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Crop biocultural traits and diversity dynamics among Bassari farmers

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Abstract
Cultural and ecological dimensions of agriculture are often considered as contrasting in agricultural research. This is well reflected on approaches to variety evaluation and selection that privilege a narrow set of agronomic indicators that do not account for the complexity of farmer-crop interactions. In this work, we explore the concept of 'crop biocultural traits' to integrate the social and biological dimensions of crops and the entanglements between them. Our research is based on a case-study in a Bassari village of south-eastern Senegal, where we explored the biocultural traits that farmers assign to crops and varieties together with their abundance, distribution and trends. We focus on six local staple crops, namely sorghum, Bambara groundnut, fonio, maize, rice and peanut. Our methods include key-informant and semi-structured interviews, individual trait scoring exercises and participatory workshops. Our results reveal that Bassari farmers characterize crops and varieties considering both their agronomic but also their socio-economic and cultural traits. Bassari maintain a basket of crops and varieties that, together, bear multiple and complementary traits. However, no biocultural trait alone can explain crop and variety abundance, distribution, and trends. We conclude that understanding crop diversity dynamics requires embracing the complexity of biocultural interactions. We argue that this is also a matter of ontological pluralism and of viewing agricultural knowledge as a collective effort and a common good. Only by including diverse ways of knowing will it be possible for plant breeding and conservation efforts to address farmers contextualized needs and priorities.

Keywords Agrobiodiversity · Biocultural diversity · Neglected and underutilised species · Local knowledge · Smallholder farmers · West Africa

Introduction: bridging crops social and biological dimensions through the notion of biocultural traits

Crop diversity is an important asset for adapting farming systems to global environmental changes. Growing a diverse portfolio of crops and varieties can stabilize food production and income, limit pests and disease outbreaks, and make households less vulnerable to environmental and market fluctuations (Bellon et al. 2020; Gaudin et al. 2015; Lin 2011; Renard and Tilman 2019). A diverse crop and varietal portfolio also provides the basis for a varied diet, with direct benefits for human health (Bezner et al. 2019; Jarvis et al. 2011).

Crops and varieties grown by farmers are not only the result of pragmatic and conscious decisions. Crop diversity results from the interplay between the biophysical evolution of the crop and farmers' cultural practices, social interactions, knowledge, and belief systems governing its

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management and structure (Caillon et al. 2017; Garine et al. 2017; Howard 2010; Leclerc and Coppens d'Eeckenbrugge 2012; Nazarea 2006). Farmer's crop portfolios thus result from complex processes influenced by farmer's socio-demographic characteristics, such as gender, age, or wealth (Bezner et al. 2019; Calvet-Mir et al. 2011; Jarvis et al. 2011), but also cultural background and social organization (Leclerc and Coppens d'Eeckenbrugge 2012; van Etten 2006). Farmer's crop portfolios are also influenced by broader environmental and socio-economic trends that shape the geographical distribution of crops and varieties (Abubakari and Gasparatos 2021; Bezner Kerr and Wynberg 2024; Labeyrie et al. 2021; Leff et al. 2004; van Etten 2019).

The multiplicity of enablers, constraints, and context-specific interactions potentially shaping farmers crop portfolios makes it difficult for disciplinary research to adequately capture farmers' decision-making (Boster 1984a, b; Demongeot, 2023). In a recent effort to overcome disciplinary boundaries, Demongeot et al. (2022) provided a first synthesis of the complexity of values held by farmers towards their crops. This work showed how farmers decision-making concerning what crops to grow depends on factors encompassing economic, agronomic, ecological and socio-cultural dimensions of agriculture, thus stressing the need for research that better acknowledges farmers' stewardship and the complexity underpinning farmers' decision-making processes.

Farmers' crop portfolios have mostly been explored at taxonomic level (species and variety levels; Aguiar et al. 2020; Khoury et al. 2014; Montenegro de Wit 2016). However, approaches that focus on farmers' crop and variety diversity with an emphasis on their specific traits are gaining attention but remain relatively scarce (Martin and Isaac 2015, Isaac et al. 2018). Functional ecologists have defined traits as '*any morphological*, *physiological or phenological features measurable at the individual level*, *from the cell to the whole-organism level*, *without reference to the environment or any other level of organization*' (Violle et al. 2007, p. 3). Studying traits and trait diversity is useful because it offers a level of abstraction that illuminates functional similarities and complementarities among crops and among farmers' varieties, beyond taxonomic classifications.

Indeed, trait-based approaches are increasingly used in agronomic research to study farmers' crop portfolios. In particular, two bodies of literature are gaining prominence: the functional traits and the technology transfer literatures. The functional traits literature focuses on the interaction between ecological and agronomic traits and their link with agroecological functions (Guiguitant et al. 2021; Isaac et al. 2018; Isaac and Martin 2019; Wood 2018). In contrast, the technology transfer literature explores varietal adoption and farmers' preferences with an emphasis on yield and a limited number agronomic properties but gradually recognizing the importance of use-traits (Agre et al. 2017; Akimowicz et al. 2020; Mukerjee et al. 2023; Timu et al. 2014). Despite recent advances and with some exceptions (Skarbø 2014; Wendmu et al. 2022), these bodies of literature largely under-represent the complexity of socio-cultural factors influencing farmers crop portfolios.

Ignoring socio-cultural dimensions risks missing important aspects to understand farmers' local valuation of crops and local crop dynamics. Indeed, research in ethnobiology and anthropology has largely shown that farmers' crop diversity preferences go beyond purely ecological and agronomic dimensions. Crops are used for multiple purposes and bear multiple valuable traits beyond yield, resistance, or taste. The literature provides numerous examples illustrating that the social dimensions of farmer-crop interactions—such as identity, shared traditions, and sense of place—are key factors influencing farmers' crop portfolios and management practices (Aumeeruddy-Thomas et al. 2017; Calvet-Mir et al. 2012; Garine et al. 2017; Tekken et al. 2017; Wencelius 2016). For example, Caillon and Lanouguère-Bruneau (2005) found that farmers in Vanuatu cultivate in big surfaces taro varieties with locally appreciated agronomic and organoleptic properties. Farmers also cultivate in smaller surfaces a number of varieties that, while not particularly performing or pleasant to consume, held important social values, like cultivars considered magical or important for the identity and collective memory of the cultural group. In a similar vein, Zapico et al. (2020) found that losses in knowledge and practices associated to rice cultivation were important factors to explain the cultivation trends and rice varietal losses among local communities living in the Sarangani uplands in the Philippines, where the ritual value of upland rice and farmers' attachment to traditional varieties had historically been a motor for their conservation.

In this work, we aim to go beyond characterizing crops and varieties exclusively focusing on agronomic and biological traits to provide a more holistic picture of the multiple traits that characterize the diversity of crops and varieties that farmers maintain over generations. We do so by using the concept of biocultural traits. Since the concept of biocultural traits applied to crop diversity is not yet defined in the literature, we operationalize it by expanding the standard definitions of plant traits rooted in ecology and agronomy (Occelli et al. 2024; Violle et al. 2007) with biocultural trait definitions rooted in ethnobiology literature (Ferreira Júnior et al. 2022; Franco-Moraes et al. 2023; Santoro et al. 2018), which allows us to include the socio-economic and cultural dimensions of crops. We define biocultural traits as the biological, agronomic, socio-economic, and cultural characteristics of a particular crop species or variety that influence farmers' uses and management practices. Correlatively, we conceptualise crops as complex biocultural elements that emerge through a dynamic and multi-scalar network of ecological and socio-cultural interactions, which include both material and immaterial relations.

Our study focuses on a Bassari smallholder farming community of south-eastern Senegal with a complex and mostly subsistence-based farming system. The overarching goal of this work is to gain a deeper understanding of the biocultural traits that Bassari farmers associate to their crops and varieties and to explore whether and how these traits are linked to local crop diversity dynamics. To achieve this goal, our specific research objectives are: (1) to identify the biocultural traits used by Bassari farmers to characterise crops and varieties; (2) to analyse whether the level of familiarity that Bassari farmers have with a variety influence its characterization; (3) to examine the trade-offs and synergies between biocultural traits; and (4) to assess whether the biocultural traits used by Bassari farmers to characterise varieties are associated with their abundance, distribution, and temporal trends.

Study site: a Bassari community of south-eastern Senegal

Research was conducted among the Bassari inhabiting south-eastern Senegal (Fig. 1). Bassari are an ethnolinguistic social group of around 20,000 people living in south-eastern Senegal and northern Guinea. The study area is located near the Guinea border, below the Gambia River, in a hilly terrain formed by the northern foothills of the Fouta Djallon Massif, covered by the south-Sudanese wooded savannah.

The region is characterised by low altitude (approx. 80–380 m a.s.l.), a tropical dry or savannah climate, annual mean temperatures around 28 ºC, and an unimodal rainy season from May/June to September dominated by the West African monsoon system (ANACIM 2020; Sultan and Janicot 2003). Historical trends show that, after the droughts of the 1960s and 1980s, the area has experienced a partial recovery of precipitation from the 1990s onwards (ANACIM 2020). Nonetheless, future climate predictions for the West African region indicate a trend towards higher temperatures and shorter rainy seasons (Sultan and Gaetani 2016).

Most agriculture-related work in the area occurs in the short rainy season, whereas most off-farm work and income diversification activities occur during the longer dry season. Bassari families obtain most of their food needs from subsistence farming, which they complement with edible wild plant gathering, sporadic hunting, and purchase of other food products. Crops not consumed in the household are sold in the local market (Porcuna-Ferrer et al. 2024a).

Cotton and horticultural crops (e.g., lettuce, tomato, carrots, onions, cabbages) are the only crops produced almost exclusively for sale. The six main local staple crops are sorghum (*Sorghum bicolor*), Bambara groundnut (*Vigna subterranea*), fonio (*Digitaria exilis*), maize (*Zea mays*), rice (*Oryza sativa*), and peanut (*Arachis hypogaea*) (Fig. 2). Except for rice, cultivated exclusively in plain areas that get flooded during the rainy season and that are never subject to crop rotation, all the other crops are cultivated in rotation. A traditional crop rotation includes the alternance of legume and cereal crops. In terms of gender roles, women and men carry their agricultural activities independently and some crops are gender-specific. Sorghum is exclusively cultivated and managed by men whereas Bambara groundnut is exclusively managed by women. All other staple crops show different degrees of involvement of men and women (Porcuna-Ferrer et al. 2023a).

Bassari agricultural practices have undergone important changes in the last decades, including switching crop species and increasing reliance on external inputs. Traditional Bassari staple crops are increasingly abandoned while rice, maize, peanut and cotton have been progressively adopted, driven by off-farm migration, increased cash needs, and the role of external agents such as non-governmental organisations (NGOs), agricultural extension services, and development projects among others (Porcuna-Ferrer et al. 2024b).

Methods

Data collection

Primary data collection was conducted between November 2019 and March 2020 and between December 2020 and June 2021. All primary data collection was done in one of the biggest Bassari villages of south-eastern Senegal, with 109 households. The studied village is representative of the agronomic and socio-economic conditions of the Bassari territory. Data were collected with the help of local interpreters who translated from Bassari (local language) to French. Primary data collection comprised key informant interviews ($n=18$), participatory workshops ($n=2$), semi-structured interviews ($n=47$), and individual surveys ($n=60$ households, $n=120$ farmers, with an equal gender distribution).

Inventory of crops and varieties cultivated in the village.

We focused on the six main staple crops cultivated in the village: sorghum, fonio, Bambara groundnut, maize, rice,

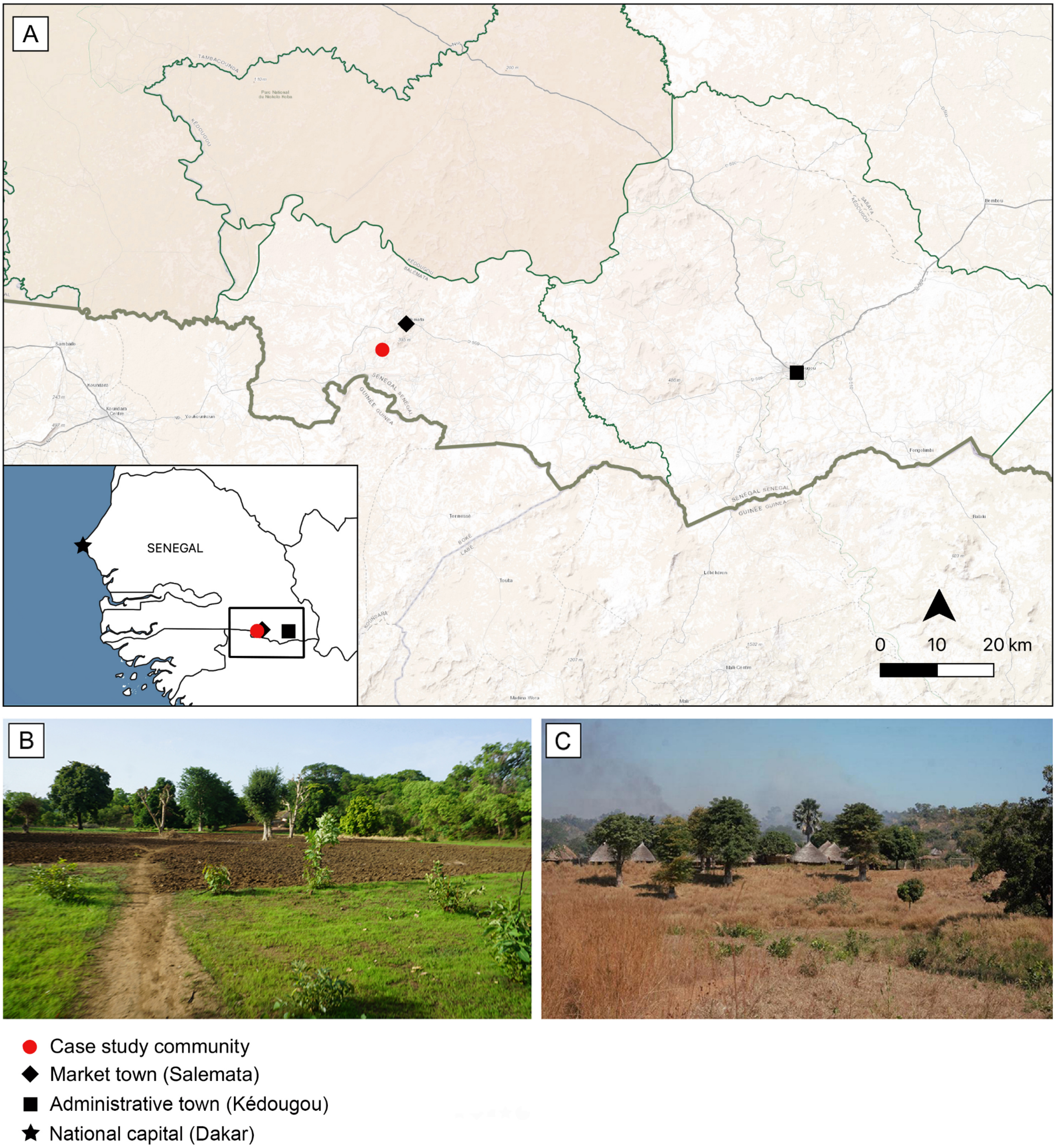

Fig. 1 Case-study area. (A) Location of the study site. Photos (B) and (C) depict the landscape of the case-study community during the rainy season and the dry season, respectively

and peanut. To obtain a comprehensive list of the varieties of these crops currently grown in the village, we conducted key informant interviews and field visits. We use the term 'variety' to refer to emic categories identified by farmers as a management unit composed by seed lots of the same kind, corresponding to plants with similar phenotypic and use characteristics according to farmers' perspective (Louette and Smale 2000).

Key informants were selected through snowball sampling, asking for local agriculture experts (e.g., 'Who in the village knows a lot about farming?'), and for local experts for each of the selected crops (e.g., 'Who in the village

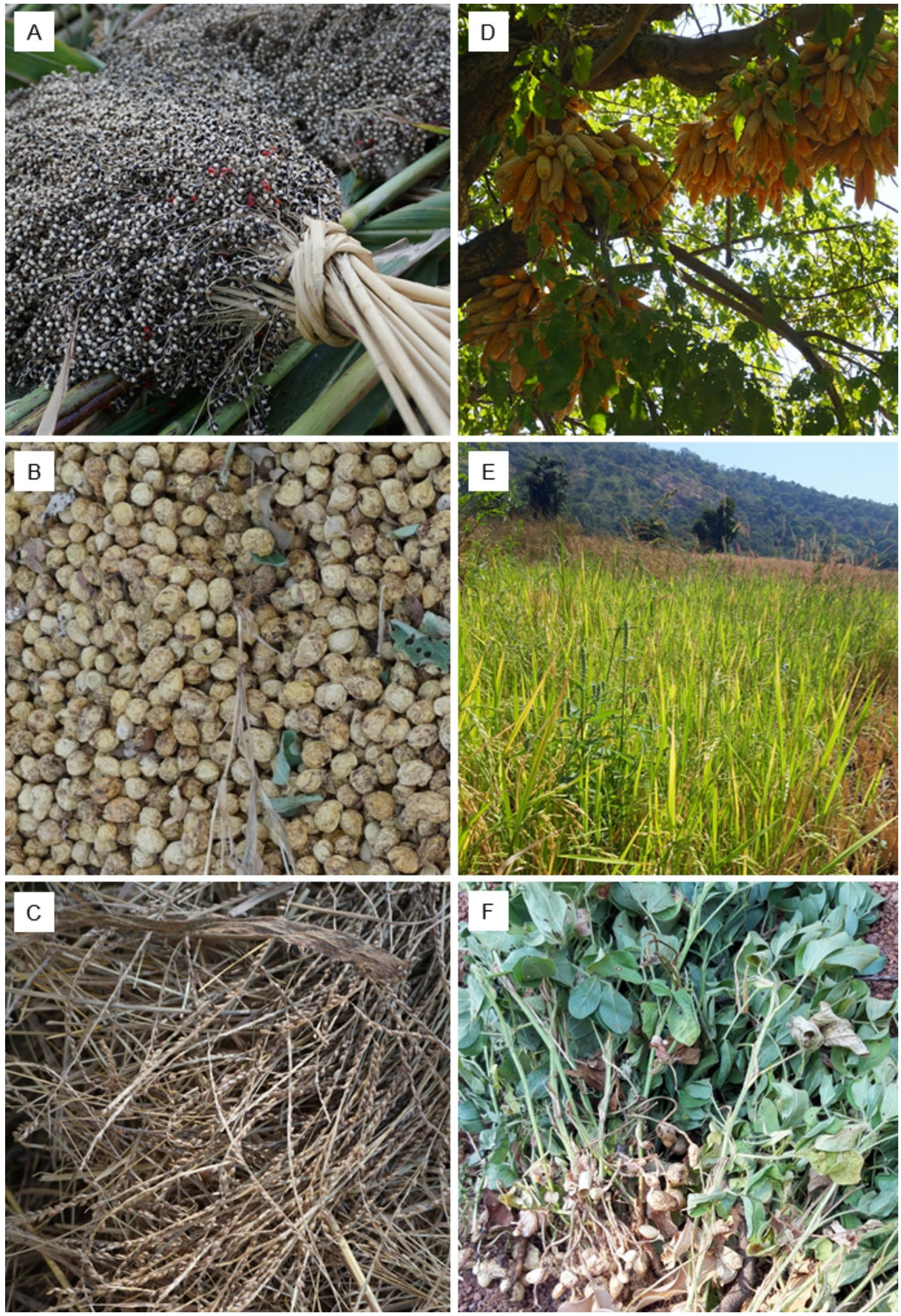

Fig. 2 Bassari staple crops: (A) sorghum, (B) Bambara groundnut, (C) fonio, (D) maize, (E) rice, (F) peanut

knows a lot about fonio?' 'And about sorghum?'). During interviews, we always used the same order of crops and asked respondents to cite all the varieties they knew for each crop. Since there is no Bassari word for 'variety' or ´landrace´, we used synonyms (e.g., ´What are all the types of [crop x] that are currently cultivated in the village?´). Varieties were documented using the vernacular names. We considered that the list was completed when saturation was reached and additional interviews with new key informants did not add any new name. We then conducted field visits to collect samples for each of the varieties recorded. If we obtained a new variety that had not been mentioned by key informants, we included it in our list and used informal interviews with the interpreters and the farmers to fill in the necessary information.

Finally, we organised two participatory workshops, one with men and one with women, to obtain a consensual list of all the varieties cultivated for each staple crop selected.

Workshop participants were selected with the help of the village head. We aimed at selecting a group of people from different ages and for whom agriculture was the main livelihood activity. During the workshop, we provided participants with a pile of small transparent bags containing seeds from all varieties identified during interviews and a second pile with cards with the vernacular name of the varieties. We asked participants to match the bags of seeds with the cards with names, grouping those vernacular names that referred to the same varieties. In the cases where a vernacular name corresponded to more than one variety, we asked to split those in two different cards. This allowed us to identify synonyms with variety names.

Identification of crops' and varieties' biocultural traits.

To assess the biocultural traits assigned by farmers to each crop species and variety, during the key informant interviews we asked: 'What are important characteristics to identify this crop/variety?', 'What other characteristics define this crop/variety?', 'What are the main uses of this crop/variety (e.g., food, fodder, medicinal, ritual)?', 'Are there any other characteristics that are important for the uses of this crop/variety?' For example, if a crop or variety was important to make traditional fermented beer, or to make *enap* - traditional staple dish-, we asked for the characteristics that would result in good beer, good *enap*, etc. Then, we documented all the key phenological, morphological, management, use, and symbolic features mentioned by key informants for each crop and variety. We solved contradictions regarding these features resulting from information provided by different key informants by triangulating the information. In cases when contradictions were not possible to solve, we discussed them during the participatory workshops. We used this information to make a list of biocultural traits. We aimed at having a comprehensive list of biocultural traits that was generic enough to be used for all staple crops and varieties grown locally, but specific enough to capture the complexity of social and biological dimensions of crops and varieties.

To deepen our understanding of biocultural traits and how different traits might have affected farmers' adoption or abandonment of certain varieties, we conducted semi-structured interviews. Interviewees were selected through convenient quota sampling, aiming at capturing the diversity of gender, age, and wealth characteristics in the village. We started the semi-structured interviews by asking farmers to list all the crops and varieties that they cultivated during the last cropping season and all the ones that they had abandoned in the last 15 years. We also asked interviewees to list those crops and varieties that had experienced an increase or a decrease in the cultivated surface at household-level. For every type of change (adoption, abandonment, change in surface), we asked for the reasons, paying particular attention to identifying biocultural traits mentioned by farmers. We added to our list any trait that had not been mentioned before. For example, respondents mentioned that they were abandoning or decreasing the surface cultivated with certain varieties 'because it's difficult to crush the grains' or 'because the work in the fields is hard.' We coded both responses under a new biocultural trait named 'workload'.

Our final list included 11 biocultural traits affecting crop and variety choices: earliness, water needs, resistance to dry spells, soil fertility requirements, pest resistance, market value, yield, workload, multiple uses, organoleptic preference, and symbolic importance (Table 1).

Crop and variety scoring on biocultural traits.

To evaluate the relative salience of each biocultural trait for each crop species and variety, we conducted individual surveys. To select informants for the individual surveys, we first selected households through random sampling, using a village census as a basis. In each of the selected households, we interviewed both a man and a woman who had cultivated a field during the last cropping season ($n = 120$ farmers in 60 households). Within a household, adults were selected following convenience sampling.

The survey consisted of an individual scoring exercise that had two main parts. In the first part, interviewees were given a set of cards with photographs and vernacular names from the six main staple crops (Fig. 3). Farmers were asked to rate each of the crop species for the 11 biocultural traits using a scoring scale of 'low', 'medium', or 'high' (1–3 scale). For example, for the trait 'workload' for each crop species we asked: 'Is this [showing the card] a crop that requires a small or a big workload? On a scale 1 to 3, how would you describe the workload associated with the cultivation and processing of this crop?' Farmers successively placed each of the six crops in three different piles depending on whether they required low, medium or high workload. Once they finished scoring all crops for workload, we asked about another biocultural trait until all crop species were scored for the 11 biocultural traits.

In the second part of the interview, farmers were asked to repeat the same scoring exercise but for varieties. To keep interview time within max. 1.5 h/person, we selected the varieties of four gender-typical staple crops: sorghum and maize (typically men's crops), and Bambara groundnut and peanut (typically women's crops). The selection accounts for intra-household differences in terms of experience, time spent with the crop, and decision-making. Men and women were asked to score different varieties: men scored sorghum and maize varieties, whereas women scored peanut and

Table 1 Biocultural traits evaluated

Trait	Range	Description
Agronomic and biological domain		
Earliness	1–3: Low-medium-high	Time needed for a crop species or variety to reach maturity. A score of 3 entails that the crop species or variety manages to complete the cycle within a short period of time (short cycle).
Water needs	1–3: Low-medium-high	Water needed for a crop species or variety to successfully complete its cycle. Different crop phases can have different water requirements, farmers were asked to make a general estimation. A score of 3 entails that the crop species or variety has high water needs.
Dry spell resistance	1–3: Low-medium-high	Tolerance that a crop species or variety has to the lack of water. Because different crop phases can have different tolerances to lack of water, farmers were asked to make a general estimation. A score of 3 entails that the crop species or variety tolerates dry spell periods.
Soil fertility requirements	1–3: Low-medium-high	Soil fertility needed for a crop species or variety to achieve good yields. A score of 3 entails that the crop species or variety has high soil fertility requirements.
Pest resistance	1–3: Low-medium-high	The extent to which a crop species or variety is resistant to production and storage pests and diseases, including seed-eating birds in the fields and insects damaging the grains during storage. A score of 3 entails that the crop or variety is highly resistant to pests and diseases.
Socio-economic and cultural domain		
Market value	1–3: Low-medium-high	Value that a crop species or variety can have if sold. It includes cultural limitations for selling and the price that can be gained. A score of 3 entails that the crop or variety can be easily sold at the local market for a good price.
Yield	1–3: Low-medium-high	The extent to which a crop species or variety has good yields (amount of production per local unit of area) considering both, good and bad years. It can include the yield in grain and in flour. A score of 3 entails that, in general, the crop species or variety has high yields, also in years with anomalies related to weather, pests, or crop management.
Workload	1–3: Low-medium-high	Amount of labor required for crop production and processing. It includes, for example, the ease or difficulty of harvesting or cooking a certain crop or variety. A score of 3 entails that the crop species or variety has high work requirements.
Multiple uses	1–3: Low-medium-high	It includes the value of a crop species or variety for animal feeding (e.g., the use of crop residues as fodder) but also the usage of parts of the crop for healing practices or for art-craft. The specific uses evaluated depend on the crop species. A score of 3 entails that the crop species or variety can be used for multiple purposes.
Organoleptic preference	1–3: Low-medium-high	Valuation of a crop species or variety for its nutritional value, colour, smell and taste. This category includes the value of a variety for a specific characteristic, such as the quality of the flour for cooking a traditional dish. A score of 3 entails that the crop species or variety is appreciated for its positive organoleptic characteristics.
Symbolic importance	1–3: Low-medium-high	Value of a crop species or variety for individual and collective identity, sense of place, use in ceremonies, celebrations, rites and other traditional practices. A score of 3 entails that the crop species or variety has a high symbolic value in the local culture.

Fig. 3 Pictures showing the methods of data collection: (A) participatory workshops to obtain a consensual list of varieties locally grown for each staple crop, (B) and (C) individual surveys with scoring exercise according to biocultural traits at crop species and at variety levels, respectively

Bambara groundnut varieties. For variety scoring, we used seed bags except for maize, for which we used the corncobs (Fig. 3).

We documented the level of familiarity of the interviewees with the varieties, i.e., whether the interviewee knew the variety because had cultivated it the previous cropping season (hereafter familiar) or not (hereafter not familiar). Varieties that were cultivated in the past by the farmer, as well as those varieties grown by another household member, neighbor or friend, were considered as not familiar.

During the individual survey, basic socio-demographic data were also collected, including individual-level (i.e., age and gender) and household-level data. Household-level data encompassed the number of household members (incl. gender and approximate age), the crop species cultivated for food consumption (incl. minor and major crops), the varieties cultivated for each of the main staple crops, and the total area cultivated by the household (incl. the area cultivated for each staple crop).

Variety abundance, distribution, and trends.

To get an assessment of the varieties' abundance, distribution, and trends at village-level, during the participatory workshops, we used the four-cell method (Rana et al. 2005). For each staple crop, we drew a 2 × 2 matrix on the floor and asked participants to allocate seeds of each of the varieties grown in the village to one of the four cells, corresponding to varieties grown by (1) many farmers, in large areas; (2) many farmers, in small areas; (3) few farmers, in large areas; or (4) few farmers, in small areas. Varieties cultivated by many farmers in large areas were considered 'predominant' and varieties cultivated by few farmers in small areas were considered 'rare'. With women, we did the four-cell method for Bambara groundnut and peanut, and with men we did it for sorghum and maize.

We then repeated the exercise but asking about the abundance and distribution of varieties 15–20 years ago. Varieties introduced post-2000s were considered 'recently introduced', varieties introduced pre-2000s were considered 'long-term introduced' and varieties present in the local farming system since the 1960s or earlier were considered 'traditional varieties'. This exercise allowed us to distinguish those varieties that had increased or decreased cultivation–considering the number of farmers and the area cultivated at village-level in the last 15–20 years– from those that had been completely abandoned, only recently introduced, or for which no clear trend was reported. For varieties cultivated in the past but not anymore and for which we did not have physical seeds, we used coloured cards with the local name written on them.

Data analysis

Crop and varietal diversity cultivated and associated biocultural traits.

We used descriptive statistics to document the number of farmers cultivating each crop species and variety, to report the mean surface cultivated with each crop species and variety at household-level, and to characterise crop species and varieties according to biocultural traits.

Farmers' familiarity with the variety and variety trait scorings.

To explore whether the level of familiarity with the variety influenced farmers' scoring of the variety biocultural traits, we conducted a series of Wilcoxon tests, one per variety and trait (Supplementary Material 1). For each biocultural trait and variety, we compared farmers' scorings (1–3 corresponding to low/medium/high) between the two groups of farmers (those who were familiar and those who were not familiar with the variety). Differences in biocultural trait scorings between the two groups of farmers were considered as statistically significant when $p < 0.05$.

A complementary analysis to assess the relation between familiarity and scoring was implemented using a Chi-square test, with a contingency table that crossed the two groups of farmers (familiar and not familiar) against the three potential scores of the biocultural traits (1, 2, and 3).

Varieties biocultural traits versus abundance, distribution, and trends.

To assess how biocultural traits are distributed among varieties, we classified varieties according to (1) abundance and distribution (predominant versus rare varieties) and (2) temporal trends (increase, decrease, no clear trend).

For each biocultural trait (scored 1–3), we calculated the median score for all the varieties that belong to the same group and represented them with the use of flower diagrams. We then inferred some general trends by comparing the median score of varieties across different biocultural traits with their abundance/distribution and cultivation trends. To compare these scores, we conducted two separate Wilcoxon tests: one comparing predominant versus rare varieties, and the other comparing varieties with increasing versus decreasing cultivation (Supplementary Material 1). Differences in varieties scoring of biocultural traits depending on their abundance/distribution and trends were considered as statistically significant when $p < 0.05$.

For data analysis we used R version 4.4.1 (R Core Team 2024), packages *ggplot2* (Wickham et al. 2024) and *geomtextpath* (Cameron and Brand 2024) for figures; *coin* (Hothorn et al. 2023) for Wilcoxon tests, as well as multiple helper functions from *tidyverse* (Wickham and RStudio 2023) and *data.table* (Barrett et al. 2024).

Results

Crop and varietal diversity cultivated

All the farmers interviewed belong to smallholder households, with a mean surface cultivated of 2.1 ha. Households cultivate a mean of 4.8 staple crops, combining cereals (sorghum, maize, rice, fonio) and legumes (Bambara groundnut and peanut). Peanut and maize were the most frequently cultivated crops (cultivated by 100% and 98% of the households, respectively), followed by Bambara groundnut (91%), and sorghum (66%). Fonio had the lowest cultivation frequency (36% of the households). The mean surface cultivated depends on the crop species, with peanut and maize having the biggest surfaces and Bambara groundnut and fonio the smallest (Table 2).

Altogether, Bassari farmers cultivate 7 varieties of sorghum, 20 varieties of maize, 7 varieties of Bambara groundnut, 10 varieties of peanut, 8 varieties of rice, and 4 varieties of fonio. On average, households reported growing 1.7 varieties of maize and 2.6 varieties of peanut on the same cropping season. For all the other crops, most households reported to cultivate only one variety (Table 2). For each specific crop, most farmers planted one variety in a big surface and the other varieties in smaller surfaces. Only for maize, most farmers mentioned cultivating two varieties in big surfaces, generally a short-cycle variety to provide food at the beginning of the season and a long-cycle variety to provide food at the end. Varieties recently introduced were generally cultivated in small surfaces as a trial and only in exceptional cases (e.g., an unexpected shock or seed shortage) farmers reported cultivating them in a big surface.

Table 2 Socio-demographic and agroecological characteristics of the surveyed households

	Mean	Min	Max
Socio-demographic characteristics			
Number of household members	9.03	1.00	23.00
Number of adults in the household	4.24	1.00	10.00
Gender ratio (#women/#men)	0.56	0.25	1.00
Agroecological characteristics			
Cultivated surface (in hectares)			
Total area under cultivation	2.07	0.62	8.62
Sorghum surface	0.38	0.06	0.75
Maize surface	0.55	0.13	2.50
B. groundnut surface	0.15	0.06	0.38
Peanut surface	0.62	0.13	2.50
Rice surface	0.39	0.13	1.13
Fonio surface	0.23	0.13	0.50
Crop diversity - species level			
Number of edible crop species	17	8	23
Number of staple crop species	4.81	3.00	6.00
Crop diversity - variety level			
Number of sorghum varieties	1.37	1.00	3.00
Number of maize varieties	1.68	1.00	4.00
Number of B. groundnut varieties	1.26	1.00	2.00
Number of peanut varieties	2.57	1.00	6.00
Number of rice varieties	1.36	1.00	3.00
Number of fonio varieties	1.05	1.00	2.00

The number of farmers cultivating each sorghum variety differed. One sorghum variety was cultivated by 72% of the interviewees, whereas the other varieties were cultivated by ≤27% of the interviewees, with four sorghum varieties cultivated by < 10% of the farmers. Such dominance pattern has changed through time as, in the past, these four rare varieties were cultivated by > 35% of the interviewees and two of them by > 54% of the interviewees (Fig. 4). In the last 15–20 years, farmers reported three sorghum varieties to have decreased and one sorghum variety to have increased in cultivation. From all the sorghum varieties cultivated, only two are currently grown in big surfaces.

Maize is the crop with the highest number of varieties cultivated. Two maize varieties are cultivated by ≥75% of the interviewed farmers, 16 are cultivated by 45–67% of the farmers, and two are cultivated by ≤25% of the farmers (Fig. 4). Two varieties were reported to be clearly decreasing and six varieties to be increasing in cultivation. Nine varieties are grown in big surfaces and 11 are grown only in small surfaces. All maize varieties grown in big surfaces are increasing cultivation and have a medium-high cultivation frequency.

Bambara groundnut is the crop more homogeneously distributed in terms of cultivation frequency, with all varieties being cultivated by 39–60% of the farmers interviewed (Fig. 4). Only one of the Bambara groundnut varieties was reported to have increased in cultivation in the last 15–20 years whereas four were reported to have decreased in cultivation. The four varieties that are decreasing in cultivation are often grown together in the same field, since they have the same cycle. Grains are separated only post-harvest and not always, as many farmers also use them mixed for cooking and sowing. For two Bambara groundnut varieties there was no clear trend stated as they have been only recently introduced in the case-study community. The four varieties reported to be decreasing in cultivation are the ones cultivated in bigger surfaces.

Two peanut varieties are cultivated by ≥84% of the interviewed farmers, four by 17–42% of the farmers, and four other by < 11% of the farmers (Fig. 4). Two peanut varieties have increased and two other have decreased in cultivation

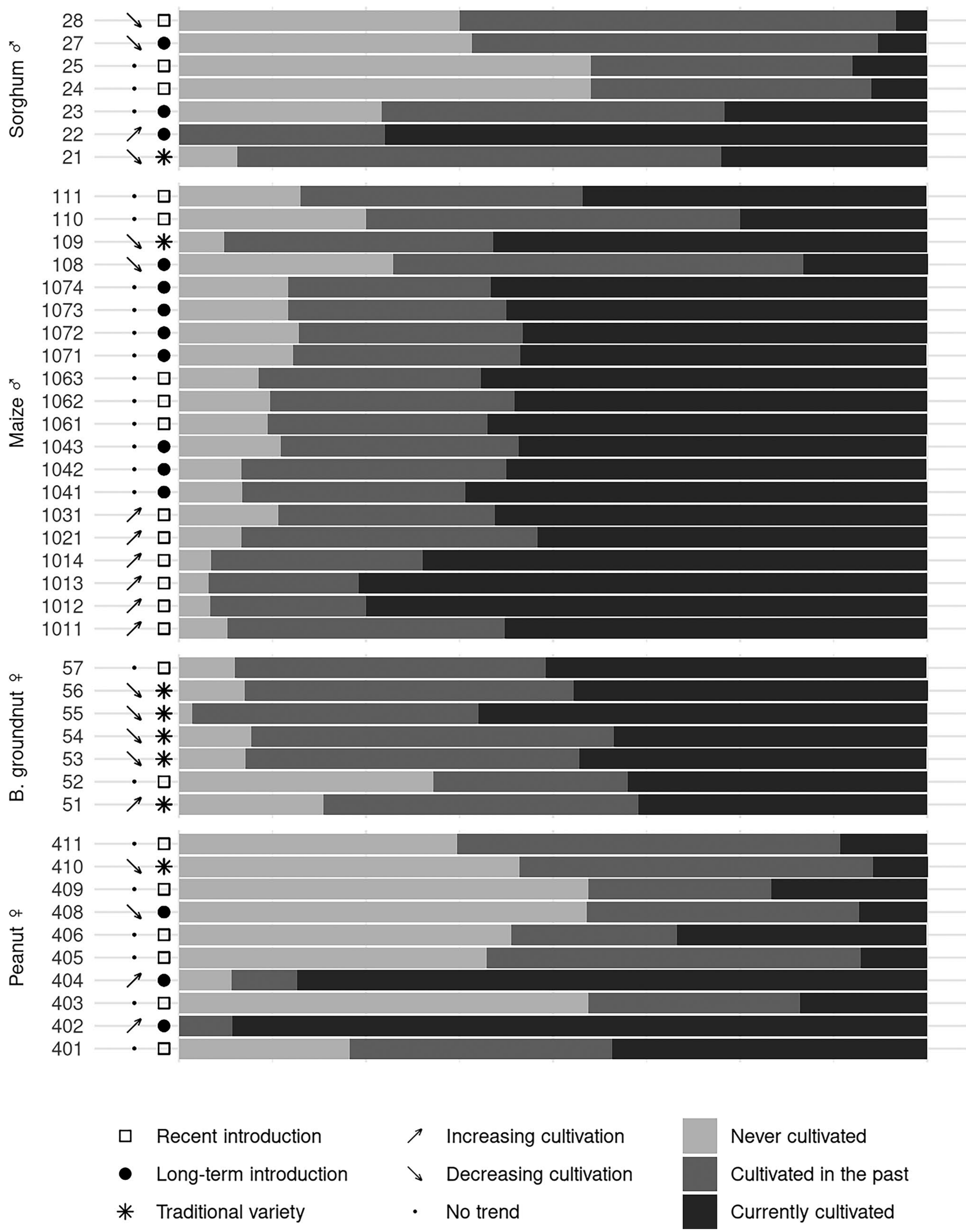

Fig. 4 Cultivation trends of varieties of the four selected staple crops. Variety IDs are listed on the left. The bars indicate the proportion of farmers who currently cultivate, previously cultivated, or have never cultivated the variety. Sample sizes for each crop: sorghum (n=38), maize (n=57), Bambara groundnut (n=53) and peanut (n=58)

frequency in the last 15–20 years. All the other varieties have been introduced in the last 15 years and no clear trend was reported. Only the two peanut varieties that are increasing in cultivation were reported to be grown in big surfaces.

Biocultural traits associated to local staple crop species and varieties

Biocultural traits across staple crops.

Comparing the six staple crop species based on traits within the agronomic and biological domain, farmers generally perceived Bambara groundnut to have a longer growth cycle than peanut, and sorghum to have a longer cycle than maize, fonio, and rice, despite recognizing significant intraspecific variability in the earliness of different varieties within each species (Fig. 5). In terms of water needs, fonio, sorghum and Bambara groundnut were considered to have lower water needs than maize, peanut and rice, being rice the crop with the highest water needs. For resistance to dry spells, respondents noted significant intra-specific variability; however, fonio and sorghum were generally considered the most tolerant, while rice and maize were seen as the least. Both Bambara groundnut and peanut were rated as having intermediate resistance to dry spells, with Bambara groundnut receiving higher scores than peanut.

In terms of soil fertility requirements, fonio was considered to grow best in nutrient-poor soils. Rice and maize were considered to grow only in nutrient-rich soils, and for both crops most farmers reported the use of chemical fertilisers. Concerning pest resistance, peanut and Bambara groundnut were considered to be more vulnerable to pests, especially during storage, compared to cereal crops. For cereal crops, maize and sorghum were the most vulnerable to pests and fonio the least affected.

Regarding traits within the socio-economic and cultural domain, fonio and peanut were perceived as the crops with the highest market value, while Bambara groundnut was seen as having the lowest (Fig. 5). In the Bassari tradition, Bambara groundnut is exclusively used for consumption and cannot be commercialized. In terms of yield, maize was considered to be the most productive and fonio the least. Among legumes, peanut was considered to have higher yields than Bambara groundnut. Concerning workload, fonio was considered the most labor-intensive crop for harvesting and processing, followed by sorghum, Bambara

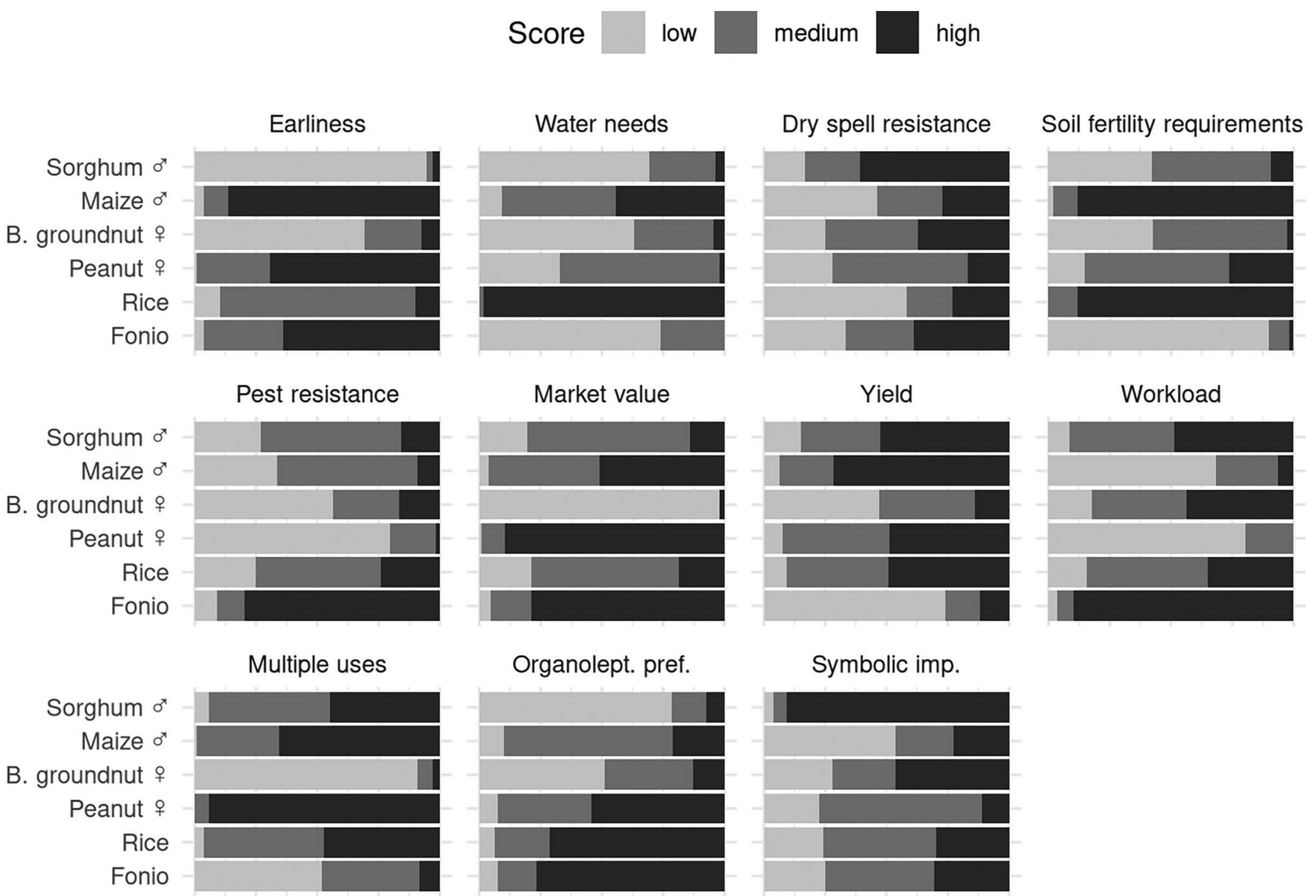

Fig. 5 Farmer assessments of biocultural traits at the species level. The bars indicate the proportion of farmers who assigned crops a low, medium, or high score for each biocultural trait

groundnut, and rice. Maize and peanut were reported as having the lowest workload requirements.

Aside from human consumption, the main use mentioned for all crops was fodder. Peanut was considered to have the highest fodder quality and Bambara groundnut and fonio the lowest. In terms of organoleptic preference, fonio and rice were the crops most valued and sorghum the least. For symbolic importance, sorghum was regarded as having the greatest significance for Bassari identity and traditions, followed by Bambara groundnut.

Biocultural traits across varieties.

When comparing varieties of the four selected staple crop species there was a high variability considering the scoring of the traits (Fig. 6).

Scoring of sorghum varieties differed in terms of cycle. Most of the varieties evaluated were considered of medium to short cycles and only one was considered to have a long cycle. Resistance to dry spells, soil fertility requirements, water needs, and workload were closely linked to the cycle of the varieties, with the long-cycle variety (sorghum 21) considered to be less resistant to dry spells and more demanding in terms of water needs, soil fertility requirements, and workload. Sorghum 21 was also perceived as more susceptible to pests. Farmers noted that this variety has a sweeter taste, which attracts birds. Also, since this variety remains in the fields after all other crops have been harvested, all birds feast on it, resulting in significant losses. Three sorghum varieties (sorghum 21, 22 and 23) were considered to have higher symbolic importance, more positive organoleptic traits, and to hold more diversity of uses compared to the other varieties.

For maize, long-cycle varieties were considered less tolerant to dry spells, having higher water needs and soil fertility requirements, and being less resistant to pests and diseases compared to short-cycle varieties. Farmers considered short-cycle varieties as having a higher market value

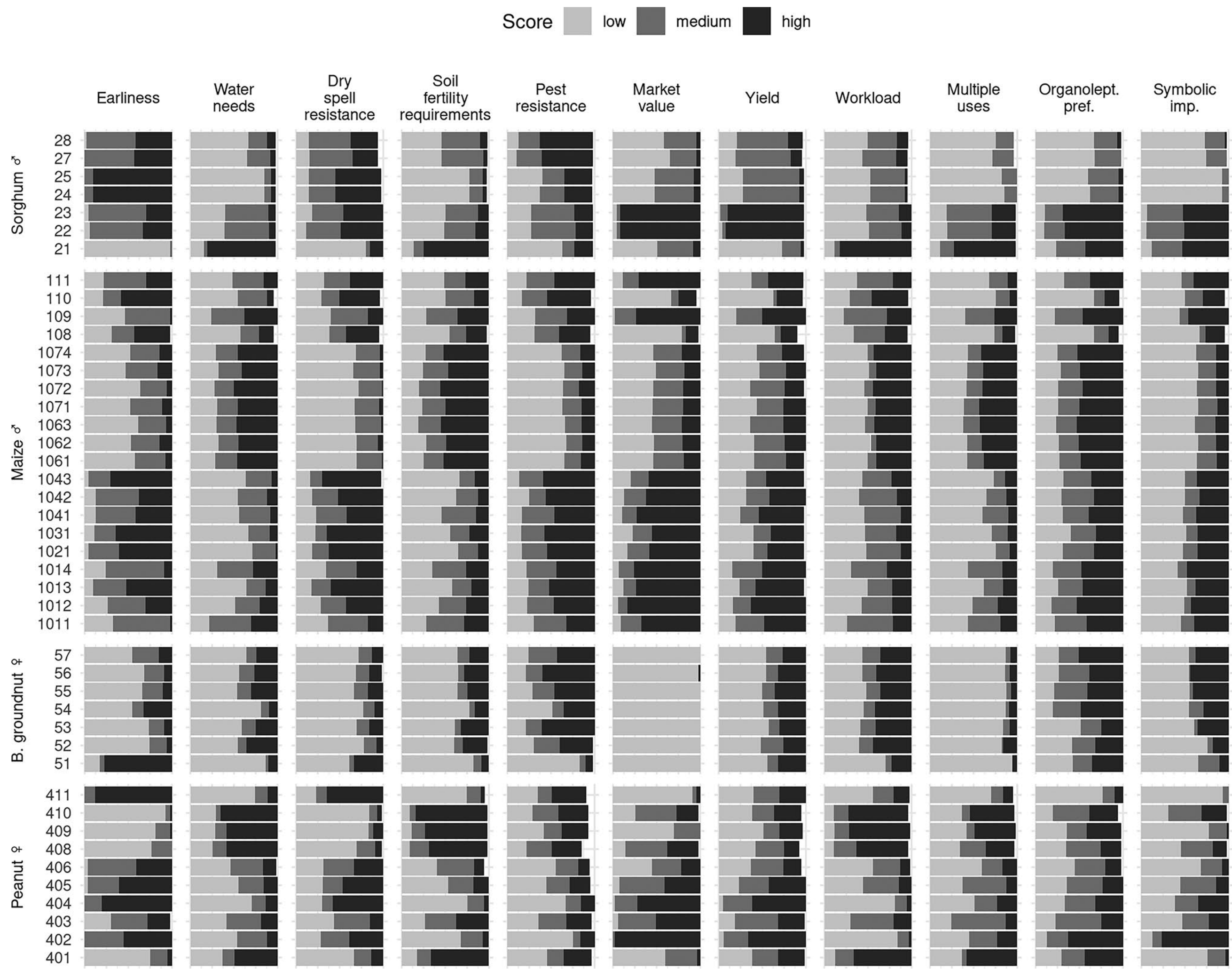

Fig. 6 Farmer assessments of biocultural traits at the variety level. Variety IDs are listed on the left. The bars indicate the proportion of farmers who assigned varieties a low, medium, or high score for each biocultural trait

and higher symbolic importance than long-cycle varieties which in turn were scored as having more diversity of uses. There were no clear patterns in terms of yield or organoleptic preference among maize varieties.

Most Bambara groundnut varieties were considered to have similar growth cycles, except for one variety with a shorter cycle– B. groundnut 51–, which differed from the others in several traits. Farmers reported that B. groundnut 51 required less workload, had lower water needs, lower soil fertility requirements, and exhibited higher resistance to dry spells compared to other varieties. However, this variety was also reported to have lower pest resistance and lower symbolic importance compared to the other varieties. Among the remaining varieties, the main variability was reported in organoleptic preferences, particularly regarding their suitability for traditional dishes. Differences were noted in flour quality for preparing *enap* and the sweetness and size of the grains for cooking *emegue*.For other biocultural traits, farmers did not identify important differences between varieties.

For peanut, four varieties had long cycles and all the rest medium- or short-cycles. Long cycles were associated with lower dry spell resistance and with higher water needs and soil fertility requirements. Interviewees noted that pest resistance, primarily to storage pests, was often associated with the hardness of the husk or the grain, which they related with grain colour. Long-cycle varieties were also described as having more leaves and received higher scores for multiple uses due to their higher fodder quality. Yield and market value differed greatly between varieties. Market value, in particular, was partly influenced by organoleptic preference, with grain colour being a key factor in scoring. Varieties organoleptic preference also depended on the cooking use: some varieties were scored higher because they were good to be grilled and eaten as snacks, others for oil extraction or butter making, and others for cooking *mafe*, a traditional dish. Symbolic importance was linked to organoleptic properties, and in general, light-coloured varieties were preferred over reddish or darker ones.

Farmer's familiarity with the varieties and biocultural trait scorings

Results of the Wilcoxon test indicate that farmers who were familiar with a variety scored its biocultural traits differently than those who were not familiar with it (Supplementary Material 2). Overall, 11.16% of the traits showed significant differences in scores between familiar and unfamiliar farmers. The Chi-square test also rejected the independence between trait scores and farmers' familiarity with the variety (*X-squared* = 6.5579; *p-value* = 0.038). Considering all traits and varieties, 10.78% of the Chi-square tests implemented rejected the hypothesis that farmers' scoring of a variety was independent of their familiarity with that variety.

For sorghum, we only found statistically significant differences in the scoring of biocultural traits between farmers familiar with the variety and those unfamiliar for one variety. Specifically, differences were found for the variety sorghum 21 (known as *degaff ilian* by Bassari farmers), a traditional variety that is now cultivated by few farmers and in small surfaces but that was widely cultivated in the past. Farmers unfamiliar with the variety scored its soil fertility requirements lower than farmers familiar with it.

The scoring of maize varieties showed the most significant differences between familiar and unfamiliar farmers. Specifically, we found differences for 19 out of the 20 varieties present in the village. The only variety for which we found no differences between the two groups of farmers is maize 1041 (known as *maka iwarax undundu* by Bassari farmers), a variety introduced in the 1980s cultivated in small surfaces by most farmers. Organoleptic preference, yield, pest resistance, earliness, market value, and multiple uses were assessed differently by farmers who were familiar with different maize varieties compared to those who were not. In all cases, unfamiliar farmers scored organoleptic preference, yield, pest resistance, earliness and market value higher than familiar farmers, while familiar farmers scored multiple uses higher. We did not find any significant differences in the scoring of water needs, soil fertility requirements, workload, or symbolic importance between familiar and unfamiliar farmers for any of the maize varieties evaluated.

For Bambara groundnut, we found differences in trait scoring between familiar and unfamiliar farmers for one recently introduced variety (B. groundnut 57, known as *oyal usikatika* by Bassari farmers) and two traditionally cultivated varieties that are commonly grown together and that are being abandoned (B. groundnut 53, *oyal obanax*; and B. groundnut 56, *oyal ond yër-yër*). For all three varieties, unfamiliar farmers scored lower their water needs than familiar farmers. For B. groundnut 56 and 57 unfamiliar farmers also scored their soil fertility requirements lower than familiar farmers.

For peanut varieties, we found differences among four recently introduced varieties cultivated in small surfaces (peanut 401, known as *utika cameroun* by Bassari farmers; peanut 403, *utika otëgët ondebetas ofeshax*; peanut 405, *utika otëgët ondebetas ombarax* and peanut 409, *utika undundu opeshax*). Specifically, for peanut 401, unfamiliar farmers scored lower the water needs of the variety than familiar farmers. For peanut 403, 405, and 409, unfamiliar farmers gave higher scores than familiar farmers for earliness, market value, and workload and multiple uses, respectively.

Varieties biocultural traits versus abundance, distribution, and trends

Variety abundance and distribution.

The comparison of biocultural trait scores between predominant and rare varieties shows that different traits are prioritised for varieties across different crops (Supplementary Material 3). In general, predominant varieties had more positive biocultural trait bundles than rare varieties, but–regardless of the crop– predominant varieties did not have better scores than rare varieties for all biocultural traits.

Results from the Wilcoxon test reveal significant differences between predominant and rare varieties for all crops. For maize, sorghum and peanut, predominant varieties scored significantly higher for yield, market value and organoleptic preference compared to rare varieties. In terms of earliness, predominant varieties of maize and Bambara groundnut scored lower, while they scored significantly higher in water needs and soil fertility requirements compared to rare varieties. The opposite was true for peanut. Compared to rare varieties, predominant peanut and sorghum varieties scored significantly higher for dry spell resistance and symbolic importance. Finally, while predominant Bambara groundnut varieties scored significantly higher for pest resistance and workload compared to rare varieties, the opposite was true for peanut varieties (Fig. 7).

Variety temporal trends.

When comparing the biocultural trait scores of varieties that are increasing versus those that are decreasing in cultivation, we find that varieties increasing in cultivation tend to have more positive trait bundles than varieties that are decreasing in cultivation (Supplementary Material 4).

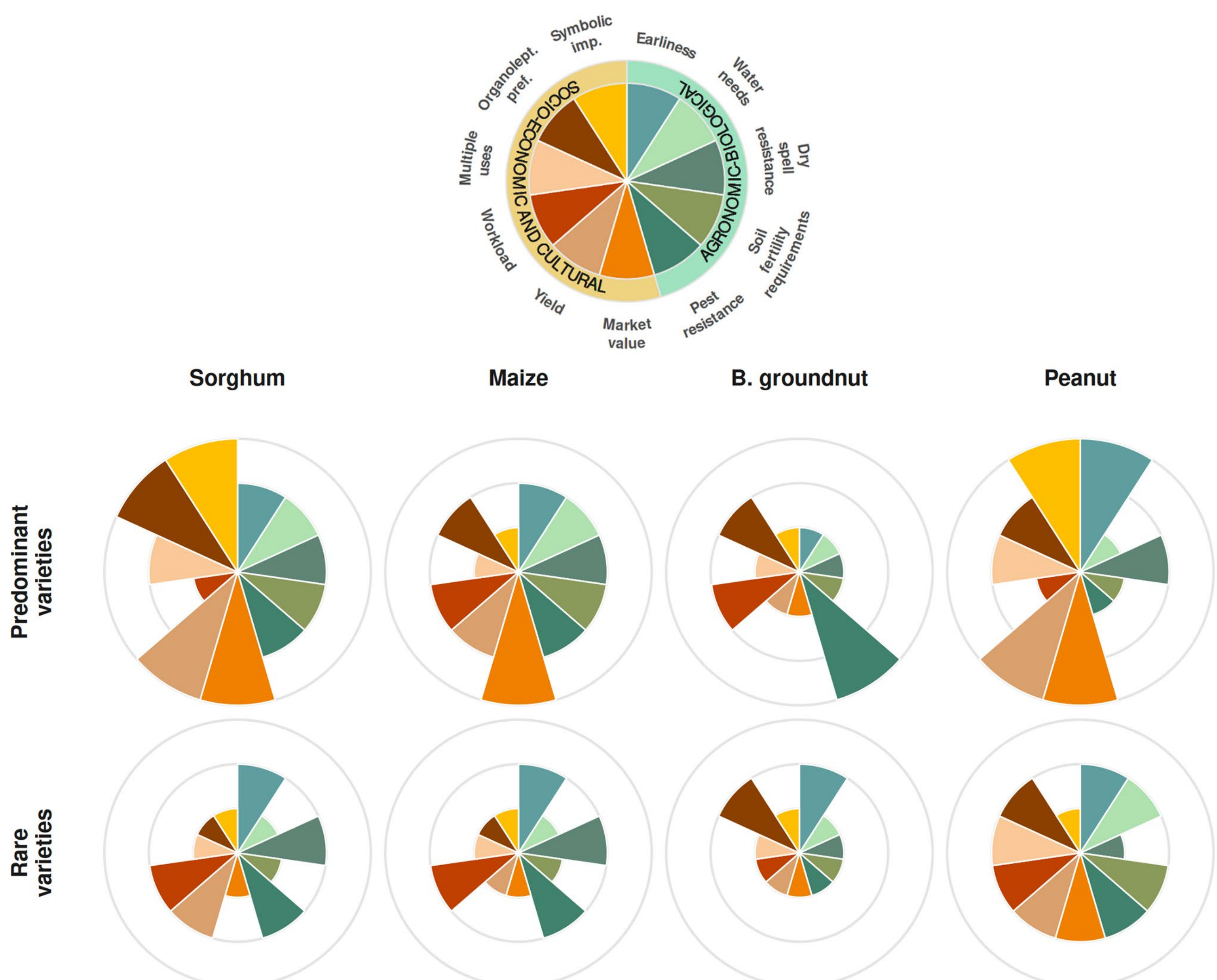

Fig. 7 Flower diagrams illustrating biocultural trait bundles for each crop based on the abundance and distribution of varieties in the case-study community (predominant vs. rare). The length of the petals represents the median score for each trait

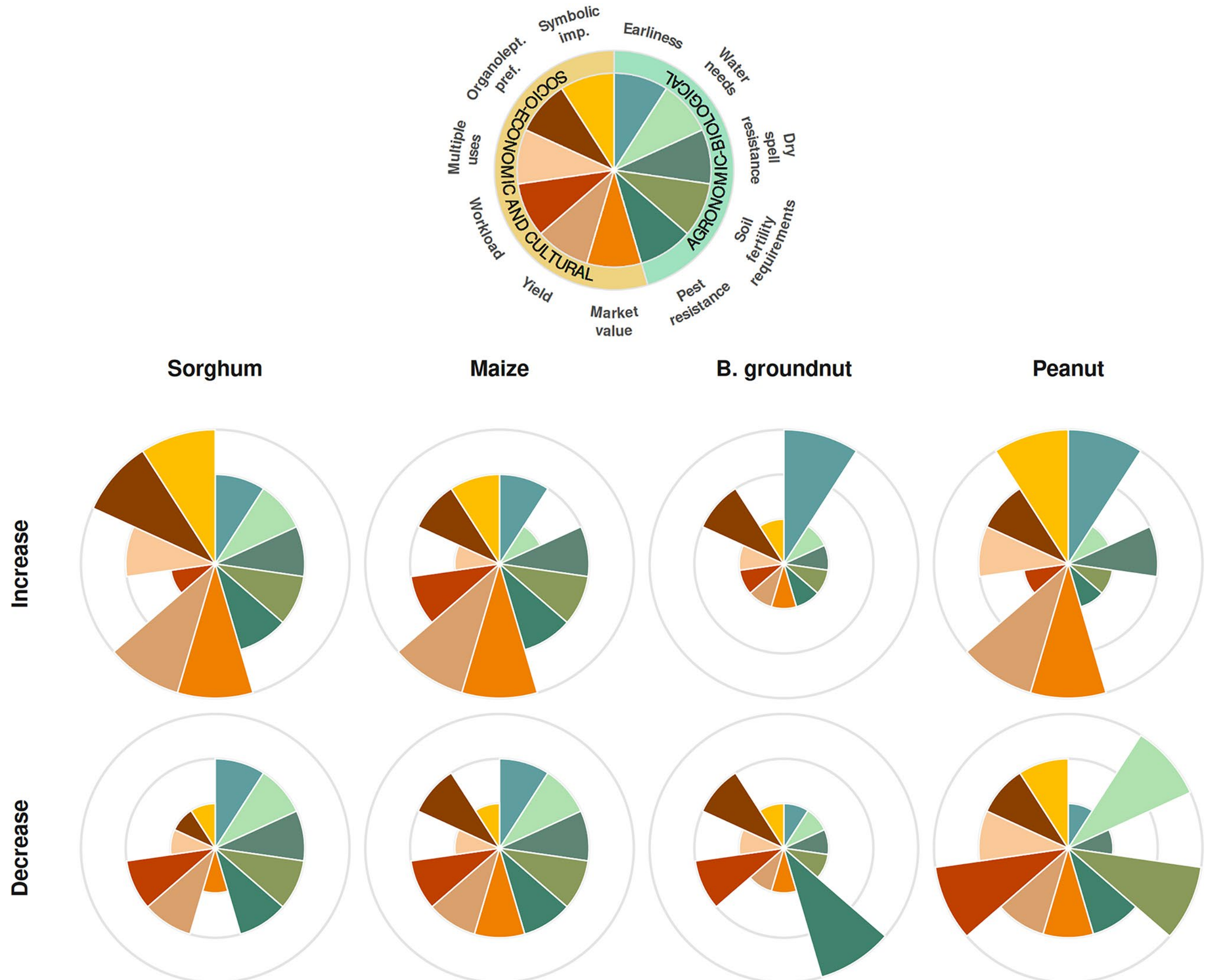

Fig. 8 Flower diagrams illustrating biocultural trait bundles for each crop based on the cultivation trends of varieties in the case-study community (increasing vs. decreasing cultivation). Varieties that were recently introduced or had no clear trend reported are excluded. The length of the petals represents the median score for each trait

Results from the Wilcoxon test show that the patterns of variation in scoring according to cultivation trend are crop specific. Across all crops, varieties that are increasing in cultivation were scored significantly higher for earliness and significantly lower for workload than varieties with a declining trend. Except for sorghum, varieties that are increasing in cultivation were scored significantly lower for water needs than varieties that are decreasing in cultivation. For sorghum, maize and peanut, varieties with an increasing trend were scored significantly higher for dry spell resistance, yield, market value and organoleptic preference. For sorghum, peanut and Bambara groundnut, varieties with an increasing trend were scored significantly lower for soil fertility requirements than varieties with a decreasing trend. Symbolic importance scored significantly higher for sorghum and peanut varieties increasing in cultivation but lower for those of Bambara groundnut. Pest resistance scored significantly higher for maize varieties increasing cultivation but significantly lower for varieties of all other crops showing an increasing trend. Sorghum varieties with an increasing trend scored significantly higher in multiple uses than varieties with a decreasing trend, but the opposite was true for peanut varieties (Fig. 8).

Discussion

Results from this work illustrate the multidimensional nature of farmer-crop interactions. Our findings emphasize the need to incorporate the socio-cultural dimensions of crops, in addition to the commonly examined ecological and agronomic factors, when studying farmers' preferences and the dynamics of local crop diversity. In what follows, we discuss the four main findings of our research, each aligned with one of our specific research objectives.

Farmers' characterization of crop species and varieties combines agronomic, biological, socio-economic, and cultural dimensions

Agronomic and ecological research has focused on understanding crops as biological objects. Crops have functional characteristics, or traits, that through abiotic-biotic interactions affect, not only their role in the agroecosystem, but also the way the agroecosystem functions and the agroecosystem's capacity to adapt to environmental changes (Altieri 1999; Wood et al. 2015). Social sciences' literature, notably ethnobotany and anthropology, has a large tradition of demonstrating that crops are also social and cultural objects. Beyond playing important roles for the functioning of the agroecosystem, crops are also a key part of culture, intricately intertwined with livelihood practices, spiritual beliefs, culinary traditions, medicinal uses, and other material and immaterial functions and needs (Caillon et al. 2017; Garine et al. 2017; Howard 2010; Nazarea 2006).

By building on farmers' multifaceted relations with crops and varieties, our research attempts to operationalize the notion of crops' biocultural traits, which brings together socio-economic and cultural dimensions along with biological and agronomic ones. In line with other literature, our results highlight that organoleptic (Skarbø 2014; Wendmu et al. 2022) and symbolic traits (Caillon and Lanouguère-Bruneau 2005) are important for farmers' variety characterization and preference. Bassari farmers valued those varieties with organoleptic characteristics adapted to local quotidian receipts. For example, certain sorghum varieties were especially valuable for the preparation of sorghum beer (*ngody*), some Bambara groundnut varieties were valued for their quality to make *enap*, and some peanut varieties were valued for having enough oil to make a good *mafe*.

Ethnographic literature has also shown that there are important immaterial dimensions that shape the meaning that a crop or variety has for a particular society (Howard 2010; Salick et al. 1997). The notion of crop biocultural traits accounts for crops' immaterial dimensions by including their cultural and symbolic importance in the repertoire of traits evaluated. Among the Bassari, the symbolic importance of crops was related to their significance in food for ceremonial contexts and to their role in connecting to the collective past and the ancestors. Bassari farmers valued and maintained some varieties because they connected them with their mythological past (e.g., varieties that appeared in their origin myths) or because they represented a souvenir of a trip or a memory of a person. The cultural importance of varieties was tightly related with their organoleptic characteristics. For example, the colour of the grains determined crops' adequacy for certain uses - i.e., peanut varieties with reddish or blackish grains were forbidden for certain rituals or ceremonies but sorghum varieties with reddish grains were valued for the preparation of the sorghum beer. The symbolic importance and organoleptic characteristics of varieties also affected their market value. Interviewees noted that at the weekly market, reddish peanut grains are harder to sell, as this color is either forbidden by the traditions of certain neighboring ethnolinguistic groups or unsuitable for preparing specific traditional dishes.

In sum, even though the biocultural traits identified in our case-study are species- and context- specific, our research sheds light on the myriad of factors relevant for farmers crop preferences and on the limits of the dominant research paradigm that follows a strict agronomic logic. Crop breeding and agronomic evaluation research largely relies on the idea that varieties need to maximize utility, neglecting the diversity of values and experiences that link farmers and their crops, which are often rooted in culture (Demongeot 2023). Our findings show that a focus on agronomic-biological traits alone provides a narrow understanding of the traits that matter to farmers. Our research brings to the fore the importance of looking at farmers crop portfolios in terms of biocultural trait bundles, considering aspects such as the organoleptic characteristics of crops or their symbolic importance in a particular context along with more traditional agronomic aspects such as yield, crop cycle or drought-tolerance in variety characterization and evaluation processes.

Farmers' level of familiarity with varieties influences their scoring of biocultural traits

Ethnobotanical research has advanced the idea that there is a certain level of consensus within a community concerning varieties' naming and basic characteristics (Boster 1984a, b; Reyes-García and Li 2023). This consensus allows communication within the group, which explains why farmers belonging to the same ethnolinguistic community use the same names to refer to the same variety, but names vary across ethnolinguistic groups (Labeyrie et al. 2019; Perales et al. 2005; Wencelius 2016). Research has also shown that, despite this consensus, knowledge is not distributed homogeneously within the same community. Internal norms of decision-making and task-distribution affect how knowledge is distributed. Gender, or other socio-economic aspects at individual or household-level (e.g., farm size), can affect the way crops and varieties are characterised and valued, even within a same ethnolinguistic community (Krishna and Veettil 2022; Mukerjee et al. 2023; Weltzien et al. 2019).

Our results add to this literature by showing that differences among farmers in how they evaluated the biocultural traits of varieties was partly explained by farmer's level of familiarity with the varieties. We also found that differences in trait scorings between familiar and unfamiliar farmers were more likely to occur for newly introduced varieties or for those varieties that were being abandoned than for predominant varieties.

One plausible interpretation of our results is that, for newly introduced varieties, there has not been enough time for farmers to communicate and learn from each other concerning the characteristics and qualities of these varieties. Therefore, only those farmers with first-hand experience cultivating newly introduced varieties have access to knowledge on their management, uses and characteristics. Our ethnographic observations confirm this interpretation, particularly with maize, the crop where we found more differences in biocultural trait scorings between familiar and unfamiliar farmers. Although maize has been a part of the Bassari farming system at least since the 1930s, its cultivation has increased dramatically in recent decades, driven by agricultural development projects that introduced numerous research-improved varieties along with fertilizer and pesticide input packages (Porcuna-Ferrer et al. 2024b). The rapid and recent introduction of new maize varieties likely limited the possibility for knowledge sharing and hindered the integration of new knowledge about them into the collective memory of the community. Conversely, for varieties being abandoned, like the case of the sorghum variety *degaff ilian*, the loss of collective knowledge may explain the higher levels of disagreement between familiar and unfamiliar farmers. As traditional varieties are replaced by new ones, the knowledge associated with them becomes obsolete and gradually fades from the collective memory (Ladle et al. 2023).

Our research opens new avenues for exploring the factors that influence the diversity of crop valuations within a community and how new and old knowledge about crops and varieties is acquired and shared. These insights have important implications for the adaptive capacity of smallholder farming societies worldwide (Fernández-Llamazares et al. 2015; Gómez-Baggethun and Reyes-García 2013; Ibarra et al. 2024; Reyes-García et al. 2014).

Trade-offs in biocultural traits prevent any single crop or variety from meeting all farmers' needs

Agronomic and ecological literature acknowledges that morphologic and physiologic traits are not independent. For example, a plant cannot be efficient in simultaneously maximising vegetative growth and reproduction, or soil cover and yield, because trade-offs exist between different traits that limit the possible combinations and outcomes of plant characteristics (Díaz et al. 2016; Guiguitant et al. 2021). Constraints in plant physiology also prevent a plant from simultaneously being efficient in all conditions, e.g., under severe drought vs. milder conditions (Vadez et al. 2024). In a similar way, our results indicate that no single variety or cultivar maximised all the biocultural traits evaluated, meaning that no single crop or variety could fulfill all the biocultural needs and functions desired by farmers.

For example, varieties more appreciated in terms of organoleptic characteristics or symbolic importance were not necessarily the ones better adapted to local changing climatic conditions. Thus, several varieties valued for their taste or relevance in the Bassari tradition had medium- to long-cycles and were less adapted to the shortening of the rainy season and increasing frequency of dry spells, which are common climate change impacts documented in the case-study region (Porcuna-Ferrer et al. 2023b). Our results, however, also suggest that trade-offs between biocultural traits are difficult to generalise as they are highly crop- and variety- specific. For example, maize short-cycle varieties generally had higher market value than medium- or long-cycle varieties, whereas for sorghum the opposite was true.

It is also important to note that, although our work compares biocultural traits of individual crops and varieties, Bassari households combine the cultivation of several crops and varieties within the same cropping season. Ultimately, our analysis reveals that Bassari farmers navigate trade-offs between biocultural traits, and the cultivation of diverse species and varieties enables them to build a trait portfolio that supports both their livelihoods and well-being. While common trends in trait preferences exist, there are notable interindividual variations in how these trade-offs are balanced and in varietal preferences. These differences likely contribute to the remarkable diversity of crops and varieties cultivated across the study area.

To better understand how farmers articulate trade-offs and complementarities of different crops and varieties, future research should look at the baskets of crops and varieties that farmers cultivate in terms of biocultural trait bundles. Such approach would allow to move beyond understanding the specific trade-offs that exist between the biocultural traits of a particular crop or variety, to understanding the trade-offs that exist between the biocultural traits of those crops and varieties that belong to the same portfolio.

No biocultural trait alone can explain variety abundance, distribution, and temporal trends

Research in other parts of the world has shown that farmers belonging to different ethnolinguistic groups can have very different trait preferences for the same crop species.

These preferences are shaped by the role of the crop within the specific culture and agroecosystem and influence crop dynamics (Diop et al. 2023; Fischer 2021; Labeyrie 2013; Roy et al. 2023; Westengen et al. 2014). For instance, early maturity was not a driving trait for varietal preference and adoption among Mbeere farmers in southern Kenya, whereas it was crucial for the Kunama and Tigrayan ethnolinguistic groups in northern Ethiopia (Wendmu et al. 2022; Timu et al. 2014). In Uganda, sorghum farmers prioritized varieties that were well-suited for making *posho*, a traditional bread, while in Ghana, farmers valued varieties based on their suitability for producing beer and *tuo*, a traditional dish (Andiku et al. 2021; Buah et al. 2010). Our findings add empirical evidence to this body of literature by illustrating that even within the same ethnic group, farmers prioritize different biocultural trait bundles depending on the specific local role(s) and function(s) of the crop species or variety.

For example, our findings reveal that even though peanut and Bambara groundnut occupy similar positions in the traditional Bassari crop rotation and in the local agroecosystem, there are important differences in the biocultural traits characterising their predominant varieties. Predominant peanut varieties exhibited higher market value, but lower pest resistance compared to rare varieties. In contrast, for Bambara groundnut, predominant varieties had higher pest resistance, but there was no significant difference in market value between predominant and rare varieties as market value was scored low for both. These differences suggest that despite their similar ecological functions, the selective biological and cultural pressures shaping the dynamics of these crops may differ. The distinct biocultural roles that peanut and Bambara groundnut play among the Bassari, influenced by their divergent socio-economic histories, likely contribute to explain these differences (Porcuna-Ferrer et al. 2024b). Peanut has been a motor of economic development for Senegal and is abundant in local markets (Bernards 2019). Farmers often sell big shares of their peanut harvest and repurchase peanuts in the market during the lean season. This strategy mitigates the risk of on-farm storage losses due to pests, while capitalizing on the market value of varieties. In contrast, Bambara groundnut has no presence in the local market due to Bassari traditions discouraging its sale, with all grain storage occurring exclusively on-farm. This likely explains why market value is consistently scored low across all Bambara groundnut varieties, while pest resistance is a key trait among the predominant varieties.

Our results further suggest that understanding the biocultural traits that farmers use to characterise and value varieties can help understand the dynamics and main drivers affecting smallholder farming systems. For instance, previous research in other regions of Senegal has shown that farmers often adopt short-cycle varieties to adapt to climate change (Lalou et al. 2019; Ruggieri et al. 2021; Sultan et al. 2015). However, our findings reveal that while climate-adaptive traits (i.e., earliness of the variety, dry spell resistance) are significant in explaining variety adoption trends among Bassari farmers, other traits, such as market value, symbolic importance or organoleptic preference, are equally, if not more important, as shown by their scoring among predominant varieties. Bassari farmers adopt short-cycle varieties to meet subsistence and cash needs in a drying climate, while maintaining the cultivation of long-cycle varieties for ceremonial and ritual purposes. These results are in line with the literature that highlights that smallholder farming systems are affected by a multiplicity of drivers and that to navigate change, farmers balance in their decisions trade-offs and synergies between different factors, e.g., market vs. rainfall (Caviedes et al. 2023; Dempewolf et al. 2023; Galappaththi and Schlingmann 2023; Ibarra et al. 2019; Labeyrie et al. 2021; Marchant Santiago et al. 2023).

Our results also show that the biocultural traits of varieties are not static but evolve in response to changing conditions. For example, sorghum variety 21 (*degaff ilian*), once widely cultivated, is now being increasingly abandoned, partly due to its long-cycle, which prevents it from reaching full maturity as the rainy season shortens. In its place, sorghum varieties 22 and 23 (*degaff xamere*) have taken over in fields, kitchens and ceremonies. Initially, elders did not permit the use of *degaff xamere* in ritual practices, but this has changed, and *degaff xamere* is now recognized as having similar symbolic importance to *degaff ilian*. This shift illustrates how symbolic values can evolve to adapt to new constraints.

Overall, our study shows that there is a wide set of biocultural traits that guide Bassari farmers crop preferences. Cultural variables, so far neglected in most agricultural research, play an important role in farmers' decision making. Aspects such as the preparation of traditional foods or the celebration of ceremonies are important factors driving the maintenance and cultivation of diverse crop portfolios. However, the multiple changes taking place in the local farming system, including an increasing market integration and climate change, are also shifting the bundle of biocultural traits prioritized by farmers in their crop and variety portfolios. Building on the literature that argues that diversification at landscape, crop species, and variety levels is important to support the sustainability of farming communities (Abson et al. 2013; Cabell and Oelofse 2012; Caviedes et al. 2024; Renard and Tilman 2019), we argue for the importance of considering diversity also at the trait-level.

Finally, our findings underscore that while inter- and transdisciplinary approaches are essential for achieving a more comprehensive and holistic understanding of farmer-crop interactions, they are not enough. Integrating farmers' priorities is critical for understanding crops biocultural traits and crop diversity dynamics at the local level. Better accounting for farmers preferences, which reflect their way of knowing and being, enables more situated and comprehensive understandings, moving beyond disciplinary perspectives (Caviedes et al. 2023; García del Amo, 2022; Reyes-García et al., 2024; Orlove et al. 2023). Shifting from inter- and transdisciplinary approaches to inter-epistemological approaches involves embracing ontological pluralism, which can help envisioning more just and equitable research and development in crop diversity (Bezner Kerr and Wynberg 2024).

Conclusion

Integrating the complexity of crops biological and socio-cultural dimensions is key to ensure that crops and varieties are adapted to local agroecosystems while also satisfying the myriad of farmers' needs. Our study shows the importance of considering cultural traits along with ecological and agronomic traits to understand the way farmers characterize and value varieties. For that, we operationalize the notion of biocultural traits and relate the abundance, distribution and temporal trends of varieties with their bundle of biocultural traits. By enabling a deeper understanding of farmers' concerns and priorities, the notion of biocultural traits can warrant more inclusive and horizontal processes of variety selection and evaluation and better target crop diversity conservation efforts, crop breeding programs, or climate change adaptation policies to respond to criteria and needs that are not only relevant to researchers and policymakers, but also to local populations.

Ethics statement

Prior to data collection, we obtained free prior informed consent from the local authorities at village and regional levels, as well as from each individual participating in the research. This research was approved by the Ethics Committee of the Universitat Autònoma de Barcelona (CEEAH 4903) and follows the recommendations of the International Society of Ethnobiology Code of Ethics (ISE 2006).

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10460-025-10725-0.

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