Mapping population vulnerability and climate change in Africa

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International Seminar on Population Dynamics and the Human Dimensions of Climate Change
Canberra, Australia, 27-29 November 2012

Abstract This paper develops and maps the first spatially explicit, integrative measure of vulnerability to climate change as a function of vegetation and demographic dynamics for Africa at a spatial resolution of 5 square kilometers. Increasing climate variability as well as declining and more irregular precipitation significantly impacts agricultural production, food security, and disease in many African countries; recent estimates predict that without rapid global emission mitigation by 2030, this will lead to an increase in the incidence of malaria by 17%, malnutrition by 16%, and diarrhea by 5%. However, we know little about where these impacts may be most devastating to children’s health outcomes. Our analysis integrates time-series remotely-sensed imagery capturing changes in vegetation condition with continent-wide analyses of temperature and precipitation trends and population distribution in a rule-based classifier to create a present and future vulnerability index. Results suggest a near doubling of the population in some areas (such as the East African Horn) is linked with hotspots of degradation in vegetation condition, but that the most significant land cover change and vegetation degradation trends are observed in areas experiencing drying precipitation trends in addition to increasing population pressures.

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I. Introduction

Research increasingly points to the potentially devastating health effects of climate change in places that already experience significant health burdens (Haines and McMichael 1997; Patz, Campbell-Lendrum et al. 2005; Confalonieri, Menne et al. 2007; Byass 2009; Hope 2009; Portier, Thigpen et al. 2010). The African continent is salient in climate change predictions as the world's most vulnerable region, related to and exacerbated by recurring drought, crop failures, water scarcity issues, and disease burden (Fischer, Shah et al. 2005; Haile 2005; Verdin, Funk et al. 2005; Christensen, Hewitson et al. 2007; Collier, Conway et al. 2008; Cooper, Dimes et al. 2008; Hope 2009; Durack, Wijffels et al. 2012). Specifically, Campbell-Lendrum et al (Campbell-Lendrum, Pruss-Ustun et al. 2003) predict increases of malaria by 17%, malnutrition by 16%, and diarrhea by 5% as a result of climate change in Africa by 2030 absent of significant global emission mitigation. This disease burden will be disproportionally felt by poor households, where increased vulnerability results in a downward spiral as feedback relationships among disease, poverty, population growth, and environmental degradation reduce adaptive capacity (Bremner, Lopez-Carr et al. 2010).

In such a volatile context, due to their physiological and cognitive immaturity, poor children are at increasing risk to the diseases most likely to be impacted by climate including water or food-borne disease, vector-borne disease, malnutrition, and respiratory problems (Shea and The Committee on Environmental Health 2007; The United Nations Children’s Fund (UNICEF) 2008; Seal and Vasudevan 2011). However, there is little understanding of where these impacts may be most devastating. We hypothesize that one of the most important specific characteristics of a population’s vulnerability to climate change is location, and without a better understanding of vulnerability geographies, the effective targeting of climate change response and public health interventions remains impotent. In this paper we create an integrative measure of exposure and sensitivity components of child health vulnerability to climatic and demographic change for the African continent and identify ‘hot spots’ of high vulnerability. Specifically, we develop and map a novel, spatially explicit, integrative measure of vulnerability to climatic and demographic change of children under five for the African continent at a spatial resolution of 5 square kilometers by piloting a regional-scale analysis of the interplay of these factors in the East African Horn region of Africa. Spatial analysis reveals current clusters, or “hot-spots”, of vulnerability, uncovering heretofore unknown spatial information critical for researchers, policy makers, and the public to visually apprehend and interactively explore the scale, magnitude, and location of possible climate change effects on children’s health in Africa.
II. Conceptual Framework

We define vulnerability as a function of human and societal sensitivity and adaptive capacity when exposed to environmental and climate changes (Yohe and Tol 2002; Turner, Kasperson et al. 2003; Kuriakose 2009). In focusing on a child’s increased risk to climate related disease, we define climate change as an exposure component, while vegetation and demographic change are sensitivity components that may alter a child’s ability to mitigate exposure. Adaptive capacity denotes a system’s ability to adjust, modify or change in response to shock or stress (Brooks, Adger et al. 2005). This paper responds to the need to increase understanding of physical and social change in African ecosystems in order to implement suitably informed adaptive strategies (Thornton, Jones et al. 2011). We expect that, depending on location and multiple interacting system-wide paths, disease vulnerability increases with exposure and sensitivity at increasing rates, while exposure and sensitivity consequently decreases with increased adaptive capacity (Yohe and Tol 2002; Luers, Lobell et al. 2003; Luers 2005). By mapping and analyzing spatial and temporal climatic variability in conjunction with vegetation and demographic change, we aim to enhance our future understanding of the variability in location of factors that best predict vulnerability of children under-five to climate related disease. (Meyerson, Merino et al. 2007; Samson 2011). The identification of emerging at-risk populations is increasingly important in the arena of climate change impacts, mitigation, and adaptation. This issue is particularly important in the context of food security crises that may be avoided if we develop a better understanding of potential predictive factors, effective monitoring, and early warning products and systems. In this paper we conduct an analysis of changes in precipitation and population density at continental scale. This analysis is a critical part of the larger overarching goal of our research to create a continental-scale measure of vulnerability to increased climate variability.

The analysis in this paper allows us to identify broad regions which may become more susceptible to the results of increasing spatial and temporal precipitation variability, thus heightening their populations’ vulnerability to climate change. While calculating a vulnerability index is beyond the scope of this paper, we conceptualize vulnerability as a function of the sensitivity and adaptive capacity of socio-ecological systems when exposed to environmental and climate changes (Turner et al., 2003). This conceptualization allows us to identify regions that are currently affected by observed climate changes and that might be most at risk from potential future impacts. We do so by integrating population
change both as total and under-five children population with a 30-year precipitation change analysis for the African continent to arrive at a rough quantification of potential population vulnerability hotspots.

Data and Methods

This paper presents a continental-scale analysis at the intersection of population and rainfall change as proxies for sensitivity and exposure to climate change and variability. The secondary focus is on prototyping an analysis that expands the population-climate continental analysis into an analysis incorporating vegetation change as a proxy for ecosystem health at a regional scale (East African Horn Region). We highlight areas that show significant drying trends over the last 30 years and correlate those drying trends with vegetation productivity, localized changes in population density, and predicted increases in children under five to 2015. For precipitation change, we identify regions over the entire continent of Africa where significant changes in rainfall have occurred during the growing season within the last 33 years using rainfall data collected by the Famine Early Warning Systems (FEWS) Network. Relative to population density, we focus on regions where significant human population density increases have occurred from the 1990s to 2010. We propose that locations of long-term decreasing trends in precipitation and increasing human population densities represent potential hotspots of population vulnerability to climate changes and inherent food security. Lastly, as a case study for eventual continental scale application, we use continuous vegetation analysis at the regional scale for the East Horn of Africa to observe spatial confluence of decreasing precipitation, population increase, and decreasing vegetation greenness as measured by NDVI. Table 1 presents a comprehensive list of type, source, and temporal/spatial resolutions of the data utilized in the paper.

Table 1: Data used in the pilot study analysis for East Africa

<table>
<thead>
<tr>
<th>Data</th>
<th>Spatial scale</th>
<th>Temporal scale</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean monthly main growing season rainfall</td>
<td>10-km; continental scale</td>
<td>1979-2010</td>
<td>FEWS Net FCLIM interpolation</td>
</tr>
<tr>
<td>eMODIS NDVI, 10-day max. value composites</td>
<td>250-m; continental scale</td>
<td>2001 to 2012</td>
<td>USGS EROS</td>
</tr>
<tr>
<td>AfriPop under-five change</td>
<td>1-km; continental scale</td>
<td>2000, 2005, 2010, 2015</td>
<td>AfriPop.org</td>
</tr>
<tr>
<td>FEWS Net livelihoods zones</td>
<td>Sub-national; 23 African</td>
<td>Various</td>
<td>USAID FEWS Net</td>
</tr>
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An important aim of this paper is to create a methodology to integrate existing data into one interim measure of vulnerability for the African continent. In sum, we aim to identify places with (a) decreasing trends in precipitation, coupled with (b) medium or high population densities, and (c) declining trends in vegetation condition (a proxy for ecosystem health) at a regional scale. Our methods involve three consecutive steps as described below.

1. **Analysis of changes in observed precipitation from 1980 to 2010 for the entire African continent (exposure component).** Changes in precipitation were measured using a blend of available gauge and satellite data to assess the temporal variability and trends in the climate. For the continental-scale analysis, we used the FEWS Net standardized precipitation index (SPI) 0.1 degree spatial resolution data from 1979 to 2010 available at: [http://earlywarning.usgs.gov/fews/africa/web/imagbrowsc2.php?extent=afsp](http://earlywarning.usgs.gov/fews/africa/web/imagbrowsc2.php?extent=afsp). The SPI calculates rainfall anomalies as normalized variables which convey the probabilistic significance of the observed or estimated rainfall in locations where the rainfall regime is not well-understood (McKee 1993). The current SPI dataset for Africa uses the Collaborative Historical African Rainfall Model (CHARM) (Funk, Michaelson et al. 2003) and probability distribution to parameterize historical rainfall amounts (Husak 2007). We used the mean March-April-May SPI data for 1979 to 1998 and 1999 to 2010 to determine the difference between the average growing-season precipitation values in the decade prior to the major 1998 El Nino (Galvin, Boone et al. 2001) and the ensuing, drier decade (Fig. 1).

2. **Analysis of both population density changes from 1990 to 2010 using a combination of population datasets and changes in densities of children under 5 from 2000 to 2015 (sensitivity component).**

First, to calculate changes in overall population changes between 1990 and 2010, we used the Global Rural-Urban Mapping Project (GRUMPv1) population density grids at 30-minute resolution for the years 1990, 1995, and 2000 from the Socio-Economic Data and Applications Center (SEDAC). We also use the 1 km resolution 2010 AfriPop population density dataset created by the University of Florida, the most up-to-date and accurate population density dataset in existence for Africa. We were primarily interested in calculating population density changes from 1990 to 2010. However, the GRUMPv1 and AfriPop datasets have inherently different spatial resolutions which hamper comparative population change estimates. To account for this disparity, we combined the two datasets and calculated
a standardized pixel-by-pixel distribution of population density for the African continent, using population density data from 1990 to 2010 (Eq. 1 and Fig. 2).

\[
\text{Eq. 1}
\]

where \( \varepsilon \) represents a constant value equal to 2 for this calculation.

AfriPop launched the *alpha* version Africa-wide 1km datasets at the beginning of 2012, which contains five-yearly time steps of density data for children under five years old from 2000 including a projection for 2015. The AfriPop demography data is based on a unique combination of the most recent country-specific census data, satellite imagery, and expert knowledge to map settlements and populations, as well as land cover, infrastructure and other geospatially-referenced ancillary data (Tatem and Linard 2011; Linard 2012a). We used this data to calculate a percent change in children under 5 density from 2000 to 2015 (Fig. 3), and to create rule-based classifiers to understand the spatial overlap between changing population and climatic parameters.

3. *Creation of a map of ‘hotspots’ of drying precipitation trends and population change from 1990 to 2010, including a map of hotspots that accounts for percent change in the population of children under five from 2000 to 2015 using high-low thresholds in a dynamic decision-tree classifier framework.*

Building towards an understanding of vulnerability as the confluence of exposure and sensitivity, we integrate the exposure climate product from method 1 with a sensitivity component represented by both overall change in population density and under 5 percent density change from 2000 to 2010 as derived from the AfriPop online database at the 1 square kilometer resolution (Linard, Gilbert et al. 2012). To produce a continental-scale map of likely hotspots of vulnerability defined by drying precipitation trends and increasing population density, we created a decision-tree classifier that was applied in ENVI. The decision-tree classifier (also known as a rule-based classification) was applied sequentially on both the total population and children under 5 population to highlight regions where population in 2010 had increased relative to 1990 by more than 50 people/km\(^2\) for total population (based on GRUMP/AfriPop data), and by more than 50\% for under 5 children, for the period 2000 to 2015. The second rule in the classifier was set using a threshold whereby pixels where decreasing trends
in SPI between 1979 and 2010 of more than -0.5 were observed were classified as high exposure. Once combined, the population and climate data yielded rough ‘hotspots’ that highlight, on the one hand, regions where drying precipitation is being accompanied by increasing human populations, and, on the other, regions where only significant drying trends have been observed over the last 30 years and where the drying trends have not been accompanied by population increases as well.


The eMODIS is a 10-day maximum-value composite at 250m spatial resolution, ideal for near-real time vegetation condition and change monitoring. For this analysis, the images were aggregated to 2.5 km resolution by averaging 10 X 10 blocks of pixels. Dekads 11 to 15 (April 11 – May 31) were averaged to capture the approximate period of peak vegetation response to the spring rains in most of Kenya, southern Ethiopia and Somalia. Eleven seasons (2001-2011) were available for analysis. Linear trends were fit to the 2.5 km pixel data and the resulting maps were used to select larger boxes for further aggregation. Statistical significance of linear trends was determined using a t-test on the regression slope coefficient. There were 12 observations, one for each dekad 11-15 average, so the tests were based on 10 degrees of freedom. Note that while many pixel values went into each spatial/temporal dekad 11-15 average, the averages are all separated from each other by almost a year. The residuals from the trends do not exhibit any clear evidence of autocorrelation on these interannual time scales. We performed this analysis in order to attempt to capture any changes occurring on the ground that are not captured by an analysis of rainfall patterns or population increases and that may suggest other human-induced processes operating on the landscape.

III. Results and Discussion

1. Continental-scale analysis of rainfall trends

A continental map depicting the change in the standardized precipitation index (SPI) between the period 1979-1998 and 1998-2010 is shown in Fig. 1. SPI values greater than zero indicate conditions wetter than the median, while negative SPI values indicate drier than median conditions. The magnitude of change in SPI for Africa during this time period exceeds -0.7, with maximum values of -1.56, which typically indicate severe drought conditions (Funk, Michaelsen et al. 2003) in several main ‘hotspot’
regions including northeastern Egypt, the Eritrean coast, eastern and south-central Ethiopia, throughout the horn region of Somalia, coastal Congo, and much of the inland Democratic Republic of the Congo. Also salient in the analysis are extensive declines in SPI across Rwanda, Burundi, and northwestern Tanzania. Regions with less significant decreases in precipitation over the last 32 years extend across much of central tropical and subtropical Africa, coastal southern Africa (particularly Malawi, Mozambique, South Africa, and Madagascar), and along the west and north African coasts (Fig. 1).

2. Continetal-scale analysis of population trends

Fig. 2 illustrates the corresponding spatial distribution of population density changes from 1990 to 2010, based on the combined GRUMPv1 for 1990 and 2000 and AfriPop 2010 population density estimates (Eq. 1). Spatial coincidence emerges between regions of significant decreasing precipitation trends and high increases in population density over the last 20 years particularly in the Lake Victoria region. A similar convergence is observed along the downstream sections of the Nile, the Nile Delta, the Moroccan coast, and West Africa; especially in Guinea, Sierra Leone, Ivory Coast, Ghana, and extensively in Malawi and Mozambique. Fig. 3 displays change in total under 5 child population between 2000 and 2015 calculated using AfriPop Demography data. A near doubling in 15 years of children under 5 is observed in pockets of the central African rift valley, Darfur, northern Nigeria and eastern Kenya. These are areas that will suffer from continued population momentum over the coming decades, making difficult efforts to curb population growth and thus the size of vulnerable populations exposed to climate change.

3. Continetal-scale analysis of convergence trends of increasing population and decreasing precipitation

Fig. 4 presents areas (in red) where under a rule-based classification whereby population in 2010 had increased relative to 1990 by more than 50 people/km² (based on GRUMP/AfriPop data), and declining trends in SPI precipitation between 1979 and 2010 of more than -0.5 were observed. The areas highlighted in yellow are areas of observed declining SPI precipitation between 1979 and 2010 of more than -0.5. Most of Nigeria, Zimbabwe, and the Lake Victoria basin, and much of the DRC, southern and coastal Mozambique, central southern Sudan and Kenya and central Ethiopia following the fertile rift valley emerge as hot spots of dramatic increasing population density coupled with notable precipitation decline.
Fig. 5 shows areas highlighted in olive of observed declining SPI precipitation between 1979 and 2010 of more than -0.5. Areas in red result from a rule-based classification where under 5 population is projected to increase by 2015 relative to 2000 by more than 50% and declining trends in SPI precipitation between 1979 and 2010 of more than -0.5 were observed. Considerable swaths of central Africa, from Nigeria and Cameroon, through the DRC and encompassing much of central Eastern Africa, the eastern African horn region, greater Cairo and northeast Egypt, southern coastal and eastern central South Africa, Mozambique, and Zimbabwe are all showing significant precipitation declines. Sub-national pockets of Nigeria, the Lake Victoria basin, and selected areas of the east African horn where these trends overlap with at least a 50% projected under 5 population increase between 2000 and 2015.

4. Regional-scale analysis of convergence trends of increasing population and decreasing green vegetation

Because decreased rainfall is imperfectly correlated with changes in vegetation productivity, especially where irrigation is used, it is useful for information on vulnerability in terms of subsistence food security to observe where populations are growing yet crop output appears to be decreasing. Southern Somalia, southern Sudan, the Lake Victoria Basin and the central African rift valley are highlighted in Fig. 6 as having experienced change in vegetation productivity (as measured by the normalized different vegetation index, NDVI) during the main growing season months (April-May) for East Africa from 2001 to 2012. Specifically, Fig. 6 presents the results of a pixel-by-pixel linear trend analysis performed on the growing season mean NDVI from 2001 to 2012. Strikingly, in parallel with drying precipitation trends along the 36-40° longitude band for East Africa (Fig. 1), a longitudinal band of vegetation browning is observed as well, extending over much of the pastoralist and rainfed agricultural lands in Kenya, Ethiopia and Somalia. The band of consistent NDVI declines extends farther north into Ethiopia, affecting both the pastoralist an agro-pastoralist regions in the southern part of the country, as well as areas used primarily for farming. Significant vegetation declines are also highlighted along the southern half of the Somali coast, an area mainly used for agro-pastoralism but where farming and population densities have been expanding.
Fig. 1. Change in the Standardized Precipitation Index (SPI) between 1979 and 2010.
Fig. 2. Total population change from 1990 to 2010 calculated using GRUMPv1 and AfriPop total population data.
Fig. 3. Change in total under 5 child population between 2000 and 2015 calculated using AfriPop Demography data.
Fig. 4. Map of Africa showing areas (in red) where population in 2010 had increased relative to 1990 by more than 50 people/km² and declining trends in SPI precipitation between 1979 and 2010 of more than -0.5 were observed. The areas highlighted in yellow are areas of observed declining SPI precipitation between 1979 and 2010 of more than -0.5.
Fig. 5. Map of Africa showing areas (in red) where under 5 population is projected to increase by 2015 relative to 2000 by more than 50% and declining trends in SPI precipitation between 1979 and 2010 of more than -0.5 were observed. The areas highlighted in olive are areas of observed declining SPI precipitation between 1979 and 2010 of more than -0.5.
Fig. 6. Change in vegetation productivity (as measured by the normalized different vegetation index, NDVI) for the main growing season months (April-May) for East Africa from 2001 to 2012.

Fig. 7. Change in children under five and drying trends.
IV. Conclusions and Future Work

Locations where prolonged precipitation decline attends increasing human population densities represent hotspots of high population vulnerability to climate changes and food insecurity. In this paper we identify regions of significant drying trends over the last 30 years and correlate those drying trends with vegetation productivity and more localized changes in population density and predicted increases in children under five to 2015. Results demonstrate that a near doubling of the population in some areas (such as the East African Horn) is linked with hotspots of degradation in vegetation condition, but that the most significant land cover change and vegetation degradation trends are observed in areas experiencing drying precipitation trends in addition to increasing population pressures. Importantly, and not measured here, these coupled trends of fast growing populations, and dramatic drying trends are located in some of the globe’s most destitute areas on the globe’s poorest continent. People located in the regions highlighted in this analysis, particularly central, southern, and eastern Africa are not only highly exposed to climate change through more people on land with less rainfall but they are also among the most socio-economically marginalized, with extremely low mean annual earnings and poor to absent educational and alternative employment possibilities.

Further results developed based on the continental-scale analysis will provide estimates and locations of future numbers of children vulnerable to climate change-related disease and in contributing to enhancing our understanding of local adaptation needs and mitigation mechanisms to current and future environmental change. Based on our preliminary analysis (Fig. 7), we have identified a second highly likely location for another more detailed study – the Lake Victoria region in East Africa comprised of northeastern Tanzania, eastern Kenya and southern Uganda. Fig. 7 shows the percent increases in under-five children between 2000 and 2015 based on AfriPop’s demography dataset at the continental scale, as well as an inset showing drying trends based on observed satellite and station rainfall measured as the difference between 1979-1998 and 1999-2010 standardized precipitation index. This highly populated region is repeatedly subjected to the effects of recurrent droughts and flooding associated with increasing rainfall variability and the associated detrimental effects of human health, especially malaria and diarrhea (Olago, Marshall et al. 2007).

We expect to create a product that will assist in identifying where children are vulnerable to climate related disease based on observed trends in rainfall variability, vegetation degradation, and increases in under-five density over the last decade. Given its continental scale and computational ease, this product will be highly transferable, making it ideal for sharing with relevant stakeholders and
researchers. The final implementation can be performed in the free statistical package R, thus allowing us to share the model so that it can be downscaled and modified to fit specific needs at various spatial scales. A potential pitfall might be represented by gaps in the spatial coverage of our climate or NDVI datasets (due to lack of coverage of rainfall stations or oversaturation in the case of NDVI), reconcilable through data interpolation. Finally, we expect to produce a highly usable hot spot map of the vulnerability classifications, with distinct regions represented by different vulnerability types, allowing for enhanced understanding of where social and physical processes are impacting vulnerability. The hot spot map will be continental, but more importantly, regions of interest will be observable at 5 kilometer resolution.

We envision the results of our work to have a direct impact on coupled human-environment theory. The richness of our integrated human and environmental data at a continental scale is rare today but we believe that it represents the future of integrated geographical, climate, environmental, and sociological research. The tools and products we develop will be made available to researchers and practitioners globally. Lastly, we hope our results can be used immediately by national and international development agencies to help save people’s lives in the short term and to foster a more sustainable human development under the threat of continued climate change in Africa.
References


