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Climate risk and food security in Mali: A historical perspective on adaptation

Alessandra Giannini[1], **P. Krishna Krishnamurthy**[2], **Rémi Cousin**[1], **Naouar Labidi**[2], and **Richard J. Choularton**[2]

[1]International Research Institute for Climate and Society, Earth Institute at Columbia University, Palisades, New York, USA, [2]United Nations World Food Programme, Rome, Italy

Key Points:
- The effects of multidecadal drought are still felt in the Malian Sahel
- Livelihood diversification has positive effects on food security
- Adaptation needs to address an increasingly variable climate, on subseasonal and interannual timescales

Corresponding author:
A. Giannini, alesall@iri.columbia.edu

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Abstract We combine socioeconomic data from a large-scale household survey with historical climate data to map the climate sensitivity of availability and access dimensions of food security in Mali, and infer the ways in which at-risk communities may have been impacted by persistent climatic shift. Thirty years after 1982–1984, the period of most intense drought during the protracted late 20th century drying of the Sahel, the impact of drought on livelihoods and food security is still recognizable in the Sahelian center of Mali. This impact is expressed in the larger fraction of households in this Sahelian center of the country—the agro-ecological transition between pastoralism in the north, and sedentary agriculture in the south—who practice agriculture but not livestock raising, despite environmental conditions that are suitable to their combination. These households have lower food security and rely more frequently on detrimental nutrition-based coping strategies, such as reducing the quantity or quality of meals. In contrast, the more food secure households show a clear tendency toward livelihood diversification away from subsistence agriculture. These households produce less of what they consume, yet spend less on food in proportion. The analysis points to the value of interdisciplinary research—in this case bridging climate science and vulnerability analysis—to gain a dynamical understanding of complex systems, understanding which may be exploited to address real-world challenges, offering lessons about food security and local adaptation strategies in places among the most vulnerable to climate.

1. Introduction: Climate Influences Malian Livelihoods

The West African Sahel became a globally recognized political entity following famine in the early 1970s [*Mann*, 2015], when it endured the most outstanding, abrupt climatic shift of the instrumental record [*Greene et al*., 2009] in the sudden onset of persistent drought. Evidence is accumulating that anthropogenic contribution to this shift may have been significant, and attributable to the effect of sulfate aerosol-induced cooling of the North Atlantic [*Rotstayn and Lohmann*, 2002; *Chang et al*., 2011; *Booth et al*., 2012], which aggravated greenhouse gas-induced warming of the tropical oceans [*Giannini et al*., 2003; *Held et al*., 2005; *Du and Xie*, 2008]. Continued drought is not a warranted outcome of global anthropogenic interference with the climate system [*Giannini et al*., 2013], as the most recent years of repeated regional flooding suggest [*Tschakert et al*., 2010]. However, the magnitude and severity of the Sahelian drought of the 1970s and 1980s, and its impact on agricultural development strategies and on food security provide an opportunity to examine the relationship between climate and livelihoods and to build an evidence base of adaptation options available to at-risk populations in a context of increasing exposure and sensitivity to a highly variable climate.

The quest to better understand the relationship between climate and food security is made all the more relevant by the recent repeated crises in East Africa (2011) and the Sahel (2012), and by the current condition of large regions of southern Africa. In the wake of a strong El Niño event, the latter is characterized as "stressed/crisis" based on the Integrated food security Phase Classification (http://www.fao.org/docrep/010/i0275e/i0275e.pdf). These events underscore the role of climate anomalies in triggering food insecurity in semiarid sub-Saharan Africa.

This case study focuses on Mali, a large, land-locked country at the heart of the West African Sahel spanning the latitudinal transition from desert in the north, through semiarid (Sahelian) grassland in the center, to wooded (Sudanian) savanna in the south. As is the case for its immediate land-locked neighbors — Burkina Faso and Niger — the Malian economy is still largely dependent on agriculture, measured by the contribution of agriculture to national gross domestic product (36.9% in 2006; *World Bank*, 2015). A majority of the population engages in agriculture (66% in 2006; *World Bank*, 2015), and derives the largest fraction of income from agricultural production, a median value of 70% of income among the rural households surveyed here. Mali and its neighbors are among a minority of sub-Saharan African countries which have met or surpassed the target of 10% of government expenditures going to agricultural development set by the Africa Union's Comprehensive Africa Agriculture Development Program (http://www.resakss.org/map/). Yet, apart from irrigated rice, agricultural production in Mali is rainfed, and therefore highly sensitive to climate [*Butt et al*., 2005; *Government of Mali*, 2007].

Remarkably, staple crop production has risen steadily since the early 1970s — the driest period in the instrumental record — an observation that alone calls into question simple extrapolations which equate the impact of climate change on food security to that on agricultural productivity or production. Cereal production has increased at the same rate as population over the last decade, with imports contributing to only 5% of the national cereal budget, and dependence on food aid has decreased from 4 kg of cereal per person in 1990 to 0.5 kg/person in 1999 [*Réseau de Prévention des Crises Alimentaires* (*RPCA — Food Crisis Prevention Network*, 2011]. These aspects all contributed to the resilience shown by Malian households to the 2008 global food price crisis [*Moseley*, 2011; *Smale et al*., 2011].

Nevertheless, climate, especially rainfall, remains a major determinant of livelihood classification [*FEWSNET*, 2016]. Figure 1a illustrates this relationship. The 400 mm/year rainfall climatology contour broadly demarcates the limit between agriculture-based and pastoralist livelihoods. The desert north livelihood zones (1 – 2), to the north of this contour, receive less than 400 mm/year, hence have historically relied on pastoralism and trans-Saharan trade. Agriculture becomes possible in the Sahelian center (livelihood zones 3 – 9), which receives between 400 and 800 mm/year of precipitation. In the Sudanian south (livelihood zones 9 – 11), more than 800 mm/year of precipitation make it possible to cultivate cotton, a historically important cash crop.

The 600 mm/year contour further divides the Sahelian center of Mali, characterized by the transition between predominance of pastoralism and agriculture, into two main livelihood zones; rainfed millet/sorghum and millet/transhumant herding. In this Sahelian center further livelihood complexity is introduced by exploitation of water resources, whether small- (such as the inner delta and flood plains of the Niger River) or large-scale (such as the irrigation schemes of the *Office du Niger*). The Sahelian center is the focus of our analysis. In administrative terms (Figure 1b), it includes the northern portions of Kayes, Koulikoro and Ségou regions, the entire Mopti region, and the southernmost portions of Timbuktu and Gao regions.

The context of our analysis is the significant, recognized large-scale vulnerability of livelihoods to climate. We adopt the definition of vulnerability espoused by Working Group II of the Intergovernmental Panel on Climate Change (reviewed in *Adger*, 2006), which decomposes vulnerability into exposure, sensitivity, and adaptive capacity. We set out to inform the problem of how to objectively identify households that can be made food insecure by climate events, with both short-term, "crisis" intervention, and longer-term, adaptation planning in mind. We present a high-resolution analysis of the climate sensitivity of availability and access dimensions of food security in Mali, based on an extensive household survey. Again, "sensitivity" is that component of vulnerability that is related to socioeconomic attributes that define the inability to cope with an impact, and is complementary to the physical "exposure" to such impact [*Adger*, 2006; *Ribot*, 2010]. The exposure considered here is that of rural Malian livelihoods to climate variability and change, as manifest in late 20th century drought.

We describe data and methodology in Section 2 and the analysis in Section 3. In Section 3.1 we review the temporal relationship between national-scale agricultural production and climate. In section 3.2 we describe the spatial impact of the late 20th century persistence of drought on livelihoods in the Sahelian center of Mali. In Section 3.3 we relate the availability and access dimensions of food security, whether aggregated geographically at the scale of livelihood zones or statistically by means of cluster analysis, to patterns of livelihood diversification and expenditure. We conclude in Section 4, with an overview of lessons learned in adaptation.

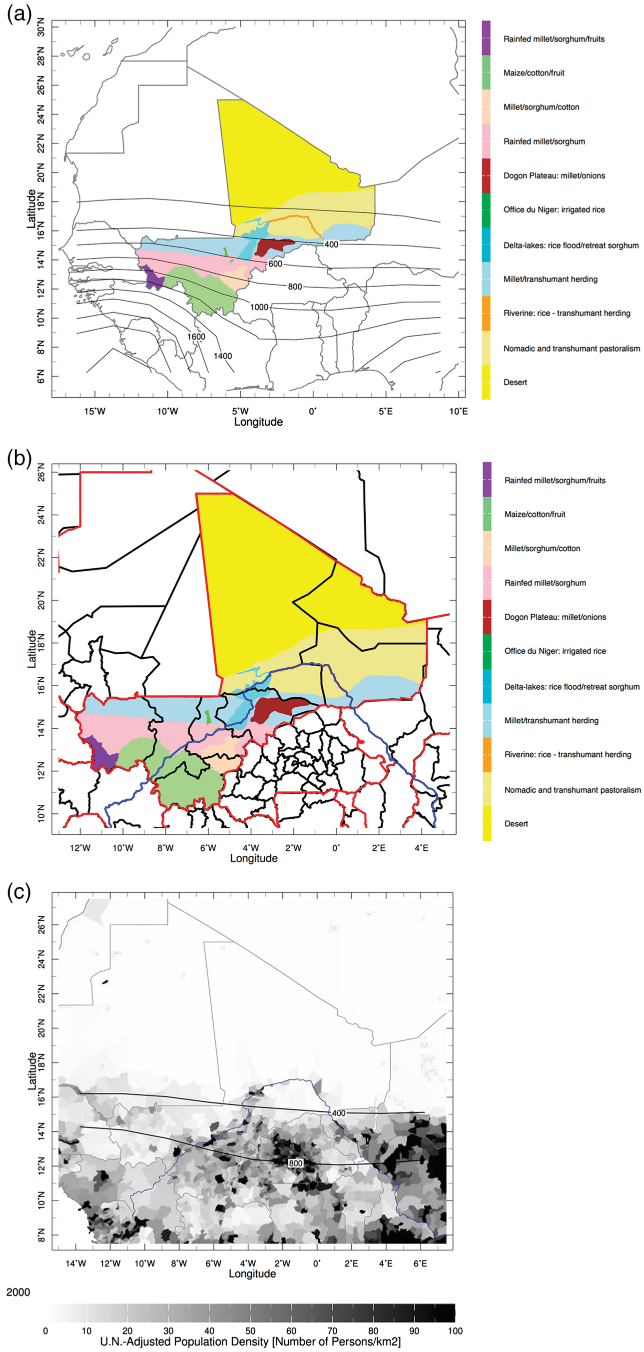

Figure 1. Livelihoods, climate and demography of Mali. (a) livelihood zones as defined by the Famine Early Warning Systems Network in 2005, in colour, overlaid by the 1979–2007 precipitation climatology from GPCP [*Adler et al*., 2003] with contour every 200 mm/yr. (b) The same livelihood zones as in (a), but overlaid by the administrative boundaries of the eighth named régions. (c) Population density in 2000, in shading, from Global Population of the World—Version 3 [*Balk et al*., 2005], overlaid by the 400 and 800 mm/yr rainfall climatology contours.

2. Data and Methods: The CFSVA in the IRI Data Library

In this study, we exploit household-level data about socioeconomic and food security status. To illustrate the nexus of climate change and food security [*Schmidhuber and Tubiello*, 2007] we analyze household survey entries in two ways, described in greater detail below:

1. We use the livelihood zones as defined by the Famine Early Warning System Network (FEWSNET; see Figure 1) to aggregate the household survey data. Aggregation facilitates the comparison with historical climate information in a geospatial analysis [*Bohle et al*., 1994; *Hyman et al*., 2005; *Jankowska et al*., 2011];
2. We perform cluster analysis at household level to explore the relationships among variables representative of the availability and access dimensions of food security. We then map the spatial variation in the frequency of household cluster occurrence by livelihood zone.

The household survey data come from the 2005 Comprehensive Food Security Vulnerability Analysis (CFSVA) collected in Mali. A CFSVA [*UN World Food Programme*, 2009] is an extensive household survey to characterize the spatial variation in livelihoods and food security during baseline (noncrisis) conditions. The "non-crisis" condition of a CFSVA here is defined in contrast to an "Emergency Food Security Assessment," which is typically taken "in the event of a natural disaster, conflict or economic shock" (http://www.wfp.org/food-security/assessments/emergency-food-security-assessment). While country CFSVAs are repeated every few years, survey design and data management have only recently become sufficiently homogeneous to warrant comparison in time. For this reason, in this study we highlight the analysis of spatial variation in the patterns of food security captured in one survey, conducted in 2005 in Mali, which included 2074 rural households in 209 villages [*UN World Food Programme*, *UNICEF and Hellen Keller International*, 2005]. The 209 villages were chosen to sample seven homogeneous "classes" or "strata," identified through a Principal Component Analysis of (1) a community poverty index taken from 1998 census data, (2) the agricultural production potential based on data from the national Système d'Alerte Précoce (Early Warning System), and (3) 15 variables describing agro-ecological, demographic, and geophysical conditions based on remote sensing observations [*UN World Food Programme*, *UNICEF and Hellen Keller International*, 2005].

2.1. Geospatial Mapping in Livelihood Zones

The CFSVA data, along with the FAOSTAT [*UN Food and Agriculture Organization*, 2016a] and CountryStat [*UN Food and Agriculture Organization*, 2016b] data, used for this study were obtained in tabular formats. The CFSVA included over 800 socioeconomic variables at the household level, albeit excluding by design any variables that directly measure wealth. In order to analyze these variables, on their own and jointly with climate variables, we imported the survey into the IRI/LDEO Data Library (DL; http://iridl.ldeo.columbia.edu). The DL is a repository allowing for web browser-based analysis and visualization. It unifies datasets from various sources through the use of standardized structures and metadata semantics. Even though it was originally designed and built for climate data, this study provided an opportunity to demonstrate its flexibility in overlaying data characterized by different spatiotemporal dependence, such as point-wise household socioeconomic data and coarse-resolution gridded climate data. After importing the data into the DL, all the DL statistical functions were available to apply to these variables. These functions span in complexity from averages and standard deviations to percentiles, including the median, to correlation and Principal Component or Cluster Analysis. Additionally, GIS capacities in the DL facilitated aggregation and mapping of household-level variables onto geographical geometries such as livelihood zones or administrative boundaries. The unifying capacities of the DL allowed for an integrated geospatial and statistical analysis of climate impacts on food security, as shown here in Figures 1 and 3–7.

2.2. Cluster Analysis

In parallel to the spatial analysis, we applied the version of *Hartigan and Wong's* [1979] k-means algorithm that is implemented in the DL in the function called "k-means136" (http://iridl.ldeo.columbia.edu/dochelp/Documentation/funcindex.html). The procedure performs a singular value decomposition (SVD) to make an educated first guess about the location of the cluster centroids, and iterates until the solution converges.

As SVD operates on variance and the metric for k-means is squared Euclidian distance, the variables analyzed were normalized before being subjected to cluster analysis. This transformation gives equal weight to otherwise potentially very disparate ranges of values. The results were then transformed back into meaningful quantities by multiplying the unitless outputs of cluster analysis by each variable's standard deviation and adding each variable's mean.

3. Analysis

3.1. Climate Impacts Agricultural Production

The evolution of staple crop production (millet, sorghum, maize, and rice) at national scale during the period 1961–2007 (Faostat: *UN Food and Agriculture Organization*, 2016a) is closely linked to rainfall, but more so on the interannual, or year-to-year, than on the longer, interdecadal timescale (Figure 2). The drought and famine of the early 1970s, which came after more than a decade of anomalously wet conditions, and culminated in 1972–1973, coincided with a major decrease in agricultural production. Since that initial shock, national production has been increasing. Even the most severe multiyear drought of the instrumental record (1982–1984) did not have a comparably devastating effect to the 1972–1973 drought. Despite only a partial recovery in precipitation, agricultural production has doubled in the 1990s and tripled in the 2000s with respect to 1961. This long-term increase in agricultural production can be linked to increases in the yield of rice and maize, around 3% per year during 1990–2009 [*Staatz and Boughton*, 2011], and in the area harvested of millet and sorghum [*Giannini et al*., 2012]. These trends have been attributed to various causes, including market liberalization under structural adjustment programs [*Staatz et al*., 1985; *Diarra et al*., 2000], the agro-meteorological assistance program to rural communities led by the *Direction Nationale de la Météorologie* [*Konaté and Traoré*, 1987; *Konaté and Sokona*, 2003; *Diarra and Dibi-Kangah*, 2007], large-scale irrigation in the case of rice [*Staatz and Boughton*, 2011], and extensification associated with population growth [*Bilsborrow*, 1992; *Block*, 2010].

Despite the presence of large, unrelated trends in climate and agricultural production, the interannual coincidence in fluctuations in rainfall and crop production confirms the influence of climate on agricultural output. This influence is captured in a correlation value of 0.73 between year-to-year differences [*Lobell and Field*, 2007] in precipitation and in the total production of millet, sorghum, rice, and maize, statistically significant at greater than 1% level for a series of length approximately 50 years.

3.2. Long-Term Drought Constrained Livelihoods and Food Security

The connection between climate and the availability dimension of food security through agricultural production is relatively immediate, and as such has been extensively explored by climate scientists crossing over into the domain of climate change impacts. However, the relationships between climate, livelihoods and the access dimension of food security are more complex, and intriguing. We focus on the qualitative influence of persistent drought on livelihoods by contrasting the two large Sahelian livelihood zones in the center of Mali, labeled "rainfed millet/sorghum" and "millet/transhumant herding" (Figures 1a, 1b). These

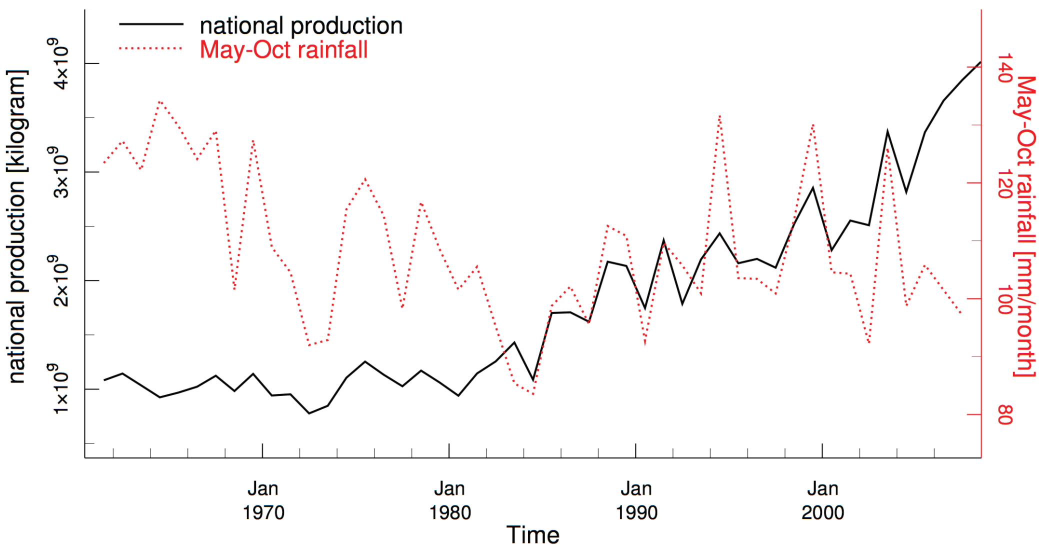

Figure 2. Climate and agricultural production in Mali. Time series of annual production of the main staple crops, in the solid line, and May–October seasonal precipitation, in the dashed line. National agricultural statistics are from the *UN Food and Agriculture Organization* [2016b]. Rainfall data from GPCC [*Rudolf et al*., 1994] is averaged over 12°N–16°N, 15°W–5°E.

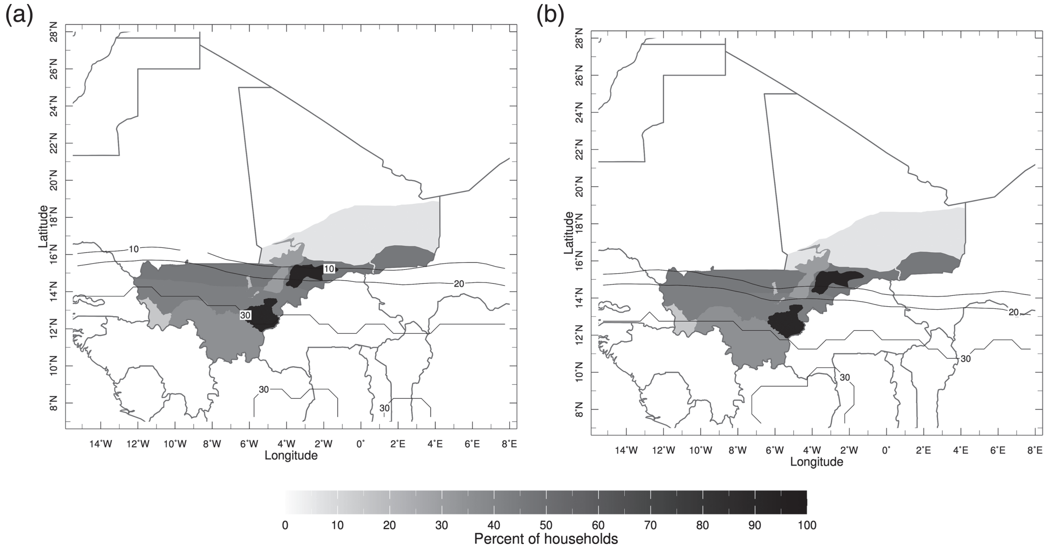

Figure 3. The suitability of millet production across the late 20th century Sahelian climate shift. In contour is the number of years that it rained at least 450 mm [*Mitchell and Jones*, 2005] during the May–October season (a) during the wet 1941–1970 period and (b) during the dry 1971–2000 period, contour is every 10. In shading, the same in both panels, is the percentage of households that produced millet at the time of the CFSVA survey. (Here and in all similar plots, the northernmost "desert" livelihood zone is masked.)

zones represent the transition from the predominance of sedentary agriculture to a mixed livelihood system, which in the inner delta of the Niger River traditionally combined agriculture with transhumant fishing and/or herding [*Davies*, 1996].

Correlations between rainfall and total cereal production (CountryStat: *UN Food and Agriculture Organization*, 2016b) are significant at subnational scale in the only region that falls entirely in the Sahelian center, the administrative region of Mopti. Over 1984–2007 the correlation is significant at 1% level whether detrended or not: the respective values are 0.55 and 0.56.

The climate record shows the progressive deterioration in conditions for agricultural production during the 1970s and 1980s, followed by a partial recovery (Figure 2). We argue that the shift in rainfall climatology affected the sustainability of production of crops such as millet. In the 20th century, Malian climate evolved from a "wet" period between 1941 and 1970 to a "dry" period between 1971 and 2000 [*AGRHYMET*, 2010]. The contours in Figure 3 illustrate the number of years during a given 30-year period when at least 450 mm of rain were accumulated between May and October. The minimum rainfall required to grow millet is 450 mm [*UN Food and Agriculture Organization*, 2016c] assuming no adaptation to make more efficient use of rainfall. During the wet period, 1941–1970, on the left in Figure 3, even the northern millet/transhumant herding zone received sufficient rainfall to produce millet in 20 of 30 years. This pattern shifted entirely during the dry period, 1971–2000, on the right in Figure 3. The 20 years out of 30 contour line (the middle line in Figure 3a) is almost precisely replaced by the 10 of 30 years contour line (the top line in Figure 3b), meaning that this marginal livelihood zone that had been receiving sufficient rains to grow millet in 2 of 3 years during the wet period, received sufficient rainfall in only 1 of 3 years during the dry period. The shift experienced by the millet/transhumant herding livelihood zone, the northern of the two livelihood zones focus of this analysis, represents the most significant impact of persistent drought. Households that were previously capable of storing enough grains to withstand a 1-year drought (one year in three failing) were suddenly and persistently faced with failure in two years out of three as a result of climatic changes [*Davies*, 1996].

Given the reduced capacity to cope with more frequent crises, these households may well have crossed a tipping point, or undergone an irreversible transformation, responding to the loss of livelihood by migrating toward the inner delta, by migrating abroad [*Findley et al*., 1995], or by engaging in alternative livelihood activities [*Davies*, 1996]. The drought-induced erosion of livelihoods in the Sahelian center is clear in the lower percentages of households engaging in both agricultural production and livestock raising (Figure 4).

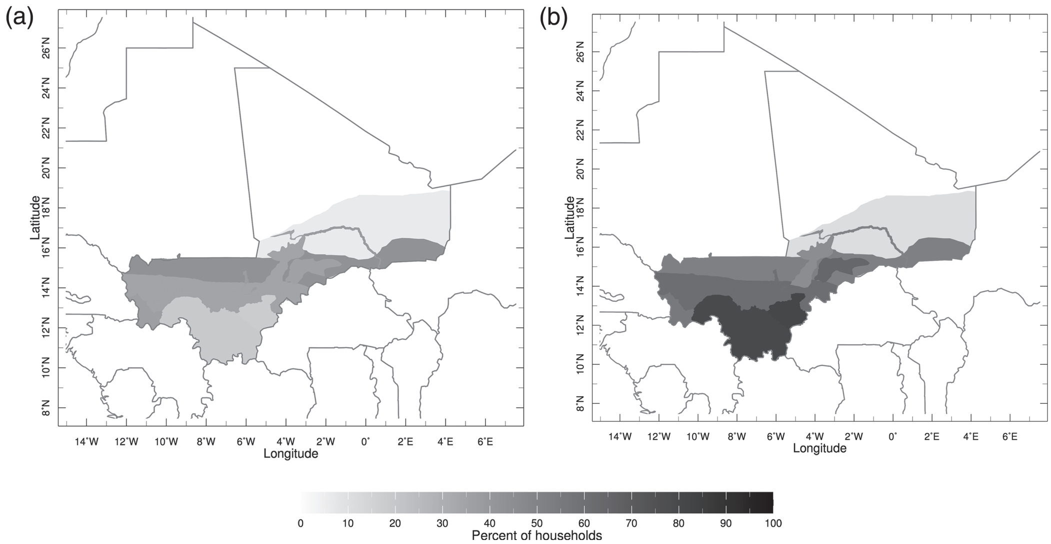

Figure 4. Impact of drought on livelihoods. The proportion of households by livelihood zone that engage in (a) agriculture, but not in livestock raising, (b) both agriculture and livestock raising, aggregated by livelihood zones (excepted the northernmost, "desert" livelihood zone, which is masked).

In the Sahelian center, a greater proportion of households that practice agriculture do not practice livestock raising (Figure 4a), compared to the majority of households in the Sudanian south practicing the two activities in combination (Figure 4b). Overall, 424 of 1176 households (36%) in the livelihood zones of the Sahelian center practice agriculture, but not livestock raising, with the highest percent (43%) in the "millet/transhumant herding" zone, against 135 of 657 (21%) in the livelihood zones of the Sudanian south. We realize that the definition of engaging in "livestock raising" may underscore cultural differences, in the sense that the practice of entrusting livestock to specialized "livestock raisers" is more widespread in the Sahelian center of Mali than in the Sudanian south [*Turner*, 1999; *Powell et al*., 2004]. Therefore we caution that "livestock owners" do not necessarily equate with "livestock raisers." However, in the Sahelian center this interpretation is supported by lower numbers, in the CFSVA survey, in per capita ownership of animals, large and small, or large only, in the northern (millet/transhumant herding) than in the southern (rainfed millet/sorghum) of the two livelihood zones.

In a context where livestock is a key source of income diversification as well as a mechanism for wealth accumulation [*Abdulai and Crole Rees*, 2001; *Barrett et al*., 2001; *Crane*, 2011], we interpret the inability to afford livestock as a result of progressive erosion of wealth, and we associate it with persistent drought. This suggests that in the Sahelian center vulnerable households do not practice livestock raising or own fewer animals because they cannot afford them. These households score consistently lower on a variety of indicators of nutritional and socioeconomic status, as can be seen by comparing them to households that engage in both agriculture and livestock raising (Table 1).

The unique evolution of late 20th century Sahelian climate and its long-term impact on agricultural production and rural livelihoods [*Watts*, 1983] are reflected in the spatial pattern of food security captured in the CFSVA. In the Sahelian center of Mali, food security is higher in the relatively southern/wetter rainfed millet/sorghum livelihood zone than in the millet/transhumant herding zone immediately to its north. This is illustrated by the spatial variation in median household food consumption score [*UN World Food Programme*, 2008], a measure of food frequency and diet diversity over the 7 days prior to the survey (Figure 5a), and in coping strategy index, measured by the percent of households changing nutritional habits due to shocks over the 12 months preceeding the survey (Figure 5b).

3.3. Livelihood Diversification Improves Access to Food and Adaptative Capacity

The geography of food sources is linked to the rainfall climatology: food consumed from own production, that in this largely rural society we interpret to represent the availability dimension of food security, is higher

Table 1. Food Security and Socioeconomic Status Indicators for All Surveyed Households, for Households That Do Not Diversify Economic Activity Beyond Agriculture and/or Livestock, and for Households That Do Diversify.

		All	"Not Diversified"	"Diversified"
Number of households	Agriculture only	566	183	383 (68%)
	Livestock raising only	275	165	110
	Agriculture and livestock raising	1142	794 (70%)	348
Food consumption score	Agriculture only	53	51	54
	Livestock raising only	58	57	61
	Agriculture and livestock raising	57	56	60
Recourse to nutrition-based coping strategies	Agriculture only	29.5	41	24
	Livestock raising only	24	29	16
	Agriculture and livestock raising	24	29	13
Food consumed from own production	Agriculture only	21	19	23
	Livestock raising only	13	13	13
	Agriculture and livestock raising	27	26	29
Expenditures: % food/total (median per capita food, nonfood, total; in local currency [FCFA])	Agriculture only	62 (1626, 1025, 2898)	65 (1843, 1129, 3067)	61 (1554, 920, 2757)
	Livestock raising only	82 (6593, 1424, 8346)	84 (6436, 1128, 7789)	78 (7059, 1980, 9177)
	Agriculture and livestock raising	50 (1503, 1597, 3710)	51 (1565, 1559, 3691)	46 (1396, 1708, 3765)
Percent of households buying food: at harvest, during the dry season, during the agricultural season, at all times	Agriculture only	40, 10, 32, 9	32, 15, 28, 9	44, 8, 34, 9
	(Livestock raising only)	—	—	—
	Agriculture and livestock raising	27, 12, 42, 9	28, 11, 42, 9	24, 15, 43, 11

in the south, compared to that of the north (Figure 6a). This pattern largely mirrors the fact that the wetter, more stable climate for agriculture is in the south, and that as one moves north the climate becomes drier and more variable. On average, the Sudanian south, the more densely populated region (Figure 1c), produces excess millet and sorghum, whereas surplus rice is produced in the Inner Delta of the Niger River, and in the Office du Niger irrigation scheme [*FEWSNET*, 2016].

The comparison between the spatial patterns of food security (Figure 5) and availability (Figure 6a) underlines the apparent limited role of the latter in explaining the former. Here we argue that food access provides a closer approximation of food security. To describe access, we consider two variables: the median number of economic activities that households engage in (Figure 6b), a measure of livelihood diversification, and the season in the year when agricultural purchases are most important, or its derived quantity, the percent of households that buy food at all times (Figure 6c). Taken in isolation, this last measure can be interpreted as a signature of food insecurity: households that cannot produce sufficient food for their own consumption are constrained to buy food at all times [*Staatz and Boughton*, 2011]. However, in conjunction with livelihood diversification, this characteristic can also be interpreted to mean the opposite: in an attempt to reduce vulnerability to climate by diversifying livelihoods away from climate-sensitive agricultural activities households may be exchanging availability (from own production) for higher incomes and access to market, independent of climatic outcomes.

These considerations are synthesized using a k-means cluster analysis [*Hartigan and Wong*, 1979; *Sietz et al*., 2011; *Kok et al*., 2016] of households that combines the two variables depicting food security, that is, food consumption score and coping strategy index (Figure 5), the variable associated with availability, that is, percent of food consumed that comes from own production (Figure 6a), the two variables associated with access, that is, number of economic activities (Figure 6b) and period of most significant food purchase, and two variables characterizing expenditure, and indirect wealth, that is, per capita expenditures on nonfood items, and percent of food expenditures on total (see Section 2 for details on the methodology and its application). The food consumption score can take on values to a maximum of 112, with values

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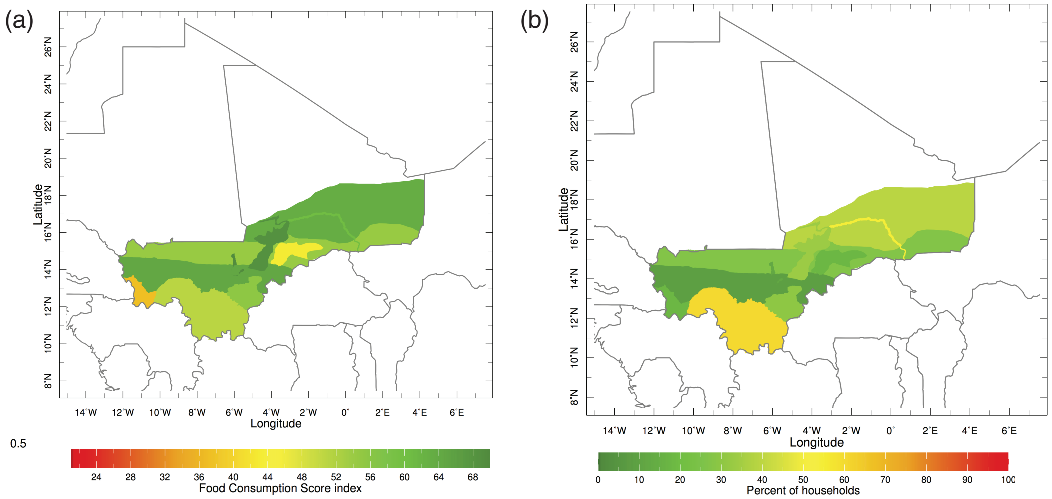

Figure 5. Indices of food security. (a) Median household food consumption score, (b) median household coping strategy index, or portion of households employing a food-related coping strategy, aggregated by livelihood zones. On the red to green colour scale, red denotes low food security, green high food security.

less than 21 classified as poor (food insecure), between 21 and 35 as borderline, and higher than 35 as satisfactory. The coping strategy index is equal to 1 if the household recurs to nutrition-based coping strategies, such as reducing the number of meals or caloric or nutritional intake, equal to 0 if it does not. The number of economic activities ranges between 0 and 4. The period during which agricultural purchases are most important is coded as 1 = at harvest, 2 = during the dry season, 3 = during the following agricultural/rainy season, and 4 = at all times. Per capita nonfood expenditures are entered in the local currency, CFA Francs (the exchange rate between Euro and CFA Franc is fixed, at 1 Euro = 656 CFA Francs).

The analysis excludes households that are exclusively pastoralist, and divides the remaining households, those that practice agriculture, whether in combination with livestock raising or not, into four clusters (Table 2 and Figure 7). Two clusters, 2 and 4, have high food security, that is, high food consumption score and low coping strategy index. They are the most diversified in terms of number of economic activities. Cluster 4, the most food secure, albeit by a small margin when compared to cluster 2, derives a larger proportion of food from own production, and consequently starts buying agricultural products later in the year following harvest. Cluster 2 is the smallest in size, only 70 households compared to 500–600 each in the other clusters, and spends significantly more money on nonfood items, an order of magnitude more in the local currency, spending the least on food as a proportion of the total. Although the CFSVA survey by design does not collect direct measures of wealth, we dub this the "wealthy" cluster.

Cluster 3 is the least food secure—with lowest food consumption score and highest recourse to food-based coping strategies. It is not the least diversified, but it derives the largest proportion of food from own production. It spends the least on nonfood items, though not the highest proportion on food. Cluster 1 is the least diversified. It has intermediate food security, derives the least nutrition from own production, and consistently starts buying agricultural products earliest, closest to harvest, spending the largest proportion on food expenditures. In other words, while less diversified than other clusters that may mix agricultural and other economic activities, it has a profile that suggests migration away from agriculture writ large.

In geographical terms, among the households in the Sahelian center we find that it is the households in the rainfed millet/sorghum zone rather than those in the adjacent zones that have diversified their livelihoods most successfully (Figures 6b and 7d). The food consumption score in this zone (Figure 5a) is higher, while the coping strategy index is lower (Figure 5b), and the proportion of households buying food at all times (Figure 6c) is lower than in adjacent zones. Cluster 4, one of the two food secure clusters, is predominant in this livelihood zone (Figure 7d).

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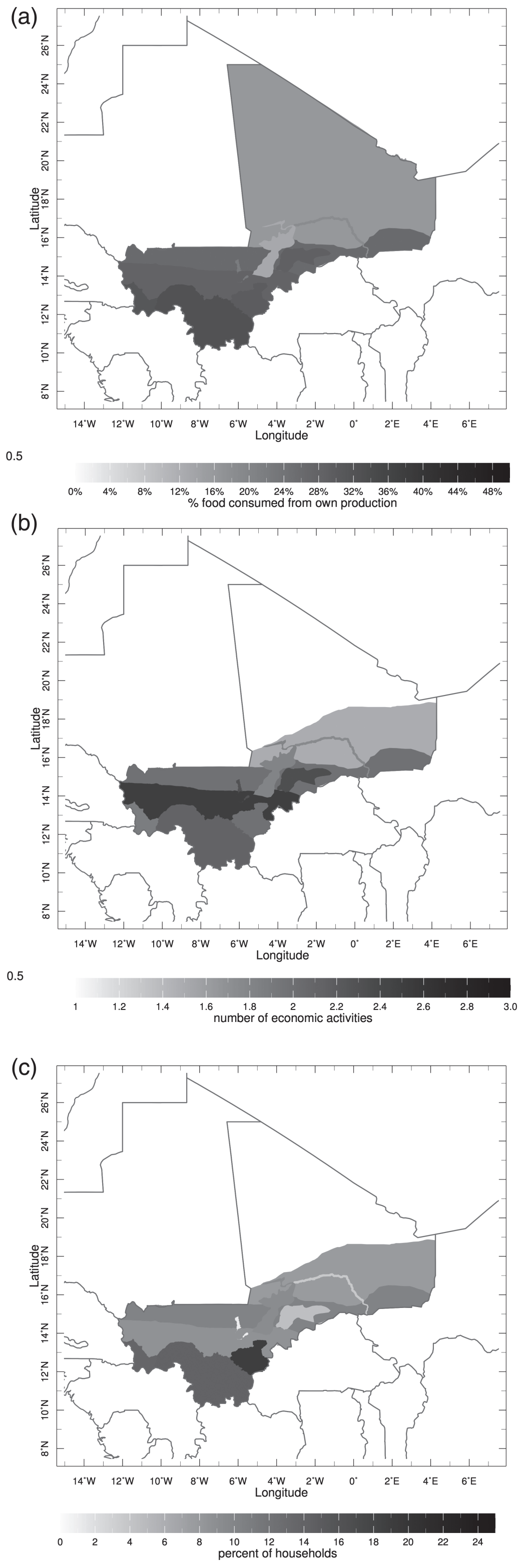

Figure 6. Dimensions of food security. (a) Median percent of food consumed coming from own production, (b) median number of economic activities that households engage in, and (c) percent of households buying food at all times, aggregated by livelihood zone.

Table 2. Cluster Analysis With Four Clusters: Number of Households in Each Cluster, and Values of the Cluster Centroids in: (1) Food Consumption Score, With a Maximum Value of 112; (2) Coping Strategy Index, Which Takes on Values Equal to 1 if the Household Recurs to Nutrition-Based Coping Strategies, Equal to 0 if It Does Not; (3) Percent of Food Consumed That Is Derived From Own Production, (4) Number of Economic Activities, Ranging Between 0 and 4; (5) Period During Which Agricultural Purchases Are Most Important, Where 1 = at Harvest, 2 = During the Dry Season, 3 = During the Following Agricultural/Rainy Season and 4 = at All Times; (6) Per Capita Nonfood Expenditures, in CFA Francs, and (7) Percent Food Expenditures on Total.

Cluster Number	Number of Households in Cluster	Food Consumption Score	Normalized Coping Strategy Index	Percent Consumed from Own Production	Number of Economic Activities	Period of Most Significant Food Purchase	Expenditures on Nonfood Items (F CFA)	Percent of Expenditures on Food
1	589	58	0.62	13	1.6	1.1	1677	0.71
2	70	70	0.49	16	2.3	1.9	13,544	0.32
3	605	40	0.63	40	2.1	2.3	1346	0.42
4	535	72	0.30	24	2.5	2.6	2466	0.52

In contrast, in the millet/transhumant herding zone, as in the southern cotton-producing zones, livelihood diversification is lower, and dependence on access to markets, measured by the percent of households that buy food at all times throughout the year (Figure 6c), is higher. Cluster 1, the least diversified, dominates the millet/transhumant herding zone, while cluster 3, the least food secure, dominates the southern cotton producing zones.

To summarize results, in the Sahelian center of Mali availability of food is problematic because local production is insufficient, but access to food is also a significant issue when limited livelihood diversification away from climate-sensitive activities constrains the ability to purchase. This is the situation that characterizes the relatively food insecure millet/transhumant herding livelihood zone in comparison to the adjacent rainfed millet/sorghum zone. This depiction is consistent with the identification of the northern edge of the Sahelian center of Mali as the geographical "front-line" of child malnutrition [*Jankowska et al*., 2011], and with the location of "stressed" food security conditions in 2012 [*FEWSNET*, 2012].

4. Conclusion: Lessons Learned in Adaptation

The Malian case study explored here illustrates an interdisciplinary approach in assessing the sensitivity of food security to climate change, one that by necessity spans across spatial scales, from the high resolution of household surveys to the subcontinental homogeneity of climate patterns. Our starting point is the recognition that food security is multifaceted, and that agricultural productivity is but a partial representation of the availability dimension of food security. Therefore, to provide a starting point to scenario development of possible futures, we complement quantitative assessments of the impact of past or projected changes in temperature and precipitation on crop productivity, which are marred by uncertainty in model projections of precipitation change [*Lobell and Burke*, 2008; *Tebaldi and Lobell*, 2008], with an interpretation of the spatial variation of food security in Mali as enveloped by the recent historical trajectory of regional climate.

Our analysis mines the wealth of information collected by WFP in its CFSVAs, household surveys taken in times not of crisis, overlaying it with an in-depth understanding of the recent climatic past of the broader Sahelian region, including consideration of adaptive responses to the region's preeminent historical climatic change: persistent late 20th century drought. It shows that despite the apparent return to a relatively favorable climate, that is, a "partial recovery" in seasonal precipitation, and a national-scale increase in agricultural productivity/production, food insecurity can be identified, described and interpreted that is consistent with the late-20th century persistence of drought.

This realization opens up questions that would best be answered with analyses at intermediate scales between village and subcontinental region, specifically, at the landscape scale [*Mbow et al*., 2014]. These would refine large-scale analyses such as those conducted by *Kok et al*. [2016] on the vulnerability of small-holder farmers in the world's drylands. They would also complement the analysis by *Sietz and Van Dijk* [2015], on the reasons for adoption of soil and water conservation in West Africa, with measures of

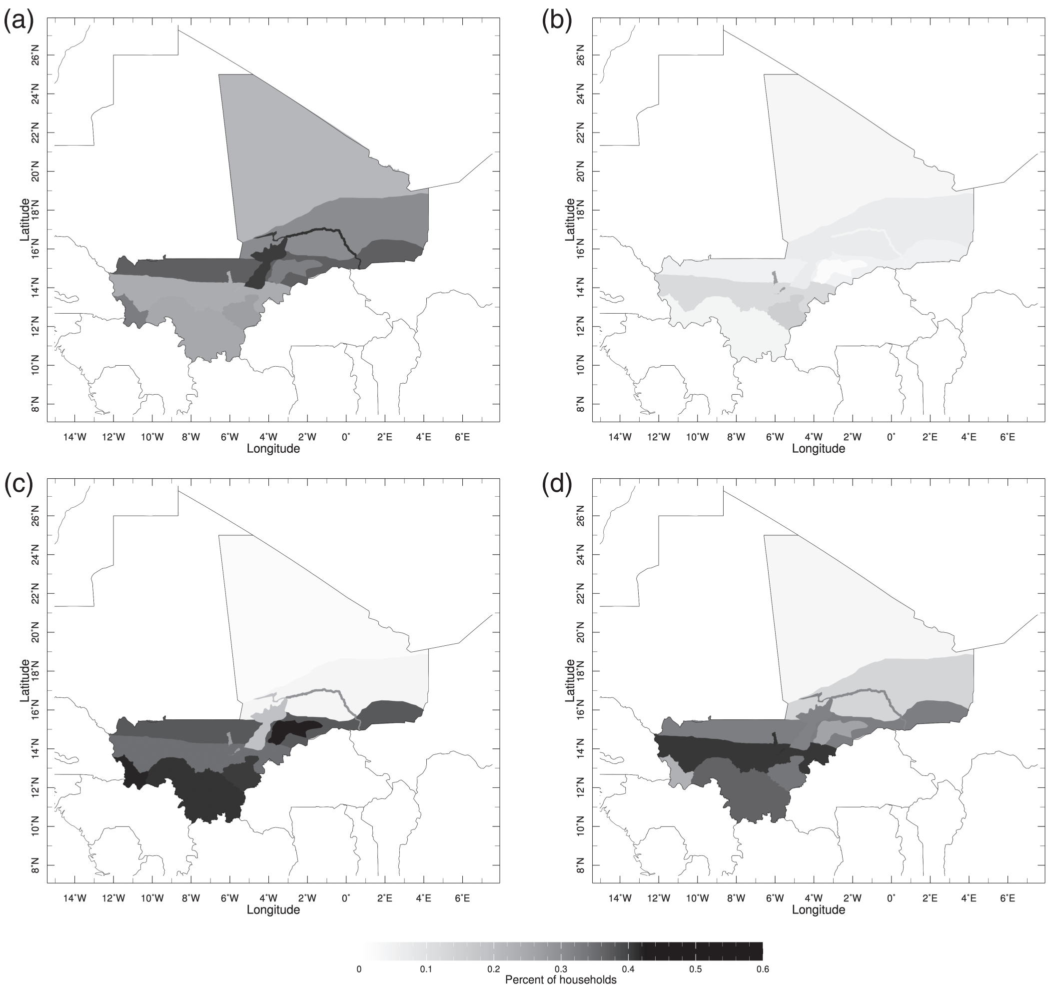

Figure 7. Spatial distribution of clusters. Percent of households in each livelihood zone belonging to clusters (a) 1, that is, the least diversified, (b), 2, that is, the "wealthiest," (c) 3, that is, the least food secure and (D) 4, that is, (together with 2) the most food secure.

their impact. The landscape scale is justified if the intent is to explore adaptation on the ground, in this case, the adaptation expressed in decades of lessons learned in reversing land degradation in response to persistent drought. We refer here specifically to experimentation with local knowledge in agro-forestry and soil and water conservation, which allow for efficient rain harvesting [*Botoni and Reij*, 2009; *Reij et al*., 2009; *Tougiani et al*., 2009; *Sietz et al*., 2011]. Widespread adoption of these techniques may already have and could continue to contribute significantly to adapting vulnerable livelihood systems to an increasingly unpredictable climate. A quantitative assessment of their impact, for example, on food security, is all the more relevant, given that future climate change is likely to bring increasingly erratic rainfall to the Sahel, as anecdotal evidence already indicates [*West et al*., 2008], and can and should be brought to bear in adaptation planning.

From a methodological point of view, socioeconomic household surveys such as the CFSVAs conducted by WFP used here, the Living Standards Measurement Studies conducted by the World Bank, and the Demographic Health Surveys funded by the US Agency for International Development provide a wealth of information that is yet to be fully exploited. Aggregation of the results of these surveys to a spatial level that facilitates comparison with high-resolution remote sensing imagery characterizing land cover/land use change could contribute to a quantification of the nexus between climate and environmental change, whether degradation or amelioration, and food security in ways not attempted before.

Finally, as demonstrated here, ultimately food access remains a critical aspect of food security in Mali. Therefore, at a practical level, the lesson learned from the long-term view presented here is that explicit consideration and support should be given to national or regional policies that promote livelihood diversification into nonclimate sensitive activities [*Mertz et al*., 2011] to contrast the deepening of adaptation deficits among the poorest — too poor to diversify, hence adapt. In Mali, a country in the grip of a profound political crisis, to be consistent with this analysis, priority should be given to the regions that have been shown to be most at-risk already, starting with the Sahelian center.

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