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Abstract: This study develops a novel approach for examining and projecting observed climate trends in the Sahel. Focusing on Mali, temperature and precipitation trends and livelihood zones are used to explore baseline relationships between climate, livelihood, and malnutrition in 407 Demographic and Health Survey (DHS) clusters with a total of 14,238 children, producing a uniquely thorough spatial analysis of climate and health. The relationships between climate, livelihood, and three measures of malnutrition - anemia, underweight, and stunting - where assessed. The evidence suggests links between livelihoods and all measures of malnutrition, as well as a link between climate and stunting. A 'front-line' of vulnerability, related to the transition between agricultural and pastoral livelihoods, is identified as an area where mitigation efforts might be focused. Additionally, climate is projected to 2025 for the Sahel, and demographic trends are introduced to explore how the intersection of climate and demographics may shift the vulnerability 'front-line', potentially exposing an additional 6 million people in Mali, up to a million of them children, to heightened risk of malnutrition from climate and livelihood changes. Holding constant morbidity levels, approximately one quarter of a million children will suffer stunting, nearly two hundred thousand will be malnourished, and over one hundred thousand will become anemic in this expanding arid zone by 2025. Climate and health research conducted at finer spatial scales and within shorter projected time lines is necessary to reveal current and near future vulnerability hot spots that should be prioritized to receive adaptation measures, and to identify areas with similar characteristics that could also be at heightened risk in the near-term. Such meso-scale coupled human-environment research may facilitate appropriate policy interventions strategically located beyond today's vulnerability front-line.

1) Cover Letter

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Dear Editor:

Please find attached for *Applied Geography* review our article entitled "Climate Change and Human Health: Spatial Modeling of Water Availability, Malnutrition, and Livelihoods in Mali, Africa" for the special upcoming issue concerning climate and health.

In the article we develop a climate trend analysis for the Sahel, and Mali in particular, coupling the data with Demographic and Health Survey cluster data for the country. Our results provide a compelling picture concerning the current impact of climate on malnutrition of children in Mali, and consider future health and climate related outcomes for the country.

All correspondence for the article should be directed to Marta Jankowska, with contact information above. We request that Marta Jankowska and David Lopez-Carr be listed as co-first authors. We also provide a list of potential reviewers for the article.

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Thank you for your kind regard.

Sincerely,

Marta Jankowska
David Lopez-Carr

***2) Title Page (WITH author details)**

Climate Change and Human Health: Spatial Modeling of Water Availability, Malnutrition, and Livelihoods in Mali, Africa

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Abstract

This study develops a novel approach for examining and projecting observed climate trends in the Sahel. Focusing on Mali, temperature and precipitation trends and livelihood zones are used to explore baseline relationships between climate, livelihood, and malnutrition in 407 Demographic and Health Survey (DHS) clusters with a total of 14,238 children, producing a uniquely thorough spatial analysis of climate and health. The relationships between climate, livelihood, and three measures of malnutrition – anemia, underweight, and stunting – where assessed. The evidence suggests links between livelihoods and all measures of malnutrition, as well as a link between climate and stunting. A 'front-line' of vulnerability, related to the transition between agricultural and pastoral livelihoods, is identified as an area where mitigation efforts might be focused. Additionally, climate is projected to 2025 for the Sahel, and demographic trends are introduced to explore how the intersection of climate and demographics may shift the vulnerability 'front-line', potentially exposing an additional 6 million people in Mali, up to a million of them children, to heightened risk of malnutrition from climate and livelihood changes. Holding constant morbidity levels, approximately one quarter of a million children will suffer stunting, nearly two hundred thousand will be malnourished, and over one hundred thousand will become anemic in this expanding arid zone by 2025. Climate and health research conducted at finer spatial scales and within shorter projected time lines is necessary to reveal current and near future vulnerability hot spots that should be prioritized to receive adaptation measures, and to identify areas with similar characteristics that could also be at heightened risk in the near-term. Such meso-scale coupled human-environment research may facilitate appropriate policy interventions strategically located beyond today's vulnerability front-line.

Keywords: Climate, Malnutrition, Mali-Africa, Adaptation

1.1 Introduction: Climate and Malnutrition

Human well-being is linked to the environment through a complex web of relationships. The vicious circle model describes positive feedback relationships among population growth, poverty, and environmental degradation (including climate change), which can lead to a downward spiral for poor households (Bremner, et al., 2010), and includes health deterioration. The Intergovernmental Panel on Climate Change (IPCC) has declared with "very high confidence" that climate change already contributes to the global burden of disease (Confalonieri, et al., 2007). Mounting evidence suggests that this health burden currently is, and will continue to extend to malnutrition as agriculture and food security becomes increasingly impacted by climatic events (Legg, 2008; McMichael, 2001; Oborsteiner, et al., 2010; Patz, et al., 2005; WHO 2002). The 2004 Comparative Risk Assessment (CRA), part of the larger Global Burden of Disease Project, estimated that 17,000 deaths and 616,000 disability adjusted life years could be attributed to malnutrition caused by climate change in Africa in 2000 (McMichael, et al., 2004). More than 200 million people remain malnourished in sub-Saharan Africa countries and this number could grow by 12 million as temperatures rise and crop yields fall (McMichael, et al., 2008).

Because of their physical, physiological, and cognitive immaturity, children are particularly vulnerable to the health effects of environmental hazards, including those that are climate related (Shea & The Committee on Environmental Health, 2007; UNICEF, 2008). Chronic malnutrition results in stunting among a third of all children under five years born in developing countries; and climate change is expected to reduce food security, primarily in areas where malnutrition is already a major health concern (Costello, et al., 2009). The effects of childhood anemia, stunting, low body weight, or wasting, even if the malnutrition is the result of a temporary environmental or economic change, can linger for decades. This, in turn, may result in impaired health and development, limited learning capacity, impaired immune systems, reduced adult work performance and productivity over the life-course, and an increased chances of giving birth to undernourished babies (ACC/SCN and IFPRI 2000; Alderman, 2010; Cohen, et al., 2008).

Current projections of climatic effects on health in the Sahel have been based on conflicting and data-poor global climate models. Yet down-scaling, particularly with a measure of confidence, may be a worthy scientific endeavor. While climate variables will be similar throughout a relatively large geographic area, the events that lead to the malnourishment of a child are inherently local, revolving around economics, livelihoods, demographics, and adaptation, potentially creating areas of high vulnerability that have yet to be identified. We frame our study within the context of adaptation measures to an increasingly dryer Sahel region of Africa, and discuss potential implications for children's health outcomes. In section 1.4 we provide a research plan for the study, followed by climate and health modeling methods, results, and a discussion that incorporates climate trends with projected migration into an assessment of future malnutrition in Mali.

1.2 Adaptation: Livelihoods and Migration

Food access and availability are the poor's primary interface between nutrition and climate change (Bloem, et al., 2010). The primary driver of food security is agricultural system stability, and societies with insecure food supplies are more susceptible to shocks in agricultural productivity (Alderman, 2010; Darnton-Hill & Cogill, 2010; Haines & McMichael, 1997). Increasing temperatures and decreasing precipitation over semi-arid regions such as the African Sahel will result in decreased yields of rice, corn, millet, wheat, and other primary crops in the next decades (Lobell, et al., 2008). Because many farmers in food insecure regions grow crops to consume and sell, decreasing yield impacts both household incomes as well as nutritional well being (Brown & Funk, 2008). The inability to protect the household against shocks which degrade incomes and livelihoods has adverse consequences across generations through reduced investment in nutrition, health, and schooling (Alderman, 2010). A conceptual understanding of livelihoods, interfaced with climate-based variables to analyze the potential for exposure to particular hazards, permits the assessment of both risk and adaptation potential by livelihood zone (Verdin, et al., 2005).

Based on the importance of livelihoods for food security, governments and development organizations that are serious about alleviating future malnutrition might strategically invest beyond areas of current vulnerability, to areas where climate change is projected to shift livelihood zones – in other words, a focus on the moving 'front-line' of vulnerability is necessary to mitigate future food insecurity as places transition from one livelihood to another. Furthermore, these front-lines will likely be accompanied by migration. Traditionally, research on rural adaptation to changing environmental conditions has not focused on migration (Bilsborrow, 1987; Carr, 2009), as much as on agricultural responses (Geist & Lambin, 2001; Turner II, et al., 1977). When migration is induced by poverty and malnutrition from declining agricultural yields, which in turn can be caused by climate change, then the latter remains an underlying factor. A decline in crop yields across climate vulnerable regions of sub-Saharan Africa results in considerable numbers of environmentally-induced migrants (Adepoju, 2003; Swain, 1996). Yet little research exists on migration promoted by gradual environmental change (Findlay & Hoy, 2000; Mortreux & Barnett, 2009), nor on the exposures these migrants face in their new homes.

1.3 Health and Climate in the Sahel and Mali

Considerable uncertainty remains regarding the link between global warming and future Sahelian drought (Christensen, et al., 2007). A complex set of climate processes drive large decadal variations in June-July-August-September (JJAS) rainfall across the Sahel, however the primary sources of rainfall variability are the Atlantic (Folland, et al., 1986; Hastenrath, 1990; Lamb & Peppler, 1992) and Indian (Giannini, et al., 2003) Oceans. Some studies have suggested that the recent warming of the northern tropical Atlantic will enhance future Sahelian rainfall (Cook, 2008; Hoerling, et al., 2006), while others state that warming over the Indian Ocean may predominate (Lu & Delworth, 2005), or that the response of the Sahel may vary, with drying in the eastern Sahel and increased rainfall in the west (Held, et al., 2005). This latter pattern appears consistent with recent observations, which have seen a 're-greening' of large areas of the Sahel (Olsson, et al., 2005), combined with drying across Sudan, Ethiopia and Kenya (Funk, et al., 2008; Verdin, et al., 2005; Williams & Funk, 2011).

In addition to the uncertainty surrounding the future state of the tropical Oceans, substantial spread separates the way current climate models project rainfall changes, independent of the simulated sea surface temperature (SST) patterns (Cook, 2008; Giannini, et al., 2008). This suggests that the local response of the models to changes in atmospheric composition may play a greater role (at least in the models) than the spatial distribution of tropical SSTs. Analysis of climate observations provides an alternate way to evaluate decadal climate variations. This leads to results that differ from climate simulations suggesting, for example, that eastern Africa is becoming drier (Funk, et al., 2008; Verdin, et al., 2005; Williams & Funk, 2011), rather than wetter as indicated in the IPCC 4th assessment (Christensen, et al., 2007). While studies of observed changes cannot provide attribution (establishing a causal link between observed trends and anthropogenic emissions), they can provide important information for planning and mitigation efforts by mapping how the 'local velocity' of climate change interacts with climate mean fields and gradients, population distributions, climate sensitivity, and livelihoods (Funk, et al., 2010; Funk & Verdin, 2010).

Climate change is expected to have an overwhelmingly negative impact on health in sub-Saharan African countries, despite this region's relatively small contribution to the anthropogenic causes of climate change (Ramin & McMichael, 2009). Multiplying the number of malnourished individuals by particular crops' contribution to average per capita calorie consumption in the Sahel, Lobell et al. (2008) found that sorghum and millet were very important crops for the region in terms of hunger. Rainfed cereals including millet, maize, and sorghum are particularly important for Mali, constituting 85% of consumed cereal calories there (Moseley, et al., 2010). Yet under some climate scenarios, cereal productivity in Africa is projected to decrease by about 10% by 2080, with consequent risk of hunger in the region increasing by 20% (Rosenzweig, et al., 2001).

Malnutrition is already a significant problem for Mali, and projected increases of hunger risks could have catastrophic impacts on the population's health and economic productivity. The 2006 Demographic and Health Survey (DHS) found that 60% of children aged 6 to 59 months are moderately or severely anemic, while 50% of children 18 to 23 months are stunted and 25% are underweight (DHS 2007). Overall, acute malnutrition affects 15% of children less than five years old as measured by World Health Organization standards. In the only extensive study on climate and health in Mali, Butt et al. (2005) found crop yield changes by 2050 will range from minus 17% to plus 6% at the national level, forage yields will fall by 5 to 36%, and livestock animal weights will be reduced by 14 to 16%. In terms of health, their study found climate change is projected to increase the proportion of the country's population at risk of hunger from 34% in 2005 to 64-72% in the 2050s, unless adaptation measures are successfully implemented (Butt, et al., 2005).

1.4 Research Plan

We aim to examine how malnutrition in Mali is partially a result of climate, and utilize the results to speculate where future climate change will impact malnutrition. The work presented here is completed in three stages, all revolving around creating a spatial approach to establishing a baseline for climate impacts on malnutrition in Mali, and exploring future effects. Mali was selected as the study site due to its wide range of land cover and agricultural livelihoods. As a part of the Sahel, Mali's climate and related nutritional situation can be generalized to countries throughout sub-Saharan Africa with similar climate and agricultural characteristics.

The first stage develops the datasets used to capture trends in climate variables. At present, trend estimates are typically presented with no accounting for the spatial accuracy of the estimation procedures, producing unreliable results. Our method attempts to rectify this problem by using an approach supported by the US Agency for International Development's (USAID) Famine Early Warning System Network (FEWS NET). We therefore refer to a derived gridded trend product as FEWS NET Trend Analyses (FTA), and a long term mean field as FEWS NET Climatology (FCLIM). Additionally FEWS NET livelihood zones are utilized to obtain a better understanding of vulnerabilities throughout Mali, and potential adaptation strategies.

The second stage integrates malnutrition data from the DHS at the cluster level, utilizing population epidemiology as suggested by Woodward and Scheraga (2003) to develop a baseline relationship among climate, livelihoods, and malnutrition at a finer scale than previously observed. We assume that malnutrition as influenced by climate and livelihood zones will be similar for individuals living close together (for example a village), but differences may emerge at a larger scale, in this case among clusters. Therefore conclusions about climatic and livelihood impacts on health will be drawn at the cluster level, providing novel spatial richness when compared to national-level assessments.

The final stage projects our climate model to 2025, and incorporates demographic changes to discuss potential compounding impacts of climate and demographics on future malnutrition. This stage is not a modeled projection, but rather an exploration of established baseline trends, and is purposefully focused on the next fifteen years. While long-term projections are vital for understanding possible overall changes in a region, the focus on the short term may uncover immediate areas of vulnerability.

Data

2.1 Climate Data

The FCLIM method incorporates climate, satellite, and physiographic data using a total of ten specific input variables listed in Table 1. Below is a brief description of each variable.

Table 1. Climate data modeling products.

Data products			**Sources**
Station observations	**Acronym**	**Dates**	
1. Seasonal rainfall [mm]		1960-2009	Ethiopian Nat. Met. Agency, Aghrymet, GHCN, FAO, GTS
2. Seasonal air temperature [°C]		1960-2009	GHCN

Satellite observations			
3. MODIS Land Surface Temperatures [°C]	LST	2003-2009	NASA
4. Meteosat Infrared Brightness Temperatures-10th Percentiles [°C]	IR10	2001-2009	NOAA/CPC
5. Meteosat Infrared Brightness Temperatures-90th? Percentiles [°C]	IR90	2001-2009	NOAA/CPC
6. Merged Rainfall Estimates v. 2 [mm]	RFE2	2001-2009	NOAA/CPC
Physiographic predictors			
7. Latitude [°]	Lat		
8. Longitude [°]	Lon		
9. Elevation [m]	Elev		USGS GTOPO30
10. Slope [m per m]	Slp		USGS GTOPO30

Two dense rainfall station datasets were provided for the Sahel by the Ethiopian NMA (~100 stations) and the Centre Régional Agrhymet (~700 stations). These stations were augmented by rainfall records from the GHCN archive and United Nations' Food and Agriculture Organization's FAOCLIM database. Overall, records of 1,339 rainfall stations and 178 temperature stations were examined.

Four satellite fields were used to improve the spatial resolution and precision of the satellite grids. The high correlations between our *in situ* data and these fields supported regression models to interpolate among sparse station observations guiding the rainfall and temperature FCLIM and the rainfall FTA modeling[1]. Land Surface Temperature (LST) maps at 1-km resolution were produced by the LST group at University California Santa Barbara using thermal infrared (TIR) data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS). In addition to LST, thermal near infrared (TIR, 11 um) brightness temperatures from geostationary Meteosat weather satellites were also used in our regression modeling to guide estimates of rainfall and air temperature. Multi-satellite rainfall estimates (RFE2) from NOAA CPC (Xie & Arkin, 1997)were also used as potential guides to the FCLIM and FTA estimates for rainfall data.

Four physiographic indicators were used as potential predictor variables for precipitation and temperature: latitude, longitude, elevation and slope. Mean elevation and slope fields were derived from GTOPO30 data on a 0.05° grid. The four satellite fields (LST, IR10, IR90, and RFE2) were resampled to the same grid.

2.2 Livelihood Zones and Health

Livelihoods are a way of understanding food economies as represented by a typical rural household's everyday circumstances and ability to obtain access to food (Boudreau, et al., 1998). This study will utilize the FEWS NET livelihood zones, which attempt to define how households obtain and maintain access to critical resources (http://www.fews.net/pages/livelihoods-learning.aspx?l=en). FEWS NET delineates 13 livelihood zones for Mali. Similar zones were aggregated, resulting in 8 dummy coded regions.

Health data was drawn from the 2006 Demographic and Health Survey IV (DHS) for Mali (DHS 2007). Increasingly researchers are taking advantage of global positioning systems (GPS), which during recent rounds of DHS surveys have begun to provide location attributes of clustered households (Tanser & Le Sueur, 2002). DHS data have been analyzed in hundreds of studies in the public health literature, less so with the use of GPS points, yet DHS data has been used to study human environmental impacts (De Sherbinin, et al., 2008; Sutherland, et al., 2005). However the

[1] The temperature gauge density was not sufficient to support the use of satellite & topographic data in the derivation of the FTA.

use of DHS cluster data to examine climate effects on human has not been attempted to our knowledge.

The survey sample of 410 clusters is stratified, weighted, and representative at the national, regional (8 regions plus Bamako), and residential (urban/rural) levels. The analysis for this study will revolve around the national and residential levels. 407 clusters were successfully surveyed including 14,238 children. Three commonly utilized measures of nutrition were selected from the DHS for analysis: the child's level of anemia (the amount of iron in the blood), the child's measure of stunting (height divided by age indicative of chronic malnutrition), and the child's measure of underweight status (weight divided by age indicative of short term malnutrition). The DHS measures anemia through hemoglobin levels adjusted by altitude, and assigns children one of four categories: severely anemic, moderately anemic, mildly anemic, and not anemic. Stunting and underweight are assessed by number of standard deviations from the World Health Organization (WHO) child growth standards, with measures -2 standard deviations away from the guidelines considered malnourished (WHO & UNICEF, 2009).

Methods

3.1 The FEWS NET Climatology FCLIM Method

The FCLIM uses satellite mean fields and physiographic predictors (Table 1) to guide the spatial interpolation of station data for point estimates of long term means and decadal trends. This procedure has been used to guide trend analyses of Kenyan and Ethiopian rainfall (Funk, et al., 2008; Funk & Verdin, 2010). The FCLIM approach involves exploratory analysis and selection of a relatively small number (typically 4-6) of predictors, and the identification of a characteristic scale determined primarily by station density. Instead of focusing on the ability of datasets to represent *temporal* variations in weather, the FCLIM approach focuses on the ability of these variables to represent *spatial* gradients of temperature and precipitation. The core of the FCLIM model fitting is based on local spatial correlations between station data and satellite and physiographic predictors. At a local scale, satellite fields typically exhibit a strong spatial covariance with in situ observations, and this can be used to make accurate long term mean and trend maps. Satellite fields also typically exhibit local spatial correlations that are much stronger and more consistent than physiographic fields.

The FCLIM methodology was developed using a multivariate set of predictors including physiographic variables (latitude, longitude, elevation, and slope), and satellite observations of rainfall, infrared brightness temperatures, and LST. The first step used moving window regressions to create a 'first cut' estimate of the gridded field estimated at each target grid cell (i.e., each 0.1° cell across the maps). Each station value was then paired with the closest grid cell, and residuals were estimated. For each location **l,** a matrix of centered predictors ($\mathbf{X_w}'$) and a vector of observed values ($\mathbf{y_w}'$) can be used to identify a local multivariate regression using:

$$\mathbf{y_{est}} = b_o + \mathbf{b}^T \mathbf{X_w}' \qquad \text{(Equation 1)}$$

A model semi-variogram was then fit to the residuals and geostatistical interpolation techniques (kriging and inverse distance weighting (IDW)) were used to produce another grid of values. Because the model semi-variogram explicitly quantifies the spatial de-correlation with increasing distance, kriging produces spatial maps of standard error, contingent on the spatial distribution of the observation network. The moving window regression and residual fields were summed, creating an estimate that combines correlated exogenous predictors and the spatial covariance of the in situ observations. At each grid location, the final FCLIM estimate combines the local regression intercept (b_o), a vector of local regression slope values (**b**), a vector of local gridded satellite and physiographic predictors (**x**), and a local estimate of the kriged residuals (k):

$$FCLIM = b_o + \mathbf{b}^T\mathbf{x} + k \qquad \text{(Equation 2)}$$

Comparisons of kriging and IDW suggest similar levels of accuracies. In this work, IDW is used with automated cross-validation procedures to assess accuracy, and geostatistical kriging within the final analyses. The kriging procedure produces maps of expected standard error. Two methods then quantify error that include cross-validation, which examines the ‘at-station’ accuracies of the FCLIM and FTA models, and the analysis of the kriging standard error fields, which quantifies the spatial uncertainty associated with the gridded FCLIM and FTA spatial predictions.

3.2 Trend Surfaces

Both long term mean fields and trend maps provide critical information for the Sahel, where as in many semi-arid regions of the tropics, burgeoning populations literally find themselves ‘up against a wall’ of the environmental limit capable of sustaining even low-yield rainfed agriculture. Across these semi-arid drylands, the high temperatures of arid regions largely arise due to limited soil moisture, which limits evaporation forcing the surface to transmit energy back to the atmosphere as a flux of heat energy. The atmosphere’s ability to absorb moisture from the surface, its Potential Evapotranspiration (PET), increases with increasing temperatures, and relatively simple temperature-based PET estimates have been shown to be robust *relative* indicators of atmospheric moisture demand (Mavromatis, 2007; Vicente-Serrano, et al., 2010). This study uses Thornthwaite’s original (1948) formulation to estimate the JJAS total potential evapotranspiration in millimeters, for each 0.1° FCLIM pixel, using that pixels’ average air temperature resulting in a simple ‘water balance’ index where positive values represent wet areas where soils remain moist for most of the rainy season, and negative values are regions where atmospheric water demand exceeds the rainfall supply.

$$PPET = Rainfall - PET \qquad \text{(Equation 3)}$$

The temperature and precipitation trends derived from the FCLIM process are combined to create PPET for the study as an input variable for the malnutrition modeling by assigning a PPET value to each DHS cluster based on latitude, longitude coordinates. Because the PPET maps for Mali express a strong southwest-to-northeast east gradient, this study examines 1990-2009 and 2010-39 southwest-to-northeast transects of Mali rainfall, air temperature, PPET and population. These transects extend from -8°E, 12.9°N and end at -0.9°E, 15.7°N. Population data is derived from the Gridded Population of the World data set (CIESIN 2005). Population values for 2025 were projected based on the 1990 to 2010 population changes, and are only meant to broadly indicative of demographic inertia.

3.3 Modeling Malnutrition

We examined potential relationships between PPET, livelihood zones, and three measures of childhood malnutrition – anemia, underweight, and stunting. The ordinal variable anemia was ranked from not anemic (1) to severely anemic (4), and together with the continuous variables, stunting and BMI, were calculated as mean cluster values (Table 2). Twelve variables commonly considered important for malnutrition outcomes were assessed concerning the child, the child's mother, or the child's household. Low variability (more than 80% responses in one category or value) and high Pearson's correlation values with other variables (above 0.4) resulted in the removal of seven variables. All remaining variables were aggregated to the cluster level, and utilized as controls in the multivariate model (Table 2).

Table 2. Global cluster descriptive statistics for model input variables.

Variable	Description	Mean	Standard Deviation
Anemia	Cluster anemia measure	2.397	0.519
Stunting	Cluster stunting measure (height/age)	-1.394	0.719
Underweight	Cluster underweight measure (weight/age)	-1.216	0.487
Age of Head	Cluster average of age of household head	41.904	3.930
CEB	Children ever born per mother in cluster	4.409	0.909
Wealth	Average cluster household wealth	3.131	1.121
Age of Child	Average age (months) of children in cluster	27.501	2.785
Unprotected Well	Percent of cluster using an unprotected well for drinking water	37.062	34.248

Multivariate linear regression analysis in Predictive Analytics Software (PASW) Statistics 18 software was used for all regressions. Two regression sets were run, the first on all clusters representing the national level, and the second set on clusters classified by the DHS as rural, representing the residential level. Within each set, an iteration of three regressions was performed for each malnutrition measure. Model set 1 focused on climatic effects on malnutrition. Model set 2 focused on the influence of livelihood zones. Finally, to better understand the effects of climate beyond livelihood zones, model set 3 was run with both climate and livelihood zones.

Results

4.1 Observed Warming Trends

Averages of station data for selected countries are shown Figure 1. The time-series were smoothed with seven-year running means. Sudan-Niger-Mali has experienced a 1960-2009 increase of more than 1.0 °C, while Kenya-Ethiopia has experienced an increase of about 0.7 °C. The magnitude of the temperature increases is equal to or greater than the interannual standard deviations (0.5 °C for Kenya-Ethiopia, 0.65 °C for Sudan-Niger-Mali). This warming can disrupt the seasonal cycle of crops, draw more water from the soil and plants, and reduce the amount of grain produced. The magnitude of the observed trends can be large. By the year 2025, a temperature trend of 0.2 °C per decade would be associated with a warming of 1 °C since 1975.

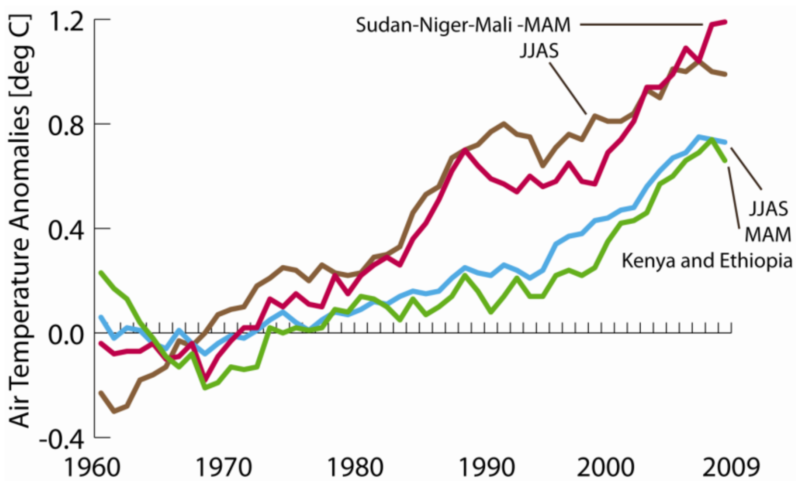


Figure 1. Time series (smoothed with a seven year running mean) of air temperature anomalies for three countries in the Sahel (Sudan, Niger, Mali) and two countries in the Greater Horn of Africa (Kenya and Ethiopia).

4.2 Trend Analysis with Sigma Fields

During JJAS, the inter-tropical front establishes itself north of the equator, and the Sahel receives the bulk of its rains. A strong north-south temperature gradient appears during the JJAS period, with the southern edges of the Sahelian countries receiving the most rainfall and coolest air temperatures. Figure 2 shows the FEWS NET trend analysis maps for JJAS rainfall and air temperatures. Pockets of rainfall reduction appear near the border of Senegal and Mali, as well as southern Chad and Sudan. This drying is likely linked to drying in southwestern Ethiopia. The JJAS temperature show values ranging from near zero to more than 0.4° C per decade. Warming is generally greater in Senegal-Mali and southern Sudan-Ethiopia than in Niger and northern Sudan and Ethiopia. The warming patterns tend to mirror the inverse of the rainfall trends. In some of the areas, the magnitude of the decadal temperature trends (up to 0.4°C per decade) approaches the inter-annual air temperature standard deviation, and thus indicates large changes in climate.

When evaluating climate trends, two primary factors should be considered: 1) how large are the observed trends, and 2) how large are the estimated trends vis-à-vis the underlying uncertainty of the interpolated fields. The latter factor is rarely considered, and can often be obfuscated by the analysis of interpolated monthly or seasonal data. One simple way to evaluate these two components is to divide the interpolated trend fields by the standard error in the interpolation. The resulting unitless 'sigma' images retain the sign of the underlying trend fields, but are now expressed in units of standard errors (Figure 3). Values of 1, 2, and 3 correspond to the 85%, 98% and 99.9% confidence levels, respectively. Most regions covered in this analysis had sigma values with absolute values of greater than 2; thus the signal-to-noise ratio for the trend analysis is high and our confidence in the spatial accuracy of the results high. This is surprising considering that the associated station densities were on the order of ~1 rainfall station every 5,000 km^2, and 1 temperature observing site every 40,000 km^2. The appropriate use of satellite fields helped achieve this result, reducing the geo-spatial random error and improving the signal-to-noise ratios. The sigma fields shown in Figure 3 suggest that the resulting trend analyses can be accepted with a high degree of confidence, either because of the high density of observations and reasonable levels of predictability in the rainfall trends, or that the trend signal is coherent (everywhere positive) and the spatial covariance pattern of the warming trends is relatively simple.

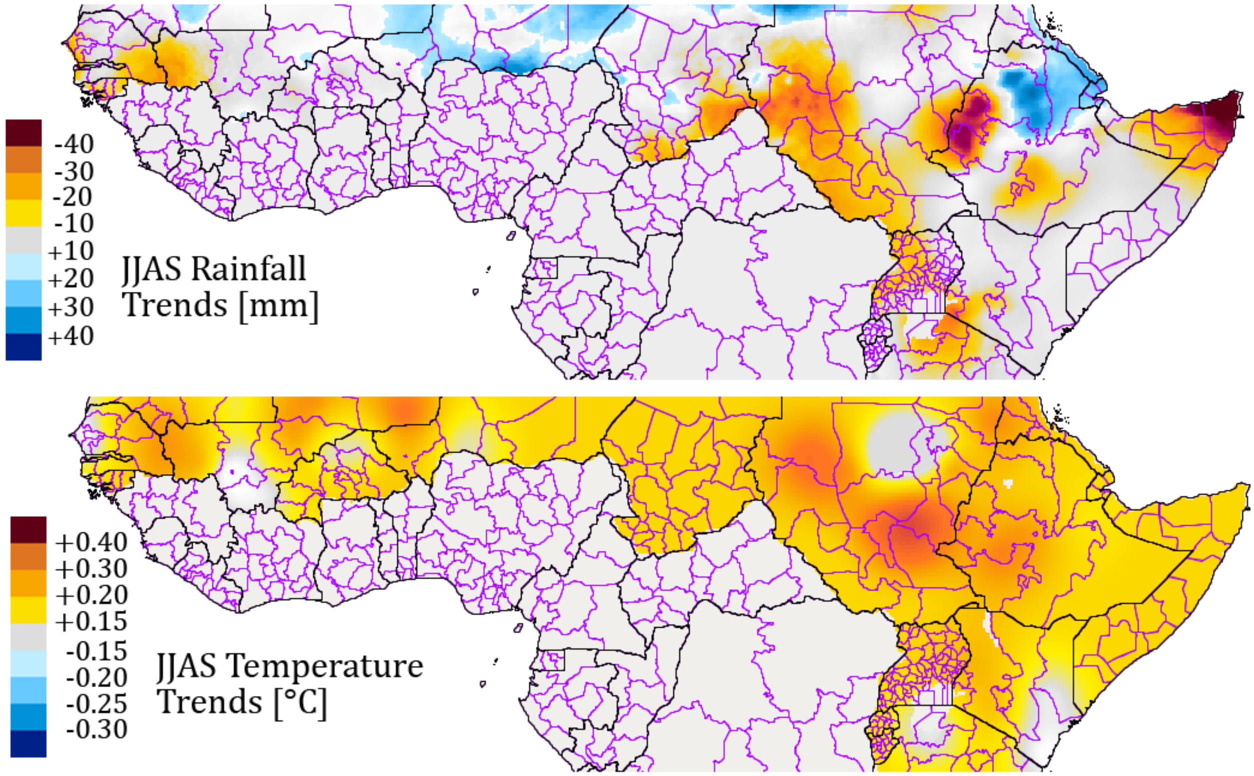


Figure 2. 1960-2009 rainfall and temperature trend maps.

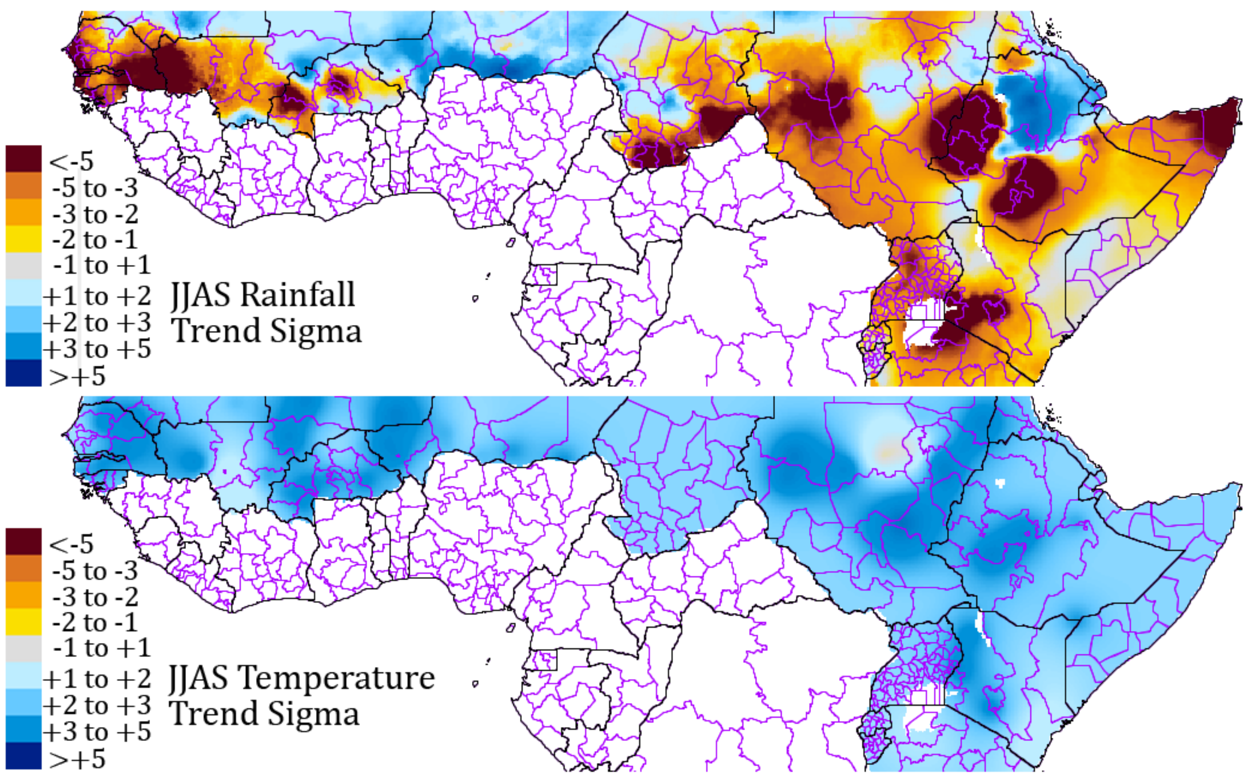


Figure 3. 1960-2009 rainfall and temperature trend sigma maps.

4.3 PPET and Livelihoods

We can visualize climate and climate change across Mali by examining southwest-to-northeast PPET (the combined temperature and precipitation measure) transects across the country (Figures 4). These transects, created by rotating the coordinate system by 45° and averaging, show the spatial transition from the wet-cool southwest to hot-dry north-east; a climate transition that broadly corresponds to a spectrum of livelihoods that range from agricultural, agro-pastoral and pastoral modalities. The transition across the country is dramatic, with main season rainfall varying from >700 mm to less than 300 mm, across a distance of approximately 250 km, marking one of the worlds steepest rainfall gradient. Air temperature variations are similarly marked, transitioning from 27°C to ~31°C. The -100 PPET lines for the 1990-2009 and 2010-2039 periods are marked, designating (imprecisely) a transition point between agricultural and pastoral livelihoods. Note that this -100 line shifts southwest-ward, suggesting that the area of the country suitable for farming is diminishing with time.

Examining the observed 1990-2009 transects and the 2010-2025 projected transects, we observe that the pattern of decreasing rainfall in the west and increasing rainfall in the east displays a dichotomous change, with the inflection point centered just north of the -100 PPET lines (Figure 4). This dichotomous pattern contrasts with the anticipated pattern warming, which is broadly similar all across the country.

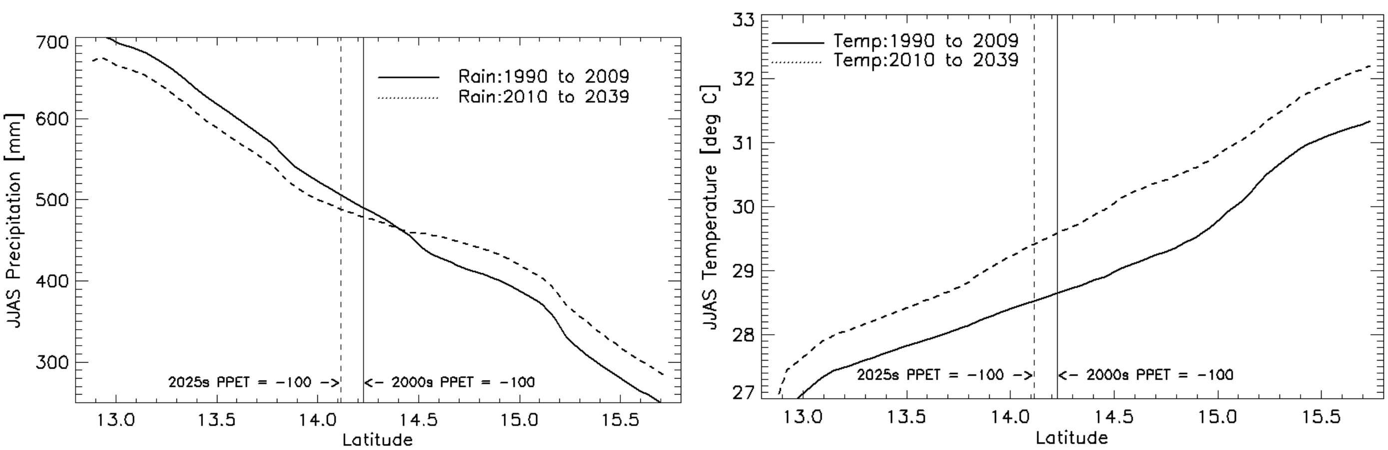


Figure 4. Southwest to northeast transects of average JJAS precipitation (left) and air temperature (right). Transect begins at -8°E, 12.9°N and ends at -0.9°E, 15.7°N).

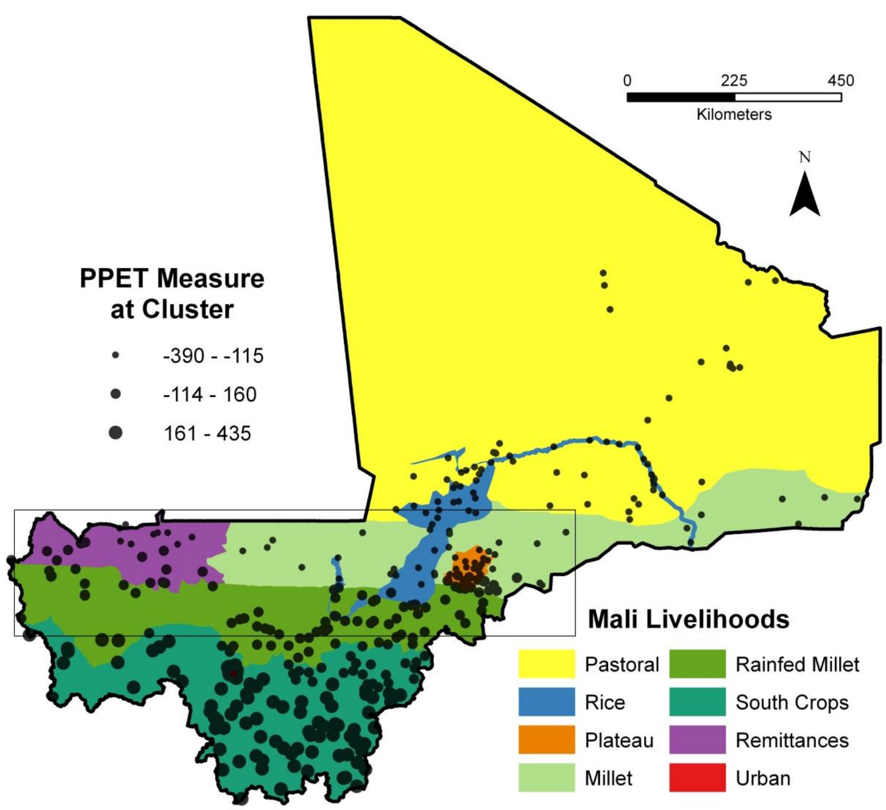
The 8 livelihood zone groupings are displayed in Figure 5, and mean health values for livelihoods of particular interest are in Table 3. The pastoral livelihood is characterized by having rainfall less than 200mm, being sparsely populated, and relying on livestock and limited agriculture. People are particularly susceptible to threats to their herds, with limited activities to serve as secondary response strategies. The rice livelihood is dependent on rice production for food, but also includes livestock rearing, as well as some minimal farming. For all of these livelihoods, there is a reliance on water from the Niger River and its inland delta for water. Coping mechanisms typically involve additional sales of livestock to increase income.

Table 3. Livelihood zones, arid climate zone, and health variable means.

Zone	Description	# Clusters	Anemia $\bar{x}$	Stunting $\bar{x}$	Underweight $\bar{x}$

Arid Climate	Clusters with PPET values less than -100	144	2.287	-1.576	-1.335
Pastoral	Nomadism, trans-Saharan trade, transhumant pastoralism	38	1.903	-1.454	-1.229
Rice	Fluvial rice, Niger Delta rice, Irrigated rice, livestock rearing	50	2.272	-1.612	-1.453
Plateau	Millet, shallots, wild foods, tourism	27	2.469	-1.715	-1.277
Millet	Millet and transhumant livestock rearing	33	2.469	-1.492	-1.320
Rainfed Millet	West and central rainfed millet/sorghum	68	2.570	-1.402	-1.255
South Crops	Sorghum, millet, cotton, maize, fruit	120	2.535	-1.492	-1.214

The plateau, millet, and rainfed millet livelihoods highlight the transitional nature of this region from pastoral semi-arid to agricultural livelihoods, as well as from sparse to moderate population density. The PPET = -100 contour runs directly between the millet and rainfed millet livelihoods (Figure 5), highlighting the importance of climate in shaping these livelihoods. This contour is particularly important as a driver of the transition from rainfed crops to semi-arid subsistence, and highlights the frontline of potential vulnerability to decreasing precipitation and increasing temperature. The millet livelihood contains a greater dependence on agriculture and less on livestock, but remains a food deficit area. The rainfed millet livelihood receives reliable rainfall that is sufficient to support a variety of crops and also sedentary livestock, although livestock rearing is of less importance.



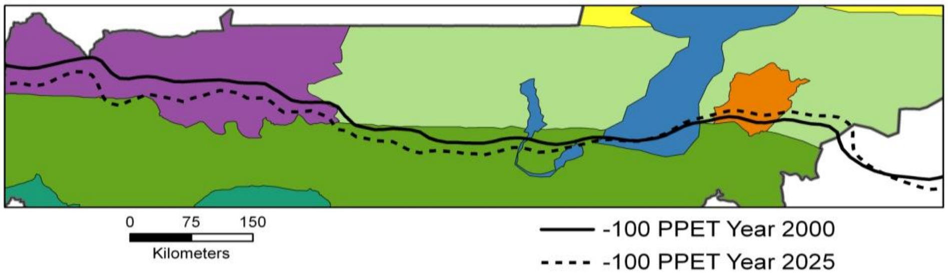


Figure 5. Livelihood zones for all of Mali with DHS cluster locations and the PPET gradient throughout the country (above). The -100 PPET contour lines in year 2000 and 2025 situated between the millet and rainfed millet livelihoods (below).

4.4 Malnutrition Modeling

Results for the climate models are in Table 4. The PPET < -100 zone was significant for all health measures when including all clusters, and significant for stunting when including only rural clusters. For all clusters, the standardized β coefficients for stunting and underweight were -0.165 and -0.159 respectively, both highly significant. Therefore, a cluster's location

Table 4. Multivariate regression results with PPET < -100 zone variable for all cluster and rural cluster models.

	Anemia All Clusters		Anemia Rural Clusters		Stunting All Clusters		Stunting Rural Clusters		Underweight All Clusters		Underweight Rural Clusters	
Adjusted R2	0.139		0.120		0.322		0.148		0.201		0.046	
	Beta	**Std Error**	**Beta**	**Std Error**	**Beta**	**Std Error**	**Beta**	**Std Error**	**Beta**	**Std Error**	**Beta**	**Std Error**
Variable												
Age of Child	-0.102*	0.009	-0.148**	0.011	-0.196***	0.011	-0.290***	0.014	-0.097*	0.008	-0.191**	0.010
CEB	0.106	0.034	0.127	0.041	-0.190***	0.042	-0.133*	0.053	-0.082	0.031	-0.002	0.039
Age of Head	-0.025	0.006	-0.124*	0.007	0.231***	0.008	0.205***	0.010	0.120**	0.006	0.117	0.007
Unprotected Well	-0.008	0.001	-0.015	0.001	0.096*	0.001	0.072	0.001	0.075	0.001	0.025	0.001
Wealth	-0.277***	0.029	-0.211***	0.048	0.365***	0.036	0.094	0.062	0.378***	0.026	0.056	0.046
PPET< -100 zone	-0.149**	0.052	-0.111	0.064	-0.165***	0.063	-0.138*	0.083	-0.159***	0.047	-0.126	0.061

p<.001 = ***   p<.01 = **   p<.05 = *

Table 5. Multivariate regression results with livelihood zone variables for all cluster and rural cluster models.

	Anemia All Clusters		Anemia Rural Clusters		Stunting All Clusters		Stunting Rural Clusters		Underweight All Clusters		Underweight Rural Clusters	
Adjusted R2	0.205		0.166		0.326		0.169		0.220		0.075	
	Beta	**Std Error**	**Beta**	**Std Error**	**Beta**	**Std Error**	**Beta**	**Std Error**	**Beta**	**Std Error**	**Beta**	**Std Error**
Variable												
Age of Child	-0.078	0.009	-0.112	0.011	-0.201***	0.011	-0.290***	0.014	-0.108*	0.008	-0.204***	0.010
CEB	0.066	0.033	0.076	0.040	-0.168***	0.041	-0.097	0.050	-0.077	0.030	0.008	0.037
Age of Head	-0.027	0.006	-0.120*	0.007	0.240***	0.008	0.212***	0.010	0.138**	0.006	0.144*	0.007
Unprotected Well	-0.008	0.001	-0.014	0.001	0.081	0.001	0.061	0.001	0.050	0.001	0.008	0.001
Wealth	-0.269***	0.028	-0.179**	0.048	0.388***	0.035	0.112	0.062	0.388***	0.026	0.065	0.045
Pastoral	-0.276***	0.084	-0.272***	0.105								
Rice	-0.098*	0.073	-0.022	0.090	-0.164***	0.092	-0.175**	0.116	-0.212***	0.067	-0.215***	0.085
Plateau					-0.099*	0.120	-0.135*	0.140				

p<.001 = ***   p<.01 = **   p<.05 = *

within the PPET < -100 zone significantly predicts worse malnutrition for both stunting and underweight measures, likely due the climate-driven livelihoods in these areas that fail to support cereal crops. The standardized β coefficient for anemia was -0.149 at $\alpha = .01$. As lower values of anemia indicate less anemia, a cluster's location within the PPET < -100 zone significantly predicts lower cluster anemia measures, likely due to the practice of livestock rearing in these areas, and accompanied meat and thus iron consumption.

When excluding urban clusters from the analysis, the PPET < -100 zone remained significant for only the stunting measure with a β value of -0.138 at α=.05. Comparison of adjusted R^2 values between all cluster and rural only cluster models indicate that more variability is explained when including all clusters in the analysis. The overall stunting and underweight results are consistent with Legg's (2008) findings across sub-Saharan Africa, where more arid regions were correlated with worse nutritional measures, and less densely populated areas (rural) did not show higher prevalence of malnourishment than high density areas (urban). Legg's study did not include anemia however, which this study shows to be impacted positively when clusters are located in arid climate, likely due to access to meat.

Multiple models with different combinations of livelihoods were run, and resulted in three significant livelihood zones pastoral, rice, and plateau (Table 5). The pastoral livelihood was highly significant for both the all cluster and rural only cluster anemia model, with standardized β coefficients at -0.276 and -0.272 respectively, however more variability was explained by the all cluster model as indicated by R^2 scores. The rice livelihood zone was significant at α=.05 with β=-0.098, indicating a slight positive impact on anemia. This may be due to livestock rearing activities within the rice livelihood zones. The coefficient is notably smaller and less significant than the pastoral livelihood, and becomes insignificant in the rural only model. The pastoral livelihood is located in the most northern area of Mali, and the significance of this livelihood for reduced anemia measures is consistent with the climate model results. However, other livelihoods north of the PPET < -100 contour are not significant for anemia. These livelihoods have little livestock rearing, emphasizing the importance of livestock rearing for anemia measures.

The rice livelihood zone becomes significant at α=.001 for the all cluster stunting and underweight models, as well as the rural underweight model. It is also significant at α=.01 for the rural stunting model. In these models a cluster's location within a rice livelihood zone has negative consequences for health, with the largest standardized β coefficients of all models in the livelihood and climate analyses, and higher R^2 values when compared to stunting and underweight all and rural climate models. Two large areas within this zone are arid regions that rely heavily on livestock for their well being, but because of their access to pooling water on the Niger River and within the Niger Delta, they are also able to grow rice. In all regards other than rice cultivation, they are similar to the pastoral livelihood zones, explaining their negative impacts on stunting and underweight.

There is less difference observed between all cluster and rural only cluster models within the livelihood models as compared to the climate models. One exception to this is the plateau livelihood, which is significant at α=.05 for stunting in both the all and rural only cluster models, however the standardized β is equal to -0.135 for rural clusters as opposed to -0.099 for all clusters. This would indicate that rural clusters in the plateau livelihood experience a larger negative impact on stunting than rural and urban areas combined. All adjusted R^2 values were higher for the livelihood models than climate models, indicating that livelihoods explain more variability of the malnutrition measures than climate. However, both sets of models when examined in ensemble highlight the complex pathway through which malnutrition is influenced by climate, where climate functions through livelihoods to impact malnutrition.

To test if the climatic health effects found in the first set of models was entirely explained by the livelihoods, the all cluster climate models were re-ran to include both PPET < -100 and the significant livelihoods for each health outcome (Table 6 shows only the PPET < -100 and livelihood results). Climate becomes insignificant for anemia and underweight when considering livelihoods, however it remains significant for stunting, and the adjusted R^2 score increases when compared to the other stunting models. This finding is particularly important when considering the meaning of the malnutrition measures. Anemia and underweight are more short term measures of malnutrition, for example, in response to climatic seasonal flux and shocks, which based on our findings are absorbed by livelihood vulnerabilities and adaptation capabilities. Stunting is a comparatively chronic measure of malnutrition. Our results indicate that climate in Mali, in the form of the arid zone of PPET measures under -100, influences stunting beyond the significant effect of livelihoods, underscoring a component of malnutrition that may not be easily mitigated at the local livelihood level.

Table 6. Combined rice livelihood and PPET zone models for all clusters.

	Anemia All Clusters		**Stunting All Clusters**		**Underweight All Clusters**	
Adj. R^2	0.189		0.332		0.224	
	Beta	**Std Error**	**Beta**	**Std Error**	**Beta**	**Std Error**
PPET < -100	0.011	0.065	-0.99*	0.072	-0.086	0.05
Pastoral	-0.282***	0.098				
Rice	-0.104	0.086	-0.121**	0.102	-0.177***	0.073
Plateau			-0.074	0.124		

p<.001 = ***   p<.01 = **   p<.05 = *

Discussion

5.1 The Moving Front-Line

The results of the study demonstrate that the arid and semi-arid climate of Mali as defined by PPET < -100, 1) negatively influences underweight and positively influences anemia through livelihoods, 2) negatively influences stunting when controlling for livelihood effects, and 2) is shifting southward, enveloping more land, and consequently as it moves towards the more densely populated southern region of the country, more Malians. This front-line, as demonstrated by the FCLIM method results, can be extended east and westward throughout the Sahel, and the land located between the 2000 and 2025 contours is extensive at 18,285 km^2. Children living within the 2000 and 2025 PPET -100 contours will become more vulnerable to stunting as climatic effects beyond livelihoods impact their nutrition.

While our findings indicate that climatic factors in addition to livelihoods are influencing stunting, livelihoods are important factors for all of the malnutrition measures. The shifting of the PPET < -100 front-line directly translates to a change from rainfed millet and sorghum production to more vulnerable non rainfed livelihoods. As only 3% of Mali's arable land is irrigated, the shifting of PPET into the southern, agricultural areas of the country will have significant impact not only on those living within this region, but also on Mali's ability to sustain its food needs and export cash crops (Butt, et al., 2006). Furthermore, a household's ability to deal with shocks is directly related to their current food and income source (Moseley & Logan, 2001). For those currently living with pastoral livelihoods, shifting PPET will likely have less of an influence on their way of life than those with rainfed livelihoods transitioning to non rainfed crops or even pastoral livelihoods. Therefore this shifting front-line of change must become a policy priority.

Incorporating demographic trends into this scenario from the Gridded Population of the World estimates pushes more people into the vulnerable arid zone. Transects are used to visualize the climatic distribution of Mali's population (Figure 6). The population tends to be much denser towards the climatically favorable southwest, and this is also where we anticipate to see the most demographic change by 2025, with the population increasing by ~50% to 66 million (Table 7). At the same time, population across the agriculturally vital southwest will decrease, and air temperatures will rise, increasing PET (Figure 4), reducing PPET values and shifting the associated contours (Figure 5). If climate remains constant (the same as the 1990-2009 mean), population growth estimates suggest that an additional ~4.4 million people will live north-east of the -100 PPET contour by 2025, with children presumably at a greater risk of stunting. If both expanding population and the southwestward shift of the -100 contour are taken into account, the increase in exposed population increases to 6 million; approximately three quarters of a million to nearly one million will be children[2]. Holding constant observed morbidity levels, by 2025 approximately one quarter of a million children will suffer stunting and nearly two hundred thousand will be malnourished in this expanding arid zone. Our regression results suggest that we can isolate climate change as the cause of a statistically significant number of these children suffering from stunting (Figure 8).

Table 7. Mali population totals for 2010 and 2025.

	Total [millions]	**PPET -100 position based on 1990-2009 climatology**		**PPET -100 position based on 2010-2039 climatology**	
		PPET > -100	PPET <= -100	PPET > -100	PPET <= -100
2010	44.8	32.4	12.4	31.2	13.6
2025	65.8	49	16.8	47.4	18.4

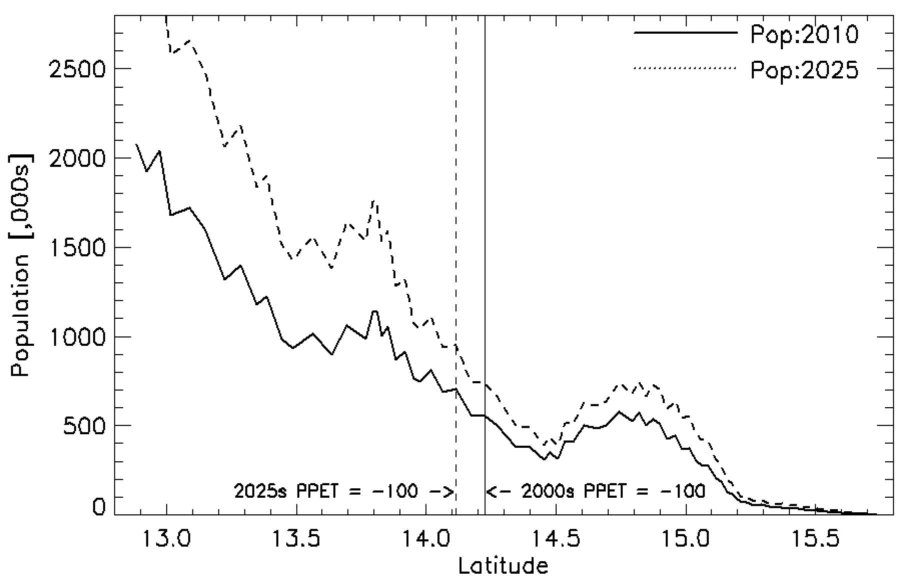


Figure 6. Southwest to northeast transects of Gridded Population of the World estimates (2010), and 2025 projections based on the 2010 data and the 2010 to 2000 change in population.

[2] Based on numbers for low, medium, and high variant 2025 population projections by the United Nations for Mali.

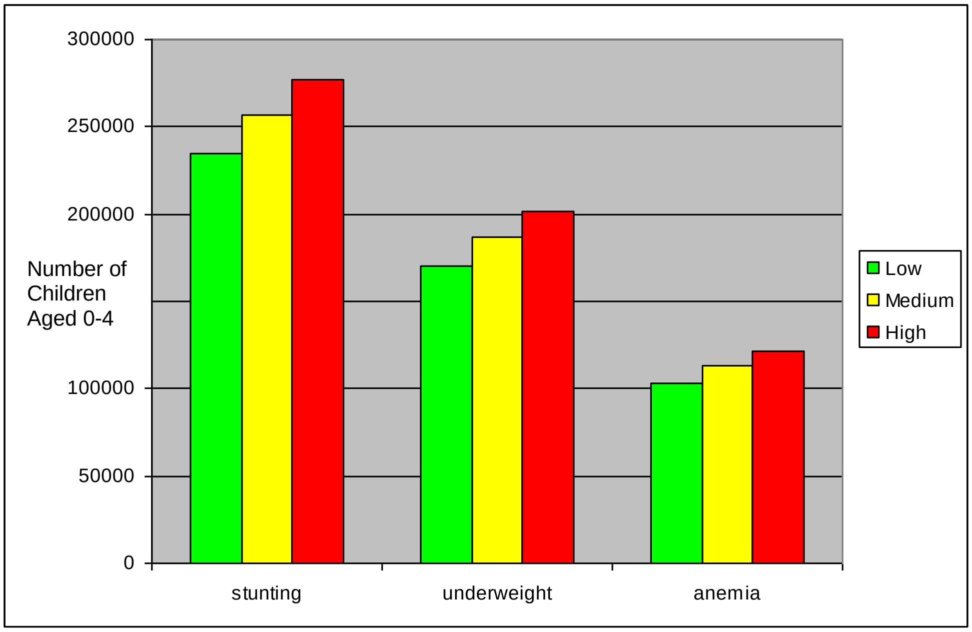


Figure 7. High medium and low variant projections for 2025 for children in the -100 or lower PPET zone in 2025 at risk of stunting, being underweight, and suffering from anemia.

5.2 Conclusion

We developed in this article a novel approach to examine and project climate and health trends in the African Sahel through the spatial coupling of FEWS NET climate data and DHS health data in Mali. Results suggest that underweight and anemic respondents appear influenced by livelihoods (negatively and positively respectively) and mitigation efforts should therefore focus on livelihood adaptation strategies. However stunting, a chronic outcome of malnutrition, is influenced by climate in addition to livelihood, presenting a more complicated picture for mitigation, and the need for future research to identify aspects of this climate-stunting pathway. The moving vulnerability 'front-line' is projected to expose 6 million additional Malians, from three-quarter of a million to one million will be children, to malnutrition from climate and livelihood changes in the near future when both climate and demographic change is taken into account.

This research responds to a call over recent years for meso-scale research of coupled natural and human systems to link to local and global-scale analyses where the vast majority of human-environment work is done (Marston, et al., 2005; Turner II, et al., 1990). The adaptation literature is largely focused on small village-level case studies, and implies climate change as a cause when it remains unproven or insufficiently referenced as the true source of adaptation (Butt, et al, 2005; Bremner, et al, 2010). Further, institutional and household adaptation is highlighted while place adaptation remains insufficiently recognized as a critical human and physical geographical context for describing resilience (Confalonieri, et al, 2007; Alderman, 2010). Perhaps most importantly, adaptation studies have yet to fully consider how climate change will transform geographies, and thus places of adaptation. In other words, case studies of adaptation may take place in villages or regions that twenty years hence will hold relatively little or relatively great promise for *future* adaptation (Lobel, et al, 2008). Future research may usefully consider the concept of shifting places of vulnerability and climate front-lines.

Policy interventions may interpret our results for Mali to concentrate adaptation efforts in our designated current and projected future front-line zone. Butt et al. (2006) highlight adaptation measures that could significantly decrease the economic and health impacts of climate change for Mali. We propose that these strategies be intensely applied in our designated current and projected front-line zone to aid mitigate the current and near future transition from rainfed to non rainfed crops. By translating ‘global climate change’ into estimates of local climate velocity, and intersecting climate and health, specific at-risk populations may be identified. Our methodology may be extended to other nations facing similar potential human health consequences of changing climate, particularly neighboring nations where climate and health data are available. Future research might continue to push the spatial boundaries of analysis to finer spatial and temporal scales, while still achieving geographic spread. Investments in such research efforts would undoubtedly pay high dividends in advancing the identification of climate vulnerability hot spots. Only by advancing such research can the scientific community provide increasingly informed policy prescriptions towards spatially targeted and temporally preventative adaptation measures.

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***Research Highlights**

Highlights:

>We model cluster level malnutrition of children in Mali with climate and livelihood zones.

>Livelihoods have statistically significant impacts on all malnutrition measures.

>Climate has a statistically significant negative effect on stunting when controlling for livelihood zone.

>Climate and demographic trends are projected to 2025, and incorporated with malnutrition and livelihood zone information to examine the impacts of climate, demographics, and livelihoods on malnutrition in the future.

>A moving climatically driven vulnerability front-line is identified where prioritized adaptation measures to enhance food security should be focused.