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Review

What role can crop models play in supporting climate change adaptation decisions to enhance food security in Sub-Saharan Africa?

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A B S T R A C T

In Sub-Saharan Africa (SSA) efforts to achieve food security are challenged by poverty, low soil fertility, unequal global trade relationships, population growth, weak institutions and infrastructure, and future climate changes and variability. Crop models are the primary tools available to assess the impacts of climate change and other drivers on crop productivity, a key aspect of food security. This review examines their role and suitability for informing climate change adaptation decisions in the SSA context. Perception of climate change is rarely the only factor leading to changed farming practices, with labor availability, recent extreme climatic events (floods or droughts) and access to formal credit, constituting the main factors farmers respond to. Further, farmers' socio-economic status constrains the adaptations they make in response to these drivers. Many crop modeling studies reviewed investigating climate change adaptation currently do not capture many of these drivers, adaptations nor constraints. However, a number of areas were identified where crop models could aid in adaptations decision-making. For instance, crop models can: test which changes farmers are making are most robust to future climate scenarios; be used as tools for experimentation in farmer organizations to build farmer capacity, minimize risk and empower farmers; be linked to economic, farm systems or livestock models to widen the scope of potential impacts, adaptations and farmer constraints considered, and to probe the interactions of cropping systems with other systems; and evaluate various indicators of resilience. Finally it is suggested that one of the greatest benefits of linking crop models across disciplines and in integrated assessment frameworks may be providing a platform to bring specialists and stakeholders from diverse backgrounds together to assess climate change adaptation options to enhance food security in SSA.

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1. Introduction

Hunger is prevalent in Sub-Saharan Africa (SSA) and the region faces considerable challenges to achieving food security due to a complex mix of factors that include widespread poverty, high dependence on degraded natural resources, unequal global trade relationships, population growth, and weak institutions and infrastructure (Brown, 2009; von Grebmer et al., 2008; Wheeler and von Braun, 2013). Food security encompasses food availability (crop productivity is the key determinant but it also includes food waste), food access (reflects incomes and the ability to purchase food, as well as market factors), stability of access and availability (influenced by climate variability and prevalence of extreme events) and food utilization (linked to the nutritional quality and safety of food) (FAO, 2002; FAO, IFAD and WFP, 2013). In the semi-subsistence conditions typical in many regions of SSA, crop productivity has an important influence on food security (Ringler et al., 2011). It both contributes directly to household food availability, as well as influencing incomes, local food prices and farmers' ability to invest in other cropping, farming and livelihood activities (Vermeulen et al., 2012; Jalloh et al., 2013). As climate change and variability are expected to produce negative impacts on crop growth, it can be expected to further challenge efforts to achieve household and regional food security (Easterling et al., 2007; Goklany, 2007; Meinke et al., 2009; Mertz et al., 2010; Wheeler and von Braun, 2013).

Despite the complexity and uncertainty associated with farming systems and food security, there is an urgent need for science to support adaptation decision making at all levels (Cash et al., 2003; McIntyre, 2009; FARA, 2013). Crop models are the primary tool available to assess the impacts of climate change on crop productivity, a key determinant of both food availability and access, as cropping represents an important income source in many parts of SSA. As such, they will have an important role to play in describing how cropping systems respond to key drivers. It is largely recognized that they must be improved to better account for the impacts of elevated CO_2 concentrations, high temperatures at critical crop growth stages, changing pest and weed dynamics (Soussana et al., 2010), better quantify model uncertainty (Challinor et al., 2009) and be better calibrated and validated for local conditions. Rötter et al. (2011) present a good summary of the present challenges to improve crop models. What is less clear from the literature is how these tools should be used in informing climate change adaptation decisions beyond the prediction of climate and standard management impacts on yield.

A starting place could be looking for evidence of farmer's actual adaptations, key drivers and constraints (Howden et al., 2013), as documented in social sciences literature (Mertz et al., 2009, 2011; Gbetibouo et al., 2010; Bryan et al., 2009) to investigate if crop models adequately represent reality and to identify potential synergies between the contextual nature of these studies and the predictive power of crop simulation models to better inform and support adaptation decisions. Some options that can impact crop yields may not be easily testable in current approaches to the application of crop models, and adaptations will need to be evaluated in a broader framework which integrates crop models with expertise and knowledge from outside the realm of modelers and agronomists. However, there are two key reasons for trying to bring these two ways of knowing about agricultural adaptations closer together. Pragmatically, the successful uptake by farmers of expert generated adaptations options will be more likely if they are involved and their input incorporated from the beginning. Secondly, adaptation science, in which crop models produce quantitative information, is powerful in that it generates knowledge on the set of feasible future options for landuse change (Hulme, 2011; Weichselgartner and Kasperson, 2010). Excluding farmers from the process of knowledge creation while including those who fund research has implications for whose value system shapes scientific endeavors and ultimately the direction of agricultural development (Hulme, 2011; Sarewitz, 2004).

This paper proposes to review the crop modeling and social sciences literature on adaptation studies in SSA to attempt to answer the following questions: (1) What are the main drivers of change farmers respond to and what factors enable adapted cropping systems? (2) How does the current application of crop models in adaptation studies match with the reality of farmer changes in cropping systems? and (3) How can knowledge and methodologies from crop modeling and the social sciences be combined to lead to actionable adaptation knowledge?

2. Sub-Saharan African context: climate change predictions and need for adaptation

2.1. Climate change forecasts for SSA

There is a consensus among the 21 CMIP3 GCMs that median temperatures increases across Saharan, East, West and Southern Africa will be between 3 °C and 4 °C by the end of the century relative to the period 1980–1999 for June–July–August for the A1B SRES scenario (Christensen et al., 2007). Rainfall evolution will vary between regions. Predictions for a decrease in mean precipitation for Southern Africa and an increased average in East Africa are considered robust across models (Christensen et al., 2007) and in agreement with Hulme et al. (2001), However, there is no model consensus for changes in West Africa's precipitation amounts with divergence in predicted changes between an 18% decrease to an increase of 16% for the same emissions scenario and period. The lack of agreement between GCMs is related to their coarse resolution and the complex bio-physical factors that determine precipitation in West Africa (Christensen et al., 2007). Extreme events such as droughts and prolonged periods of high temperatures are more likely and their prediction more robust than changes in mean precipitation (Christensen et al., 2007; Challinor et al., 2007; Field et al., 2012).

2.2. Climate change impacts on food security

Despite agriculture's prominent role in national economies across SSA, large parts are currently net grain importers (e.g. West Africa) (Brown, 2009). This results in lower grain prices on domestic markets and a crude assumption is that this translates into improved food security for net food buyers. Climate change is expected to contribute to higher world market prices for cereals which would make food less accessible for net importers and buyers (Wheeler and von Braun, 2013). In terms of expenditures, many smallholder farmers are net buyers as they often purchase grain during the hunger season at a higher price and are forced to sell at harvest when prices are lowest- or even before harvest to obtain credit and buy food (Brown, 2009). Further, repeated extreme events like droughts or heat waves reduce poor people's ability to cope with crop failures or maintain food security as their savings, productive assets and human capital are more frequently diminished (Devereux, 2001; Thornton et al., 2011). Globally higher food prices resulting from negative climate impacts on key crops, are predicted to result in a 1.3% decrease in food availability across SSA by the middle of the century (Ringler et al., 2011). However, there is likely to be great variability in how this decline in access will be distributed across regions and groups (Ringler et al., 2011). In a study to identify vulnerable hot spots of food insecurity in SSA in 2030, Liu et al. (2008) found that the impacts of climate change are expected to be worse for food security than for food availability or crop productivity alone.

2.3. Climate change impacts on crop productivity in Sub-Saharan Africa

Numerous crop modeling studies have attempted to evaluate potential climate change impacts on SSA cropping systems (Butt et al., 2005; Schlenker and Lobell, 2010; Müller, 2009), though as Muller et al. (2011) note in a review of impact studies for SSA, it is difficult to generalize their findings due to different assumptions and methods regarding GCMs, emission scenarios, downscaling, crop models, locations, scales, cropping systems and timeframes considered. In some cases, weather generators have been used to generate daily weather variables from monthly GCM outputs (Liu et al., 2008), though such techniques are known to underestimate the severity of extremes, expected to be significant for future impacts (Muller et al., 2011). As an example, consider the 16 agricultural impact studies across West Africa reviewed by Roudier et al. (2011) with a total of 190 simulations (not accounting for CO_2 fertilization though using various emission scenarios, crops, GCMs, models and areas). They found median yield losses predicted for temperature increase across all crops for West Africa was 15% assuming no changes in precipitation, while precipitation decreases or increases result in yield losses of 21% and 10%, respectively. Yield losses will be larger for the Sudano-Sahalian zone than for coastal areas in the Guinean zone as warming is moderated by vicinity to the ocean. When CO_2 fertilization effects are included there is again divergence on expected outcomes, with Muller et al. (2011) predicting yield increases by 8% for Africa by 2046–2055 relative to 1996–2005 and Parry et al. (2004) finding no significant impact until 2080. The differences highlight the uncertainty concerning plant response to increased atmospheric $[CO_2]$ at field and larger scales, and its representation in crop models, particularly in combination with water stress (Ainsworth et al., 2008; Tubiello et al., 2007; Soussana et al., 2010).

Although it is difficult to compare different studies for reasons outlined above, comparing across different studies can give insights into the relative sensitivities of crops, as well as main drivers of changes. The impact studies reviewed for West Africa suggest that mean yields of the main crops: maize, sorghum, millet, cassava and cowpea, are all predicted to be both positively and negatively impacted by climate change depending on the choice of GCM, SRES scenario and crop modeling approach (Roudier et al., 2011). Using a panel analysis for SSA across a range of 16 GCM outputs, maize, sorghum and millet yields were all predicted to decrease by 2055 compared to base-line yields from 1961 to 2000 (Schlenker and Lobell, 2010), though maize yields are the most sensitive with median yield losses predicted at approximately 23%. Butt et al. (2005) simulated greater yield losses for sorghum (between 11% and 17%) than for maize (12%) and millet (6–12%) in Mali using EPIC with climate outputs from CGCM and HadCM to 2030. Likewise, using GEPIC to predict yield changes to 2030 in Sub-Saharan Africa, Liu et al. (2008) found sorghum yields would not change, while maize (3–4%) and millet (7% and 27%) could both expect yield increases. Similarly, in an application of CROPSYST in Cameroon, sorghum yields (−7% to +8%) were found to be more negatively affected than maize (+7% to +16%) by 2020 for HadCM3 and GISS and A1 and B1 (Tingem and Rivington, 2009).

Across much of SSA, the crop modeling studies reviewed predict mean temperature increases, elevated $[CO_2]$, and increased frequency of high temperatures, droughts and floods to be key drivers of future impacts. The key driver of future climate change impacts in the analysis of Schlenker and Lobell (2010) was mean temperature increase as this had a much larger effect on relative yield changes than precipitation. Many of the crops evaluated are already near their optimum temperature for development and are thus sensitive to temperature increases (Hatfield et al., 2011). However, this may not reflect the reality of the climate sensitivities of these crops, rather than the standard deviations of historical rainfall amounts are greater than the standard deviation of predicted changes (Schlenker and Lobell, 2010) and that current low yields and cropping systems already reflect the high variability in precipitation. In the Tingem and Rivington study (2009), increased temperatures were determined to be the main driver of yield decreases via accelerating phenological development, especially to the 2080 horizon. The effects of elevated $[CO_2]$ offset the yield losses associated with increased temperatures to 2020. Challinor et al. (2007) and Wheeler et al. (2000) reported that extreme events are expected to have large negative impacts on crop productivity. Simulations presented in Porter and Semenov (2005) suggest that greater annual temperature variability (doubled SD) resulted in equivalent yield losses as a 4 °C increase in average temperature and more than doubled the coefficient of yield variation of wheat. Non-linear temperature response of respiration and high temperatures effects on reproductive fertility were stated as likely explanations.

The studies are limited in enabling an understanding of what the future of agriculture will be, as is illustrated by the variation in expected impacts as a function of the study methodology. Adaptations or likely evolutions of farming practices were only considered in the studies of Tingem and Rivington (2009) and Butt et al. (2005) for the studies reviewed in West Africa. While process based models can allow for this, it is a limitation to the application of statistical models (Challinor et al., 2009) as is their predictive inapplicability outside the range of historical temperatures they are developed with. However, in the meta-analysis of Roudier et al. (2011) statistical and process-based models both predicted the same yield decrease of −12% though the process based models had a greater dispersion as they were able to capture non-linear responses. In the application of the process based models, designed at the field level, few explicitly justified or stated how they scaled their models to larger areas. Further crop models are currently limited in their ability to simulate elevated $[CO_2]$ (Soussana et al., 2010), crop response to temperature at specific growth periods (Boote et al., 2013), and the interaction of these with water and nutrient stress and photoperiod (Craufurd and Wheeler, 2009). Finally, intercrops and crop rotations are very important components of many cropping systems and yet there have been relatively few efforts to test the robustness or skill of crop models to simulate these systems (Challinor et al., 2007).

3. What is known about adaptation options in SSA?

3.1. Farmer perceptions of climate change and major drivers of change in their practices

Whether or not farmers correctly discern climate changes is an open question and may simply depend on specific circumstances. South Africa, Thomas et al. (2007) and Gbetibouo et al. (2010) concluded that the farmers they consulted were able to correctly describe and identify changing climates (or weather patterns) over the past 50 and 20 years, respectively. In Kenya, Bryan et al. (2013) report that the large majority of farmers reported increased average temperatures and decreased average precipitation, though these trends were not actually present in the climate data. Likewise, in Thomas et al. (2007), farmers in three regions of South Africa reported they perceived increased rainfall variability, whereas only in two cases was this supported by climate data. Also, in one community, farmers perceived less rainfall and a shorter growing season, whereas an analysis of climate data did not detect a drying trend. Conversely, other studies suggest that what farmers perceive as climate changes are not always linked to long term changes, but to recent and short term trends (Bryan et al., 2009, 2013). Mertz et al. (2009) found farmers in the Sahel-Sudanian zone and the Sudanian zone of Senegal were able to recall extreme events very well.

Regardless of whether or not they correctly perceive climate change, perception alone does not appear to lead to changed practices. Fewer than 50% of farmers who perceived climate changes adopted adaptations in South Africa and Ethiopia (Gbetibouo et al., 2010; Bryan et al., 2009). While 80% of farmers consulted in Kenya reported changing their practices in response to perceived climate changes that were not detected in actual climate data (Bryan et al., 2013). Mertz et al. (2010) report that 30–50% of farmers consulted in the Sudano-Sahelian zone of West Africa stated climate as a reason for making changes to their farming practices. Further, Bryan et al. (2009) found many farmers adapted their farming practices without perceiving climatic changes, suggesting that other factors contribute to farmer decisions to adopt new farming practices. Generally, household size (more labor), recent extreme climatic events (floods or droughts) and access to formal credit were the most significant factors leading to adaptation. Access to extension services, having a radio (proxy for wealth), distance to market, more land, and secure land title were also found to be important. Interestingly, Bryan et al. (2009) found that in South Africa access to information was not an important factor leading to adaptation – suggesting the type of support and way it is presented is very important.

Technically, climate forecast information is now much improved (downscaled and a good degree of confidence in predicting the frequency of dry spells) (Hansen et al., 2011). The failure of climate forecast information to realize its potential in the past has been attributed to being developed without the involvement or input of farmers or others involved in the agricultural sector (Vogel and O'Brien, 2006; Hansen et al., 2011), issues of trust (Crane et al., 2011) and problems with how the information was communicated (Hansen et al., 2011). Roncoli et al. (2009) found that when farmers in Burkina Faso were engaged in pilot projects and intensive interactions with researchers, they were likely to use climate forecast information to change management practices. Receiving training and education is seen to be critical to the successful uptake of forecast information (Hansen et al., 2011). Finally, as with other technologies, marginalized groups often do not have equal access to these technologies (Roncoli et al., 2009; Vogel, 2000).

While the above knowledge generalizes some of the key drivers of farming systems' change perceived by farmers, the relative mix and importance varied with the specific context (Bryan et al., 2009; Mertz et al., 2010; Doss and Morris, 2001). Tschakert (2007) reports that farmers in Senegal are responding many drivers, with their ability to adapt their practices challenged by poor health, unemployment, and inadequate community infrastructure. Bryan et al. (2013) found that though the farmers they followed in Kenya were making changes, most were unable to adopt the options they were most interested in (agroforestry and irrigation) because of a lack of capital. Bryan et al. (2013) were not able to generalize constraints to adaptations, as they found that different factors were relevant for different adaptations. However, Bryan et al. (2009) found that farmer income level in South Africa and Ethiopia influenced whether or not a specific factor would lead to adaptation, with extreme events likely to lead to adaptations for the lowest income farmers as they have no choice but adapt to survive, but unlikely to do so for middle income farmers, as they would conserve their limited resources and not invest in adaptations. Subsidies and farm input support was likely to lead to wealthier farmers adapting whereas they had a negative influence on the poorest farmers suggesting government support is not well designed to address the needs of the poorest farmers (Bryan et al., 2009). In the Sudano-Sahelian zone of West Africa, Mertz et al. (2010) found that adaptation measures identified as promising depended on the rainfall zone farmers lived in. Farmers in the driest zones stated their primary response to changing conditions was prayer. In the wettest zones (700–900 mm) there is a focus on soil water conservation strategies and agricultural intensification, and a concurrent move away from livestock, even though livestock are felt to be more climate resilient. This indicates a belief in or commitment to staying in agriculture on the part of many smallholders, despite evidence that migration and off-farm employment is increasing (Mertz et al., 2010, 2011). The persistence or resilience of cropping in this area may actually serve as a barrier to more transformative adaptations in land use that could improve food security (Mertz et al., 2011). Evaluations of potential adaptations must consider farmer's socio-economic context in addition to bio-physical factors. Finally, when eliciting information from farmers about how and why they are changing their farming practices, researchers should make sure early questions focus on wider issues such as environmental risk, uncertainty, and food security and only discuss climate themes if brought up by respondents, or in the later stages, with non-directional (Thomas et al., 2007).

3.2. Current adaptations of farming systems

The literature on adaptations in agriculture from the social sciences contains much detail and nuance on changes in farm level management and land use in response to a number of drivers (Mertz et al., 2009, 2011; Gbetibouo et al., 2010; Tschakert, 2007; Bryan et al., 2009, 2013). Of the adaptations identified in this literature, summarized in Table 1, we wanted to understand which were possibly attributable to climate drivers as opposed to other drivers (i.e. lack of capital, political factors, illness, theft, wildlife, economic instability, labor shortage), and for those in response to climatic factors, which variables they are most responsive to (variability, extreme or surprise events, shorter seasons, perceived warming, wetting or drying trends), though many adaptations could be a response to many drivers.

It was difficult to attribute the adaptations to one particular climatic driver (Table 2), as many appear to be robust to changes in a number of climate variables, though especially so to reduction in rainfall amounts, rainfall variability and/or extreme events. Notwithstanding using more resilient varieties or crops, few of these adaptations seem to be explicitly chosen on the basis of being responsive to increased temperatures, though it is recognized elevated temperatures impact plant–soil–atmosphere water relationships in a number of ways. The implications of this observation are that many changes farmers are currently making in their farming practices may not be very robust under future climates where higher temperatures and more frequent extreme events are expected to produce large negative impacts (Schlenker and Lobell, 2010) and as reviewed above. Likewise, proposed adaptations to climate change must be able to address the other drivers that farmers respond to. This seems to imply that climate change adaptations must be evaluated in a framework that considers a range of development goals and done so with the involvement of the stakeholders who will be impacted by their selection.

3.3. Crop models and their use in SSA agricultural climate change adaptation studies

The results of a review of cropping systems models suitable for impact and adaptation assessments in SSA are presented in Table 3. For a model to be appropriate for use in adaptation studies, it should minimally be responsive to the key climatic variables expected to drive climate impacts on the region's cropping systems

Table 1
Review of agricultural adaptations studies in Sub-Saharan Africa found in the social sciences literature.

Study authors and adaptation (scale)	Where and methodology	Key research focus	Main findings	Role for crop models?	How can this contribute to crop modeling?
Osbahr et al. (2010)	South Africa and Mozambique	Identify successful adaptations on the basis of: increased commercial production; diversified crop production; investments in labor and irrigation pumping; experimentation with resilient varieties, planting densities, and soil conservation practices (contour tillage and mulching)	Factors leading to successful adaptations include: strong local leadership and support; linking informal and formal institutions including information flow and credit; rules and structure in organization; equitable benefits as whole community involved; local ownership through production of local knowledge; economies of scale; leadership to initiate experimentation and knowledge sharing on new technologies	Tool in knowledge sharing and experimentation from key individuals to wider community	Highlights the emphasis of resilience (varieties as well as systems) as successful adaptation goal
Formation of farmers associations (village)	Focus groups (63), closed and open ended questions in household questionnaires (121) and in-depth interviews				
Doss and Morris (2001)	Ghana	Investigated influence of gender on technology adoption	Farmer gender was not a significant explanatory variable for either technology, but the gender of the household head was	Assess the implications of gender and adaptations on crop productivity, yield stability and soil fertility	Reminder of importance of explicit consideration of gender. Adaptations tested in models are likely to be valued more highly and influence adaptation policy – and this may have negative impact women and household food security
Modern maize varieties and fertilizer use (national)	National scale survey of maize growers (420 in 60 villages) on adoption of modern varieties (MV) and fertilizer use 0		Education, land ownership, interaction with extension agents and labor availability all influenced technology adoption, and women disadvantaged on all factors		
Thomas et al. (2007)	South Africa	Analysis of the responses of farmers to their perception of rainfall parameters and other drivers, and analyze whether they are short term coping or longer term adaptations	Farmers correctly perceive many rainfall parameters	None of the adaptations tested for suitability under changing climatic conditions – crop models could test some of the adaptations to see how robust they are under future climate scenarios	Inform range of possible adaptations
Switching to livestock, shorter season varieties, changing plant density, utilizing landscape spatial diversity to benefit from rainfall or water variability, collective actions (village)	Comparison of bio-physical data on 8 rainfall parameters and farmer perception of climate from farm visits, focus group discussion, questionnaires (open- and closed-ended), semi-structured interviews, and 30 interviews with key people		Farmers adapt to climatic factors but also to lack of capital, political factors, illness, theft, wildlife, economic instability, labor shortage and crime Many changes in farming practices considered as coping mechanisms		
Gbetibouo et al. (2010)	South Africa	Understanding link between climate changes and adaptations and factors enabling adaptations	Most farmers recognized increasing temperatures (89%) and decreasing rains (81%), but less than 1/3 made any adaptations	With more data on management and soils, could evaluate the adaptation strategies to see if successful in minimizing yield losses or increase water productivity	Profiles of the types of farms/farmers likely to adapt can be used to test the impacts of adaptation studies at larger scales shown to minimize yield losses and impacts on individual
New crops, changing varieties, planting dates, irrigation, water harvesting. reapportioning area	794 surveys of farmers on their perceptions, adaptations and constraints with open ended		Barriers: poverty; lack of access to credit, water and markets; low savings; insecure property rights;		

(*continued on next page*)

Table 1 (*continued*)

Study authors and adaptation (scale)	Where and methodology	Key research focus	Main findings	Role for crop models?	How can this contribute to crop modeling?
between crops and livestock (farm)	questions on climate change perception		lack of knowledge		
	Create logit model using household, farm (soil fertility), institutional (extension, climate info, credit, land tenure) and other (climate) variables		Factors that lead to adaptation included: household size and wealth; farm size; farming experience; perception of soil fertility; access to credit; extension; tenure security; high temperature and low rainfall		
Kristjanson et al. (2012)	Kenya, Uganda, Tanzania and Ethiopia	Looked at relationship between innovativeness (as measured by adopting new technologies i.e. crop of variety types, land use and management practices) and food security (number of food deficit months)	Over past 10 years large diversity of changes in farming practices noted for many people	Test if they would be successful adaptations for CC	Identify range of adaptations and proportion of adopters
Range of adaptations (household)	Analysis of household-level baseline survey undertaken as part of a CCAFS research program		For food security, site, land size, HH size and innovativeness are significant explanatory variables		If not shown to be successful for CC, can use this info to examine other drivers which push farmers and identify adaptations that meet farmers immediate needs with CC
			For innovativeness, site, information, production diversity, social networks, water availability and cash source, and food deficit months were significant explanatory variables		
Mertz et al. (2009)	Senegal (between Sahel-Sudanian and Sudanian climatic zones)	Understand past and current adaptations in farming systems	Range of adaptations identified but climate rarely considered by farmers as main driver of change in farming practices, though it may be a factor. Concerns with winds, especially as they impact animal health which is generally poor, were most common when questioned directly about climate	Test adaptations in response to other drivers for robustness under different climate scenarios	High uncertainty in climate change predictions requires a very cautious and careful policy response
	Household questionnaires, group and key informant interviews (semi-structured and open)	Determine the key drivers of change and assess relative importance of climatic related drivers			
Tschakert (2007) (household)	Senegal	Understand local risk perceptions, conceptual understandings of climate variability and change, and determinants adaptive capacity	Many factors constrain adaptation decision making including poor health, unemployment and limited infrastructure	Tool in knowledge sharing, experimentation and social learning	Assessment of climate change adaptations must account for the range of drivers and constraints facing farmers if they are to inform changed farming practices
	Participatory ranking of major risks; conceptual mapping of climate variability; household surveys		Social learning is key to building adaptive capacity with potential role for researchers to make contributions		
Bryan et al. (2009)	Ethiopia and South Africa	Understand past and current adaptations in farming systems	Farmers respond more to shocks than changes in mean variables	Tool in experimentation and social learning to build adaptive capacity, potentially empowering farmers to identify means to overcome constraints	Assessment of climate change adaptations must account for the range of drivers and constraints facing farmers if they are to inform changed farming practices
Sale of livestock, changed feeds, changing cultivation area, irrigation, changed planting dates, afforestation, water harvesting, tree planting,	Household surveys with open-ended questions (1783 surveys)	Determine the key drivers of change and assess relative importance of climatic related drivers	Farm-level adaptation involves more than adopting new technologies	Test adaptations in response to other drivers for robustness under different climate scenarios	

changing variety type, changing crop type, soil conservation (household)			Strategies should be targeted to meet the unique needs and constraints of different groups of farmers		
Bryan et al. (2013)	Kenya	Understand past and current adaptations in farming systems	Households face many challenges in adapting to climate change, with the most important constraints varying with the adaptation in question. Many households have made small adjustments (in particular, changing planting decisions). Many report being interested in agroforestry or irrigation but lacking the capital and knowledge to do so	Tool in experimentation and social learning to build adaptive capacity, potentially empowering farmers to identify means to overcome constraints	Assessment of climate change adaptations must account for the range of drivers and constraints facing farmers if they are to inform changed farming practices
Sale of livestock, irrigation, changed planting dates, afforestation, water harvesting, tree planting, variety type, soil conservation (household)	Household surveys and participatory rural appraisals (710 households in 7 districts)	Determine the key drivers of change and assess relative importance of climatic related drivers		Test adaptations in response to other drivers for robustness under different climate scenarios	

and able to model the main crops, cropping systems and management strategies. The climate variables expected to drive negative impacts across SSA, presented earlier, are increased temperatures, extreme high temperature events and elevated atmospheric CO_2 concentrations. Of the cropping systems models reviewed, the range of processes responsive to temperatures is a function of the specific model. The variability of model responses to rising temperatures represents one method of quantifying uncertainty in crop responses to rising temperatures. However, the impacts of more frequent high temperatures on grain and seed set in crops are only explicitly accounted with algorithms in CROPGRO and the APSIM models for maize, millet and sorghum, though it is increasingly recognized as critical for the useful application in crop models (Challinor et al., 2009; Soussana et al., 2010). Likewise, while all of the models reviewed here are responsive to elevated $[CO_2]$, only APSIM and CERES have been tested with FACE data, though in both cases for wheat. The CROPGRO responsiveness to $[CO_2]$ has been tested with leaf level photosynthetic and transpiration measurements. In general, development and testing for responsive to water stress has been more rigorous in all of the models, though the interaction with other stresses, particularly heat stress at flowering and elevated $[CO_2]$ requires more work (Craufurd and Wheeler, 2009). CERES and APSIM have been tested most extensively and with the greatest number of crops. While CropSyst and EPIC use simpler routines for some physiological processes, they simulate a greater range of soil processes and management practices.

Despite crop models often being described as tools to facilitate climate change impact assessment and support adaptation decisions (UNFCCC, 2012), relatively few instances of their use in adaptation studies are found in the literature. Our interest was primarily in understanding methodologies used in crop modeling adaptation studies and how they shape the adaptation space. This overview, presented in Table 4, of the use of crop modeling studies to evaluate agricultural adaptations highlights two roles crop models currently play. (1) Crop models were used to generate yield response functions for climate and management for use as inputs to economic models (Claessens et al., 2012; Butt et al., 2005). (2) Crop models were used as tools to analyze interactions of management, environment and climate, organizing scientific understanding at that level of complexity and highlighting the areas where knowledge gaps exist (Challinor et al., 2009). For example, Thornton et al. (2010) were able to examine altering the spatial distribution of various crop types to optimize production. They also demonstrated the extreme variability in responses (−20% to +20% current yield) expected for bean and maize, depending on climate scenario and model, soil type and climate zone in East Africa. The question of the appropriate scale to evaluate adaptation decisions on is especially relevant for data poor regions like large parts of SSA with limited adaptive capacity.

Notably absent is evidence of meaningful interaction with farmers, extension agents or policy makers, although Claessens et al. (2012) state they consulted with such stakeholders to determine the adaptations to test. The one exception is the study of Ebi et al. (2011) in Mali who used crop models to organize and quantify impacts of adaptations identified by stakeholders. In a subsequent workshop they used the model outputs as a basis of discussion and to provide context to stakeholders as they prioritized adaptation options in an iterative process. Cash et al. (2003) argue that for adaptation science to be useful for supporting adapted behaviors it must be seen as being sound, relevant and legitimate. Legitimacy is associated with being fair and interactions and dialogue between stakeholders and the intended users of knowledge is seen to be critical to achieving legitimacy (Cash et al., 2003).

AgMIP (www.agmip.org) is a large international collaborative model improvement and comparison initiative with a goal to use

Table 2
Current adaptations farmers are making in their cropping and farming systems in response to climatic and non-climatic drivers.

Adaptation	
Climatic driver	Non-climatic driver
• formation of farmers associations which enabled a range of other changes and experimentation (risk taking)	• formation of farmers associations
• diversified crop production	• diversified crop production
• investments in labor and irrigation	• investments in labor and irrigation
• soil conservation practices (contour tillage and mulching)	• soil conservation practices (contour tillage and mulching)
• shifting production between cropping and livestock keeping	• shifting production between cropping and livestock keeping
• reapportioning areas between crops and livestock	• reapportioning area between crops and livestock
• collective actions such as livestock holdings and commercialization	• collective actions such as livestock holdings and commercialization (esp. vegetables)
• use of resilient varieties	• increased commercial production
• water harvesting	• water harvesting
• using shorter season varieties	
• utilizing landscape spatial diversity by moving some gardens nearer to water sources or to areas with different rainfall patterns (via access to land through family, friends or small groups for projects)	
• varying planting dates	
• changing planting densities	

combinations of climate, crop and economic models to perform regional integrated climate impact assessments on agricultural systems across world regions. They develop socio-economic scenarios of future development, representative agricultural pathways (RAPs), consistent across climate, crop and economic models, to define farm level management adaptations (Rosenzweig et al., 2013). However, it is not clear which, if any, stakeholders are involved in defining the RAPs and it is yet to be seen if their model outcomes will be shared with and or of interest to policy and other decision makers. However, some regional AgMIP initiatives use the CCAFSs (CGIAR Research Program on Climate Change, Agriculture and Food Security) (ccafs.cgiar.org/scenarios) participatory multistakeholder, regional scenarios of future socio-economic development. These scenarios were envisioned as a means to frame and evaluate the feasibility of CCAFS-generated strategies and policies, as well as being a method to integrate outcomes across CCAFS initiatives such that they are more relevant and useful to decision makers.

4. Future roles for crop models in climate change adaptation studies in SSA

4.1. What can crop models contribute?

First of all, a combination of crop modeling work with survey data or in-depth interviews can triangulate results and increase confidence if the findings support each other or add complimentary knowledge to broaden understanding of the potential of an adaptation (Nuijten, 2011). Many of the studies in the social sciences report on adaptation that were identified by farmers in response to a number of drivers in addition to climate (Kristjanson et al., 2012; Mertz et al., 2010; Thomas et al., 2007), but no analysis is provided as to how these adapted practices would perform under future climatic conditions (Thomas et al., 2007). Crop models could compliment these studies to explore the future impacts on adaptations due to climate change and start to tease out which adaptations are most robust under future conditions.

Formation of farmers groups was identified by Osbahr et al. (2010) as a successful adaptation in Southern Africa that enabled farmers to experiment with a number of adapted farming techniques. Within the group structure farmers were able to profit from scale effects in terms of marketing and access to inputs, as well as to minimize individual risk by transferring risk to the group. Local ownership and leadership, experimentation and knowledge sharing were identified as key factors leading to the success of the groups (Waithaka et al., 2006) and improving adaptive capacity (Tschakert, 2007). With appropriate expertise, crop models could be an excellent tool for experimentation – that promotes social learning (Meinke et al., 2009) important for organizational function and access to tools that can give farmers more power when articulating their needs (for storage facilities, better access to infrastructure – roads and/or irrigation, better access to markets) at political levels. As acknowledged in the literature on Participatory GIS (PGIS), technology promotion in groups can serve to reinforce existing power relations of those with more formal education or resources. The literature on PGIS is extensive (Cutts et al., 2011) and lessons learned in this field would likely be applicable to minimize such negative consequences.

Little evidence of work on the potential of irrigated systems for West Africa was found in the crop modeling literature. A recent study on small scale irrigation and water management technologies indicate significant opportunities for smallholder farmers to improve their food security and reduce poverty (Giordano et al., 2012). Burney et al. (2010) tested an innovative solar powered drip system in the Sudano-Sahel and it performed very favorably in terms of economic returns, impacts on food security and environmental sustainability. While several significant barriers exist to the adoption of irrigation technologies, crop models (together with other information about water availability, etc.) could also be useful for spatial targeting of irrigation possibilities.

4.2. How can crop modeling adaptation studies be improved?

The current limitations of models to respond to the key climatic drivers of yield were discussed in an earlier section. With regards to simulating management options, looking at farmers' current and adapted management practices should inform crop modelers about adaptations they should test (Thomas et al., 2007). While it is understood that many adaptations will not be testable with crop models, such as taking off farm employment, using crop insurance, forming farmers' organization or new trade and market relationships, this review has also highlighted that many of the bio-physical adaptations that can be evaluated using crop models are very case specific and will be influenced by a variety of social, economic and bio-physical factors. Crop modeling adaptation studies should be aware of and acknowledge these constraining and/or enabling factors as they conduct their analysis so as to more completely understand the impact (and on who) of the adaptation in

Table 3
Characteristics of cropping systems models suitable for adaptation studies in SSA.

Model	Where has it been tested in West Africa?	Which crops relevant for WA?	Which processes are responsive to temperature?	Sensitivity to high temperature at key growth stages?	Sensitivity to atmospheric [CO_2]	Sensitivity to water stress?	Which management options?	Other comments
DSSAT – CERES (Ritchie and Otter, 1985; Jones et al., 1986)	Sudan-Savanna in Ghana (MacCarthy et al., 2010); Sudan-Savanna in Burkina Faso (Tojo Soler et al., 2011); sub-humid Ghana (MacCarthy et al., 2012); humid Togo (Dzotsi et al., 2003)	Maize (MacCarthy et al., 2012; Tojo Soler et al., 2011; Dzotsi et al., 2003); rice (Xiong et al., 2009); sorghum (MacCarthy et al., 2010; Tojo Soler et al., 2011); millet (Sharma et al., 2010; Thornton et al., 1997)	Phenology, photosynthesis (RUE), kernel # per plant (via impact on the duration of the grain setting phase), kernel growth rate, evapotranspiration	No – kernel number appears to be influenced by temperature other than as it affects carbohydrate supply check if affects translocation	Yes (tested with FACE experiments for wheat under N and water stress using RZWQM2 for soil water processes – Ko et al., 2010)	Flooding and drought	Nitrogen fertilization (MacCarthy et al., 2010, 2012; Tojo Soler et al., 2011); crop rotations (Tojo Soler et al., 2011); residue management (SOM with Century in Tojo Soler et al., 2011); intercropping (maize/wheat – Knörzer et al., 2011); tillage; irrigation	
DSSAAT – CROPGRO (Jones et al., 2003)	Sudan-Savanna of Burkina Faso (Tojo Soler et al., 2011); Guinean Savanna zone of Ghana (Naab et al., 2004)	Cowpea (Bastos et al., 2002); cotton (Tojo Soler et al., 2011); groundnut (Tojo Soler et al., 2011; Naab et al., 2004); tomato (Ventrella et al., 2012)	Phenology, leaf level photosynthesis, respiration, seed lipid concentration, nitrogen fixation, specific leaf area, leaf expansion rate, internode elongation, evapotranspiration	Yes, in PODS. for, relative # of pods set in a day decreases past threshold temperature to 0 at a second threshold	Yes (tested at leaf scale for soybean – Alagarswamy et al., 2006)	Flooding and drought	Nitrogen fertilization (Tojo Soler et al., 2011); crop rotations (Tojo Soler et al., 2011); residue management (SOM with Century in Tojo Soler et al., 2011); irrigation	
APSIM (Keating et al., 2003)	Sudan-Savanna in Ghana (MacCarthy et al., 2009); sub-humid Ghana (Fosu-Mensah et al., 2012); Sahel in Niger (Akponikpè et al., 2010)	Maize (Fosu-Mensah et al., 2012); sorghum (MacCarthy et al., 2009); millet (Akponikpè et al., 2010); chickpea (Robertson et al., 2001b); cowpea (Adiku et al., 1993); cotton; pigeonpea (Robertson et al., 2001a); mucuna; groundnut (Robertson et al., 2001a)	Phenology, photosynthesis (RUE), leaf area, N content, rate of senescence, speeds grain filling rate (but duration decreases with temperature – therefore final kernel weight reduced), grain N-content, rate of rooting depth advance, evapotranspiration	No – cotton, legumes Yes – sorghum, millet and maize – potential kernel number is reduced past a threshold value during flowering	Yes (tested with FACE experiments for wheat under N and water stress – Asseng et al., 2004)	Drought (Song et al., 2010)	Nitrogen fertilization (MacCarthy et al., 2009); P-fertilization; residue management (SOM and erosion); intercropping; tillage; irrigation	Phenology responsive to N and P deficiency; accounts for acidity
EPIC (Williams et al., 1989)	Sub-humid Guinean zone Bénin (Gaiser et al., 2010a; Srivastava et al., 2012; Worou, 2012); semi-arid Sudan-Savanna in Bénin (Gaiser et al., 2010a; Srivastava et al., 2012); Nigeria (National scale – Adejuwon, 2006)	Maize (Gaiser et al., 2010a; Adejuwon, 2006); yam (Srivastava et al., 2012); rice (upland and lowland – Worou, 2012); millet (Adejuwon, 2006); sorghum (Adejuwon, 2006); cassava (Adejuwon, 2006)	Phenology, reduces biomass accumulation (RUE), harvest index, evapotranspiration	No	Yes	Drought (Gaiser et al., 2010a)	Nitrogen fertilization; P fertilization; intercrops; crop rotations; residue management (with CENTURY); fallow availability (Gaiser et al., 2010b; Srivastava et al., 2012); irrigation	Considers acidity, but poor performance on highly acidic tropical soils (aluminum saturation >35%) (Gaiser et al., 2010a); considers erosion; does not consider iron toxicity for rice (Worou, 2012)

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Table 3 (*continued*)

Model	Where has it been tested in West Africa?	Which crops relevant for WA?	Which processes are responsive to temperature?	Sensitivity to high temperature at key growth stages?	Sensitivity to atmospheric [CO_2]	Sensitivity to water stress?	Which management options?	Other comments
CROPSYST (Stöckle et al., 2003)	Burkina Faso (National scale – Badini et al., 1997); Cameroon (Tingem et al., 2009)	Bambara nut (Tingem and Rivington, 2009); maize (Tingem et al., 2009); sorghum (Tingem et al., 2009); millet (Badini et al., 1997); cotton (Sommer et al., 2008)	Phenology, biomass accumulation (RUE), rate of senescence, evapotranspiration	No	Yes	Drought	Flooded rice management (Confalonieri and Bocchi, 2006); crop rotations; residue management (effect on SOM); fallow availability; tillage (Donatelli et al., 1997); irrigation	
STICS (Brisson et al., 2003)	Mali (Folliard et al., 2004)	Sorghum (Folliard et al., 2004); maize (Brisson et al., 1998); legumes (Corre-Hellou et al., 2009)	Phenology, biomass accumulation (RUE), rate of senescence, grain filling, energy balance to determine canopy temperature, evapotranspiration	No	Yes	Drought	Intercropping (Brisson et al., 2004); irrigation (Mailhol et al., 2001); N fertilization (Mailhol et al., 2001); residue management (Scopel et al., 2004)	
SIMPLACE/APES (Adam et al., 2012; Rötter et al., 2012)		Maize (Adam et al., 2012; Belhouchette et al., 2009; Therond et al., 2011)	Phenology, leaf area growth rate, biomass accumulation (RUE), evapotranspiration, root penetration and growth	No	Yes	Drought changes rooting patterns, reduces LUE and LAI and increases leaf death rate	N(PK) fertilization (Van Ittersum et al., 2008; Belhouchette et al., 2011; Adam et al., 2012), crop rotation; residue management; irrigation (Belhouchette et al., 2011)	Modular framework which can combine different model components into a site-specific, problem and data oriented model solution
SARRA-H (Dingkuhn et al., 2003; Berg et al., 2011)	Sahel and Sudan savanna of Senegal, Mali, Burkina Faso, Niger and Chad (Berg et al., 2011; Dingkuhn et al., 2003)	Millet (Berg et al., 2011); sorghum and maize	Biomass accumulation, phenology, maintenance respiration, senescence, evapotranspiration	No	Yes	Drought	No	

Table 4
Review of crop modeling studies investigating agricultural adaptations to climate change in Sub-Saharan Africa.

Study and adaptation(s) evaluated	Where and scale	Modeling approach	Criteria to identify success	Factors leading to success	How was/were the adaptation(s) selected?	Evidence of integration?	Who and how might this knowledge be used?
Tingem et al. (2009)	Cameroon	Cropsyst, current climate from 25 years and additional 25 years generated with ClimGem GISS and HadCM3, A2 and B2 maize, sorghum and Bambara gnut	Yield increase	Longer maturity varieties compared to currently used varieties which had accelerated development rate due to higher temperatures	Not stated	None	Adaptation proposed for change in farm management but state results relevant for policy decisions – develop new cultivars using marker assisted selection and genetic engineering
Shifting planting dates; hypothetical cultivars	Provincial (single climate station per site and soils from ISRIC database)			Do not show rain data or explain cause for yield increases with change in sowing date			
Butt et al. (2005)	Mali	EPIC with PHYGROW (rangeland), NUTBAL (livestock) and MASM (Mali Agriculture Sector Model – economic impact on consumers, producers and trade balance)	1 – Risk of Hunger Index (ROH) (FAO, 1996). ROH heavily dependent on availability and does not capture income and food access	All adaptations reduce CC negative impact on ROH and total surplus, as well keeping the CV at 1996 levels for surplus indicators (as opposed to 8-fold increases without adaptations)	Not stated	Yes, used crop, rangeland, livestock and economic models	Good example at an early attempt to perform an integrated assessment and gives an indicator of how many will benefit/suffer from CC with(out) adaptation – though ROH not best estimator
Heat resistant cultivars; migration of cropping patterns; modified trade patterns; improved cultivars; expansion of cropland	National (crop model applied at level of national agro-ecological zones (85) results then aggregated to 9 zones)	To 2030	2 – Consumer, producer and foreign surplus as economic indicators	Shifting crop mix and trade had larger impacts than using heat resistant varieties (almost no impact – could be limits of EPIC?)		No evidence of consultation with farmers	Study useful to highlight the level of assumptions and although results presented here focus on aggregate economic indicators, allows consideration of impacts on various production components and understanding the drivers of the changes
		CGCM and HadCM with [CO$_2$] at 1.5 $*$ present Impacts with no adaptations: maize −12%, gnut −12%, cotton +4% to 6%, sorghum −12% to 17%, millet −6% to 12% and cowpea −8% to 12%		Expansion of crop land and use of high yielding varieties both mitigate losses to 1996 levels Adaptation study does not account for pop growth BUT in a small sensitivity analysis demonstrate with pop growth, ROH rises to 81% even with expansion of crop land high yielding varieties			
Ebi et al. (2011) builds on Butt et al. (2005)	Mali (village)	Analysis of Butt extended to include the RCM MAGICC/ SCENGEN (500 km grid) and a wet scenario using HadCM2 and A1B to capture uncertainty in rainfall changes	Evaluated the feasibility, cost, level of technical assistant required, effectives for future climate and current adequacy with farmers and stakeholders	NA	Workshop with farmers from village, NGO workers, extension workers and scientists to identify adaptations	Yes	Shortcoming of this study – these adaptations are not evaluated with models – perhaps some are too complex or input data too coarse to make farm level predictions Essentially presenting two separate analysis
For modeling study: Heat resistant varieties; heat resistant varieties with early planting; and supplemental irrigation for potato		Maize and potato – different impacts due to rain simulations. Adaptations greatly reduced yield losses for potato and minimal effect on maize		Adaptations not evaluated with the model	Crop model used to quantify impact on yields of adaptations 2nd workshop to prioritize adaptations (crop model results used to provide context for stakeholders)		Still nice framework to evaluate each adaptation on the basis of these criteria and with different stakeholders

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Table 4 (*continued*)

Study and adaptation(s) evaluated	Where and scale	Modeling approach	Criteria to identify success	Factors leading to success	How was/were the adaptation(s) selected?	Evidence of integration?	Who and how might this knowledge be used?
Range of soil and water conservation techniques; crop diversification and agroforestry; access to credit for water control, fertilizers and stores							Many of the adaptations of the farmers were very costly (may have been design of the study) and most desired immediate impacts to deal with current challenges
Thornton et al. (2009, 2010)	East Africa (Burundi, Kenya, Rwanda, Uganda, and Tanzania)	DSSAT (CERES and BeanGro) run at pixel level for maize and beans (only as a second crop where season long enough)	Relative yield – evaluated at system level and household level (note: they use only averages and do not present variability in yield changes)	System adaptations: 1 – shift production to areas more likely to experience gains (i.e. high lands where temp increases will not surpass high temperature threshold) 2 – increase regional trade but do not evaluate – economic analysis	Not stated	Yes, qualitative consideration of possible adaptations considering economics, trade and household caloric availability	Highlight the need to base adaptations on site specific conditions and the 2009 study found very high variability in terms of the impacts experienced even after using average GCM outputs
Shift production in space; (trade distribution; drought resistance varieties; shifting sowing date evaluated only qualitatively)	Regional – gridded datasets at 10 arcmin (18 km)	HadCM3 and ECHam4		Household level: Where small yield decline occurs due to increase in mean temperatures at higher elevations (see Thornton et al., 2009) shifting planting date had no impact in either direction			
		A1F1 and B1		Where yield reductions are predicted to be severe switching crops from maize to sorghum or millet, gave lower absolute yields for both millet and sorghum. Also CV higher for sorghum and maize			
		ISRIC WISE database soil data FAOSTAT yield statistics and land farm system classification based on an FAO livestock system classification Found wide range of impacts ranging from +20% to −20% on both bean and maize. Large spatial variability					
Claessens et al. (2012)	Kenya	Survey data	Reduction in % of farmers living in poverty	Relatively high yields and returns of the dual purpose sweet potato and increased feed quality impact on milk production and income	Consultation with farmers, extension agents and policy makers	Yes with livestock and economic models and an analysis based on poverty of individual farmers	Raise critical issue related to scaling – importance of adaptation/impact at individual level, but need to make policy and analysis at larger spatial scale
Improved drought and heat resistant maize	Community – economic model applied at farm level (input level, management, etc.) and DSSAT 4.0 used to generate yield response functions to climate and management						

Dual purpose sweet potato	DSSAT TOA MD HadCM3 and ECHam4 A1FI and B1 Consider the % of farmers likely to adopt each adaptation Use different scenarios of possible future socio-economic conditions conducive or not to adaptations

question. Further, the interactions of livestock and residue management, labor availability, and intercropping strategy are elements that could be handled by crop models, though requiring development and extensive testing.

System resilience was highlighted as a successful adaptation goal (Osbahr et al., 2010; Ifejika Speranza, 2010; Webber et al., 2014), as opposed to simply maintaining highest yield levels. Many crop models are able to simulate a number of bio-physical variables and could be used to substantiate general statements about the ability of adaptation to build resilience (Kahiluoto et al., 2014). To do so, emphasis should be placed on defining system boundaries, key variables influencing system resilience and associated indicators and thresholds that crop models (especially when combined with hydrological models) are capable of predicting. The challenge to crop modelers will be in defining appropriate system boundaries to balance the reality of what crop models can simulate with the reality of feedbacks and interactions of the systems it is embedded in at larger scales likely to include many socio-economic variables. The focus on resilience rather than maximum productivity further supports calls by a number of authors of the need to improve crop models ability to both simulate drought and heat resistant cultivars, to improve related model routines and to integrate with economic or agent based models (Challinor et al., 2009; Soussana et al., 2010).

Doss and Morris (2001) found that at least one technology was less likely to be adopted by female farmers living in female headed household. As the proportion of farms headed by women is likely to shift in the future as men migrate to other locations for work, the appropriateness or success of certain adaptations may also change. More broadly, their results highlight that technologies are not value-free constructs (Meinke et al., 2009). What is tested in models is likely to be valued more highly and influence adaptation policy – and may inadvertently impact women (and household food security) negatively if gender is not accounted for. Minimally, modelers need to be aware that not all technologies are available to all groups of people and be explicit about which groups of farmers would and would not have access to the options they evaluate. In their study methodologies, they could evaluate technologies that are available (given present constraint) to women versus men, or richer versus poorer farmers.

As noted above, the impacts of any particular adaptation on food security will likely be a function of site specific bio-physical and farmer characteristics (Bryan et al., 2009; Mertz et al., 2010; Doss and Morris, 2001). Claessens et al. (2012) examined the impact of farm bio-physical and economic heterogeneity on the economics of adaptations. When adaptations are shown positive on larger scale but adoption is low, explanations often include risk aversion or technology constraints. However, Claessens et al. (2012) indicate that farm bio-physical and economic (labor and capital) spatial heterogeneity can explain lack of adoption, again highlighting the need for careful consideration of scale when designing and evaluating adaptation options. However, their study appears to have used relatively static yield response functions as inputs to their economic model. Are there interactions between bio-physical and farm socio-economic traits that would produce different yield response functions (Tittonell et al., 2008)? Is it sufficient to consider diversity of farmers in the farm systems models or should this explicitly be accounted for in the crop models to see what yields different farmer/environment combinations can achieve? Addressing these questions may contribute a first step to understanding and possibly quantifying the farm level variability (Tittonell et al., 2008) associated with adaptations evaluated at higher spatial scales, and generating the knowledge needed to guide food security and poverty reduction decisions. As crop models are typically developed for application at the field scale up-scaling to the farm, and larger areas poses particular challenges (Ewert et al., 2011).

As an alternative to the continual improvement of crop models, linking crop models to other models (economic, farm systems or livestock) offers the option to widen the scope of potential impacts and constraints of adaptations to climate change considered, as well as to probe the interactions of cropping systems with other systems in which farmers operate (Jarvis et al., 2011). In two of the crop modeling adaptation studies reviewed here, crop model simulations of crop yield response to climate and management were linked to economic (Butt et al., 2005) or farm systems models (Claessens et al., 2012), allowing an analysis of the impacts of adaptations on regional economics or the relative number of farms that could be expected to benefit or suffer from different combinations of climatic, management and socio-economic factors, respectively. Linking crop models to livestock models could address the critical issue of crop residue management to help assess the relative merits with regard to improving food security of the use of residues for building soil fertility versus as a livestock forage and if this relationship changes under possible future climatic conditions (Giller et al., 2009; Valbuena et al., 2012).

Integrated assessment modeling frameworks (Fischer et al., 2005; Ewert et al., 2009; Thornton et al., 2011), in which crop models have an important role to play, represent the logical extension to the concept of linking models across disciplines and scales. These frameworks have emerged in response to the complexity of human–nature systems that contain many nested and interacting subsystems to understand system behavior, feedbacks and interactions across scales and systems (Ericksen et al., 2009; Ewert et al., 2011). For example, Morton (2007) proposed a framework for studying the impacts of climate change on smallholder systems that recognized their complexity and high location-specificity. This framework incorporated key stressors on rural livelihoods that affect smallholder's crops and animals at the levels of individual fields, bio-physical processes affecting production at a landscape, watershed or community level; and impacts of climate change on human health and livelihoods. The SEAMLESS-IF framework is an attempt to improve the flexibility of integrated assessment frameworks in terms of models used and sustainability outputs generated, as well as increase transparency and understanding of model performances to end users (Ewert et al., 2009). Examples of integrated assessment frameworks in West Africa include IMPETUS (integrated approach to the efficient management of scarce water resources in West Africa) and the GLOWA Volta project (Speth et al., 2011). Both initiatives aimed to develop decision support tools for water management in their respective West African basins, integrating knowledge across social, economic and natural sciences and scales. While such frameworks are important to organize knowledge across disciplines (thereby highlighting knowledge gaps) and garner insights into how real systems behave, the unquantifiable amount of uncertainty nested in such models, related to model structure and model parameters and input data may limit their utility to framing 'what if' discussions. Further their scope can be so great that it becomes impossible to track all of the subjective assumptions and value judgments that go into their construction. It is noteworthy to remark that a complimentary goal of both IMPETUS and GLOWA was to build the region's research and management capacity and one may speculate that the ultimate value of such integrated assessments frameworks, in their current form, may lie in providing a scientific scaffolding on which to bring scientists and stakeholders from many backgrounds together to inform land use decisions.

5. Conclusions

The present review attempted to investigate some ways that crop models can contribute to evaluating adaptations to climate change in agriculture and support their adoption to improve food security in SSA. A great deal of knowledge from the social sciences literature regarding farmers' perceptions of change, adaptations and constraints can benefit crop modeling studies. When combined with the predictive power of crop models, a number of potential synergies emerge from these two disparate fields: crop models can support experimentation and social learning in farmer organizations; quantitative outputs from crop models can triangulate qualitative information gathered from farmers; crop models can evaluate expected outcomes of changes in cropping practices motivated by other drivers to future climate change or climate variability; knowledge from the two can be combined to probe the appropriate scale to evaluate the impacts of adaptations on food security of farming households; and finally the consideration of farmers knowledge and perceptions reminds crop modelers of the need to engage with those who their research has the potential to help to improve (and sustain) their livelihoods. However, our review points to the need for a shift in the manner in which crop modeling research is conducted if it is to be useful in building more resilient cropping systems and improving food security outcomes. There is an urgent need to focus on the needs of decision makers, and this can be done by involving them from the outset. Crop modeling studies must capture the reality in which management decisions are made and be linked to action research with partners on the ground (NGOs/CSOs/local government agencies) who work directly with farmers in testing adaptation options (Howden et al., 2013).

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