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Mapping the vulnerability of crop production to drought in Ghana using rainfall, yield and socioeconomic data

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A B S T R A C T

This study evaluates new multi-scale, multi-indicator methods for assessing the vulnerability of crop production to drought at a national and regional scale. It does this by identifying differences across and within ten regions of Ghana, a country that faces many climate and crop production challenges typical of sub-Saharan Africa. In particular, we illustrate how a quantitative national and regional study is a critical first step in assessing differences in the drought sensitivity of food production systems and show how such an assessment enables the formulation of more targeted district and community level research that can explore the drivers of vulnerability and change on a local-scale. Finally, we propose methodological steps that can improve drought sensitivity and vulnerability assessments in dynamic dryland farming systems where there are multiple drivers of change and thresholds of risk that vary in both space and time. Results show that the vulnerability of crop production to drought in Ghana has discernible geographical and socioeconomic patterns, with the Northern, Upper West and Upper East regions being most vulnerable. Partly, this is because these regions have the lowest adaptive capacity due to low socioeconomic development and have economies based on rain-fed agriculture. Within these regions we find considerable differences between districts that can be explained only partly by socioeconomic variables with further community and household-scale research required to explain the causes of differences in vulnerability status. Our results highlight that national and regional scale multi-indicator vulnerability assessments are a vital (and often ignored) first step in assessing vulnerability across a large area. These inputs can guide both local-level research and also demonstrate the need for region-specific policies to reduce vulnerability and to enhance drought preparedness within dryland farming communities.

Introduction

Research and policy debates on the world's drylands are increasingly focused on the challenges of undertaking coupled human-environmental assessments in systems typified by multiple drivers of change and dynamic thresholds that lead to high levels of variability in both space and time (Reynolds et al., 2007). This leads to significant applied geographical research challenges for developing and applying suitable frameworks for assessing climate change vulnerability (e.g. Adger, 2006; Fraser, 2007; Turner et al., 2003) and for providing cross-sectoral and multi-scale policy advice in relation to climate change and land degradation (e.g. Reed et al., 2011).

The purpose of this paper is to show how these challenges may be addressed by conducting a multi-scalar climate vulnerability analysis for Ghana as a case study. Mapping climate vulnerability of Ghana is important because the IPCC's regional assessments of climate change impacts for Africa imply declining grain yields are likely and predict that agricultural production and food security in sub-Saharan Africa will be negatively affected particularly relating to increased drought intensity and frequency linked to greater inter-annual rainfall variability (Boko et al., 2007). Further, recent climate-crop modelling studies suggest that agriculture will be disproportionately affected in West Africa (e.g. Lobell et al., 2008), but the impacts will vary spatially and understanding the complexity of such systems requires further investigation through more detailed assessments of key regions such as that provided in this paper. This paper also builds from analyses undertaken in other

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parts of the globe where data are more widely available and variability is not as marked (e.g. Simelton, Fraser, Termansen, Forster, & Dougill, et al., 2009).

To assess the integrated nature of rural agricultural development challenges, the concept of vulnerability emerged within development debates in the 1990s (Chambers, 1994) and has been widely applied to a range of climate-related issues. In the IPCC's Third Assessment Report, McCarthy, Canziani, Leary, Dokken, and White et al (2001, p. 6) define vulnerability as "the degree to which an environmental or social system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes". Assessing vulnerability, therefore, requires an integrated assessment across a range of disciplinary spheres and scales requiring new geographical assessment tools and frameworks. Vulnerability is context-specific and what makes one region or community vulnerable may be different from another community (Brooks, Adger, & Kelly et al., 2005). However, there are certain generic determinants of vulnerability including developmental factors that are likely to influence the vulnerability of a particular region or community even in diverse socioeconomic contexts (Brooks et al., 2005). Thus, one of the key features of vulnerability is its dynamic nature that may change as a result of changes in the biophysical as well as the socioeconomic characteristics of a particular region (Adger & Kelly, 1999). Hence, vulnerability assessments should be ongoing processes in order to highlight the spatial and temporal scales of vulnerability of a region (see Luers, 2005). Furthermore, the vulnerability of a system to climate change may be characterised as a function of the exposure, sensitivity and adaptive capacity of the system (McCarthy et al., 2001).

Exposure was defined by O'Brien et al. (2004, p. 305) as the "degree of climate stress upon a particular unit of analysis; it may be represented as either long-term changes in climate conditions, or by changes in climate variability, including the magnitude and frequency of extreme events". The characterisation of exposure in the vulnerability literature has often included the stressors as well as the entities under stress (see e.g. Polsky, Neff, & Yarnal, 2007; Turner et al., 2003). For instance, Polsky et al. (2007) argue that the characterisation of exposure (to drought in this study) should consider the intensity and frequency of exposure. Sensitivity reflects the responsiveness of a given system (in this case crop productivity) to climatic stimuli, either positively or negatively, and may be influenced by the socioeconomic and ecological conditions of the system (IPCC, 2001). Adaptive capacity in the context of climate change has been defined by the IPCC (2007) as the capacity of a system to adjust to the changing climate in order to reduce potential damages and take advantage of associated opportunities. Adaptive capacity is thought to be closely linked to livelihood asset ownership (Moser, 1998). This means that people who have more assets (financial, human, natural, physical and social) are generally considered to have a higher adaptive capacity and therefore less vulnerable (Moser, 1998).

Several scholars have attempted to holistically assess the vulnerability of communities or farming systems to climate change using a variety of different approaches (e.g. Fraser, 2007; Luers, Lobell, Sklar, Addams, & Matson, 2003; Simelton et al., 2009; Turner et al., 2003). Some have applied quantitative crop modelling to identify where harvests may decline or increase due to climate change (e.g. Challinor, Ewert, Arnold, Simelton, & Fraser, 2009; Challinor, Simelton, Fraser, Hemming, & Collins, 2010; Lobell et al., 2008). For example, Challinor et al. (2010) use a crop model that simulates biophysical adaptive capacity, and add a socioeconomic vulnerability index to highlight socioeconomic adaptive capacity. These quantitative models offer useful communication and visual tools to policy makers by making complex scientific data more comprehensible (Fraser, 2006). However, crop models as vulnerability assessment tools are subject to various limitations. For instance, the adaptations included in most crop models are hypothetical and often assume either "no adaptation" or "optimal adaptation" by farmers (Kandlikar & Risbey, 2000).

Another typical approach to quantifying vulnerability is to define a set of proxy indicators (Luers et al., 2003) and assess vulnerability by estimating indices or averages for those selected indicators (Gbetibouo, Ringler, Hassan, 2010). Indicators are useful for monitoring and studying trends and exploring conceptual frameworks and are also applicable across different scales including household, district, regional and national (Gbetibouo et al., 2010). However, indicators are limited by a lack of information on the choice of appropriate variables and the relative weightings required to establish a vulnerability index in a particular region (Luers et al., 2003). These limitations led Simelton et al. (2009) to use statistical tools and correlate crop drought vulnerability with socioeconomic indicators as a way of identifying the factors that make regions resilient or vulnerable to drought in China. This approach is useful in that it uses rainfall and harvest data to establish the characteristics of vulnerable and resilient cases. The limitation, however, is that this approach considers only two components of vulnerability (exposure and sensitivity) without fully capturing adaptive capacity.

The aim of this paper is to develop and apply a multi-scale quantitative approach to vulnerability assessment within Ghana to identify which of the country's regions and districts are most vulnerable to drought. To achieve this aim, the study objectives are:

1. to develop a methodological approach that combines aspects of crop drought vulnerability with socioeconomic indicators;
2. to use existing rainfall and yield data as well as proxy indicators of adaptive capacity to evaluate the exposure, adaptive capacity and sensitivity of Ghana's ten regions and the districts within the most vulnerable regions;
3. to reflect on the utility of using this sort of quantitative approach as a tool for use in other countries.

By meeting these objectives, this paper contributes to geographical and scientific debates on the development of integrated vulnerability assessments that can be applied in geographical areas for which more detailed data may be lacking. This paper highlights the value of initial broad-scale quantitative analyses as the starting point for more detailed, multi-method analyses of climate change vulnerability. This sort of methodological innovation is widely called for across the climate and development literature (Keskitalo, 2008; Yin, Huang, & Huang, 2002) and our study develops geographical analysis tools that offer important new methodological opportunities. Furthermore, this paper has policy implications as it identifies the most vulnerable regions and districts to drought and provides policy makers with appropriate information on vulnerability to feed into a more targeted climate adaptation policy in Ghana.

Study area and methods

Study area

Ghana covers a range of agro-ecological zones typical of West Africa and is located between latitudes 4.5°N and 11.5°N and longitudes 3.5°W and 1.3°E. Administratively, Ghana is divided into 10 regions, which are further sub-divided into 170 districts within six agro-ecological zones (Fig. 1). Average annual rainfall ranges between 800 and 2400 mm, along a gradient that sees increased aridity from south to north (Ghana Government, 2008). Generally,

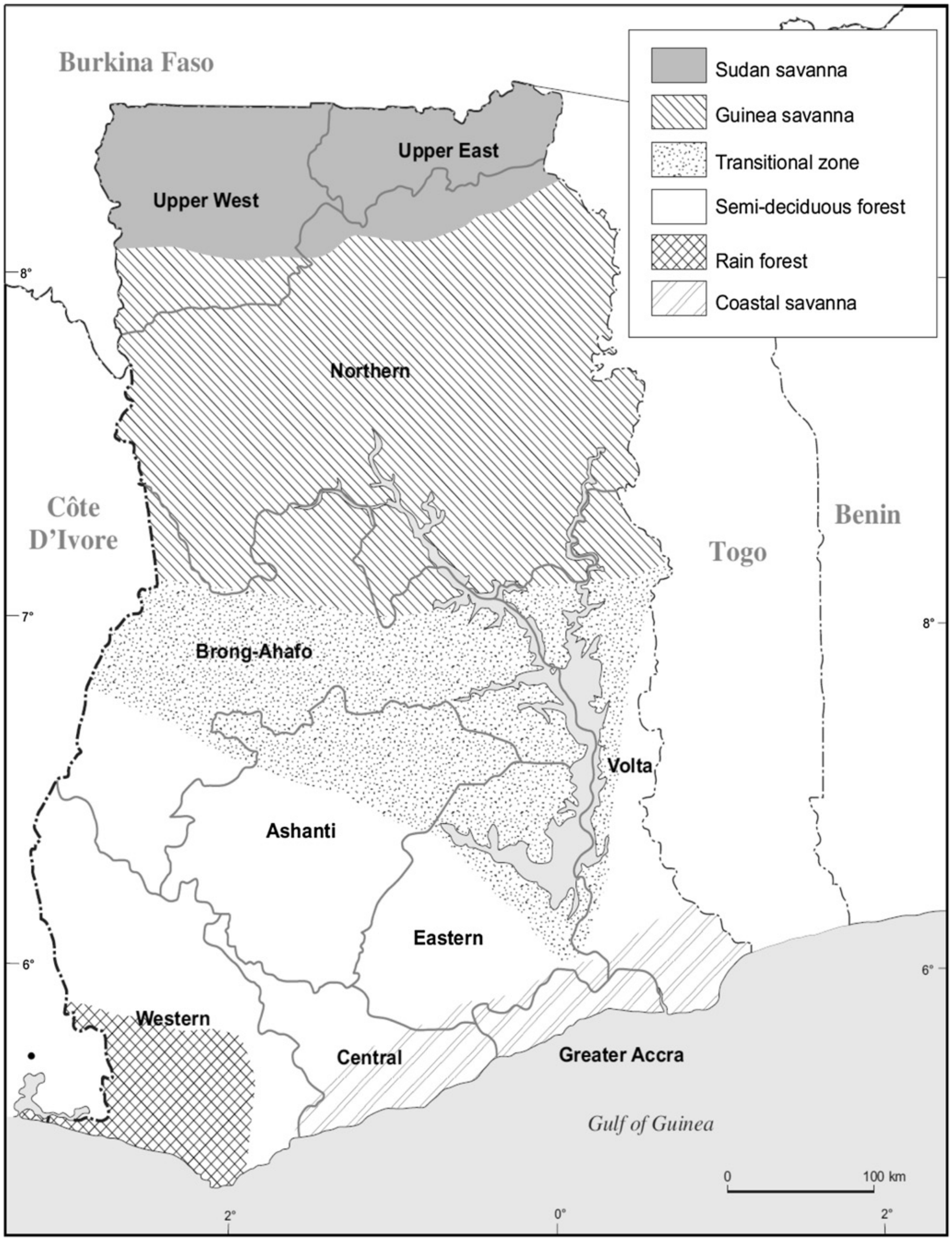

Fig. 1. Ghana showing the administrative regions and agro-ecological zones.

most parts of Ghana have annual temperatures above 24 °C (Ghana Environmental Protection Agency (GEPA), 2001).

Ghana's population is around 18.9 million (Ghana Statistical Service, 2000). The country's economy depends on rain-fed agriculture. Agriculture provides employment to about 57% of Ghana's labour force and contributes to about 44% of its Gross Domestic Product (Ministry of Food and Agriculture, Ghana (MoFA), 2007). The amount and pattern of rainfall play a key role in determining agricultural productivity (Seini et al., 2004) with Ghana's agricultural production highly sensitive to drought events. In recent years, climate-related problems such as drought and floods have resulted in severely reduced food production (MoFA, 2007).

In terms of future predictions, annual mean temperature in Ghana has been projected to increase by 0.6 °C, 2.0 °C and 3.9 °C by the years 2020, 2050 and 2080 respectively, whilst rainfall has been projected to decrease by 2.8%, 10.9% and 18.6% for the same periods (GEPA, 2007). These future predictions of warming and drying, together with greater variability, will lead to increased intensity and frequency of extreme events of droughts and floods as witnessed across dynamic dryland environments globally (Reynolds et al., 2007). The increased temperature and reduced rainfall will also mean increased evaporation and further reduction of runoff and available water. This shortens the length of the growing season in Ghana, as in many sub-Saharan African countries (Lobell Bänziger, Magorokosho, & Vivek, 2011), and this will have substantial implications for crop yields and food security.

Research design and methods

This research forms the basis of an integrated and multi-scale approach to explore the drivers of farming system vulnerability to drought at the national, regional, district and community levels.

This paper presents the first stages of this research programme in which we develop and apply a crop drought vulnerability index and socioeconomic indicator approach to map vulnerability at national and regional scales. Work presented in this paper took three stages that correspond to the following conceptualization of vulnerability:

$$V = f(E + S - AC) \tag{1}$$

In this equation, V is vulnerability of regions to drought, E is exposure to drought (reflected in the size of drought), S is the sensitivity of crop harvest to rainfall perturbations, and AC is adaptive capacity of regions to cope with drought (determined using socioeconomic proxy indicators). Following this, there were three stages of this research. The first stage involved the determination of sensitivity of crop harvest to drought by creating a crop yield sensitivity index that made use of historic yield data at both national and regional scales. The second stage involved using existing rainfall data to estimate drought exposure at the same spatial scales by calculating national and regional level exposure indices. The third stage involved the determination of an adaptive capacity index by using proxy socioeconomic data available from the Ghanaian census.

Determining 'sensitivity' of crop harvest to rainfall perturbations

In this paper, sensitivity is inferred through the harvest losses associated with different droughts and is determined through the development of a crop yield sensitivity index. To determine the sensitivity of crop harvest to rainfall perturbations, a crop yield sensitivity index was calculated using methods adapted from Simelton et al. (2009). Yield data for maize for all 10 regions of Ghana were obtained from the national Ministry of Food and Agriculture, for the period 1992–2007. Maize was selected as the test crop because it is the main crop grown, being consumed as a staple across the country (Kasei & Afuakwa, 1991), and is of importance to the country's socioeconomic development. The period of 1992–2007 was selected due to the availability of yield data.

We followed Lobell, Cahill, & Field (2007) and Easterling, Chenl, Hays, Brandle, & Zhang (1996) processes of detrending whereby a linear model of the time series of the actual yield was removed from the data by dividing the projected linear trend value by the actual observed value. This was done to reduce the influence of increased agricultural technology in order to highlight inter-annual yield variation as a result of rainfall. According to Lobell et al. (2007), this is an important step that is required to explore the relationship between climate factors and crop yield. To determine the crop yield sensitivity index, we calculated the linear trend for each yield for each region between 1992 and 2007. The equation for this trend line was used to calculate the expected yield in each year. The expected yield was then divided by the actual yield for each year to generate a crop yield sensitivity index as per regional analyses previously applied in China (Simelton et al., 2009) (see Equation (2)).

$$\text{Crop yield sensitivity index} = \text{expected yield}/\text{actual yield} \tag{2}$$

Determining 'exposure' to drought

In this paper, exposure is defined as the degree to which a particular system is exposed to meteorological drought (Fraser, 2007; Tilahun, 2006) given that drought is the major threat to African farming systems (UNDP, 2007). Therefore, this paper uses meteorological data as a way of creating an exposure index that reflects the degree to which different farming regions were exposed to drought. The estimation of exposure to drought followed the procedures developed by Simelton et al. (2009) for the calculation of the exposure index. Monthly rainfall data were obtained from the Ghana Meteorological Agency for 1971–2007. A standard 30-year climatological period, in this case from 1971–2000, was used to eliminate year-to-year variations and is considered adequate for agro-meteorological planning (Todorov, 1985). The maize growing period in Ghana is 126–200 days between April and August and this period coincides with the moisture requirements during flowering (Kasei & Afuakwa, 1991). To develop the exposure index, the average of the 30-year rainfall period for the 5-month period (April–August) from 1971–2000 was divided by each year's average rainfall for this period (April–August) which represents the growing season for maize as shown in Equation (3) below.

$$\begin{aligned}\text{Exposure index} = {} & \text{mean long-term growing season rainfall} \\ & \text{for 1971–2000/mean growing season} \\ & \text{rainfall for each year 1992–2007}\end{aligned} \tag{3}$$

Whilst data on the number of people that have been exposed to drought in the past in the study area are lacking, we examined qualitatively the type of crops grown and the nature of farmland in the study area so as to account for the other dimensions of *exposure unit* which include the entities under stress (see Polsky et al., 2007). However, in terms of climate factors this study considered only rainfall because it is the most critical hydrological variable for agricultural productivity (Tilahun, 2006) in the study area (see Seini, Botchie, & Damnyag, 2004). Sivakumar, Das, & Brunini (2005) have reported that significant reductions in crop yield have always been attributed to abnormally low precipitation-induced drought rather than warming-induced increases in evapotranspiration rates.

Determining 'adaptive capacity' to cope with drought

In this paper, adaptive capacity is defined as the ability of a region to cope with the impacts of climate change (particularly drought) and it is estimated by a set of proxy socioeconomic indicators. The adaptive capacity required to cope with drought is thought to depend on five livelihoods assets: financial, human, natural, physical and social capital assets (e.g. Gbetibouo et al., 2010). Two proxy indicators of adaptive capacity were considered for this study: human capital (represented by literacy rates (%)) and financial capital (represented by poverty rates (%)). These proxy socioeconomic indicators were obtained from the census data by the Ghana Statistical Service (2000). Although this is a simplifying assumption, these two proxy indicators (see equation (4)) were selected because they were the only indicators where data were available for all ten regions. Nevertheless, these are considered to be appropriate by a wide range of literature (e.g. Brooks et al., 2005; Gbetibouo et al., 2010). In this study, natural capital is included in the sensitivity component of vulnerability and it is assumed that the greater the natural capital the less the sensitivity of that region to the impacts of drought. Lack of data prevented the inclusion of social and physical capital assets in the national and regional level data analyses and these two capital assets will be explored in subsequent phases of this multi-scale research using household and village level livelihood studies in regions identified by this study as being notably vulnerable to drought.

$$\begin{aligned}\text{Adaptive capacity} = {} & (\text{Literacy rate}/100) \\ & + ((100 - \text{Poverty rate})/100)\end{aligned} \tag{4}$$

Hence, the overall mean vulnerability of a particular region was estimated from the following:

$$\begin{aligned}\text{Vulnerability} = {} & [(\text{crop yield sensitivity index} \\ & + \text{exposure index}) - \text{adaptive capacity}]\end{aligned} \tag{5}$$

Mapping crop drought vulnerability at the regional scale

The methods described above were used to map vulnerability at the national scale where proxy socioeconomic data were available. Having identified the most vulnerable regions, we then mapped food system vulnerability at the regional scale within the most vulnerable regions in order to identify the most vulnerable districts within these regions. Due to the lack of proxy socioeconomic data at the regional levels, a crop drought vulnerability analysis following the procedures adapted by Simelton et al. (2009) was used to achieve this (equation (6)).

$$\text{Crop drought vulnerability index} = \text{crop yield sensitivity index}/\text{exposure index} \quad (6)$$

It was hypothesised that in situations where major droughts resulted in insignificant crop losses in a particular district then there may be underlying high levels of adaptive capacity, reflecting the socioeconomic conditions of the district. Such a district is considered 'resilient'. In contrast, in situations where there were large losses in crop harvest following minor rainfall perturbations then there may have been underlying low levels of adaptive capacity that made such an area 'vulnerable'. In this study, we use the crop drought vulnerability analysis to estimate vulnerability indices for only vulnerable districts within the most vulnerable regions. Despite its limitations, the crop drought vulnerability index approach is useful as it uses rainfall and regional crop harvest data to identify vulnerable cases in geographical regions where there are limited proxy socioeconomic indicators with which to estimate adaptive capacity.

In the regional level analysis, we focused on foods more associated with these poor regions, namely sorghum and millet for the construction of the crop yield sensitivity index. Whilst regional geographical boundaries in Ghana have remained constant, district boundaries have changed over the study period and this makes it difficult to have reliable data for this finer level analysis. We overcame this challenge by not considering districts that have recently had their borders changed.

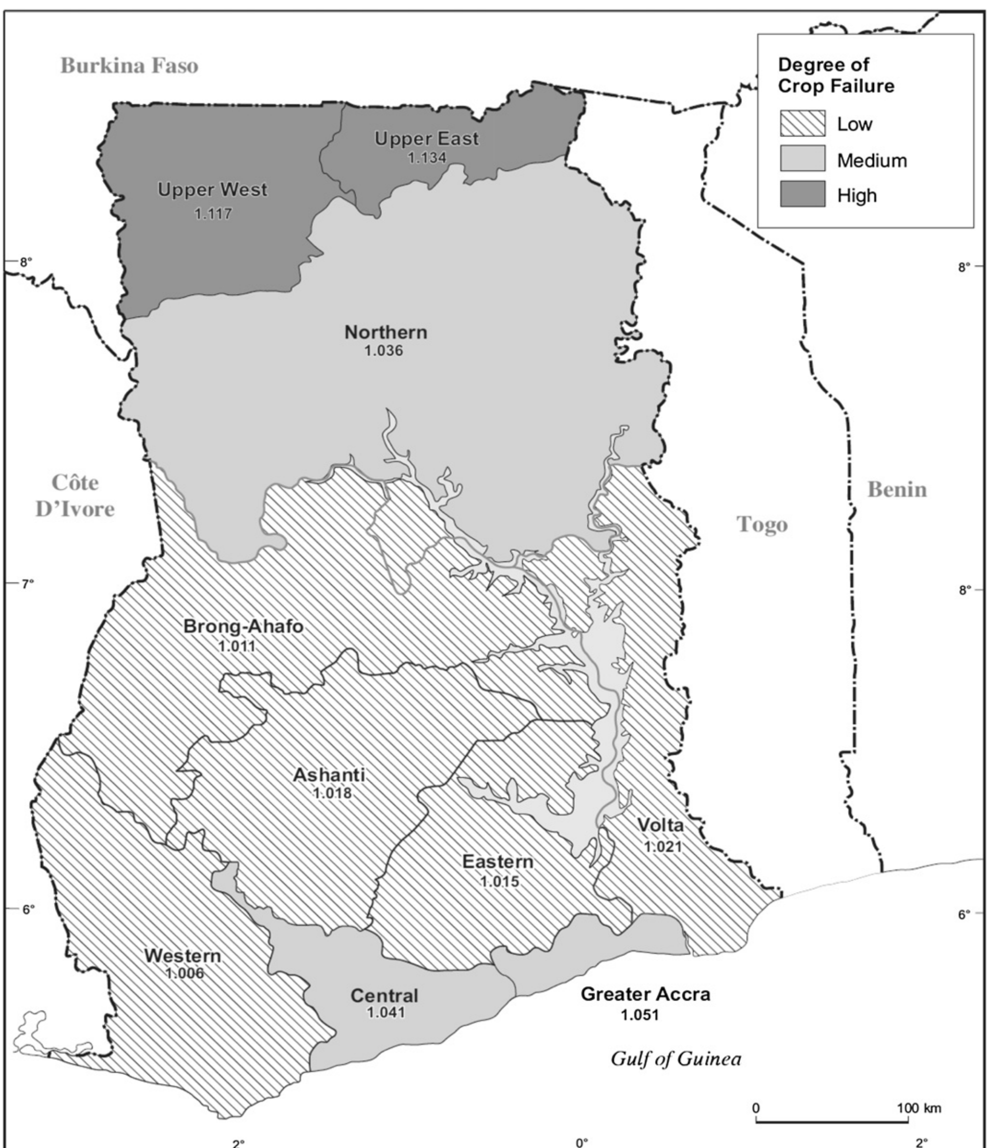

Fig. 2. Crop yield sensitivity indices of the various regions in Ghana.

Data analysis

Once overall mean vulnerability was calculated, a *k*-means cluster analysis using the STATISTICA software package was undertaken to group the regions according to vulnerability. K-means clustering is a statistical approach that groups cases into distinct clusters by seeking groups that minimise variability within clusters and maximise variability between clusters (Levia & Page, 2000). K-means cluster analysis has been applied to several geographical problems (e.g Ahern, Naamanm, Nair, & Yang, 2006; Kennedy & Naaman, 2008; Levia & Page, 2000) and we assess its value to spatial vulnerability assessments in dynamic systems here.

Results

The overall crop yield sensitivity of the various regions in Ghana to drought is presented in Fig. 2. The analysis indicates that the Upper East and Upper West regions are the most sensitive in terms of exposure to drought. Farmers in these two regions mostly practice subsistence farming and are heavily dependent on rain-fed agriculture. Because of the inherent low soil fertility in these regions (see Quansah, 2004), only certain types of crops (mainly cereals such as maize, sorghum and millet) can thrive and these crops require an appreciable amount of water during growth.

With regard to drought intensity, Fig. 3 shows that the majority of regions in Ghana experienced medium levels of drought with the four regions of the south experiencing high levels of drought and the most northwest region a low levels of drought.

The overall adaptive capacity for the various regions is shown in Fig. 4. The Northern, Upper East and Upper West regions show the lowest adaptive capacity of all the regions in Ghana suggesting that these regions have the lowest capacity to cope with drought. The Greater Accra and the Ashanti Regions show the highest adaptive capacity (Fig. 4).

Fig. 5 shows the results of the k-means cluster analysis and demonstrates that there are three different clusters according to their vulnerability: half of the regions in Ghana are moderately vulnerable to drought, whilst a third is highly vulnerable and only two regions have low vulnerability. Fig. 6 presents this analysis spatially, showing that the Northern, Upper East and Upper West regions are the most vulnerable to drought while the lowest vulnerability regions are the most urbanized and developed regions: Ashanti and Greater Accra.

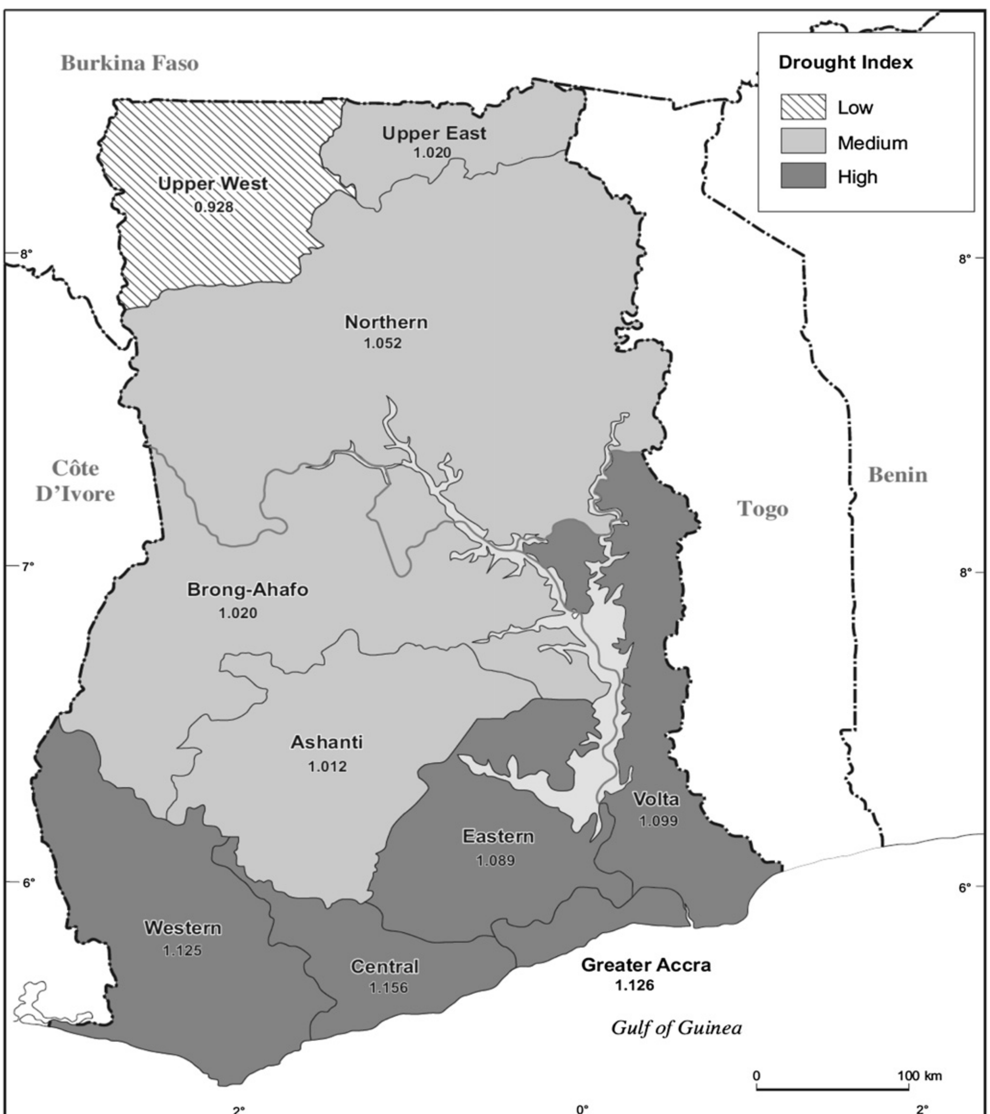

Fig. 3. Exposure indices of the various regions in Ghana.

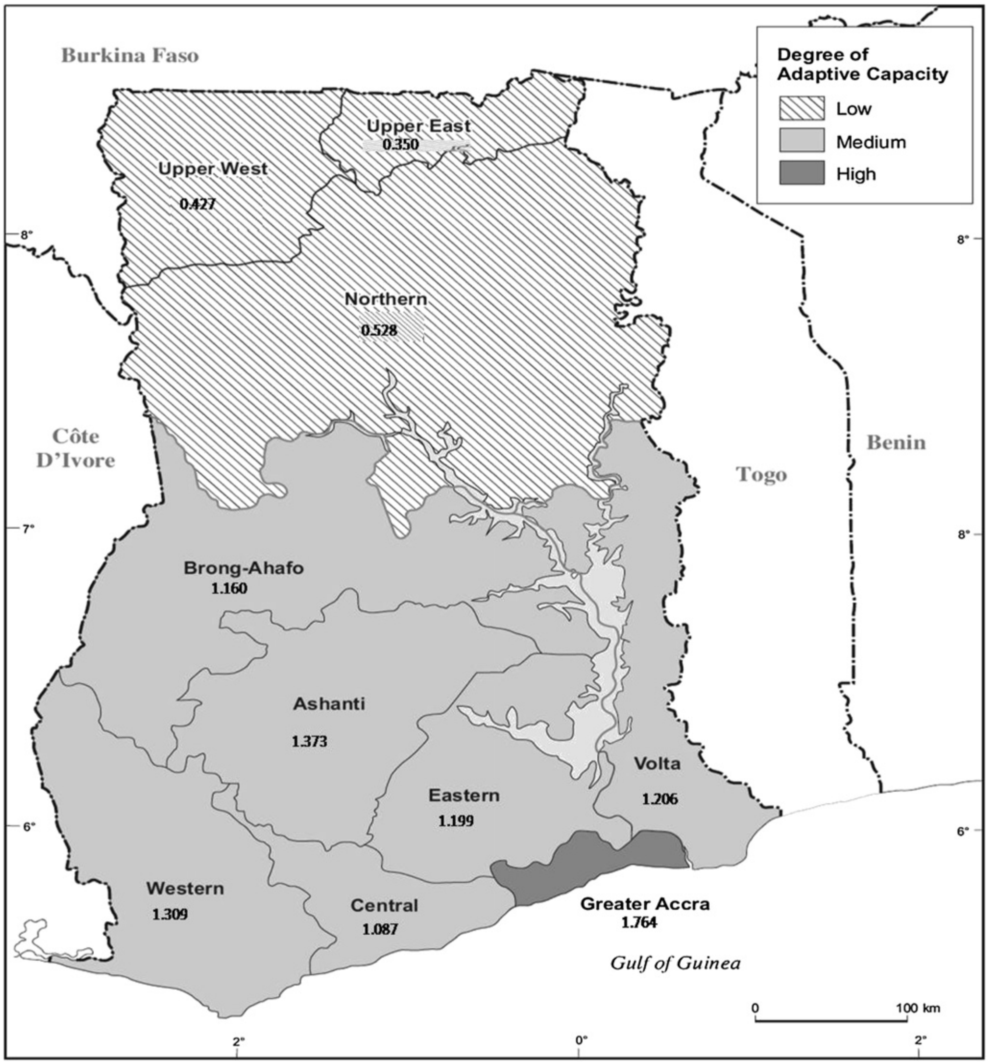

Fig. 4. Adaptive capacity indices of the various regions in Ghana.

Figs. 7, 8 and 9 provide a regional level breakdown for the three most vulnerable regions (Upper East, Upper West and Northern regions). In general, millet recorded high vulnerability indices in all the districts within the three most vulnerable regions compared with sorghum and maize except in the Bawku East district in the Upper East (Fig. 7), Wa district in the Upper West (Fig. 8) and Saboba and Zabzugu districts in the Northern region (Fig. 9). The districts within the Northern regions recorded the lowest vulnerability indices for all crops during the study period. For instance, Gambaga and Damongo in the Northern regions recorded the lowest vulnerability indices for both millet and maize (Fig. 9).

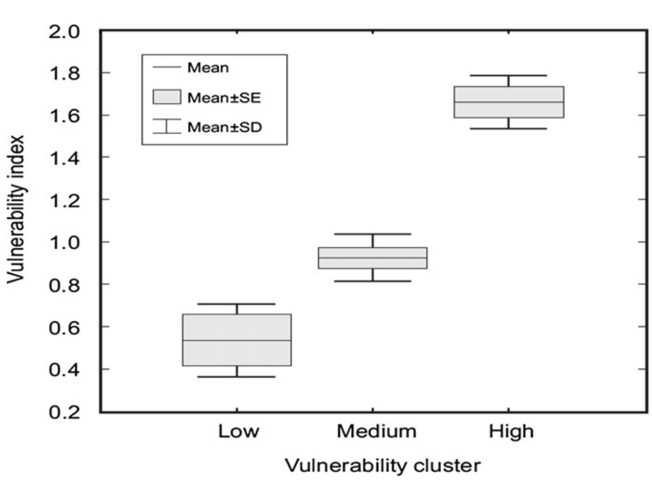

Fig. 5. Box and whiskers plot of vulnerability indices clusters derived by k-means cluster analysis.

While the standard errors within the data are high, the general trend is that the districts in the Upper East region recorded higher mean vulnerability indices for both sorghum and millet compared with those in the Northern and Upper West regions. Within the Upper East region, the Bongo district recorded the highest mean vulnerability index for the investigated period (Fig. 7) and, therefore, has become the focus of an ongoing research programme at the village and household levels.

Discussion

The results show that there are strong spatial and socioeconomic patterns in terms of vulnerability to drought in Ghana. In particular, results suggest that the vulnerability of the regions is highest in the Northern, Upper West and Upper East regions (Fig. 6) that are characterised by low levels of social, economic and physical assets (Ghana Statistical Service, 2000). Even within these

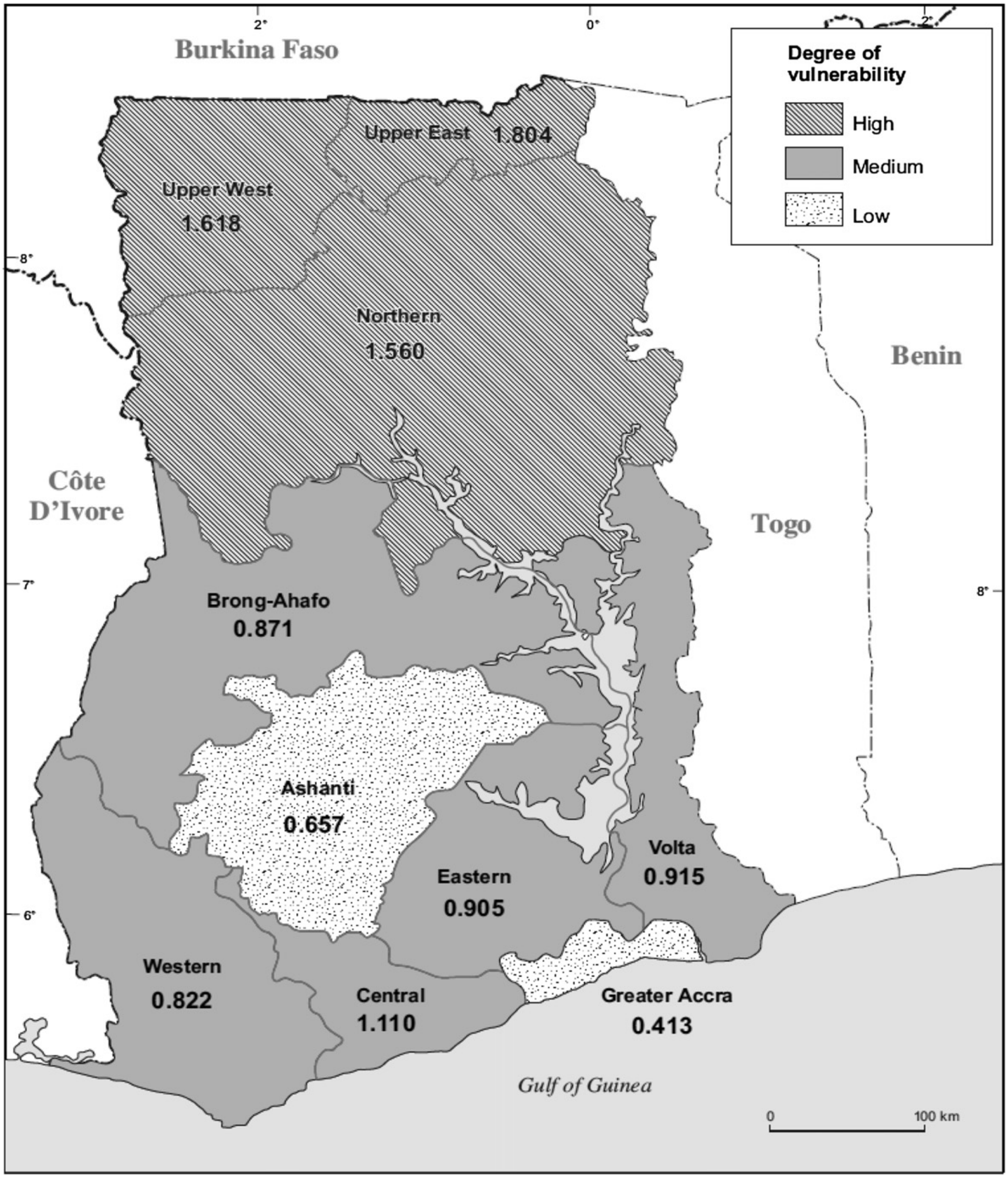

Fig. 6. Vulnerability indices of the various regions in Ghana.

vulnerable regions, there was different vulnerability among the various districts. The Bongo district (Upper East region) recorded the highest mean vulnerability index due to the high poverty level and low literacy rates in the region in general and the Bongo district in particular.

The major crops grown in the study area include maize, cassava, plantain, rice and yam in Southern Ghana and, millet, sorghum and maize in Northern Ghana (see Kasei & Afuakwa, 1991; MoFA, 2007). These are crops that require an appreciable amount of water during growth and the persistent droughts in the various regions especially in the most vulnerable regions (i.e. Northern, Upper East and Upper West) have often resulted in low production from such crops. Soils in the Upper East region and the Bongo district in particular are characterised by stoniness and gravel and these, together with iron-pan in the soils, make them highly unproductive and poor at retaining moisture (Quansah, 2004). Continuous cropping of farmlands in the Upper East region without the addition of appropriate soil amendments has left the soil with low fertility and in a highly unproductive state. High poverty levels in the Upper East region make it difficult for farmers to afford fertilizers to improve the fertility of the soils. In addition, low socio-economic development and erratic rainfall patterns (in terms of both onset and duration) make farmers in the Upper East region in general, and the Bongo district in particular, extremely vulnerable.

Poverty can lead to marginalisation and limit the amount of capital assets that may be needed to reduce the impacts of

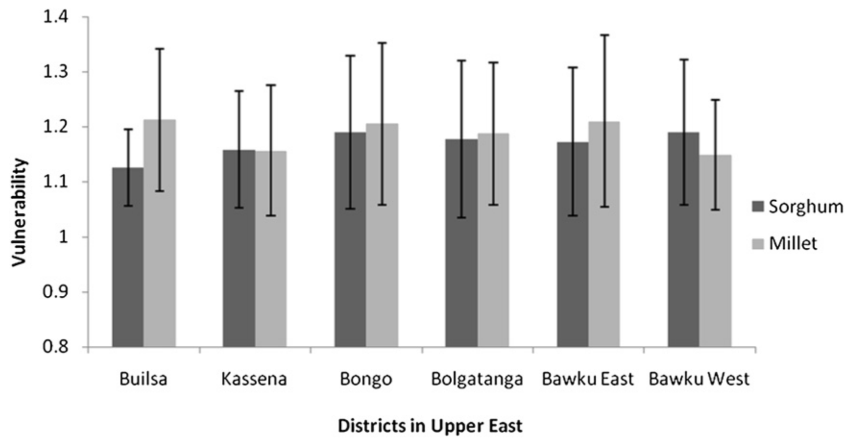

Fig. 7. Mean vulnerability indices of districts in the Upper East region, Ghana.

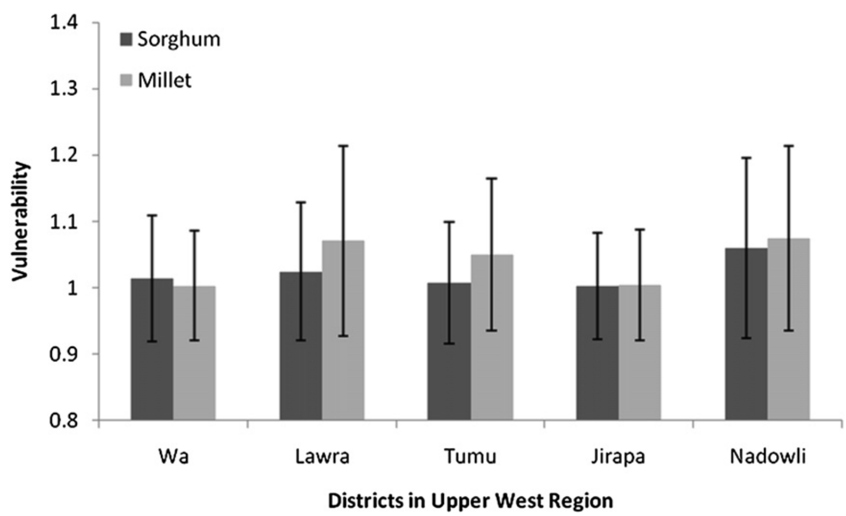

Fig. 8. Mean vulnerability indices of districts in the Upper West region, Ghana.

drought on livelihoods of farming communities (Adger & Kelly, 1999) such as those in the Northern, Upper West and Upper East regions. For example, an estimated 90%, 80% and 70% of people in the Upper East, the Upper West and the Northern regions respectively are considered to be poor (Ghana Statistical Service, 2000). Though poverty may not be directly equated with vulnerability, it constrains the capability of communities to cope with the impacts of drought (Sen, 1999). This is because the poor are confronted with other non-environmental shocks and stresses that place additional constraints on their limited assets to

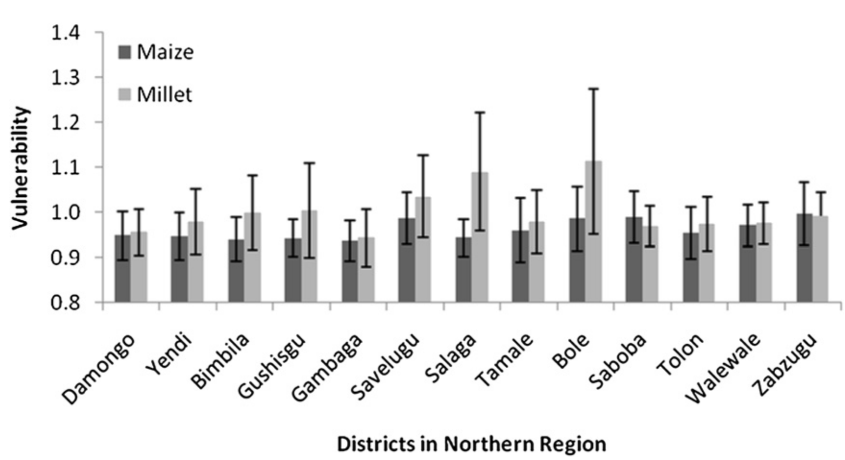

Fig. 9. Mean vulnerability indices of districts in the Northern region, Ghana.

cope with the impacts of drought (Stringer et al., 2009). Moreover, poverty may compel people to live in environmentally fragile areas which could worsen their vulnerability to climate and other environmental changes. High poverty levels in these vulnerable regions will further inhibit the potential for sub-Saharan Africa's poor farmers to manage the impacts of climate change (see Morton, 2007).

The results from this study further reveal that the Guinea Savannah and Sudan Savannah agro-ecological zones are the most vulnerable to increasing drought events in Ghana (Figs. 1 and 6). These agro-ecological zones experience an uni-modal rainfall pattern and are predominantly characterised by drier conditions and fragile agro-ecosystems. As a result, these types of regions are also likely to be vulnerable to climate change. Soils within the Guinea and Sudan Savannah agro-ecological zones have poor fertility that, together with desertification, exacerbates food insecurity in these regions.

Our results support the findings of Gbetibouo et al. (2010) for South Africa that indicate that the vulnerability of a farming region to drought is linked to the socioeconomic development characteristics of that particular region. Indeed, vulnerability is greatly influenced by the degree of development and socioeconomic status of a particular group or community (Ribot, Magalhaes, & Panagides, 1996). The ability of a community or region to cope with the impacts of climate change is reflected in the assets and entitlements that a community or region can assemble to reduce vulnerability (Moser, 1998). It is well documented that the entitlements of individuals to capital assets including financial, human, natural, physical, and social capitals could affect their ability to cope with the impacts of climate change (Sen, 1981).

Many writers have highlighted the role of social capital in coping with the impacts associated with environmental (climate) change in communities (see e.g. Adger, 2003; Fraser, 2006; Pretty, 2003). Pretty (2003) argues that households which are socially well connected are better placed to cope with the impacts of an environmental (climate) change. For instance, people can rely on their social networks including friends and family for food and shelter during drought or flood induced famine. In addition, financial capital assets such as savings, remittances and pensions offer an individual other livelihood options and thereby reduce their vulnerability to environmental change. Natural capital assets including natural flow stocks and other environmental resources (Scoones, 1998) may provide useful economic opportunities to communities and individuals. Members of a community may also pick wild fruits during famine to reduce their vulnerability to drought induced famine.

Physical assets are also crucial in reducing the impacts of environmental change. For instance, good road networks and other transportation routes in farming communities may play a crucial role in determining how emergency and relief items reach these vulnerable communities (see Adger, Brooks, Bentham, Agnew & Ericksen, 2004). Access to markets and good road networks can greatly influence the vulnerability of farmers in that good road networks will mean that farm produce is transported to the market in good time and sold in order to obtain financial resources. Human capital assets such as education may also affect the vulnerability of a particular community to environmental change. This is because education can enhance the adaptive capacity of a particular region (see Brooks et al., 2005). For instance, education may increase the income earning opportunities of rural households whose livelihoods depend on agriculture (see Paavola, 2008). This is because the poorly educated may be excluded from well paid wages jobs due to their lack of skills for such jobs (Rakodi, 1999). Education is particularly important in rain-fed agriculture dependent countries like Ghana where most of the workers in non-farm jobs are educated. In addition, education can greatly enhance a person's capacity to access information which may include the use of new technology (Weir, 1999).

Adaptive capacity is also dependent on the availability of appropriate government and non-governmental institutions and policies as well as structures in mediating access to the livelihood assets and entitlements. However, these factors have not been considered in this analysis due to a lack of available data and will be considered further in the next phases of this research programme that will explore household and village level data in much more detail.

The next phase of this research is to explore the drivers of vulnerability and identify the adaptation pathways of individual farmers to climate variability and change at a local-scale. In this regard, the quantitative and large scale analysis presented here enabled us to identify case study districts within these regions, from which study villages were chosen using expert interviews and village level census data (where this exists). The findings presented in this paper, however, go beyond simply setting up the next phase of more in-depth research. This study also enables policy and development project advice and extension activity to be focused on areas with the greatest need in terms of vulnerability to climate change and future drought events.

Conclusions

This study has developed and applied a quantitative, multi-scale and multi-indicator analysis that has identified the relative vulnerabilities of the various regions in Ghana, as well as the relative vulnerabilities of different districts within the most vulnerable regions. The proposed spatially-explicit methodology is integrative in that it shows both the biophysical conditions of these farming regions by way of an exposure index and a crop yield sensitivity index whilst considering the socioeconomic conditions of the regions. Vulnerability has been expressed as a function of exposure, sensitivity and adaptive capacity (McCarthy et al., 2001). Exposure was determined by developing an exposure index, whilst sensitivity was estimated through construction of a crop yield sensitivity index. Proxy indicators including poverty levels and literacy levels were used to estimate the adaptive capacity of the various regions in Ghana, thus extending the methodology employed by Simelton et al. (2009).

The analysis shows that vulnerability to drought in Ghana is linked to the level of socioeconomic development and is spatially differentiated. This suggests the need for region- and district-specific climate adaptation policies, as different regions and districts within them display different levels of vulnerability. The farming communities in the most vulnerable regions (Northern, Upper East and Upper West) largely depend on rain-fed agriculture, which is very sensitive to climate change, as a key livelihood strategy. Thus, livelihood diversification strategies including non-farm income sources should be vigorously pursued by policy makers in these regions. The implication of the results presented in this study is that policy makers need to formulate more specific and targeted climate adaptation policies to reduce the vulnerabilities of farmers whose livelihoods depend largely on rain-fed agriculture. Ultimately, this will enhance drought preparedness within dryland farming regions and communities in Ghana. The approach outlined in the present study is particularly useful in evaluating the vulnerability of a particular region, community or system to drought in developing countries where data for proxy socioeconomic indicators of exposure, sensitivity and adaptive capacity may be less readily available.

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References

Adger, W. N. (2006). Vulnerability. *Global Environmental Change, 16*(3), 268–281.

Adger, W. N. (2003). Social capital, collective action, and adaptation to climate change. *Economic Geography, 79*(4), 387–404.

Adger, W. N., Brooks, N., Bentham, G., Agnew, M., & Eriksen, S. (2004). *New indictaors of vulnerability and adaptive capacity*In *Technical Report, 7*. Norwich, UK: Tyndall Centre for Climate *Research*.

Adger, W. N., & Kelly, P. M. (1999). Social vulnerability to climate change and the architecture of entitlements. *Mitigation and Adaptation Strategies for Global Change, 4*(3–4), 253–266.

Ahern, S., Naaman, M., Nair, R., & Yang, J. (2006). World explorer: Visualizing aggregate data from unstructured text in geo-referenced collections. *Proceedings of the JCDL 2007*. ACM Press, New York, pp.1–10.

Brooks, N., Adger, W. N., & Kelly, P. M. (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change, 15*, 151–162.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., et al. (2007). Africa. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.

Challinor, A. J., Ewert, F., Arnold, S., Simelton, E., & Fraser, E. D. G. (2009). Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. *Journal of Experimental Biology, 60*(10), 2775–2789.

Challinor, A. J., Simelton, E. S., Fraser, E. D. G., Hemming, D., & Collins, M. (2010). Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China. *Environmental Research Letters, 5*. 034012 (8pp).

Chambers, R. (1994). The origins and practice of participatory rural appraisal. *World Development, 22*(7), 953–969.

Easterling, W. E., Chenl, X., Hays, C., Brandle, J. R., & Zhang, H. (1996). Improving the validation of model-simulated crop yield response to climate change: an application to the EPIC model. *Climate Research, 6*, 263–275.

Fraser, E. D. G. (2006). Food system vulnerability: using past famines to help understand how food systems may adapt to climate change. *Ecological Complexity, 3*(4), 328–335.

Fraser, E. D. G. (2007). Travelling in antique lands: using past famines to develop an adaptability/resilience framework to identify food systems vulnerable to climate change. *Climatic Change, 83*(4), 495–514.

Gbetibouo, G. A., Ringler, C., & Hassan, R. (2010). Vulnerability of the South African farming sector to climate change and variability: an indicator approach. *Natural Resources Forum, 34*, 175–187.

Ghana Environmental Protection Agency. (2007). *Climate change and the Ghanaian economy*. In *Policy advice series, Vol. 1*. Accra, Ghana: Ghana Government Policy Document.

Ghana Environmental Protection Agency. (2001). *Ghana's initial national communications report under the United Nations framework convention on climate change*, Accra, Ghana.

Ghana Government. (2008). *Ghana climate change impacts, vulnerability and adaptation assessment: Under the Netherlands Climate Assistance Programme (NCAP)*, Accra, Ghana.

Ghana Statistical Service. (2000). *Population and housing census (2000)*. Accra, Ghana: Ghana Government.

IPCC. (2001). *Summary for policymakers. Climate change 2001: Impacts, adaptation, and vulnerability: A report of working group II of the IPCC*. Geneva: IPCC.

IPCC. (2007). Climate change 2007: impacts, adaptation and vulnerability. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linder, & C. E. Hanson (Eds.), *Contribution of working group II to the fourth assessment report of the IPCC*. Cambridge: Cambridge University Press.

Kandlikar, M., & Risbey, J. (2000). Agricultural impacts of climate change: if adaptation is the answer, what is the question? *Climatic Change, 45*(3–4), 529–539.

Kasei, C. N., & Afuakwa, J. J. (1991). Determination of optimum planting date and growing season of maize in the northern savannah zone of Ghana. *Soil Water Balance in the Sudano-Sahelian Zone (Proceedings of the Niamey Workshop)*. IAHS Publ. no. 199, 1991.

Kennedy, L., & Naaman, M. (2008). Generating diverse and representative image search results for landmarks. *Proceeding of the 17th International Conference on World Wide Web*. April 21–25, 2008. Beijing, China, pp. 1–10.

Keskitalo, E. C. H. (2008). Vulnerability and adaptive capacity in forestry in northern Europe: a Swedish case study. *Climatic Change, 87*, 219–234.

Levia, D. F., Jr., & Page, D. R. (2000). The use of cluster analysis in distinguishing farmland prone to residential development: a case study of Sterling, Massachusetts. *Environmental Management, 25*, 541–548.

Lobell, D. B., Cahill, K. N., & Field, C. B. (2007). Historical effects of temperature and precipitation on California crop yiels. *Climatic Change, 81*, 187–203.

Lobell, D. B., Bänziger, M., Magorokosho, C., & Vivek, B. (2011). Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change, 1*, 1–4.

Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science, 319*, 607–610.

Luers, A. L. (2005). The surface of vulerability: an analytical framework fro examining environmental change. *Global Environmental Change, 15*, 214–223.

Luers, A. L., Lobell, D. B., Sklar, L. S., Addams, C. L., & Matson, A. P. (2003). A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. *Global Environmental Change, 13*, 255–267.

McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., & White, K. S. (Eds.). (2001). *Climate change 2001: impacts, adaptation and vulnerability*. Cambridge: Cambridge University Press.

Ministry of Food and Agriculture, Ghana. (2007). *Food and agriculture sector development policy*. Accra, Ghana: Ghana Government Policy Document.

Morton, J. F. (2007). The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, 104, 19680–19685.

Moser, C. O. N. (1998). The asset vulnerability framework: reassessing urban poverty reduction strategies. *World Development, 26*(1), 1–19.

O'Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., et al. (2004). Mapping vulnerability to multiple stressors: climate change and globalization in India. *Global Environmental Change, 14*, 303–313.

Paavola, J. (2008). Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental Science & Policy, 11*, 642–654.

Polsky, C., Neff, R., & Yarnal, B. (2007). Building comparable global change vulnerability assessments: the vulnerability scoping diagram. *Global Environmental Change, 17*, 472–485.

Pretty, J. (2003). Social capital and the collective management of resources. *Science, 302*, 1912–1914.

Quansah, C. (2004). *Socioeconomic development programme for the transborder onchocerciasis-freed zone of Burkina Faso and Ghana*. The agricultural development and natural resources management component, *GCP/RAF/376/BEL*. Accra: Ghana.

Rakodi, C. (1999). A capital assets framework for analysing household livelihood strategies: implications for policy. *Development Policy Review, 17*, 315–342.

Reed, M. S., Buenemann, M., Atlhopheng, J., Akhtar-Schuster, M., Bachmann, F., Bastin, G., et al. (2011). Cross-scale monitoring and assessment of land degradation and sustainable land management: a methodological framework for knowledge management. *Land Degradation and Development, 22*, 261–271.

Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S. P. J., et al. (2007). Global desertification: building a science for dryland development. *Science, 316*(5826), 847–851.

Ribot, J. C., Magalhaes, A. R., & Panagides, S. S. (Eds.). (1996). *Climate variability, climate change and social vulnerability in the semi-arid tropics*. Cambridge: Cambridge University Press.

Scoones, I. (1998). *Sustainable rural livelihoods: A framework for analysis*In *Working paper, 72*. UK: Institute for Development Studies.

Seini, A. W., Botchie, G., & Damnyag, L. (2004). *Environmental services provided by selected farming systems in Ghana*In *Technical Publication, Vol. 65*. Legon, Accra, Ghana: Institute for Statistical, Social and Economic Research, University of Ghana.

Sen, A. K. (1999). *Development as freedom*. New York: Anchor Books.

Sen, A. K. (1981). *Poverty and famines: An essay on entitlement and deprivation*. Oxford: Clarendon Press.

Simelton, E., Fraser, E. D. G., Termansen, M., Forster, P. M., & Dougill, A. J. (2009). Typologies of crop-drought vulnerability: an empirical analysis of the socio-economic factors that influence the sensitivity and resilience to drought of three major food crops in China (1961–2001). *Environmental Science and Policy, 12*(4), 438–452.

Sivakumar, M. V. K., Das, H. P., & Brunini, O. (2005). Impacts of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics. *Climatic Change, 70*, 31–72.

Stringer, L., Dyer, J., Reed, M. S., Dougill, A. J., Twyman, C., & Mkwambisi, D. (2009). Adaptations to climate change, drought and desertification: insights to enhance policy in southern Africa. *Environmental Science and Policy, 12*(7), 748–765.

Tilahun, K. (2006). Analysis of rainfall climate and evapotranspiration in arid and semi-arid regions of Ethiopia using data over the last half a century. *Journal of Arid Environments, 64*, 74–487.

Todorov, A. V. (1985). Sahel: the changing rainfall regime and the "Normals" used for its assessment. *Journal of Climate and Applied Meteorology, 24*(2), 97–107.

Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., et al. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*, 100(14), 8074–8079.

UNDP. (2007). *Human Development Report 2007/2008: Fighting climate change: Human solidarity in a divided world*. New York: USA. United Nations Development Programme. http://www.preventionweb.net/english/professional/publications/v.php?id=2272.

Weir, S. (1999). *The effects of education on farmer productivity in rural Ethiopia. Centre for African Economics*In *Working paper, Vol. 91*. Oxford, UK: University of Oxford.

Yin, Y., Huang, Y. F., & Huang, G. H. (2002). An integrated approach for evaluating adaptation options to reduce climate change vulnerability in coastal region of the Georgia Basin. *Annals of GIS, 8*(2), 86–96.