Plant Genetic Resources: Characterization and Utilization

cambridge.org/pgr

Characterizing sorghum (*Sorghum bicolor* [L.] Moench) varieties diversity to identify those with contrasting traits of interest for intercropping systems in the Sudano-Sahelian zone of West Africa

Aminata Ganeme[1,2,3], Clarisse Pulchérie Kondombo[4], Louis-Marie Raboin[4,5,6], Julie Dusserre[5], Roger Kabore[7], Myriam Adam[2,4,8] and Salifou Traoré[1]

[1]Université Joseph Ki-Zerbo, Unité de Formation et de Recherche en Sciences de la Vie et de la Terre (UFR/SVT), 09 BP 848, Ouagadougou, Burkina Faso; [2]UMR AGAP Institut, Univ Montpellier, CIRAD, INRAE, Institut Agro, Montpellier, France; [3]Centre d'Etudes Régionales pour l'Amélioration de l'Adaptation à la Sècheresse (CERAAS), BP 3320, Thiès, Sénégal; [4]Institut de l'Environnement et de Recherches Agricoles (INERA), 04 BP 8645, Ouagadougou, Burkina Faso; [5]AIDA, Univ. Montpellier, CIRAD, 34398, Montpellier Cedex 5, France; [6]Centre de Coopération Internationale pour la Recherche Agronomique et le Développement (CIRAD), UPR AIDA, BP596, Ouagadougou, Burkina Faso; [7]Association Minim Song-Panga (AMSP), BP 268, Kaya, Burkina Faso and [8]CIRAD, UMR AGAP Institut, Bobo-Dioulasso 01, Burkina Faso

Research Article

Cite this article: Ganeme A, Kondombo CP, Raboin L-M, Dusserre J, Kabore R, Adam M, Traoré S (2022). Characterizing sorghum (*Sorghum bicolor* [L.] Moench) varieties diversity to identify those with contrasting traits of interest for intercropping systems in the Sudano-Sahelian zone of West Africa. *Plant Genetic Resources: Characterization and Utilization* **20**, 87–97. https://doi.org/10.1017/S1479262122000168

Received: 6 July 2021
Revised: 6 September 2022
Accepted: 9 September 2022
First published online: 4 October 2022

Key words:
Crop performance; intercropping; morphological trait; root system; Sorghum variety; varietal selection

Author for correspondence:
Aminata Ganeme,
E-mail: amiganame@yahoo.fr

Abstract

Sorghum is an important staple crop in Sub-Saharan Africa. In the Sudano-Sahelian zone of West Africa, sorghum is mainly intercropped with cowpea, but these intercropping systems are facing low-productivity problems. The overall aim of this research was to identify sorghum varieties with different agro-morphological and physiological traits that could improve the performance of the intercropping systems. We followed a two-step methodology comprising (i) identification of varieties and plant traits of interest in intercropping systems, using participatory methods, and (ii) agro-morpho-physiological characterization of 50 sorghum varieties, to examine the range of variation in traits of interest. The results show that landraces are the varieties most widely used by farmers, and that 82.5% of farmers consider the variety type they choose for intercropping to be important. Farmers mentioned plant height, number of leaves and stem diameter as important traits to consider. Analysis of variance showed significant differences between varieties for half of the 24 agro-morpho-physiological traits studied. Hierarchical clustering identified three main groups of varieties, distinguished by morphological traits such as stem diameter, total number and size of leaves (group 1), root traits (depth, growth angle, dry matter) and relative chlorophyll content (groups 2 and 3). Based on this classification, we recommend several varieties from each of the three groups, exhibiting contrasting traits, for an assessment of their performances in intercropping systems.

Introduction

Sorghum (*Sorghum bicolor* [*L.*] *Moench)* is an important staple crop for millions of people, especially in West Africa, where the crop is the third most popular cereal crop and accounts for 20.7% of total cereal production (FAO, 2020). It is mainly grown by subsistence farmers in an extensive farming system (vom Brocke *et al.*, 2014). Sorghum varieties grown in this context are mainly local *Guinea* varieties (Zongo *et al.*, 2005). *Guinea* varieties are hardy and well adapted to the diversity of traditional cropping systems and to a wide range of production objectives (Barro-Kondombo *et al.*, 2010; vom Brocke *et al.*, 2014). Nevertheless, some low and variable sorghum yields have been reported in farmers' fields (Dabat *et al.*, 2012; Diarisso *et al.*, 2015; Ganeme *et al.*, 2021), resulting in insufficient output, particularly in the current context of climatic and demographic change and their effects (reduced periods of rainfall, overexploitation of the soil, increased food demand) (vom Brocke *et al.*, 2014). Accordingly, breeding programmes have been implemented and improved varieties with high yield potential have been developed (vom Brocke *et al.*, 2010, 2020; Sory *et al.*, 2020). The number of sorghum varieties has increased over the years, providing farmers in the region with a wider choice (vom Brocke *et al.*, 2020).

In Sudano-Sahelian areas of Burkina Faso, sorghum is often intercropped with cowpea, sown in the same seed holes (Dabat *et al.*, 2012; Ganeme *et al.*, 2021). Cereal and legume intercropping is a traditional and widely used cropping system in Sub-Saharan Africa (Namatsheve *et al.*, 2020). Intercropping is considered to be a sustainable agro-ecological practice because it has numerous benefits for crop productivity, soil fertility and nutrient cycling (Mazzafera *et al.*, 2021). Legumes are recognized for their role in improving soil fertility due to their ability to fix atmospheric nitrogen (Bado *et al.*, 2006, 2012; Zongo *et al.*, 2021) and their contribution to weed control (Bedoussac *et al.*, 2015; Stomph *et al.*, 2020; Gu *et al.*, 2021). Intercropping also reduces soil degradation, by reducing rainwater runoff (Zougmore *et al.*, 2000; Kariaga, 2004; Ali *et al.*, 2007). In addition, legumes can be used to diversify diets and forage resources while making agricultural production more secure (Protin *et al.*, 2009; Coulibaly *et al.*, 2012; Dabat *et al.*, 2012). Compared with monocrop systems, legumes intercropped with cereals increase and stabilize yields (Frison *et al.*, 2011; Lithourgidis *et al.*, 2011; Raseduzzaman and Jensen, 2017). However, the productivity of cereal-legume intercropping systems can be influenced by a range of management practices such as spatial arrangement, crop density, fertilization and sowing date (Masvaya *et al.*, 2017). These factors together determine the degree of mutual benefit and competition between the intercropped species (Namatsheve *et al.*, 2020). It is also important to consider the choice of which species and/or varieties to intercrop, owing to intra- and/or inter-species competition (Litrico and Violle, 2015; Annicchiarico *et al.*, 2019). The competitive ability of an intercrop component is related both to morphological characteristics such as plant height and leaf size for light interception (Kammoun, 2014; Namatsheve *et al.*, 2020), and to root characteristics (depth, number, biomass) for water and nutrient uptake (Masvaya *et al.*, 2017; Stomph *et al.*, 2020). Using varieties with different canopy structures and root system architectures could enable crops to capture a greater range and quantity of resources, so reducing inter-species competition. The greater the trait differences between the crops, the more efficient will be their resource utilization and the more stable and productive the cropping systems (Lithourgidis *et al.*, 2011).

Intercropping systems are a dominant current practice in the Sudano-Sahelian zone of West Africa (Dabat *et al.*, 2012; Namatsheve *et al.*, 2020; Ganeme *et al.*, 2021); they have great potential with regard to the agro-ecological transition. Our study aimed to help enhance these cropping systems by identifying sorghum varieties with agro-morphological and physiological traits affecting performance in an intercropped system. The specific objectives were (i) to identify varieties used by farmers, and the farmers' views on plant traits that are useful in intercropping systems, and (ii) to assess, among a large number of sorghum varieties, the range of variation in key morphological, physiological and root traits assumed to be relevant for intercropping.

Materials and methods

The study was carried out in the Sudano-Sahelian zone (600–900 mm) of Burkina Faso in two types of location: on-farm (within the region 12°49′–13°13′N and 1°32–1°4′O) and on-station (12° 16′N and 2°09′O) (Fig. 1).

Survey of varietal diversity and farmers' varietal preferences for intercropping systems

The on-farm survey was carried out from May to June 2017, to collect information about the diverse varieties used by farmers in intercropping systems, and to collect landrace seeds. Fifteen (15) villages spread around three municipalities (Boussouma, Korsimoro and Guibaré) (Fig. 1) were selected. These municipalities representative of the region have been identified as intercropping systems are of importance in farmers fields. Focus groups were organized in each of the 15 villages (one session per village). The main aim was to collect general information on the type of intercropping practiced in the region and the varieties grown. A first round of individual surveys was then carried out with 170 randomly-chosen farmers among those who had taken part in the focus groups (with each farmer representing a household). The number of farmers surveyed was 87 in seven villages in Boussouma, 47 in six villages in Korsimoro and 36 in two villages in Guibare. Farmers were chosen on a voluntary basis and because of their interest in intercropping systems. The targeted intercropping system involves placing the seed of both crops in the same seed hole, with different spatial arrangements (Ganeme *et al.*, 2021). The data collected through a semi-structured questionnaire (Supplementary material/Questionnaire) focused on the types of cropping system, the varieties being grown and the respondent's preferred intercropping system. Finally a second round of individual surveys was carried out to collect farmers' perceptions about the morphological traits of the sorghum varieties suited to the most commonly practiced intercropping system.

After the survey, approximatively 200 g of seeds from farmers' landrace seed stocks were collected from the surveyed farmers in each village. The collected seeds were then used for our agro-morpho-physiological evaluation.

Agro-morpho-physiological evaluation of sorghum varieties

The agro-morpho-physiological evaluation was carried out on-station at the Saria experimental station of the Institute for Environment and Agricultural Research (INERA) (Fig. 1). The soils on this station are mainly tropical ferruginous soils such as Luvisols and Lixisols (Yelemou *et al.*, 2008). The evaluation was carried out during two rainy seasons (2017 and 2018). Total rainfall during the experiment was 794.45 mm (on 62 days spread over seven months) in the 2017 rainy season and 864 mm (on 68 days spread over eight months) in the 2018 season.

The plant materials used for the evaluation were 50 sorghum varieties comprised of 17 landraces collected from farmers during the surveys (2.1 section), eight improved varieties from the INERA breeding programme, six of which are already being grown by farmers (MRSI, 2014; Ganeme *et al.*, 2021), and 25 newly-bred lines produced by participatory variety selection carried out on-farm within the framework of the INERA-Saria breeding programme (Sory *et al.*, 2020; vom Brocke *et al.*, 2020). The list of varieties is provided in the Supplementary Data (online Supplementary Table S1).

The experimental design was an alpha lattice with 10 blocks of five varieties per block in three replications. Plot size was two 6 m rows per variety. Sowing took place on 11 July in 2017 and 16 July in 2018, with an inter-row spacing of 80 cm and inter-hole spacing of 20 cm. Thinning was performed 15 days after sowing (DAS) to one plant per hole (1.6 plants m^{-2}). Mineral NPK fertilization (14N-23P-14K-6S-1B) was applied at a rate of 100 kg ha^{-1} at first weeding (14 DAS), and urea (46% nitrogen) at a rate of 50 kg ha^{-1} at 45 DAS.

Ten quantitative agro-morphological traits were used to describe phenotypic diversity. The morphological data included plant height from the ground to the base of the flag leaf (heigfl, cm), length (lealen, cm) and width (leawid, cm) of the third leaf below the panicle, the total number of leaves (numtol), number of green leaves at maturity (numgrl) and stem diameter (stedia, cm). Assessments were made on four randomly chosen main stems per plot. These morphological traits were chosen because they are assumed to be

https://doi.org/10.1017/S1479262122000168 Published online by Cambridge University Press

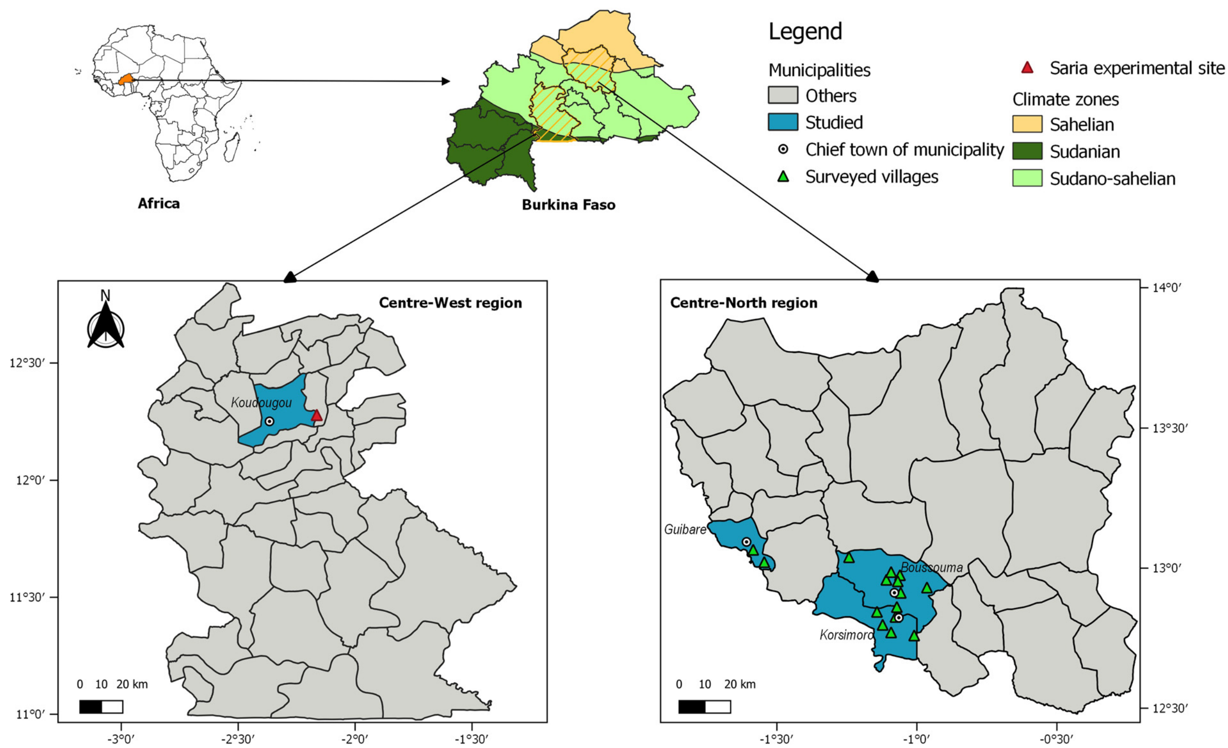

Fig. 1. Site map of the area studied in Burkina Faso.

important in terms of competition for light, and thus to make an essential contribution to performance in intercropping systems. Cycle length from sowing to 50% heading (cycle, days), dry straw yield at harvest (dry straw, kg ha^{-1}), grain yield (grain_yield, kg ha^{-1}) and 100-grain weight (seed_weight, g) were measured on a plot basis, as these are critical traits for assessing the overall performance of the plant and relating them to other traits. Finally, the classification of Harlan and de Wet (1972) was used to characterize the botanical races of the varieties evaluated.

Measurements of the photosynthetic activity of the 50 sorghum varieties were taken at the milk grain stage during the two rainy seasons (2017 and 2018). We did this because we assumed that the plant's ability to use available light efficiently can affect its performance in an intercropping system. These measurements were taken with a MultispeQ device, which is a phenotyping tool (Kuhlgert *et al.*, 2016) used to evaluate the environmental and phenotypic traits of plants, such as leaf pigmentation, and photosynthetic activity (plant growth capacity). Measurements were performed in each replication under optimum sunlight conditions between 9 and 11 a.m. on the third leaf below the panicle, on two randomly chosen plants per plot. The measured variables were (1) the percentage of incident light used for photosynthesis (Phi2, %) and, by extension, the amount of sugar produced (as needed for plant growth); (2) the percentage of incident light dissipated in the form of heat (PhiNPQ, %) to avoid damage to the photochemical system; (3) the percentage of unused incident light that could be harmful to photochemistry (PhiNO, %); (4) the light energy circulating in the chloroplasts after exposure to light (LEF), where LEF is an approximate measure of photosynthesis; and (5) the relative chlorophyll content of the leaf (%), an indicator of the plant's physiological status. These variables (Phi2, PhiNQ, PhiNO and LEF) are indicators of photosynthetic activity and provide an overview of plant status and the plant's capacity to resist environmental stresses (Baker and Rosenqvist, 2004).

Ex situ *characterization of the root systems*

Root characteristics are a key element in soil resource capture, so it is essential to assess their range of variation. In 2017 and 2018, young plants of each of the 50 varieties were harvested during their vegetative stage, at 14 or 21 days, and their root systems characterized under controlled conditions using the Rhizoscope at CIRAD-Montpellier. The Rhizoscope (online Supplementary Fig. S1) is a tool for phenotyping the root systems of young plants (Borianne *et al.*, 2018). Trials were carried out in four containers of 48 rhizoboxes each and continuously supplied with a nutrient solution. Lighting, temperature and hygrometry were controlled throughout the experiment. Seeds were germinated beforehand and then placed at the top of the rhizobox (one seed per rhizobox), which was filled with small beads to support the roots (Audebert *et al.*, 2012). Plants were allowed to grow for 14 days in 2017 and 21 days in 2018 before harvesting and taking measurements. The data collected per plant (using Fiji software) were as follows: root depth (root_depth, cm); root growth angle, i.e. the direction of root elongation with respect to the vertical (root_angle, °); number of roots (num20, num40); average diameter of the roots at depths of 20 and 40 cm (diam20 and diam40, cm); height of aboveground part (height); root dry matter (root_biom); aboveground dry matter (juv_biom).

Participatory assessment of the varieties

During the field evaluation, a participatory assessment of the 50 varieties was carried out at the maturity stage by 30 farmers in 2017 and 25 in 2018. The purpose of this assessment was to identify the varieties most liked by the farmers in the study panel so as to guide our final choice of varieties for future assessment in intercropping systems. The farmers were selected from among those surveyed on the basis of availability and willingness. The participatory assessment was based on the farmers' criteria for choosing their varieties (vom Brocke *et al.*, 2010; Kondombo *et al.*, 2016). These criteria were cycle length (app_cycle), grain productivity (app_Prod), fodder (app_fod) productivity, plant height (app_hei), grain quality (app_gqu) and acceptability (app_acc). These traits were defined in agreement with farmers. Evaluation was done using a scale from 1 (bad) to 4 (excellent).

Two assessments were performed: group scoring and individual scoring. For the group scoring, each group was comprised of five farmers. Each group was encouraged to discuss among themselves before attributing a score on each of the six criteria for each variety (vom Brocke *et al.*, 2010). In addition, each group was invited to indicate which variety they would like to keep, or use, in intercropping. For the individual scoring, each farmer assigned a score (ind_note) for each variety (taking all criteria into account), with a colour-coded card.

Data analysis

Descriptive statistics were used to describe the varietal diversity and main traits of interest for intercropping as reported by the farmers in the survey. The frequency of citation of a specific variety, its use as a sole crop or intercrop and the traits of interest for intercropping were calculated and plotted using R software (4.0.5 version). The traits mentioned by farmers were quantified (mean/average, minimum, maximum) using morphological data collected on-station on varieties obtained from farmers.

Analysis of the agro-morpho-physiological data first consisted of assessing the variability between the varieties for each quantitative trait by calculating the coefficient of variation (CV). Using the R package *LmerTest* (Kuznetsova *et al.*, 2017), linear mixed-effect models were fitted on all quantitative data collected, to estimate the variety effect. Variety was used as a fixed effect, whereas year, replication, block within replication and variety × year were considered random effects, following the mixed model described below:

$$Y_{ijkl} = \mu + G_i + \beta_j + \rho_{jk} + G_i \times \delta_l + \varepsilon_{ijkl},$$

where μ is the general mean of the measured trait, G_i is the effect of variety, β_j is the effect of replication, ρ_{jk} is the effect of the block within replication j, $G_i \times \delta_l$ is the variety × year interaction and ε_{ijkl} is the random error.

For the participatory assessment, the Kruskal–Wallis test was used to compare evaluation scores between varieties.

A principal component analysis (PCA) was conducted on quantitative agro-morpho-physiological traits with previously identified significant variety effects. This enabled us to identify the most discriminating variables. Hierarchical clustering for principal components was then performed, to identify different groups of varieties. Evaluation scores were used as quantitative supplementary variables in the PCA, to identify the group most appreciated by farmers according to their various traits. The FactoMineR package was used for the analysis, whereas the Factoextra and ggplot2 packages were used for the visualization and graphic representation of the data (Husson *et al.*, 2020). To test for significant differences, we described and compared these discriminating variables according to the groups of varieties obtained, using the multiple comparison method of the R Multcomp package (Bretz *et al.*, 2011).

Results

Diversity of sorghum varieties in farmers' fields and farmers' varietal preferences for intercropping with cowpea

The farmers surveyed grew 25 sorghum varieties, including 19 landraces and six improved varieties (Fig. 2a). In all the municipalities, each farmer grew an average of two sorghum varieties. Five landraces and two improved varieties were used in all three municipalities. Three landraces and three improved varieties were common to Boussouma and Korsimoro municipalities and one landrace was common to Boussouma and Guibare (online Supplementary Table S1).

All farmers surveyed used sorghum landraces, whereas only 23.5% of them used improved varieties. *Rouko*, *Fiib-miougou*, *Pisnou*, *Pissopoé* and *Mitindaade* were the five landraces most used by farmers (>15%) (Fig. 2a). Of the improved varieties, ICSV 1049, Kapelga and Sariaso 15 were the most frequent, with 9.4, 4.7 and 4% of farmers growing them, respectively (Fig. 2a).

All varieties identified on the farms are used both in intercropping systems and as sole crops, except for two landraces (Kazinga and Gnouga) which are only used as sole crops (Fig. 2a). Most farmers (82.5%) considered the type of variety used for intercropping to be important. Landraces were the most used in intercropping systems (Fig. 2a). Of the improved varieties, only the *Caudatum* type are not always used in intercropping systems (Fig. 2a). These varieties are less often used in intercropping than as sole crops (Sariaso 11: 2.4% in sole crops and 1.2% in intercropping; ICSV 1049: 5.3% in sole crops and 4.1% in intercropping) (Fig. 2a). In general, all farmers (100%) used landraces in this cropping system, while only 14% cultivated improved varieties intercropped with cowpea (Fig. 2a).

According to the farmers, plant height, number of leaves and stem diameter are the most important sorghum morphological traits to consider for intercropping with cowpea (Fig. 2b). No other criteria were mentioned by farmers. Regarding plant height, most farmers (71.8%) considered that sorghum with an average height of approximately 2 m is favourable for intercropping, whereas 15.5% of the farmers found that the taller sorghum varieties (3–4 m) could also be grown when intercropped with cowpea. Others (12.7%) had no preferences about plant height for intercropping (Fig. 2b). Regarding leaves, 81.7% of farmers considered that sorghum with a low number of leaves (<20) is favorable to intercropping, while 2.8 and 1.4% considered that sorghum with average leaf number (approximately 20) and width (approximately 10 cm), was most suitable for intercropping. Regarding stem diameter, 62% of farmers considered that sorghum of large diameter (>17 cm) was best for intercropping and 35.2% thought that average diameter (approximately 12 cm) was better. Others (2.8%) had no preferences about stem diameter (Fig. 2b). In general, the farmers agreed that sorghum varieties that make a lot of shade have a negative impact on associated cowpea, and are not suitable for intercropping.

Varieties evaluation

Race characterization and variability in agro-morpho-physiological characteristics

Based on the description of sorghum spikelet characteristics (Harlan and de Wet, 1972), sorghum varieties belong to two

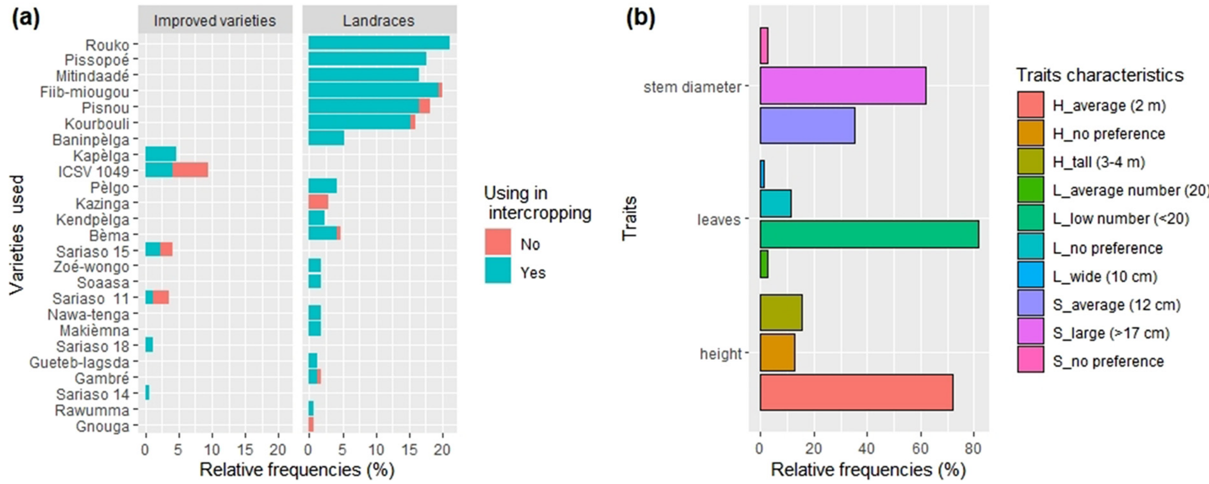

Fig. 2. (a) Varieties used by farmers and (b) farmers preferred traits for intercropping. *Note*: H_, characteristics relative to height; L_, characteristics relative to leaves; S_, characteristics relative to stem.

botanical races (*Guinea* and *Caudatum*) and an intermediary race (*Guinea-Caudatum*). In the study area, the *Guinea* race was the most frequent, accounting for 85% of the samples, followed by *Caudatum* at 12% and *Guinea-Caudatum* (3%). The landraces and the new improved lines were both mainly of the *Guinea* race, with 94% (16 varieties out of 17) and 92% (23 varieties out of 25), respectively. Improved varieties were mainly of the *Caudatum* race (5 varieties out of 8).

A high degree of variability was observed between varieties for all quantitative variables studied, with CVs above 10% for 20 out of the 24 variables analysed (Tables 1 and 2). The highest CVs (over 40%) were observed with roots traits such as root biomass at vegetative stage, varying from 0.1 to 1.4 g per plant, and number of roots at 40 cm deep, varying from 0.0 to 11. The lowest CVs (under 10%) were observed with crop cycle, total number of leaves and leaf length (Table 1).

The analysis of variance revealed significant differences (Table 1) between varieties for agro-morphological traits such as cycle length, plant height, leaf number, length and width, stem diameter and weight of 100 seeds. However, the number of green leaves at maturity (overall mean = 3), dry straw yield at harvest and grain yield did not differ between varieties (Table 1). The earliest varieties were *Baniaringa* and Kapelga, with an average cycle of 60 days (sowing to heading), 14 days earlier than ICSV 1049, an improved *Caudatum* variety. The tallest varieties (>270 cm) and those with high seed weight values (>2 g) were some new improved lines. The highest leaf numbers (>22) and widths (>9 cm) were recorded in improved *Caudatum* varieties (online Supplementary Table S2).

For the photosynthesis traits, only the relative chlorophyll content differed significantly ($P = 0.02$) between varieties (Table 1). The highest relative chlorophyll contents (>65%) were recorded in landraces such as *Mitindaade*, *Kazinga* and *Asset*a, while the lowest (<55%) were recorded in improved varieties (online Supplementary Table S2).

Among root traits characterized at the vegetative stage, differences between varieties were significant for root depth, root growth angle, root dry matter and aboveground dry matter (Table 2). There was no difference in number and diameter of roots at 20 or 40 cm deep. The number of roots varied from 5 to 25 at 20 cm and from 0 to 11 at 40 cm (Table 2). The deepest roots (>70 cm) and highest root dry matter (>0.7 g per plant) were recorded in new improved lines such as PSE08 Tbou/3-1-1, PSE08 Tbou/3-1-2 and landrace *Zoewaongo* while the lowest values for these factors were recorded in PSE09 G1/20-1-1, *Fibsablega* and *Kapelga* (online Supplementary Table S2).

Significant random effects of replication, block and year were observed for plant height, biomass, grain yield, LEF, relative chlorophyll content (Table 1), root depth and root diameter at 40 cm (Table 2).

Participatory assessment of varieties

Farmers' ratings ranged from 1 (bad) to 4 (excellent) for all evaluation criteria. The Kruskal–Wallis test indicated significant differences in scores between varieties for cycle length ($P = 0.046$), grain quality ($P = 0.019$), productivity ($P = 0.017$), acceptability ($P = 0.008$) and individual rating ($P = 0.006$) (online Supplementary Table S3). The 10 best-rated varieties for cycle length had an average cycle length of 65 days compared to 68 days for the 10 lowest-rated. Grain quality was assessed by seed weight. The best-rated varieties for seed weight had an average of 1.9 g, while the lowest-rated was 1.7 g. The best-rated for productivity had an average yield of 1822 kg ha^{-1} compared to 1563 kg ha^{-1} for the lowest-rated. For all criteria, the *Guinea* varieties were the most appreciated by farmers, except for forage, where the *Caudatum* varieties were well represented (online Supplementary Table S3).

As regards desirability, three landraces (*Baninpelga*, *Gueteb-lagsda*, *Mitindaade*), three inbred lines (PSE08 G1/17-1-2-1, PSE08 G1/21-1G-1, PSE09 G1/2-1-1) and one improved variety (Sariaso 18) were unanimously (100% 'Yes') appreciated by farmers (online Supplementary Fig. S2). Three new improved lines (PSE 08 silo/28-1-1, PSE07 S1/31-1Z-2 and PSE08 Tbou/3-1-1) were unanimously disliked by farmers (100% 'No'). Twenty-three varieties received more Yes than No votes, while 14 varieties received more No than Yes votes. Finally, three varieties were equally liked and disliked (50% 'Yes' and 50% 'No') (online Supplementary Fig. S2).

Principal component analysis on quantitative agro-morpho-physiological traits with significant variety effects

Because of the high agro-morpho-physiological variability observed in most traits, a PCA was conducted on the 12 traits with significant variety effects.

https://doi.org/10.1017/S1479262122000168 Published online by Cambridge University Press

Table 1. Results of the analysis of variance on the agro-morphological and photosynthetic traits (average of 2 years data) of the 50 sorghum varieties of Burkina Faso

	Fixed effects	Random effects							
	Genotypes	Replication	Block	Year	Genotypes × year				
	F	Estimated variance				Minimum	Maximum	Mean	Coefficient of variation
Agro-morphological traits									
cycle (days)	5.0***	0.2 ns	1.3***	0.4 ns	1.8**	55	75	66	5.2
heigfl (cm)	7.9***	43.9*	255.7***	224.3***	76.8 ns	98.3	326.9	227	19.1
stedia (mm)	3.2***	0.2**	0.00 ns	4.9***	0.00 ns	8.1	30.8	11.7	23.8
lealen (cm)	3.4***	1.6**	2.5***	0.00 ns	4.8*	52	76.4	65.9	7.8
leawid (cm)	7.6***	0.1***	0.0*	0.0***	0.00 ns	6.6	10.3	7.5	11
numtol	5.7***	0.1***	0.00 ns	0.4***	0.00 ns	17	23	20	7.4
numgrl	1.2 ns	0.0 ns	0.0 ns	0.9***	0.2*	1	5	3	29
dry_straw (kg ha^{-1})	1.0 ns	9011 ns	67,639**	230,111***	127,713 ns	2299	5940	4375	16.7
grain_yield (kg ha^{-1})	1.53 ns	12,910**	32,223***	2961 ns	3157 ns	869	2410	1701	19.6
seed_weight (g)	2.8***	0.0 ns	0.0 ns	0.0***	0.0 ns	1.1	2.5	1.9	12.9
Photosynthetic traits									
Phi2	0.9 ns	0.0***	0.0**	0.0***	0.0 ns	0.1	0.5	0.3	36.6
PhiNPQ	0.6 ns	0.0***	0.0***	0.0***	0.0**	0.2	0.8	0.4	27.1
PhiNO	1.0 ns	0.00***	0.0 ns	0.0 ns	0.0 ns	0.1	0.4	0.3	17.4
LEF	1.0 ns	173.3***	160.5***	1660.6***	133.50*	36.5	174.8	88.3	33.4
chlorophyll (%)	2.7**	0.00ns	5.4***	24.9***	6.0 ns	35.4	71.6	59.7	12.4

***Very highly significant at $P = 0.000$; **highly significant at $P < 0.001$; *significant à $P < 0.01$;. significant at $P < 0.05$; ns, not significant.
Traits abbreviation : Cycle, length from sowing to 50% heading; heigfl, plant height from the ground to base of the flag leaf; numtol, total number of leaves; numgrl, number of green leaves at maturity; stedia, stem diameter; lealen, length of third leaf under the panicle; leawid, width of the third leaf under the panicle; dry_straw : dry straw at harvest; grain_yield, grains yield; seed_weight, weight of 100 grains; Phi2, percentage of incident light used for photosynthesis; PhiNPQ, percentage of incident light dissipated in the form of heat; PhiNO, percentage of unused incident light that could be harmful to photochemistry; LEF, the light energy circulating in the chloroplasts after exposure to light; chlorophyll, relative chlorophyll content of the leaf.

Table 2. Results of the analysis of variance on the root traits (average of 2 years data) of the 50 sorghum varieties

		Fixed effects	Random effects						
		Genotypes	Repetition	Year	Genotypes × year				
Variable's description	Variable's codes	*F*	Estimated variance			Minimum	Maximum	Mean	Coefficient of variation
Plant height at juvenile stage	juv_height (cm)	1.5 ns	0.0 ns	23.2***	3.4 ns	41.0	70.0	59.7	9.2
Root's depth	root_depth (cm)	2.7***	0.0 ns	261.2***	0.0 ns	32.0	98.5	61.0	22.8
Root's insertion angle	root_angle (°)	2.4***	3.6 ns	12.1*	0.0 ns	80.2	132.7	107.3	10.0
Number of roots at 20 cm deep	num20	1.1 ns	2.1**	14.5***	3.0 ns	5	25	13	34.5
Mean diameter of roots at 20 cm deep	diam20 (cm)	1.1 ns	0.0 ns	0.0***	0.0 ns	0.1	0.1	0.1	17.9
Number of roots at 40 cm deep	num40	1.4 ns	0.1 ns	3.9***	0.2 ns	0	11	5	50.6
Mean diameter of roots at 40 cm deep	diam40 (cm)	0.9 ns	0.0 ns	0.0*	0.0*	0.0	0.2	0.1	27.5
Roots dry matter	root_biom (g per plant)	1.7*	0.0 ns	0.1***	0.0 ns	0.1	1.4	0.5	52.1
Aboveground dry matter at juvenile stage	juv_biom (g per plant)	1.7*	0.0 ns	0.0***	0.0 ns	0.3	1.9	0.9	34.7

***Very highly significant at $P = 0.000$; **highly significant at $P < 0.01$; *significant à $P < 0.05$; ns, not significant.

The principal components PC1 and PC2 explained 35.6 and 22.2% of the overall variance respectively (Fig. 3a). PC1 was explained by morphological traits (leaf width, stem diameter, total number of leaves) and cycle length on the one hand, and on the other hand by relative chlorophyll content. PC2 was explained by root traits (root depth and biomass at juvenile stage). As regards evaluation scores, fodder score was negatively ($r = -0.28$) correlated with PC1, while acceptability ($r = 0.12$) and individual scores ($r = 0.30$) were positively correlated. The cycle length score was positively correlated ($r = 0.19$) with PC2 (Fig. 3a).

According to the similarity of discriminating agro-morpho-physiological characteristics, three groups of varieties can be distinguished (Fig. 3b):

- Group 1 (G1) is composed of six varieties: four improved varieties, one new improved line and one landrace. Five varieties are of the *Caudatum* race, whereas the landrace is of the *Guinea-Caudatum* race. This group mainly differs from the other groups by longer crop cycle (group average of 71 days), higher leaf number (22), wider leaves (average 9.3 cm) and wider stem diameter (14 mm) (Fig. 4). This group was appreciated by farmers for its fodder quality (group mean score = 3.2, see online Supplementary Table S3 for score per variety).
- G2 is the largest group with 25 varieties. It is composed of three improved varieties, 13 new improved lines and nine landraces. All these varieties are of the *Guinea* race, except one new improved line which is of the *Guinea-Caudatum* race. G2 was particularly characterized by short crop cycle length (group average 65 days), lower number of leaves (19), lower dry straw at vegetative stage (0.79 g per plant) and high relative chlorophyll content at maturity (62.9%) (Fig. 4). Farmers appreciate G2 for its short crop cycle (group mean score = 3.1).
- G3 is composed of 19 varieties: one improved variety, 11 new improved and seven landraces. All varieties are of the *Guinea* race, except one improved variety which is of the *Caudatum* race. G3 is the group with the most developed root system compared to G1 and G2. It had (group average) the deepest roots (67.5 cm), the highest root biomass (0.7 g per plant) and dry straw at juvenile stage (1.13 g per plant) (Fig. 4). G3 is mainly appreciated for its grain quality (group mean score = 3.1) and acceptability (2.8).

Significant differences were found between the three groups for the most discriminating traits identified by PCA (Fig. 4). G1 and G3 obtained the highest dry straw yield at maturity with group averages of 4607.6 and 4559.4 kg ha^{-1} respectively. G3 obtained the highest grain yield with 1804.8 kg ha^{-1}, but the difference between the groups was not significant (Fig. 4).

Discussion

Our study showed that the sorghum varieties most often used by farmers in the study areas were landraces. The *Guinea* botanical race is the most highly represented in the landraces and in the overall sample. The high proportion of *Guinea* among the landraces of this area can be explained by the history of sorghum domestication: according to Fuller and Stevens (2018), the diversification of cultivated sorghum took place at three geographic centres, including West Africa for the *Guinea* and *Bicolor* races. We have also shown that farmers appreciate the *Guinea* varieties better than *Caudatum* on most evaluation criteria. Farmers' preference for

https://doi.org/10.1017/S1479262122000168 Published online by Cambridge University Press

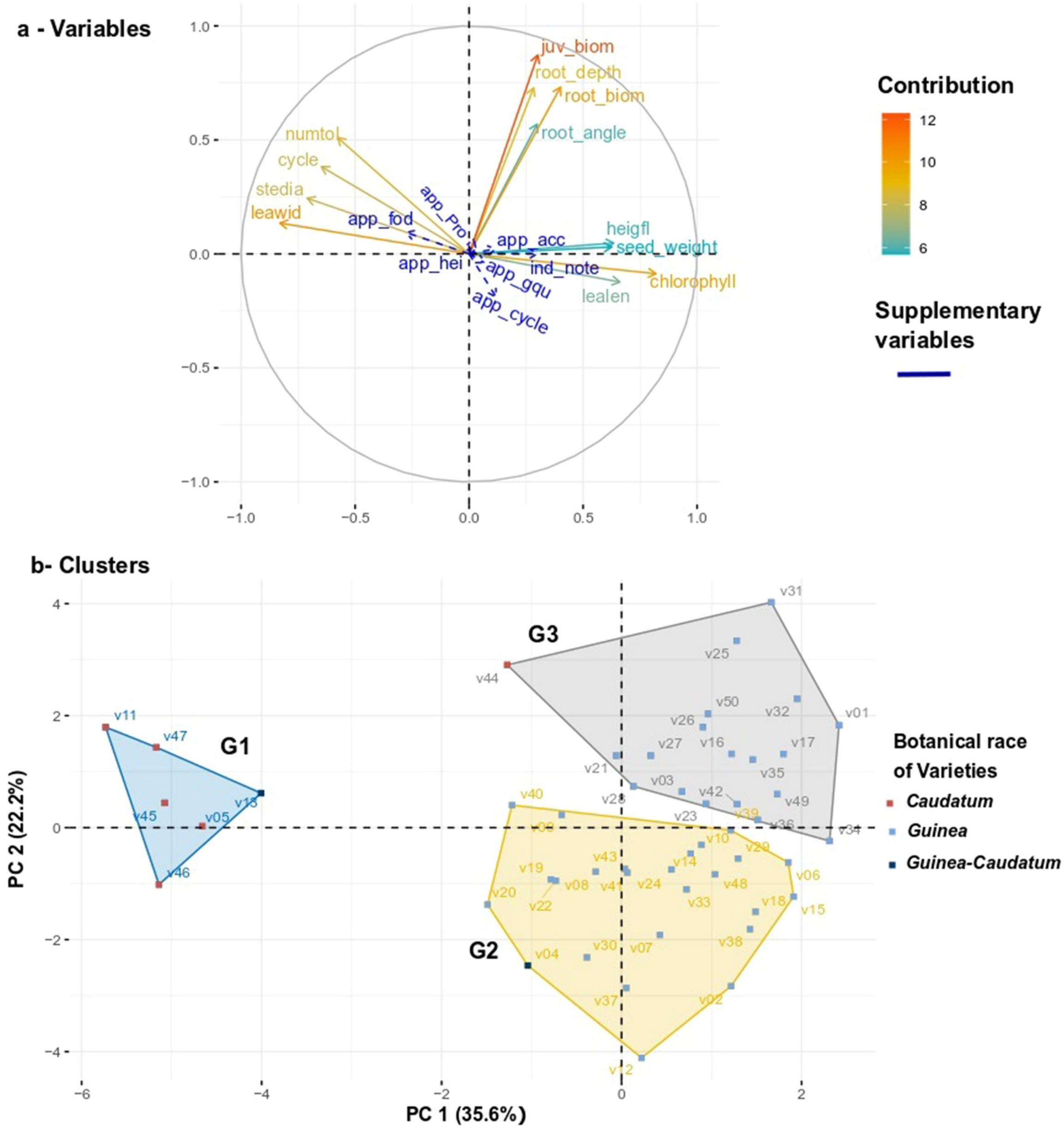

Fig. 3. Results of principal component analysis indicating (a) the most influent variables for PC1 and PC2 and (b) hierarchical clustering, indicating the three different groups of varieties. Variables abbreviations: leawid, width of the third leaf below the panicle; stedia, stem diameter; cycle, cycle length from sowing to 50% heading; numtol, total number of leaves; Juv_biom, aboveground dry matter at juvenile stage; root_depth, root depth; root_biom, root dry matter; root_angle, root insertion angle; heigfl, plant height from ground to base of flag leaf; seed_weight, weight of 100 grains; chlorophyll, relative chlorophyll content of the leaf; lealen, length of third leaf below the panicle; app, farmers' scores; hei, plant height; fod, fodder quality; Pro, grain productivity; acc, acceptability; ind_note, individual score; gqu, grain quality.

Guinea can be explained by the fact that its grains are considered to be of better quality and better suited to local dishes than *Caudatum*. The same observation was made by Gueye *et al.* (2016) in Senegal, where culinary preferences are one of the main criteria for adopting particular varieties. In addition to these preferences, the other criteria farmers mentioned for their variety preferences were productivity, earliness (cycle length) and adaptability to their soils and crop system (traditional intercropping system) (vom Brocke *et al.*, 2010; Kondombo *et al.*, 2016).

Agro-morpho-physiological characterization of sole crops showed a high degree of variability between the varieties studied; most of the quantitative characteristics had a CV of more than 10%. Root dry matter and depth, dry straw at the vegetative stage, leaf number and width, stem diameter, cycle length and relative chlorophyll content were the traits that discriminated most between varieties. Intra-specific variability in agro-morphological traits could be explained by genetic, environmental and crop management factors (Barro-Kondombo *et al.*, 2008, 2010). Because of phenotypic plasticity, plant varieties cultivated under diverse conditions can adapt to environmental constraints by changing some of their traits. Nebie *et al.* (2013) showed that race and climatic zone are the factors that explain the most agro-morphological variability between 117 accessions of sweet stem sorghum from Burkina Faso. Race was also a factor in the three groups of varieties we identified

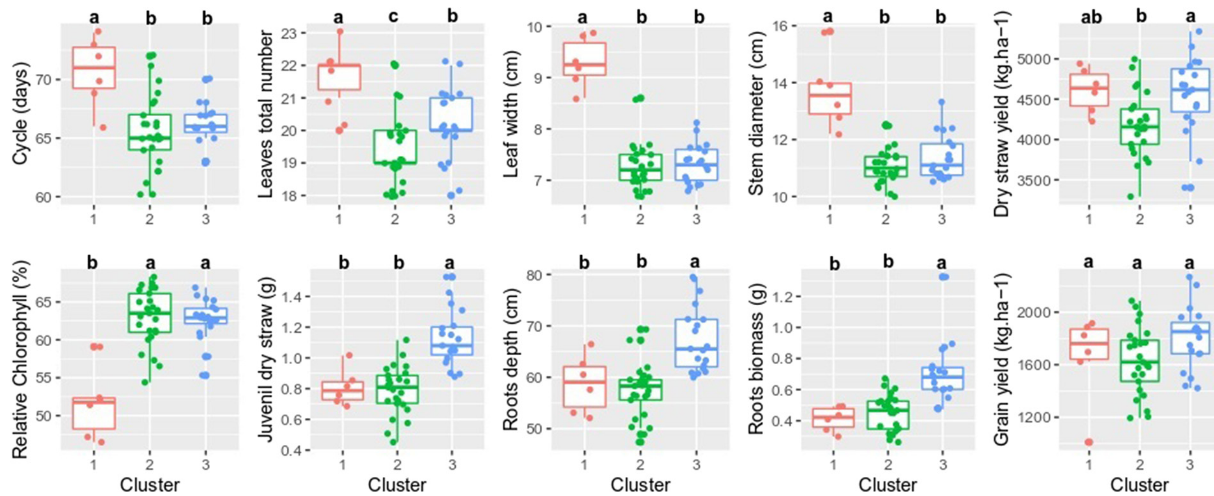

Fig. 4. Boxplots presenting the most discriminating variables according to varieties group, grain yield and dry straw yield. *Note*: Boxplots with different letters are significantly different (P-value < 0.05).

from differences in morphological and physiological traits. Similar plant traits involving height, leaves and stems were observed between two groups, G2 and G3, which were mainly comprised of *Guinea* race varieties. The similar cycle length observed between these two groups might be related to the common geographical origin of the varieties concerned (Barro-Kondombo *et al*., 2008). Our G1 group, mostly composed of *Caudatum* varieties, is characterized by a longer cycle and larger vegetative organs (leaves, stem). Our results are in line with those of Nebie *et al*. (2013) and Gueye *et al*. (2016), who showed that a longer crop cycle favours vegetative organ growth.

According to farmers, to optimize the system's yields it is important to consider the varieties to be intercropped. Several authors agree that productivity in an intercropping system is highly dependent on the choice of species and/or varieties (Lithourgidis *et al*., 2011; Litrico and Violle, 2015; Annicchiarico *et al*., 2019). Unlike sole crops, whose performance depends mostly on management practices, soil and climate, associated crops also involve interactions between species (Kammoun, 2014). Farmers pointed out that with intercropping, it is important to consider morphological traits such as height, leaf number and stem diameter. These morphological components determine the structure of the canopy and thus partly determine the light interception efficiency of the system as a whole, whence a potential gain compared to sole crops (Kammoun, 2014; Stomph *et al*., 2020). These components also determine how available light is shared between the intercropped species. According to Louarn *et al*. (2010), the leaf area developed by each species, the height of the plants in the canopy and the spatial orientation of their aerial vegetative organs are the three main plant architecture components that play a part in apportioning solar radiation. The considerable foliage of the varieties in our Group 1 may therefore make them more competitive when intercropped; farmers told us that '*sorghum varieties that generate a lot of shade have a harmful effect on the associated cowpea*'. This is one reason why most of the farmers considered improved (*Caudatum*) varieties unsuitable for intercropping and preferred to use *Guinea* landraces, which cast less shade because they have fewer leaves.

Our study identified a group of varieties (G3) with deeper, more developed roots (greater biomass) that could be interesting for intercropping systems. Roots are involved in complementarity and/or spatiotemporal competition for resource acquisition (Litrico and Violle, 2015) and in adaptation to water stress (Schenk, 2006). According to Ozier-Lafontaine *et al*. (1998), the main characteristics that determine the water uptake capacities of each intercropped species are rooting speed and depth, the density and distribution of the root system, and root life span. Deep roots can penetrate far into the soil and bring up water and nutrients from deeper soil layers, while shallow roots can only use resources in the top layer (Lithourgidis *et al*., 2011). So, intercropping two species with these different root system architectures may have the benefit of spatial complementarity in resource uptake (Stomph *et al*., 2020). The G3 group also showed higher relative chlorophyll content than the others. Chlorophyll content allows plants to better resist water stress, especially after flowering (Harris *et al*., 2007; Reddy *et al*., 2014). The well-developed root system and high relative chlorophyll content of G3 could explain why it had the highest grain and straw yields of the three groups.

To obtain higher productivity in the intercropping system, it is important for plant breeding programmes to optimize the complementarity between intercropped species by selecting for interaction traits that reduce interspecies competition and improve the productivity of each of the associated species (Lithourgidis *et al*., 2011; Litrico and Violle, 2015). We suggest varieties v05, v11 and v46 from G1, v06, v07 and v24 from G2 and v03, and v17 and v36 from G3 to represent varieties with contrasting plant traits (online Supplementary Table S2). Moreover, these varieties are among those that farmers most appreciate, with an acceptability score of more than 2.5 (online Supplementary Table S3). By assessing the agronomic performances of these varieties intercropped with cowpea, researchers could identify those best suited to intercropping systems.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1479262122000168

Acknowledgments. The authors are grateful to the farmers who participated in the surveys and the assessment of varieties, and for contributing landrace seeds. We would like to thank Issaka Ouédraogo, Technician in the traditional cereal programme at the Saria research station and Audrey Dardou, Technician in the PAM team at CIRAD (responsible for the Rhizoscope), for their help in data collection. The authors are grateful to the Avril Foundation, which entirely financed this study via the ORACLE project (Optimization of Cereal and Legume Rotations and Intercropping), and the German Academic Exchange Service (DAAD) which awarded a PhD scholarship to the first author. We would like to thank Gilles Trouche and Kirsten Vom Brocke for providing constructive comments on an earlier version of the manuscript.

References

Ali I, Khan F and Bhatti AU (2007) Soil and nutrient losses by water erosion under mono-cropping and legume inter-cropping on sloping land. *Pakistan Journal of Agricultural Research* **20**, 215–233.

Annicchiarico P, Collins RP, De Ron AM, Firmat C, Litrico I and Hauggaard-Nielsen H (2019) Do we need specific breeding for legume-based mixtures? *Advances in Agronomy* **157**, 141–215.

Audebert A, Roques S, Dardou A, Rouan L, Gozé E, Frouin J, Ahmadi N, Oura JT, Ghneim T and Courtois B (2012) Phenotyping root architectural traits a tropical japonica rice panel in view of association mapping. *ISRR* 2012: '*Roots to the Future*'.

Bado BV, Bationo A and Cescas MP (2006) Assessment of cowpea and groundnut contributions to soil fertility and succeeding sorghum yields in the Guinean savannah zone of Burkina Faso (West Africa). *Biology and Fertility of Soils* **43**, 171–176.

Bado BV, Lompo F, Bationo A, Segda Z, Sedogo MP, Cescas P and Mel VC (2012) Nitrogen recoveries and yields improvement in cowpea sorghum and fallow sorghum rotation in West Africa savannah. *Journal of Agricultural Science and Technology* **2**, 758–767.

Baker NR and Rosenqvist E (2004) Applications of chlorophyll fluorescence can improve crop production strategies: an examination of future possibilities. *Journal of Experimental Botany* **55**, 1607–1621.

Barro-Kondombo CP, vom Brocke K, Chantereau J, Sagnard F and Zongo JD (2008) Variabilité phénotypique des sorghos locaux de deux régions du Burkina Faso: La Boucle du Mouhoun et le Centre-Ouest. *Cahiers Agricultures* **17**, 107–113.

Barro-Kondombo CP, Sagnard F, Chantereau J, Deu M, vom Brocke K, Durand P, Gozé E and Zongo JD (2010) Genetic structure among sorghum landraces as revealed by morphological variation and microsatellite markers in three agroclimatic regions of Burkina Faso. *Theoretical and Applied Genetics* **120**, 1511–1152.

Bedoussac L, Journet EP, Hauggaard-Nielsen H, Naudin C, Corre-Hellou G, Jensen ES, Prieur L and Justes E (2015) Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. *Agronomy for Sustainable Development* **35**, 911–935.

Borianne P, Subsol G, Fallavier F, Dardou A and Audebert A (2018) GT-Root S: an integrated software for automated root system measurement from high-throughput phenotyping platform images. *Computers and Electronics in Agriculture* **150**, 328–342.

Bretz F, Hothorn T and Westfall P (2011) Multiple comparisons Using R. *CRC Press* 193.

Coulibaly K, Vall E, Autfray P and Sedogo P (2012) Performance technico-économique des associations maïs/niébé et maïs/mucuna en situation réelle de culture au Burkina Faso: potentiels et contraintes. *Tropicultura* **30**, 147–154.

Dabat M, Lahmar R and Guissou R (2012) La culture du niébé au Burkina Faso: une voie d'adaptation de la petite agriculture à son environnement ? *Autrepart* **62**, 95–114.

Diarisso T, Corbeels M, Andrieu N, Djamen P, Douzet JM and Tittonell P (2015) Soil variability and crop yield gaps in two village landscapes of Burkina Faso. *Nutrient Cycling in Agroecosystems* **105**, 199–216.

FAO (2020) FAOSTAT. Retrieved on 16 November 2020, from http://wwwfaoorg/faostat/fr/#data/QC.

Frison EA, Cherfas J and Hodgkin T (2011) Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. *Sustainability* **3**, 238–253.

Fuller DQ and Stevens CJ (2018) Sorghum domestication and diversification: A current archaeobotanical perspective. In Mercuri A, D'Andrea A, Fornaciari R and Höhn A (eds), *Plants and People in the African Past*. Switzerland: Springer Nature Switzerland AG, pp. 427–452.

Ganeme A, Douzet J-M, Traore S, Dusserre J, Kabore R, Tirogo H, Nabaloum O, Ouédraogo NW-ZS and Adam M (2021) L'association sorgho/niébé au poquet une pratique traditionnelle en zone soudano-sahélienne à faible rendement: état des lieux et pistes d'amélioration. *International Journal of Innovation and Applied Studies* **31**, 836–848.

Gu C, Bastiaans L, Anten NPR, Makowski D and van der Werf W (2021) Annual intercropping suppresses weeds: a meta-analysis. *Agriculture, Ecosystems and Environment* **322**, 107658.

Gueye T, Sine B, Cissé N, Diatta C and Ndiaye S (2016) Characterization of phenotypic diversity of Sorghum collection for developing breeding material. *International Journal of Sciences* **2**, 38–48.

Harlan JR and de Wet JMJ (1972) A simplified classification of cultivated Sorghum. *Crop Science* **12**, 172–176.

Harris K, Subudhi PK, Borrell A, Jordan D, Rosenow D, Nguyen H, Klein P, Klein R and Mullet J (2007) Sorghum stay-green QTL individually reduce post-flowering drought-induced leaf senescence. *Journal of Experimental Botany* **58**, 327–338.

Husson F, Josse J, Le S and Mazet J (2020) Package 'FactoMineR'. Available at http://factominer.free.fr.

Kammoun B (2014) *Analyse des interactions génotype x environnement x conduite culturale de peuplements bispécifiques de cultures associées de blé dur et de légumineuses à graines à des fins de choix variétal et d'optimisation de leurs itinéraires techniques* (PhD Thesis). University of Toulouse.

Kariaga BM (2004) Intercropping maize with cowpeas and beans for soil and water management in Western Kenya. 13*th International Soil Conservation Organisation Conference*.

Kondombo CP, Deu M, Chantereau J, Martin G, Chapuis E, Letourmy P, Zongo JD, Sagnard F and vom Brocke K (2016) Patterns of genetic structure and phenotypic diversity in sorghum landraces in relation to farmers' management in Burkina Faso. *International Journal of Biological and Chemical Sciences* **10**, 1747.

Kuhlgert S, Austic G, Zegarac R, Osei-Bonsu I, Hoh D, Chilvers MI, Roth MG, Bi K, TerAvest D Weebadde P and Kramer DM (2016) MultispeQ Beta: a tool for large-scale plant phenotyping connected to the open photosynQ network. *Royal Society Open Science* **3**, 160592.

Kuznetsova A, Brockhoff PB and Christensen RHB (2017) lmerTest package: tests in linear mixed effects models. *Journal of Statistical Software* **82**, 1–26.

Lithourgidis AS, Dordas CA, Damalas CA and Vlachostergios DN (2011) Annual intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science* **5**, 396–410.

Litrico I and Violle C (2015) Diversity in plant breeding: a new conceptual framework. *Trends in Plant Science* **20**, 604–613.

Louarn G, Corre-Hellou G, Fustec J, Lô-Pelzer E, Julier B, Litrico I, Hinsinger P and Lecomte C (2010) Déterminants écologiques et physiologiques de la productivité et de la stabilité des associations graminées-légumineuses. *Innovations Agronomiques* **11**, 79–99.

Masvaya EN, Nyamangara J, Descheemaeker K and Giller KE (2017) Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid Southern Africa? *Field Crops Research* **209**, 73–87.

Mazzafera P, Favarin JL and de Andrade SAL (2021) Editorial: intercropping systems in sustainable agriculture. *Frontiers in Sustainable Food Systems* **5**, 634361.

MRSI (2014) Catalogue national des especes et variétés agricoles du Burkina Faso. 81 p.

Namatsheve T, Cardinael R, Corbeels M and Chikowo R (2020) Productivity and biological N2-fixation in cereal-cowpea intercropping systems in sub-Saharan Africa. A review. *Agronomy for Sustainable Development* **40**, 30.

Nebie B, Nanema RK, Bationo/Kando P, Traore ER, Labeyrie V, Sawadogo N, Sawodogo M and Zongo J-D (2013) Variation de caractères agromorphologiques et du Brix d'une collection de sorghos à tige sucrée du Burkina Faso. *International Journal of Biological and Chemical Sciences* **7**, 1919–1928.

Ozier-Lafontaine H, Lafolie F, Bruckler L, Tournebize R and Mollier A (1998) Modelling competition for water in intercrops: theory and comparison with field experiments. *Plant and Soil* **204**, 183–201.

Protin PV, Corre-Hellou G, Naudin C and Trochard R (2009) Impact des pratiques de fertilisation sur la productivité des prairies et mélanges céréales-protéagineux et la qualité du fourrage. *Fourrages* **198**, 115–130.

Raseduzzaman M and Jensen ES (2017) Does intercropping enhance yield stability in arable crop production? A meta-analysis. *European Journal of Agronomy* **91**, 25–33.

Reddy NRR, Ragimasalawada M, Sabbavarapu MM, Nadoor S and Vishnu PJ (2014) Detection and validation of stay-green QTL in post-rainy sorghum involving widely adapted cultivar M35-1 and a popular stay-green genotype B35. *BMC Genomics* **15**, 909.

Schenk HJ (2006) Root competition: beyond resource depletion. *Journal of Ecology* **94**, 725–739.

Sory J-BA, Kondombo CP, Sawadogo N, Vom Brocke K, Kabore R and Sawadogo M (2020) Évaluation de la performance agronomique de lignées de sorgho [*Sorghum bicolor* (L) Moench] sélectionnées par les agriculteurs de la région du Centre-nord du Burkina Faso. *Science et Technique: Revue Burkinabè de la Recherche Sciences Naturelles et Appliquées* **5**, 149–163.

Stomph TJ, Dordas C, Baranger A, de Rijk J, Dong B, Evers J, Gu C, Li L, Simon J, Jensen ES, Wang Q, Wang Y, Wang Z, Xu H, Zhang C, Zhang L, Zhang WP, Bedoussac L and van der Werf W (2020) Designing intercrops for high yield yield stability and efficient use of resources: are there principles? *Advances in Agronomy* **160**, 1–50.

vom Brocke K, Trouche G, Weltzien E, Barro-Kondombo CP, Gozé E and Chantereau J (2010) Participatory variety development for sorghum in Burkina Faso: farmers' selection and farmers' criteria. *Field Crops Research* **119**, 183–194.

vom Brocke K, Trouche G, Weltzien E, Kondombo-Barro CP, Sidibé A, Zougmoré R and Gozé E (2014) Helping farmers adapt to climate and cropping system change through increased access to sorghum genetic resources adapted to prevalent sorghum cropping systems in Burkina Faso. *Experimental Agriculture* **50**, 284–305.

vom Brocke K, Kondombo CP, Guillet M, Kaboré R, Sidibé A, Temple L and Trouche G (2020) Impact of participatory sorghum breeding in Burkina Faso. *Agricultural Systems* **180**, 102775.

Yelemou B, Yameogo G, Bationo BA, Millogo-Rasolodimby J and Hien V (2008) Biologie florale et mode de reproduction sexuée de Piliostigma reticulatum (DC) Hochst. *International Journal of Biological and Chemical Sciences* **2**, 281–291.

Zongo JD Gouyon PH, Sarr A and Sandmeier M (2005) Genetic diversity and phylogenic relations among Sahelian sorghum accessions. *Genetic Resources and Crop Evolution* **52**, 869–878.

Zongo KF, Hien E, Mare BT and Guebre D (2021) Performance de l'association mixte sorgho-niébé sur les productivités du sorgho et des sols en zone Soudano-Sahélienne du Burkina Faso. *International Journal of Biological and Chemical Sciences* **15**, 987–1005.

Zougmore R, Kambou FN, Ouattara K and Guillobez S (2000) Sorghum-cowpea intercropping: an effective technique against runoff and soil erosion in the Sahel (Saria Burkina Faso). *Arid Soil Research and Rehabilitation* **14**, 329–342.