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RESEARCH ARTICLE



Differential household vulnerability to climatic and non-climatic stressors in semi-arid areas of Mali, West Africa

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ABSTRACT

Semi-Arid Regions (SARs) of West Africa are considered climate change “hotspots” where strong ecological, economic and social impacts converge to make socio-ecological systems particularly vulnerable. While both climatic and non-climatic drivers interact across scales to influence vulnerability, traditionally, this inter-connectedness has received little attention in vulnerability assessments in the region. This study adopted the vulnerability patterns framework, operationalized using the Multidimensional Livelihood Vulnerability approach to include both climatic and non-climatic stressors to analyze differential household vulnerability in SARs of Mali. Findings showed that while drought was the most mentioned climate-related stressor, households were also exposed to a diversity of environmental and socio-economic stressors, including food scarcity, livestock disease, labour unavailability, crop damage, and erratic rainfall patterns. The typology revealed three vulnerability archetypes differentiated by adaptive capacity and sensitivity. Availability of productive household members, household resource endowments, livelihood diversification and social networks were the main discriminant factors of household adaptive capacity, while challenges relating to food and water security make households more sensitive to stressors. The analysis highlighted the heterogeneity in household vulnerability patterns within and across communities. Failing to account for this heterogeneity in adaptation planning might result in a mismatch between adaptation needs and interventions, and potentially in maladaptation.

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1. Introduction

In Semi-Arid Regions (SARs), global warming is particularly enhanced, with local temperatures increasing faster than the global average (Huang et al., 2017). A global warming of 2°C rather than 1.5°C would mean a warming of 3.2–4.0°C over semi-arid drylands, with disastrous impacts including decreased crop yields and runoff, increases of more severe and longer drought, and more favourable conditions for malaria transmission (Hoegh-Guldberg et al., 2018; Huang et al., 2017).

The situation in SARs of West Africa presents significant and urgent challenges that call for rapid attention. These areas are not only climate change exposure hotspots (Bathiany et al., 2018; de Sherbinin, 2014; Turco et al., 2015), but also hotspots of climate change impacts because of the unique biological, environmental and socio-economic attributes of the region (de Sherbinin, 2014; Diffenbaugh & Giorgi, 2012; Müller et al., 2014). These increased climate change impacts will be persistent over time, independent of emissions pathways

considered in the global arena (Bathiany et al., 2018; Diffenbaugh & Giorgi, 2012; Turco et al., 2015). This underscores the urgency of concerted efforts to reduce vulnerability and enhance the resilience of communities and ecosystems to increasing and potentially irreversible climatic challenges. Effectively achieving the aims of these efforts will require a better understanding of who, why and how human systems are vulnerable to inform effective adaptation planning.

There has been extensive empirical research conducted over the last few decades exploring who, where, how, and why human systems are vulnerable to the changing climate (Ford et al., 2018; McDowell et al., 2016; Räsänen et al., 2016; Tonmoy et al., 2014; Williams et al., 2018). Vulnerability assessment has gained importance for policy purposes and become a necessity for informing policy and decision making (Hinkel, 2011; McDowell et al., 2016; Tonmoy et al., 2014). In sub-Saharan Africa, the number of vulnerability assessments has increased over time, with the agricultural sector being the most common focus (McDowell et al., 2016; Williams et al.,

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2018). Recognition that early investigations privileged climatic factors over social ones has, over time, pushed vulnerability research beyond a sole focus on climate in vulnerability assessment, with vulnerability now being conceived as a condition or state embedded in socio-economic processes (Bohle et al., 1994; Cardona, 2004; Chambers, 1989; Ford et al., 2018; Räsänen et al., 2016). In SARs of West Africa, vulnerability of local communities is driven not only by climatic factors but also by a diversity of biophysical, socio-economic, cultural and political factors (Antwi-Agyei et al., 2017; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Ouédraogo et al., 2016). The most common climatic stressors in the region include droughts, erratic rainfall, floods, and winds (Antwi-Agyei et al., 2017; Epule et al., 2018; Nyantakyi-Frimpong & Bezner-Kerr, 2015). Non-climatic biophysical and socio-economic stressors frequently reported include lack of money, high cost of farm inputs, cattle destruction of crops, livestock pest, limited access to markets and lack of agricultural equipment (Antwi-Agyei et al., 2017; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Segnon, 2019). Inequality in decision making processes and access to resources resulting from patriarchal local culture and institutions also shape the differential vulnerability of social groups (Ahmed et al., 2016; Antwi-Agyei et al., 2017).

While climatic stressors and accompanying risks are a dominant driver of vulnerability in SARs of West Africa (Epule et al., 2018; Gautier et al., 2016), complex interconnections between multiple climatic and non-climatic stressors, operating across different scales, are also important influences (Antwi-Agyei et al., 2017; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Ouédraogo et al., 2016; Räsänen et al., 2016). While there are increasing studies pointing at the multiple stressors (Antwi-Agyei et al., 2017; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Räsänen et al., 2016) driving differential vulnerability, the way in which these multiple climatic and non-climatic stressors interact to shape vulnerability is not well documented in this region. Furthermore, conventional vulnerability assessments based on indicators typically use aggregation methods to compute a composite index at community level (Hahn et al., 2009; Hinkel, 2011; Tonmoy et al., 2014; Vincent & Cull, 2014), an approach that often fails at capturing intra-community heterogeneity and diversity. Indicator-based vulnerability assessment and mapping approaches are most often conducted at community, district or national scale, missing crucial details about variation at household level (Antwi-Agyei et al., 2017). Finding ways to capture these intra-community dynamics is crucial for effective targeting of adaptation interventions and adaptation planning. Capturing intra- or within community heterogeneity could also be vital to enhancing the relevance of vulnerability assessments (Antwi-Agyei et al., 2017).

To fill this gap, this study analysed the diversity of climatic and non-climatic stressors facing smallholder farmers in Koutiala, a SAR of Mali, and assessed household vulnerability to both climatic and non-climatic stressors. Specifically, the following questions were addressed: (i) what are the climatic and non-climatic stressors driving household vulnerability?, (ii) what additional factors shape household vulnerability?, (iii) are there patterns in household vulnerability?, and how similar are households in terms of vulnerability patterns?. The study adopted the Vulnerability Patterns framework

(Kok et al., 2016; Sietz et al., 2011) to construct household vulnerability archetypes and explore intra-community heterogeneity and diversity in household vulnerability patterns. We hypothesized that households within community are not homogenous in terms of their vulnerability to climatic and non-climatic stressors and using a pattern or archetype analysis will reveal the differential vulnerability.

2. Conceptual framework

Rooted in natural hazard and poverty studies, the concept of vulnerability has gradually entered into research on adaptation of people to socio-ecological changes (Adger, 2006; Cutter, 1996; Fussler, 2007). Although there are diverse interpretations of vulnerability, according to different fields of study and traditions, vulnerability is most often conceptualized as the susceptibility of a system to perturbations or stresses shaped by its exposure and sensitivity to perturbations or stresses, and the capacity to adapt (Adger, 2006; Fussler, 2007; Nelson et al., 2007; Smit & Wandel, 2006; Tonmoy et al., 2014). Increasingly, vulnerability is conceptualized as a condition, including characteristics of exposure, sensitivity, and adaptive capacity, determined by social, economic, physical and environmental factors or processes, which increase the susceptibility of a system to the impact of hazards, rather than as a direct outcome of a perturbation or stress (Adger, 2006; Fussler & Klein, 2006; Miller et al., 2010; O'Brien et al., 2007). Exposure is the nature and degree to which a system experiences environmental or socio-political stress (Adger, 2006; Fussler & Klein, 2006). Sensitivity is the degree to which a system is modified or affected, either adversely or beneficially, by perturbations, such as climate-related stress (Adger, 2006; Fussler & Klein, 2006). Adaptive capacity is “the ability of a system to evolve in order to accommodate environmental hazards or policy change and to expand the range of variability with which it can cope” (Adger, 2006; Brooks et al., 2005; Engle, 2011; Smit & Wandel, 2006). It represents the preconditions necessary to enable adaptation, including physical and social resources, and the ability to mobilize these resources to respond to perceived or current stresses (Brooks et al., 2005; Engle, 2011; Nelson et al., 2007).

Measuring vulnerability is notoriously challenging as assessments suppose theoretically specified connections or linkages between often non-observable elements (Crane et al., 2017). These non-observable elements are assumed to constitute vulnerability, supported by theoretical models that are then measured through sets of proxy indicators (Crane et al., 2017; Hinkel, 2011; Tonmoy et al., 2014; Vincent & Cull, 2014). Assessing vulnerability entails the operationalization of the vulnerability frameworks selected (Crane et al., 2017; Hinkel, 2011). Indicators are commonly used to operationalize vulnerability, either deductively, based on theoretical frameworks, or inductively based on data used to build statistical models, or using a normative approach based on (individual or collective) value judgments (Crane et al., 2017; Hinkel, 2011; Tonmoy et al., 2014; Vincent & Cull, 2014). Indicator-based vulnerability assessments have been widely applied because they provide opportunities to incorporate socio-economic and biophysical components of vulnerability and are relatively easy to perform

and simple to communicate to the policymakers and the general public (Tonmoy et al., 2014; Vincent & Cull, 2014).

This study adopted the Vulnerability Patterns framework (Kok et al., 2016; Sietz et al., 2011) to explore the diversity in household vulnerability patterns in SARs of Mali. The Vulnerability Patterns framework is similar to the IPCC framework, but provides a considerable elaboration of adaptive capacity, specifically on coping capacity to adjust to climate-related risks, manage loss and damage or explore alternative opportunities (Crane et al., 2017). This framework applies the cluster analysis methodology as a way to deliver useful insights into recurrent combinations of measurements based on similarities among systems of analysis, in cases where such a clustering exists (Crane et al., 2017; Kok et al., 2016; Sietz et al., 2011). The method helps identify specific constellations or groups of indicator values with recognizable patterns (Kok et al., 2016). To operationalize the framework, we adopted and modified the Multidimensional Livelihood Vulnerability Index (MLVI), developed by Gerlitz et al. (2017). The MLVI assesses multidimensional livelihood vulnerability to environmental (including climatic) and socio-economic changes with household as unit of analysis (Gerlitz et al., 2017). The MLVI is an expansion and modification of the Livelihood Vulnerability Index (LVI) (Hahn et al., 2009) using multidimensional index construction approach (Gerlitz et al., 2017). Developed based on the Sustainable Livelihood (SL) framework, the LVI offers a pragmatic and flexible tool for vulnerability assessment and has been widely used in the literature (Gerlitz et al., 2017; Hahn et al., 2009). The SL framework has been widely used as a theoretical basis for deductively selecting indicators for vulnerability assessment. The SL framework relies on the understanding of how people access the social, human, financial, natural and physical capital assets (Reed et al., 2013) and has been shown to be relevant for assessing the capacity of households to withstand various socio-ecological shocks (Hahn et al., 2009). The SL framework is particularly pertinent to explore vulnerability to climate-related shocks since it offers a space for analysing not only key components that make up livelihoods but also contextual factors that affect livelihoods (Reed et al., 2013). These components are also intimately related to the elements that make a system

or unit of analysis exposed or more sensitive to climate change impacts and influence their ability to cope with socio-ecological change (Hahn et al., 2009; Reed et al., 2013).

The MLVI modifies and extends the initial seven components of the LVI, resulting in twelve components so that it addresses factors that are relevant to the authors' specific context (Figure 1) (Gerlitz et al., 2017). As in the initial LVI, each component is composed of several measurable and specific vulnerability indicators (Gerlitz et al., 2017; Hahn et al., 2009).

3. Materials and methods

3.1. Study area

This study was undertaken as part of a broader research programme "Adaptation at Scale in Semi-Arid Regions of Africa and Asia" (ASSAR). ASSAR's overarching research objective is to use insights from multiple-scale, interdisciplinary work to improve the understanding of the barriers, enablers and limits to effective, sustained and widespread adaptation to climatic and non-climatic risks in semi-arid regions of Asia and Africa. The study was carried out in the Cercle of Koutiala, a semi-arid area in southeastern Mali (Figure 2). The climate is typical of the Sudano-Sahelian region, with annual rainfall ranging from 400 to 800 mm, with high inter-annual and intra-seasonal variability. The rainy season starts in June and ends in October with rainfall peaking in August. The dry season is made up of a relatively cold period (November to February) and a hot period (March to May). Daily average temperatures range between 22°C (during cold period of November to February) and 35°C (hot period of March to June), with an average maximum temperature of 34°C during the rainy season and 40°C during the hot dry season. The natural vegetation is a tree and shrub savannah with an understory of annual and perennial grasses in a complex mosaic. Soils are poor, of sandy or sand-loamy texture and often gravelly.

Koutiala belongs to the administrative region of Sikasso, and is 140 km north of Sikasso town. It covers an area of 8740 km² (about 12.17% of the total area of Sikasso region and 0.7% of the country's total area). According to the latest population

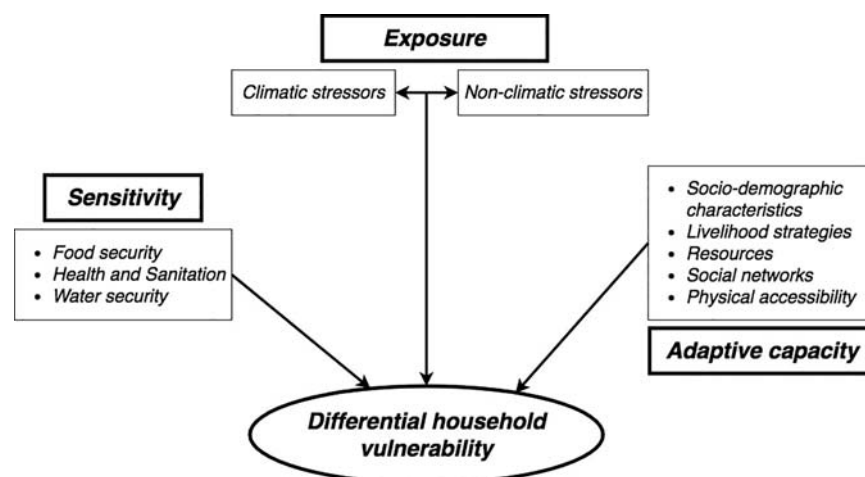


Figure 1. Conceptual framework of the study.

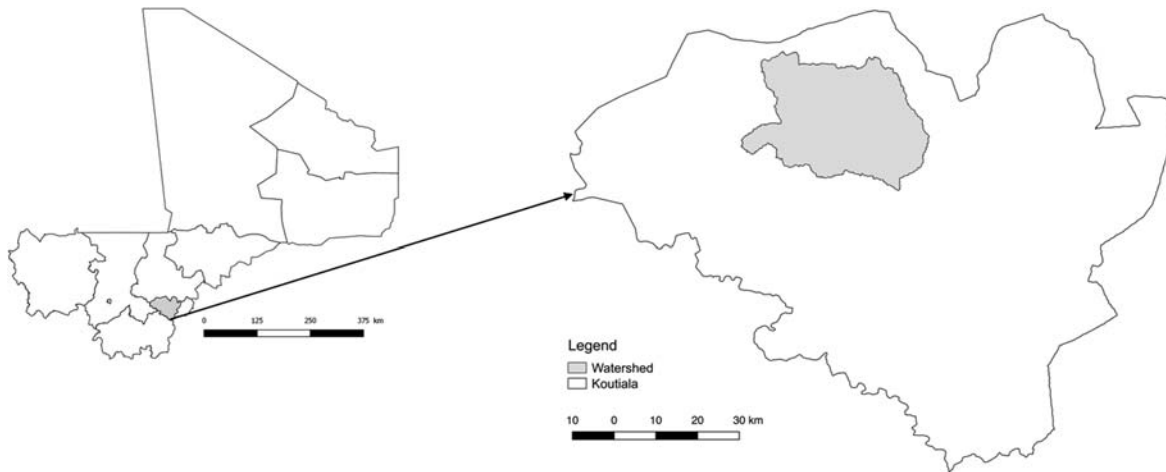


Figure 2. Location of the study area.

census of 2009, Koutiala is home to 575,253 people, with an average density of 52.32 inhabitants per km². Sikasso region is known to be Mali's breadbasket and supplies a considerable amount of food to the rest of the country as well as incomes through cotton cultivation. Koutiala, in particular, is considered as “white gold” district because of the significant contribution of cotton production to agricultural systems and food production (Laris et al., 2015; Sidibé et al., 2018). Based on the latest population census, cotton production occupies 90% of Koutiala population (Laris et al., 2015; Laris & Foltz, 2014; Sidibé et al., 2018). In addition to cotton, Koutiala is also an important maize production area and rank second in terms of maize production in Sikasso region, contribution to about 14% (56,714 t) to the total maize output (Diallo et al., 2020). While a diversity of crops is cultivated, cotton, maize, sorghum, pearl millet and groundnut are the main crops in Koutiala (Segnon, 2019). After cotton and cereal cultivations, livestock production is the second main livelihood activity in Koutiala.

Over the last 50 years, a gradual and spatially variable increase in the annual mean temperature has been observed in West African region (Daron, 2014; Riede et al., 2016; Sylla, Nikiema, et al., 2016), with the highest (0.6–3.0°C) temperature increases observed in northern parts of the region, particularly in Mali (Daron, 2014). This increase has been faster in SARs of the region and faster than global warming (Klutse et al., 2018; Sarr, 2012). In Koutiala, minimum temperature has been increasing faster than maximum temperature (Segnon, 2019). There has been a substantial spatial and temporal (multi-decadal, annual and seasonal) variability in rainfall patterns over the past 50 years in the West Africa region, especially in the SARs, with a very dry period in the 70s and 80s (Biasutti, 2019; Daron, 2014; Nicholson, 2013; Riede et al., 2016; Sanogo et al., 2015; Sarr, 2012). After the severe drought periods, rainfall seems to be recovering, but this recovery is characterized by new rainfall features including false start and early cessation of rainy seasons, increased frequency of rainy days along with increased precipitation intensity, more frequent dry spells, increasing number of hot nights and warm days (Biasutti, 2019; Salack

et al., 2016; Sanogo et al., 2015). Rather than a rainfall recovery, the SARs of West Africa is experiencing a new era of climate extremes (Biasutti, 2019; Bichet & Diedhiou, 2018; Panthou et al., 2018). An analysis of rainfall data from Koutiala weather station confirmed the strong spatio-temporal variability in rainfall patterns than a clear significant change (Segnon, 2019).

The new rainfall conditions termed “hybrid rainy seasons” induced by global warming and characterized by false start and early cessation of rainy seasons and increased frequency of intense daily rainfall (Salack et al., 2015; Salack et al., 2016) have serious implications for agricultural production, which is mainly rain-fed in the SARs of West Africa (Gautier et al., 2016; Salack et al., 2015; Sultan et al., 2013; Sultan et al., 2014; Sultan & Gaetani, 2016; You et al., 2011). In the Sahel, variability and changes in temperature and precipitation have led to a significant decline in tree density and species richness (Gonzalez et al., 2012). It is very likely that services and functions derived from tree-based ecosystems were also affected/reduced. Changes in the number of rainy days and the timing of the rainy season negatively affected vegetation growth in the semi-arid Sahel (Zhang et al., 2018). Climate change and variability also led to a southward shift of the climatic zones in West Africa (Gonzalez et al., 2012), with serious consequences for agricultural output and human livelihoods (Sissoko et al., 2011). In addition, the strong spatio-temporal variability in rainfall patterns has far-reaching impacts on water quality and availability, on crop yield and production, and thus on food security in the region (Ben Mohamed, 2011; Gautier et al., 2016; Sissoko et al., 2011; Sultan & Gaetani, 2016; Zougmore et al., 2016). The late twenty-first century projections reveal an extension of torrid, arid and semi-arid climate regime throughout West Africa, with the recession of moist and wet zones (Sylla et al., 2016). The current Sahel, mainly semi-arid in present-day conditions, is expected to face a moderately persistent future arid climate (Sylla et al., 2016). In Mali, projected cereal crops yield reductions are expected to reduce food availability and food self-sufficiency, especially of smallholder farmers, who are already food

Table 1. Vulnerability dimensions, components, and indicators.

Dimensions	Components	Indicators	Description
Adaptive capacity	Socio-demographic status	Education of household head	Educational attainment of household head
		Dependency ratio	Ratio of No. of household member under 15 and over 65 years of age to household member between 19 and 64 years of age
	Livelihood strategies	Household productive members	No. of household member under 15 and over 65 years of age
		Agricultural livelihood diversity	No. of primary livelihood strategies
		Non-agricultural livelihood diversity	No. of secondary or tertiary livelihood strategies
	Resources	Total livelihood diversity	No. of all livelihood strategies
		Agricultural land	Household total farmland size (ha)
		Livestock (TLU)	No. of livestock (TLU – Tropical Livestock Unit)
		Diversity of livestock types	Number of livestock types
	Social networks	Agricultural equipment (plough, cart, seed drill, sprayer, draught animal, donkey)	No. agricultural equipment (plough, cart, seed drill, sprayer, draught animal, donkey) owned by the household
CBOs membership		Does the household belong to a community-based group (Yes/No)?	
Diversity of CBOs membership		No. of CBOs in which household belong to	
Physical accessibility	Political access		How easy is it to access political powers in the community (5-point Likert scale response from 1 – Not easy all to 5 – Very easy)
		Road practicability	Is the road leading from household to feeder or tarred roads practicable all year-round (1 – Not practicable, 2 – Fairly practicable, 3 – Practicable all year-round)
Sensitivity	Food security	Market orientation	Does household sell part or entire production (Yes/No)
		Source of household food	Where does the household get most of its food (1 – Own production only; 2 – Own production [2/3] & purchase [1/3]; 3 – Own production [1/3] & purchase [2/3])
	Health & Sanitation	Food self-sufficiency	Food self-sufficiency
		Number of month with insufficient food	No. of month household struggles to get sufficient food to cover its needs
		Crop diversity	No. of crops grown by household
		Drinking water quality	Does household use a source that, by nature of its construction, adequately protects the water from outside contamination, in particular from faecal matter
	Water security	Toilet facility quality	Does household use sanitation facilities that hygienically separate human excreta from human contact
		Illness (Health case number)	No. health case in household
		Household member with chronic illness	No. household member with chronic illness
		Average time to closest health facility	Average time to closest health facility
Availability of health facility in the village		Availability of health facility in the village	
Diversity of water source		Number of water source used by household	
Exposure	Environmental shocks	Water sufficiency	Water sufficiency
		Number of month with insufficient water	No. of month household struggles to get sufficient water to cover its needs
Socio-economic shocks	Socio-economic shocks	Environmental shocks experienced over the past 12 months	Environmental shocks experienced over the past 12 months
		Socio-economic shocks experienced over the past 12 months	Socio-economic shocks experienced over the past 12 months

insecure (Butt et al., 2005; Traore et al., 2017). In Sikasso region, southern Mali, white (Irish) potatoes, a key cash crop for households, will be the most affected by changing climatic conditions by 2060, with yields decreasing, under both dry and wet conditions, by almost 25% (Ebi et al., 2011).

3.2. Data collection

To assess household vulnerability to climatic and non-climatic stressors, a household survey was designed and conducted in the 10 villages selected within a watershed in Koutiala (see Figure 2). The communities were randomly selected from a list of communities located within the watershed. The selected communities were Danzana, Dentiola, M'Pessoba (in M'Pessoba district), Fonfona (Tao district), Oudiala, Zansoni (in Fakolo-Kou district), N'Tossoni, Diéla (in N'Tossoni district), Ntiesso (in Koutiala district), and Zangorola (in N'Golonianasso district). The household survey sample size was determined following Krejcie and Morgan (1970):

$$s = \frac{X^2 N p (1 - p)}{d^2 (N - 1) + X^2 p (1 - p)}$$

where s is the required sample size, i.e. the number of farm household to be surveyed; X^2 is the table value of chi-square for one degree of freedom at the confidence level fixed at 95%; N is the population size, i.e. the total population of household in Koutiala based on the latest population census; p is the population proportion, i.e. the proportion of farm household. In Sikasso region, where the study area is located, about 60% of households are farm households; d is the degree of accuracy and fixed at 0.05 (5%). The sample size following the above formula is 368 households. Oversampling was done to increase the sample to 501 households. Roughly 50 households were randomly selected in each community. A household was defined as “a group of people living in the same dwelling space who have at least one common plot together or one income-generating activity together (for example, herding, business, or fishing) and who acknowledge the authority of a man or woman who is the head of household” (Beaman & Dillon, 2012).

The MLVI framework (vulnerability as a function of exposure, sensitivity, and adaptive capacity) (Gerlitz et al., 2017) was adopted and modified to suit the context of the semi-arid study area to assess household vulnerability to climatic and non-climatic factors. The MLVI is composed of

12 components which address factors that are relevant to authors' specific context (Gerlitz et al., 2017). In this study, components that were not relevant to the study area context (e.g. environmental stability was linked to the mountain specificities of the Hindu Kush Himalayas region where the MLVI was developed) were removed, resulting in 10 components (Table 1 and Figure 1). Each component is operationalized by a number of measurable and specific indicators (Gerlitz et al., 2017). A preliminary list of indicators was identified based on a review of literature in the SARs of West Africa (Achigan-Dako et al., 2013; Segnon, 2019). The list of indicators was revised and refined during participatory workshops with local stakeholders, including communities and local experts in the study area (Table 1). The indicators were documented through the household survey using a semi-structured questionnaire. The survey questionnaire was pre-tested with 20 households (within Koutiala cercle, but not in study villages; these households did not participate in this research) to ensure that the questions were understandable.

3.3. Data analysis

The vulnerability pattern approach (Kok et al., 2016; Sietz et al., 2011) was adopted in analysing household vulnerability patterns. To identify and analyse household vulnerability patterns, typologies or archetypes of vulnerability were constructed using Factor Analysis of Mixed Data (FAMD) (Pagès, 2014) combined with a Hierarchical Cluster Analysis using the package *FactoMineR* (Lê et al., 2008). FAMD is similar to Principal Component Analysis but allowed to simultaneously quantify categorical and quantitative variables while reducing the dimensionality of the data (Akohoue et al., 2018; Pagès, 2014). Since we have both categorical and quantitative indicators in our dataset, we used FAMD. To identify the relevant number of components to retain, the eigenvalues of the components were analysed and components with eigenvalue greater than one were kept (Abdi & Williams, 2010).

Hierarchical Clustering on Principal Component (HCPC) analysis (Husson et al., 2017) was performed on factors constructed from FAMD to identify homogenous archetypes. Before performing the HCPC analysis, the clustering tendency of the data was assessed using the Visual Assessment of cluster Tendency (VAT) algorithm (Bezdek & Hathaway, 2002). Clustering tendency was assessed to evaluate whether the dataset contains meaningful clusters (i.e. non-random structures) or not, in other word the feasibility or validity of the clustering analysis on the data (Bezdek & Hathaway, 2002). To evaluate the clustering validity and identify the optimal number of clusters, the silhouette method (Rousseeuw, 1987) was used. It measures the quality of a clustering by determining how well each object lies within its cluster (Rousseeuw, 1987). A high average silhouette width indicates a good clustering and the optimal number of clusters k is the one that maximizes the average silhouette over a range of possible values for k (Rousseeuw, 1987). Descriptive statistics was used to describe the archetypes identified and summarize the climatic and non-climatic stressors. We used Chi-square test to test if the types of stressors were archetype-dependent. To test whether vulnerability archetypes were independent of study communities (or research sites), we also used Chi-

square test. All the statistical analyses were performed in R statistical environment (R Core Team, 2019).

4. Results

4.1. Household socio-economic profiles

Over 98% of households interviewed were headed by a male. Household head ages ranged from 19 to 84 years, with mean age of 48.33 (\pm 12.28) years. More than 86% of the households interviewed belonged to Minianka ethnic groups, which is the dominant sociolinguistic group in the study area. The rest of households interviewed were either Peulh (about 4%) or belonged to other groups (6%) which were Bambara, Sonike and Senoufo.

About 34% of household heads had no formal education, while about 21% and 5% of them attained primary and secondary educations respectively. About 11% of the household heads attained Islamic or Koranic education and 28% had been trained to read and write in a local language. Islam is the dominant religion in the study area and was practiced by more than 95% of the households interviewed. On average, households interviewed had about nine productive members (number of household members between 19 and 64 years of age), but this varied largely (from 1 to 58 productive members). Dependency ratio (number of household members under 15 and over 65 years of age to number of household members between 19 and 64 years of age) ranged from 0.17 to 6.5, with an average of 1.42. More than 63% of the households had a dependency ratio greater than one and 39% of them had a value greater or equal to 1.5. A summary of the descriptive statistics of household socio-economic and demographic characteristics is presented in Supplementary Material Table S1.

Farming was the main livelihood activity of all the surveyed households. Figure 3 illustrates the diversity and importance of cultivated crops in the study area. Cultivated crops per household ranged from two to 22, with an average of 10.42 \pm 3.65. In total, 25 different crops were cultivated by the surveyed households. While there was a diversity of crops (see Figure 3), maize (cultivated by more than 99% of the surveyed households), sorghum (about 97% of the surveyed households), pearl millet (about 95% of the surveyed households), cotton (about 92% of the surveyed households), groundnut (about 89% of the surveyed households) and cowpea (88% of the surveyed households) were respectively the most cultivated crops by the surveyed households. Crops cultivated by few households were soybean, Taro, Fonio, banana and watermelon (Figure 3).

4.2. Diversity of climatic and non-climatic stressors

Stressors to which household were exposed to in the study area were of both climatic and non-climatic nature. Figure 4 illustrates the diversity of stressors to which households were exposed. Drought was the most experienced stressors by the majority of surveyed households (77.25%). Other stressors included food scarcity (42.32%), livestock disease (41.72%), erratic rainfall patterns (21.16%) and floods (9.58%). Other key non-climatic stressors experienced by households were damage to crops and farms by livestock (25.55%), scarcity of labour to perform farm activities (24.95%), inability to access

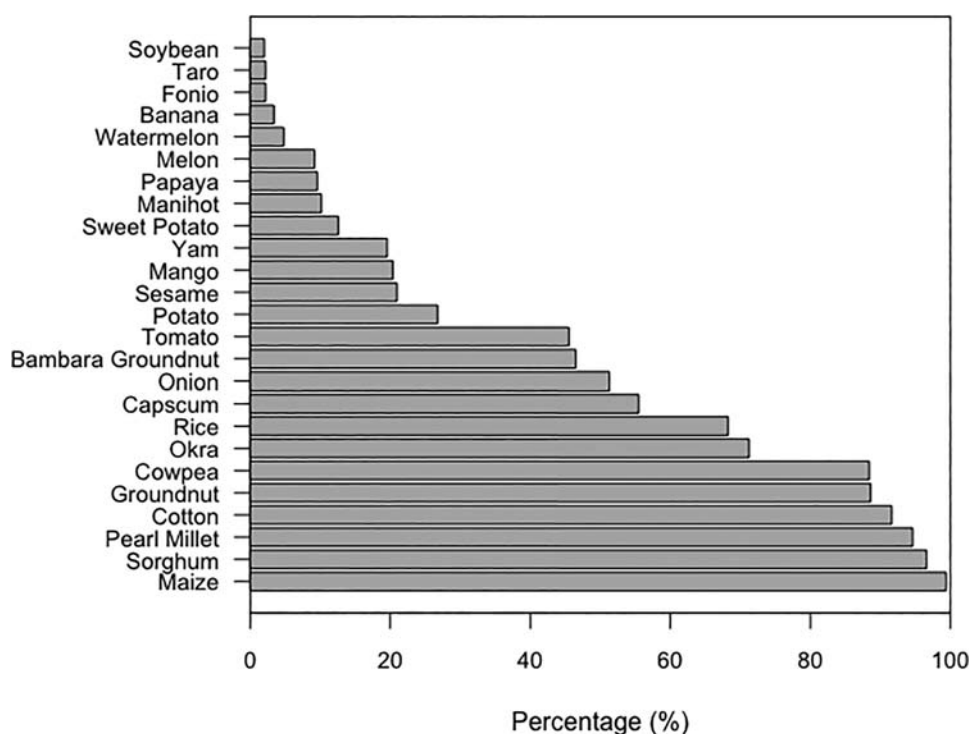


Figure 3. Diversity of cultivated plants and their importance.

fertilizer (10.98%), and death (9.98%) or sickness of a household member (9.78%).

Over the past 12 months prior to the survey, the total number of shocks experienced by households ranged between one and seven, with a median number of three per household (mean 2.73 ± 1.35). It ranged from zero to five for both environmental and socio-economic shocks, and a median number of

one (mean 0.81 ± 0.93) for socio-economic shocks and a median number of two (mean 1.92 ± 0.83) for environmental shocks.

4.3. Household vulnerability patterns

The Factor Analysis of Mixed Data (FAMD) analysis showed that the first 12 Principal Components (PC) have eigenvalues

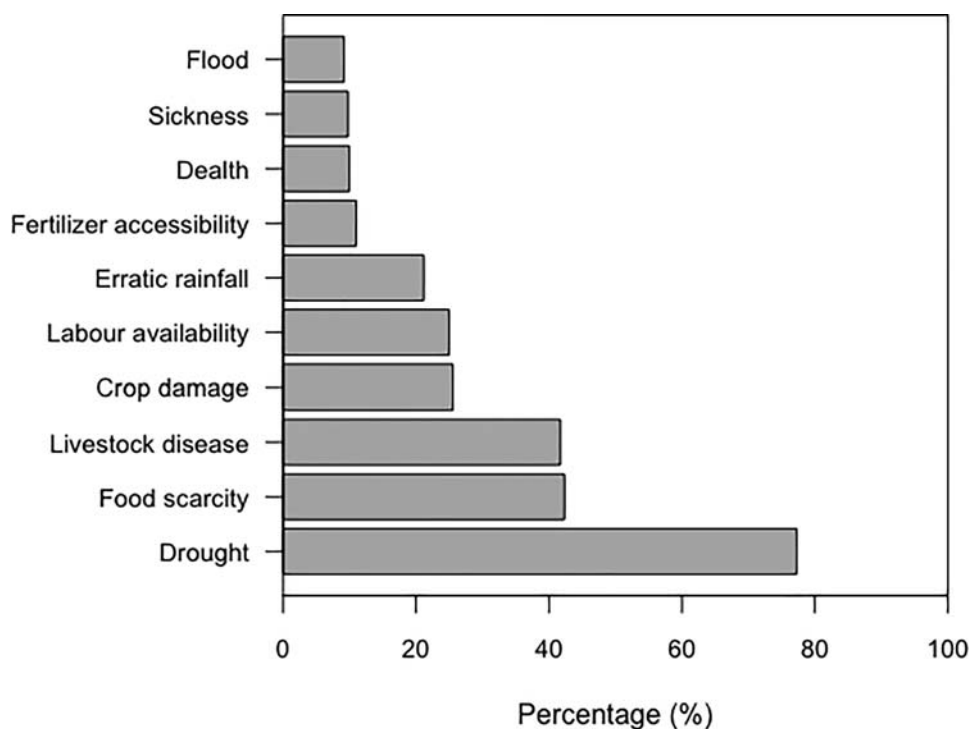


Figure 4. Diversity of stressors/shocks experienced by surveyed households.

greater than one and accounted for 61.20% of the total variance (Figure S1). In addition to these first 12 PCs, the next four components with eigenvalues close to 1 (above 0.9) were included in order to increase the total variance to be used in the further analysis. The first 16 components accounted for 71.61% of the total variance and were considered in the clustering analysis. Supplementary Material Figure S1 presented the eigenvalues and the percentage of variance explained by the first 16 PCs included in the cluster analysis. Supplementary Material Table S2 presented the correlation of the indicator variables with the first five principal components. Supplementary Material Figure S2 illustrated the quality of representation of these variables on the principal components.

The results of the feasibility of clustering analysis performed confirmed that there is a cluster structure in the data (Supplementary Material Figure S3). The dark diagonal blocks in Supplementary Material Figure S3 clearly indicate the presence of clusters, as well as the isolated singleton in data. The Hierarchical Clustering on Principal Component (HCPC) analysis showed three clusters or archetypes of household vulnerability patterns (Figure 5). This was supported by the analysis of the dendrogram (Figure 6), which clearly revealed three classes. Cluster validity analysis performed using the silhouette method indicated the average silhouette width was maximized when the number of clusters was three (Supplementary Material Figure S4). The highest average silhouette width is 0.4, indicating that households have been acceptably clustered in each archetype.

The most discriminant indicators of household vulnerability patterns were related to socio-demographic status (education and number of household productive members), livelihood strategies (all the three indicators, see Table 2), household resources (all the indicators, see Table 2), food security (all

the indicators, see Table 2), water security (diversity of water source and water sufficiency), social network (membership of CBOs and diversity of CBOs), physical accessibility (road practicability), and health and sanitation (drinking water quality, toilet facility quality, illness and average time to health facility). Indicators that were not discriminant included variables related to environmental and socio-economic stressors. In addition, a Chi-square test of independence indicated that there was no dependence between vulnerability archetypes and either overall stressors (Chi-squared = 20.845, $df = 18$, p -value = 0.287), environmental stressors (Chi-squared = 13.802, $df = 8$, p -value = 0.087) or socio-economic stressors (Chi-squared = 6.2593, $df = 8$, p -value = 0.618). This result indicated that stressors were not specific to any archetypes and that households were similarly exposed to stressors across communities.

Table 2 presents the description of the three vulnerability archetypes according to the discriminant vulnerability indicator variables. Vulnerability archetype 1 was composed of households with low resource endowments and limited livelihood activities and comprised 43.31% of surveyed households. Households in this vulnerability archetype had smaller land holdings (9.40 ± 3.66 ha, $p < 0.001$), fewer livestock (4.38 ± 4.18 TLU, $p < 0.001$) and less agricultural equipment (number of ploughs, drought animals, carts, donkeys, seed drills, and pesticide sprayers; $p < 0.001$, Table 2) than average. They had limited productive household members (6.88 ± 3.58 , $p < 0.001$), were involved in few livelihood activities (2.68 ± 0.88 , $p < 0.001$), especially agricultural livelihood activities (1.91 ± 0.71 , $p = 0.023$), cultivated lower numbers of crops (9.22 ± 2.93 , $p < 0.001$), had limited water sources to satisfy household needs (1.04 ± 0.19 , $p < 0.001$) and belonged to fewer farmer- or community-based organization (1.11 ± 0.49 , $p < 0.001$). About 75% of households in vulnerability archetype 1 also did not have access to an improved drinking

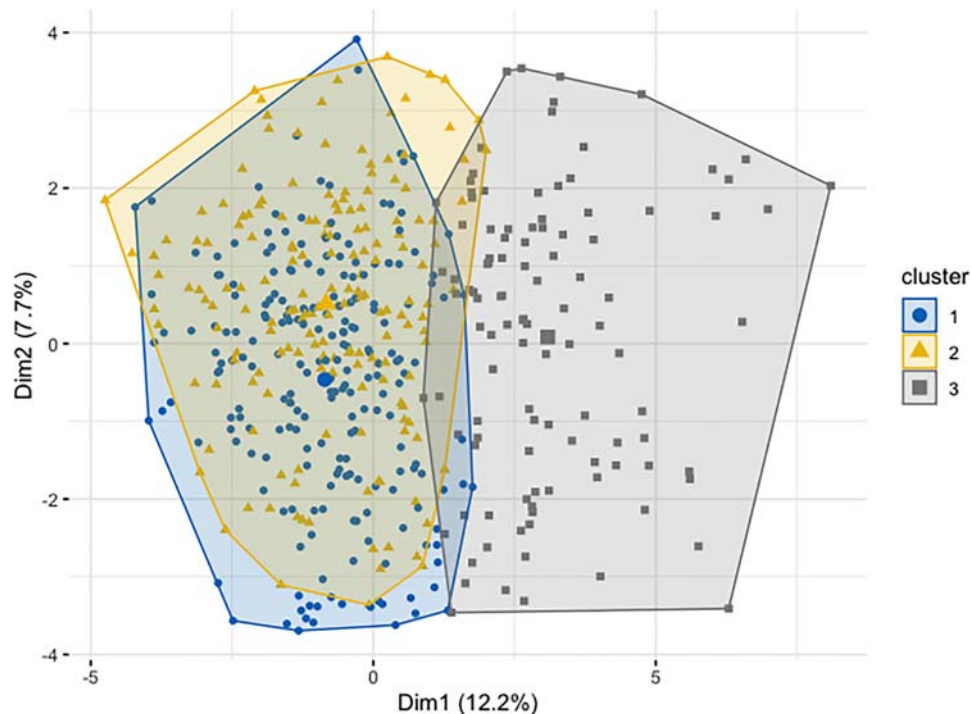


Figure 5. Archetypes of household vulnerability patterns.

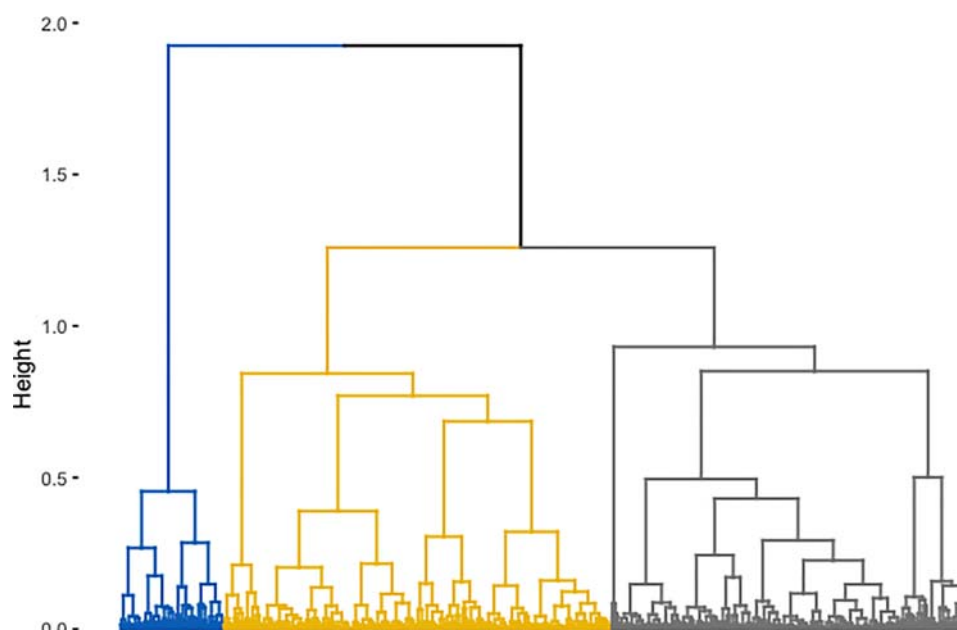


Figure 6. Dendrogram showing the grouping of households into vulnerability archetypes.

water source ($p < 0.001$, Table 2). About 28% of households that buy more food to supplement their own production to satisfy household needs belong to vulnerability archetype 1 ($p < 0.001$, Table 2). This archetype can be characterized as a mildly vulnerable archetype.

Vulnerability archetype 2, which is composed of 35.13% of surveyed households, was also composed of households with low resource endowments and limited livelihood activities (Table 2) but was characterized by prevalent food insecurity conditions. Households in vulnerability archetype 2 had smaller land holdings (9.71 ± 4.49 ha, $p < 0.001$), fewer livestock (3.79 ± 3.75 TLU, $p < 0.001$) and less agricultural equipment (number of ploughs, drought animals, carts, donkeys, seed drills, and pesticide sprayers; $p < 0.001$, Table 2) than average households. They had limited productive household members (7.45 ± 4.22 , $p < 0.001$), and were involved in fewer livelihood activities (2.65 ± 0.87 , $p < 0.001$), particularly non-agricultural livelihoods activities (0.66 ± 0.64 , $p < 0.001$). More than 81% of households in vulnerability archetype 2 were not food secure and were unable to feed their households with their own production all the months of the year ($p < 0.001$). The number of months in which households of this vulnerability archetype did not have sufficient food to satisfy household needs was higher than the average (2.39 ± 1.71 vs. 1.97 ± 1.64 , $p < 0.001$). About 58% of households that bought more food to supplement their own production to satisfy household needs belong to vulnerability archetype 2 ($p < 0.001$, Table 2). Only about 14% of households in this vulnerability archetype produced enough food to satisfy household needs ($p < 0.001$). More than 98% of households in this vulnerability archetype used both improved and non-improved drinking water sources and more than 69% of them did not have access to improved toilet facilities ($p < 0.001$). Households in this archetype had, however, more water sources than average households or households in other archetypes (2.07 ± 0.26 , $p < 0.001$) and about 53% of them had enough water to satisfy household needs year-round ($p = 0.001$, Table 2). Compared to other

archetypes, vulnerability archetype 2 was composed of less educated households: about 48% of them received no education and almost 50% of households with no education belong to this archetype, while only about 12% of them received primary education. Households in this vulnerability archetype can be characterized as highly vulnerable.

Vulnerability archetype 3 included 21.56% of surveyed households and was composed of households with high resource endowments and livelihood activities, and a diverse social network, and food secure households (Table 2). Households in this vulnerability archetype had larger land holdings (18.88 ± 6.39 ha, $p < 0.001$), larger (14.34 ± 8.68 TLU, $p < 0.001$) and diverse livestock resources (3.96 ± 0.79 livestock type, $p < 0.001$), and more agricultural equipment (number of ploughs, drought animals, carts, donkeys, seed drills, and pesticide sprayers; $p < 0.001$, Table 2) than average. They had more productive household members (15.83 ± 9.10 , $p < 0.001$), and were involved in a larger variety of livelihood activities (3.23 ± 1.02 , $p < 0.001$), both agricultural (2.15 ± 0.80 , $p = 0.023$) and non-agricultural (1.08 ± 0.72 , $p < 0.001$). About 99% of households in vulnerability archetype 3 were members of at least one farmer- or community-based organization ($p = 0.041$, Table 2), with most of them having more diverse membership than average (1.44 ± 0.60 , $p < 0.001$). They cultivated a higher number of crops (12.68 ± 3.55 , $p < 0.001$) and reported fewer months than average (1.37 ± 1.44 , $p < 0.001$) in which households did not have sufficient food to satisfy household needs. Households in this archetype either produced enough food to satisfy household needs year-round (about 38% of households in the archetype) or supplemented an amount of food lower than their own production from external sources (about 55% of households in the archetype). About 43% of households in this archetype were food self-sufficient ($p < 0.001$, Table 2). However, more than 66% of households in this archetype did not have enough water to satisfy household consumption needs year-round ($p = 0.001$,

Table 2. Characterization of household vulnerability patterns based on discriminant indicators.

Indicators	Modalities	Cluster 1 (43.31% HH)	Cluster 2 (35.12% HH)	Cluster 3 (21.56% HH)	Global average or percentage	p-value
Education	None		49.71 (48.30)	12.87 (20.37)	34.13	<0.001
	Literacy		28.28 (23.30)	28.28 (37.96)	28.94	
	Primary		22.86 (13.64)		20.96	
Household productive members		6.88 (3.58)	7.45 (4.22)	15.83 (9.10)	9.01 (6.52)	<0.001
Agricultural livelihood diversity		1.91 (0.71)		2.15 (0.80)	1.99 (0.74)	0.023
Non-agricultural livelihood diversity			0.66 (0.64)	1.08 (0.72)	0.80 (0.68)	<0.001
Livelihood diversity		2.68 (0.88)	2.65 (0.87)	3.23 (1.02)	2.79 (0.94)	<0.001
Agricultural land		9.40 (3.66)	9.71 (4.49)	18.88 (6.39)	11.55 (6.04)	<0.001
Livestock (TLU)		4.38 (4.18)	3.79 (3.75)	14.34 (8.63)	6.32 (6.80)	<0.001
Diversity of livestock type		3.03 (1.43)	2.99 (1.47)	3.96 (0.79)	3.22 (1.39)	<0.001
Number of plough		1.86 (1.07)	1.81 (1.08)	3.58 (1.79)	2.21 (1.45)	<0.001
Number of draught animal		2.29 (1.25)	2.23 (1.35)	4.74 (1.73)	2.79 (1.73)	<0.001
Number of donkey		1.22 (0.63)	1.19 (0.83)	2.45 (1.18)	1.48 (0.99)	<0.001
Number of cart		1.04 (0.36)	1.01 (0.35)	1.84 (1.06)	1.20 (0.67)	<0.001
Number of pesticide sprayer		0.52 (0.55)	0.64 (0.66)	1.28 (0.65)	0.72 (0.68)	<0.001
Number of seed drill		0.47 (0.52)	0.49 (0.51)	1.04 (0.53)	0.60 (0.57)	<0.001
CBOs membership	Yes			22.67 (99.07)	94.21	0.041
	No			3.45 (0.93)	5.79	
Diversity of CBOs membership		1.11 (0.49)		1.44 (0.60)	1.19 (0.56)	<0.001
Road practicability	Not practicable year-round	66.67 (10.14)	12.12 (2.27)		6.59	0.015
	Practicable year-round		38.53 (74.43)		67.86	
Source of household food	Own production [1/3] + Purchase [2/3]	28.07 (7.37)	57.89 (18.75)		11.38	<0.001
	Own Production		18.90 (13.64)	32.28 (37.96)	25.35	
	Own production [2/3] + Purchase [1/3]			18.61 (54.63)	63.27	
Food self-sufficiency	Not food self-sufficient		39.67 (81.82)	17.08 (57.41)	72.46	<0.001
	Food self-sufficient		23.19 (18.18)	33.33 (42.59)	27.54	
Number of month with insufficient food			2.39 (1.71)	1.37 (1.44)	1.97 (1.64)	<0.001
Crop diversity		9.22 (2.93)		12.68 (3.55)	10.42 (3.64)	<0.001
Drinking water quality	Improved	77.46 (25.35)	2.82 (1.14)		14.17	<0.001
	Not Improved	78.26 (74.65)	0.00		41.32	
	Both	0.00	78.03 (98.86)		44.51	
Toilet facility quality	Not Improved		40.13 (69.32)	14.14 (39.81)	60.68	<0.001
	Improved			28.76 (40.74)	30.54	
	Both		11.36 (2.84)	47.73 (19.44)	8.78	
Illness (Health case number)			1.45 (1.76)	2.50 (2.80)	1.99 (2.28)	<0.001
Average time to health facility		13.27 (11.47)	17.03 (14.77)		14.61 (13.02)	0.009
Diversity of water source		1.04 (0.19)	2.07 (0.26)		1.52 (0.57)	<0.001
Water sufficiency	Water sufficient		44.34 (53.41)	16.98 (33.33)	42.32	0.001
	Not water sufficient		28.37 (46.59)	24.91 (66.67)	57.68	

Table 2); only 33% of them were water secure. This vulnerability archetype was composed of fewer households with no education (20.37%) and more literate households (37.97%). Households in this vulnerability archetype can be characterized as less vulnerable.

4.4. Distribution of vulnerability archetypes across community

Figure 7 showed the distribution of the three vulnerability archetypes across the study communities. Except in one community (Zankorola) where only two archetypes were identified, all the three vulnerability archetypes were represented in all the 10 study communities. While the medium vulnerability archetype is the most represented (with 43.31% of surveyed households) followed respectively by high (35.13% of surveyed households) and low (21.56% of surveyed households) vulnerability archetypes, their distribution varied across community (see Figure 7). Chi-square test of independence indicated that there was a significant association between archetypes and community

(Chi-squared = 144.12, df = 18, p -value < 0.001). High vulnerable households were more represented respectively in Danzana (70% of the surveyed households), Diela (63%), Ntossini (51%) and Mpessoba (48%). Zankorala seems to be better off with only medium (75%) and less (25%) vulnerable households. In addition to Zankorala, medium vulnerable households were more represented in Oudiala (78%), Zanzoni (64%) and Dentiola (48%). In Ntiosso, the three archetypes are fairly distributed with respectively 43%, 29% and 27% of high, low and medium vulnerability households. A similar observation is also made in Fonfana with respectively 46%, 30% and 24% of high, low and vulnerability households (Figure 7).

5. Discussions

5.1. Diversity of climatic and non-climatic stressors

Our findings highlight the diversity of stressors to which households are exposed to in the study area. Drought was the most mentioned stressor in the study area, confirming previous

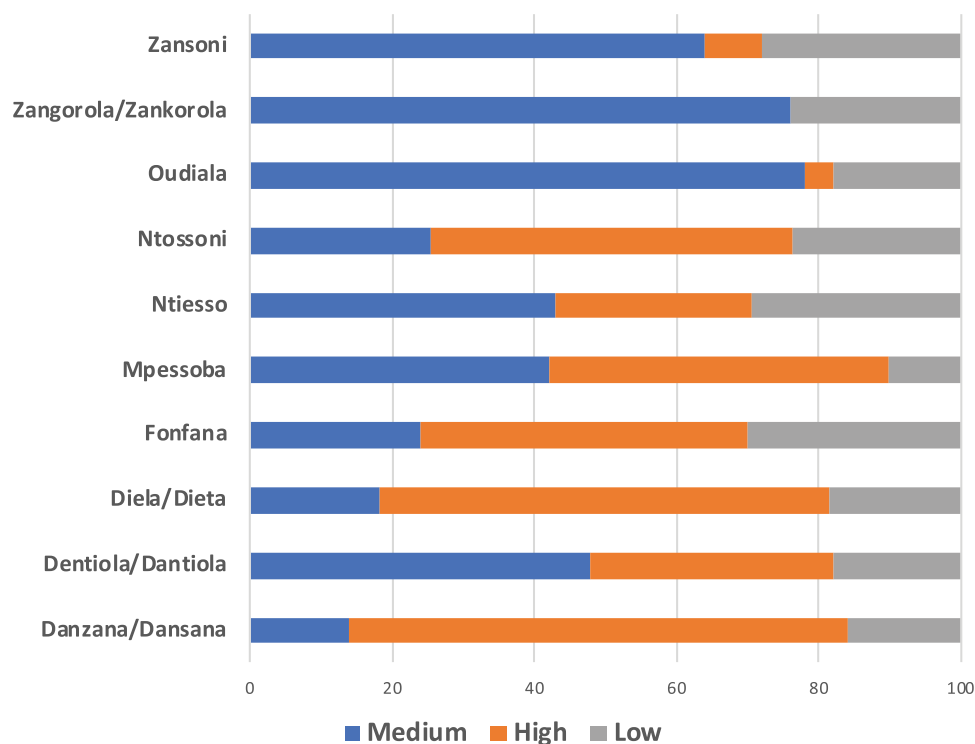


Figure 7. Distribution of vulnerability archetypes across the study communities.

studies that have reported drought as the most important climatic stressor in SARs of West Africa (Epule et al., 2018; Gautier et al., 2016). The second most mentioned stressor was food insecurity. This is consistent with previous studies highlighting the association between food insecurity and high vulnerability in Africa (McDowell et al., 2016; Williams et al., 2018). While climatic stressors, namely drought, were the most mentioned, households were also exposed to a wide range of climatic and non-stressors, including food scarcity, livestock disease, labour unavailability, crop damage, inaccessibility to fertilizer, erratic rainfall patterns, and death or sickness of a household member. Climatic stressors were just one among many challenges. Indeed, a recent systematic review of climatic stressors in the SARs of West Africa has shown that while climatic drivers are dominant, there is, however, an increasing recognition of the influential role of non-climatic stressors (Epule et al., 2018). Our findings emphasized the interconnections between multiple climatic and non-climatic stressors to which households are vulnerable in this region and contribute to the increasing and growing ‘multiple stressors’ studies in sub-Saharan Africa (Ahmed et al., 2016; Antwi-Agyei et al., 2017; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Räsänen et al., 2016; Williams et al., 2018). Multiple non-climatic stressors operating at different scales drive vulnerability (Räsänen et al., 2016) and climate change intersects with many socio-ecological challenges that smallholder farmers are facing in SARs (Ahmed et al., 2016; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Ouédraogo et al., 2016).

5.2. Heterogeneity in household vulnerability patterns

Indicator-based vulnerability assessments typically use aggregation methods to compute a composite index at a given

scale (country, region, sub-region or community) (Hahn et al., 2009; Hinkel, 2011; Tonmoy et al., 2014; Vincent & Cull, 2014). This fails to capture intra- or within scale differential vulnerability and treats community or sub-region as homogeneous. The vulnerability pattern approach used in this study to construct vulnerability archetypes illustrated the heterogeneity in household vulnerability patterns within and across communities (see Figure 7). All the three vulnerability archetypes identified were represented in all the 10 study communities. This implies that households are not uniform or homogeneous in terms of vulnerability to climatic and non-climatic risks both within and across communities. Within the same community, high, medium and low vulnerability household can be present. By revealing and describing patterns in household vulnerability, our study contributes to the growing bodies of studies that operationalize vulnerability pattern approach through archetype analysis in various contexts across the world (see Akohoue et al. (2018); Kok et al. (2016); Nazari Nooghabi et al. (2019); Sietz et al. (2011); Sietz et al. (2012); Vidal Merino et al. (2019)).

5.3. Drivers of household vulnerability patterns

We found that key determinants of household vulnerability patterns were socio-demographic status, livelihood strategies, household resource endowments, food security, water security, social network, physical accessibility, and health and sanitation. Exposure to stressors was not discriminant. This implies that household vulnerability patterns in the study area were mainly shaped by household adaptive capacity and sensitivity. The non-association between vulnerability

archetypes and stressors implies that household exposure to stressors was similar across the archetypes and communities. These findings confirmed that differential vulnerability can be explained not just by the difference in exposure to climate-related and environmental hazards but largely by social and economic processes (Thomas et al., 2019). Our findings are, however, inconsistent with Nazari Nooghabi et al. (2019) results, where drought was a key vulnerability-driving factor for one of the three wheat farmer vulnerability archetypes in Northeast Iran. Socio-economic drivers were key vulnerability factors for the two other archetypes (Nazari Nooghabi et al., 2019).

Thomas et al. (2019) identified four broad themes – resource access, governance, culture, and knowledge – as useful in explaining differential local-scale vulnerability. In our study, resource access and knowledge were key determinants of differential vulnerability patterns. Resource endowments (agricultural land, livestock and agricultural equipment in this study) are one crucial factor that shapes people's ability to plan for and respond to climate change challenges (Thomas et al., 2019). Resource endowments influence vulnerability by reducing or increasing exposure, sensitivity, and adaptive capacity (Thomas et al., 2019). Marginalization and deprivation arising from social stratification play important roles in unequal access to resources, which in turn explains differential sensitivity to and capacity to respond to climate impacts (Thomas et al., 2019). Knowledge and information interact, directly and indirectly, with vulnerability to climate change by shaping peoples' adaptive capacity, exposure, and sensitivity (Thomas et al., 2019). Different types and sources of information and modes of knowledge transmission affect how people understand, perceive, and act on information (Thomas et al., 2019). While information is necessary, it is not alone sufficient for reducing vulnerability (Thomas et al., 2019).

In the study area, household socio-demographic characteristics such as household size or number of productive household members determined household ability to respond to various socio-ecological challenges such as labour availability, ability to produce enough food (in terms of diversity and quantity) to ensure food security, household members' sickness or death. In fact, family labour, especially child labour, is still playing an important role in West African farming systems, and elsewhere in Africa. Indeed, according to the 2016 Global Estimates of Child Labor, the agriculture sector accounts for 85% of all child labour in Africa (ILO, 2017). For instance, one of the main drivers of farmers' decisions to adopt, as well as to intensify the use of soil and water conservation practices to adapt to climate change in SARs of West Africa is the presence of children in the household (Kpadonou et al., 2017). The household labour force is also one of the key drivers of the adoption of climate-smart technologies and practices in southern Mali (Ouédraogo et al., 2019). These highlight how crucial household size and labour are for household adaptive capacity in the region.

Previous research has shown that vulnerability in SARs of Africa is gendered differentiated (Rao et al., 2019). As female-headed households were rare in our study area context, our analysis was unable to reveal gender-differentiated vulnerability patterns. A replication of our approach in a context

where female-headed households are culturally accepted and common might provide better insights regarding gender and household vulnerability patterns. Consistently with previous studies highlighting the association between food insecurity with high vulnerability in Africa (McDowell et al., 2016; Williams et al., 2018), our findings also showed that food insecurity was a key determinant of vulnerability patterns.

6. Conclusions

This study analysed the diversity of stressors experienced by smallholder farmers in SARs of Mali and provided a typology or archetype of household vulnerability. The combined vulnerability patterns and MLVI approaches used in this study to construct archetypes of vulnerability offer a pragmatic way to reveal the heterogeneity in household vulnerability to both climatic and non-climatic stressors within and across communities. The findings showed that while climatic stressor, mainly drought, was the most reported stressor, households in the study were exposed to a diversity of environmental and socio-economic shocks, including food scarcity, livestock disease, labour unavailability, crop damage, inaccessibility of fertilizer, erratic rainfall patterns, death or sickness of a household member. Climatic stressors or risks were just one among many socio-ecological challenges facing smallholder farmers in SARs. The typology revealed three household vulnerability archetypes differentiated by adaptive capacity and sensitivity dimensions, implying that households were similarly exposed to stressors. Availability of productive household members, household resource endowments (agricultural land, livestock and agricultural equipment), livelihood diversification and social networks are the main discriminant factors of household adaptive capacity. Challenges to get sufficient food and water to satisfy household needs throughout the year make households more sensitive to stressors. The analysis also highlighted the heterogeneity in household vulnerability patterns within and across communities and the context-specific driving forces of vulnerability in SARs. Failing to account for this heterogeneity in vulnerability patterns across scales and nuanced understanding of context-specific drivers in adaptation planning might result in a mismatch between adaptation needs and interventions, and potentially in maladaptation.

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Disclosure statement

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
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