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Characteristics and socioeconomic performance of neglected and underutilized plant species (NUS) production systems in Burkina Faso

Quanli Wang[1,*], Eric Brako Dompreh[1,2], Blandine Marie Ivette Nacoulma[3], Miyuki Iiyama[4], Kangbéni Dimobe[3,5], Mohammad Naushad Emmambux[6], Mame Samba Mbaye[7], Adjima Thiombiano[3] and Alexandros Gasparatos[1,*]

1 Institute for Future Initiatives (IFI), The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8654, Japan
2 WorldFish, Jalan Batu Maung, Penang 11960, Malaysia
3 Laboratory of Plant Biology and Ecology, University Joseph Ki-Zerbo, 03 B.P. 7021, Ouagadougou, 03, Burkina Faso
4 Information Program, Japan International Research Center for Agricultural Sciences, 1-1 Owashi, Tsukuba 305-8686, Japan
5 Département de Eaux, Forêts et Environnement, Institut des Sciences de l'Environnement et du Développement Rural (ISEDR), Université Daniel Ouezzin Coulibaly, BP 176, Dédougou, Burkina Faso
6 Department of Consumer and Food Sciences, Faculty of Natural and Agricultural Sciences, University of Pretoria, Pretoria 0028, South Africa
7 Laboratory of Botany and Biodiversity, Department of Plant Biology, Faculty of Science and Techniques, Cheikh Anta DIOP University, B P 5005 Dakar-Fann, Senegal
* Authors to whom any correspondence should be addressed.

E-mail: wang.quanli@outlook.com and gasparatos.alex@gmail.com

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Abstract

Agricultural systems in Sub-Saharan Africa (SSA) are often characterized by low agrodiversity and high vulnerability to climate change, both of which can compromise food security and livelihoods. Many neglected and underutilized plant species (NUS) are known for their nutritional value and climate resilience, presenting a potential solution to conserve agrodiversity and contribute to local livelihoods and food security. However, NUS is commonly used as an umbrella term, obscuring potential differentiation between NUS systems in terms of their characteristics and socioeconomic performance. Here we characterize NUS production systems in three regions of Burkina Faso, a country experiencing food insecurity, poverty and arid and semi-arid climatic conditions, where many local communities rely on NUS for their food and livelihoods. We conducted 432 in-person surveys with households cultivating NUS on farms and/or collecting from the wild. Using principal component analysis and hierarchical clustering analysis we identify three distinct NUS production systems: NUS cultivation on farms predominantly for market sales (Cluster 1), NUS collection from the wild predominantly for market sales (Cluster 2), and NUS collection from the wild predominantly for self-consumption (Cluster 3). Through propensity score matching we identify that households in Cluster 1 had better socioeconomic performance compared to the other two clusters across all five income and food security variables considered here. However, there are no significant differences in the socioeconomic performance of Clusters 2 and 3. Our results indicate that: (a) NUS systems are not homogenous but can have a high degree of differentiation; (b) NUS are not solely emergency resources during severe food insecurity periods, (c) many NUS producers exhibit strong market orientation. Such findings can provide nuance in the current debates on whether and how can NUS provide promising alternatives to the other more widely produced crops in SSA.

1. Introduction

Food insecurity is a major sustainability challenge facing Sub-Saharan Africa (SSA), especially in its arid and semi-arid areas [1]. Accelerated climate change constraints the ability of agricultural systems that over-rely on few crops promoted during the Green Revolution (e.g. maize, rice, wheat) to deliver the food necessary for the rising population [2]. This is partly because agricultural systems characterized by low agrodiversity and dominance of a few crops (e.g. maize) tend to be highly vulnerable to climate change [3]. These environmental realities are compounded by the generally low agricultural productivity, endemic rural poverty, and restrictive land use policies to further constraint the sufficient production of food crops at the yields necessary to cater for the growing food needs of the equally growing population [1, 4]. Massive and coordinated effort would be needed to tackle food insecurity and malnutrition in an environmentally and socially sustainable manner [5, 6]. There is no single solution to this complex interface of food security, climate change, agrodiversity decline and rural livelihoods, but diverse and context-specific responses would be needed [1, 5, 6].

One possible response is to leverage the potential of diverse neglected and underutilized plant species (NUS) that are climate-resilient and nutrient-rich [3, 7, 8]. Although there is no universally accepted definition for NUS, the term 'neglected' generally underscores the limited research investment compared to major crops and the term 'underutilized' generally points to their untapped livelihood potential [9]. Very diverse plant species can fall under this umbrella term of NUS including '*wild, semi- or fully domesticated plants from various food groups (cereals, vegetables, legumes, roots and tubers, fruits, spices) with diverse growth forms (field crops, trees, shrubs, vines, etc.)*'[9].

Many NUS are well-adapted to the challenging climatic conditions of arid and semi-arid SSA, showing potential for mitigating food insecurity and rural poverty in the context of climate change [3, 10]. There have been calls to enhance NUS production and utilization across SSA given their high potential to contribute to nutrition, climate change adaptation and agrodiversity conservation [11, 12]. The African Orphan Crops Consortium, for example, has created a database of >100 NUS in SSA that should be the focus of extensive research [13]. National and international efforts have sought to enhance NUS production and utilization, including by providing planting material, developing improved seed varieties, offering education and training (e.g. related to nutrition, production, trading), and generally developing NUS markets [3, 14–16].

However, NUS have only rarely increased their relevance beyond the rural production and harvesting areas or successfully penetrated larger markets (e.g. in cities) [17]. Strengthening NUS value chains is very challenging not the least due to the general lack of understanding about the characteristics, capabilities, needs and preferences of small-scale NUS producers, as well as the very diverse barriers hindering their integration in commercial food systems [17–19].

Arguably, underlying factors constraining NUS production are the substantial knowledge gaps about the (a) agronomic properties of promising NUS, (b) characteristics of NUS production systems, (c) factors influencing household engagement in NUS cultivation/harvesting, and (d) socioeconomic performance of NUS systems. Despite the aforementioned calls for expanding NUS production [3, 17, 18], the current literature has generally failed to provide a clear picture of the actual characteristics and performance of NUS production systems. Furthermore, NUS is often used as an umbrella term in debates comparing them to Green Revolution crops (e.g. maize, wheat, rice), which has arguably created room for some generalizations about their low productivity and marketability, limited income generation potential, narrow production/collection periods (e.g. during low food security periods), and limited importance within household livelihood strategies (e.g. secondary activity to enable self-consumption). However, NUS encompasses very diverse species and production models. Although some studies have alluded to the large diversity of NUS production systems [18, 20], few have provided a clear picture of the differentiation between NUS production systems and their comparative performance.

Burkina Faso is an ideal context to explore NUS system differentiation due to its challenging climatic conditions and relatively undiversified economy that is heavily reliant on small-scale, subsistence-based and rainfed agricultural production (box S1, supplementary material). Agricultural systems are dominated by cotton and food crops promoted during the Green Revolution, and are vulnerable to droughts, rainfall variability, market price fluctuations, and political instability [21]. In this challenging context many local communities have been relying on NUS cultivated on farms and/or collected from the wild [21]. Various policies have promoted NUS but these efforts have been fragmented due to significant knowledge gaps [22].

The aim of this study is to unravel the differentiation in the characteristics and performance of NUS production systems in Burkina Faso. We conducted 432 in-person surveys at the Center and Southwest regions with households that cultivate NUS on farms and/or collect NUS from the wild. We used a combination of principal component analysis (PCA) and hierarchical clustering analysis (HCA) across ten variables to unravel differentiation in NUS systems, and propensity score matching (PSM) to compare their socioeconomic performance.

2. Materials and methods

2.1. Study site

Burkina Faso is a landlocked country situated in West Africa, spanning three main climatic zones: Sahelian, Sudan-Sahelian, and Sudanian zones, from north to south. Much of the country receives very little rainfall and experiences marginal conditions for agriculture. The El Niño Southern Oscillation (ENSO) influences year-to-year climatic variability and extreme weather events such as heatwaves, floods and droughts [23].

The country relies on an underperforming agricultural sector, dominated by cotton production, for food and livelihood (box S1, supplementary material). A large fraction of food crops come from small-scale farming operations characterized by small plot sizes (3.19 ha on average, table S1 supplementary material), use of unimproved production technologies, lack of supporting environment, low market orientation, and high levels of food self-consumption [24]. Crop production is highly vulnerable to challenging and changing environmental conditions such as soil degradation, erratic rainfall patterns, and accelerating climate change [3]. The significant decline in agrodiversity (e.g. sorghum diversity) has been linked to the switch to crops such as cotton, maize and other crops promoted during the Green Revolution, as well as rainfall decrease and soil degradation [25].

In many parts of the country rural households rely on NUS for their livelihoods [26], often complementing the cultivation of standard food crops such as maize [21]. Despite overseas development assistance projects aiming at building capacity, raising awareness, and creating NUS value chains [26], the policy framework is fragmented and the NUS value chains remain rather weak [22].

We conducted research in rural areas with high NUS prevalence and use, whether cultivated on farms (e.g. cereals, tubers) or collected from the wild (e.g. wild fruit). The main selection criterion for the study areas was to identify locations with both prevalence and actual use of NUS, whether cultivated on farms, collected from the wild or both. This reflects the aim of this research which is to unravel the differentiation in the characteristics and performance of NUS production systems, rather than to explore the characteristics and performance of specific species or compare areas.

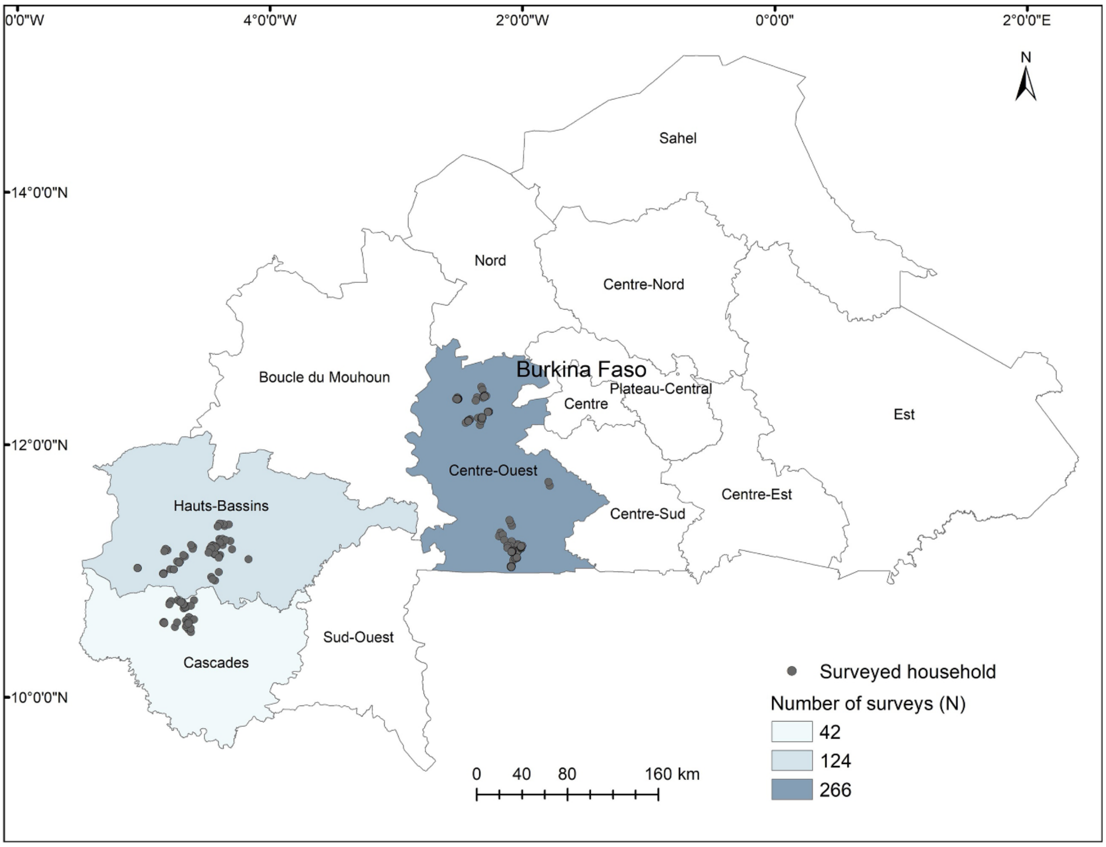
Considering the lack of comprehensive lists of NUS producers (e.g. from the Ministry of Agriculture), we identified the study areas following a three-step process. First, we identified promising broad study areas (i.e. at the region and province level) through species distribution maps generated from the West African plant database [27], NUS samples from the *herbarium* collections of the University of Ouagadougou (OUA) and the outputs of other relevant research activities where team members previously engaged. Second, we cross-referenced the identified broad study areas with other evidence from the aforementioned sources, literature, and discussions with external experts to ensure that the NUS were not simply present in the those areas but were also actually used by the local communities. We eliminated areas in the northern part of the country (which falls in the Sahelian agroecological zone) due to security concerns, ending up with areas in the three study regions Centre-Ouest, Hauts-Bassins, and Cascades (figure 1). Third, through focus group discussions (FGDs) in each region with relevant stakeholders including farmers, government officers, and academics we identified specific study sites and communities characterized both by NUS prevalence and actual use by local communities.

Overall, the study regions exhibit average levels of development and poverty within Burkina Faso (table S2, supplementary material), which are nevertheless much lower compared to global or SSA standards [28, 29]. All regions are characterized by an arid climate, experiencing low annual rainfall and extended dry periods (figure S1, supplementary material). Hauts-Bassins and Cascades fall largely in the Sudanian zone, while Centre-Ouest mostly in the Sudano-sahelian zone. Most of the population in these regions is rural and engaged in agriculture. Common food crops in all areas include maize, sorghum, millet, rice, and groundnuts, while cotton is mainly produced in Hauts-Bassins (see crop seasonality in figure S1, supplementary material). Average land sizes in Hauts-Bassins and Cascades are comparatively larger (5.64 ha and 5.84 ha respectively) than Centre-Ouest (2.48 ha), with the average land size for Burkina Faso being 4.72 ha (table S1, supplementary material).

2.2. Data collection

Primary data were collected through an in-person household-level structured questionnaire, consisting of six modules: (a) household characteristics, (b) farm characteristics and output, (c) NUS cultivation and harvesting from wild, (d) NUS perceptions, (e) income and expenditure, and (f) food security. These modules mostly contained closed-ended questions. The survey was designed to reduce to the extent possible recollection challenges from respondents (box S2, supplementary material). The survey was refined through pre-testing and feedback from FGDs and expert consultations conducted to inform site selection (section 2.1).

Data collection was undertaken through in-person interviews with households engaged in NUS cultivation on farms and/or harvesting from the wild. Households were selected through transect walks in the study communities. This was due to the absence of a comprehensive database on NUS production in Burkina Faso, both in terms of species and areas,



Characteristics	Study Regions		
	Centre-Ouest	Hauts-Bassins	Cascades
Population (N)	1,659,339	2,238,375	812,062
Rural population (%)	83.60	54.23	80.57
Area (km^2)	21,726	25,343	18,434
Annual rainfall (mm/yr)	520-570	910-950	850-920
Days with no rain (days/yr)	314	273	274
Human Development Index (HDI) in 2022	0.429	0.469	0.453
Number of surveys (N)	266	124	42

Figure 1. Study areas and characteristics of study regions in Burkina Faso. *Source*: The World Bank [29].

as well as the general fragmentation of NUS-related activities [22] (see limitations in box S2, supplementary material).

The survey was conducted from 10 August to 5 October 2023. In total 432 household surveys were collected in French across all study areas (figure 1) by trained enumerators. The respondents participated in the survey after providing oral consent. The collected data was digitized on tablets using the *Kobotoolbox* platform, uploaded daily, and checked by the first author for quality and completeness. Feedback was communicated as needed to the enumerators to ensure the consistency and quality of the survey.

2.3. Data analysis

2.3.1. NUS prevalence and perceptions

Descriptive statistics were used to identify the prevalence of and perceptions for different NUS (section 3.1). For each NUS we assessed 25-26 individual perception statements, spanning five major categories, namely food security, livelihoods, crop characteristics, cultivation/harvesting characteristics, and support mechanisms (section 3.1). The perception categories and individual statements were identified through the critical reading of the literature and their relevance was confirmed during the FGDs and pre-testing of the survey. The perceptions were elicited using a 5-point Likert Scale (1 = strongly disagree; 2 = disagree; 3 = neither agree nor disagree; 4 = agree; 5 = strongly agree), and visualized with bar charts. Full perception statements are provided in table S3 (supplementary material). All perceptions are for NUS cultivated/collected by the household and not for NUS purchased from the market.

2.3.2. Characterization of NUS systems

For the NUS system characterization (section 3.2) we used ten variables related to NUS production systems (table 1). The selection of these variables was informed by a literature review and expert

Table 1. Variables used for NUS system characterization and socioeconomic performance assessment.

Variable	Unit
Variables for NUS system characterization	
Number of NUS collected	Number
Number of NUS cultivated	Number
Share of NUS-related income in total household income	%
Share of NUS self-consumption to total NUS cultivation/collection	%
Number of months for NUS collection	Months
Perceived NUS importance for household livelihoods	Average score (1–5)
Farm size	ha
Years of agricultural experience	Years
Credit access	Yes = 1, No = 0
Farming group membership	Yes = 1, No = 0
Variables for socioeconomic performance	
NUS income	USD yr^{-1}
On-farm income	USD yr^{-1}
Household income	USD yr^{-1}
Food consumption score (FCS)	Score
Months of food insufficiency	Number
Household characteristics	
Age of household head	Years
Gender of household head	% of male
Education of household head	Years
Household size	Number

Note: The methods for the estimation of socioeconomic performance variables is included in box S3 (supplementary material).

consultations and aimed at covering critical aspects of NUS production systems. The ten variables reflect four key dimensions of food production systems, namely (a) inputs, (b) markets and consumption, (c) management and institutions, (d) agrodiversity and diversification. These dimensions have been identified as very pertinent for delineating the characteristics and/or developing typologies of small-scale food systems [30–32].

We employed a combination of PCA and HCA [31, 33, 34]. These techniques are well-documented for their ability to identify differences among farmers engaged in different agricultural activities [31, 35].

First, we normalized the scores of the ten variables, considering that they have different units. This normalization process essentially helped standardize the analysis. Normalization was performed using the *scale* function of R version 4.3.2.

Second, we conducted the PCA to distill the dominant characteristics of these variables into principal components (defined as linear combinations that capture the maximum variance across the dataset) (figure S2, supplementary material) [34, 36]. For the PCA we used the R-package *FactoMineR* [37]. Using the elbow method, we identified the principal components, i.e., the variables responsible for causing a distinct change (elbow point) in the slope of the explained variance ratio (figure S3(a), supplementary material) [36].

Third, we conducted the HCA using the five variables with the highest quality of representation identified through the PCA (figure S3(b), supplementary material). The analysis was conducted using the R-package *dendextend* [38]. We employed Euclidean distance and Ward's method to minimize the accumulated error in the sum of squares (variance) that arises from clustering [39]. The optimal number of clusters was identified using the elbow and average silhouette methods to ensure robust cluster differentiation (figure S4, supplementary material). The elbow method involves plotting the variance explained by different numbers of clusters and identifying the elbow point, where the rate of variance after decreasing sharply it levels off, suggesting an appropriate cluster count for analysis or model training [36]. The average silhouette method determines the optimal number of clusters by finding the value that maximizes the average silhouette score, reflecting the best cluster cohesion and separation [40]. We conducted one-way ANOVA tests for the five clustering variables to test whether the identified clusters accurately reflect radically distinct NUS production systems.

Finally, to better understand the differentiation between clusters, we compared between clusters (a) periods of perceived climatic events and food insufficiency, (b) periods of NUS collection and harvest, (c) energy consumption from different NUS, and (d) income from sales of different NUS. Box S3 (supplementary material) outlines how each variable was estimated.

2.3.3. Socioeconomic performance of NUS systems

We assessed the socioeconomic performance of the identified NUS production systems (section 3.3) across five variables that cover the livelihoods and food security status of households. Livelihood-related variables include NUS income (in USD), on-farm income (in USD) and total household income (in USD)[8]. Food security variables include the food consumption score (FCS) (a composite measure of food diversity) (table S4, supplementary material) and the number of months without adequate food. Box S3 (supplementary material) outlines how each variable was estimated.

When comparing socioeconomic performance between clusters we must account for potential confounding effects due to demographic and socioeconomic household characteristics. In other words, although we differentiate NUS production systems through PCA and HCA (figures S2–S4, supplementary material), the actual differences in livelihood and food security levels between clusters may be affected by potential confounding linked to education, farm size or agricultural experience. To overcome this, we applied PSM analysis, which enables group comparison under similar observable characteristics (covariates). The PSM has been used in many studies of food production systems including agriculture [41] and aquaculture [42] to address potential confounding from household and farm characteristics.

We considered the following confounding variables: age of household head (years), gender of household head (dummy variable), education of household head (years), household size (number of persons), agricultural experience (years), farm size (hectares), credit access (dummy variable), and farm group membership (dummy variable). The PSM analysis was conducted with the R-package *MatchIt* [43].

We applied a 0.1 caliper width of each propensity score standard deviation in the nearest-neighbor approach, as this width was shown to optimize the absolute standardized mean difference compared to other technical options (figure S5, supplementary material). An absolute standardized mean difference of less than 0.1 is considered indicative of better matching between groups. Through the PSM approach, the distribution of propensity score seems to be balanced between the comparison clusters (figure S6, supplementary material). After the PSM approach, we conducted a T-test on socioeconomic performance variables between the comparison clusters.

3. Results

3.1. NUS preferences and perceptions

Eight NUS were collected and/or cultivated by the study households (figure 2). The NUS collected from the wild were mainly wild plants and fruits: weda (*Saba senegalensis*) (35.3%), balanites (*Balanites aegyptiaca*) (19.5%), African orange (*Strychnos spinosa*) (16.2%), sweet detar (*Detarium microcarpum*), and jujube (*Ziziphus spp.*). The NUS cultivated on farms were fonio (*Digitaria exilis*) (21.1%), taro (*Colocasia esculenta*) (16.8%), and souchet (*Cyperus esculentus*) (10.2%). Table S5 (supplementary material) summarizes the characteristics of each NUS.

NUS collection from the wild and/or harvesting from farms was not concentrated on a specific season but spanned different times of the year (figure 3). NUS collection and harvesting did not generally occur during the high food insecurity and low rainfall months (August–September) (section 3.2), with the exception of fonio and taro whose main harvest is in early autumn and late summer respectively.

We observe certain similarities and differences in producers' perceptions of the five NUS collected from the wild (figure 4). Perceptions over NUS characteristics were mixed, with most respondents perceiving them as nutritious, tasty, and good for diet diversification, but generally not filling (expect balanites and African orange) and lacking medicinal properties and importance for local culture. Perceptions about their collection and preparation characteristics varied. The NUS collected from the wild were uniformly perceived as having good tolerance to extreme events, but the perceptions over their collection, preparation and scarcity varied substantially between species. Notably, adult women and girls were primarily responsible for the collection of all five NUS within their respective households (figure S7, supplementary material). Perceptions about the contribution of these NUS for food security were mixed. Most respondents perceived NUS collected from the wild as important food sources during collection periods (which spans many months for most; figure 3) but not as important food sources throughout the year or during food insecurity periods (since collection periods are mostly outside food insecure months; figures 3 and 8(b)). Furthermore they were rather willing to collect and consume these NUS even when having sufficient food. Similarly, some collected NUS were perceived as important income sources during collection months, but not for the rest of the year, and respondents were often indifferent or unsatisfied with their selling price (except sweet detar). This is also reflected in that despite the existence of markets for NUS collected from the wild, respondents agreed about the lack of policy support or advocacy to improve value chains (figure 4).

We observe rather different perceptions for the cultivated NUS compared to collected NUS (figure 5). In terms of NUS characteristics and production/-preparation characteristics, most households reported that cultivated NUS offered nutritional and diet diversity benefits and were important for local

[8] The different income streams were captured in West African CFA francs (XOF) and were transformed in USD using the following exchange rate: 1 USD = 623.91 XOF in 2022.

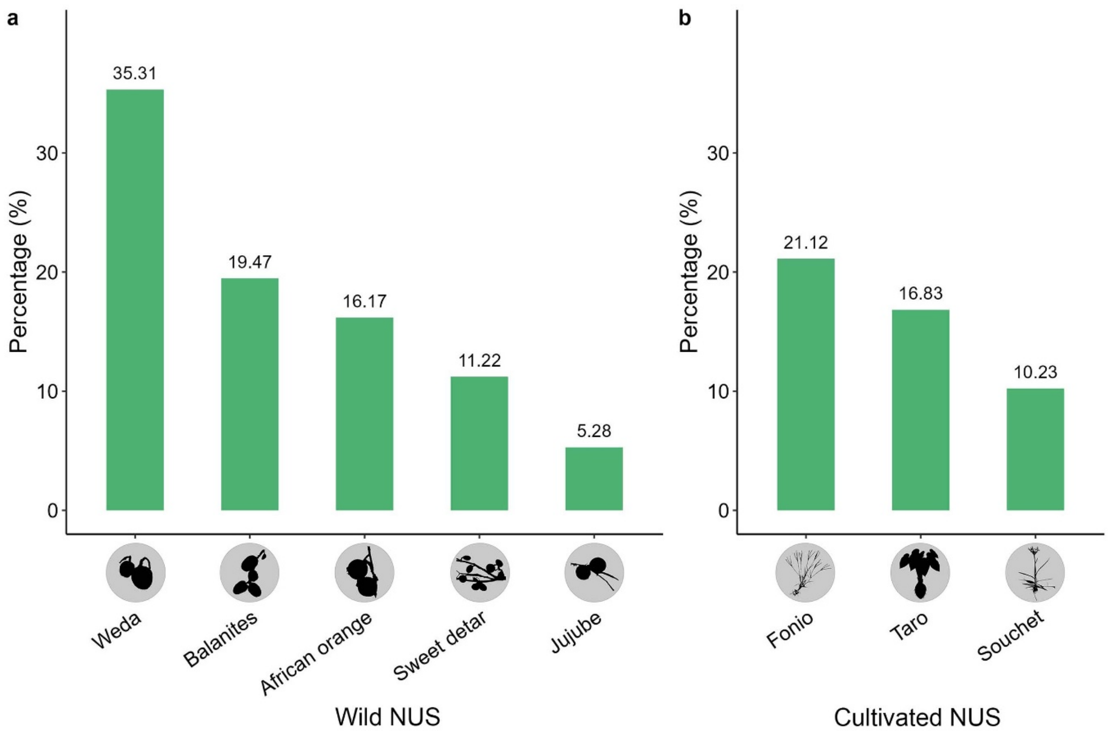


Figure 2. Types of NUS and fraction of households engaging in collection from the wild (panel (a)) and cultivation on farms (panel (b)).

culture, but also noted that their cultivation was challenging, possibly due to sensitivity to extreme weather conditions. Fonio was considered as an important food source throughout the year, while taro was mostly important during the harvesting period (which starts at the tail-end of the food insecurity period; figure 3). Fonio and souchet were perceived as good income sources throughout the year (incl. during periods of food and income scarcity) rather than only during the harvesting period, with households generally satisfied with income from sales. This is likely associated with the generally higher perceived support from policies or advocacy initiatives compared to NUS collected from the wild.

3.2. Characterization of NUS systems

The PCA suggests that the first two dimensions explained 76.5% of the total variance, indicating a strong representation of the data by these components (figure S2, supplementary material). In order of highest loadings (i.e. quality of representation) the five variables used for the HCA were: (a) number of NUS cultivated, (b) number of months for NUS collection, (c) number of NUS collected, (d) perceived NUS importance for household livelihoods, (e) share of NUS self-consumption to total NUS collection/cultivation (figure S3(b), supplementary material). The HCA indicates that the optimal number of clusters was three (figure S4 supplementary material), which implies three rather distinct clusters (i.e. NUS systems in our case) (figures 6, 7, and figure S8, supplementary material).

Cluster 1 is oriented towards NUS cultivation on farms for sale in markets. Approximately 75.0% of NUS harvest was directed towards sales in commercial markets, with the generated NUS income accounting for a sizable proportion (24.9%) of total household income, which is higher than the other two groups (figure 7). Thus NUS had significantly higher perceived importance for household livelihoods (2.81 points on a 5-level Likert scale) compared to other groups (figure 7).

Cluster 2 is oriented towards NUS collection from the wild for market sales. Practically no household in this cluster reported NUS cultivation (figure 6). Producers invested on average 2.9 months for NUS collection, the highest period among groups (figure 7). Approximately, 96.0% of the NUS collected from the wild was geared towards market sales, accounting for a sizable portion (18.4%) of total household income. Overall, NUS had relatively high perceived importance for household livelihoods (2.15 points on a 5-level Likert scale).

Cluster 3 is oriented towards NUS collection from the wild for household self-consumption. Practically no household in this cluster reported NUS cultivation (figure 6). Producers collected on average the most NUS species than other groups, investing a substantial amount of time for collection (2.8 months) (figure 7). Approximately 96.1% of the collected NUS

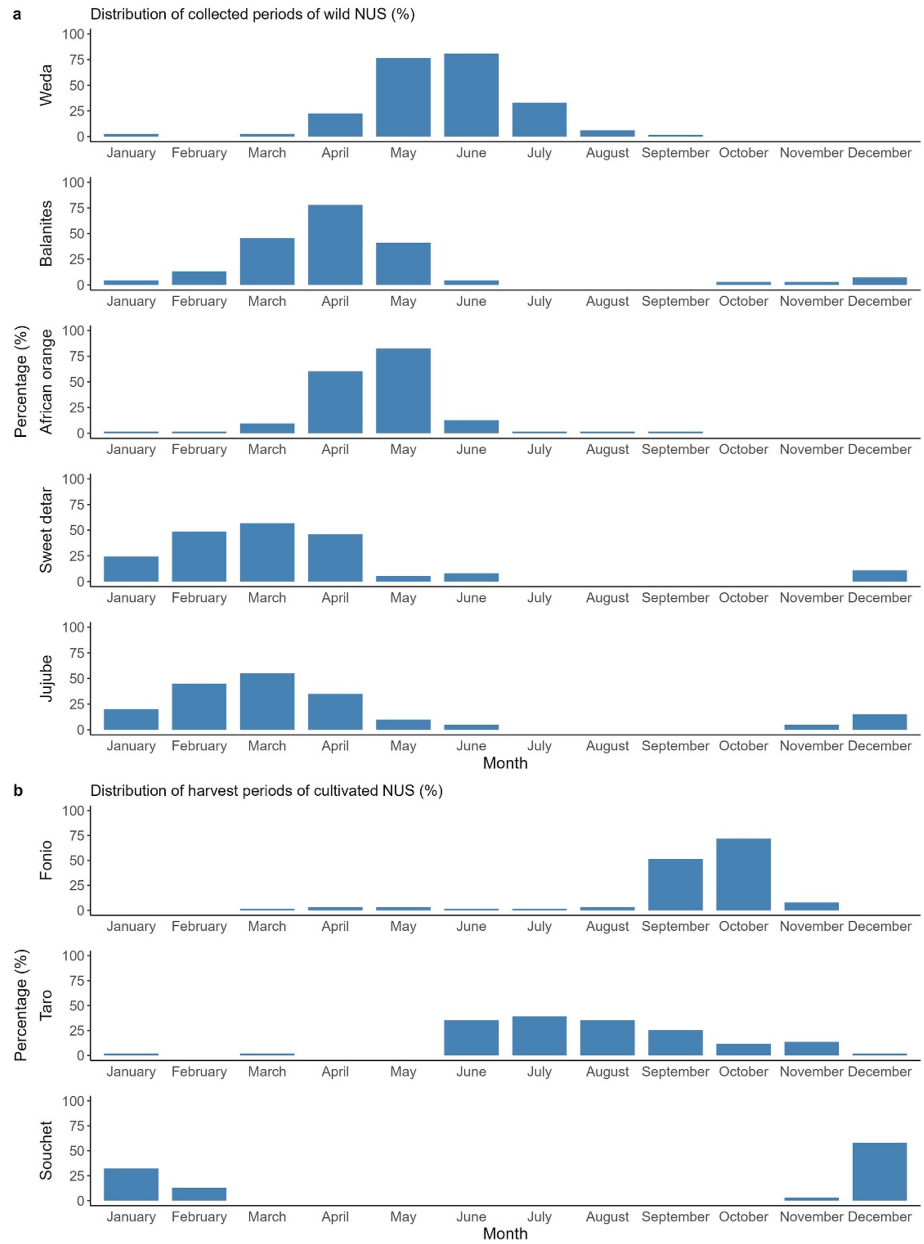


Figure 3. Fraction of households that engage in NUS collection from the wild (panel (a)) and NUS harvesting in farms (panel (b)) by month of the year. Fractions are estimate on the basis of those households that collect or harvest the specific NUS and not on the basis of the entire sample ($n = 432$). For any individual NUS, bars do not add up to 100% across all collection/harvest months, as households often collect or harvest NUS over multiple months.

was used for household self-consumption (figure 6), with NUS income accounting for a mere 3.9% of total household income (significantly lower than the other groups; figure 7). This cluster is also characterized by smaller farm sizes and lower farm group membership (though not always significant, figure 7), further suggesting that NUS is an important supplement for households' food needs.

A sizable fraction of the households in Clusters 2 and 3 reported that climatic events disrupted their livelihoods and food sufficiency between July and September (figures 8(a) and (b)). Interestingly, a similar fraction of Cluster 1 households reported food insufficiency for July and August, but declined sharply for September (figure 8(b)) when fonio harvesting starts (figure 3). This suggests that NUS collection from the wild did not provide any tangible benefit in fulfilling household food needs for Clusters 2 and 3 during this challenging period (figure 8(b)), especially considering that NUS collection from the wild generally occurred before (practically no household reported NUS collection from the wild from July onwards; figures 3 and 8(c)). This is also reflected in the perceptions that NUS is an important food source only during the collection period and not throughout the year (figure 4). Conversely, NUS cultivated on farms were harvested during this challenging period (figures 3 and 8(d)), contributing to energy intake (mainly fonio) and income generation (mainly taro) for households in Cluster 1 (figures 8(e) and (f)).

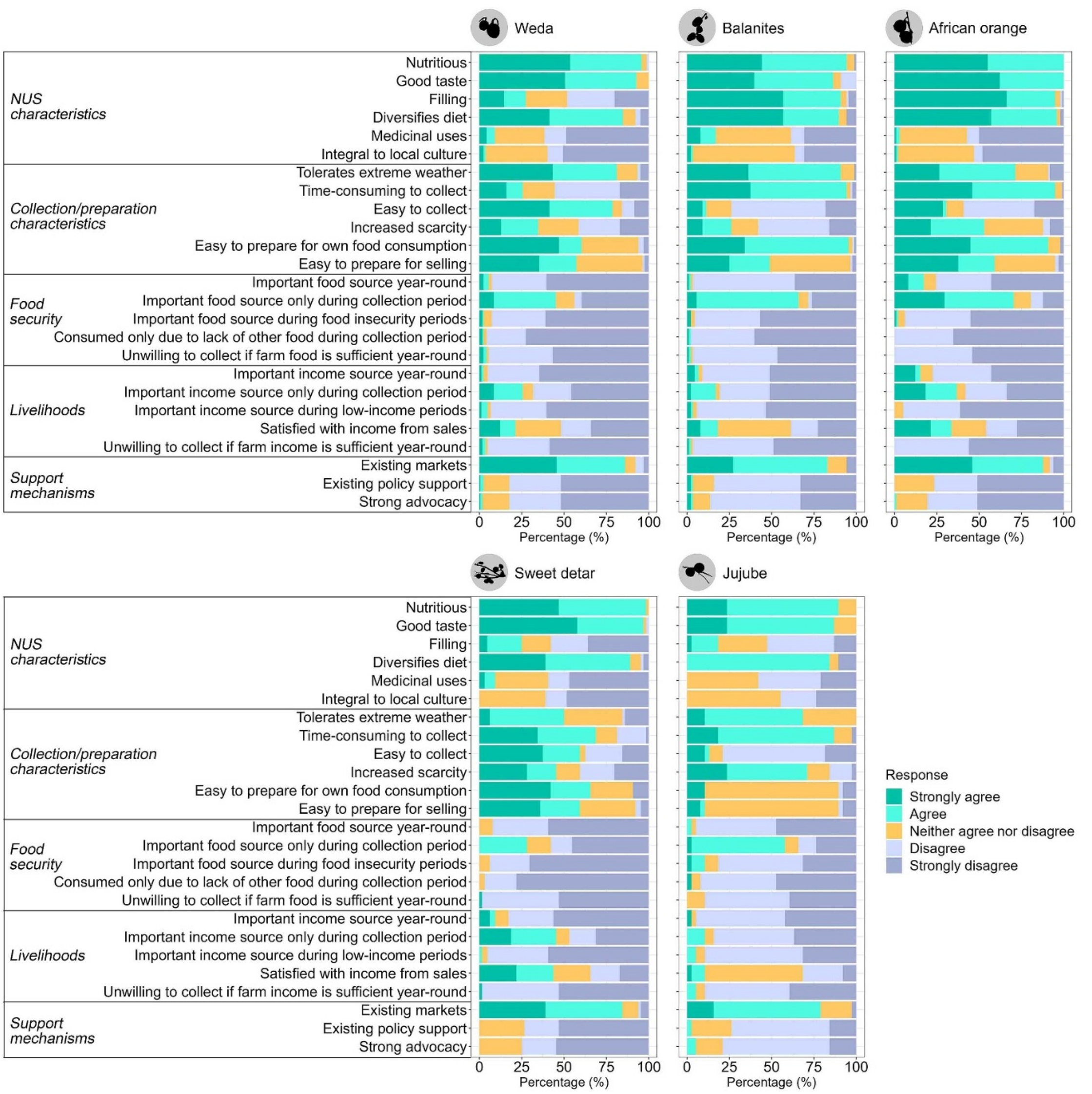


Figure 4. Perceptions for NUS collected from the wild. Stacked bar charts indicate respondent perceptions for 25 individual perception statements spanning five perception categories, elicited using a 5-point Likert Scale (section 2.3.1). All perceptions are for NUS collected by the household and not for NUS purchased from the market.

Table S6 (supplementary material) provides the percentage contribution of each NUS for energy intake and household income for each cluster.

There are no statistically significant differences in the demographic characteristics of clusters in terms of age, gender, or education level of household heads (figure S8, supplementary material). The only exception is the significantly larger size of households in Cluster 3, which is reasonable considering their strong engagement in NUS collection from the wild. However, we observe that younger and more educated farmers tend to engage in market-oriented NUS cultivation (Cluster 1), whereas older, less educated, and larger households tend to be more reliant on NUS collection from the wild (Clusters 2 and 3). Finally, although households of each cluster are encountered in every study area, there are some regional patterns with Cluster 1 mainly concentrated in Hauts-Bassins and Cascades, and Clusters 2–3 in Centre-Ouest (table S7, supplementary material).

3.3. Socioeconomic performance of NUS systems

Figures 9 and S9 (supplementary material) display the socioeconomic performance of the three NUS systems across the five livelihoods and food security variables. Generally, the three NUS systems seem to have rather different socioeconomic performance, considering the statistically significant differences observed for several socioeconomic performance variables across group comparisons.

Cluster 1 consistently performs better across all socioeconomic performance variables (see pairwise comparisons in the first two columns of figure 9). Cluster 1 has the highest income (NUS, on-farm, total), with the differences with

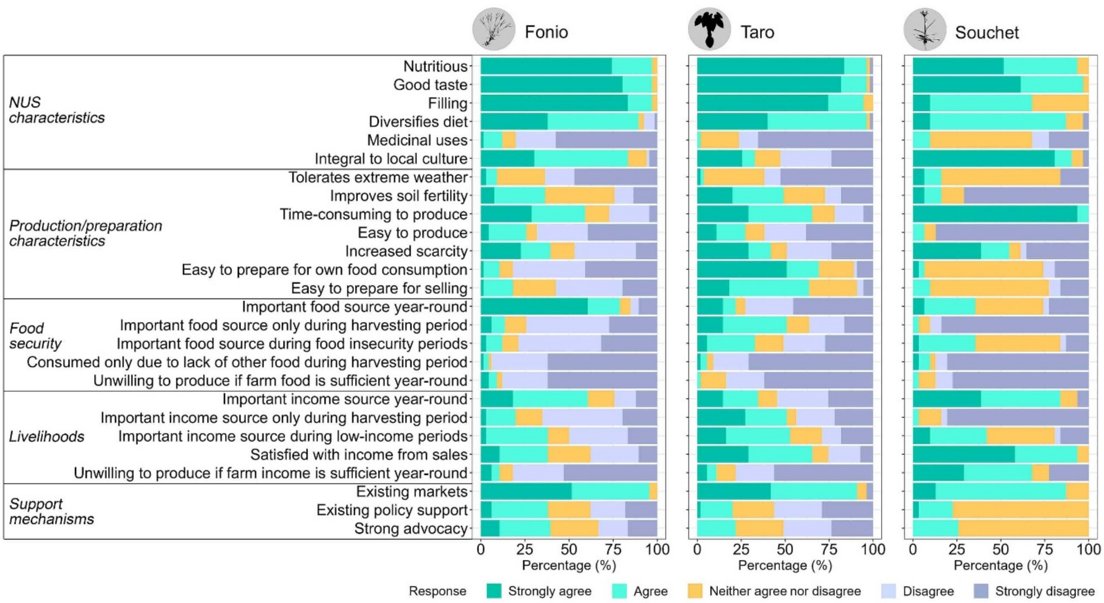
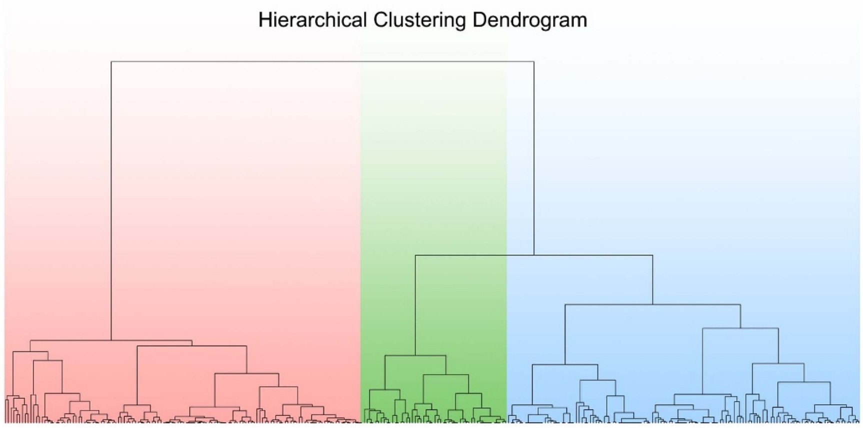


Figure 5. Perceptions for NUS cultivated on farms. Stacked bar charts indicate respondent perceptions for 26 individual perception statements spanning five perception categories, elicited using a 5-point Likert Scale (section 2.3.1). All perceptions are for NUS cultivated by the household and not for NUS purchased from the market.



	Cluster 1	Cluster 2	Cluster 3
Number of NUS collected	0.07	1.31	1.52
Number of NUS cultivated	1.142	0.000	0.008
Share of NUS self-consumption to total NUS collection/cultivation	24.99	4.03	96.13
Number of months for NUS collection	0.30	2.90	2.80
Perceived NUS importance for household livelihoods	2.81	2.15	1.85
Sample size	127 (41.9%)	51 (16.8%)	125 (41.3%)

Figure 6. Main characteristics of NUS producers within each cluster. The five variables indicated in the cells are those used for HCA (section 2.3.2).

Cluster 3 always being statistically significant. However, the only statistically significant difference for an income variable between Cluster 1 and Cluster 2 is for NUS-related income, arguably due to the strong market orientation of Cluster 1 and its specialization in NUS that have been identified as particularly important sources of income at different times of the year (figure 5). Cluster 1

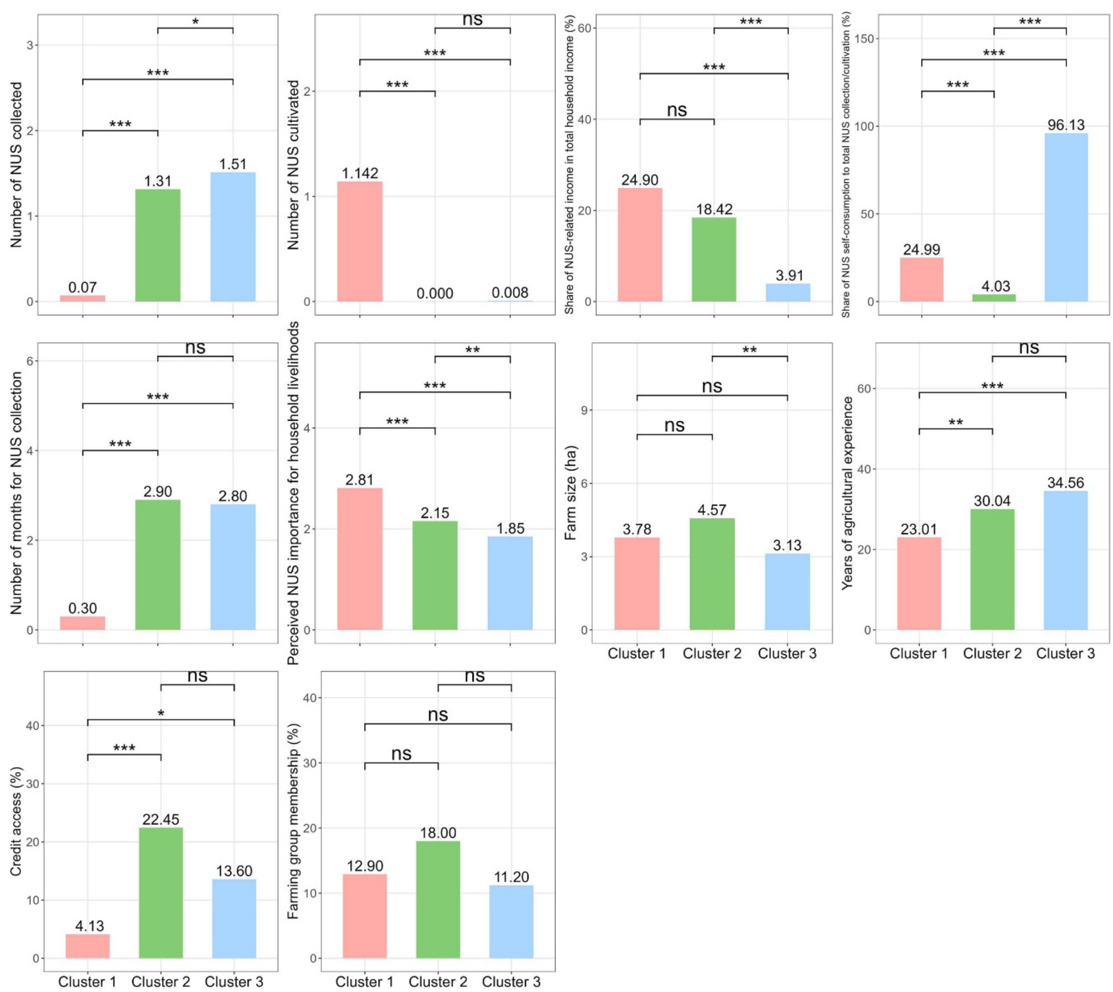


Figure 7. Differences in NUS production system characteristics variables between clusters. The horizontal square brackets represent the pairwise comparisons between the clusters at the opposite tips of the brackets. Symbols above each square bracket denote the statistical significance of the differences for each production characteristics variable as follows: '*' $P < 0.05$, '**' $P < 0.01$, '***' $P < 0.001$, and 'ns' not significant.

has significantly fewer months of inadequate food compared to Clusters 2 and 3, which can be largely explained by the fact that NUS such as fonio and taro were harvested in months associated with inadequate food (figures 3(b), 8(b), and (d)).

Cluster 2, which is characterized by NUS collection from the wild for market sales, has the second-best socioeconomic performance. However, the differences for most variables are marginally higher (but not statistically significant) compared to Cluster 3, which is characterized by NUS collection from the wild for self-consumption. The only statistically significant difference is for NUS-related income, which is not necessarily surprising given the greater market orientation of this group (figure 6). The results seem to imply that there are no particularly significant differences in socioeconomic performance whether households decide to focus on NUS collection for sales or self-consumption.

4. Discussion

4.1. Implications of differentiation in NUS systems

Our results suggest significant differentiation both between individual NUS and NUS production systems. Respondents had largely positive perceptions about the characteristics and ability of NUS to provide food and income during harvesting/collection periods (figures 4 and 5). However, only cultivated NUS such as fonio and souchet were perceived as important food and income sources throughout the year (figures 4–6). Ease of cultivation/collection and preparation differs substantially between individual NUS. Importantly, beyond this differentiation between individual NUS we identify significant differentiation between NUS systems. In a nutshell, Cluster 1 tends to cultivate NUS on farms mostly for market sales, Cluster 2 tends to collect NUS from the wild predominately for market sales, and

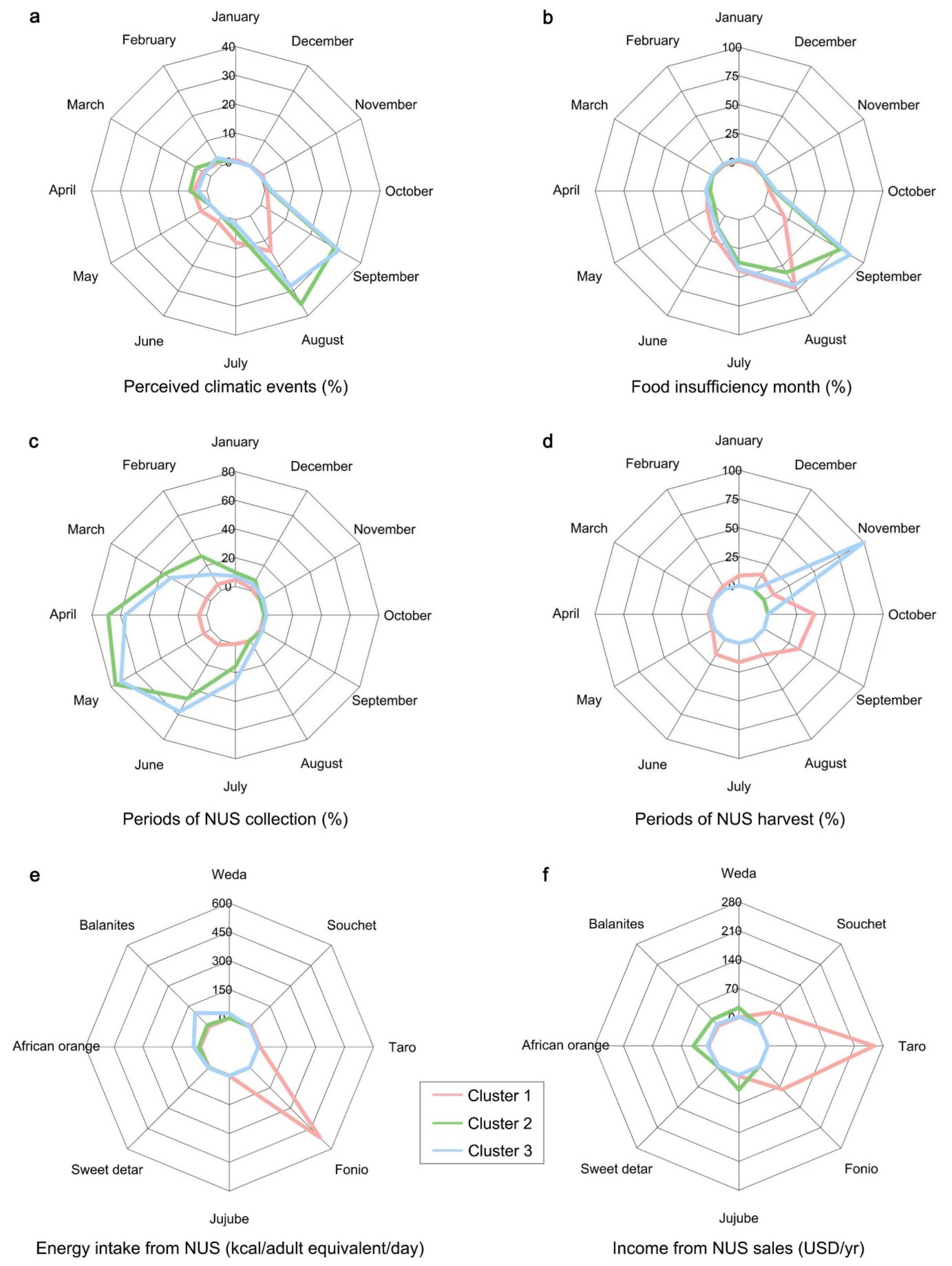


Figure 8. Periods of climatic events and food insufficiency (panel (a), (b)), periods of NUS collection and harvest (panels (c), (d)), and energy intake and income generation from NUS (panels (e), (f)).

Cluster 3 tends to collect NUS from the wild predominately for self-consumption (figure 6). Cluster 1 performs better for most socioeconomic performance variables (figure 9) and perceives NUS as an important component of their livelihoods. Although both Clusters 2 and 3 engage in NUS collection from the wild for several months of the year, NUS is considered as an important livelihood component only for Cluster 2 (figures 6 and 9). This differentiation partly reflects and partly questions three features of the NUS literature as discussed below.

First, as outlined in section 1 NUS is often used as an umbrella term both to differentiate them

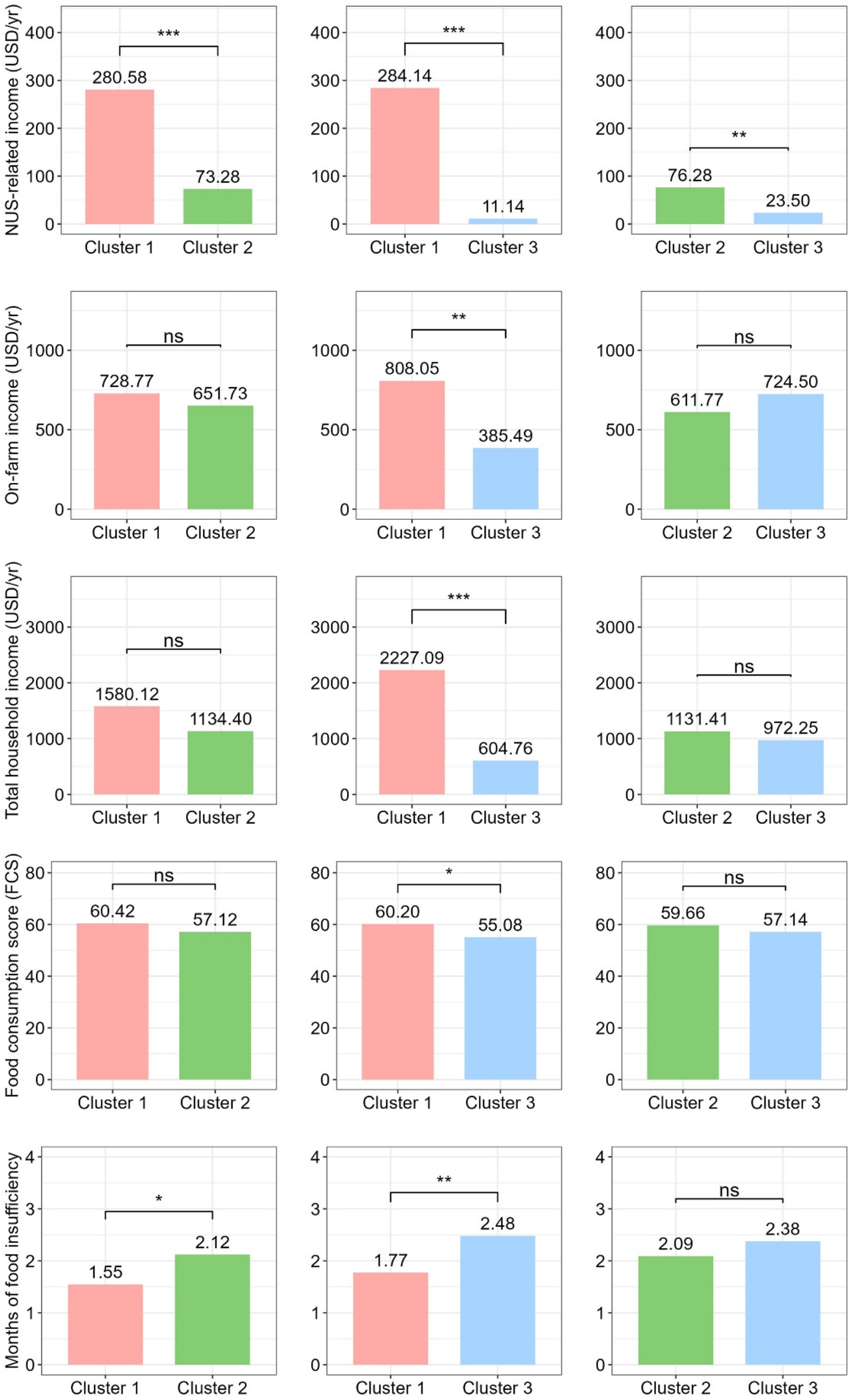


Figure 9. Differences in socioeconomic performance variables between clusters after PSM. The horizontal square brackets represent the pairwise comparisons between the clusters at the opposite tips of the brackets. Symbols above each square bracket denote the statistical significance of the differences for each socioeconomic performance variable as follows: '*' $P < 0.05$, '**' $P < 0.01$, '***' $P < 0.001$, and 'ns' not significant.

from more prevalent food crops promoted during the Green Revolution (e.g. maize, rice, wheat) and to highlight their unique potential for agrodiversity conservation, climate resilience and food security [18]. However, this obscures differentiation within these systems in terms of access (e.g. cultivation on farms vs. collection from the wild) and the livelihood strategies associated with these NUS (e.g. self-consumption vs. market sales). This implicitly bundles together NUS systems with very different agroecological characteristics, socioeconomic performance, and potential for rural livelihoods and food security. This has arguably created room for some generalizations as discussed in the next two paragraphs. However, here we find a clear differentiation between NUS production systems, which implies the need for both more nuanced research on NUS characteristics and impacts in different geographical contexts [19] and context-specific messaging to producers, consumers, and other stakeholders [17].

Second, a common generalization in the NUS literature is their better adaptation to local climates and lower vulnerability to climate change, which makes NUS ideal livelihood and food security buffers during periods of extreme climatic conditions [3, 44] (section 1). However, our results only partially reflect this generalization, highlighting a much more diverse situation on the ground. Several NUS are indeed perceived as tolerant to extreme weather conditions (figures 4 and 5), but only Cluster 1 seems to benefit from NUS during these periods of the year (July–September; figure 3(b)). Actually, many households collect NUS from the wild (Clusters 2–3) before periods of extreme climatic conditions and food insufficiency (January–May/June; figure 3(a)). Although we did not specifically ask questions about the storage of the NUS collected from the wild before food insecurity periods (i.e. balanites, African orange, sweet detar, jujube; figure 3), the response patterns in the perceptions questions (figures 4 and 5) suggest that these NUS are primarily consumed during collection periods and mostly in fresh form (table S5 supplementary material). This implies that in our case the NUS collected from the wild are immediately consumed, rather than stored to be consumed during food insecurity periods. This finding challenges the generalization that NUS have potential only (or mostly) as food and income buffer options during challenging periods. In fact, most of the NUS collected from the wild in our study areas offer food and livelihoods over extended periods of the year.

Third, another generalization is that most NUS (especially those collected from the wild) are geared towards self-consumption. This reflects the common narrative that NUS value chains are generally underdeveloped (or even lacking) in most rural parts of SSA [45] and should be strengthened to provide viable livelihood benefits to producers [18, 21]. However, we find that two of the three clusters have strong market orientation, selling a significant fraction of both NUS cultivated in farms (Cluster 1) or collected from the wild (Cluster 2), and in turn perceiving them as very important elements of their household livelihoods (figure 6). This finding is very important as it implies that even in rural areas there can be market opportunities (see 'existing market' perceptions for all NUS in figures 4 and 5), though with very little perceived support structures (see 'existing policy support' in figures 4 and 5). This reinforces the call for strengthening NUS value chains, especially in rural areas.

4.2. Policy and practice recommendations

Based on our findings we identify three interconnected recommendations: (a) strengthen NUS value chains, (b) identify and communicate the diversification potential of NUS, and (c) move beyond simple narratives in NUS research and messaging.

Regarding (a), our results imply that while markets exist for practically all NUS studied, there seems to be minimal policy and advocacy support to strengthen value chains. Efforts to strengthen value chains should be mindful of the criticism that many NUS remain marginal livelihood options due to the significant time requirements for cultivation/collection and preparation [8, 18], which is corroborated our perception analysis (figures 4 and 5). This, combined with the generally low satisfaction with income generation for most NUS (souchet is a key exception) (figures 4 and 5), implies that price incentives will likely be crucial for strengthening NUS value chains [17]. More broadly, creating producer support mechanisms, facilitating consumer access, and generally fostering a conducive policy environment are all also important action areas for strengthening NUS value chains in rural areas and creating new urban markets options, which echo the findings of a recent policy analysis for NUS in Burkina Faso and Niger [22]. Considering the knowledge deficits about many NUS and the capacity deficits of many producers, actions to strengthen NUS value chains could involve disseminating knowledge and technologies to producers, disseminating market information to consumers, offering marketing training programs, fostering farmer cooperatives, and facilitating partnerships between farmers and other private sector entities [14]. This will likely require cross-sectoral cooperation among multiple stakeholders, such as government agencies, international organizations, civil society, NUS growers, traders, and processors, and consumer organizations [46].

Regarding (b) NUS are produced in tandem with other crops, which inherently makes NUS consumption and marketing a livelihood diversification strategy. Agricultural diversification can have positive effects to rural households [17, 32, 47], with some studies demonstrating that household livelihood diversification through NUS might help alleviate poverty [12] and food insecurity [10]. However, such findings are often anecdotal, with a notable lack of robust evidence about the actual mechanisms mediating the alleviation effects through diversification. Well-structured research programs should unravel the mechanisms linking NUS diversification with poverty and hunger alleviation, estimate the magnitude of these benefits, and communicate it properly to producers to enhance NUS viability.

Regarding (c), our findings partly reflect and partly question some generalizations in the NUS literature (section 4.1). We argue for a much more nuanced approach to the research and messaging about the unique attributes and overall potential of NUS across different species, agroecological zones, production systems, and local socioeconomic contexts [3, 17]. This will likely prevent oversimplifications and generalizations about their benefits and constraints, while helping identify truly appropriate options and support mechanisms to enhance the positive outcomes of NUS in SSA.

5. Conclusion

This study explored the differentiation in the perceptions, characteristics and socioeconomic performance of NUS systems in Burkina Faso. We identified three distinct NUS production systems, namely NUS cultivation on farms for market sales (Cluster 1), NUS collection from the wild for market sales (Cluster 2), and NUS collection from the wild for self-consumption (Cluster 3). These clusters rely on different NUS, have different market orientations, and obtain rather different socioeconomic benefits over different times of the year, not necessarily only during the periods of severe food insecurity. Our results make a strong case for strengthening NUS value chains, exploring further whether (and how) NUS diversify household livelihoods, raising awareness to NUS producers, and moving beyond simple narratives in NUS research and messaging.

Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information. The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare that there are no known financial and non-financial conflicts of interest associated with the outcomes of this publication.

Authors contribution

Quanli Wang and Alexandros Gasparatos contributed to the study conception and design. Data collection was performed by Eric Brako Dompreh and Blandine Marie Ivette Nacoulma. Data analysis was performed by Quanli Wang. The first draft of the manuscript was written by Quanli Wang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethical statement

The Research Ethics Committee of the University of Tokyo determined that this study does not require ethical review, in accordance with research ethics guideline in Japan titled 'Ethical Guidelines for Life Science and Medical Research Involving Human Subjects' and 'The University Research Ethics Regulation'.

ORCID iDs

Quanli Wang 0000-0002-8400-5102
Miyuki Iiyama 0000-0001-7034-929X
Kangbéni Dimobe 0000-0001-5536-9700
Alexandros Gasparatos 0000-0001-9323-1366

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