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Climate warming causes declines in crop yields and lowers school attendance rates in Central Africa

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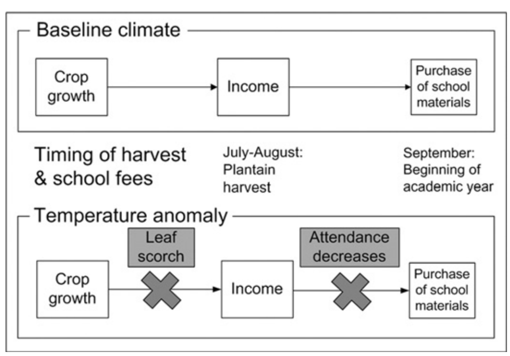
HIGHLIGHTS

- Plantain yield in Cameroon declined 43% from 1991 to 2011.
- Climatic variables explained the reduction in productivity ($R^2 = 0.68$).
- Education levels in rural households correlated with crop productivity ($R^2 = 0.82$).
- By 2080 we predict a 39% decrease in plantain yields and 51% in education outcomes.
- Farmer training could enhance the adaptive capacity of food production systems.

GRAPHICAL ABSTRACT



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ABSTRACT

Although a number of recent studies suggest that climate associated shifts in agriculture are affecting social and economic systems, there have been relatively few studies of these effects in Africa. Such studies would be particularly useful in Central Africa, where the impacts of climate warming are predicted to be high but coincide with an area with low adaptive capacity. Focusing on plantain (*Musa paradisiaca*), we assess whether recent climate change has led to reduced yields. Analysis of annual temperature between 1950 and 2013 indicated a 0.8 °C temperature increase over this 63-year period - a trend that is also observed in monthly temperatures in the last twenty years. From 1991 to 2011, there was a 43% decrease in plantain productivity in Central Africa, which was explained by shifts in temperature ($R^2 = 0.68$). This decline may have reduced rural household wealth and decreased parental investment in education. Over the past two decades, there was a six month decrease in the duration of school attendance, and the decline was tightly linked to plantain yield ($R^2 = 0.82$). By 2080, mean annual temperature is expected to increase at least 2 °C in Central Africa, and our models predict a concomitant decrease of 39% in plantain yields and

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51% in education outcomes, relative to the 1991 baseline. These predictions should be seen as a call-to-action for policy interventions such as farmer training programs to enhance the adaptive capacity of food production systems to mitigate impacts on rural income and education.

1. Introduction

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) outlined hypotheses about the impacts of climate change on agriculture, disease, ecosystems, and water resources in Africa (Niang et al., 2014). Regarding agriculture, the Fifth Assessment hypothesized that with warmer temperatures and decreased rainfall, crop yields will decline. Since the Fifth Assessment was published, the effects of climate change on yield have been predicted for cocoa in West Africa. By the 2050s, increases in maximum temperature are forecast to cause declines in areas suitable for cocoa production in countries along the Gulf of Guinea (Schroth et al., 2016). In addition to effects on agriculture, the Fifth Assessment hypothesized that the geographic ranges of vector-borne and water-borne diseases will expand and that the geographic boundaries of ecosystems will shift affecting wildlife and natural resources (Niang et al., 2014).

The sensitivity of crop yields to climate change is often complex encompassing both direct biophysical effects, such as the impact of shifts in temperature and precipitation on plant growth, as well as indirect effects, such as the impact of climate on the abundance of pathogens, vectors, and their predators (Ye et al., 2015). Examples of reduced yields attributed to climate change include rice and wheat in India (Burney and Ramanathan, 2014) and the productivity of a variety of staple food crops in Sub-Saharan Africa (Blanc, 2012). Banana (*Musa* spp.) and plantain (*Musa paradisiaca*) are predicted to be highly sensitive to the direct effects of climate change due to their narrow temperature and water tolerance (Jarvis et al., 2012). In Cameroon in Central Africa (Fig. 1(A)), plantain is expected to be sensitive to climate change because the predicted increase in temperature could delay flower development and bunch emergence causing yields to decline (Turner et al., 2007). Furthermore, the irrigation requirements of banana are 1200 mm in tropical climates and declines in precipitation below this threshold could induce water stress (FAO, 2015). As discussed below, adaptation via changes in management such as genetic improvement of *Musa* might partially mitigate the impacts of climate change on plantain yield, but will not eliminate them entirely due to the significant time and investment required to establish crop breeding programs.

As most farmers in Central and West Africa rely on rain for irrigation, the vulnerability of the region's agricultural production systems to drought is high. Over the last 40 years, one of the strategies that rural populations have adopted in response to drought is to abandon agriculture and migrate away from farming areas (Njock and Westlund, 2010). For example, in 1972 and 1983–4 droughts prompted major migration events involving millions of people who relocated from dry ecosystems in the Sahel to humid coastal ecosystems along the Gulf of Guinea (Gautier et al., 2016; Mertz et al., 2010; Ouedraogo et al., 2010). Future droughts and demographic shifts such as substantial growth of the population under 15 years of age are predicted to result in increased population vulnerability and migration in northern Nigeria, western Cameroon, and coastal areas of the Republic of Congo and the Democratic Republic of Congo (Lopez-Carr et al., 2014).

Understanding the impacts of climate change on crop productivity in Central Africa is vital due to the economic importance of the region's agricultural sector. For example, in Cameroon >70% of the rural population works on small farms (Yengoh, 2012). Given the importance of crop production, the negative effects of climate change on food crop yields could impact the dynamics of supply and demand in the plantain sector. A decrease in the supply of plantain would increase demand due to shortages, but whether this would affect prices would depend on buyers' willingness and ability to pay more for plantain. The most recently-available price data from Cameroonian markets is from 2009 to 2011 and indicates that the price per kilogram rose 55% over this period, increasing from 100 to 150 Central African Francs per kilogram (Institut National de la Statistique, 2012). However, over longer periods, climate change may reduce consumer income, making buyers unable to match increased plantain prices.

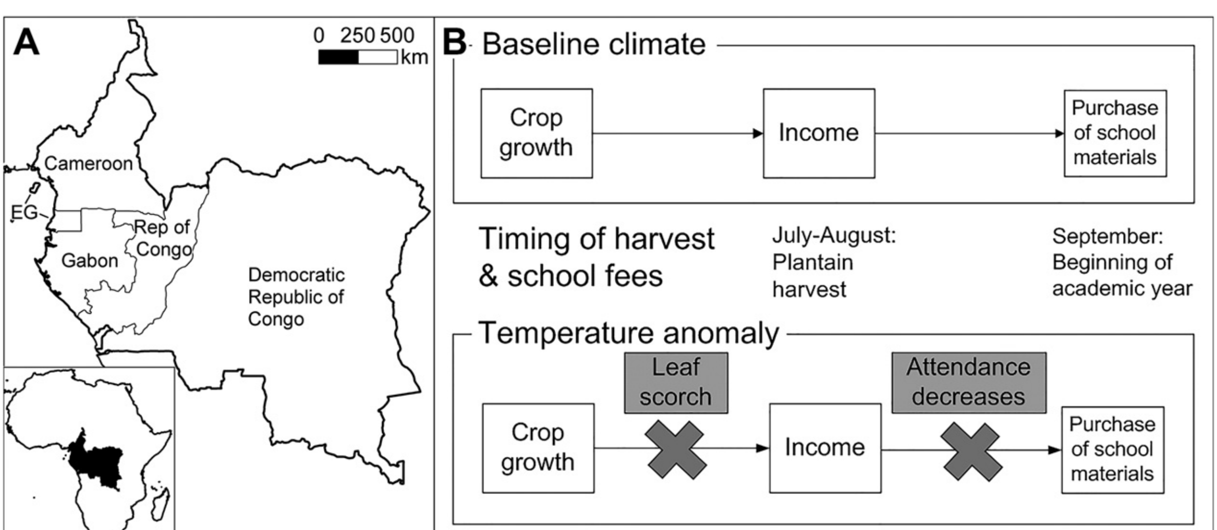

Fig. 1. Study area and schematic of climate change impacts on crops: (A) countries of Central Africa. EG = Equatorial Guinea; (B) mechanisms by which climate change could affect plantain yields and school attendance in Cameroon.

In light of the social and economic importance of agricultural production in Central Africa, more research is needed on the mechanisms by which climate change might affect crop yields, farmer decision-making, and rural household income. A number of mechanisms have been posited to explain how climate change might affect agriculture and socio-economic status in rural areas. For example, van Vliet (2010) conducted focus groups in the Southwest Region of Cameroon, which indicated that crop yields affect educational attainment in rural areas because parents utilize income from crop sales to purchase their children's textbooks, uniforms, and other school supplies. The impact of climatic events on agricultural productivity and farmers' household income has also been analyzed in other developing countries, including Bangladesh, Cote d'Ivoire, Indonesia, India, and Vietnam (Bui et al., 2014; Jensen, 2000; Mottaleb et al., 2013; Skoufias, 2003; Thomas et al., 2004). The results of these analyses demonstrate that when extreme weather events destroy crops such as rice, farm households experience reduced income, prompting parents to spend less on their children's schooling and this leads to a decrease in the children's overall educational attainment.

In light of these findings in other countries, one might hypothesize that if crop yields in Cameroon decrease due to anomalously high temperatures, rural producers would earn less from the harvest, be less inclined to purchase school supplies, and be less willing in general to expend time and scarce household income of educational activities (Fig. 1(B)). According to this hypothesis, climate change-associated temperature increases would be accompanied by gradual declines in indicators of educational attainment such as rates of enrollment, literacy, and graduation.

Our objectives were to test associations between climate change, crop yields and education outcomes in Cameroon by examining meteorological data, crop yields, and graduation rates over a twenty-year period (1991–2011). Focusing on plantain (*Musa paradisiaca*), we assessed whether recent climate change has reduced yields, and the resulting social and economic effects on rural households. After assessing recent climate change and educational trends, we used IPCC scenarios to develop predictions about future crop yields and education outcomes over the period from 2030 to 2080.

2. Materials and methods

This analysis focused on Cameroon because it is a country in Central Africa for which the most in-depth data are available on climate, crop yields, and education outcomes. To provide a context for a detailed investigation of the complex interaction between climate change, agricultural productivity, and school attendance over the past twenty years, we first examined climate variability in Cameroon over the past six decades. In particular, we analyzed trends in mean annual temperature at the national scale from 1950 to 2013 using the Climate Research Unit CY 3.22 data set (Harris et al., 2014), which allowed us to assess whether temperatures in the last two decades are anomalously high, relative to the historical baseline. The annual temperature data exhibited different trends during the study period. From 1950 to 1975, the data were relatively flat, then from 1975 to 2013 temperature increased sharply. In light of this, to plot trends in temperature, a segmented model was fitted to the annual temperature data using a regression tree (De'ath and Fabricius, 2000).

After examining these temperature trends, we conducted a more detailed analysis of co-variability between climate, crop growth, and education endpoints. This stage of the analysis was restricted to 1991–2011 because educational and agricultural data were collected systematically during this period, using standardized surveys with consistent methodologies. The crop data were supplied by Cameroon's Ministry of Agriculture and Rural Development (MINADER), which carried out surveys of crop prices, surface area cultivated, tons harvested per hectare cultivated, and food imports and exports. We used crop surveys from 1991, 1998, 2004, and 2011 because education data were available for these years. Our analysis focused on plantain yields because, as noted above, this crop is an important food staple in Central Africa (Temple et al., 2011). The local economy depends on plantain to the extent that bananas and plantains are Cameroon's number one agricultural export and agriculture is the largest sector of the economy (Institut National de la Statistique, 2012). The agricultural productivity data are reported at the Region scale (Fig. S1).

We note that in Cameroon the production, export, and marketing of bananas and plantains is regulated by a state-owned industry, the Cameroon Development Corporation (Wanie and Tanyi, 2013). The plantain productivity data utilized in this analysis was based on agricultural surveys carried out by MINADER, which used statistical techniques to estimate production by gathering data from a representative sample of farms (Labé and Palm, 1999). The same survey methodology was used consistently in all years of the surveys.

We obtained household wealth and education data from Demographic Health Surveys (DHS), which are questionnaire-based inventories of maternal and child health and nutrition, education endpoints, and other development indicators such as access to electricity, medical care, and sanitary water sources (Coffey, 2015). These surveys are based on a standardized methodology developed by the US Agency for International Development (USAID) and have been implemented in 38 countries in Sub-Saharan Africa (Short Fabic et al., 2012). To estimate wealth, we utilized the results of these surveys, which recorded the presence of goods such as radios and bicycles. Household with more goods were classified as wealthier. The wealth data did not incorporate revenue from crop production, so it was not possible for us to distinguish income generated by plantain from other income sources. To protect the privacy of survey participants, the DHS data were aggregated to the Region scale before being released to us for analysis. For consistency with the DHS education data, we aggregated the plantain and climate data to the Region scale.

During the study period from 1991 to 2011, Cameroon's rural population increased from 6.6 to 9.3 million, but most population growth was in Regions suboptimal for plantain such as the arid North and Extreme North. The percentage of the population of school age (ages 5–19) did not change during the study, comprising approximately 38% of the population as a whole in both 1991 and 2011 (Institut National de la Statistique, 2012)

To evaluate interactions between climate and agricultural production, we selected climate data based on both spatial as well as temporal criteria. As our objective was to test for associations among climatic variables, plantain yield, and educational attainment in 1991, 1998, 2004, and 2011 at the spatial scale of the ten Regions of Cameroon, we required climatic data with an annual temporal resolution and a spatial scale smaller than each Region (mean area: 47,000 km^2). Although using a data set with a high spatial resolution would have been effective for characterizing intra-Regional climatic variation, it would have prevented us from analyzing inter-annual variation. For example, WorldClim uses a 1-km spatial scale but the temporal scale is 50 years (Hijmans et al., 2005). In light of this, we selected a climatic data set with a coarser spatial but finer temporal resolution, ERA-Interim, which utilizes 80 km grid cells and is available for each year since 1979 (Dee et al., 2011), thus meeting both the spatial and temporal requirements of the analysis.

We analyzed seven precipitation and temperature variables at the regional scale (Table S1). The climatic variables included both annual means and measures of seasonality because seasonal variation is an important determinant of crop growth (Gu et al., 2008). The analysis used the mean value of each climatic variable in each Region. The calculation of mean values was carried out with the Zonal Statistics function in ArcGIS 10.3.1. As the climate data were in raster format and the Regions were in vector format, a pixel of the climate raster was considered inside a Region and counted toward the mean if the pixel centroid was located inside the Region.

Following established protocols (Feng et al., 2010), we tested for statistical associations between climate, crop yields, and education by fitting a system of two equations to the data:

$$Y_i = \alpha_i + A_i\beta + W_i\theta + \varepsilon_i \tag{1}$$

$$A_i = \delta_i + Z_i\gamma + \mu_i \tag{2}$$

The first equation models the effect of plantain yield and household wealth on educational attainment. A_i is plantain yield in Region i of Cameroon, W_i is wealth, and Y_i is the highest year of education completed per household member, averaged over all households in the Region. The parameter β represents the effect of crop yields on years of education completed. If the estimated value of β is large relative to its standard error, then we can infer that plantain yield is a significant driver of the number of years of education completed. The parameter α is the intercept and ε represents random error. In the second equation, which represents the effect of climate on crop productivity, A_i is plantain yield in Region i, and Z_i is a matrix of precipitation and temperature variables. In this model, the functional form of the relationship between plantain yield and climatic variables is linear, and the climatic variables are mean annual temperature and dew point temperature (Table S2). The parameter γ represents the effect of the climatic variables on plantain yield, θ is the coefficient of the wealth variable, δ is the intercept, and μ is a random error term.

Fitting the equations to the data required the use of specialized techniques. Ordinary least squares (OLS) was unsuitable because in order to provide unbiased estimates of β, OLS requires that the errors ε and μ are uncorrelated. This assumption is violated because plantain yield is the response variable in the second equation and the predictor variable in the first equation. To address this, we utilized an econometric method called instrumental variables regression (Feng et al., 2010), which circumvents the problem of correlated errors by using the climatic variables as proxies for plantain yield in the following manner. The second equation is fitted to the data to obtain an estimate of the effect of climate on plantain yield, $\hat{A}$. Then, when fitting the first equation, A is replaced with the prediction $\hat{A}$. In this manner, the instrumental variable regression provides unbiased estimates of β, the parameter that represents the effect of plantain yield on the highest year of education completed. We implemented this approach using PROC SYSLIN in SAS 9.2 and conducted hypothesis tests to determine the statistical significance of β.

After fitting regression models to the data for the period of 1991–2011, we used the results to develop predictions about future crop yields and education outcomes. The Fifth Assessment Report developed four Representative Concentration Pathways (RCPs) that model different scenarios of anthropogenic emissions and the implementation of climate change mitigation policies during the 21st Century; these range from RCP 2.6, which assumes aggressive mitigation, to a business-as-usual scenario, RCP 8.5. For each RCP, we analyzed 17 generalized circulation models for the years 2030, 2050, and 2080 (Table S1). We then applied the regression models developed from the 1991–2011 data to the three future time points to predict the impacts of climate change on crop growth and measures of school completion over the next sixty-five years.

3. Results

Analysis of annual temperature trends in Cameroon from 1950 to 2013 using the CRU CY data set indicated a 0.8 °C temperature increase during this period (Fig. 2). Using CRU TS, we also compared the mean temperatures of the five-year periods centered on 1991 and 2011. The results indicated that temperature increased significantly over this period ($t = -2.603$, $df = 6.066$, $p = 0.02$; Fig. S2). Thus, data from the past two decades reinforces the increasing temperature trend observed in the data spanning the past sixty-three years.

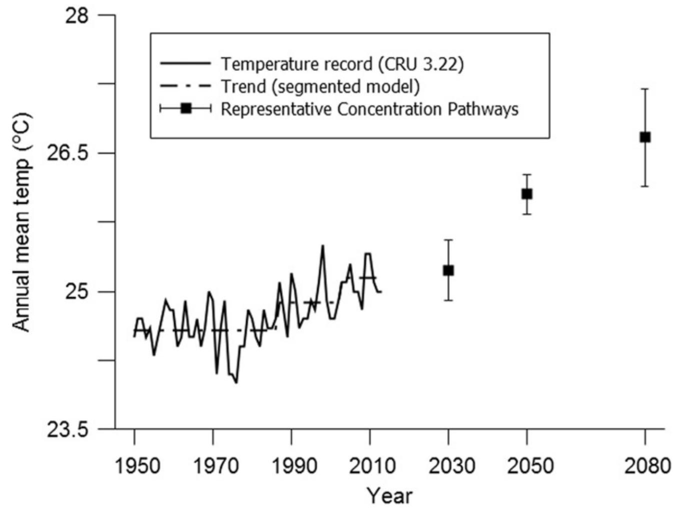

Fig. 2. Temperature anomaly in Cameroon since 1950 and predicted temperature increases until 2080, according to IPCC scenarios.

Next, we assessed the impact of climatic variation on the dynamics of crop production from 1991 to 2011. During this time interval, dew point temperature in Cameroon decreased an average of 6.2%, resulting in increased dryness, potentially impacting the photosynthesis and productivity of crop plants ($t = 8.876$, $df = 24$, $p = 4.78 \times 10^{-9}$; Fig. 3).

During the period from 1991 to 2011, there was also a 344% increase in the area of plantain cultivated in Cameroon (Fig. S3). To assess whether the surveys of plantain productivity were collected data at a representative sample of farms, we compared the number of farms surveyed to the total number of rural farm households per Region (Bureau Central des Recensements et des Etudes de Population, 2010; Ministry of Agriculture, 2012). The results indicated that survey effort per Region was proportional to the total number of farm households ($r = 0.915$, $p = 0.0002$).

The increase in plantain production was uniform across the Regions of Cameroon ($F = 0.971$, $df = 3{,}28$, $p = 0.42$). However, the spike in cultivation was counteracted by a decrease in tonnage harvested per hectare, with declines totaling 43% between 1991 and 2011 (Fig. 4). Productivity first dropped 49% from 1998 to 2004, and although there was an uptick in mean yield from 2004 to 2011, the increase was slight

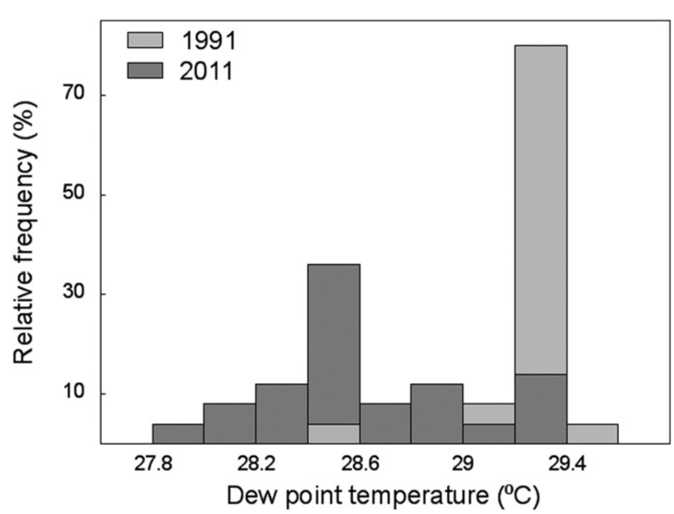

Fig. 3. Changes in dew point temperature in Cameroon, 1991–2011. The 1991 dew point temperatures were higher than those in 2011, indicating that was an increase in dryness during the study period. The data shown are for the month of April in the Adamaoua, Nord, and Extrême-Nord Regions shown in Fig. S1. The data are from the ERA-Interim data set and represent the five-year average centered on 1991 and 2011, respectively.

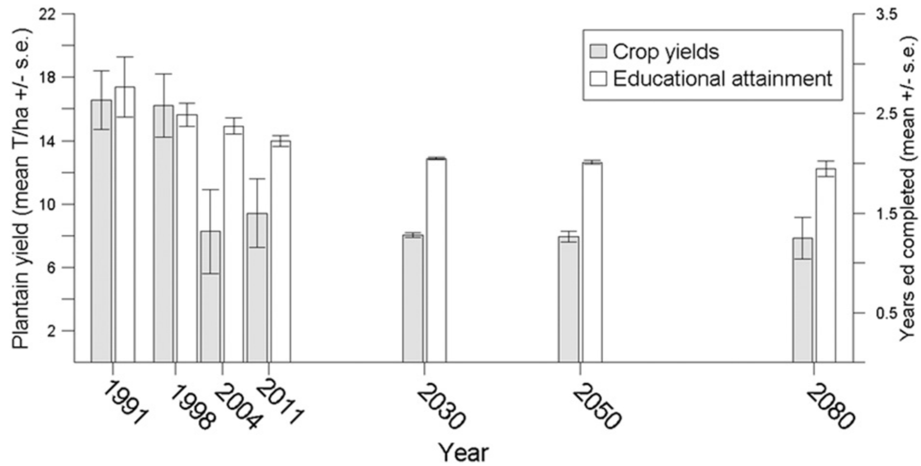

Fig. 4. Change in plantain yield and education levels since the 1990s and predicted effects of climate change on crop yield and education for the period of 2030–2080.

at only 14% and smaller than the confidence limits in 2004 and 2011. Thus, there was no evidence that plantain yield had recovered to the levels reported in the 1990s.

The decrease in plantain productivity led us to investigate associations between climatic factors and crop yield. Given that there was a significant increase in temperature and a significant decrease in plantain yield between 1991 and 2011, we tested whether the observed climatic trends could explain patterns of crop production. The linear regression model based on temperature and precipitation variables provided a good fit to the plantain yield data ($R^2 = 0.68$, $F = 5.817$, $p = 0.04$; Table S2). The use of annual mean temperature predicted yield more accurately than the use of lagged seasonal temperature (Akaike weight 0.91, Table S3). Furthermore, the linear model based on mean temperature and dew point temperature predicted plantain yield more accurately than a quadratic model (Table S4). The results indicated a significant association between temperature and plantain productivity, which is supported by experimental data on plantain and banana physiology. For example, field experiments Côte d'Ivoire have shown that there is a significant relationship between temperature and banana bunch emergence and flower development (reviewed in Turner et al., 2007).

Although precipitation was not significant in our model, rainfall declined in Cameroon during the study period (Fig. S4). If this trend continues, precipitation may become a limiting factor on plantain yield in the near future. A salient example is the Adamaoua Region. In 1991, total precipitation was 1481 mm, but by 2011, rainfall had decreased by 132 mm, to 1349 mm. If the pattern of declining rainfall continues, by 2034, precipitation in Adamaoua could drop below the 1200 mm minimum water requirement for plantain production (FAO, 2015).

In the next phase of the analysis, we evaluated trends in education outcomes from 1991 to 2011. We examined years of post-secondary education for students between 19 and 24 years of age. Between 1991 and 2004, there was a decline in the average number of years of school completed, but the decrease from one period to the next was not significant (Fig. 4). The trend continued in 2011, when mean years of schooling was 2.22 years, which represented a 19.5% decrease from the 2.76 years reported in 1991. The level of educational attainment in 2011 was significantly lower than two decades earlier. The significant decline in school completion prompted us to test whether school dropout rates were linked to crop failure. When we investigated this using instrumental variables regression, plantain yield emerged as the most significant driver of the number of years of school completed, and household wealth was also significant ($R^2 = 0.82$, $F = 22.07$, $p = 0.0009$, Table S2).

The declining trend in plantain yield and educational measures over the period of 1991 to 2011 led us to analyze predictions about climate change in Cameroon in the coming decades, and project the effects of climate change on food crops and school attendance. To assess this, we compared the mean temperature during the baseline period of 1960–1990 to temperature projections according to the Fifth Assessment's RCPs. Results indicated that relative to baseline, average annual temperatures in Cameroon are expected to increase an average of 0.63 °C in 2030, 1.45 °C in 2050, and 2.07 °C in 2080 (Fig. 2).

Our analysis of climate and crop yields from the past two decades showed that temperature accurately predicted plantain yields. In light of this association in the observed data, we explored how climate might drive crop yields in the future. To examine this, we refit the regression models constructed from 1991 to 2011 data using future temperatures, according to RCP scenarios. The projections predict that plantain yields in Cameroon will continue to decline, dropping to 47% of 1991 levels by 2030 and 39% by 2080 (Fig. 4). If these relationships hold, one would predict similar declines in future education outcomes. With increasing temperatures and decreasing crop yields, the highest grade of school completed is projected to decrease to 71% of 1991 levels by 2030, from 2.76 years on average to 1.95 years. This trend will continue in the second half of the 21st century, when years of schooling will decrease to 1.74 years on average by 2050, which represents 63% of 1991 levels and will drop further to 1.42 years by 2080, which is 51% of the 1991 baseline. As with the temperature predictions, the uncertainty about future crop yields and graduation rates is lower in the 2030s than in the 2050s and 2080s, because all RCPs predict similar temperature increases in the early decades of the 21st Century but diverge substantially by mid-century and thereafter.

4. Discussion

Our findings about recent temperature increases and crop declines in Central Africa, as well as our predictions about future temperature and crop yields, are all supported by previous studies of climate change in Sub-Saharan Africa (Blanc, 2012; Jarvis et al., 2012; Niang et al., 2014). With respect to recent climate trends, the present analysis indicates that mean annual temperature in Cameroon has increased by 0.8 °C since the 1950s. This is consistent with the IPCC's Fifth Assessment Report, which reported a 1 °C temperature increase across Central Africa as a whole during this time period (Niang et al., 2014). Regarding crop productivity, our analysis of plantain production in Cameroon indicated that yields decreased 43% from 1991 to 2011. Similar declines have been reported for other food staple crops across Sub-Saharan Africa, including millet, sorghum, and maize where in each case there was a statistically significant association with climatic factors (Blanc, 2012). When we examined future climate scenarios, results indicated that mean temperature in Cameroon will increase at least 2 °C in 2080, relative to the baseline period of 1960–1990. This prediction is compatible with the Africa chapter of the Fifth Assessment Report, which also concluded that by 2080 temperatures will increase by at least 2 °C in Central Africa relative to 1986–2005 under RCP 2.6. However, we note that the magnitude of the predicted temperature increase depends on numerous factors such as the RCP considered and the baseline to which future temperatures are compared. For example, under RCP 8.5 annual temperature in Cameroon is predicted to increase 3–7 °C in 2050 relative to the 1950–2000 baseline (Fig. 5).

The evidence of increasing temperatures and declining crop yields in Central Africa reported here lends urgency to the implementation of climate change mitigation policies in the agricultural sector. Nevertheless, our finding that plantain yield and educational attainment will continue to decline during the period from 2030 to 2080 should not be seen as a foregone conclusion. Instead, this prediction represents a likely outcome in the absence of positive interventions. Thus, our findings can serve as a call-to-action for the development of programs that enhance the adaptive capacity of food production systems. A promising mitigation approach is genetic improvement of *Musa* to breed plantain that are tolerant of high temperatures, however, breeding programs are time-consuming and require significant investment (Ramirez et al., 2011). As noted above, Central and West Africa experienced major droughts in the 1970s and 1980s, and climate change may trigger future droughts that would reduce water available to irrigate crops such as plantain. Approaches that could mitigate this include storing rainfall in reservoirs (De Martino et al., 2012). The storm water could later be released into channels to irrigate farmland.

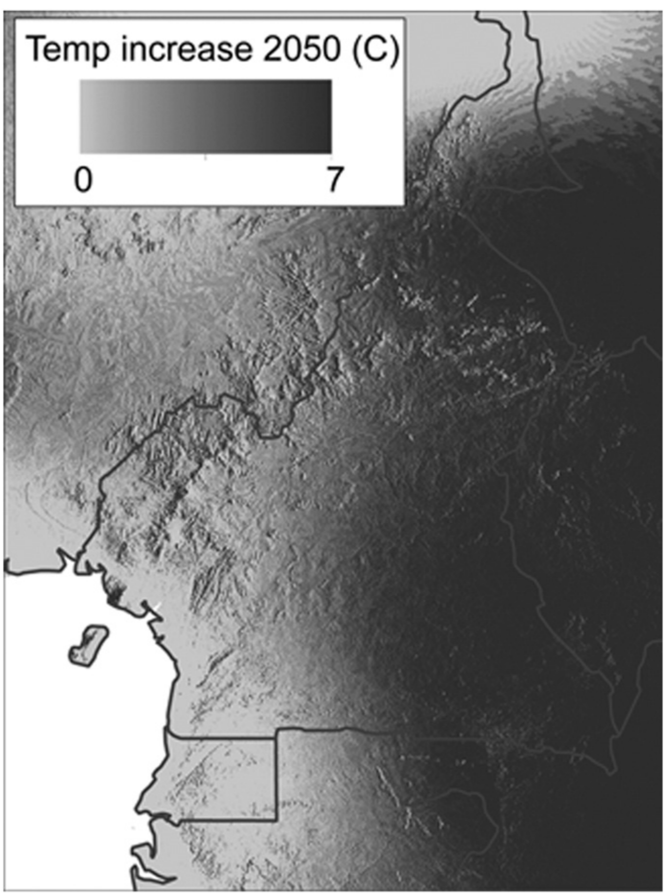

Fig. 5. Temperature increase in Central Africa in 2050 relative to the 1950–2000 baseline. Temperature in 2050 was predicted based on RCP 8.5 using the CCCMA_CANESM2 Generalized Circulation Model (Ramirez and Jarvis, 2015). Under this scenario, global CO_2 emissions increase from 2015 levels of 400 ppm to 590 ppm in 2050. In Cameroon, this would result in mean annual temperature of 27.8 °C. During the baseline period, the mean annual temperature was 24.3° (Hijmans et al., 2005). The mean increase in Cameroon would be 3.4 °C (range: −0.2–7.3 °C). Coastal regions are predicted to experience the low levels of warming, whereas in the eastern and northern regions models forecast a higher magnitude of warming.

Although climate change will likely impact social dynamics in diverse sectors of Central African society, the social relationships in subsistence populations, such as the Baka and Bakola in Cameroon (Nkem et al., 2013), are particularly susceptible to such disruption. Studies of indigenous hunters and foragers have demonstrated that climatic changes often bring about profound changes in social networks. For example, the destruction of crops by extreme weather events impacts social relations in hunter-gatherer communities by increasing rates of food sharing among families (Gurven et al., 2012). If climate change disrupts food supplies in Central Africa, there may be an increase in cooperation and resource sharing in the region's hunter-gatherers and subsistence farmers.

Aside from climatic variables, other factors may have affected plantain productivity, such as plot age. Field experiments with bananas have reported both positive (Sirisena and Senanayake, 1997) and negative (Smale and Tushemereirwe, 2007) effects of age on yield. In light of this, it is possible that the decline in plantain productivity observed in Cameroon was due to crop senescence. However, we can neither reject nor confirm this hypothesis as the available data were aggregated to the Region scale and do not allow us to separate new plantain areas from old plots.

There is no data to suggest that changes in fertilizer use explain the observed pattern of plantain yield. Quantitative data on plantain use for all ten Regions is only available beginning in 2009. Since then, there has been no change the percentage of farmers using fertilizers ($p = 0.38$), and only 30% of farmers use chemical fertilizers of any kind (Institut National de la Statistique, 2012). Prior to 2009, although quantitative data are unavailable, expert reviews indicate that infrastructural issues and import taxes have discouraged the widespread use of fertilizers (Yengoh and Ardo, 2014).

Our findings suggest a number of opportunities for future research. Our analysis used data on plantain yield, education outcomes, and average wealth level at the Region scale as data on income from plantain or spending on education were unavailable at the household scale. Nevertheless, focus groups indicate that parents use income from crop sales to buy children's school materials (van Vliet, 2010). Based on the focus groups carried out by van Vliet (2010), we hypothesized that plantain sales affect parental income, spending on education-related materials, and school attendance. However, this hypothesis awaits confirmation via livelihood surveys to quantify household income generated from crop sales and household expenditures on education.

We utilized dew point temperature to predict plantain productivity. A different climate variable that is more closely linked to plant productivity is vapor pressure deficit (VPD), which measures the extent to which drought stress causes plants to reduce CO_2 uptake and photosynthesis, closing their stomata to decrease water loss. Although various approaches have been proposed to estimate VPD over large geographic regions using a combination of satellite data, ground-based meteorological records, and statistical interpolation methods (e.g. Hashimoto et al., 2008; Zhang et al., 2014), this remains an area of ongoing research in the remote sensing community, and VPD estimates were not available for Cameroon for the duration of the study period.

Our analysis examined total annual precipitation in Cameroon, but the effects of rainfall on crop productivity depend on a variety of factors in addition to the total amount of rainfall, such as the intensity and duration of rain and the volume of runoff (De Paola et al., 2013). Future work could analyze extreme intensity rain events in the region and calculate runoff in different soil types. For example, the city of Douala, Cameroon, which is an important port and economic hub, currently receives >3000 mm of precipitation per year with >700 mm falling in the month of August alone (Institut National de la Statistique, 2012).

Climate models predict that due to climate change Douala will experience a decrease in the intensity and total volume of precipitation that will fall during any given storm (De Paola et al., 2014). Further, we assume that precipitation is uniform within 80 km grid cells, but there may be significant spatial variability in rainfall within a region of this size. Future research could use rain gauge data and numerical simulations to assess spatial variation in rainfall and runoff (De Paola and Ranucci, 2012).

In addition to climate change, future studies could investigate how factors such as dropping out of school to enter the workforce or due to illness affects educational attainment in Central Africa. Another unresolved question is the extent to which declines in crop yields in the region are due to factors such as reduced soil fertility caused by overcropping or use of non-improved cultivars that are susceptible to pests (Jarvis et al., 2012). Future work could also expand this analysis to assess whether plantain declines in Cameroon affect plantain availability in other Central African states that import Cameroonian crops. Since Cameroon is the breadbasket for neighboring countries such as Equatorial Guinea and Gabon, decreases in Cameroonian crop yields could affect food availability regionally.

5. Conclusions

Our results showed that over a 63-year period beginning in the 1950s Cameroon experienced a 0.8 °C increase in mean annual temperature. During a more recent 20-year period beginning in the 1990s, we found a 6.2% increase in dew point temperature, which is a measure of dryness. The 20-year study period was also characterized by declines of 43% in plantain productivity and six months in school attendance. We hypothesize that crop failures reduced the income of rural households resulting in decreased parental investment in education. Regression models fitted to climatic and agricultural data for the period 1991–2011 were projected forward to 2080 using IPCC Representative Concentration Pathways. According to the projections, there will be a further decline of 39% in plantain yields and 51% in education outcomes. Crop breeding programs have the potential to mitigate these climate change impacts.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.08.041.

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