LETTER

Vulnerability of sorghum production to extreme, sub-seasonal weather under climate change

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Abstract

In the tropics, extreme weather associated with global climate teleconnections can have an outsized impact on food security. In Ethiopia, the El Niño Southern Oscillation (ENSO) is frequently linked to drought-induced food insecurity. Many projections hold that El Niño events will become more frequent or more intense under climate change, suggesting that El Niño associated droughts may become more destructive. Agricultural vulnerability to extremes under climate change, however, is a function of exposure, sensitivity, and adaptive capacity. Sensitivity, in this context, can depend on sub-seasonal distribution of rainfall. This paper investigates crop sensitivity to sub-seasonal rainfall variability under climate change in a food insecure area of the Ethiopian highlands through analysis of process-oriented crop model results for the years 1981–2100 driven by 14 GCMs chosen for the ability to represent ENSO and rainfall characteristics of the study area. Further, adaptive capacity in the region is investigated with in-depth interviews and focus groups concerning the 2015 strong El Niño event. Crop model results for sorghum highlight that exposure and sensitivity to sub-seasonal extremes of low rainfall can diverge significantly from sorghum’s response to seasonal drought. Even though climate change will bring generally warmer and wetter seasons to the study area, there is an increased occurrence of sub-seasonal failure of rains early in the rainy season which will likely have negative impacts on sorghum yield. In-depth interviews show that biophysical constraints significantly reduce farmer adaptive capacity to this type of sub-seasonal extreme. This work highlights the need to consider sub-seasonal weather when assessing climate change threats to agriculture, particularly for subsistence farmers in the developing world.

Introduction

Climate change ushers in two types of exposure in agriculture: exposure to trends in mean climate conditions and exposure to changing weather variability and extreme events (O’Brien et al 2004). Projections of crop yield based on changes in the mean generally indicate that climate trends will have stronger negative yield impacts on tropical regions than in temperate regions (Challinor et al 2014). In food insecure regions such as Africa, grain yield of multiple crops is likely to decrease (Challinor et al 2007, Burke et al 2009, Schlenker and Lobell 2010, Thornton et al 2011). There are exceptions to these trends, such as portions of the Ethiopian Highlands, in which changes in mean climate conditions might lead...
to increased crop yield (Thornton et al. 2009, Dale et al. 2017).

Projections based on mean climate conditions, however, do not consider potentially important changes in the frequency or intensity of extreme events. Today, extreme weather and drought are major hazards for rainfed agriculture in the tropics (Dilley 2005). Extreme heat and drought damage crop output on a global scale (Leak et al. 2016) and recurring droughts result in widespread food insecurity and need for humanitarian intervention in sub-Saharan Africa (SSA) (Haile 2005). Furthermore, sequential or prolonged extremes can have adverse effects on the functioning of agroecological systems and on social resilience that last beyond the extreme events themselves (Rosenzweig et al. 2001).

The effects of extreme weather on agricultural systems under climate change is a pressing area of research (Easterling and Apps 2005) with extreme events under a changed climate having potentially larger impacts on crops than changes in mean climate parameters alone (Rosenzweig et al. 2001). Studies show that extreme heat associated with climate change, for example, will lead to widespread losses globally (Teixeira et al. 2013, Deryng et al. 2014). Drought risk is likely to increase under changing climate of the 21st century in Africa (Li et al. 2009). Sub-seasonal rainfall variability is a form of short duration extreme that can have large impacts on crop development and grain yield (Bolanos and Edmeades 1996, Barron et al. 2003, Harris et al. 2007, Ceglar and Kajfez-Bogataj 2012). These dry spells are known to pose significant risks to food security in regions of SSA, with the nature of their impacts highly dependent on soil and management (Barron et al. 2003).

In the Ethiopian Blue Nile Highlands, climate research has highlighted the need to study impacts around both the rainfall trend and El Niño–influenced extreme events (Mokria et al. 2017). Major drought events have widespread economic impact and reducing vulnerability to future climate variability is a key development initiative for Ethiopia (Conway and Schipper 2011). Droughts linked to the El Niño Southern Oscillation (ENSO) have been associated with famines in Ethiopia over hundreds of years (Wolde-Georgis 1997), and the recent 2015 strong El Niño event had widespread impacts to agriculture, livestock and food security (United States Agency for International Development (USAID) 2016). In the Nile Basin and the Greater Horn of Africa, a trend towards more frequent El Niño events over the 21st century may expand drought-prone areas (Gizaw and Gan 2017).

With this increasing potential for climatic drought in Ethiopia, the country is an important area in which to investigate climate change impacts to sorghum from extreme, sub-seasonal rainfall deficit.

Sorghum is of major importance to food insecure areas of Africa including Ethiopia (ICRISAT 1996). In SSA, it is often grown by subsistence farmers on marginal fields with low use of inputs (Reynolds et al. 2015). Its drought tolerance makes it an important crop for climate resilience in smallholder systems of Africa (Hadebe et al. 2017). In climate change simulations, though, sorghum in West Africa shows large decreases and high variability of yield driven by higher temperatures, but traditional varieties are somewhat more resilient (to yield variability) than current improved options (Sultan et al. 2013). Sorghum is also sensitive to dry spells (Rurinda et al. 2013). Differences in patterns of early and mid-season rain can have a dramatic effect on yield under current climate (Rurinda et al. 2014). Sorghum yield is most sensitive to drought after panicle initiation and post-flowering/early grain-filling (de Camargo and Hubbard 1999, Assefa et al. 2010). In East Africa, early growing season droughts were also shown to significantly decrease yield in sorghum (Elagib 2015). In the early growing season, during vegetative growth stages, water stress will affect rate of leaf appearance, plant height and leaf area (Blum and Arkin 1984, Assefa et al. 2010). Understanding the sensitivity of sorghum to region-specific timing of dry periods will be particularly useful for crop breeders to create phenologically- and physiologically-appropriate cultivars (Rao et al. 1999, Sultan et al. 2013), however, studies of climate change and water stress have been mainly concerned with annual and seasonal measures of drought (Li et al. 2009, Elagib 2014, Guo et al. 2016). Our study seeks to assess how sub-seasonal rainfall extremes under a changing climate will impact important crops like sorghum in ways not seen by seasonal measures of drought, especially in areas of the developing world faced with chronic food insecurity.

Data and methods

This study uses mixed methods approach for understanding vulnerability of sorghum production to climate change and sub-seasonal rainfall variability in the context of the Ethiopian Highlands. Process-oriented crop modeling allows assessment of sorghum’s sensitivity to rainfall extremes under climate change. Survey and interview evidence from the 2015 strong ENSO event will illustrate adaptation options and constraints to adaptation in this sorghum-based production system of the Ethiopian highlands. The Blue Nile Highlands is a region of subsistence agriculture, with mixed crop-livestock systems. We focus specifically on a relatively warm and dry portion of these highlands in which climate vulnerability is high and in which sorghum is an important crop (Simane et al. 2016).

Crop model data and resampling for extreme events

To unravel the influence of sub-seasonal rainfall on sorghum under climate change for this study area in Ethiopia, this study utilizes a synthetic dataset from a
previous climate change impacts study (Eggen et al in review). That study uses crop modeling software, the Decision support tool for agrotechnology transfer 4.6 (DSSAT) (Hoogenboom et al 2015), calibrated for a local varietal of sorghum for our study area using local management norms and site-specific soil measurements (see supplemental information, appendix A is available online at stacks.iop.org/EnRL/14/045005/mmedia). That study ran climate change scenarios using modeled weather data (including daily maximum and minimum temperature and daily rainfall) from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) with representative concentration pathways (RCP) 4.5 and 8.5.

The number of simulated observations in the modeled dataset is nearly 50 000 observations for the years 1981–2100. There are 16 management-soil treatments (4 planting dates × 2 fertilizer regimes × 2 soil composites) with 14 climate models realizations for each year 1981–2010 and 28 climate model realizations (14 models × 2 RCPs) for each year 2011–2100. More information about this dataset may be found in the supplemental information appendix B. These simulation results were examined statistically for sensitivity to seasonal drought and measures of extreme early rain deficit based on farmer interviews relating to the 2015 strong El Niño event.

Climate scientists typically define extreme precipitation using the 10th percentile of the rainfall distribution as the threshold (Easterling et al 2000, Knapp et al 2015, Mokria et al 2017). This same threshold has also been applied in our study area, the Blue Nile Highlands, in a long-term study of El Niño influence (Mokria et al 2017). For rainfall, the 10th percentile of the historical CHIRPS-derived rainfall record for the years 1980–2016 for each month is used in the analysis to signify an extreme dry condition.

Probability distribution functions of mean yield were created from the dataset of crop model simulations using a random sub-sampling process (Efron 1982). Non-parametric techniques such as this are valuable when data are not normally distributed and when investigating the statistical properties of sub-populations of large datasets (Hollander 2013). For the set of observations with an extreme weather condition and the set of observations without the condition, the mean yield of 50 treatments was taken 5000 times to create distributions of mean yield in the presence and absence of the extreme weather. Probability density functions were then generated from the samples of the means of the grain yield to illustrate the effect of the chosen extreme weather conditions.

**Climate model selection**

Projections of future climate were drawn from the Coupled Model Intercomparison Project, Fifth generation (CMIP5; Taylor et al 2011). CMIP5 GCMs vary widely in their representation of rainfall seasonality, variability, and teleconnections relevant to simulation of extreme weather (Jury et al 2004, Bhattacharjee and Zaitchik 2015, Siam and Eltahir 2017). Model representation of ENSO variability and teleconnections to East Africa are particularly important. In Ethiopia, since 1811, 40% of extreme dry years in the Upper Blue Nile correspond to El Niño events (Mokria et al 2017). Studies have also shown that the strength of ENSO events is negatively associated with precipitation in Ethiopia and the Blue Nile Highlands (Segele and Lamb 2005, Block and Rajagopalan 2007, Segele et al 2009).

To select reliable GCMs, then, we focus on model representation of ENSO variability, of ENSO teleconnections to East Africa, and of basic seasonality in the study region. Statistically downscaled realizations for representative concentration pathways 4.5 and 8.5 were obtained for 22 GCMs participating in CMIP5, via the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP; Thrasher et al 2012). These candidate GCMs were then chose from the literature for their representation of ENSO or their performance relative to rainfall in the Nile basin (Cai et al 2014, Bhattacharjee and Zaitchik 2015, Siam and Eltahir 2017). We selected 14 models that perform reasonably with respect to these criteria (table 1). Our selection process was inclusive rather than restrictive; if a study found that the GCM performed well with respect to one of the listed criteria, and if no other study specifically ruled the model out, then it was included in our ensemble.

**Interviews and focus groups**

Interviews and focus groups were conducted with farmers in the study area in December 2016–January 2017 as the farming season was ending. Interviews addressed management and agronomic challenges of the production system. A total of six individual, in-depth, semi-structured interviews and three focus groups with a total of 12 participants were carried out in 2 study villages used in the crop modeling study (Eggen et al in review) that were also sampled as part of the 9 study villages used in a larger socio-economic survey (see below). All 9 of these villages are located in a subsistence-oriented, sorghum-growing agroecosystem (Simane et al 2015). Farmers were recruited in equal groups based on the size of their landholdings (Large: >2 ha, medium: 1–2 ha, small: <1 ha). This was done since management is likely to vary based on landholding size, but in no sense was this small sample intended to be representative of the larger communities.

Interview questions focused on the farm management for the 2014, 2015 and 2016 growing seasons. Focus groups concentrated on finding a consensus opinion of management norms and agronomic challenges without prompting for specific years. In both settings, open form questions probed major
challenges to farming in the area and the decision parameters around crop management including crop choice and rotation, planting dates, fertilizer use, and soil management. Reaching a consensus in focus groups was intended to understand how specific management parameters used in the crop model calibration field trials compared to wider held norms. It also generates differences of opinion which provides insight into who, where, and when management may be constrained. In both cases, experiences from the recent 2015 strong ENSO-influenced season were a major subject of discussion.

Additionally, the study uses data from a larger-scale socioeconomic survey completed in November/December 2014 and December 2015/January 2016. These survey respondents were drawn from randomly sampled villages across the study area (table 2). Survey-provided data on participants’ crop choices and crop mix in those two seasons will be presented in discussion below to supplement the qualitative data from one-on-one interviews and focus groups.

Results

Crop model simulations provided thousands of realizations of sorghum yield for the study area. These data are used below to understand the impact of seasonal and sub-seasonal rainfall deficits on sorghum productivity in a changing climate. First, we consider farmers’ experiences and reactions to the 2015 El Niño event, as

Table 1. List of climate models used in crop simulation.

| Model     | Agency                                           | Reason                                                                 | Citations                          |
|-----------|--------------------------------------------------|------------------------------------------------------------------------|------------------------------------|
| CanESM2   | Canadian Centre for Climate Modelling and Analysis, Canada | Significant historical correlation for upper Blue Nile in mean and seasonality of rainfall, skill in capturing extreme El Niño | Cai et al (2014), Bhattacharjee and Zaitchik (2015) |
| CESM1-BGC | National Center for Atmospheric Research (NCAR), USA | Significant historical correlation for upper Blue Nile in mean, variability, and seasonality of rainfall, skill in capturing extreme El Niño | Cai et al (2014), Bhattacharjee and Zaitchik (2015) |
| CNRM-CM5  | National Centre of Meteorological Research, France | Skill in capturing extreme El Niño, captures ENSO teleconnection with Nile Basin | Cai et al (2014), Siam and Eltahir (2017) |
| CSIRO-Mk3-6-0 | Commonwealth Scientific and Industrial Research Organisation, Australia | Significant historical correlation for upper Blue Nile in mean, variability, and seasonality of rainfall | Bhattacharjee and Zaitchik (2015) |
| GFDL-CM3  | NOAA Geophysical Fluid Dynamics Laboratory, USA | Skill in capturing extreme El Niño, captures ENSO teleconnection with Nile Basin | Cai et al (2014), Siam and Eltahir (2017) |
| GFDL-ESM2G | NOAA Geophysical Fluid Dynamics Laboratory, USA | Skill in capturing extreme El Niño, captures ENSO teleconnection with Nile Basin | Cai et al (2014), Siam and Eltahir (2017) |
| GFDL-ESM2M | NOAA Geophysical Fluid Dynamics Laboratory, USA | Skill in capturing extreme El Niño, captures ENSO teleconnection with Nile Basin | Cai et al (2014), Siam and Eltahir (2017) |
| IPSL-CM5A-LR | L’Institut Pierre Simon Laplace, France | Skill in capturing extreme El Niño, captures ENSO teleconnection with Nile Basin | Bhattacharjee and Zaitchik (2015) |
| IPSL-CM5A-MR | L’Institut Pierre Simon Laplace, France | Skill in capturing extreme El Niño, captures ENSO teleconnection with Nile Basin | Bhattacharjee and Zaitchik (2015) |
| MRCGCM3   | National Institute for Environmental Studies, Japan | Significant historical correlation for upper Blue Nile in mean, variability, and seasonality of rainfall and strength of global climate teleconnections | Cai et al (2014), Bhattacharjee and Zaitchik (2015) |
| MPI-ESM-LR | Max Planck Institute for Meteorology, Germany | Skill in capturing extreme El Niño | Cai et al (2014) |
| MPI-ESM-MR | Max Planck Institute for Meteorology, Germany | Skill in capturing extreme El Niño | Cai et al (2014) |
| MRI-CGCM3 | Meteorological Research Institute, Japan | Skill in capturing extreme El Niño | Cai et al (2014) |
| NorESM1-M | Norwegian Climate Center, Norway | Skill in capturing extreme El Niño | Cai et al (2014) |

Table 2. Number of villages and participants in socioeconomic survey.

| Year | Number of villages | Number of respondents |
|------|-------------------|-----------------------|
| 2014 | 9                 | 98                    |
| 2015 | 9                 | 95                    |
an example of extreme drought. This leads into analysis of crop simulations to characterize sorghum sensitivity to rainfall deficits. Finally, we apply this understanding to project sorghum yield sensitivity under future climate conditions. The large majority of rainfall in the study area falls between May and October, with a peak in July and August. June rainfall, which is critical to planting and early development of field crops, has a lower correlation (0.29) with seasonal rainfall total compared with July and August correlation to seasonal rainfall (0.67 and 0.73, respectively) based on Climate Hazard Group Infrared Precipitation with Stations (CHIRPS) product (Funk et al 2015).

The 2015 ENSO event and adaptive capacity

In the study area, the 2015 ENSO-influenced cropping year had lower rainfall than any in recent history. This provides a view into how farming communities cope with extreme weather that may become prevalent under climate change. Cropping season rainfall is typically lower in ENSO years (figure 1), but the strong and extended El Niño of 2015 led to rainfall that was about 15% less than even recent El Niño history (figure 1)8. It was also the second hottest El Niño over these 25 years. Mean rainfall over these years was 890 mm and average temperature was 21.7 °C.

Farmers stated repeatedly that sorghum is their most important subsistence crop. For the study area, the major rotation in the fields is sorghum with tef (Simane et al 2013). Maize is grown primarily in garden plots and fields adjacent the home (all referred to as homestead plots in the text). In the survey years, sorghum and tef were the most important crops in acreage. In 2014 nearly all households grew sorghum, but in 2015, fewer households grew sorghum and it decreased significantly in total acreage (table 3).

Farmers reported in interviews and focus groups that the lack of rain early in the 2015 rainy season was more severe than any year of their lifetime with several even stating that 2015 was significantly worse than specific seasons of the 80 and 90 s that were associated with widespread famine. Although total failure of a sorghum crop in the study area is rare, the lack of early season rain in 2015 caused significant reduction in crop performance, with some farmers reporting failure of sorghum crops. This is consistent though with findings in Sudan of the importance of early season drought on historical sorghum yield (Elagib 2015) even though the most water intensive period for sorghum is just before and after flowering (Assefa et al 2010). Some farmers reported coping with the ENSO event by replanting sorghum fields twice after seedlings died or did not emerge. Others planted other

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8 Note that the limited timeseries data presented in figure 1 are consistent with the findings of Mokria et al (2017) which used a 200-year rainfall reconstruction from tree ring data for another study site also in the Blue Nile Highlands.
crops such as tef after sorghum failure as a coping mechanism, which may explain some of the reduction in sorghum area for 2015 seen in the survey (table 3).

Despite the difficulties in the 2015 ENSO season, interviews showed that farmers still value sorghum for its ability to withstand dry spells and to provide them subsistence production with little or no fertilizer. That is consistent with subsistence management of traditional varietals of sorghum across SSA (Sultan et al 2013, Reynolds et al 2015). The farmers say it is the only crop option that can succeed on some of their most marginal fields in terms of soil texture and morphologic position. This is a significant constraint on their adaptive capacity. They see maize—a crop that is popular elsewhere in the Ethiopian Highlands, and that might be used as a substitute for sorghum—as having great potential, but feel it is only worth the risk where they may manage fields with inputs of organic matter to aid water retention and when they have the resources to acquire inorganic fertilizer. Currently that is primarily in homestead plots that are also more easily protected from pests and theft.

Both maize and sorghum here are long season crops. Appropriate crop selection for climate change and interannual variability is a likely adaptation strategy for increasing and maintaining yield in SSA (Bodin et al 2016). Here we see that, with current varietals available to these Ethiopian farmers, crop substitution of maize for sorghum is both unlikely and unhelpful. This information of farmers’ experience of the biophysical limitations among their current crop mix is essential for crop breeders to create varieties which work within the constraints of the system.

Extreme thresholds of sub-seasonal rainfall for sorghum and maize

Given farmers’ stated experiences with the 2015 ENSO event and literature on sorghum in East Africa (Elagib 2015), we examine the sensitivity of sorghum yield both to seasonal drought—i.e. years that have low total rainy season precipitation—and to early season rainfall deficits. Planting occurs in late-April and early-May, and early season deficits are defined using rainfall in June—when the plant should be experiencing rapid vegetative growth and steadily increasing water demand (Assefa et al 2010). June rainfall totals that fall in the bottom 10 percent of the historic record are defined as sub-seasonal extremes.

Figure 2 shows sorghum response to seasonal rainfall drawn from simulations with DSSAT using the 1981–2010 baseline simulations. The figure shows the 10th percentile of the rainfall distribution as a measure of an extreme condition for growing season rain: a threshold of 770 mm. The figure shows that for contemporary, baseline simulations (1981–2010), yields drop when rainfall is below the 770 mm threshold shown here. The figure, however, shows that the drop off in yields also occurs for higher rainfall totals and maximum yields are achieved at a rainfall level close to the 770 mm threshold (~810 mm). This suggests that across the range of seasonal rainfall, yield is highly variable and, in many cases, seasonal rainfall is not limiting.

The yield response to low June rainfall is more pronounced. Figure 3 shows how June rainfall is associated with sorghum yield in the baseline simulations from 1981 to 2010. The tenth percentile of rainfall in June, our definition of an extreme event, is 78 mm and shown on the figure. This threshold corresponds with two recent poor rainfall years, 2015 and 1982, which had rainfall of 72 mm and 83 mm respectively for June and were tied to very strong ENSO events. Figure 3 shows that yields fall significantly around the 10th percentile of rainfall of 78 mm and that they are generally higher above that threshold.

Exposure and sensitivity in resampled yield distributions

Crop model simulation results were resampled to investigate the influence of these extreme seasonal and June rainfall conditions on the distributions of sorghum mean yields (figures 4 and 5). Figure 4 shows probability density distributions of sorghum mean yield when seasonal rainfall is below 770 mm and figure 5 shows the effect when June rain falls below 78 mm. The probability density curves were also scaled to give the two distributions a meaningful, relative size based on occurrence of the weather condition in the climate modeled data.

Sensitivity to mean climate change can be seen in the four panels of figures 4 and 5 as the overall mean yields (dotted distributions) move left along the x-axis. Sensitivity to extreme rainfall is shown by the difference between the extreme rainfall condition-generated distribution (blue with yellow line) and the distribution without the extreme condition (green with red line) in each panel. The change in exposure to the extreme condition is found by looking at the change in relative sizes of the distributions (labeled their proportion) among the four panels (a)–(d).

Extremely dry Junes drive significant reductions in yield (high sensitivity) (figure 5) while the resampled simulation means are not sensitive to seasonal drought (figure 4). Sorghum yields in years with poor June rains are 40% less than years without a dry June for the baseline case. This is a major concern since sorghum will be increasingly exposed to extremely dry early seasons, the proportion of the dry condition increases in each panel of figure 5. In figure 4 with seasonal drought, the mean and extreme weather distributions overlap illustrating sorghums resilience in low rainfall seasons. In contrast to early season drought exposure, with climate change, rains are increasing in the study area and sorghum may be less exposed to rainfall less than the 770 mm threshold.
Discussion

This study answered the call of Challinor et al (2010) to disaggregate the influence of sub-seasonal weather factors from the variability in yield seen in simulation. The result confirmed the empirical relationship with early drought and sorghum seen in Elagib (2015) and provides contrast to the focus on the period of flowering as the riskiest point of the season for water stress in sorghum (Assefa et al 2010). While the biophysical water demand of sorghum at flowering is high, in this study area, it is not a risk. July and August rains are...
highly correlated with seasonal total. Flowering of this variety occurs in August when rain is heavy and reliable. Early planting ensures there is plenty of water at boot stage, flowering and early grain fill; all occurring from late July to early. Early planting, though, also increases exposure to less reliable June rains.

Our interviews show that poor early season rain is a current challenge and simulations show this challenge could become more acute with climate change. Using a process-oriented crop model with numerous combinations of weather and local management was important for illustrating this point. Other studies dealing with sorghum and the timing of rainfall have been based on limited weather observations (Rurinda et al. 2013) or empirical relationships (Elagib 2014) making it difficult to extrapolate to climate change study. Here we also respond to studies calling for location-specific understanding of crop and climate change vulnerability for the purposes of sorghum breeding (Rao et al. 1999, Sultan et al. 2013). Sultan et al. (2013) also used a process-based model for sorghum in West Africa uncovering temperature as a driver of decreasing yields especially in hybrid sorghum. Since ours is a climate change study, increasing temperature is an important driver by itself and in terms of plant water demand. We investigated the role of higher temperatures and extreme temperatures and find that, for our study area, it does not have the explanatory power of extreme June rainfall deficit (see supplemental information, appendix C). Our study illustrates what is missed impacts assessments that aggregate seasonal drivers (e.g. Schlenker and Lobell 2010) and then shows that subseasonal drivers may also change in their influence with climate change.

One limitation of the study is that subseasonal distribution of rainfall in the future is deeply uncertain. It is difficult to quantify this uncertainty in a completely meaningful way, as it derives from future emissions trajectories, limitations in climate models evident in current performance, and unknown limitations in climate models’ ability to capture regional precipitation responses to future greenhouse gas forcing. Here we have attempted to bracket this uncertainty by using output from multiple downscaled global climate models for two emissions scenarios, but only using models that perform credibly with respect to key drivers of Ethiopian summertime precipitation variability. Our ensemble of 14 models and 2 RCPs and resampling analysis thus provides a reasonably robust, albeit imperfect, representation of current uncertainty in future meteorological conditions. As climate change progresses—and, hopefully, as models improve—it
will be important to see if early season drought is more prevalent in this study area.

Future study could more deeply investigate the role of management and adaptation in dealing with extremes under climate change. Our interviews suggest that with sorghum these farmers are highly exposed to early season drought with few adaptation options. We used a range of planting dates but we did not explicitly assess yields among different planting dates. Even if we had done that, it would have assumed a degree of static management which is a shortcoming of many climate change studies (Challinor et al. 2014). Hybrid sorghum has potential to address yield decreases in sorghum (Rao et al. 1999), but in African study areas like ours such adaptations to management would likely need to coincide with social and environmental interventions that allowed greater irrigation and fertilizer use. Such intensification of the sorghum system would include environmental consequences (Reynolds et al. 2015).

The simulations and our farmer interviews suggest that the goal, at least in the short term, should be to find a sorghum varietal which, with extreme dry early seasons, can still deliver mean yields more in line with the overall or non-dry June means. The impacts to food security are current and increasing and not simply a future risk of climate change. One farmer said, ‘If sorghum does poorly, there will be no celebrations that year,’ to illustrate how important the crop is to the social functioning of the village. These farmers would be more likely to try new sorghum varieties now than they would be to substitute other crops. Varieties that can produce with low inputs on poor soils are particularly needed. If access to such robust varietals can increase food security now, then in the future these farmers may be able to make investments in their farms that allow them to try new higher productivity improved varietals, including of other crops like maize, but that will take time.

**Conclusion**

Sub-seasonal rainfall extremes that affect sorghum in the Blue Nile Highlands of Ethiopia have the potential to drastically affect food security in the future under climate change. This vulnerability is not captured by analyses that consider only trends and inter-annual variability in climate, or by studies that approximate crop yield on the basis of seasonal conditions. One limitation of the study is the uncertainty of future rainfall in GCMs. Sorghum will be highly sensitive and increasingly exposed to extreme dry early seasons under climate change but, currently, adaptive capacity is low in the management of sorghum even though it is of major importance to food security. Future study
should focus on whether management can play a role in adaptation of resource-constrained African sorghum productions systems. Availability of new and improved varieties will likely need to be part of the solution to decreasing vulnerability to extreme events, but this will only succeed if plant breeders are aware of the agronomic and biophysical constraints that face farmers in this region, and indeed in many regions that depend on low input subsistence production systems.

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