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Spatial Mapping of Vulnerability to Multi-hazards in the Savanna Ecosystem in Ghana

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Abstract
The savannah ecosystem in Ghana is subjected to a number of hazards, including droughts, windstorms, high temperatures and heavy rainfall, the frequency and intensity of which are projected to increase during the 21st century as a result of climate variability and change. Vulnerabilities to these hazards vary, both spatially and temporally, due to differences in susceptibilities and adaptive capacities. Many mapping exercises in Ghana have considered the impacts of single hazards on single sectors, particularly agriculture. But the nature of occurrence of the hazards, sometimes concurrently or alternately, and variability of their impacts on different sectors, warrants the mapping of the vulnerabilities of multiple sectors to multiple hazards. This paper therefore presents an analysis of the spatial dimension of vulnerabilities by mapping vulnerability of sectors that support livelihood activities at a single snapshot in time, using the Upper East Region of Ghana as a case study. Spatial mapping is important as it highlights vulnerable areas and sectors, allowing an integrated and targeted approach for interventions that support adaptation to multiple stresses in the savannah ecosystem. Data collected to develop the maps were largely quantitative and from secondary sources. Other data drew on fieldwork undertaken in the region from July – September, 2013. Qualitative data were quantified by assigning categorical values as the mapping process is necessarily quantitative. Data were divided into susceptibility and adaptive capacity indicators and were mapped in ArcGIS 9.3 using weighted linear sum aggregation. Agriculture was found to be the most vulnerable sector in all districts of the Upper East Region and experienced the greatest shocks from all hazards. Although all districts were vulnerable, the Talensi, Nabdam, Garu-Temapane and Kassena-Nankana West Districts were most vulnerable. Findings highlight the importance of more targeted policy interventions to build adaptive capacity in light of the spatial distributions of vulnerability and provide a first insight into the spatial distribution of hazards across sectors in the Upper East Region of Ghana.

Key words: Ghana, Climate Variability, Hazards, Mapping.

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1. Introduction

The climate is warming, a trend that is projected to continue with increasing frequency and intensity of climate related hazards (IPCC, 2014a). According to the IPCC (2014a), vulnerability to these hazards is greatest in developing countries, especially those in sub-Saharan Africa, because of their dependence on climate-sensitive livelihood activities and their poverty. Climate hazards, especially droughts, high temperatures, heavy rainfall, floods and windstorms, occur independently of each other, alternately or concurrently, in sub-Saharan Africa. Many studies have concentrated on impacts or vulnerabilities of single hazards on single sectors (e.g. Schlenker and Lobell, 2010; Antwi-Agyei et al., 2012; Blanford et al., 2013) and have sought to map vulnerability. For example, Blanford et al. (2013) focused on the health sector and showed that malaria parasite development has both spatial and temporal variation across Africa in relation to temperature changes.

Studies have also been undertaken that focus on adaptation, especially to climate change, aimed at reducing the potential impacts on humans and ecosystems and ensuring sustainability. These studies include a focus on: adaptation to climate change by the poor (e.g. Kates et al., 2012; Maslin and Austin, 2012; Sovacool et al. 2015); the adaptive capacities of vulnerable communities (e.g. Bryan, et al., 2015; Sherman et al., 2015; Williams et al., 2015); and barriers to adaptation (e.g. Antwi-Adgyei et al., 2014; Islam et al., 2014), amongst others. Most of these studies call for concerted efforts globally and locally to address the impacts of climate change (see IPCC, 2014 for summary of studies) and paint a bleak picture of the future. It is nevertheless clear from these studies that while people in these communities and ecosystems are vulnerable, they are still adapting, albeit with some challenges.

Despite these insights from the literature, it remains unclear as to how people are vulnerable to multiple stressors, particularly if they are frequently exposed and/or sensitive to multiple hazards, alternately and concurrently. This leaves a major research gap and calls for a holistic approach to better understand the situation (Yiran, 2014). This paper extends existing knowledge by presenting a multi-hazard/multi-sector mapping and analysis focusing on the vulnerability of the savannah ecosystem of Ghana. The paper's aim is to highlight the locations and sectors that require more targeted interventions to enable more effective adaptation to the hazards. Taking a spatial mapping approach is important because it gives a pictorial view of the scale of the vulnerabilities and factors accounting for such vulnerabilities at various locations across space.

In undertaking the mapping, it is first important to set out the key definitions we are using in this study. These are summarized in Table 1.

Table 1: Definitions at a glance

Term	**Definition**	**Source**
Vulnerability	Is a function of the magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity	IPCC, 2014b:24
Exposure	Is the presence of people, livelihoods, environmental services and resources, infrastructure, economic, social, or cultural assets in places that could be adversely affected by physical events and which, thereby, are subject to potential future harm, loss, or damage	IPCC, 2012:32
Sensitivity	The degree to which a system is affected, either adversely or beneficially, by climate variability or change, while adaptive capacity is the ability of systems, humans, institutions, or other organisms to adjust to potential damages, take advantage of opportunities, or cope with the consequences	IPCC, 2014b:2
Adaptive capacity	Comprises a specific usage of the notion of capacity and is dealt with in detail in later sections of this chapter and Chapters 2 and 8 in particular	IPCC, 2012:33
Indicator	Is a variable which is an operational representation of a	

	characteristic or quality of a system, able to provide information regarding the susceptibility, coping capacity and resilience of a system to an impact of a hazard	
Drought	A prolonged abnormally dry period when there is not enough water for users' normal needs, resulting in extensive damage to crops and a loss of yields	Wilhite, 2005 (cited in Berhan et al., 2011:137)
Dry spell	A period where the weather has been dry for an abnormally long time, but shorter and not as severe a drought	Wilhite and Glantz, 1985 (cited in Mathugama and Peiris, 2011)
Flood	Is an overflow of water onto normally dry land or the inundation of a normally dry area caused by rising water in an existing waterway, such as a river, stream, or drainage ditch. It is also ponding of water at or near the point where the rain fell. A flood caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours is flash floods	National Weather Service Forecast Office (cited in Yorth, 2014:19)
Windstorm	An atmospheric disturbance characterised by strong winds with speed of above 56 miles per hour and occur with or without rain	(City of Kent, 2010)

2. Methodology

A mixed method approach was used, including household surveys, focus groups and interviews to collect primary data. Secondary data were acquired from institutions and other published sources. Data sources and methods used are outlined in detail in the following sub-sections, after presentation of information on the study area.

2.1 Study area

This study mapped vulnerabilities to hazards in the savannah ecosystem of Ghana, focusing on the Upper East Region (UER) (Fig.1). UER was chosen because it experiences all hazards that occur in the savannah ecosystem. UER has the highest proportion of poor people in the country who depend on climate sensitive livelihoods (Ghana Statistical Service, 2012), and receives the lowest amount of rainfall in the savannah zone (Logah et al., 2013).

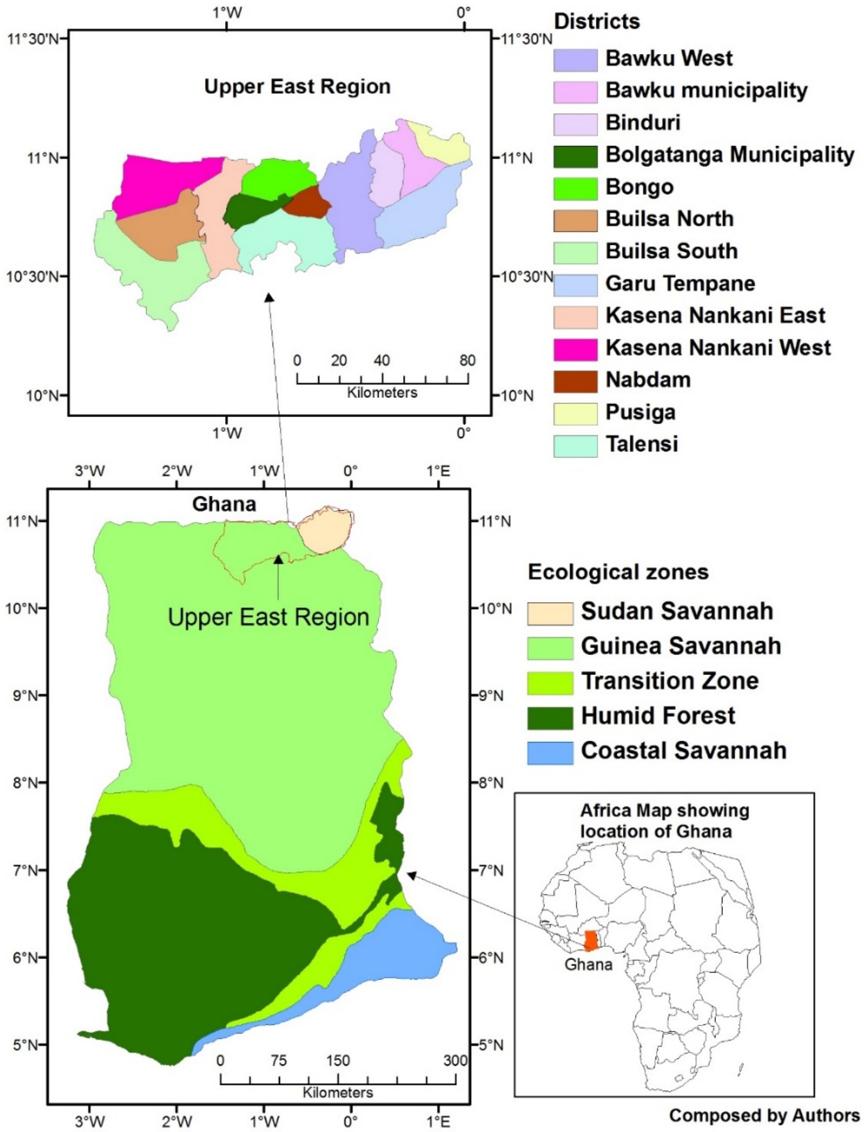

Fig. 1 Map of the UER and its location in the Savannah Ecological Zone of Ghana

UER is close to Burkina Faso and the first area to experience flooding following the opening of dams in that country. It has also been shown to be more vulnerable to hazards and is more food insecure than any other part of Ghana (e.g. Antwi-Agyei et al., 2012; WFP, 2012). These conditions made it a good case study site.

2.2 Methods

Mapping vulnerability required identifying variables that can be used as indicators in order to quantify exposure, sensitivity and adaptive capacities. A combination of household questionnaire surveys and literature review was used to identify the variables as well as obtain weights which were used to aggregate the indicators. In the household survey, a total of 210 household heads were sampled. District population data was used to identify both urban and rural samples (Table 2).

Table 2 Distribution of questionnaire surveys

District	**Classification of district**	**Town/village selected**	**Number of questionnaires**
Bawku Municipal	Urban	Bawku	20
Bawku West	Rural	Kubore	15
Binduri	Rural	Kumpalgoga	15
Bolgatanga Municipal	Urban	Bolgatanga	25
Bongo	Rural	Bongo	15
Builsa North	Rural	Sandema	15
Builsa South	Rural	Fumbisi	15
Garu-Tempane	Rural	Tempane	15
Kasena-Nankana East	Urban	Navrongo	15
Kasena-Nankana West	Rural	Kayoro	15
Nabdam	Rural	Nagodi	15
Pusiga	Rural	Koose	15
Talensi	Rural	Pwalugu	15
Total			**210**

Source: Authors

Sample sizes for rural villages/towns were equally distributed because there were no available population data for each village/town at the time of the field work (July-September, 2013) that could be used to determine appropriate sample sizes, yet we wanted to acknowledge that the district has both urban and rural dwellers. The urban sample was divided arbitrarily according to function of the town (i.e. whether it is a regional, municipal or district capital). A sampling procedure similar to restricted sampling was adopted to select both the villages/towns and the household heads to be involved in the research, because of its simplicity, representativeness and ease of implementation in GIS (see Steven and Olson, 2004; Elzinga et al., 1998). This ensured good spatial distribution of respondents.

Six individuals (largely people who had experienced a hazard) as well as representatives of twenty-five institutions were contacted for the in-depth interviews. Institutions included district offices of the Ministry of Food and Agriculture (MOFA), National Disaster Management Organisation (NADMO) and NGOs. Two institutional representatives did not respond, leaving a sample size of 23. Additionally, five focus group discussions were held with village/town members, four in rural districts and one in an urban district. Focus group discussants were selected to reflect the main social groupings of the villages/towns following discussions with local opinion leaders.

The factors identified as indicators through the interviews, especially those that did not have geographic reference system, were georeferenced. Most were georeferenced using district boundaries as the datasets, for these variables were collected at district level. Indicators were divided into susceptibility and adaptive capacity categories for different sectors supporting the livelihood activities of the people. Weights of the susceptibility indicators as well as sectors in relation to the hazards were obtained from interviews with institutional heads/representatives (experts) and the local people. Local people were asked to rank the indicators in order for us to obtain a picture of the effects of each hazard on the indictors/sectors. This was done on scale of 0-10, with the highest number given to the indicator or sector hit hardest. Ranks were compared with the weights obtained from the institutional interviewees and found to be almost the same, so average weights were used.

However, adaptive capacity indicators were difficult to rank based on their contributions to countering the susceptibilities, and consequently given equal weights.

Quantitative data for the indicators were obtained from secondary sources (reports and documents etc.) from relevant institutions. The crop failure index was calculated using crop yield data from MOFA between 1992 and 2012. Yields of five major crops (maize, rice, sorghum, millet and groundnuts) were detrended using auto-regression (implemented in Excel) to predict yields with a 3-year lag, in line with the method used by Simelton et al. (2009). Predicted yields were obtained after removing the short-term effects of technology and other factors by detrending, and therefore any production loss could be attributed to climatic hazards (Simelton et al., 2009). The crop sensitivity index was derived from the crop failure index by dividing the predicted (or expected) yield by the actual yield (i.e. crop failure index = expected yield/actual yield) for each crop in each district. Other data such as size of grassland and land availability were computed from other datasets (see Supplementary material, sections 2.1.1, 2.3 and 3.5). Qualitative data were assigned categorical values as described in Nardo et al. (2005). Data were then converted from vector data to raster data as this is considered more suitable for spatial analysis (Malczewski, 2000). After rasterisation, population, area and distance (i.e. length) data and all other absolute values (e.g. number of dams/dugouts) were divided by the number of grid cells (400 x 400 m^2) to obtain the value per grid cell. The percentage values, crop sensitivity index and the categorical scale values, particularly those below 100, were not converted to number per grid because these are relative values. See supplementary material for maps the indicators showing the quantities and measurement units.

2.3 Normalisation

After collection, indicator data were normalised and brought to a uniform dimension to avoid problems with mixed units. The rescale method (eq. 1) was used to normalise the indicators (see Malczewski, 2000; Nardo et al., 2005).

$$\text{Normalised value} = \frac{\text{value to be normalised} - \text{minimum}}{\text{maximum} - \text{minimum}} \qquad \text{eq. 1}$$

Eq. 1 rescales all values in the data to range between 0 and 1. The rescale method avoids the use of positive and negative values of an indicator in the aggregation process, which makes interpretation of the composite indicators more complex.

2.4 Aggregation

To aggregate the data at sector level for each hazard, the definition of vulnerability as the algebraic sum of susceptibility and adaptive capacity (IPCC 2014) was operationalised using the weighted linear sum overlay operation in ArcGIS 10. Many mapping exercises have negated adaptive capacity indicators when aggregating (e.g. Davies and Midgley, 2010; Kienberger et al., 2009). Vulnerability connotes adverse effects and increases with increasing susceptibility but decreases with increasing/enhanced adaptive capacity. Thus, this paper argues that susceptibility should be negated as in eq. 2:

Vulnerability = - (Susceptibility) + (Adaptive capacity) eq. 2

This conceptualisation results in negative values for grid cells having larger susceptibility values than adaptive capacity and positive values where the susceptibility values are smaller than adaptive capacity. Aggregation was done at two levels, first to susceptibility and adaptive capacity composite indices, and second, to obtain vulnerability indices (Fig. 2). This was operationalised using eq. 3.

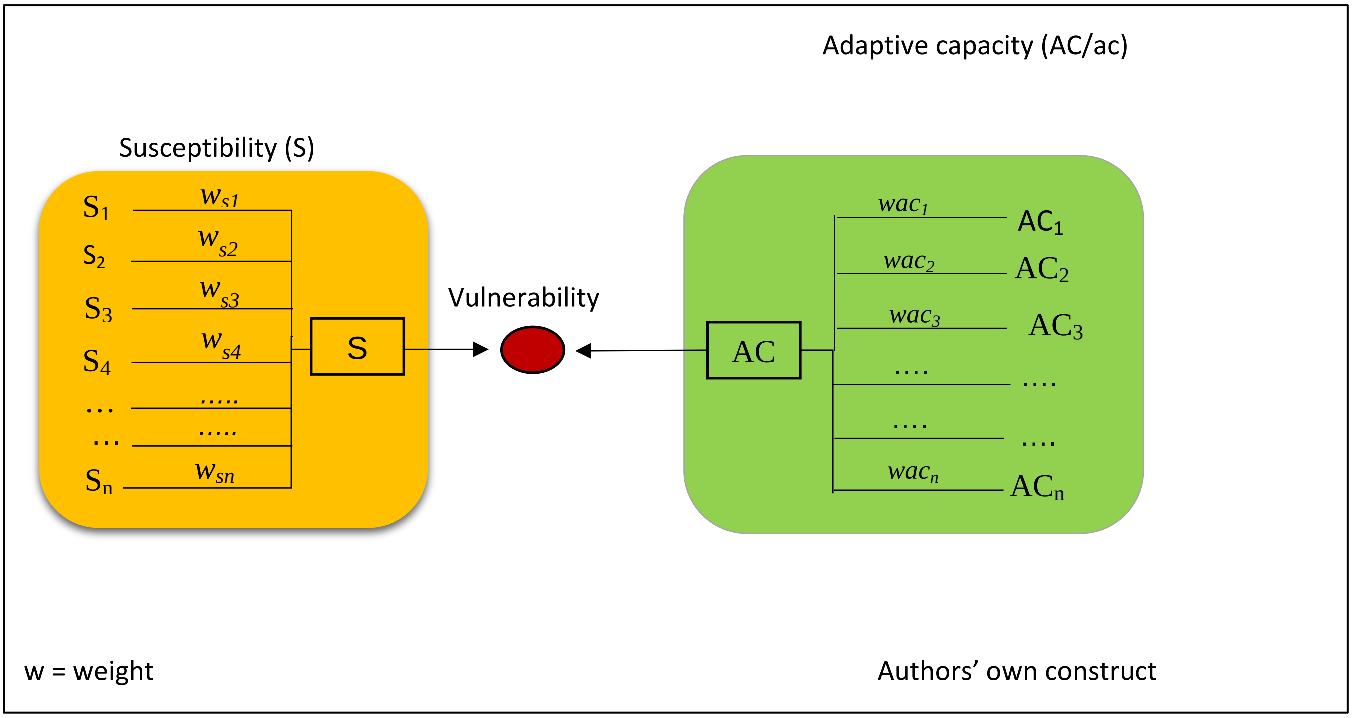

Fig. 2 Diagrammatical representation of vulnerability mapping

$$CI_d = \sum_{q=0}^{Q} w_q I_{qd} \qquad \text{eq. 3}$$

Where CI =composite index, d = sector, q = indicator, Q = number of indicators, *w* = weight and *I* = normalised indicator.

2.5 Evaluation

Evaluating a composite index is one of the most important steps in a quantitative vulnerability assessment as both the development of indicators and the building of a composite index inherits numerous uncertainties (Damm, 2010). Nardo et al. (2005:81) note that "good modeling practices require that the modeler provides an evaluation of the confidence in the model, assessing the uncertainties associated with the modeling process and the subjective choices undertaken, since the quality of a model depends on the soundness of its assumptions". Therefore, we tested the normalisation, weighting and aggregation procedures and composite indices for uncertainties (robustness and sensitivity).

The normalisation procedure was tested by using the standardised score which normalises indicators to have a mean of 0 and standard deviation of 1. The equation used for standardisation is:

Standard score = $\frac{Value-mean}{standard\ deviation}$ eq. 4

The weighting technique was tested by assigning equal weights to all indicators, because equal weights require no subjective interpretation in producing the weights, and disguises the absence of statistical or empirical facts (Nardo et al., 2005). Finally, geometric aggregation (eq. 5) was performed to test the robustness of the selected additive aggregation technique.

CI= $\prod_{q=1}^{Q} X_q^w$ eq. 5

CI = Composite Indicator, q = sub-indicator, w = weight associated to sub-indicator

The sensitivity analysis was done by computing the mean volatility between the various composite indicators and the procedures mentioned above. According to Groh et al. (2007), volatility is determined by the standard deviations of the ranks of indicators.

3. Results

The findings are presented here by looking at the indicators and their weights, the output of the uncertainty analysis and the vulnerability maps.

3.1 Indicators and weights

Indicators were grouped into sectors for each hazard (i.e. drought/high temperatures, floods/heavy rainfall and windstorms). Table 3 shows the susceptibility indicators and their weights while the adaptive capacity indicators are in Table 4.

Table 3 Weights of susceptibility indicators

Drought/high temperature		Flood/high precipitation	
Sector/Indicators	**Weight**	**Sector/Indicators**	**Weight**
Agriculture		**Health**	
Crops	0.6	Displacement	0.1
Livestock (pasture)	0.3	Casualties	0.2
Water holding capacity	0.1	Malaria	0.3
Health		Vulnerable group	0.4
Food insecurity	0.4	**Agriculture**	
population distribution	0.1	Crops	0.6
Cerebrospinal Meningitis (CSM)	0.2	Soil loss	0.3
Employed in agriculture	0.3	Erosion	0.1
Water		**Housing**	
Surface water	0.8	Buildings destroyed	0.2
Groundwater	0.2	Proximity	0.4
		Flash flood	0.3
		Type of building material	0.1
Windstorm		**Roads**	
Housing		First class	0.2
Roofing material	1	Second class	0.3
		Third class	0.5

Source: Authors N.B: Sum of the weights is equal to one (1) (Malczewski, 2000)

Table 4 Adaptive capacity indicators

Agriculture Sector		Health Sector	
Resilience	**Social**	**Resilience**	**Social**
Remittances	Wealth	Energy	Wealth
Markets	Financial institutions	Health facilities	Literacy
Animal ownership	Investment opportunities	Income generating activity	
Irrigation facilities	NGOs	Markets	Early warning
Protected land	Institutions	Food aid	Skill
Land availability	Skills	Remittances	
Income generating activity	Literacy	Land availability	
Water		Animal ownership	
Energy	Institutions	**Housing**	
Income generating activity	Investment opportunities	Remittances	Institutions
Land availability	Skills	Land availability	Wealth
	NGOs	Income generating activity	Literacy
	Wealth		NGOs
Road			Skills
Land availability	Institutions		
	NGOs		

Source: Authors

3.2 Results of evaluation

Robustness tests were done for all sectors and hazards but for illustrative purposes, we present the results for agriculture sector. The tests (Fig. S14) show similarity in the indices for all methods (i.e. normalisation, weighting and aggregation procedures), with only small variations in magnitudes. Mean volatility between the various methods was computed to determine the significance of the variations (Table 5). Volatilities are small, ranging from 0.165 for the weighting procedure to 0.24 for the normalisation procedure, indicating that the procedures were robust.

Table 5 Mean volatility of different methods

Method	Normalisation	Weighting	Aggregation
volatility	0.24	0.165	0.17

Source (Authors' own construct)

Mean volatilities of different scenarios were computed by excluding indicators in turn to test the sensitivity to each of the indicators. For the agriculture sector, composite vulnerability was calculated an additional 7 times with, excluding each per run, crop sensitivity, grassland (pasture), Water Holding Capacity (WHC), investment opportunities, institutional capacities, land availability and protected land (Table 6). From the Table, the volatilities range from 0.17 to 0.21. The vulnerability indices therefore changed very little and were not sensitive to any indicator. Thus, the indices were relied on to assess the nature of vulnerability in the region. In doing this, we constantly make reference to the original indicators.

Table 6 Mean volatility of nine scenarios

Variable changed	Excl. WHC	Excl. pasture	Excl. crop sensitivity	Excl. inst. capacity	Excl. invest	Excl. land availability	Excl. Protected land
Volatility	0.2	0.2	0.21	0.19	0.18	0.19	0.17

Source (Authors' own construct)

In presenting the vulnerability maps, we assumed that vulnerability and resilience are opposite of each other (see Bahadur et al., 2010) to denote the negative values as vulnerability and positive values as resilience. Though we recognise that people could have high adaptive capacity and still be vulnerable and that the reality is more complex, the division between resilience and vulnerability was made here to expedite our analysis. The maps are presented sector by sector for each hazard.

3.3 Vulnerability to droughts/high temperatures

The maps for the three main sectors identified to be vulnerable to drought/high temperatures are shown in Fig. 3. The degree of vulnerability of each sector is shown by the values on the maps. In Fig. 3, the agriculture sector is most vulnerable. It has the largest negative value and all values in the range are negative. The second most highly vulnerable sector is water as it had the next largest negative values but showed higher resilience than the health sector. Spatially, the highest vulnerability indices for the agriculture sector occurred in Talensi-Nabdam, Garu-Tempane and Kassena-Nankana West Districts where values were above -0.6. The next most vulnerable set of districts were the Bolgatanga Municipality, Kassena-Nankana East, Pusiga, Binduri and Bawku Municipality while Builsa North is the least vulnerable. In the water sector, the Kassena-Nankana East District is highly resilient, Bolgatanga is resilient, Bawku, Nabdam, Binduri and Pusiga Districts are vulnerable, while the rest are highly vulnerable to droughts.

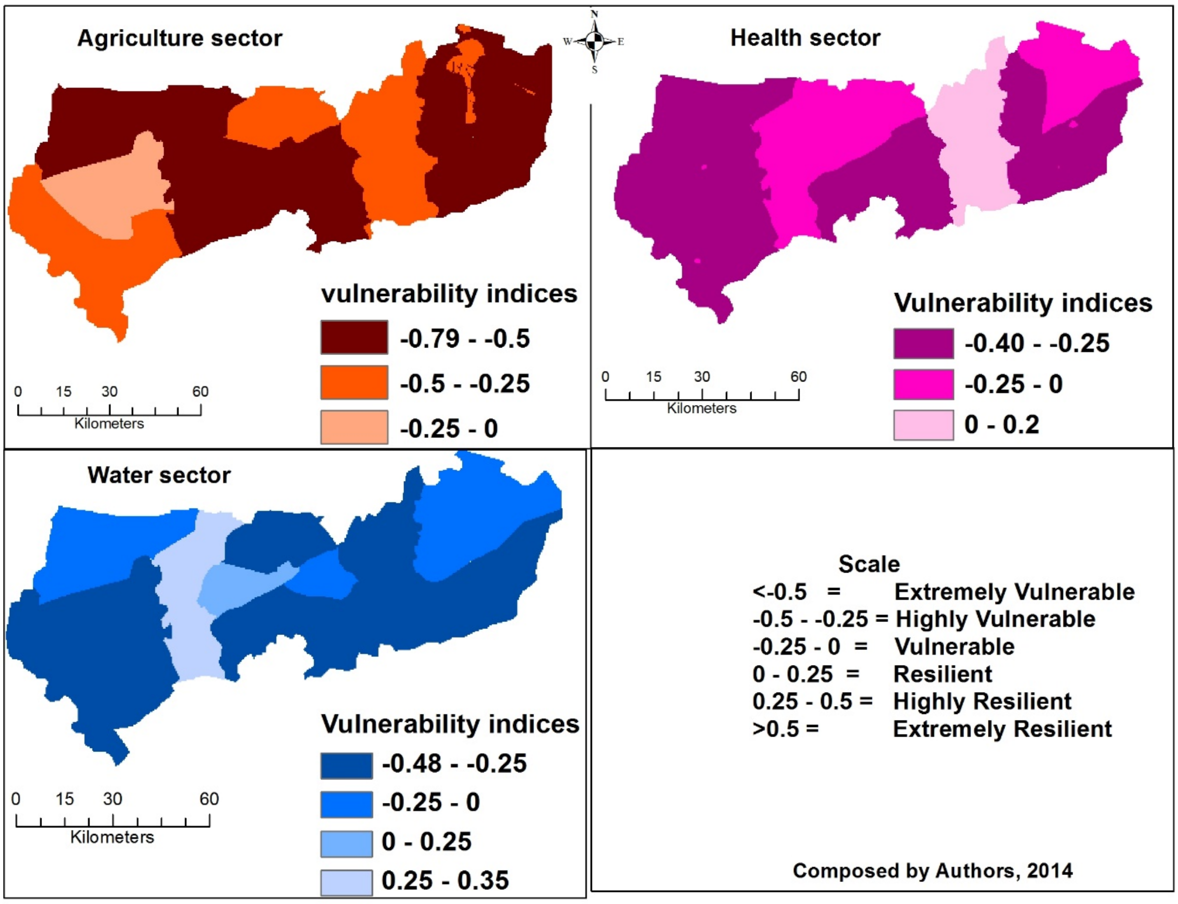

Fig. 3 Vulnerability of sectors to drought/high temperatures

Most of the participants in the household questionnaire survey stated that since they started using boreholes and/or mechanised wells, they have not experienced any major water problems, thus confirming the resilience of the water sector. The health sector shows low vulnerability due to the presence of good adaptive systems. For example, we found that remittances from relatives were used to buy food and finance healthcare, as evidenced by various respondents and illustrated as follows:: “my son is working in Accra and each month, he sends me some money which I use to buy food, medicine and take care of other needs”. Many rural communities reported some form of a healthcare system. An interview with a village/town Health Nurse in the Talensi district noted that: “since I came here, I have managed a lot of minor ailments that could lead to more severe outcomes from Cerebrospinal Meningitis (CSM) and malaria cases and I can say that there is improvement in the health status of the people in this and surrounding communities", an indication of improved adaptive capacity through provision of health facilities. The districts that are highly vulnerable to droughts/high temperatures in the health sector are Kassena-Nankana West, Builsa North and South, Talensi-Nabdam, Binduri and Garu-Tempane. The rest show low vulnerability while Bawku West is resilient to these dry and hot conditions. The highly vulnerable districts in this sector to droughts/high temperatures (section 3.1), possess high susceptibility indicators (see section 2.1.2 of supplementary material).

3.4 Vulnerability to floods/heavy rainfall

Four sectors were vulnerable to floods: agriculture, health, housing and roads. The water sector was left out due to insufficient information to determine its susceptibility. This is not expected to affect the analysis since a lot of dams/dugouts have been constructed to harvest the runoff. The vulnerabilities of the included sectors were examined spatially (Fig. 4). From Fig. 4, the agriculture and housing sectors are shown to be highly vulnerable to flooding/heavy rainfall, though the agriculture sector is most vulnerable. The Builsa North and South and Binduri Districts are highly vulnerable to floods (Fig 4) with Bolgatanga Municipality being the least vulnerable. The high vulnerability of the Builsa districts is due to high and frequent exposure to flooding. The housing sector is also vulnerable to floods, especially those houses close to rivers/streams (see section 2.2.3 of supplementary material). The health sector is vulnerable in Bolgatanga and Bawku Municipalities, Bawku West, Binduri and Pusiga Districts while the rest are resilient. These districts have a high malaria burden, a high number of displaced and injured people and/or properties destroyed due to flooding, high numbers of dependent people (disabled and children) and low adaptive capacities (see sections 2.2.2 and 3 of supplementary material). The road sector is also generally resilient across the study area.

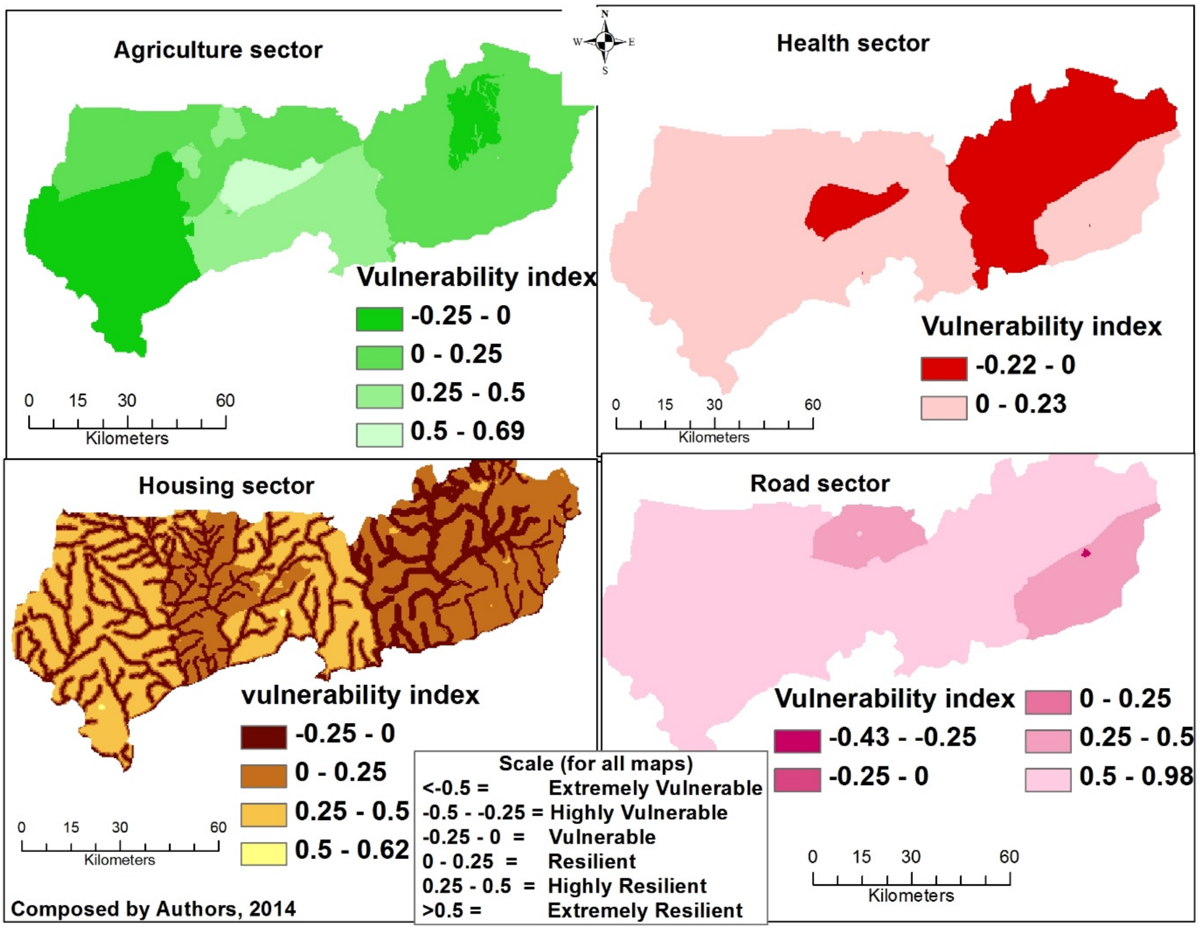

Fig. 4 Vulnerability of sectors to floods/high rainfall

3.5 Vulnerability to windstorms

The vulnerability of the region to windstorms was mapped combining its susceptibility with the following adaptive capacity indicators: wealth, income generating activity, institutions, NGOs, remittances and early warning systems. The resultant map is shown Fig. 5, where, it can be seen that the entire region is resilient to wind, especially the urban areas where resilience is high. From the questionnaire survey, over 70% of the people indicated windstorms hardly ever occur. Nearly all respondents stated that the destruction from storms that do occur is usually to roofs and they are able to re-roof immediately or in the following dry season. An old lady whose roof was affected in the last rainy seasoned said: “when my roof was ripped off, I stayed with my nephew’s wife until it was fixed for me after the rainy season”.

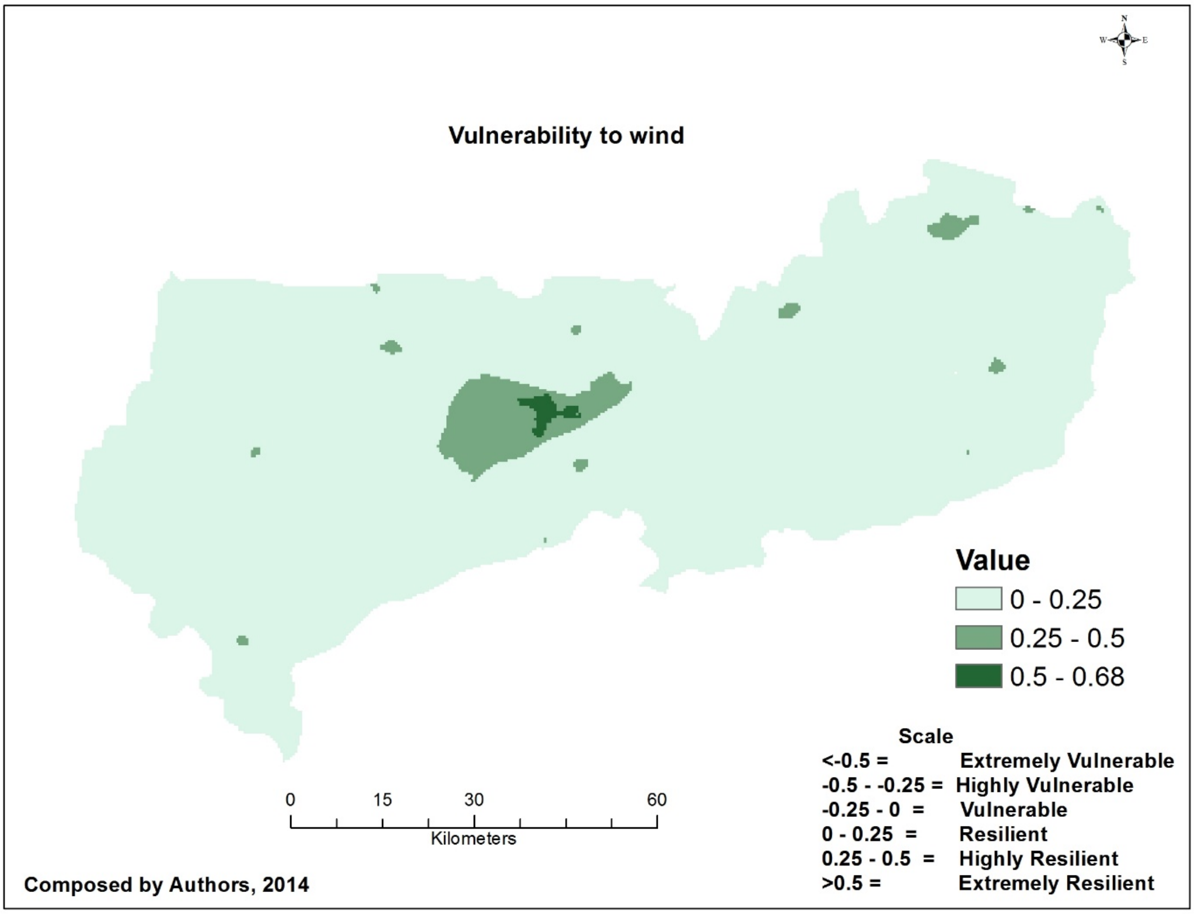

Fig. 5 Vulnerability of the UER to windstorms

4. Discussion

In this section, we discuss the spatial variation sector by sector to each hazard and then consider the aggregate vulnerability to the hazards. However, in discussing the vulnerabilities, we will make references to the original indicators in the supplementary material due to loss of information resulting from the normalisation process (see Nardo et al., 2005).

4.1 Agriculture

As shown in the results, the agriculture sector is the most vulnerable to nearly all hazards. This high level of vulnerability is because agriculture in the region is still largely rainfed, so is moderated by the climate system. Droughts/dry spells and excessive heat are found to be increasing in frequency and intensity (Logah et al., 2013; Yiran, 2014). The increased incidence of droughts/dry spells coupled with high temperature greatly affect soil moisture, which in turn affects crop production in these areas. Many studies show a negative correlation between increasing temperatures and yields of major crops in Africa (e.g. Schlenker and Lobell, 2010; Sultan et al., 2013). The highly to extremely vulnerable districts in the study were mostly those with few irrigation facilities. This is in line with the findings of Boko et al. (2007) who note that the vulnerability of the African crop production system is due to extensive reliance on rainfed crop production, high intra- and inter-seasonal climate variability, recurrent droughts and floods that affect both crops and livestock.

According to Thomas (2008), rural people in dry areas will require different options to manage climate change. These include changing their cropping systems and patterns, changing from cereal-based systems to cereal-legumes, diversification of production systems towards higher value and more water efficient practices. Some of these adaptations, particularly changing crop systems and cereal-legumes, are already in use, yet production is still low. Several factors could account for this (see Aniah et al., 2013; Bawakyillenuo et al., 2015; Yiran and Stringer, 2015), yet interventions to enhance adaptation need to be targeted considering the relative susceptibilities of each district. Efficient use of irrigation systems and practices and water harvesting technologies have been recommended for dry land areas in Asia (Thomas, 2008) and could help increase agricultural production in the savannah ecosystem, particularly in highly vulnerable districts.

The occurrence of droughts/dry spells has affected the length of the growing season for annual crops. The sowing time has shifted from April to end of May or first week of June, thus shortening the length (Yiran, 2014). Late planting has pushed the maturing time of most crops to August, the month with heaviest rainfall and flooding, resulting in crop losses as crops are washed away by floods (Yiran, 2014). Reduction in growing season coupled with increases in the frequency and prevalence of failed seasons may shift the farming system from a mixed crop-livestock towards more livestock production (Jones and Thornton, 2009; Thornton et al., 2010). Climatic and other environmental changes have also affected livestock production (Thornton et al., 2010; Dougill et al., 2010; Descheemaeker et al., 2011; Freier et al., 2012; Schilling et al., 2012). A shift from crop production may thus have great implications for adaptation, particularly in the study area where crop production is prioritised over livestock production (Amankwa et al., 2012). Although short duration crops are being introduced in the area, these are largely maize varieties (Yiran, 2014). This is changing the taste and food preference of the people as they largely eat what is produced from their own farm (Yiran and Stringer, 2015). The cultivation of one crop has been found to also negatively affect biodiversity (Olschewski *et al*., 2006, cited in Stringer et al., 2009; Giam et al., 2015; Rountree, 2015). Again, this highlights the interlinked nature of dealing with vulnerability to climate hazards, as actions in one sector can impinge on activities and outcomes in other sectors.

As noted by the IPCC (2014b), countries with very low adaptive capacities exhibit high vulnerabilities. This was shown clearly even at the local level where districts with lower adaptive capacities exhibited higher vulnerabilities, though the level of susceptibilities also varied. Low adaptive capacity stems from low agriculture productivity, the main economic activity of the people. Despite its vulnerability, agriculture is seen as a means for rural growth and poverty reduction (MOFA, 2007). Although all districts experience low productivity, those with irrigation facilities or have or some people use groundwater for dry season gardening are better off than those without (Antwi-Agyei et al., 2012). Other good local practices reported by respondents in the various interviews (such as flood recession agriculture, seed stocking, remittances, dry season gardening using groundwater with water cans and pumps (Yiran and Stringer, 2015)) helped to increase productivity and hence adaptive capacity in some districts.

Frequent losses in agricultural production are thwarting efforts to reduce poverty (UNDP, 2012). From IPCC (2014a) projections, the agricultural system in Africa is expected to face significant challenges in adapting to climate change by 2050. This may increase poverty in the already highly vulnerable districts and affect the country's ability to achieve the Sustainable Development Goals, especially goal 1 which seeks to end extreme poverty everywhere. Indeed, official figures show that 9 out 10 people in the region are poor (Ghana Statistical Service et al., 2009). Although Ghana has already halved poverty nationally since 2010, there is no improvement in the three regions in northern Ghana which occupy the savannah ecosystem (UNDP, 2012) as a result of frequent production losses. According to the UNDP (2012), these regions are in deficit and that of the UER is about 32 percentage point from the 2006 poverty incidence.

4.2 Health

Climate change and its associated hazards also have health implications for the population in the region (IPCC, 2014a). The health sector in the region is highly vulnerable to climatic hazards, particularly droughts/dry spells, high temperatures, floods/heavy rainfall. These hazards directly or indirectly cause illnesses such as CSM, malaria, headaches, cholera, rashes, among others, as well as injuries and loss of life to humans and livestock. Diseases and injuries, as well as destruction to property and life, have serious socioeconomic implications for nations. Substantial financial and logistical support is required to acquire and distribute vaccines and medicines to treat people and this brings about disruption to normal health services in the affected areas as resources are redirected (Whitson, 2005). Families and individuals are similarly affected (Whitson, 2005) as they lose property and require financial resources to seek health care. The net result of poor health is a reduction in adaptive capacity in the face of increasing climatic hazards. This is the case presently in the UER, particularly in the highly vulnerable districts. The high susceptibility to the diseases and misfortunes and the low adaptive capacity in terms of inadequate health infrastructure and health personnel, weak health insurance scheme and lack of financial resources (Ghana Health Service, 2012) helps to explain the high vulnerability of the health sector. The variations in vulnerabilities in the health sector to the hazards result from the combined effects of these factors, with the highly vulnerable districts exhibiting high susceptibilities and low adaptive capacities.

It is clear from the study that vulnerability in the health sector is also hazard dependent. It is more vulnerable to drought/high temperatures than that of flood and the other hazards. The impacts of droughts/high temperatures are more severe than those from floods/heavy rainfall, whereas adaptive capacities are the same for all hazards. Droughts/high temperatures have greater negative implications on food security and malnutrition and a higher health burden and also affect a wider area than floods/heavy rainfall, as is evident in the records of the regional health reports. The variations in impacts according to hazards have also been recognised by WHO (2008).

As shown in section 4.1, these hazards affect agricultural production which has serious implications for food security and poverty. The region is classified as food insecure with the insecurity varying from district to district (WFP, 2012). The highly food insecure districts are the high vulnerability districts. Food shortages are recurrent in region resulting in higher food prices (Akudugu, 2010) and causing people to adopt practices such as reducing food intake. Yiran (2014) reported that over 70% of the people, especially the rural poor, depend on their own production for household food supplies and reduce their food intake when their supply depletes and because of high food prices. This has negative impacts on their health and can lead to malnutrition. The Ghana Demographic and Health Survey report indicates that malnutrition in the region is very high especially among children under 5 years, with 36% being stunted and 27% underweight (Ghana Statistical Service et al., 2009) and this is largely attributed to the inability of many household to acquire sufficient food, especially in the lean season. Studies on the relationship between climate change and health show a correlation between weather variables and stunting (Grace et al., 2012; Jankowska et al., 2012), an indicator of malnutrition. Projections into the 2050s show that climate change and variability will increase the relative percentage of the severely stunted by 31-55% reversing benefits that would be derived from socio-economic development

(IPCC, 2014a). This will further worsen the health status of the people, especially those in already highly vulnerable districts.

4.3 Water, housing and road sectors

Extreme dry and hot conditions can result in water scarcity, especially for domestic use, irrigation and watering of animals, as well as the over-heating of housing units. Liebe et al. (undated) reported high evapotranspiration rates in the region and that many surface water bodies dry up when there are prolonged dry conditions. The drying up of water bodies and lowering of groundwater table during these hot conditions often result in acute water problems in the dry season in parts of the Talensi, Builsa, Bawku West and Garu-Tempane Districts; areas on rocky ground in which it is difficult to sink boreholes (Yiran, 2014). In some areas in these districts and in Nabdam, Binduri and Pusiga which have boreholes, yields are reduced in the dry season (Yiran, 2014). In other areas, even shallow wells are used to harness groundwater for both domestic and agricultural purposes (Namara et al., 2011). Thus, the nature of the groundwater, the depth of the water-table and the number and capacity of surface bodies account for the high vulnerabilities in some districts. All districts are vulnerable in the water sector, except Kassena-Nanakana East and Bolgatanga Municipal. Vulnerability is lower here due to the presence of many dams in these two districts. Conversely, extreme wet conditions recharge the water system and have been predicted to increase (IPCC, 2014a). Numerous dams and reservoirs could benefit from this, however, studies indicate high siltation of water bodies due to increased runoff and erosion, thereby decreasing the storage capacity of reservoirs (Obuobie, 2008; Adwubi et al., 2009). This means that reservoirs and dams could collapse leading to flooding downstream or store less water and dry quickly in the dry season, increasing the vulnerability of people and property.

In the housing and roads sectors, increased rainfall and subsequent flooding damage infrastructure. The situation is more serious as more and more infrastructure finds its way into valleys and close to rivers due to urbanisation. This is particularly problematic as towns grow and villages consolidate into towns, and competing demands for land, especially for residential purposes, push people to settle in flood-prone areas. Records from NADMO show more destruction to properties and casualties in most of the big towns, particularly Bolgatanga and Navrongo and districts (Binduri, Bawku West, Builsa North and South) that have more river/stream networks. Our study area is not alone in this regard. Many African cities are experiencing the consequences of floods due to urbanisation (Oteng-Ababio, 2011; UN-Habitat, 2011; Gyasi *et al.*, 2014). Urbanisation creates excessive demand for housing and roads in towns and may increase the number of people vulnerable to climate impacts (Seto, 2011). However, Yiran and Stringer (2015) found that lack enforcement of building and land use regulations in the area also contributes to the vulnerability of the housing sector. Windstorms also affect buildings. The combined effects of the extreme wet conditions and windstorms have caused people to shift to use concrete and roofing sheets, although interviews suggested modernity and taste are also increasing use of these materials. These materials trap heat and increase the risk of CSM (IPCC, 2014a). The rural roads suffer the consequences of flooding/heavy rains because they are largely untarred and easily eroded, and in some cases, bridges and culverts are washed away. This leaves the roads in very bad condition and makes the delivery of goods and services, especially emergency services, both difficult and expensive. Spatial variations in vulnerabilities here are largely due to differences in susceptibilities as adaptive capacities are fairly similar across the region (Yiran, 2014).

5. Conclusions and recommendations

In this paper we have shown that the savannah ecosystem of Ghana is highly vulnerable to multiple hazards. We demonstrated that the vulnerabilities vary sectorally and spatially from hazard to hazard and provide the first study of its kind to assess spatial vulnerability to multiple hazards across multiple sectors in the study area. We have also identified the factors that contribute to the vulnerabilities of these sectors to specific hazards. Agriculture and health sectors are the most vulnerable and their vulnerabilities to droughts/high temperature are higher than to floods/heavy rainfall. This is because droughts/high temperatures have more consequences for soil moisture content, affecting agricultural production and by extension, food security and incomes. They also contribute to water scarcity for domestic and other uses and high incidences of heat related diseases. Together, these affect the general wellbeing of the population. High susceptibilities are not adequately met by the low adaptive capacities that are harnessed through the natural, physical, social, financial and human as well as technological assets available with the region. Key to our findings is that the factors of susceptibility and adaptive capacity combine to produce the vulnerabilities vary for district to district. Also, the levels of vulnerability to droughts/high temperatures are higher than floods/heavy rainfall and windstorms respectively. Given that interventions to reduce susceptibilities and increase adaptive capacities will have to compete for funding from limited national budgets and resources, we envisage that our work will serve as a guide to policy makers, especially at the district level, to prioritise interventions to maximise adaptations to the hazards. In addition to the sectoral recommendations below, we propose that more attention be paid to reducing susceptibilities to droughts/high temperatures and that interventions should be targeted considering the strengths and weaknesses of various districts.

In the agriculture sector, the government and its development partners need make substantial progress. We have shown the spatial variations in the agricultural sector and therefore offer an opportunity for development agencies to better target interventions to enhance adaptation. The vulnerabilities of Talensi, Nabdam, Garu-Tempane and Kassena-Nankana West Districts could greatly be reduced by providing more irrigational facilities as the few dams/dugouts in these districts are largely for watering of animals. Additionally, the various districts have some potentials (captured as investment opportunities under adaptive capacity) and could be tapped to diversify their economies to reduce their dependence on agriculture in order to alleviate poverty and enhance adaptation to all hazards affecting the sector.

There is an urgent need to improve healthcare by increasing health facilities and staffing, and undertaking health campaigns, especially in the rural districts. This needs to be coupled with actions to reduce the costs of healthcare, especially for the poor. Community-based Health Planning Services (CHPS) compounds and other health facilities, immunisations, vaccinations, distributions of insecticide-treated bed nets, deworming, nutritional treatments, outreach programs aimed at sensitising the people on preventive measures. Other general services need also to be intensified. In Bolgatnaga and Bawku Municipalities, insecticide bed nets could be distributed while in the rural districts, more health facilities be built to reduce the number of people from the rural areas attending the facilities in the towns. CHPS compounds are particularly important in the rural areas as health facilities are inadequate and settlements are dispersed. Incentives should be put in place to encourage health personnel to take up posts in the rural areas. The health insurance scheme, which is pro-poor, should be strengthened.

Groundwater should be harnessed (for both agriculture and domestic use) but there is need for further research into the sustainability of its extraction to enhance adaptation in the region. The eastern part of the Talensi District in particular has high groundwater recharge rates and this could be exploited to enhance adaptation in this district. In the housing sector, it is recommended that building and land use regulations and buffer zones should be enforced in towns/villages along rivers/big streams to ensure hazard prone areas are not used for residential purposes and to protect river banks. Also other rainwater harvesting technologies in Bolgatanga, Navrongo and Bawku and included in the building codes should be introduced to reduce runoff. These technologies and regulations should be extended to the capitals of the rural districts as these will develop into bigger towns soon. Roads need improving to increase the movement of goods and services, particularly agricultural goods and emergency services. These efforts can together enhance the adaptive capacity of the area.

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Supplementary Information - Table of Contents

1 Introduction

Before vulnerability can be mapped, the data has to be converted into geographic layers. After georeferencing, all datasets were converted into raster layers since spatial analysis operations are best performed in raster format (see Damm, 2010). This supplementary material describes the data, sources and rasterisation and presents a map of the evaluation exercise.

2 Development of susceptibility layers

This section gathered all the indicators of exposure and sensitivity into geographic layers called susceptibility layers for each hazard for the various sectors. Other studies have used similar procedures to identify indicators and have combined them in this way (e.g. Kienberger et al., 2009; Damm, 2010). Susceptibility measures the degree to which systems/livelihood activities are adversely affected by hazards. The different livelihood activities identified are susceptible to different hazards, as these are located at different places over space and take place at different times. Thus, to practically implement the concept of susceptibility requires the categorisation of livelihood activities into a series of components related to sectors of the economy that are affected by the hazard in question, as proposed by Villagrán (2006, cited in Kienberger et al., 2009).

2.1 Susceptibility to drought/high temperatures layers

The people affected by drought/high temperatures engage in livelihood activities such as crop production and livestock farming, and key variables also include human population, health and water availability. The indicators that made each sector vulnerable to drought/high temperatures were identified and mapped as described below.

2.1.1 Agriculture

The agriculture sector is susceptible to events of droughts/high temperatures. Droughts result in crop failure and death of animals due to scarcity of water and fodder. In order to characterise the sensitivity of the crops, a score between 1 and 1.49 was categorised as sensitive, 1.5 to 1.99 very sensitive and 2 or above as extremely sensitive. These categories were assigned values of 1, 2 and 3 respectively. Water Holding Capacity (WHC) of the soil types in the region obtained from Amegashie (2009) serves as the impact of the hazards on the soil. Pasture availability for animals was calculated from grasslands using 2010 Aster satellite imagery. The maps for the agricultural sector susceptibility are shown in Fig. S1.

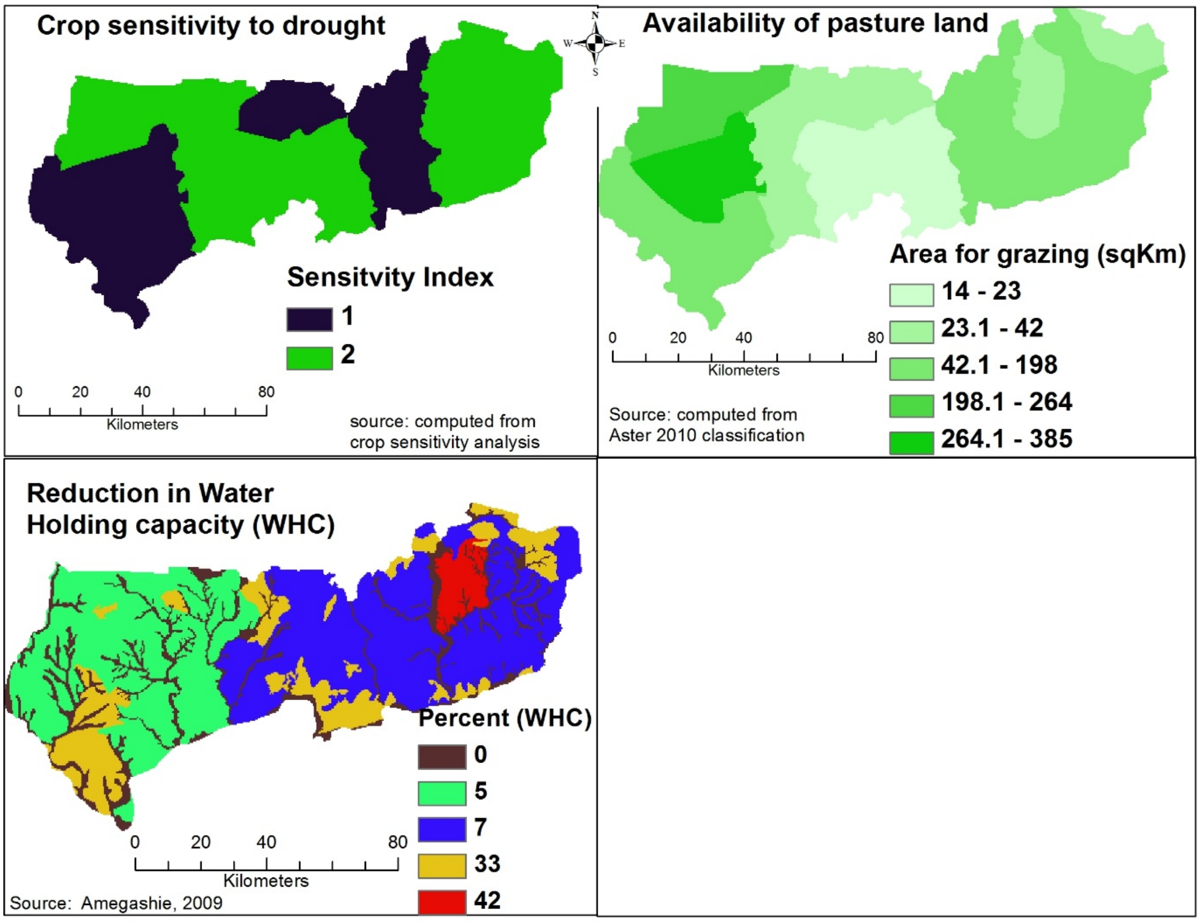

Fig. S1 Susceptibility of agriculture to drought/high temperatures

2.1.2 Health

Drought/temperature affect the population in several ways but most importantly, they can lead to food shortages and bring about illnesses such as cerebrospinal meningitis (CSM) and malnutrition, as well as a reduction in income. The food shortage component was determined using food insecurity status at district scale, obtained from the World Food Programme (WFP, 2012) report. This dataset also served as a proxy for malnutrition since it was difficult to obtain any other data on malnutrition. This dataset was linked to the district shapefiles in ArcGIS 9.3 and used to map the food insecurity indicator. Drought affects the entire population but its largest impact is on the rural population. Therefore, the distribution of the population was mapped according to whether the area was urban or rural. This data was obtained from the 2010 population and housing census which delimits rural and urban populations. It was assumed that districts with higher rural populations will be more susceptible to food crises due to droughts than those with lower rural populations. Households engaged in agriculture were considered more susceptible to droughts than those not involved in agriculture as they suffered from reduced income whenever drought occurred. Thus, the number of households involved in agriculture in each district was considered in mapping susceptibility to drought. This data was also obtained from the census report. Districts with a higher number of households in agriculture were considered more susceptible than those with lower households.

CSM case fatality rates for the various districts were used to map the CSM indicator. This data was obtained from the regional health report (Ghana Health Service, 2012). Fatality rates show the degree of susceptibility of the districts to CSM in terms of lives lost per reported case. Therefore, districts with higher case fatalities were considered more susceptible to high temperatures (i.e. heat). These indicator layers are shown in Fig. S2.

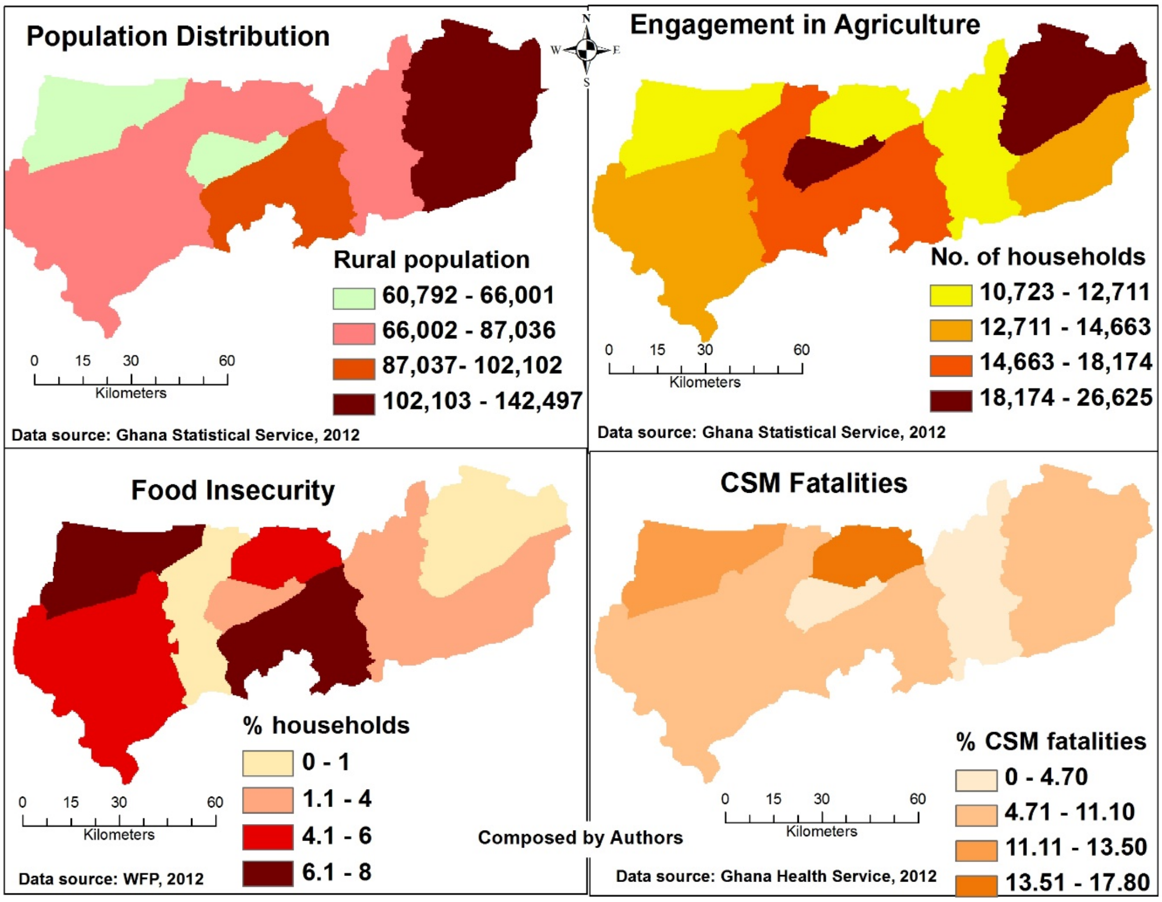

Fig. S2 Susceptibility of humans to drought/high temperatures

2.1.3 Water sector

When there is drought or high temperatures, surface water bodies dry up while ground water recharge reduces. For surface water, the number of reservoirs per district was counted and used to map susceptibility to droughts/high temperatures. The assumption is that a district with a higher number of reservoirs will be less susceptible than one with a lower number, because it may still have some reservoirs with water and less crowding of animals and humans at the remaining few water points. A similar approach was used by Kienberger et al. (2009) where they took the number of spring water bodies to indicate susceptibility to floods. Data used in the present study was obtained from the IDA (2013) in Excel format. Numbers were cross-checked with the dams identified on Google Earth in 2013 and linked to the district boundaries as some districts were divided after the 2010 population and housing census. Groundwater susceptibility was mapped using the recharge map produced by Obuobie (2008). This map showed the ranges of ground water recharges interpolated over the region. The map was exported as a .jpeg file, georeferenced and digitised. Places with low recharge were considered more susceptible to droughts/high temperatures than those with high recharge rates. This is because the region depends on groundwater for nearly all its domestic water requirements and some dry season gardening. These susceptibility layers are shown in Fig. S3.

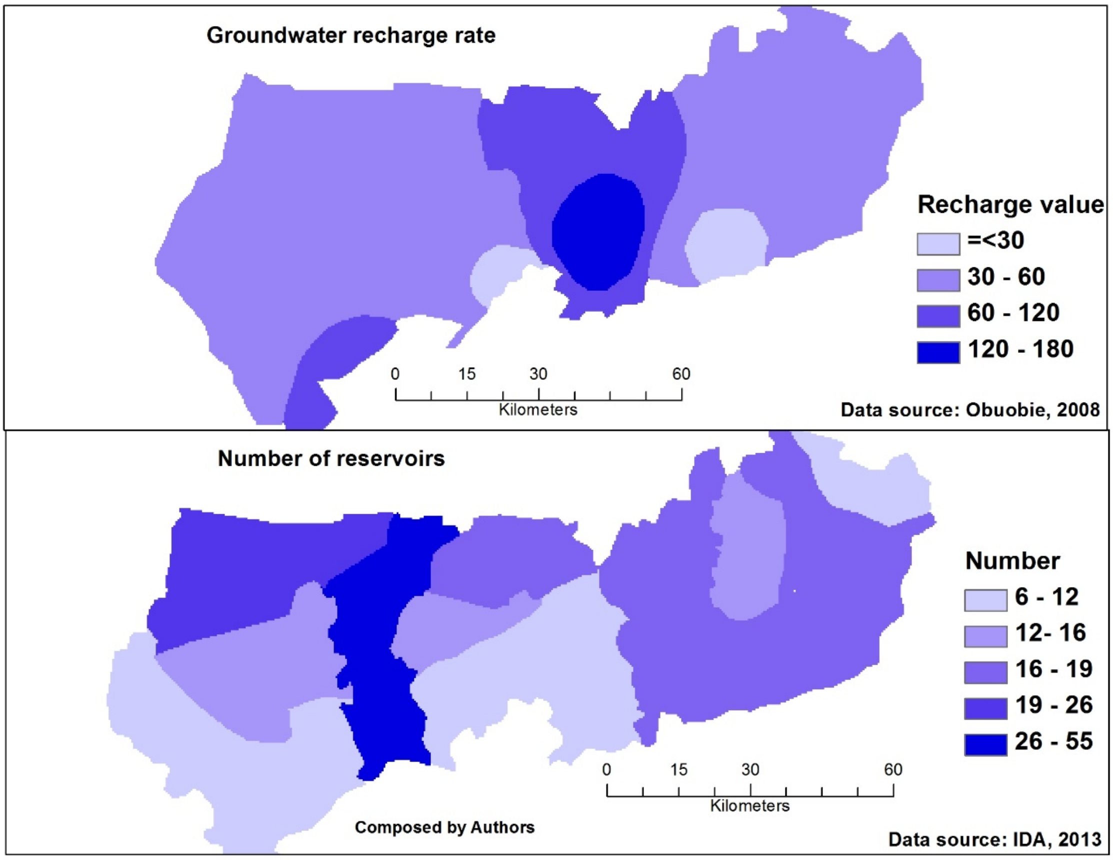

Fig. S3 Susceptibility of water sector to drought/high temperatures

2.2 Susceptibility to floods/high precipitation layers

Floods and/or high rainfall impact heavily on the livelihood activities of the people in the region. Impacts range from crop failure, erosion of soil through to health problems and siltation of water bodies. The datasets required to map the susceptibility layers are described according to the main livelihoods, based on data availability.

2.2.1 Agriculture

The average crop failure index of 2010 (see main paper, section 2.2) was used to map the crop susceptibility to floods/heavy rainfall. This indicator was used because it is the net effect of the destruction of farms by floods and the frequent heavy rains that may prevent proper pollination of crops (Derbile and Kasei, 2012). Agriculture also suffers from flooding as the soil is eroded. Thus, the erosion component was determined from a proxy. Halm and Asiamah (1984) surveyed and mapped the types of erosion occurring in the region based on the characteristics and properties of the soils. This map was digitised and used as a proxy. Erosion is determined by the properties and exposure of the soil, the land cover type and slope. These factors were considered by Halm and Asiamah (1984) in their survey. The erosion map (Fig. S4C) showed areas that were affected by normal erosion, areas affected by moderate sheet erosion, severe sheet and gully erosion and those affected by very severe erosion. These categories were confirmed by farmers to be occurring in the towns/villages. Some of the areas were visited and their GPS coordinates coincided with the map. The categories were rated 1, 2, 3 and 4 respectively using the categorical scale method (see Nardo *et al.*, 2005).

Erosion leads to nutrient and soil losses. Eroded soils are carried into water courses and dams/dugouts, silting them up and reducing their capacity. Therefore, soil loss was used as a proxy to estimate siltation of waterbodies/courses with the assumption that all the eroded soils will be deposited in the waterbodies. Amegashie (2009) sampled soils in the region and determined soil and nutrient losses due to erosion. The sites where he sampled were again plotted on the soil map and used to approximate soil and nutrient losses for the types of soils in the area. This was done based on earlier assumptions made when considering the WHC in the section of susceptibility of agriculture to drought/high temperatures. The soil losses determined were assigned to the various types of soils. Amegashie's sampling was done in 2009 at different locations within the catchment of each reservoir using modern equipment and scientific methods of data collection and analysis. Together, these datasets were combined to map the soil loss indicator. The maps are shown in Fig. S4. For crop sensitivity, the Builsa Districts were more susceptible while the Talensi, Nabdam and Bolgatanga Municipality were less susceptible. As shown in the soil erosion and soil loss maps, the Builsa Districts have a large area with high erosion and high soil losses. There is high runoff in these areas and therefore crops are washed away, resulting in high crop sensitivity to floods/heavy rains. It also means that dams/dugouts constructed in these areas are more likely to be silted faster than their counterparts in areas with less soil losses. Riverine soils (soils of riverbed) were again given a score of zero because the soils are considered unavailable for agriculture use.

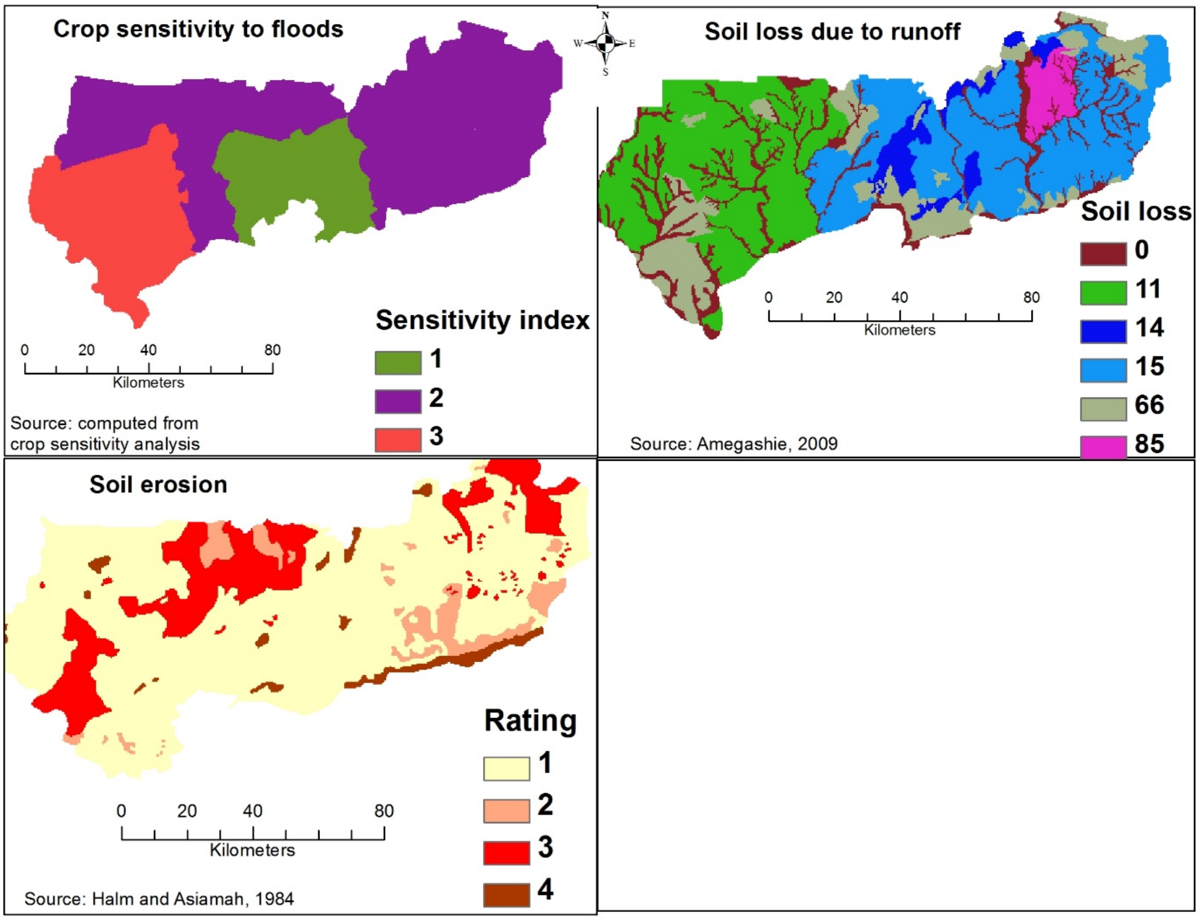

Fig. S4 Susceptibility of agriculture to flooding

2.2.2 Health

Floods/high rainfall affects housing and personal properties, and displaces people. The number of people displaced in each district was obtained from the regional National Disaster Management Organisation (NADMO) office and used to create the displacement indicator. This data was collected after the 2010 flood event that was worsened by the opening of the Bagre dam from Burkina Faso; this event is representative of regional flooding patterns but also accounts for recent water management schemes. Districts with more displaced people were considered more susceptible to floods than those with fewer displaced people. The number of casualties (i.e. injured and dead) was also used to create a casualties indicator. Casualty data was also obtained from NADMO. Districts with higher casualties were considered more susceptible to floods than those with lower numbers. Floods/heavy rainfall also leaves behind pools of water that breed mosquitoes, the vector for transmission of malaria. Thus, the districts' susceptibility to malaria was determined from the health burden due to malaria using the percentage of Out-Patient Department's (OPD) attendance, admissions and fatalities in the health facilities at the district level. Districts with high rates are more susceptible to malaria and therefore, floods/high rainfall conditions supporting transmission are generally more prevalent in the rainy season (Ghana Health Service, 2012). When there is a flood, people in the vulnerable group suffer more because they cannot help themselves. The people in this category comprised the elderly (i.e. 85+), children below 10 years old and people living with a disability. Information on these categories of people was obtained from the census data. Districts with higher numbers of these groups were more susceptible to floods than those with lower numbers. These maps are shown in Fig. S5.

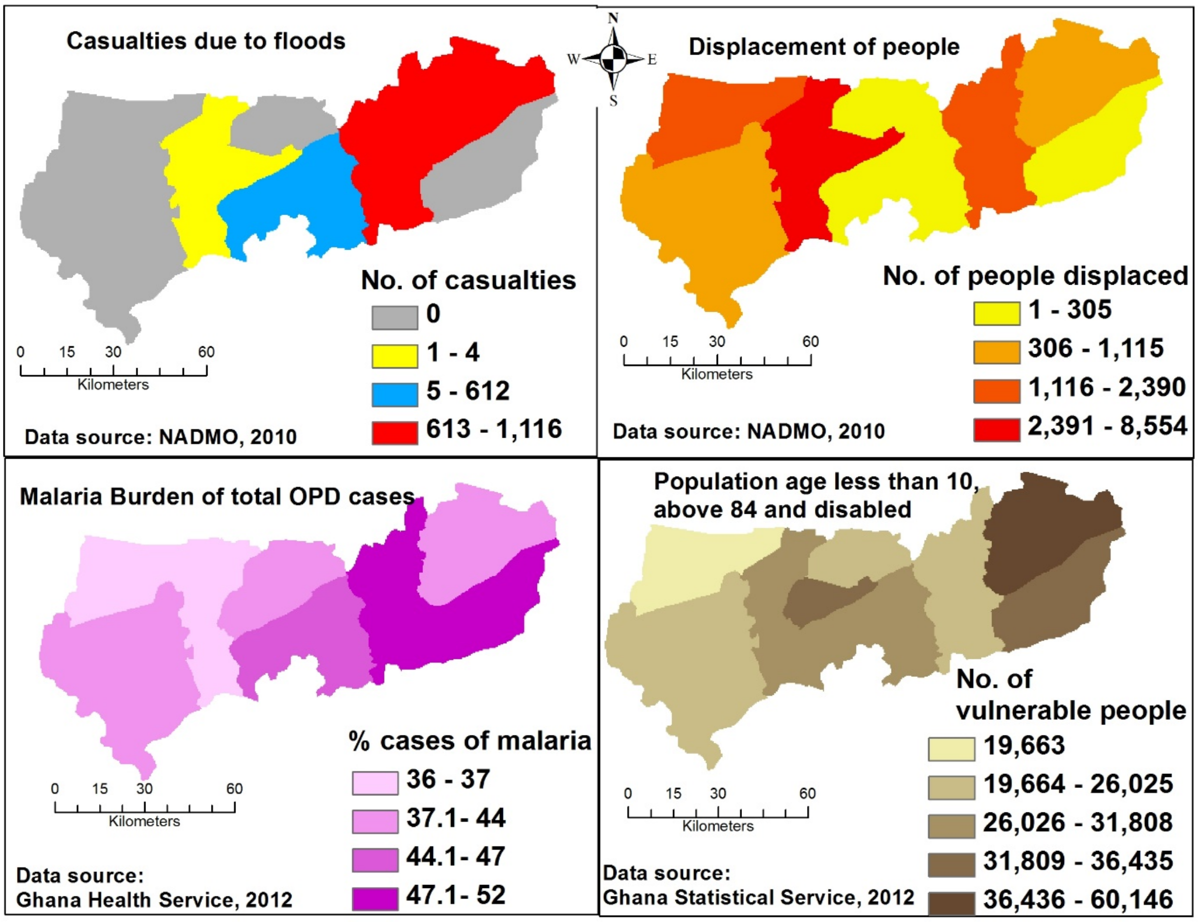

Fig. S5 Susceptibility of humans to floods/high precipitation

2.2.3 Housing

Floods/heavy rainfall affects houses and personal belongings. The number of housing units that were affected in the 2010 floods was obtained from the regional NADMO office. These consisted of houses that were partially or wholly destroyed by floods/heavy rains. Districts with higher numbers of damaged houses were considered more susceptible than those with lower numbers. These data were used to map the susceptibility of the housing units to floods/heavy rainfall. The location of the housing units in terms of proximity to a water body (especially rivers/streams) also exposes them to floods. The closer the buildings are to these water bodies, the more susceptible they are to flooding. Buffers were created from the rivers/streams with distances 500 m, 1000 m and above 1000 m. Those within 500 m were considered very close and assigned a value of 10, 500 to 1000 m were considered near and assigned a value of 5 while beyond 1000 m were considered far and assigned a value of 0. The assignment of these values was based on the categorical scale method (see Nardo et al., 2005). A similar rating scheme was used by EPA (2012).

Flash flooding in the region is more of an urban phenomenon and therefore almost all urban towns were visited to observe the drainage systems in place and their contribution to flooding. The questionnaire survey was also carried out in some of the urban centres which happen to be the district capitals and affirmed the importance of drainage. To rate the places, district NADMO officials were asked about flash flooding history of their urban towns and also 3 additional respondents who stayed in certain localities in the towns were randomly selected and asked informally if they see floods in the vicinity. These findings were combined to deliver the ranks shown in Table S2. The categorical scale was used to assign these scores.

Table S1 Ranking of localities of flash flooding

Towns/locality	**Score**
Rural	0
Bolgatanga	5
Bawku/Navrongo/Zebilla/Paga	3
Sandema/Bongo/Garu	1
Tongo/Fumbisi	0

Source (Authors' own construct)

Quality of housing also makes the area susceptible to flooding/heavy rainfall. To map this, the percentage of mud buildings in each locality (rural/urban) was determined from the type of building material used in the district. Information was obtained from 2010 census report. This was used as an indicator because mud buildings easily collapse when they become very wet. Maps of the layers to be combined to produce the susceptibility to flooding of the housing sector are shown in Fig. S6.

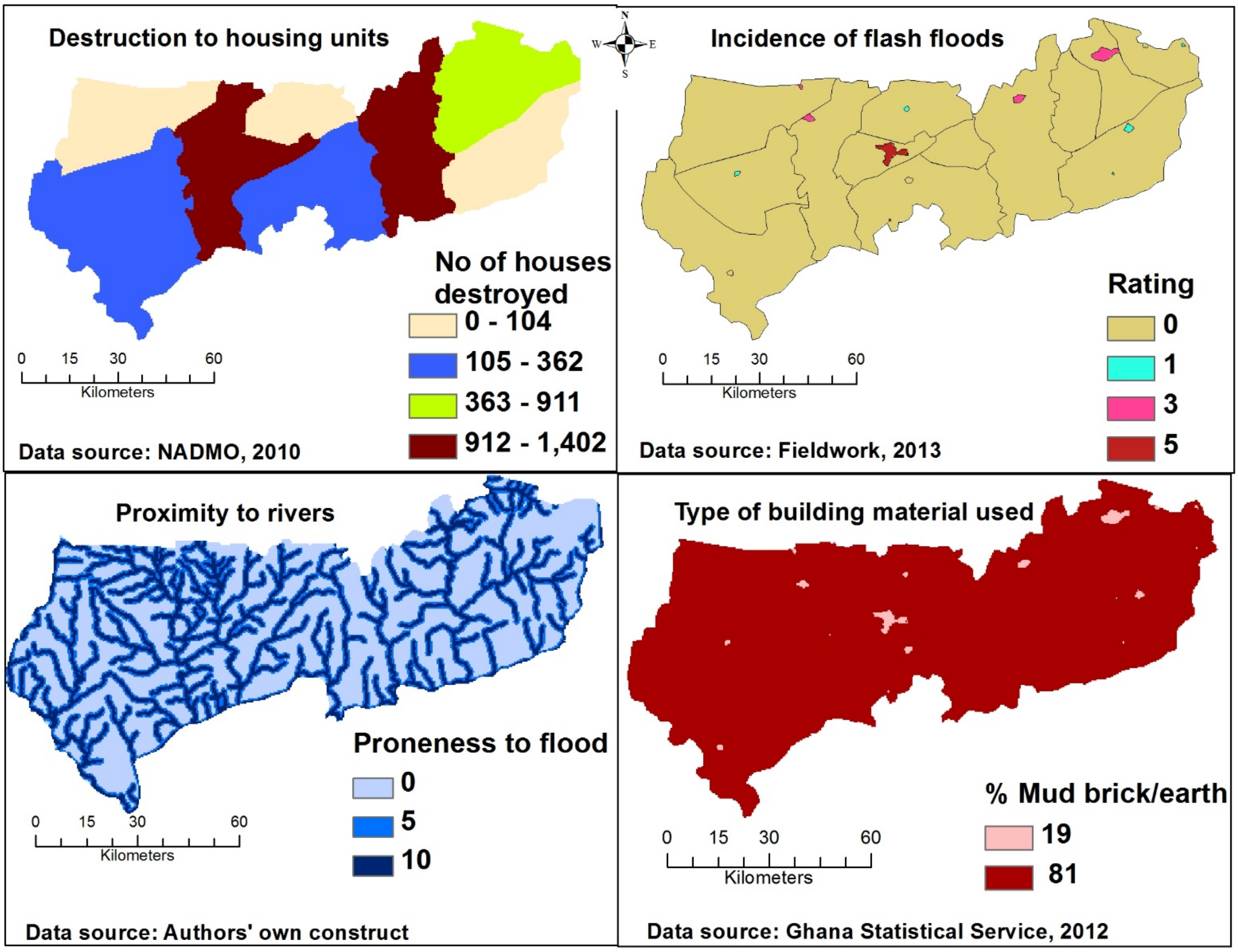

Fig. S6 Susceptibility of the housing sector to floods/high rainfall

2.2.4 Road sector

Floods/heavy rainfall sometimes causes damage to the road network. The damage could entail the road being partially or wholly eroded, or bridges washed away, cutting off communities. When this happens, aid or access to affected communities is also hampered. The susceptibility of the road sector was mapped using the surface of the roads in the area based on the classification by the Ghana Highway Authority. These classes are defined as follows: first class represents bitumen surface roads and highways, second class represents feeder roads and third class represents tracks and footpaths. The lengths of these roads in the districts were used to map the susceptibility of the roads to floods/heavy rainfall. Tracks and footpaths are more easily destroyed than feeder and tarred roads. The dataset was obtained in GIS shapefile format and classified into these classes. The classification was cross-checked on Google Earth in 2013 to update it with any new roads. Though some of the tarred roads are currently in bad shape and worse than the feeder roads, it is believed that it would not affect the results significantly.

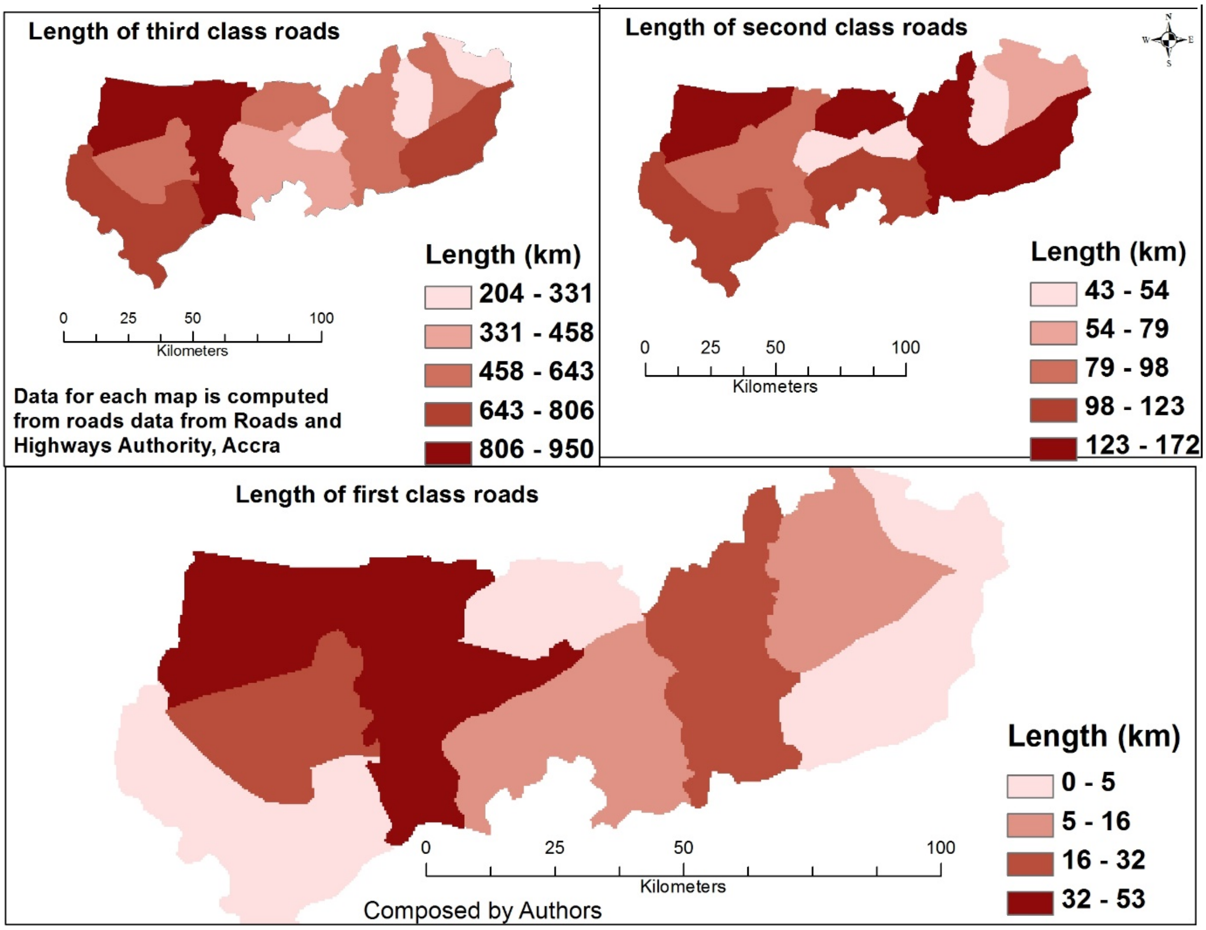

Fig. S7 Susceptibility of the road sector to floods/high precipitation

2.3 Susceptibility to windstorms

Windstorms mainly affected roofs of buildings. Although they sometimes pulled some of the crops down, the crops are often able to rise again naturally or the farmers prop them up by supporting the base with soil. It was also gathered from the field survey that the effect of winds is greater on thatch than roofing sheets and that windstorms had no effect on mud roofs. Thus, the percentage of thatch was used to map the susceptibility to windstorms. The percentage of buildings roofed with thatch was obtained from the 2010 census report. Districts with higher percentages of thatch were more susceptible to windstorms than those with lower values. The questionnaire participants attributed the strength of windstorms to the reduction in tree cover which hitherto served as wind breaks. The savannah woodland cover from the classification of the 2010 Aster image was used as a proxy. The argument is that places with high tree density will have high tree cover to serve as wind breaks and therefore will be shielded from the effects of windstorms. Based on discussions with community members and observation of disparate measures in the villages as well as literature, the ratings in Table S3 were assigned to each land cover using the categorical scale. Places with lower tree density were considered more susceptible to windstorms and were assigned higher scores. The maps for the windstorms are shown in Fig. S8.

Table S2 Rating of land cover types for windstorm susceptibility based on tree density

LANDCOVER	weight
Grass/herb with/without scattered trees (0-5 trees/ha)	50
Widely open cultivated savannah woodland (6-10 trees/ha)	40
Open cultivated savannah woodland (11-20 trees/ha)	30

Open forest (<60 %)	10
Closed savannah woodland (>25 trees/ha)	20
Reservoir	50
Riverine savannah vegetation	10

Source (Authors' own construct)

The metal sheets are attached more securely than thatch roofs, which are fastened with jute. It is also realised that the areas to the eastern part, central and some parts in west of the region have less tree cover and are more susceptible. In this area, largely north of the Intertropical Convergence Zone, winds are from the East/Northeast, and are stronger as they sweep across vast areas of unprotected land.

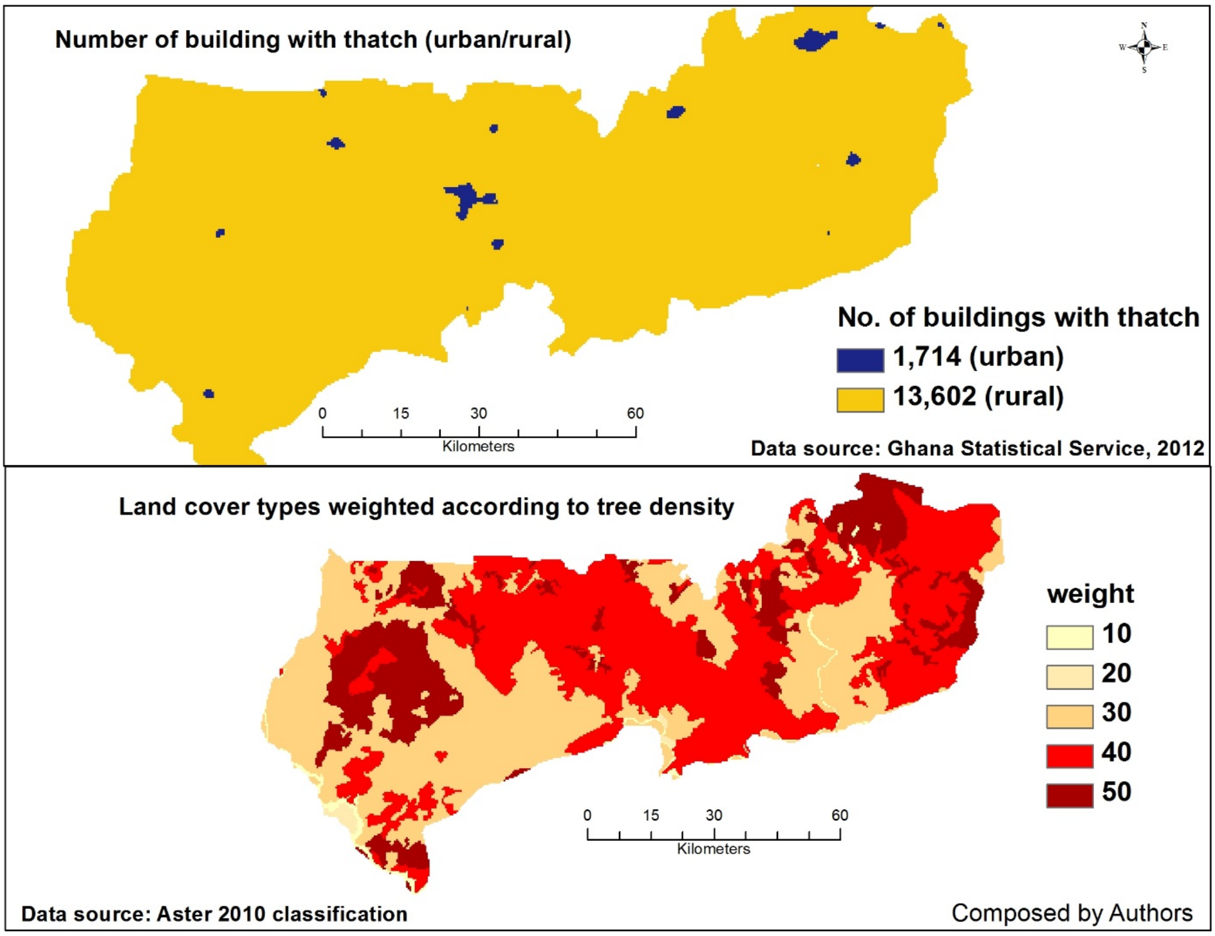

Fig. S8 Susceptibility to windstorms

3 Adaptive capacity indicator datasets

Adaptive capacity encompassed both socio-economic and natural/technological factors that the people use to respond to the hazards. The indicators identified as adaptive capacity, based on the sustainable livelihood framework, are presented below.

3.1 Human capital component

The human capital indicator was mapped using the level of skills and education of the people in the region. The literacy rate for each district was used to create a layer for education. The rationale is that the more literate population a district has, the better its chances of having more people in other (non-agriculture based) forms of employment, and hence a higher adaptive capacity. This data was obtained from the census 2010 report. The levels of skills of the district were assessed using the number of people employed in industries that are skill based. This was calculated from the 2010 census report indicating the number of economically active people in employment by region and locality. Occupations that did not require skills or training and agriculture were excluded.

3.2 Social capital

In each district, there are a number of NGOs lending support to the people. NGOs undertake a range of activities from advocacy to capacity building. Some of the NGOs provide these activities to organised groups and therefore encourage people to associate. These activities strengthen capacities to cope with the environment. The number of NGOs was obtained for each district from the institutional questionnaire, and supplemented with the list from the district profiles, and used as an indicator to map social capital. Thus, the higher the number of NGOs operating in a district, the better its social capital.

There are decentralised government institutions in the region in charge of managing some of these hazards, either directly or indirectly. The institutional capacities of institutions in the region were assessed. These institutions rated themselves in terms of the financial, physical, technological and human capacities to deal with the hazards as part of their responses to the institutional questionnaire. Interviews with institutional heads or representatives sought to find out their rate of response when a hazard occurs. The response level of the institutions was assessed by the community members. This assessment resulted in scores of 10 and 3 for institutional capacity for urban and rural districts respectively, using the categorical scale. These were used to identify the institutional capacity. The maps resulting from the data described above are shown in Fig. S9.

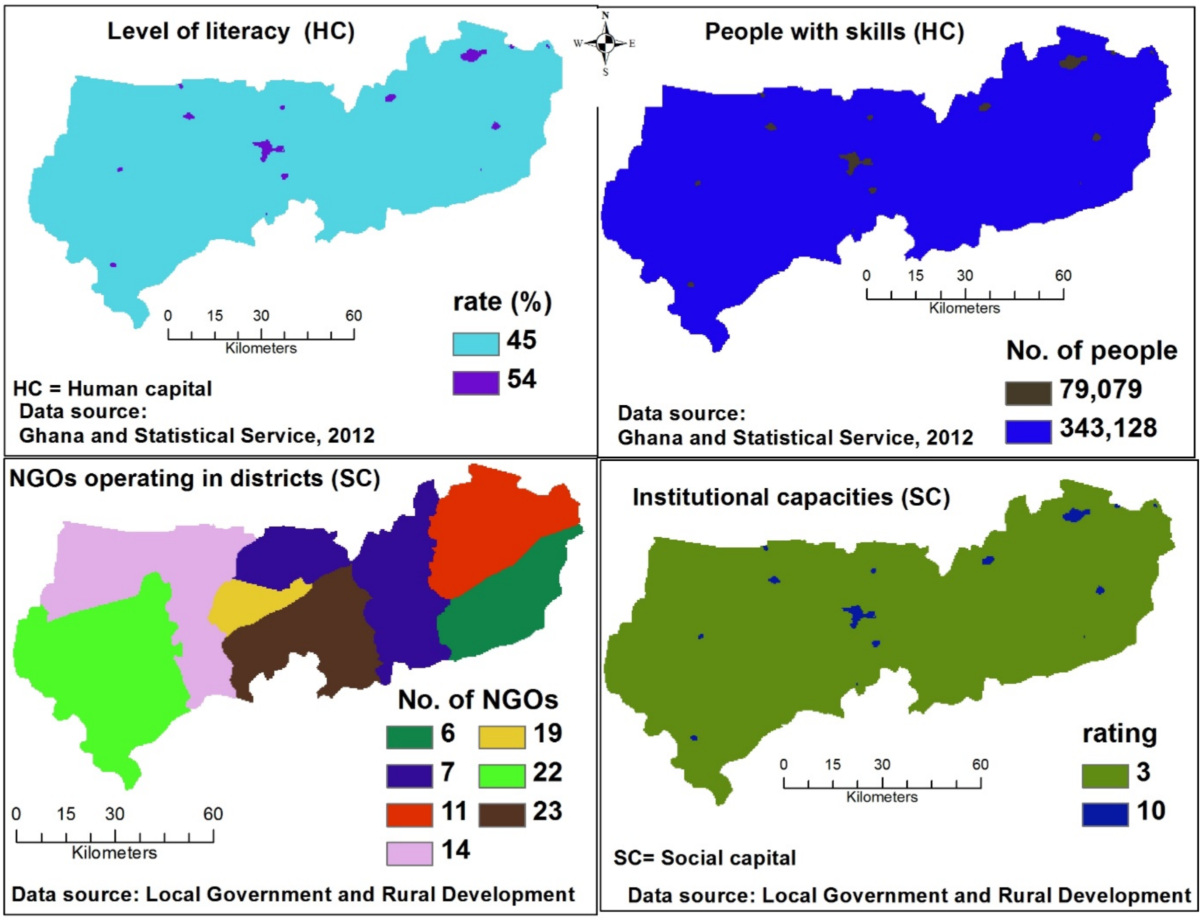

Fig. S9 Maps of Human and Social capitals

3.3 Financial capital

Financial wealth, presence of financial institutions, and investment opportunities as well as employment status, were used to map this component. Although a complex indicator, in general, financial wealth is a very good indicator of adaptive capacity as it shows the ability of people to command resources to respond to hazards. The data for this was obtained from the WFP (2012) report and supplemented with the data from the census report to segregate into urban and rural households.

Financial institutions play a role in providing credit to support the victims of hazards. The financial institutions are the mainstream banks and micro-credit agencies or NGOs which source funds and give them to the community members in the form of credits for their livelihood activities. The number of financial institutions in a district was obtained from the district assembly's profile and used to map this indicator. Though some of these financial institutions operate within the urban areas, a few of the rural people who are able to meet the requirements of the banks get access to credit. The type of financial institution was considered in determining the rating for the district. For example, a national or commercial bank is put in a higher level than a rural bank, an NGO and a micro credit facility. Table S4 shows the ratings given. A district with a higher score was considered more financially sound than those with lower scores.

Table S3 Scores of financial institutions in the districts

	Type of institution								
	National bank		**Rural bank**		**NGO**[1]		**Microcredit**		**Total**
District	**No.**	**Rating**	**No.**	**Rating**	**No.**	**Rating**	**No.**	**Rating**	
Bawku Mun.	2	10	1	5	3	2	1	1	32
Bawku West	1	10	1	5	1	2	2	1	19
Binduri	0	10	1	5	3	2	1	1	12
Bolgatanga	7	10	3	5	3	2	2	1	93
Bongo	0	10	1	5	1	2	1	1	8
Builsa North	0	10	1	5	1	2	1	1	8
Builsa South	0	10	0	5	1	2	1	1	3
Garu-Temapne	0	10	1	5	3	2	1	1	12
KN East	1	10	1	5	2	2	1	1	20
KN West	0	10	1	5	2	2	1	1	10
Nabdam	0	10	0	5	4	2	2	1	10
Pusiga	0	10	1	5	3	2	1	1	12
Talensi	0	10	0	5	4	2	2	1	10

Source (Authors' own contruct) KN= Kassena-Nankana

It must be mentioned here that although some of the NGOs may be richer and do more than the rural banks, they are rated lower than the rural banks because banking is not their core business. The investment opportunities in the districts also boost their capacity. In the district profile, the number of investment opportunities in operation was used to map this

[1] NGOs are those specifically providing financial assistance. The rating was arbitrary but based on financial capacity on the institutions

indicator. Thus, a district with the higher number of investment opportunities is adjudged to have better opportunities and hence a higher adaptive capacity. Maps are shown in Fig. S10.

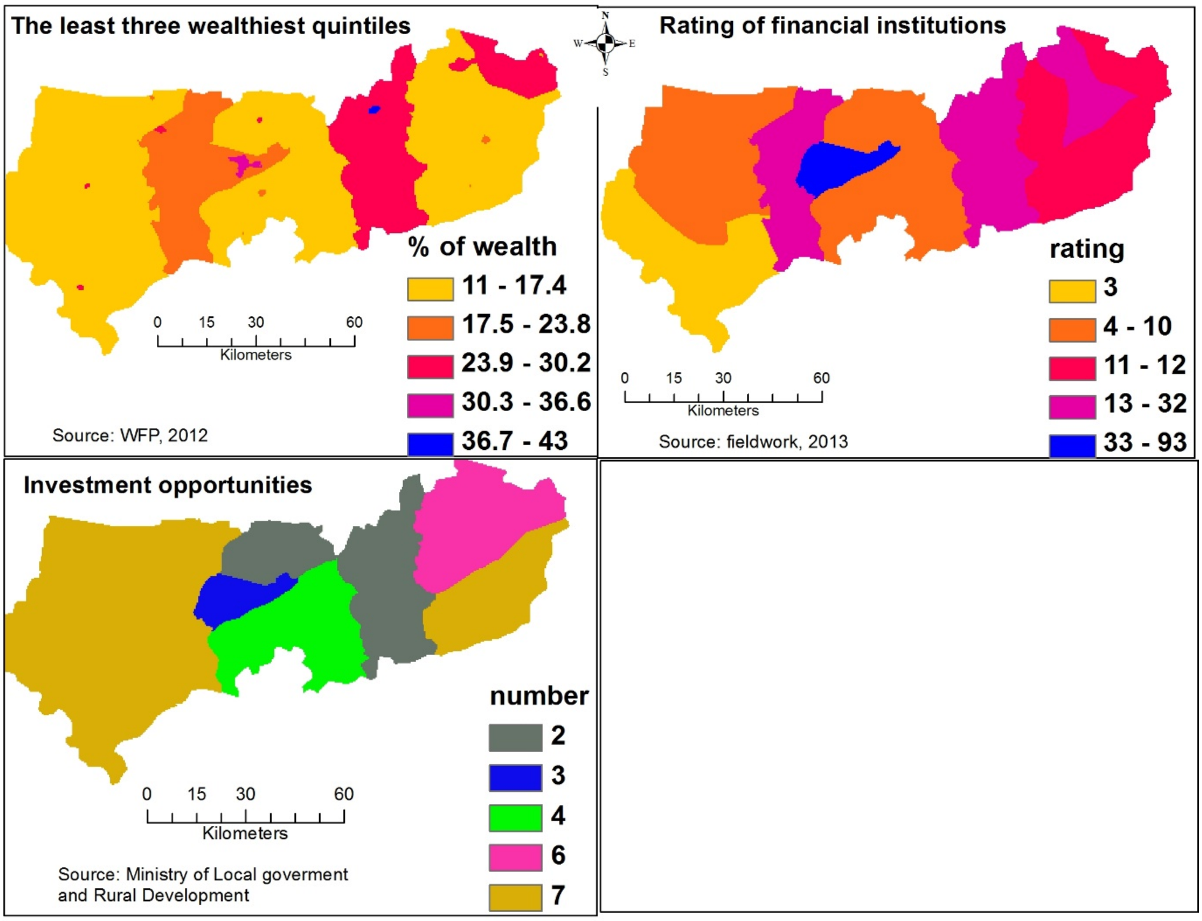

Fig. S10 Financial Capital

3.4 Natural assets

The availability of the natural environment as well as its integrity is key for adapting to hazards. This is because the people depend on natural resources to eke a living. The natural assets component was mapped using indicators such as availability of land for human activities and protected areas. It does not consider accessibility or property rights though. The size of each district was calculated and used to map the indicator for land availability. The rationale is that the size of land available in a district determines capacity to use that land to engage in a range of activities, and that this will enhance its capacity to deal with hazards. Other natural assets such minerals are part of the investment opportunities under financial capital and are therefore not considered here. The dataset was obtained from the GIS database. Another ecosystem integrity indicator that was mapped was the presence of protected forest per district. The areas of reserves per district were calculated and used.

3.5 Technology

This subsection covered the availability of technology and its use to better the livelihood activities of the people. Thus, it covered topics like the use of irrigation systems and early warning systems. An early warning system is in place. To map the capacity of the districts in terms of early warning systems, the effectiveness of the system was measured from the questionnaire survey responses on how people use the information received from the early warning system. Districts with low percentages represented those where a large number receive the information but do nothing with it because either it does not matter to them or they got the information too late and therefore could do very little with it. The analysis also showed that the early warning information was always sent out when there is evidence for floods or windstorms but never for droughts. This was apparent from the usefulness of the information: respondents moved their properties, harvested their crops, or secured their roofs before these floods or windstorms occurred. The information for this indicator was generated from the questionnaire survey and institutional survey.

Irrigation dams/dugouts are used for dry season farming. To map this indicator as a capacity to adapt, the catchment area of the dams/dugouts was determined from the data obtained from IDA (2013). The reasoning is that dams/dugouts with large catchment areas have the capacity to store more water for dry season farming than those with smaller catchments. The catchments of the two big dams in the region (Tono and Vea) extend into

Burkina Faso and some of their tributaries are dammed, but the catchment area within Ghana only was used. Maps for the natural capital and technology are shown in Fig. S11. Land availability is high in Bawku West and Builsa South Districts and low in Bolgatanga municipal and Nabdam District. It is also low in the urban areas due to urbanisation. Builsa South and Talensi Districts have high numbers of protected areas while Bawku municipal has the lowest. Kassena-Nankana East has more area under irrigation. This is expected because the largest irrigation scheme is located in this district and it has the highest number of reservoirs. It is also seen that use of information from the early warning system is high in the eastern part of the region.

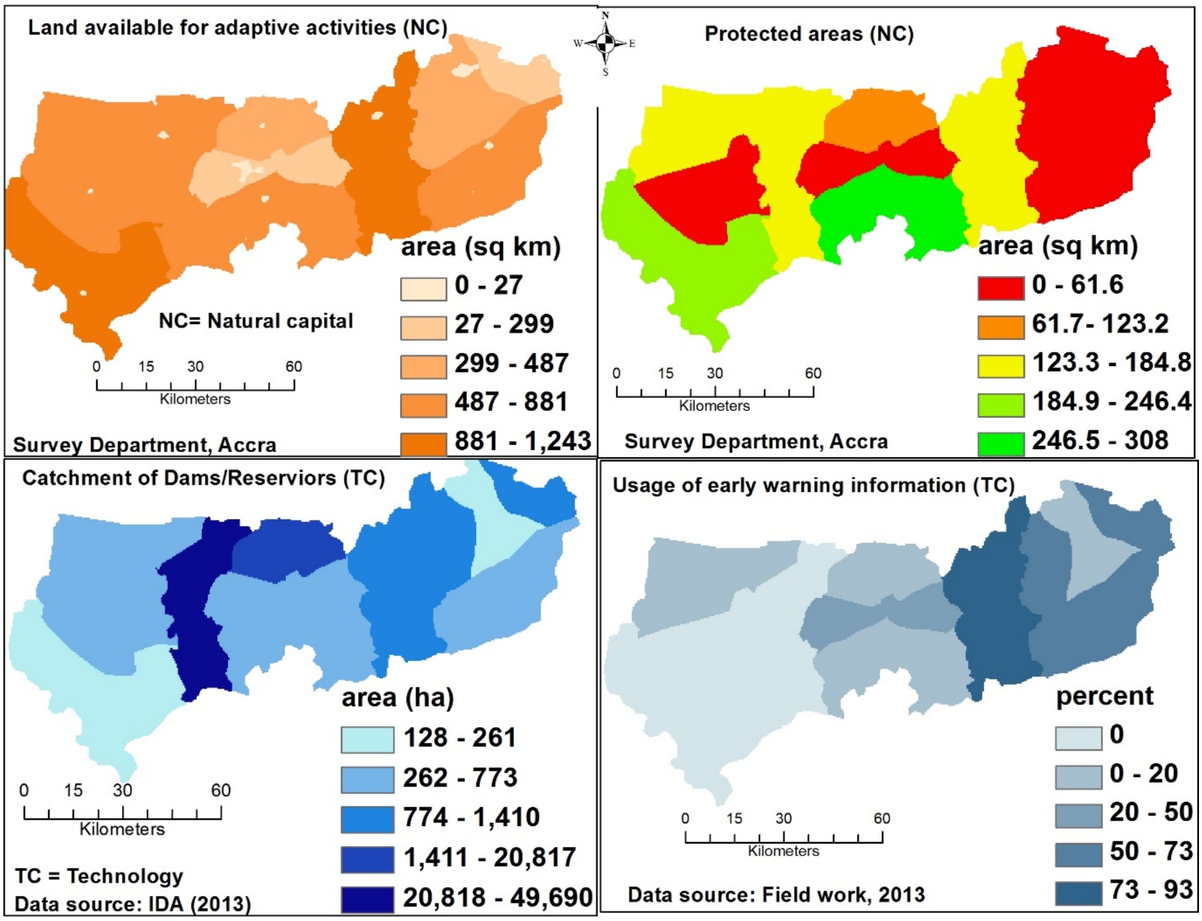

Fig. S11 Maps of Natural capital and Technology

3.6 Infrastructure

The indicators under this subsection relate to accessibility to services such as health, education, transport and the presence of markets. Health facilities were rated in the districts based on level of service, staffing logistics and facilities. For simplicity, all hospitals in the region were put in the same category. The problem with the simplification is that some hospitals are better than others in terms of service, structures, staffing, and infrastructure, but collecting these details was beyond the resources of this project. This approach has generally been used by the Regional or Districts Health Directorates when reporting the number of hospitals or classifying health facilities. Similarly, maternity homes were put in the same category as a Community-based Health Planning and Services (CHPS) compounds. Maternity homes only offer care to maternal mothers. The ratings are shown in Table S5. It is assumed that districts with higher ratings have better infrastructure and a higher adaptive capacity, health wise.

Table S4 Ratings of Markets based on functionality and structures

District	Hospital		Health Centre		Clinic		CHPS		Maternity Home		Total	Market[2]	Rate
	N	R	N	R	N	R	N	R	N	R			
Bawku Municipal	2	200	6	50	9	30	16	5	1	5	1055	Bawku	50
Bawku West	1	200	4	50	10	30	14	5	0	5	770	Zebilla	30
Bolga Municipal	2	200	7	50	7	30	14	5	0	5	1030	Bolga	50
Bongo	1	200	5	50	1	30	27	5	0	5	665	Bongo	20
Builsa	1	200	6	50	0	30	21	5	0	5	605	Sadema	30
Garu Tempane	0	200	6	50	6	30	26	5	0	5	610	Garu	30
Kassena-Nankana E	1	200	2	50	3	30	18	5	0	5	480	Navrongo	50

[2] The new districts also had markets were rated as Ambrose (Binduri)=30, Fumbisi (Builsa South)=20, Pusiga = 30 and Pelungu (Nabdam)=30

Kassena-Nankana W	0	200	6	50	1	30	25	5	0	5	455	Chiana	30
Talensi Nabdam	0	200	3	50	5	30	16	5	0	5	380	Tongo	20

Source (Authors' own construct) N.B: N=number, R=rate assigned.

Access to health services is critical because it represents the districts' capacities to handle diseases and ailments and injuries relating to the hazards. The markets however, were rated based on the level of service, functions and structures. For educational infrastructure, the number of schools in each district was used. This was because with the exception of basic schools which need to be closer to the pupils, the others are accessible to everybody. Therefore no ranking was done regarding educational infrastructure. Energy infrastructure was also used to map the adaptive capacity in relation to these hazards. Energy is needed to power the cooling systems in the face of rising temperatures and to ensure some of the systems run efficiently. The energy infrastructure was measured by the level of coverage in each district. This data was obtained from the census report. It must be noted that close to 96% of the energy from electricity is consumed by urban dwellers with about 4% consumed by rural dwellers. Thus, this was used to map the energy infrastructure as shown in Fig. S12.

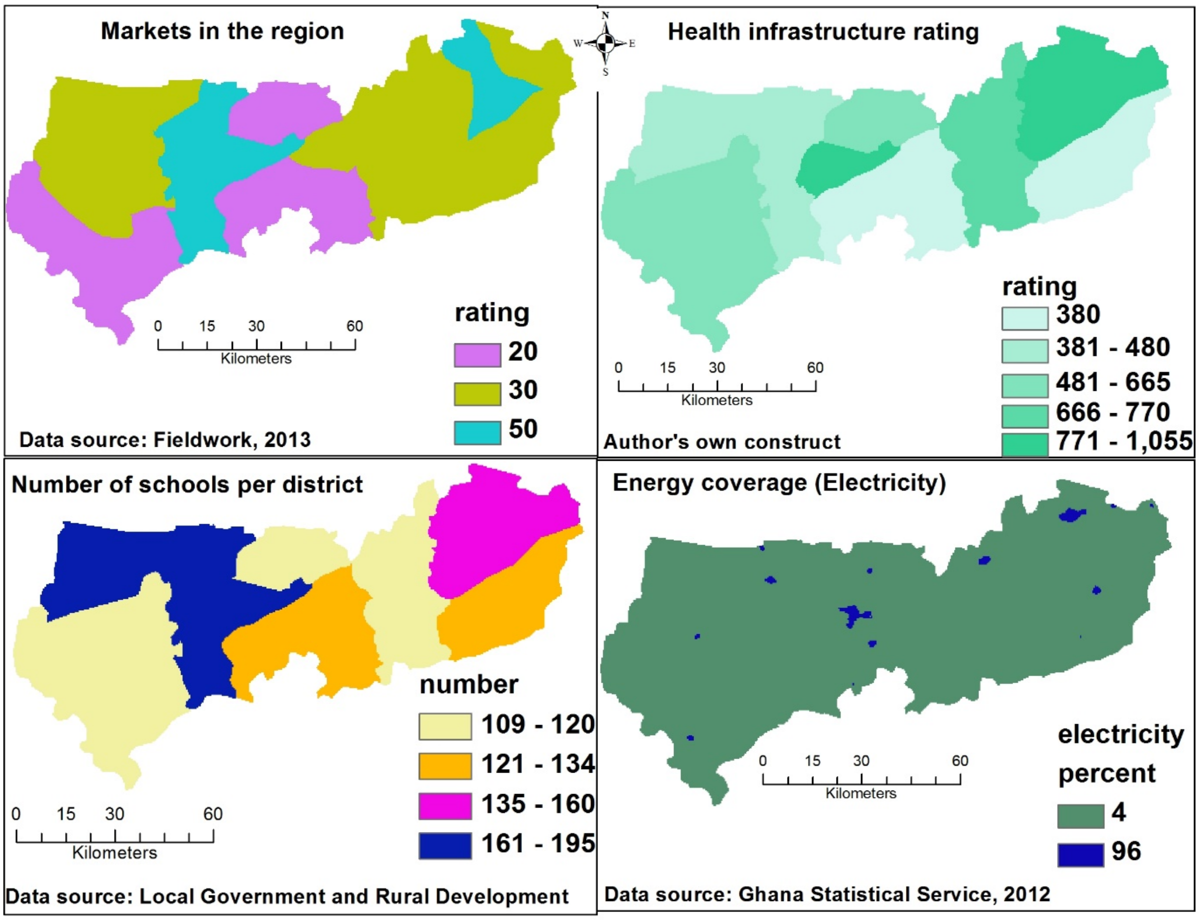

Fig. S12 Maps of infrastructural coverage

3.7 Coping strategies

Remittances received from relatives living outside of the districts were used as a measure of coping. This was considered a coping strategy because remittances were largely used for buying food, agricultural inputs or to rebuild/rehabilitate housing units. Thus, from the questionnaire survey, the percentage of households receiving remittances specifically for coping with disaster was extracted, combined with remittances from the WFP (2012) report and used to map this indicator. Most remittances go into buying food and help the people cope with food shortfalls from their own production and consequently crop failure. Another coping strategy was rearing livestock and selling them off in times of need. The dataset to map livestock ownership was derived from the WFP (2012) report which presents district level data. From the dataset, households with large livestock ownership had more coping capacity as they can sell more than those with lower numbers. Livestock ownership did not include poultry because incomes from poultry are generally low.

Also, the people are engaged in income generating activities such as food processing, petty trading, and corn mill operations, which yield additional income to support the household. The average number of household members engaged in income generating activities was used to map this indicator. Districts or areas with high percentages are assumed to be more resilient than those with low values. This dataset was obtained from the WFP report (2012). Another indicator identified was food aid. The dataset to map this indicator was obtained from the WFP report. It showed the percentage of households receiving food aid in each district. Households receiving food aid increased their ability to cope with food shortages resulting from low production on their farms. Thus, districts with a higher percentage of households receiving food aid had a higher coping capacity than those with lower percentages. The maps for coping capacity are shown in Fig. S13.

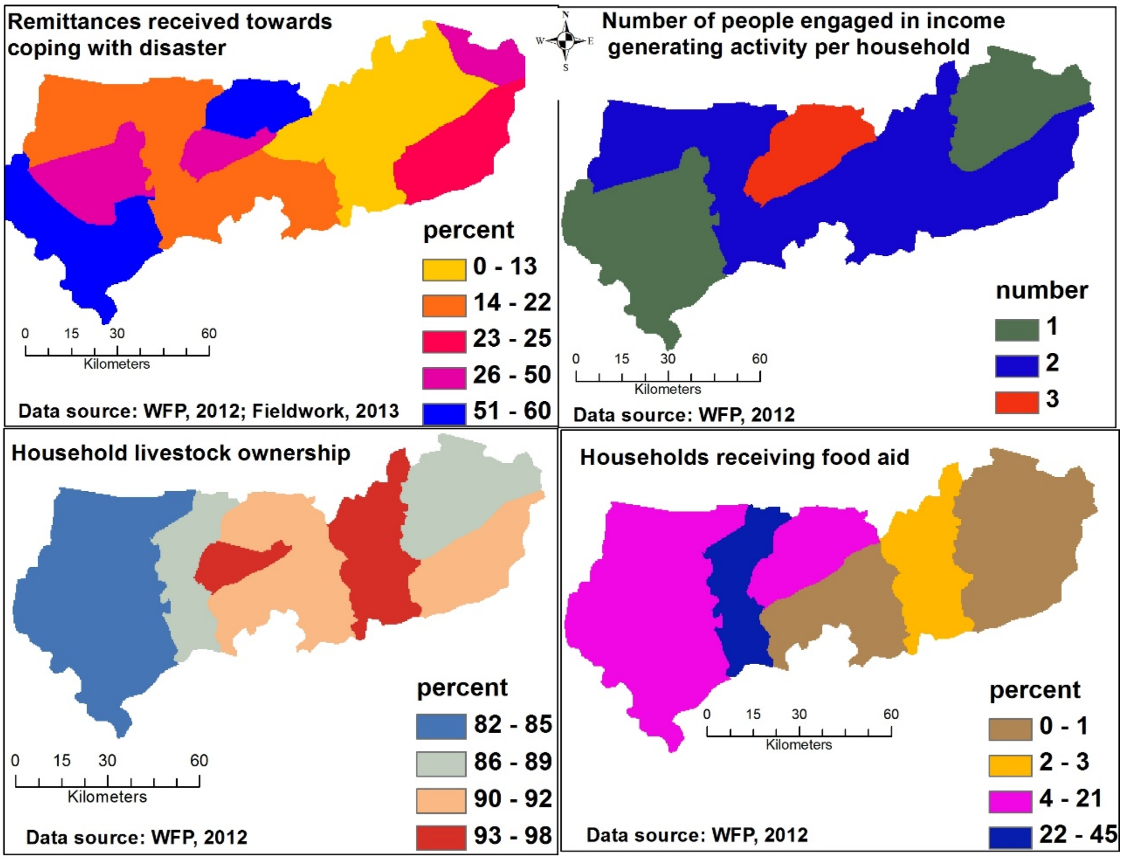

Fig. S13 Coping capacity of households in the districts

3.8 Evaluation

Evaluating a composite index is one of the most important steps in a quantitative vulnerability assessment as both the development of indicators and the building of a composite index inherits numerous uncertainties (Damm, 2010). All steps taken during the development of indicators, from gathering of data and information from various sources, scaling of data, and finally the selection of a normalisation, weighting and aggregation technique, involve subjective decisions that severely contribute to the existence of uncertainties (Nardo et al., 2005).

The robustness of the composite indices and the reliability of the calculation model were tested by comparing different normalisation, weighting and aggregation procedures. Although all indicators were tested, the agriculture sector is presented here for illustrative purposes. The results of the robustness tests are shown in Fig. S14. As can be seen in the figure, the same high vulnerability areas are indicated in each pair. It can also be observed that the vulnerabilities exhibit the same patterns although there are variations across the region.

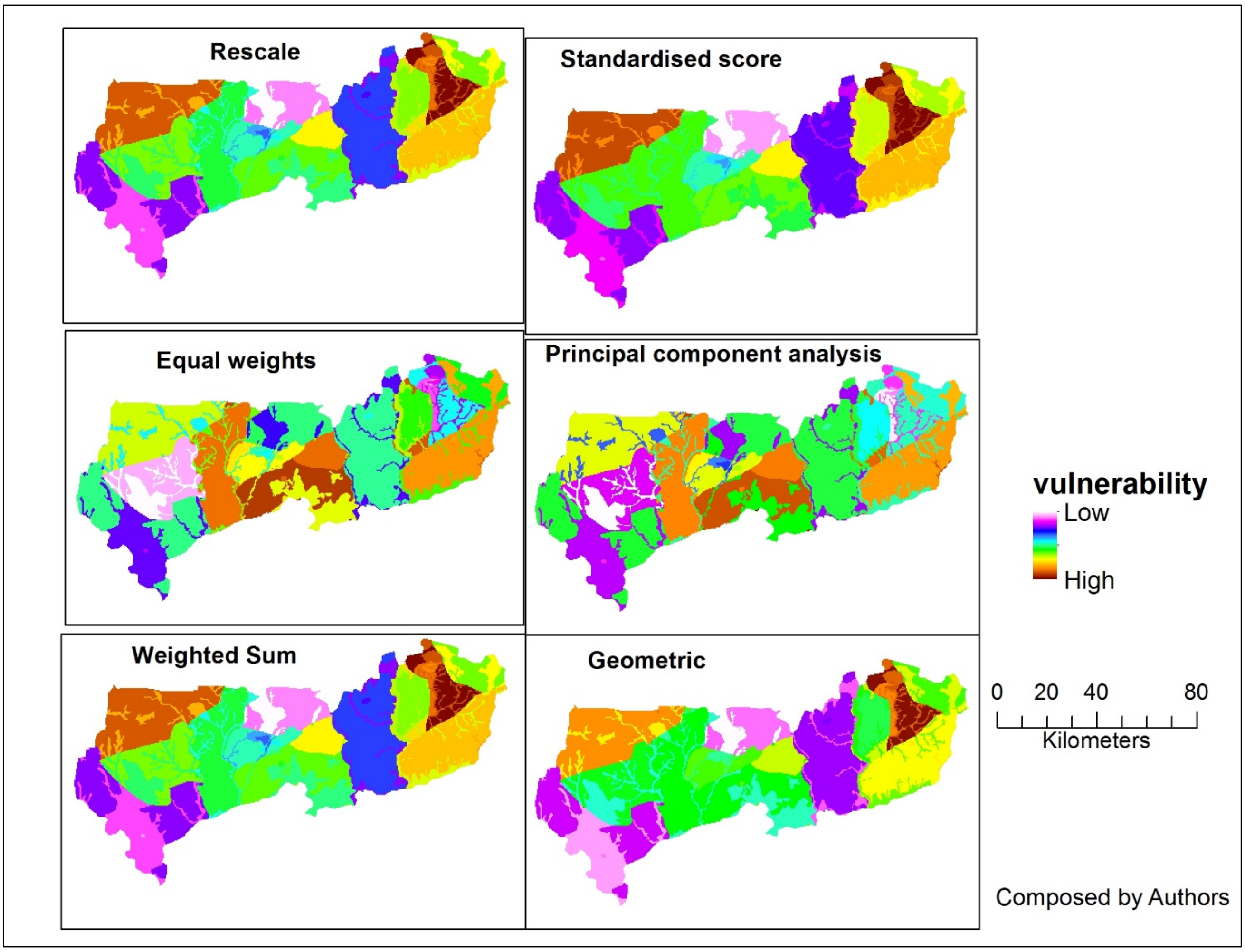

Fig. S14 Test for Robustness with the normalisation and weights

4. Conclusion

This supplementary material presented information on the indicators used for the vulnerability mapping of the various hazards occurring in the savannah ecosystem. It outlined how data on the indicators were collected and converted into geographic layers for the mapping exercise. The maps show that the susceptibilities and adaptive capacities of the sectors vary among the districts for the various hazards and this may produce variation in vulnerabilities.

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