The climate-population nexus in the East African Horn: Emerging degradation trends in rangeland and pastoral livelihood zones

Narcisa G. Pricope a,*, Gregory Husak b, David Lopez-Carr b, Christopher Funk c, Joel Michelsen b

a Department of Geography and Geology, University of North Carolina Wilmington, DeLoach Hall, DL 104, 601 South College Road, Wilmington, NC 28403-5944, United States
b Department of Geography, University of California Santa Barbara, 1832 Ellison Hall, Santa Barbara, CA 93106-4060, United States
c United States Geological Survey, University of California Santa Barbara, 1832 Ellison Hall, Santa Barbara, CA 93106-4060, United States

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A B S T R A C T
Increasing climate variability and extreme weather conditions along with declining trends in both rainfall and temperature represent major risk factors affecting agricultural production and food security in many regions of the world. The rangelands of Ethiopia, Kenya, and Somalia in the East African Horn remain one of the world’s most food insecure regions, yet have substantially increasing human populations predominantly dependent on pastoralist and agro-pastoralist livelihoods. We identify regions where substantial rainfall decrease between two periods interrupted by the 1998 El Nino event (1981–2012) in the East African Horn is coupled with human population density increases. Vegetation in this region is characterized by a variable mosaic of land covers, generally dominated by grasslands necessary for agro-pastoralism, interspersed by woody vegetation. Recent assessments indicate that vegetation degradation is occurring, adversely impacting fragile ecosystems and human livelihoods. Using AVHRR and MODIS vegetation products from 1981 to 2012, we observe changes in vegetation patterns and productivity over the last decade across the East African Horn. We observe vegetation browning trends in areas experiencing reduced main-growing season precipitation; these areas are also concurrently experiencing increasing population pressures. We also found that the drying precipitation patterns only partially statistically explain the vegetation browning trends, indicating that other factors such as population pressures and land use changes might be responsible for the observed declining vegetation condition. Furthermore, we show that the general vegetation browning trends persist even during years with normal rainfall conditions such as 2012, pointing to potential long-term degradation of rangelands on which approximately 10 million people depend. These findings may have implications for current and future regional food security monitoring and forecasting as well as for mitigation and adaptation strategies in a region where population is expected to continue increasing against a backdrop of drying climate trends and increased climatic variability.

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1. Introduction

The African continent is identified in most climate-change predictions as potentially the world’s most vulnerable populated region, exacerbating recurring droughts and crop failures, water scarcity, and disease burden. Increasing climate variability and extreme weather conditions, especially in the context of declining and more irregular precipitation in some regions (Cooper et al., 2008; Verdin et al., 2005; Durack et al., 2012), are considered major risk factors affecting agricultural production and food security in many African countries in the coming decades (Haile, 2005; Christensen et al., 2007). The largest potential impacts are likely to be felt in smallholder systems with reduced adaptive capacity, which are primarily dependent on rainfall, are largely ineffective yield-wise, and apply low levels of agricultural inputs (Muller et al., 2011). Boko et al. (2007) estimate that by 2050, yields from Africa’s rainfed farm production could decrease by 50 percent as a result of changes in climatic conditions. Moreover, many semi-arid regions throughout Africa, primarily rangelands, pastoral and agro-pastoral, on which millions of people depend for their livelihoods, are changing at a rapidly increasing rate.

The Millennium Ecosystem Assessment (Assessment, 2005) predicts that by 2050 land use and land cover changes (LULCC) will be a more significant driver of ecosystem change and biodiversity loss than climate change by a factor of 4 in Africa. Furthermore, the IPCC’s most recent report emphasizes that adaptability to climatic
change, especially among rural, subsistence-based communities, will be determined by the health of the ecosystem; which in turn is closely related to the policies and cultural practices governing resource use. Many studies in Africa point to increasing environmental and vegetation degradation due to human activities and climate change (Kassahun et al., 2008a; Roba and Oba, 2009b; Brink and Eva, 2011; Solomon et al., 2007a; Gemedo-Dalle, 2006). Even when people have adapted to changes and the harshness of these highly variable environmental conditions through the generations (Fratkin, 2001), in light ongoing rates of environmental changes and continued population increases, their ability to adapt may become threatened (Collier et al., 2008; Holmgren and Öberg, 2006; Samson et al., 2011). Understanding the extent and effects of climatic and LULC changes on livelihoods and, indirectly, adaptive capacity at regional and local scales has never been more important given that almost 50% of the Earth’s natural ecosystems have already undergone some type of alteration (Barnosky et al., 2012).

The East African Horn region, comprised primarily of Ethiopia, Kenya, and Somalia, as well as parts of Southern Sudan, Sudan, and northern Tanzania and Uganda, is one of the world’s most food insecure regions with increasing human populations that are highly dependent on the natural resource base for their livelihoods. Pastoralism constitutes the major land use in the drylands of the East African Horn (EH) region (Ericksen and Herrero, 2011). It is a diverse and dynamic livelihood system well adapted to dryland environments, typically characterized by unstable and scarce resources and particularly vulnerable to food insecurity (Ced Hesse, 2006; Thornton et al., 2003). Drylands, defined as areas receiving less than 600 mm rainfall a year, are already regions of high human vulnerability to perturbation and environmental variability. They are systems of low biological productivity covering approximately 40 percent of the Earth’s surface and providing home to over 2 billion people, more than 90 percent of whom live in developing countries and 1.1 billion of whom live in Africa. About half of the drylands population in East Africa lives below or close to the poverty line and recent regional assessments indicate that poverty is continuously increasing (Kassahun et al., 2008b; Ericksen and Herrero, 2011). Population growth in this region is also unusually high, paired with some of the highest infant mortality rates in the world, ranging from ~150 to 180 per 1000 live births (CIESIN, 2005).

Despite a lack of recent and inclusive global assessment of the state of drylands and the pastoral livelihoods they support, various regional studies in Africa indicate they are changing fast and facing increased degradation, primarily due to fragmentation, over-exploitation, climate change, and climate variability (Galvin, 2009; Munyati and Makgale, 2009; Brink and Eva, 2011). Degradation is defined differently depending on the specific context and location of occurrence but typically refers to a system shifting from a biologically productive state to an unproductive state (Huber-Sannwald et al., 2006). Despite some controversy on driving mechanisms of vegetation degradation in arid and semi-arid areas with typically unpredictable rainfall patterns (Herrmann et al., 2005; Herrmann and Hutchinson, 2005), climate variation and human activities are usually identified as the main underlying causes (Geist and Lambin, 2004; Reynolds et al., 2007). Extensive work in East Africa indicates an overall reduction in rainfall during the main and secondary rainy seasons, accompanied by an increase in the spatial and temporal variability of precipitation that is associated with changes in sea-surface temperature in both the Indian and Pacific Oceans (Williams and Funk, 2011; Lyon and Dewitt, 2012). Increasing spatio-temporal variability of precipitation (expressed in unreliable onset, duration, and intensity of rains and more frequent occurrence of dry spells during the growing periods; Speranza et al., 2008) is the most important factor driving and maintaining chronic food insecurity in the East Africa Horn region. Even during non-drought conditions, a very high proportion of EAH households face various forms of food insecurity (Messelhorn, 2005).

The climatic feedback loop in the dryland pastoralist regions of the East Africa Horn, despite being still relatively poorly understood, is complex, with implications far beyond the region. Decreasing trends in precipitation and increasing climatic variability can have direct impacts on vegetation productivity. This in turn leads to the creation of a positive feedback mechanism between decreasing vegetation cover and a further decrease in precipitation due to increasing albedo, corresponding radiative cooling of the overlying air, and a subsequent enhancement of large-scale atmospheric subsidence (Oyama and Nobre, 2003). Furthermore, ongoing vegetation clearing and degradation might contribute to increases in temperatures and wind speeds and decreases in precipitation and relative humidity, thus creating warmer and drier climates; which, in turn, might contribute to tree cover loss, vegetation degradation, increasing population vulnerability, and food insecurity, particularly in pastoral dryland regions (Hoffmann et al., 2002). For instance, recurring drought (combined with population growth and land tenure/policy changes) has been linked to land use/land cover changes in the central Rift Valley, Ethiopia as farmers have shifted from predominantly pastoral livelihoods to a crop-livestock mixed farming system, thereby better strategy to reduce vulnerability to drought (Biazin and Sterk, 2013); similar patterns were observed in the northeastern Afar Rangelands of Ethiopia (Tsagaye et al., 2010).

The identification of emerging at-risk populations is increasingly important in the arena of climate change impacts, mitigation, and adaptation, especially for our region of focus. This issue is particularly important in the context of food security crises that can be virtually avoided if we develop a better understanding of potential predictive factors, effective monitoring, and early warning products and systems (Thornton et al., 2011). In this paper, we address the spatial interplay between climate, vegetation change and degradation, and population density changes to create a regional assessment of the state and trends of the East Africa Horn’s pastoral and agro-pastoral livelihoods zones. While there is a number of disparate, small-scale studies addressing some of these components in the region (Brink and Eva, 2011; Reid et al., 2000; Serneels et al., 2001; Vanacker et al., 2005; Kiage et al., 2007), the majority of work is either anachronistic or remains based on fairly location-specific survey data (Abule et al., 2005; Desta and Coppock, 2004; Luseno et al., 2003). This paper represents the first attempt to provide a regional-scale, cross-country assessment of recent population, climate, and vegetation degradation dynamics at a multi-national scale. We focus on identifying regions where changes in the spatial distribution of main growing season rainfall (May–June) have occurred over the last 33 years using a high resolution climate dataset (5 km²) created by the Climate Hazards Group at University of California Santa Barbara and which has already proved to be a key component for early warning systems and climate vulnerability analyses (Funk et al., 2012; Hoell et al., 2013). In places like Eastern Africa, where complex topography produces extremely steep rainfall gradients on ten-kilometer scales, high resolution rainfall mapping is a critical component of effective risk management. We also determine the relative human population density increases that have occurred in this region from the 1990s to 2010 using a combination of gridded population products. We propose that locations where negative changes in precipitation observed during the main growing season occur coincidently with increasing human population densities represent potential hotspots of population vulnerability to climate changes and inherent food insecurity, thus warranting further investigation.
Secondly, we use continuous and categorical vegetation analyses at the regional scale for EAH pastoral and agro-pastoral livelihoods zones to assess if precipitation decline patterns and population increases overlap with areas of vegetation transitions and changes, as well as long-term decreasing trends in vegetation greenness and productivity, as measured by NDVI analyses from 1981 onwards. Additionally, we were interested in determining whether frequently available moderate-resolution satellite-derived vegetation products can be effectively used in on-going food security monitoring efforts in East Africa. Given their high temporal resolution and wide availability, moderate resolution satellite-derived vegetation products such as the 500 m MODIS land cover type dataset (MOD12Q1) or the 250 m expedites MODIS NDVI product recently produced by the United States Geological Survey (USGS) are suitable for performing regional-scale analyses of vegetation change and degradation (Friedl et al., 2010; Lunetta et al., 2006) and offer great promise for empowering on-going monitoring efforts, especially when used in conjunction with longer timeframe data such as the AVHRR 1981 to 2011 Global Inventory Monitoring and Modeling System (GIMMS) NDVI third generation dataset.

2. Materials and methods

2.1. Study area

The analyses presented in this paper were performed at two spatially nested geographic scales: the larger East African Horn region, with a focus primarily on the pastoral and agro-pastoral areas around Kenya, Somalia, and Ethiopia, broadly corresponding to the Somalia-Masai ecological region as originally defined by White (1983). The elevation in the EAH region ranges from a little over 5000 m, at the heart of the Eastern Afromontane Biodiversity Conservation Hotspot region, to sea level along the coasts. The climate, with the exception of the Ethiopian highlands, is generally characterized by a bi-modal precipitation regime with mean annual precipitation values between 150 and 550 mm/year. The main mechanisms that drive rainfall patterns include the intertropical convergence zone (ITCZ), effects of El Niño Southern Oscillation (ENSO), and sea surface temperatures in the Indian and Atlantic Oceans (Nicholson, 1997; Nash and Endfield, 2008; Mason, 2001). The high variability of the intra-annual rainfall distribution is the main constraint for vegetation growth. Generally, the vegetation of the EAH is mirrored in the climatic patterns.

The vegetation is characterized by a highly variable mosaic of land covers, ranging from forest to desert ecosystems, but generally dominated by grasslands interspersed by woody vegetation, especially in the drier rangelands of the EAH. It is difficult to identify precise limits on the system, as the transition into pure grassland versus forest occurs along a continuous gradient of change; this gradient makes mapping land covers in this region especially difficult. These spatial and temporal landscape patterns result from complex, dynamic interactions among climate, soils, fire, herbivory, and geomorphologic conditions (Skarpe, 1992; Roques et al., 2001; Archer et al., 1995). Human activities such as logging, clearing for cropland, shifting cultivation practices, increasing livestock stocking rates, and fire suppression have also influenced the complex interactions and changes occurring in the region (van Wilgen et al., 1997). While research on land cover change and rangeland degradation for the EAH region remains relatively limited, studies point to increasing environmental and rangeland degradation (Kassahun et al., 2008b; Roba and Oba, 2009a; Brink and Eva, 2011; Solomon et al., 2007b; Gemedo et al., 2006). A large proportion of these studies are based on longitudinal household or village-level survey data and occasionally incorporate snapshots of field-based ecological data. However, they do not provide an inclusive, regional assessment of actual hotspots of rangeland degradation for a region repeatedly subjected to recurring droughts and food crises (Kassahun et al., 2008b; Roba and Oba, 2009a; Thornton et al., 2009; Tsegaye et al., 2010). Recent work also shows that this area is especially susceptible to environmentally driven pastoral conflicts which are linked to the increasing rainfall variability and decreased land availability associated with rangeland degradation (Meier et al., 2007). Additionally, some sources cite elevated levels of rangelands degradation such that cattle are no longer viable and are becoming replaced with camels by subsistence pastoralists (Kassahun et al., 2008a,c). The need for an integrated regional-scale assessment centered on the pastoralist and agro-pastoralist regions of the EAH has never been greater, given the fragility of these ecosystems and the socio-economic burdens imposed by observed climate change impacts.

2.2. Precipitation data

High resolution climate information (~0.05°/5 km²) has been recognized as a key component of early warning systems and climate vulnerability analyses (Brown, 2008). In places like Eastern Africa, where complex topography produces extremely steep rainfall gradients on ten-kilometer scales, high-resolution rainfall mapping is a critical component of effective risk management (Hoell et al., 2013). We used two different precipitation datasets in the analysis, one that provided a longer time series and a second station-based, regional precipitation dataset that matched the temporal scale of the vegetation condition analysis from 2001 to 2012. For the longer-time scale dataset that is available back to 1981, we used the Climate Hazards Group IR Precipitation with Stations (CHIRPS) dataset that blends long-term monthly means, geostationary infrared satellite observations and available station-based precipitation observations. The monthly mean fields are derived for each month using a local regression model based on station data, Tropical Rainfall Monitoring Mission (TRMM) records (Huffman et al., 2009; Joyce et al., 2004), elevation and latitude and longitude (Funk et al., 2012). At each location the 12 monthly means were disaggregated into 72 pentads capturing the anticipated annual cycle. CHIRPS is derived from geostationary infrared satellite observations (Janowiak et al., 2001; Knapp, 2012) that are converted to precipitation estimates. The percent of normal (satellite estimate divided by satellite mean) is multiplied by the station-based means at the pentadal timescale to arrive at an unbiased satellite estimate. A pentad is defined as a unit of time consisting of roughly five calendar days. After this step, station observations are blended in to adjust the previous estimates and tie them to known rainfall amounts. These blended results are then constrained to the blended means that match the station-based means. The result is a consistent rainfall dataset from 1981 to 2012 at pentadal temporal scale, with quasi-global spatial extent and 0.05-degree spatial resolution. The CHIRPS data and additional documentation is freely available from the Climate Hazards Group website (http://chg.geog.ucsb.edu/).

Next, we calculated a standardized precipitation index (SPI) from the CHIRPS data for the main growing season months based on March–April–May–June for the EAH to obtain the best representation of the northward progression of the ITCZ into Ethiopia. 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 et al. (1993). We used the mean MAMJ SPI data for 1981–1998 and 1998–2011 to determine the difference between the average growing-season precipitation values in the decade prior to the major 1998 El Niño (Galvin et al., 2001) and the ensuing, drier decade and applied a t-test difference
of means to show only statistically significant areas where precipitation changed between the two periods. The justification for the 1981–1998 versus 1999–2011 partitioning is based on three papers detailing a substantial shift (Lyon and Dewitt, 2012; Funk, 2012) in the Indo-Western Pacific circulation after 1998. Sea surface temperatures (SST) and precipitation in the Indo-Western Pacific (155–15N, 60–170E) increased dramatically (Lyon and Dewitt, 2012; Hoell et al., 2013) and it has been suggested that these increases can help explain the 2011 East African drought that led to widespread famine (Lyon and Dewitt, 2012; Lott et al., 2013) and the increased frequency of drought in East Africa in recent years (Funk, 2012). A detailed examination of the latest phase 5 Coupled Model Intercomparison Model Project (CMIP5) simulations and a suite of climate reanalyses indicate that this recent warming is exacerbated by the coupled models. Observations indicate, however, that the 1999–2011 period is associated with an exceptionally strong western-to-central tropical Pacific SST gradient, increased western Pacific sea level heights, and an intensification of the Walker circulation. The interaction of strong gradient events and ENSO enhances the impact of La Nina events in Africa (Williams et al., 2011; Hoell and Funk, 2012) and supports the threshold we used to analyze drying trends in Africa relative to the 1998 event.

The precipitation dataset used for the regional-scale analysis was represented by the Rainfall Estimate (RFE2) dataset, which combines data from three satellite datasets linearly and uses station data to remove systematic bias for the estimation process (Brown, 2008). The National Oceanic and Atmospheric Administration (NOAA) satellite rainfall estimate (RFE2) blends cloud top temperature information measured by geostationary satellites, passive microwave data and available rainfall data from the Global Telecommunication System (GTS) network to create a 0.1-degree rainfall estimate for the continent of Africa, every day with only a few hours of latency (Xie and Arkin, 1997). While the RFE2 suffers from bias in areas of complex terrain, it outperforms many other rainfall estimates in areas without much topography (Dinku et al., 2008) as is the case for much of the continent. This rainfall product has been used to track crop water deficits (Funk and Verdin, 2009), drive crop water balance models (Senay and Verdin, 2003), and has been widely used to monitor food security in Africa (Tadross et al., 2005; Verdin et al., 2005; Tadesse et al., 2008; Sawunyama and Hughes, 2008). A pixel-by-pixel linear trend was fitted to growing-season (March–April–May) z-scored precipitation estimates from 2000 to 2012 and used in regression analyses with eMODIS NDVI data (see Section 2.6).

2.3. FEWS Net Livelihoods zones data

The livelihood zones data for Kenya, Ethiopia, and Somalia were downloaded from the FEWS Net and are available at: http://www.fews.net/pages/livelihoods-products.aspx?b=n. Livelihood zones are defined as areas where people share broadly the same pattern of livelihood, including options for obtaining food and income as well as market opportunities. Livelihood zoning informs food security analysis and assistance via spatial targeting of priority concern areas. It provides the basis for identifying geographically relevant food security monitoring indicators. Finally, it provides a sampling frame for on-the-ground assessments and assistance targeting. Livelihood patterns are primarily influenced by local factors such as climate, soil, water availability, infrastructure, social networks, and access to markets (FEWS Report 2009). Fig. 1a presents the EAH region livelihood patterns distribution in aggregated form (farming, pastoral and agro-pastoral) for the three countries.

2.4. Population density data

We used the Global Rural-Urban Mapping Project (GRUMPv1) from the Socio-Economic Data and Applications Center (SEDAC) population density grids at 30 in. resolution for the years 1990, 1995, and 2000. We also obtained 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 hampered 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. 1b).

\[
\frac{(\text{GRUMP2000} + e)}{(\text{GRUMP1990} + e)} \times \text{Afr}i\text{Po}p\text{p}2010
\]  

(1)

where e represents a constant value used to avoid division by 0 in the denominator. Finally, as we were interested in an estimate of both past and future population increases for areas that the above datasets do not provide, we downloaded the Gridded Population of the World (GPWv3) population density grid data from SEDAC at 2.5’ spatial resolution for the six time steps available, from 1990 to 2015 and calculated the mean population density for each time step in the data for aggregated regions where we identified substantial drying patterns or vegetation changes.

2.5. Land cover change and transition analyses using the MOD12Q1 product

We obtained the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover type product (MOD12Q1) from the combined NASA’s Terra and Aqua satellites, currently available from 2001 to 2009. We used the Collection 5 yearly level-3 500 m sinusoidal grid product which incorporates five different land cover classification schemes, derived through a supervised decision-tree classification method. We chose the first and most widely used classification scheme, the International Geosphere Biosphere Programme (IGBP), which includes 17 land cover classes: 11 natural vegetation classes, 3 developed and mosaicked land classes, and 3 non-vegetated land classes. We use six MODIS tiles to cover our study area for each year starting from 2001 to 2009, mosaicked and reprojected them, then performed image reclassifications to merge the original 17 classes into thirteen new classes by merging the five forested classes in the IGBP classification into a single forest class.

Despite the potential loss of resolution, we further reduced the number of classes in the IGBP classification based primarily on spectral separability between the different classes previously established for this region (Mahiny et al., 2013). We further used biogeographic, topographic, and edaphic characteristics based on geospatial data overlays and expert knowledge. The result was seven main classes: water and barren, forest (the new class included classes 2 through 5 of the IGBP classification and class 8 represented by woody savanna), shrub (containing the open and closed shrublands original classes), savanna (only class 9, savanna in the original classification), grassland (original classification class 10), crop (the cropland and cropland/natural vegetation mosaic classes), and an urban class (Fig. 2). Of the seven new classes thus aggregated from the original IGBP data, we have the least amount of confidence in our new forest class given the high amount of class mixing and inherently different responses to degradation in forests (usually associated with wood extraction) vs. degradation in...
woody savannas (often associated with shrub encroachment due to overgrazing, drying or changing fire regimes). However, this aggregation does not affect the results of this work as our main focus is on understanding the links between land cover transitions, precipitation, population and vegetation browning mainly in pastoral and agro-pastoral regions of the EAH for which we are using the original IGBP classes.

In order to smooth sparse individual pixels in the different land cover classes and rescale the 500 m data to 2.5 km data to match our other datasets, we applied a $5 \times 5$ average window on each class and generated a series of counts of pixels classified as a given class within that window. This resulted in a dataset of pixel counts for each of the seven land cover classes in such a way that, if the value of the resulting pixel was 25, the aggregated land cover type pixels in each $5 \times 5$ window (the 2.5-km resolution weighted average resulting pixel) represented a ground cover of 100 percent of that given class. This approach was employed to minimize the amount of speckling and potential classification errors in the MODIS land cover data, which might have been introduced as a result of the relatively sparse validation dataset for the decision tree classification algorithm in East Africa, despite considerable improvements in the Collection 5 land cover product (Friedl et al., 2010). This unique spatial averaging of land cover pixels allows us to focus our analysis on those regions where pixels are consistently through time and space assigned to a certain land cover class.

The frequency of pixels (counts) of a given class within a 2.5 km aggregated pixel was subsequently used to determine the relative stability of each class through the time series by creating measures of dispersion and variance, and by calculating land cover change trajectories. Our land cover change trajectories were calculated by taking the $5 \times 5$ spatial pixel counts for each class for the years 2001, 2002, and 2003 and subtracting those from the $5 \times 5$ spatial means for the last three years in the analysis (2007, 2008, and 2009). A similar approach has been used successfully for extracting large-scale land cover change information from the MOD12Q1 data in Ethiopia (Mahiny et al., 2013), but few studies in the literature use this data for regional-scale analyses of land cover change. Due to the regional scale of our analysis, the lack of appropriate resolution ground validation data, and known issues related to assessing change in land covers with this product, the objective of using the MOD12Q1 product was primarily to identify candidate land cover change areas that could then be used to guide and support the eMODIS NDVI time-series analysis discussed in the next section.

**2.6. AVHRR GIMMS and eMODIS Normalized Difference Vegetation Index (NDVI) data**

NDVI-based change analyses yield information about ground parameters, such as percent of ground cover, photosynthetic activity of the plant leaf area index, and the amount of biomass (Running and Nemani, 1988; Goetz et al., 1999; Wijaya et al., 2010). To match the temporal resolution of our climate data (Section 2.2), we use two NDVI datasets: a coarser-resolution (8 km) dataset available from 1981 to 2011 and a dataset at 250 m spatial resolution processed and made available by the USGS every 10 days, available starting in 2001 to present.

Firstly, we used the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) Global Inventory Modeling and Mapping Studies 3rd generation (GIMMS3g) NDVI 15-day composite 8 km resolution product for 1981–2011 to assess changes in vegetation productivity. The first generation of NDVI data from AVHRR sensors onboard NOAA 7 to 14 series of satellites were processed by the GIMMS group to a consistent time series of NDVI and is already available to the research community (Tucker et al., 2005). This latest version, termed the third generation NDVI data set (GIMMS NDVI3g) was just recently produced for the period July 1981 to December 2011 based on AVHRR sensor data from the NOAA 7 to 18 satellites. This dataset has improved data quality over the previous one by virtue of being calibrated to the Sea-Viewing Wide-Field-of-View Sensor, as opposed to earlier versions of GIMMS NDVI data sets that were...
based on inter-calibration with the SPOT sensor (Zhu et al., 2013). Furthermore, the NDVI3g is corrected to account for factors that do not relate to changes in vegetation greenness and applies an improved cloud masking algorithm as compared to older versions of the GIMMS dataset (Vrieling et al., 2013). The third generation GIMMS dataset is only available until 2011. The availability of this new improved NDVI3g data set and its temporal overlap with the CHIRPS precipitation dataset has allowed us to analyze them correlative (Fig. 3). Work by Fensholt et al. (2013) has shown that there must be a significant positive linear correlation between annual precipitation and the vegetation condition proxy considered. The CHIRPS data was resampled to match the GIMMS data using a bilinear resampling algorithm (Herrmann et al., 2005). The per-pixel strength of linear association between the two datasets was determined by calculating the Pearson product moment correlation coefficient (r) for the 30-year time series of observations (1981–2011).

Secondly, to obtain higher-resolution (both spatially and temporally) data on post-2000 changes in vegetation condition, we supplemented our analysis of land cover changes based on the MODIS IGBP land cover data and the AVHRR GIMMS with eMODIS NDVI-based decadal trend analyses to identify regions of anomalous vegetation browning over the last decade. The eMODIS NDVI data were processed at the United States Geological Survey (USGS).
and are available at: http://earlywarning.usgs.gov/fews/africa/web/jimgbrowsc2.php?extent=wazd. The data are originally processed at 250 m resolution from corrected MODIS L1B Terra surface reflectances. The NDVI values are produced using a weighted least squares temporal smoothing algorithm (Swets et al., 1999) to correct for clouds and other atmospheric contamination. Data are available for the period 2001 to the present and are aggregated into dekads (10-day intervals). There are three dekads in a calendar month: the first ten days of a month constitute the first dekad of the month, the second ten days – second dekad of the month, and the remaining days (8 to 11 days, depending on the month) constitute the third dekad.

We used the eMODIS NDVI data for two purposes in this paper: (1) primarily to determine if the regions with shifting land covers show a change in vegetation greenness over the same time period as well and (2) to explore the statistical relationship between rainfall and NDVI and determine how much of the NDVI trend is explained by changes in rainfall. Thus, to match the spatial scale of the MOD12Q-based land cover analysis (5 × 5 pixels), the NDVI images were aggregated to 2.5 km resolution by averaging 10 × 10 blocks of pixels. Dekads 11–15 (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. The time series for each pixel within the specified latitude and longitude boxes were averaged together, then linear trends were fit to the dekad 11–15 averages for the spatial box averages. Statistical significance of linear trends was determined using a t-test on the regression slope coefficient. There 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.

To accomplish our secondary goal of establishing the statistical relationship between rainfall and NDVI for the main growing season for the EAH, we ran linear regression models based on calculated dekad 10–14 NDVI averages and dekad 7–11 RFE2 totals for the 2001–2012 period. To match the RFE2 spatial resolution, we aggregated the NDVI images to 0.1 degree resolution then fit linear trends to the NDVI averages and selected contiguous regions with browning trends larger than –0.1/decade. We calculated average NDVI and RFE2 values within geographically defined boxes covering each browning region and, for each of these boxes, we fit linear regressions with dekad 7–11 RFE2 predicting dekad 10–14 NDVI. Finally, we added a linear trend term to the regression to determine the magnitude and statistical significance of the component of the browning trend not explained by decreasing precipitation trends.

3. Results and discussion

3.1. The East African Horn region: the regional livelihoods, population, climate and vegetation context

The last half a century has seen a considerable increase in human population numbers across the world. Many Africa countries have recorded unprecedented spikes in population since the 1960s. For example, Kenya’s population has grown by 400 percent since 1960, while Somalia and Ethiopia’s by 232 and 268 percent, respectively. All three countries have average annual growth rates above 2 percent (Table 1). Ethiopia has the highest overall population density of the three countries (>80 people/km²), while Somalia has a relatively low population density, with the majority of its population living in close proximity to the Indian Ocean coast.

Spatially, EAH population distribution appears strongly correlated with livelihoods zones (Fig. 1a and b). As expected, the largest proportion of the population in all three countries lives in farming regions, with smaller percentages in the pastoral and agro-pastoral livelihood zones. Even though the pastoral and agro-pastoral land uses in Kenya comprise over 60 percent of the total area of the country, only 15 percent of the total population resides in these regions. About 50 percent of the total population is concentrated in the high and medium potential farming regions and another 20 percent in the marginal farming areas of Kenya. In Ethiopia, on the other hand, 85 percent of the population in 2010 lived in farming livelihood zones that occupy about 50 percent of the total surface of the country, while 11 percent of the population lives in pastoral and agro-pastoral land uses which occupy 30 and 15 percent of the total country area respectively. The largest pastoral habitat in Ethiopia, known as the Somali Regional State, is classified as rangelands in proportion of 90 percent; of the estimated 4 million inhabitants of this territory, about 80 percent are classified as mobile pastoralists, 10 percent as agro-pastoralists, and 5 percent as permanent settlers (Kassahun et al., 2008b). Since pastoralist and agro-pastoralist livelihoods occupy the majority of the area and are experiencing significant population increases forecasted to increase in the coming years (Gridded Population of the World 2015 statistics), we focus our analysis on these regions.

In order to create a regional-scale assessment of vegetation degradation in relation to changes in population and precipitation, we chose the MOD12Q1 data and aggregated the original seventeen classes to seven major classes of interest (Fig. 2). The majority of the study area is covered by the shrubland cover class (aggregated from the original IGBP open and closed shrubland classes). This class is characterized by lands with woody vegetation that does not exceed 2 m tall, with either deciduous or evergreen foliage and a canopy cover greater than 10 percent (10–60 percent for the original open shrubland class and >60 percent for the closed shrublands). Second in spatial land cover extent for the EAH region is grassland (here based on the original IGBP class extent, without any merging) representing lands with herbaceous types of cover with tree or shrub cover not exceeding 10 percent. The savanna land cover class is described in the IGBP classifications lands with mostly herbaceous or other understory cover types with trees exceeding 2 m in height and a canopy closure between 10 and 30 percent. Within the three countries in the EAH, the largest patch of savanna is in northwestern Ethiopia, followed by a sparse coverage along the Somali coast. Because we have included the woody savanna land cover class in our definition of forest for this analysis (based on topographic, edaphic, and climatic considerations), the spatial extent of this class might be slightly misleading. However, most of our analysis is focused on the rangelands and pastoral regions in the EAH region and we are not directly

| Country-level statistics on total population (1960–2010), percent population increase (1960–2010), mean population density and mean growth rate (2010) for the three countries in our study area. |
|-----------------|----------|----------|----------|
| **Kenya**       | **Somalia** | **Ethiopia** |
| Total pop. 1960 (millions) | 8.1 | 2.81 | 22.55 |
| Total pop. 1980 | 16.2 | 6.43 | 35.42 |
| Total pop. 1990 | 23.4 | 6.59 | 48.33 |
| Total pop. 2000 | 31.25 | 7.39 | 65.57 |
| Total pop. 2010 | 40.5 | 9.33 | 82.95 |
| Pop. increase 1960–2010 | 400% | 232% | 268% |
| Mean pop. density 2010 | 71 | 14.87 | 82.95 |
| Mean pop. growth rate 2010 | 2.63% | 2.3% | 2.15% |

discussing the implications of observed changes in land cover types for forests in this region. Most croplands are concentrated in the Ethiopian highlands region with higher mean annual precipitation, as well as around Lake Victoria and along the Somali coast. Apart from the high human population densities recorded in the urban land cover class (2358 people/km² on average), the savanna land cover class has the highest mean population density at approximately 145 people/km² based on 2010 AfriPop data.

3.2. Coarse-scale multi-decadal changes in precipitation and vegetation condition for 1981 to 2011 based on CHIRPS and AVHRR GIMMS data

To understand the multi-decadal (1981 onwards) patterns of change in CHIRPS-derived precipitation and GIMMS-derived vegetation condition at the scale of the entire EAH, we correlated the two datasets. The per-pixel strength of linear association between the two datasets (Pearson product moment correlation coefficient ($r$)) for the 30-year time series of observations (1981–2011) is shown in Fig. 3. We used maximum growing season (MJJA) NDVI as it has been found by previous work (Lotsch et al., 2003; Herrmann et al., 2005) to be correlated best with rainfall accumulated over a period of three months (current plus previous 2 months). The areas where correlation is high reflect the tight relationship between rainfall and vegetation, while in areas where there is a weak or a negative relationship, the season may be off, there might be flawed data or maybe other factors like human-induced degradation are at work (Fig. 3).

The results of the pixel-by-pixel t-test of difference in means between the 1981–1998 and 1999–2011 period based on the MAMJ CHIRPS SPI are presented in Fig. 4a. The areas that appear white in our figure were masked based on the statistical significance criterion (0.05). Given the sample size, statistically significant shifts in SPI occur when changes between the means for each time period are roughly three-fourths of a standard deviation. Positive shifts indicate wetting conditions, while the predominant shift is identified as a negative/drying shift in the latter period (represented in red in Fig. 4a). Fig. 4a thus identifies where there has been a statistical difference in the recent period (1999–2011) compared to the preceding period (1981–1998). In the EAH, significant rainfall declines between the two periods have been observed in central and southeastern Kenya in exclusively pastoralist or agro-pastoralist zones. Declines are also documented in central Somalia and southeastern Ethiopia, specifically in the Somali Regional State where 80 percent of the population depends directly on the natural resource base for their pastoralist livelihoods. Such declines in precipitation are discussed in the literature based on ground data and household-level assessments (Kassahun et al., 2008a). Similar precipitation declines are also observed in parts of central Ethiopia where population densities are the highest in the country (Fig. 1b). The drying patterns extend north into Djibouti and Eritrea, as well as south into the riparian region of Lake Victoria, in both Uganda and central Tanzania, both regions that are experiencing huge population densities and increases.

Similarly, Fig. 4b presents the results of a pixel-by-pixel t-test difference in means performed on the growing season (MJJA) NDVI from 1982 to 2011. Unlike the SPI pattern of change, the spatial extent of areas of NDVI decline identified by our GIMMS-based analysis between the two matching time periods used for the precipitation analysis (1982–1998 and 1999–2011) is reduced, especially when compared to our assessment presented in the next section of this paper (see Fig. 9). This may be due to inherent limitations of the GIMMS dataset (Tucker et al., 2005; Fensholt et al., 2013), the very coarse resolution of the data (8 km) and thus the reduced sensitivity of the sensors to finer-scale processes or our method of aggregation over four months to capture the full extent of the main growing season rains north into Ethiopia, following the migration of the ITCZ. We identify hotspots of consistently declining NDVI in northeastern Ethiopia and parts of northern Somalia, locations in the pastoral lands in central and eastern Ethiopia, as well as along the Somali coast. The pastoral regions of Kenya, both in the northern, but particularly central regions also present declining vegetation condition and this pattern extends into central Tanzania in a manner consistent with the patterns of precipitation declines presented in Fig. 4a.

Fig. 4. (a) Difference of means between 1999–2012 and 1981–1998 CHIRPS MAMJ SPI (white areas were masked based on the 0.05 statistical significance criterion), (b) difference of means between 1999–2011 and 1982–1998 AVHRR GIMMS NDVI3g data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
These patterns are consistent with recent literature pointing to browning trends in vegetation condition by de Jong et al. (2012, 2013) and Vrieling et al. (2013). Given the data limitations discussed above, we decided to further investigate these coarse-resolution patterns using near-real time NDVI data at much finer spatial (250 m) and temporal scale (every 10-days) to focus on the period after 2000 as this period was identified in the literature as having recorded a trend reversal toward browning vegetation conditions (de Jong et al., 2013).

3.3. Finer-scale decadal vegetation transitions and browning trends based on MODIS land cover data and eMODIS NDVI

The six panels in Fig. 5 present, successively, the results of performing image change detection analyses on the aggregated MOD12Q1 land cover data for each final class representative (forest, shrub, savanna, grassland, barren, and croplands) for the larger EAH region. The starting point for the change detection was represented by the mean number of pixels, classified as a given class within the 5 x 5 average window, for the first three years of the analysis (2001–2003). The end point was represented by the same measure of land cover type for the last three years of the analysis (2007–2009). The resulting land cover change image for each of the six classes contained values ranging from −25 to 25. A value of −25, for example, indicates that a given 2.5-km pixel has changed from being classified as a certain pure class in the first three years of the analysis to being classified as a completely different class in the last three years, thus maintaining none of the original land cover type and decreasing in spatial extent by 100 percent. This case was, as expected, fairly rare and mainly occurred in regions that have transitioned directly from a natural land cover type (such as forest) to croplands. These images were subsequently reclassified into proportional ranges, highlighting areas where the land cover within any given class has changed: either increased or decreased by more than 60 percent, between 60 and 40 percent, or between 20 and 40 percent. The urban class was not included in the final output images as the spatial resolution of the sensor is not appropriate for such an application and because the spatial extent of that class is comparatively low in this region.

Fig. 5a shows the location and spatial extent of forest cover changes (including the woody savanna class) from 2001 to 2009. Change occurs mainly in regions classified by FEWS Net as primary farming regions in the Afromontane region of Ethiopia, and to a lesser extent in the farming regions of Kenya, indicating a potential conversion of forests to croplands over the time period. The hotspot areas of forest decline also correspond with regions with significant population increases since the early 1990s. As is the case with the changes highlighted for all the other land cover types, the largest amount of inter-annual change is observed in the range between 20 and 40 percent. Comparatively, the natural shrub cover for the three countries in the EAH has decreased most extensively in Kenya, particularly in three key locations: along the eastern boundary of Kenya's farming region, east of the capital Nairobi (corresponding with the pattern of observed rainfall

![Fig. 5. Land cover change trajectories based on 2001–2003 and 2007–2009 MOD12Q1 Land Cover product for the East African Horn overlaid over aggregated FEWS Net Livelihoods Zones (panels (a)–(f)).](image-url)
declines (Fig. 4a) and the direction of population expansion), in the east-central region of the country near the border with Somalia (and farther east into Somalia), and in a large swath of pastoral lands broadly surrounding Lake Rudolf in the northwestern part of the country where relatively large population increases have also been recorded (Fig. 1b). These findings are supported by regional studies based on higher resolution Landsat satellite imagery (Brink and Eva, 2011) that find a consistent decline in woody and shrub vegetation in areas close to refugee camps on the Somali-Kenya border. We further discuss potential drivers of these observed changes in shrub extent in more detail in Section 4. Savannahs are decreasing mainly along the Ethiopia-Sudan border and in patches throughout the farming regions of central Ethiopia and the Afromontane region and, to much smaller extents, in Kenya and Somalia (Fig. 5c). Grasslands have primarily declined along the Indian coast of both Kenya and Somalia and are largely being replaced by croplands (Fig. 5f and Brink and Eva, 2011). Secondly, another area of similarly significant grassland decline is highlighted in central Ethiopian-Afromontane region to the southeast of Addis Ababa where croplands are encroaching and, once again, population increase rates are among the highest for the entire EAH. Areas of barren land (Fig. 5e) show relatively small increases in hyper-arid eastern extremity of the Somali horn and in patches in the Somali State Region of Ethiopia, for both exclusively pastoralist regions. Finally, croplands appear to be expanding in pockets predominantly in central Ethiopia, along the Kenyan and Somali Indian Ocean coasts, and at the edges of the main farming region in Kenya.

As appropriate-resolution ground validation data was unavailable, we selected several locations where our MOD12Q1-based land cover change analysis revealed significant (more than 40 percent of pixels changed from 2001 to 2009) declining (or increasing) trends for each land cover type and used a trend analysis of NDVI to determine if a similar direction of change was observed. Fig. 6a–f shows a selection of areas where statistically significant declines in 2001–2011 NDVI were observed for locations that show medium to high ranges of land cover change for each aggregated class. In northwestern Ethiopia, where forest and woody savanna cover appears to be declining based on the MODIS data, the NDVI analysis reveals a similar, highly statistically significant declining trend of 6.4 percent during August–September (p = 0.0002). Other locations where the forest class has declined show declines in peak NDVI for the time period with high statistical significance, but modest absolute decline and no comparable decline in dry season minima. In terms of shrubland decline, several locations show significant decreasing trends. We highlight an area in Eastern Kenya near the border with Somalia where previous work identified similar declines, potentially attributable to the presence of the Dadaab refugee camp and very high documented rates of firewood and charcoal extraction (Brink and Eva, 2011). The Dadaab refugee camp, initiated in 1991 as a temporary solution to the Somali war, is arguably the largest in the world. It is currently home to approximately 450,000 people and continuing to expand, particularly since the 2011 drought in the East Horn region (Medicine sans Frontiers, 2012). This area shows large declines, in relative terms, of roughly 16 percent (p = 0.0095) in dry season minimum NDVI.

In areas highlighted as regions of savanna declines, parts of southern Kenya and northern Ethiopia have experienced declines of roughly 15 percent over the last 11 years in dry season minima NDVI (p = 0.023), while regions in northern Ethiopia also show declines in wet season maxima (Fig. 6c). Similarly, several locations identified as declining grasslands show negative trends in dry or transition season NDVI values, but no significant changes in wet season maxima. The region at the southern tip of Somalia along the Indian Ocean Coast shown in Fig. 6d experienced the highest amount of NDVI decline (22 percent) from 2001 to 2011 (p = 0.0169). A similar finding was presented in the latest Somalia Water and Land Information Management (SWALIM) assessment of degradation (Omuto et al., 2009). Finally, we selected several sites on the map, including those colonized by shrubs. These sites show large negative NDVI declines, as expected, in dry season NDVI than in wet season NDVI (Fig. 6e).

3.4. Emerging hotspots of vegetation degradation in pastoral regions of the East African Horn

The third spatial scale of our analysis was represented by an analysis of land cover change and NDVI trends in the pastoral and agro-pastoral regions of the East African Horn, defined broadly by the FEWS Net livelihood zones delineations. We focus on these ecosystems and land uses as they are hypothesized to be especially susceptible to anthropogenic and climate change-induced impacts (Boko et al., 2007). Furthermore, pastoral and agro-pastoral regions in EAH are also home to millions of people, most of whom are pastoralists who rely heavily on the natural resource base and whose numbers are continuing to increase in the context of high growth rates and high numbers of women with unmet needs for family planning (United Nations Population Division, 2011).

It is beyond the scope of this paper to draw causal attributions for documented changes; we remain concerned with pinpointing locations of change in relation to observed changes in precipitation pattern changes and growing population densities. As such, Fig. 7 shows pastoral areas that have undergone change in shrub cover from 2001 to 2009 and, adjacent areas where the same type of analysis reveals an expansion in grassland cover. However, given the low spectral separability between grasslands and croplands at the spatial resolution of the MODIS product (Mahiny et al., 2013), the spatial extent of expanding grasslands might be misleading and may be masking an expansion of agricultural fields, as some previous research in the region (Omuto et al., 2009) indicates. Most shrub extent change remains located at the eastern periphery of the farming regions in Kenya, as well as along the boundary between Kenya and Somalia where the Dadaab refugee camp is located (not shown on this map; located at 0°02’S, 40°18’E). The NDVI Browning trends between 2°S and 7°N latitude along a central corridor in Kenya that continues into the pastoral regions of southern Ethiopia, with the exception of the southernmost box partially located in a farming livelihood zone, are areas where we identified statistically significant long-term
declines in mean growing season (March–April–May) NDVI that may be indicative of a general degradation of the vegetation (Fig. 8). These browning regions, referred to also as hotspots hereafter, were identified independently of the rainfall and land cover change analysis.

The NDVI browning boxes (a) through (d) in Fig. 8 show regions where the long-term growing season NDVI declines remain statistically significant and overlap with regions of significant land cover change, specifically in pastoral and agro-pastoral regions (Fig. 7). Of the five locations shown to illustrate browning trends in pastoral regions, only the southernmost box (0–2° S, 38–39° E, Fig. 8a) and the area north-central Kenya (1–3° N, 37–39° E, Fig. 8b) also demonstrate consistent declining trends in precipitation over the last decade (Fig. 4a). The latter hotspot in
north-central Kenya experienced the most significant declines in precipitation of the hotspots analyzed, with a total reduction in wet season NDVI of 42.2 percent ($R^2 = 0.656$, $p = 0.0025$), while the former shows the second highest reduction of 26.5 percent ($R^2 = 0.311$, $p = 0.075$) over the last decade.

Panel (e) of Fig. 8 displays a region where, despite significant land cover changes, the NDVI browning trend remains statistically insignificant, even though change is pronounced, with a decline of roughly 17 percent over the 11 years of our analysis. As discussed in Section 3.3, this latter box, delineated between 0–2° N and 40–42° E where more than 60 percent of land change during the decade is represented by a transition from shrubs to grasslands (or possibly pastures), corresponds with the location of the world’s largest refugee camp. Our land cover change analysis stops at the end of 2009 (due to data availability) and thus does not capture the effects on land cover of the 2010 extended droughts, failed rains, and subsequent 2011 famine in the EAH region. However, the NDVI analysis does capture a significantly lower healthy vegetation signal, especially during 2011 when some of highest long-term negative anomalies for the wet season were recorded throughout our study region. Analyses of NDVI anomalies for the 2012 growing season (see Table 2 and Fig. 9) indicate that the browning trend is continuing even during normal rainfall conditions, which has been shown elsewhere to be representative of areas with severe range degradation problems (Vanderpost et al., 2011). Rangeland degradation is becoming an acutely important issue and is usually attributed to agricultural expansion into rangelands with unsuitable land management, the lack of regulation in charcoal production for local consumption and for export, uncontrolled grazing of livestock, and changing land tenure regimes for urban and agricultural development (Omuto et al., 2009; Garedew et al., 2009; Brink and Eva, 2011).

The second goal of this paper was to use continuous and categorical vegetation analyses to assess if drying trends and population increases overlap with areas of vegetation transitions and changes and long-term decreasing trends in vegetation condition as measured by NDVI analyses. To understand the statistical relationship between rainfall and vegetation browning trends, we calculated trend changes per decade for NDVI for dekads 10–14 (April–mid May) and change per decade in RFE2 rainfall for dekad 7–11 (March–mid April). We extended this regression analysis to the main growing season in 2012 to include the year following the major drought of 2011 in the EAH (Lott et al., 2013) in order to ensure our trends were not skewed. The results of the rainfall/NDVI trend analyses for 2001–2012 are presented in Table 2. Table 2 summarizes the results, at different significance levels, of the amount of variability in NDVI browning trends not explained by rainfall trends for each previous 4 dekads between 2001 and 2012. In some regions such as southern Somalia or south-central Ethiopia, the trend in NDVI not explained by declining rainfall trends is as high as 123.5% $(p = 0.0034)$ and 105.8% $(p = 0.0134)$, respectively. In other regions, such as north-central Kenya (between 0–3° N and 38–39° E, in the band of drying rainfall and browning vegetation presented Fig. 8b, where the model fit between rainfall and NDVI is very high $(R^2 = 0.846$, at 0.001 significance level), only 69.2% of the trend in NDVI is explained by declining rainfall $(p = 0.0032)$. We illustrate the results of the rainfall/NDVI regression analysis visually in Fig. 9 for a region in Kenya (2.5–6° S and 39–39° E) that corresponds the region highlighted in Fig. 8d and is also part of consistent band of drying that crosses through central Kenya highlighted by other authors (Vrielings et al., 2013; de Jong et al., 2013). For this region, the model fit between rainfall and NDVI was high $(R^2 = 0.779$, $p = 0.0011)$ and the decline in rainfall accounts for 82.4% in the observed vegetation browning trends from 2001 to 2012.

Our findings presented here are in line with recent work by Zhao and Running (2010), de Jong et al. (2012, 2013) and Vrielings et al. (2013) who show browning trends in the region at different

Fig. 7. Co-location of shrub land cover decline (by percent of 5 × 5 mean count pixel data from 2001–2003 to 2007–2009) in the left panel and transition to grassland in the right panel.
scale and also discuss the importance of analyzing shorter-term trends as inputs into understanding longer-term changes. In the context of the “debate” regarding greening vs. browning trends in the Sahel region, work by de Jong et al. (2013) showed that areas with browning trends increased over time while the area with greening trends decreased, with the Southern Hemisphere showing the strongest evidence of overall vegetation browning, especially in the Horn region. They show that a trend reversal toward vegetation browning took place in the EAH region post-1998 El Nino (specifically around 2000 for this region) and that has
recently been amplified due to a period of persistently poor rains, causing severe food insecurity in the region. Explanations for these changes vary and include shifts in hemispheric weather patterns (Wang et al., 2011; Hoell et al., 2013), while modeling shows that the lack of the long rains in early 2011 in the EAH was an effect of the systematic warming due to influence on greenhouse gas concentrations (Lott et al., 2013).

Hence, without considering other direct potential factors (discussed elsewhere in the literature by Herrmann et al., 2005; Olsson et al., 2005; Lott et al., 2013) apart from rainfall that might lead to the observed consistent negative anomalies in NDVI or changes in land cover, we used the Gridded Population of the World (GPWv3) to analyze population density changes in the hotspot locations identified above. We calculated mean population density between 1990 and 2015 for each of the hotspot areas under the assumption that growing population numbers exerting greater pressure on these rangelands have a significant impact (Seymour et al., 2010; Garedew et al., 2009; Mahiny et al., 2013). Increased population pressure in pastoral and agro-pastoral regions usually translates into higher livestock stocking rates, increased wood extraction for firewood and charcoal trade, and an intensification or extensification of agriculture (Vargas et al., 2009), all factors leading to degradation. Fig. 10a shows the trend in mean population density exclusively for pastoral regions (based on FEWS Net livelihoods zones) in each of the three countries between 1990 and 2015; during this period, Kenya’s pastoral population increases by 99 percent, Somalia’s by 104 percent and Ethiopia’s by 86 percent.

An analysis of mean population density between 1990 and 2015 performed specifically on data for the hotspots identified through our land cover analysis uncovered similar trends in mean population density with rates of increase between 1990 and 2010 ranging from 36 percent (0–2° S, 38–39° E, Fig. 8a) to 72 percent (3–5° N, 38–40° E, Fig. 8c). Each of these locations is projected to experience further increases of 5–21 percent respectively by 2015 (Fig. 10b). The hotspot in southern Kenya (0–2° S, 38–39° E) and the one in north-central Kenya (1–3° N, 37–39° E) with the highest statistically significant decadal reductions in NDVI have the least amount of increase in population density, 36 and 40 percent respectively, between 1990 and 2010 (Fig. 8a and b). This finding suggests that while increasing population density is linked with degradation hotspots in vegetation condition, the most

<table>
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<tr>
<th>Box extent</th>
<th>Location</th>
<th>Trend (change/decade)</th>
<th>Partial trend with rainfall fit</th>
<th>Non-rainfall trend</th>
<th>Model $R^2$</th>
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<td>3-5N/37-40.5E</td>
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<td>−0.1036</td>
<td>−0.1013*</td>
<td>97.7%</td>
<td>0.811*</td>
</tr>
</tbody>
</table>

* 0.05 significance.
** 0.01 significance.
*** 0.001 significance.

Fig. 9. Illustrative example of the statistical relationship between rainfall trends for dekad 7–11 (March–mid April) averages and NDVI trends for dekad 10–14 (April–mid May) from 2000 to 2012 for a region in Kenya (2.5–0 lat. S and 39–39 long. E), with annual rainfall-NDVI cycle for the same time period.
significant browning trends are observed in areas experiencing drying precipitation trends additionally. The area located at the border between Kenya and Somalia and the site of the Dadaab refugee camp shows the highest rate of change in mean population density of 146 percent (projected to increase by an additional 55 percent by 2015, representing a total of 201 percent increase relative to 1990 when the camp was created). We thus identified areas where the natural vegetation cover is shifting toward more human-dominated uses and, using an independent, continuous vegetation dataset, we show statistically significant browning trends across those regions at different times of the growing season. While increasing population density is linked with vegetation degradation hotspots, the most significant browning trends are observed in areas experiencing drying precipitation trends in addition to increasing population pressures. This finding contributes to our understanding of regional-scale interdependencies among population change, rainfall variability and landscape degradation and will require more in-depth investigation.

To conclude, our focus on the EAH region was initially motivated by chronic and recurrent food insecurity and by modeling predictions that identify on-going and future shifts in climatic and vegetation parameters such as decreases in the length of the growing season, with immediate and direct impacts on people’s livelihoods (Thornton et al., 2011; de Jong et al., 2013). Furthermore, our results bring further evidence in the context of an ongoing debate regarding greening (Olsson et al., 2005; Herrmann et al., 2005; Bai et al., 2008) vs. browning of vegetation in the Sahel and parts of East Africa and documented by recent work that shows there has been a trend reversal in vegetation condition (Zhao and Running, 2010; de Jong et al., 2012, 2013) toward browning after the turn of the millennium.

4. Conclusions

This paper focused on understanding regional spatially explicit links between population changes, main growing season precipitation and vegetation changes and livelihood profiles in the East African Horn region. We find hotspots where precipitation declines occurring over the last 15 years relative to the previous decade overlap with regions of population density increases, thus highlighting areas of potential escalating concern for food security and vulnerability to climate change in the future. We also uncovered land cover changes and vegetation browning trends that occur in areas experiencing reduced precipitation in addition to increasing population pressures. By shifting between two vegetation products with varying temporal resolutions (AVHRR which provides longer temporal coverage and eMODIS NDVI which provides real-time data with higher spatial resolution), we demonstrate that, for the last decade, decreasing main growing season precipitation only partially statistically explains the vegetation browning trends, further indicating that other factors such as population pressures might be responsible for the observed declining vegetation health. As the general vegetation browning trend persists even during years with normal rainfall conditions such as 2012, the situation appears to be representative of areas of rangeland degradation that are impacting over 10 million people throughout the Greater Horn. The recent and improved availability of the third generation 1982–2011 Global Inventory Modeling and Mapping Studies (CIMSS) third generation NDVI data was crucial for this study as it allowed us to obtain a long-term record of vegetation patterns in relation to precipitation shifts and formed the basis for our higher-resolution analysis of vegetation trends using the higher resolution eMODIS NDVI data. We suggest that implementing additional mitigation and adaptation strategies may be necessary to avoid compounding effects from both climate change and socio-economic and political instability.

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