due to its drought tolerance, sorghum can sustain biomass production under water-stressed conditions. The wide differences in Sb compared to Rb for maize, sorghum, and wheat are due to their adaptations.

Performance variations between genotypes represent genetic diversity, which is influenced by genetic compositions, the production environment, and their interaction (Hughes et al., 2008).

There was an increase in variation between genotypes of sorghum for PCs (Figure 1c). Cultivars may respond differently to growing conditions (Anderson-Teixeira et al., 2013). This is shown by the decrease in variation between cultivars of maize for total PCs by the different factors such as tillage system, fertilizers, and environmental conditions used across the studies. Wheat remains to be the crop with the lowest PCs, SCs, and RCs. There was no marked variation between genotypes for the carbon content of all the tested crops, as revealed by the constant performance (Figure 1b). The trend could be attributed to higher proportions of proteins and lipids, which are crucial components of plant tissues in maize, sorghum, and wheat. In turn, this contributed to a higher carbon content as a major constituent. Biomass and C allocation varied between roots and shoots as R/S ratios varied significantly among the wheat cultivars across the studies (Figure 1d). In a study conducted by Toscano et al. (2019), it was reported that heat-tolerant wheat genotypes exhibit a high R/S, which indicates their capacity to sustain productivity even under conditions of simultaneous drought and heat stress. This allowed the heat-tolerant genotypes to allocate more biomass to root development than the heat-susceptible genotypes. Such genotypes with high biomass accumulation and heat endurance are more appropriate for sub-Saharan Africa, where heat stress and drought are frequently co-occurring conditions.

4.4 | Associations between plant biomass and carbon variables

The strong correlations of variability in SCs and RCs and variability in Rb with PC1 show that the three traits were the most important in explaining variation among the cereal crops. Therefore, identifying shoot and RCs in varieties could be important in cultivar selection for carbon sequestration. Carbon content may be less effective in differentiating varieties. The carbon content in varieties is relatively constant and varies slightly between varieties and, in most cases, even between crop types (Ma et al., 2018). Maize was correlated with PC1, which showed that maize varieties exhibited most of the variation in this panel of cultivars while wheat varieties had the least variation. In new sorghum cultivars, biomass production can be harnessed through hybrid breeding and new genomic technologies that will accelerate sorghum improvement (Hao et al., 2021). There is high biomass production and carbon accumulation between maize cultivars but a low variability in carbon enrichment in plant parts. In contrast, wheat showed a high variableness in carbon enrichment but a low variableness in biomass production and C accumulation. Sorghum genotypes only marginally varied for plant C content and exhibited low variability in biomass and C accumulation.

5 | CONCLUSION

Maize, sorghum, and wheat showed significant variation in biomass production, carbon accumulation, and allocation to roots and shoots, demonstrating the importance of these genetic resources for selecting and developing varieties with improved C sequestration potential. However, sorghum presents the greatest potential for breeding to increase biomass production due to limited breeding in the crop. Using sorghum as a model crop for increasing carbon sequestration can go a long way in mitigating the effects of climate change. Maize and wheat will also remain important crops that can be used to support climate-smart agriculture. These findings improve our understanding of how C is allocated within roots and shoots and possibly to soils. This is especially needed when best practices such as zero tillage or cover cropping do not store carbon into soils as much as has been claimed (Baker et al., 2007; Chaplot & Smith, 2023). The meta-analysis revealed that maize and sorghum have the highest variability for Pb and plant carbon stocks, while wheat exhibited the highest variability for the below-ground biomass and carbon stocks. The data aided in crop selection and suggested that the best cultivars could be developed and identified for production and C sequestration potential for cultivation by farmers, land rehabilitation, and climate change mitigation. The present study used data based on 40 global studies that reported on allocating plant biomass and C between roots and shoots of the major cereal crops. The independent studies used varied experimental setups, data collection, and reporting, which may introduce inconsistencies and biases in the integrated analysis and conclusions. Standardization of the study protocols and data reporting may improve the reliability of the findings and recommendations. Further, the study recommends integrating multiple traits related to biomass production and carbon allocation from ongoing and diverse studies. Leaf area, root architecture, and photosynthetic efficiency should be included in future studies due to their influence on crop performance and biomass and C allocation between roots and shoots.

AUTHOR CONTRIBUTIONS

Asande Ngidi: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; writing—original draft; writing—review and editing. **Hussein Shimelis**: Conceptualization; funding acquisition; project administration; resources; supervision; validation; visualization; writing—review and editing. **Vincent Chaplot**: Conceptualization; formal analysis; funding acquisition;

methodology; software; supervision; validation; visualization; writing—original draft; writing—review and editing. **Kwame Sahamuyarira**: Conceptualization; data curation; formal analysis; methodology; software; validation; visualization; writing—original draft; writing—review and editing. **Sandiswa Figlan**: Conceptualization; funding acquisition; project administration; resources; supervision; validation; visualization; writing—review and editing.

ACKNOWLEDGMENTS

This study was supported by the African Centre for Crop Improvement (ACCI), Water Research Commission of South Africa (WRC), the University of South Africa (UNISA), and the French National Research Institute for Sustainable Development (IRD).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Sandiswa Figlan https://orcid.org/0000-0003-0395-8612

REFERENCES

Abbas, F., Hammad, H. M., Ishaq, W., Farooque, A. A., Bakhat, H. F., Zia, Z., & Cerdà, A. (2020). A review of soil carbon dynamics resulting from agricultural practices. *Journal of Environmental Management*, *268*, 110319. https://doi.org/10.1016/j.jenvman.2020.110319

Amujoyegbe, B. J., Opabode, J. T., & Olayinka, A. (2007). Effect of organic and inorganic fertilizer on yield and chlorophyll content of maize (*Zea mays* L.) and *Sorghum bicolour* (L.) *Moench*. *African Journal of Biotechnology*, *6*(16), 1869–1873.

Anderson, E. L. (1988). Tillage and N fertilization effects on maize root growth and root: Shoot ratio. *Plant and Soil*, *108*(2), 245–251. https://doi.org/10.1007/BF02375655

Anderson-Teixeira, K. J., Masters, M. D., Black, C. K., Zeri, M., Hussain, M. Z., Bernacchi, C. J., & DeLucia, E. H. (2013). Altered belowground carbon cycling following land-use change to perennial bioenergy crops. *Ecosystems*, *16*, 508–520. https://doi.org/10.1007/s10021-012-9628-x

Aquino, A. L., Cruz, P. C. S., Zamora, O. B., Aguilar, E. A., & Lasco, R. D. (2017). Carbon sequestration in organic and conventional corn production systems. *Philippine Journal of Crop Science*, *42*(3), 11–18.

Baker, J. M., Ochsner, T. E., Venterea, R. T., & Griffis, T. J. (2007). Tillage and soil carbon sequestration—What do we really know? *Agriculture Ecosystems and Environment*, *118*(1–4), 1–5. https://doi.org/10.1016/j.agee.2006.05.014

Balesdent, J., & Balabane, M. (1996). Major contribution of roots to soil carbon storage inferred from maize cultivated soils. *Soil Biology and Biochemistry*, *28*(9), 1261–1263. https://doi.org/10.1016/0038-0717(96)00112-5

Bar-On, Y. M., Phillips, R., & Milo, R. (2018). The biomass distribution on Earth. *Proceedings of the National Academy of Sciences*, *115*(25), 6506–6511. https://doi.org/10.1073/pnas.1711842115

Bolinder, M. A., Angers, D. A., & Dubuc, J. P. (1997). Estimating shoot to root ratios and annual carbon inputs in soils for cereal crops. *Agriculture, Ecosystems & Environment*, *63*(1), 61–66.

Brown, R. H. (1999). Agronomic implications of C4 photosynthesis. *C4 Plant Biology*, *1*, 473–507. https://doi.org/10.1016/B978-012614440-6/50015-X

Buytaert, W., Cuesta-Camacho, F., & Tobon, C. (2011). Potential impacts of climate change on the environmental services of humid tropical alpine regions. *Global Ecology and Biogeography*, *20*(1), 19–33. https://doi.org/10.1111/j.1466-8238.2010.00585.x

Cardinael, R., Guenet, B., Chevallier, T., Dupraz, C., Cozzi, T., & Chenu, C. (2018). High organic inputs explain shallow and deep SOC storage in a long-term agroforestry system–combining experimental and modeling approaches. *Biogeosciences*, *15*(1), 297–317.

Chadalavada, K., Kumari, B. R., & Kumar, T. S. (2021). Sorghum mitigates climate variability and change on crop yield and quality. *Planta*, *253*(5), Article 113. https://doi.org/10.1007/s00425-021-03631-2

Chaplot, V., & Smith, P. (2023). Cover crops do not increase soil organic carbon stocks as much as has been claimed: What is the way forward? *Global Change Biology*, *29*(22), 6163–6169. https://doi.org/10.1111/gcb.16917

Chen, X., Wu, Q., Gao, Y., Zhang, J., Wang, Y., Zhang, R., & Huang, R. (2020). The role of deep roots in sorghum yield production under drought conditions. *Agronomy*, *10*(4), 611. https://doi.org/10.3390/agronomy10040611

Christiansen-Weniger, C., Groneman, A. F., & Van Veen, J. A. (1992). Associative N_2 fixation and root exudation of organic acids from wheat cultivars of different aluminium tolerance. *Plant and Soil*, *139*(2), 167–174. https://doi.org/10.1007/BF00009307

Comin, J. J., Barloy, J., Bourrie, G., & Trolard, F. (1999). Differential effects of monomeric and polymeric aluminium on the root growth and on the biomass production of root and shoot of corn in solution culture. *European Journal of Agronomy*, *11*(2), 115–122. https://doi.org/10.1016/S1161-0301(99)00020-9

Daba, M. H., & Dejene, S. W. (2018). The role of biodiversity and ecosystem services in carbon sequestration and its implication for climate change mitigation. *Environmental Sciences and Natural Resources*, *11*(2), 1–10.

Das, A., Lal, R., Somireddy, U., Bonin, C., Verma, S., & Rimal, B. K. (2016). Changes in soil quality and carbon storage under biofuel crops in central Ohio. *Soil Research*, *54*(4), 371–382. https://doi.org/10.1071/SR14353

Figueroa-Bustos, V., Palta, J. A., Chen, Y., & Siddique, K. H. (2018). Characterization of root and shoot traits in wheat cultivars with putative differences in root system size. *Agronomy*, *8*(7), 109. https://doi.org/10.3390/agronomy8070109

Gan, Y. T., Campbell, C. A., Janzen, H. H., Lemke, R. L., Basnyat, P., & McDonald, C. L. (2009). Carbon input to soil from oilseed and pulse crops on the Canadian prairies. *Agriculture, Ecosystems & Environment*, *132*(3–4), 290–297.

Gautam, S., Mishra, U., Scown, C. D., & Zhang, Y. (2020). Sorghum biomass production in the continental United States and its potential impacts on soil organic carbon and nitrous oxide emissions. *GCB Bioenergy*, *12*(10), 878–890. https://doi.org/10.1111/gcbb.12736

Gedil, M., & Menkir, A. (2019). An integrated molecular and conventional breeding scheme for enhancing genetic gain in maize in Africa. *Frontiers in Plant Science*, *10*, Article 490537. https://doi.org/10.3389/fpls.2019.01430

Geng, C. N., Zhu, Y. G., Tong, Y. P., Smith, S. E., & Smith, F. A. (2006). Arsenate (As) uptake by and distribution in two cultivars of winter wheat (*Triticum aestivum* L.). *Chemosphere*, *62*(4), 608–615. https://doi.org/10.1016/j.chemosphere.2005.05.045

Gonzalez-Sanchez, E. J., Ordonez-Fernandez, R., Carbonell-Bojollo, R., Veroz-Gonzalez, O., & Gil-Ribes, J. A. (2012). Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture. *Soil and Tillage Research*, *122*, 52–60. https://doi.org/10.1016/j.still.2012.03.001

Grote, U., Fasse, A., Nguyen, T. T., & Erenstein, O. (2021). Food security and the dynamics of wheat and maize value chains in Africa and Asia. *Frontiers in Sustainable Food Systems*, *4*, Article 617009. https://doi.org/10.3389/fsufs.2020.617009

Guzman, J. G., & Al-Kaisi, M. M. (2010). Soil carbon dynamics and carbon budget of newly reconstructed tall-grass prairies in south central Iowa. *Journal of Environmental Quality*, *39*(1), 136–146. https://doi.org/10.2134/jeq2009.0063

Hao, H., Li, Z., Leng, C., Lu, C., Luo, H., & Liu, Y. (2021). Sorghum breeding in the genomic era: Opportunities and challenges. *Theoretical and Applied Genetics*, *134*(7), 1899–1924. https://doi.org/10.1007/s00122-021-03789-z

Hebert, Y., Guingo, E., & Loudet, O. (2001). The response of root/shoot partitioning and root morphology to light reduction in maize genotypes. *Crop Science*, *41*(2), 363–371. https://doi.org/10.2135/cropsci2001.412363x

Hiremath, N., Shantakumar, G., Adiger, S., & Gangashetty, P. (2013). Heterosis beeding for maturity, yield and quality characters in maize (*Zea mays* L.). *Molecular Plant Breeding*, *4*, 44–49.

Hirte, J., Walder, F., Hess, J., Büchi, L., Colombi, T., van der Heijden, M. G., & Mayer, J. (2021). Enhanced root carbon allocation through organic farming is restricted to topsoils. *Science of The Total Environment*, *755*, 143551. https://doi.org/10.1016/j.scitotenv.2020.143551

Hughes, A. R., Inouye, B. D., Johnson, M. T., Underwood, N., & Vellend, M. (2008). Ecological consequences of genetic diversity. *Ecology Letters*, *11*(6), 609–623. https://doi.org/10.1111/j.1461-0248.2008.01179.x

Hussein, M. M., & Alva, A. K. (2014). Growth, yield, and water use efficiency of forage sorghum as affected by NPK fertilizer and deficit irrigation. *American Journal of Plant Sciences*, *5*, 2134–2140.

Ibraheem, F., & El-Ghareeb, E. M. (2019). Assessment of natural variability in leaf morphological and physiological traits in maize inbreds and their related hybrids during early vegetative growth. *Egyptian Journal of Basic and Applied Sciences*, *6*, 25–45. https://doi.org/10.1080/2314808X.2019.1627771

Irving, L. J. (2015). Carbon assimilation, biomass partitioning and productivity in grasses. *Agriculture*, *5*(4), 1116–1134. https://doi.org/10.3390/agriculture5041116

Jaradat, A. A. (2013). Can carbon in bioenergy crops mitigate global climate change? In N. Tuteja & S. S. Gill (Eds.), *Climate change and plant abiotic stress tolerance* (pp. 343–420). Wiley. https://doi.org/10.1002/9783527675265.ch14

Kanchikerimath, M., & Singh, D. (2001). Soil organic matter and biological properties after 26 years of maize–wheat–cowpea cropping as affected by manure and fertilization in a Cambisol in semiarid region of India. *Agriculture, Ecosystems & Environment*, *86*(2), 155–162.

Katterer, T., Bolinder, M. A., Andrén, O., Kirchmann, H., & Menichetti, L. (2011). Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. *Agriculture Ecosystems and Environment*, *141*, 184–192. https://doi.org/10.1016/j.agee.2011.02.029

Kaushik, P., Garg, V. K., & Singh, B. (2005). Effect of textile effluents on growth performance of wheat cultivars. *Bioresource Technology*, *96*(10), 1189–1193. https://doi.org/10.1016/j.biortech.2004.09.020

Kell, D. B. (2011). Breeding crop plants with deep roots: Their role in sustainable carbon, nutrient, and water sequestration. *Annals of Botany*, *108*(3), 407–418. https://doi.org/10.1093/aob/mcr175

Kellogg, W. W., & Schware, R. (2019). *Climate change and society: Consequences of increasing atmospheric carbon dioxide*. Routledge.

Khorramdel, S., Koocheki, A., Mahallati, M. N., Khorasani, R., & Ghorbani, R. (2013). Evaluation of carbon sequestration potential in corn fields with different management systems. *Soil and Tillage Research*, *133*, 25–31. https://doi.org/10.1016/j.still.2013.04.008

Kramer, M. G., Sanderman, J., Chadwick, O. A., Chorover, J., & Vitousek, P. M. (2012). Long-term carbon storage through retention of dissolved aromatic acids by reactive particles in soil. *Global Change Biology*, *18*(8), 2594–2605. https://doi.org/10.1111/j.1365-2486.2012.02681.x

Kukal, S. S., & Benbi, D. K. (2009). Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice–wheat and maize–wheat systems. *Soil and Tillage Research*, *102*(1), 87–92. https://doi.org/10.1016/j.still.2008.07.017

Kundu, S., Bhattacharyya, R., Prakash, V., Ghosh, B. N., & Gupta, H. S. (2007). Carbon sequestration and relationship between carbon addition and storage under rainfed soybean–wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil and Tillage Research*, *92*(1-2), 87–95. https://doi.org/10.1016/j.still.2006.01.009

Li, X., Pu, H., Liu, F., Zhou, Q., Cai, J., Dai, T., Cao, W., & Jiang, D. (2015). Winter wheat photosynthesis and grain yield responses to spring freeze. *Agronomy Journal*, *107*(3), 1002–1010. https://doi.org/10.2134/agronj14.0460

Li, Z., Cofey, L., Garfn, J., Miller, N. D., White, M. R., Spalding, E. P., de Leon, N., Kaeppler, S. M., Schnable, P. S., Springer, N. M., & Hirsch, C. N. (2018). Genotype-by-environment interactions affecting heterosis in maize. *PLoS One*, *13*, e0191321.

Liang, X. G., Gao, Z., Shen, S., Paul, M. J., Zhang, L., Zhao, X., Lin, S., Wu, G., Chen, X. M., & Zhou, S. L. (2020). Differential ear growth of two maize varieties to shading in the field environment: Effects on whole plant carbon allocation and sugar starvation response. *Journal of Plant Physiology*, *251*, 153194. https://doi.org/10.1016/j.jplph.2020.153194

Liu, X. E., Li, X. G., Hai, L., Wang, Y. P., Fu, T. T., Turner, N. C., & Li, F. M. (2014). Film-mulched ridge–furrow management increases maize productivity and sustains soil organic carbon in a dryland cropping system. *Soil Science Society of America Journal*, *78*(4), 1434–1441. https://doi.org/10.2136/sssaj2014.04.0121

Lorenz, K., & Lal, R. (2014). Soil organic carbon sequestration in agroforestry systems. A review. *Agronomy for Sustainable Development*, *34*, 443–454. https://doi.org/10.1007/s13593-014-0212-y

Ma, S., He, F., Tian, D., Zou, D., Yan, Z., & Yang, Y. (2018). Variations and determinants of carbon content in plants: A global synthesis. *Biogeosciences*, *15*(3), 693–702. https://doi.org/10.5194/bg-15-693-2018

Macauley, H., & Ramadjita, T. (2015). *Cereal crops: Rice, maize, millet, sorghum, wheat*. https://www.afdb.org/fileadmin/uploads/afdb/Documents/Events/DakAgri2015/Cereal_Crops-_Rice__Maize__Millet__Sorghum__Wheat.pdf

Martin, J. K., & Kemp, J. R. (1980). Carbon loss from roots of wheat cultivars. *Soil Biology and Biochemistry*, *12*(6), 551–554. https://doi.org/10.1016/0038-0717(80)90034-6

Mathew, I., Shimelis, H., Mutema, M., & Chaplot, V. (2017). What crop type for atmospheric carbon sequestration: Results from a global data analysis. *Agriculture, Ecosystems & Environment*, *243*, 34–46.

Mathew, I., Shimelis, H., Mutema, M., Clulow, A., Zengeni, R., Mbava, N., & Chaplot, V. (2019). Selection of wheat genotypes for biomass allocation to improve drought tolerance and carbon sequestration into soils. *Journal of Agronomy and Crop Science*, *205*(4), 385–400. https://doi.org/10.1111/jac.12332

Meki, M. N., Snider, J. L., Kiniry, J. R., Raper, R. L., & Rocateli, A. C. (2013). Energy sorghum biomass harvest thresholds and tillage effects on soil organic carbon and bulk density. *Industrial Crops and Products*, *43*, 172–182. https://doi.org/10.1016/j.indcrop.2012.07.033

Meskelu, E., Mohammed, M., & Hordofa, T. (2014). Response of maize (*Zea mays L.*) for moisture stress condition at different growth stages. *International Journal of Recent Research in Life Sciences*, *1*, 12–21.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z. S., Cheng, K., Das, B. S., & Field, D. J. (2017). Soil carbon 4 per mille. *Geoderma*, *292*, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

Montanez, A., Blanco, A. R., Barlocco, C., Beracochea, M., & Sicardi, M. (2012). Characterization of cultivable putative endophytic plant growth promoting bacteria associated with maize cultivars (*Zea mays L.*) and their inoculation effects in vitro. *Applied Soil Ecology*, *58*, 21–28. https://doi.org/10.1016/j.apsoil.2012.02.009

Monti, A., Di Virgilio, N., & Venturi, G. (2008). Mineral composition and ash content of six major energy crops. *Biomass and Bioenergy*, *32*(3), 216–223. https://doi.org/10.1016/j.biombioe.2007.09.012

Msongaleli, B. M., Tumbo, S. D., Kihupi, N. I., & Rwehumbiza, F. B. (2017). Performance of sorghum varieties under variable rainfall in central Tanzania. *International Scholarly Research Notices*, *2017*, Article 2506946. https://doi.org/10.1155/2017/2506946

Mutema, M., Chaplot, V., Jewitt, G., Chivenge, P., & Blöschl, G. (2015). Annual water, sediment, nutrient, and organic carbon fluxes in river basins: A global meta-analysis as a function of scale. *Water Resources Research*, *51*(11), 8949–8972. https://doi.org/10.1002/2014WR016668

Nguyen, V. L., Palmer, L., Roessner, U., & Stangoulis, J. (2019). Genotypic variation in the root and shoot metabolite profiles of wheat (*Triticum aestivum L.*) indicate sustained, preferential carbon allocation as a potential mechanism in phosphorus efficiency. *Frontiers in Plant Science*, *10*, Article 995. https://doi.org/10.3389/fpls.2019.00995

OECD/FAO. (2022). *OECD-FAO agricultural outlook 2022–2031*. OECD Publishing.

Payne, R. W., Murray, D. A., & Harding, S. A. (2011). *An introduction to the GenStat command language*. VSN International.

Perrier, L., Rouan, L., Jaffuel, S., Clement-Vidal, A., Roques, S., Soutiras, A., Baptiste, C., Bastianelli, D., Fabre, D., Dubois, C., & Pot, D. (2017). Plasticity of sorghum stem biomass accumulation in response to water deficit: A multiscale analysis from internode tissue to plant level. *Frontiers in Plant Science*, *8*, Article 1516. https://doi.org/10.3389/fpls.2017.01516

Pfeiffer, B. K., Pietsch, D., Schnell, R. W., & Rooney, W. L. (2019). Long-term selection in hybrid sorghum breeding programs. *Crop Science*, *59*(1), 150–164. https://doi.org/10.2135/cropsci2018.05.0345

Pittelkow, C. M., Liang, X., Linquist, B. A., Van Groenigen, K. J., Lee, J., Lundy, M. E., Van Gestel, N., Six, J., Venterea, R. T., & Van Kessel, C. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature*, *517*(7534), 365–368. https://doi.org/10.1038/nature13809

Promkhambut, A., Younger, A., Polthanee, A., & Akkasaeng, C. (2010). Morphological and physiological responses of sorghum (*Sorghum bicolor* L. Moench) to waterlogging. *Asian Journal of Plant Sciences*, *9*(4), 183–193. https://doi.org/10.3923/ajps.2010.183.193

R Core Team. (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

Ritchie, J. T., Singh, U., Godwin, D. C., & Bowen, W. T. (1998). Cereal growth, development, and yield. In G. Y. Tsuji, G. Hoogenboom, & P. K. Thornton (Eds.), *Understanding options for agricultural production* (pp. 79–98). https://doi.org/10.1007/978-94-017-3624-4_5

Sainju, U. M., Whitehead, W. F., & Singh, B. P. (2005). Carbon accumulation in cotton, sorghum, and underlying soil as influenced by tillage, cover crops, and nitrogen fertilization. *Plant and Soil*, *273*(1), 219–234. https://doi.org/10.1007/s11104-004-7611-9

Sales, C. R., Wang, Y., Evers, J. B., & Kromdijk, J. (2021). Improving C4 photosynthesis to increase productivity under optimal and suboptimal conditions. *Journal of Experimental Botany*, *72*(17), 5942–5960. https://doi.org/10.1093/jxb/erab327

Schortemeyer, M., Stamp, P., & Feil, B. (1997). Ammonium tolerance and carbohydrate status in maize cultivars. *Annals of Botany*, *79*(1), 25–30. https://doi.org/10.1006/anbo.1996.0298

Shaheen, R., & Hood-Nowotny, R. C. (2005). Effect of drought and salinity on carbon isotope discrimination in wheat cultivars. *Plant Science*, *168*(4), 901–909. https://doi.org/10.1016/j.plantsci.2004.11.003

Shen, M. X., Yang, L. Z., Yao, Y. M., Wu, D. D., Wang, J., Guo, R., & Yin, S. (2007). Long-term effects of fertilizer managements on crop yields and organic carbon storage of a typical rice–wheat agroecosystem of China. *Biology and Fertility of Soils*, *44*(1), 187–200. https://doi.org/10.1007/s00374-007-0194-x

Singh, M., Guleria, N., Prakasa Rao, E. V., & Goswami, P. (2014). Efficient C sequestration and benefits of medicinal vetiver cropping in tropical regions. *Agronomy for Sustainable Development*, *34*(3), 603–607. https://doi.org/10.1007/s13593-013-0184-3

Srinivasarao, C., Deshpande, A. N., Venkateswarlu, B., Lal, R., Singh, A. K., Kundu, S., Vittal, K. P. R., Mishra, P. K., Prasad, J. V. N., Mandal, U. K., & Sharma, K. L. (2012). Grain yield and carbon sequestration potential of post monsoon sorghum cultivation in Vertisols in the semi-arid tropics of central India. *Geoderma*, *175*, 90–97. https://doi.org/10.1016/j.geoderma.2012.01.023

Stewart, B. A. (2013). Shoot: Root differs in warm season C4-cereals when grown alone in pure and mixed stands under low and high-water levels. *Pakistan Journal of Botany*, *45*(1), 83–90.

Teravest, D., Carpenter-Boggs, L., Thierfelder, C., & Reganold, J. P. (2015). Crop production and soil water management in conservation agriculture, no-till, and conventional tillage systems in Malawi. *Agriculture, Ecosystems & Environment*, *212*, 285–296.

Theocharis, A., Clement, C., & Barka, E. A. (2012). Physiological and molecular changes in plants grown at low temperatures. *Planta*, *235*(6), 1091–1105. https://doi.org/10.1007/s00425-012-1641-y

Thivierge, M. N., Angers, D. A., Chantigny, M. H., Seguin, P., & Vanasse, A. (2016). Root traits and carbon input in field-grown sweet pearl millet, sweet sorghum, and grain corn. *Agronomy Journal*, *108*(1), 459–471. https://doi.org/10.2134/agronj2015.0291

Toscano, S., Ferrante, A., & Romano, D. (2019). Response of Mediterranean ornamental plants to drought stress. *Horticulture*, *5*(1), 6. https://doi.org/10.3390/horticulturae5010006

Van de Broek, M., Ghiasi, S., Decock, C., Hund, A., Abiven, S., Friedli, C., Werner, R. A., & Six, J. (2020). The soil organic carbon stabilization potential of old and new wheat cultivars: A $13CO_2$ labeling study. *Biogeosciences*, *17*(11), 2971–2986.

Wagner, W. E., III. (2019). *Using IBM® SPSS® statistics for research methods and social science statistics*. Sage Publications.

Wang, L., Li, X. G., Guan, Z. H., Jia, B., Turner, N. C., & Li, F. M. (2018). The effects of plastic-film mulch on the grain yield and root biomass of maize vary with cultivar in a cold semiarid environment. *Field Crops Research*, *216*, 89–99. https://doi.org/10.1016/j.fcr.2017.11.010

Wang, T., Zhang, X., & Li, C. (2007). Growth, abscisic acid content, and carbon isotope composition in wheat cultivars grown under different soil moisture. *Biological Plantarum*, *51*(1), 181–184. https://doi.org/10.1007/s10535-007-0036-6

Wegener, F., Beyschlag, W., & Werner, C. (2015). Dynamic carbon allocation into source and sink tissues determine within-plant differences in carbon isotope ratios. *Functional Plant Biology*, *42*(7), 620–629. https://doi.org/10.1071/FP14152

Whaley, J. M., Kirby, E. J. M., Spink, J. H., Foulkes, M. J., & Sparkes, D. L. (2004). Frost damage to winter wheat in the UK: The effect of plant population density. *European Journal of Agronomy*, *21*(1), 105–115. https://doi.org/10.1016/S1161-0301(03)00090-X

Xia, Z., Zhang, G., Zhang, S., Wang, Q., Fu, Y., & Lu, H. (2021). Efficacy of root zone temperature increase in root and shoot development and hormone changes in different maize genotypes. *Agriculture*, *11*(6), 477. https://doi.org/10.3390/agriculture11060477

Xiong, P., Zhang, Z., Hallett, P. D., & Peng, X. (2020). Variable responses of maize root architecture in elite cultivars due to soil compaction and moisture. *Plant and Soil*, *455*, 79–91. https://doi.org/10.1007/s11104-020-04673-3

Xu, H., Vandecasteele, B., Maenhout, P., Pannecoucque, J., De Neve, S., & Sleutel, S. (2020). Maize root biomass and architecture depend on site but not on variety: Consequences for prediction of C inputs and spread in topsoil based on root-to-shoot ratios. *European Journal of Agronomy*, *119*, 126121.

Yamori, W., Hikosaka, K., & Way, D. A. (2014). Temperature response of photosynthesis in, C3, and C4, and CAM plants: Temperature acclimation and temperature adaptation. *Photosynthesis Research*, *119*(1), 101–117. https://doi.org/10.1007/s11120-013-9874-6

Zan, C. S., Fyles, J. W., Girouard, P., & Samson, R. A. (2001). Carbon sequestration in perennial bioenergy, annual corn, and uncultivated systems in southern Quebec. *Agriculture, Ecosystems & Environment*, *86*(2), 135–144.

Zuazo, V. H. D., & Pleguezuelo, C. R. R. (2009). Soil-erosion and runoff prevention by plant covers: A review. In E. Lichtfouse, M. Navarrete, P. Debaeke, S. Véronique, C. Alberola (Eds.), *Sustainable agriculture* (pp. 785–811). Springer. https://doi.org/10.1007/978-90-481-2666-8_48

How to cite this article: Ngidi, A., Shimelis, H., Chaplot, V., Shamuyarira, K., & Figlan, S. (2024). Biomass allocation and carbon storage in the major cereal crops: A meta-analysis. *Crop Science*, *64*, 2064–2080. https://doi.org/10.1002/csc2.21294