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Chapter 8

Modeling climate change impact on low-input smallholder farming systems

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1 Introduction

Smallholder farming systems need to feed more than 3 billion people by 2100 (Vollset et al., 2020), while contributing to poverty alleviation, limiting agricultural expansion and reducing the environmental footprint (Foley et al., 2011). These farming systems, especially in sub-Saharan Africa (SSA), are characterized by large yields gaps (van Ittersum et al., 2016) mostly due to poor soil fertility and poor access to inputs (e.g. fertilizers, herbicides, insecticides and irrigation facilities). The vast majority of agricultural land in SSA is rainfed, and only a fifth of the area suitable for irrigation is actually irrigated (Burney et al., 2013). Average fertilizer use is 12, 2 and 3 kg ha⁻¹ for nitrogen (N), phosphorus (P) and potassium (K), respectively (FAOSTAT, 2018), far below the

(Affholder et al., 2013). On top of that, ongoing climate change is expected to exacerbate abiotic stresses on crops and poses the additional challenge of adaptation to climate change.

Climate change is undeniable: in addition to temperature, precipitation is increasing in global annual average, but with great regional and seasonal disparity. With a business as usual scenario in 20 years' time, the world will go past the global 1.5°C warming limit set by the Paris agreements. The biosphere ability to fulfill its role as a CO₂ sink will decrease as temperature increases. Climate change leads to a greater frequency and intensity of extreme events, including heat waves, intense rainfall and prolonged droughts. In addition to climate change, farmers must adapt to already existing climate variability (Huet et al., 2022). Quantitative and qualitative approaches have been developed to capture farming system's response to climate variability, and design and assess alternatives to adapt to climate change. Farming systems are complex as they integrate several components, including crops, livestock, grassland, trees and humans (Fig. 1). This chapter presents the effect of climate change on these components and highlights potential component-level strategies to adapt to climate change. We specifically focus on challenges in evaluating climate change impact and adaptation potential in the context of low-input systems. In the final section, we go beyond the component-based approach and highlight modeling and participatory approaches that help address the challenges of assessing the effect of climate change on farming systems as a whole.

2 Modeling climate change effect on crops, livestock, grasslands and trees

Climate change will impact crop, animal, trees and grazing resources of mixed farming systems. Though understanding the effect on one component alone is not enough to understand the complex effect of climate change at farm level, we first give an overview of the effect of climate change on each component.

2.1 Effect of climate change on cropping systems

2.1.1 Impact of climate change on crop productivity and adaptation strategies

Cropping systems are the most extensively studied component of the farming systems. Crops models are useful tools to analyze and unravel the impact of climate and crop management on cropping system agronomic and environmental performances. In low-input systems, studies on the impact of climate change on grain yield and potential adaptation strategies have been

carried out. Faye et al. (2018) showed that cereal yields in West Africa would decrease by between 2% and 5% with a temperature increase of 1.5°C and 2°C, respectively. In Mali, Traore et al. (2017) assessed the effect of climate change on maize and pearl millet yield. They indicated a maize grain yield loss of up to 57% that could be offset by applying recommended fertilizer doses. Similar conclusions were drawn for sorghum (Adam et al., 2020), and the authors also highlighted the importance of designing improved management practices to improve crop yield at first. Further, crop production is likely to become more dependent on irrigation in many areas, but water resources are also negatively affected by, e.g. increased drought, or extreme events like floods. These extreme events are difficult to predict, because of the lack of observational data and the interactions with land-use change (Niang et al., 2014). Crop suitability may be altered, resulting in shifts in cropping patterns, shifts from cropping to livestock keeping activities (Jones and Thornton, 2009) and increased household vulnerability (e.g. Wichern et al., 2019; Ramirez-Villegas et al., 2013). These shifts can be captured with simple models like EcoCrop, originally developed by Hijmans et al. (2001).

Falconnier et al. (2020) and Faye et al. (2019) simulated that in low-input systems in SSA, intensified systems with improved yields become more sensitive to climate change impact, hence the need for appropriate adaptation strategies. Freduah et al. (2019) showed that climate change impact on grain yield ranged between 9% and 39% across sites, depending on farms. This diversity of response was mostly due to variations among farms in fertilizer applications, planting dates and soil types. Crop management and soil type diversity needs to be considered when designing farm-level adaptations strategies to climate change. The most common adaptation strategies to climate change are the adaptation of sowing dates and choice of cultivar with adapted crop cycle length. Modeling of crop growth and performance with current and future climate can help determine best sowing date and cultivar duration to escape the heat and drought stress than happen at the start, middle, and/or end of the growing season (Gérardeaux et al., 2021). More frequent heavy rainfalls (e.g. as in the Sahel; Taylor et al., 2017) will intensify nitrate leaching and other relevant adaptations will need to improve nitrogen use efficiency and minimize losses through leaching, e.g. relay intercropping with deep rooting cover crops (Baldé et al., 2011) and split applications of mineral fertilizer (Ganyo et al., 2018). In regions where drought occurrence may increase, drought-tolerant cultivars with adequate root traits and water-harvesting technologies (e.g. stone lines, tied ridging, zaï pits and contour ridging) can contribute to offset production losses. Finally, adaptation to heat stress requires specific cultivar with greater tolerance - but intercropping may also help to create a microclimate that could lower heat stress.

2.1.2 Modeling key processes of particular relevance to low-input cropping systems

For crop models to be meaningful in assessing the effect of climate change and the potential of adaptations to offset these effects, proper calibration against observed data is required, to avoid models simulating a correct output (i.e. close to the observation) for the wrong reason (Keating, 2020). Crop models are increasingly used to explore crop performance in the Global South under the effect of climate change and changes in crop management. However, experimental data from industrialized crops in the North do not necessarily reflect the reality in the fields of smallholder farmers in the Global South. There is an urgent need to fund research that would give priority to field experiments, particularly in family farmers' plots, in order to acquire the data required to document the specificities of the smallholder context in the Global South. For example, a model can accurately simulate grain yield, but this can be the result of a strong overestimation of total aboveground biomass and harvest index. There are physical boundaries to nitrogen concentration or dilution in plant tissues, and if nitrogen uptake and grain yield are not within the minimum and maximum nitrogen dilution boundaries (Fig. 2, derived from Falconnier et al., 2020), simulations are probably unrealistic.

For large-scale, intensified farming in the Global North, water and nutrient stress are often less of an issue than in low-input systems, as farmers often achieve close-to-potential crop yield. In such context, crop modelers focus is often more on yield-defining factors (radiation, temperature, CO₂) than on limiting factors (water and nitrogen), and rely on extensive datasets that have been collected in the past 40 years. For smallholder low-input farming in the Global South, water, nutrient and biotic constraints prevail: the number of processes that have to be accounted for drastically expands. Soil water dynamics (infiltration from rainfall, redistribution within the soil profile and evapotranspiration) influences soil moisture and nutrient supply from the mineralization of soil organic matter. This has a dramatic impact on the amount of nutrient (nitrogen in particular) that can be taken up by the plant in the absence of mineral fertilizer. The decomposition of previous residues buried into the soil, and the decomposition of the diversity of organic amendments (e.g. compost and manure) applied by farmers, also impact nutrient availability during the growing season. Soil water dynamics (prolonged droughts or heavy rains) also impact nitrogen leaching below the root zone and therefore the loss of nitrogen that would be otherwise available for crop uptake. On top of these issues, local crop cultivars (i.e. drought tolerant, sensitive to photoperiod), and intercropping of two or more crops in the same plot is a common feature of smallholder cropping systems (Ganeme et al., 2021). Intercropping involves competition and complementary for light interception, water and nitrogen

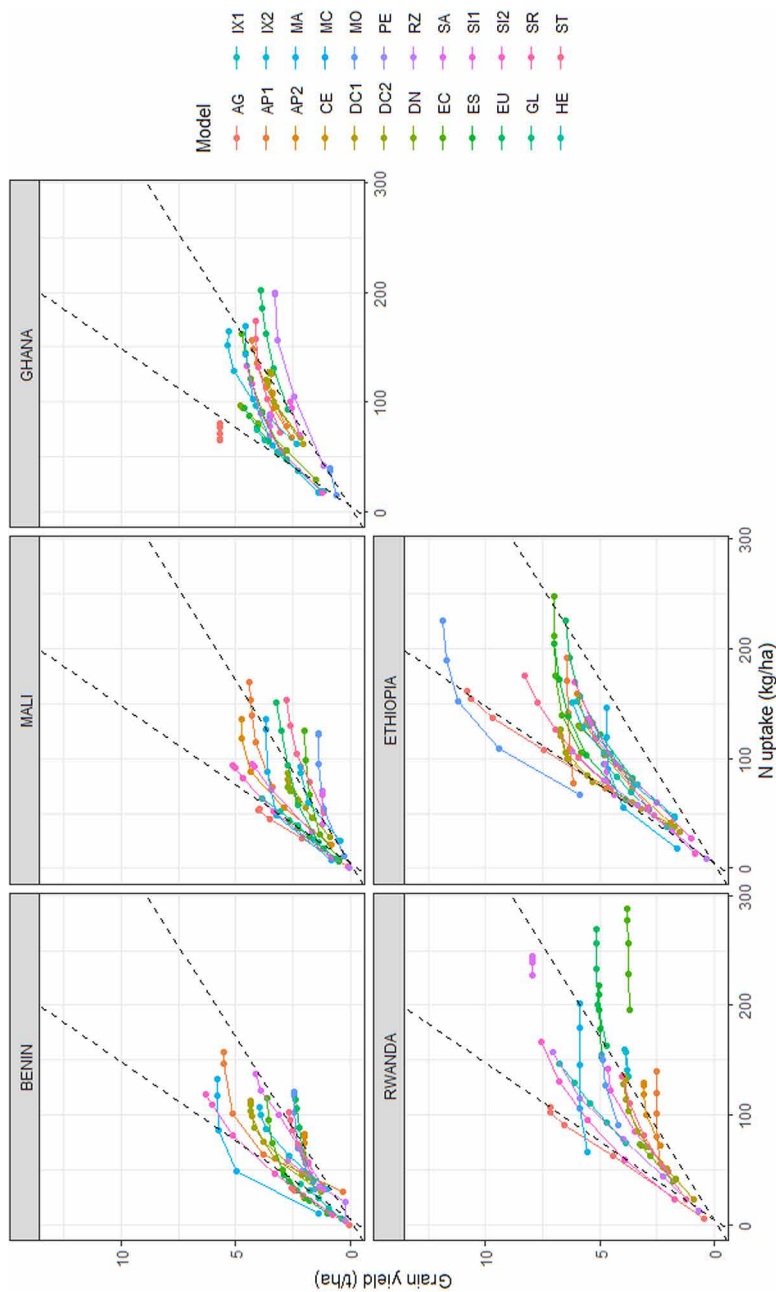


Figure 2 Simulated N uptake and grain yield for 24 AgMIP models at five sites across sub-Saharan Africa. Upper and lower dotted lines are physical boundaries corresponding to maximum and minimum N dilution in grain, respectively.

uptake between the dominant and understory plant, which adds up to the complexity of modeling low-input cropping systems. The current literature shows that the existing experiment across SSA currently lack sufficient observed data to accurately calibrate these key processes, and key species/varieties that characterize low-input conditions (Falconnier et al., 2020; Nendel et al., 2019).

However, a number of recent advances in calibrating crop models for the processes that matter in low-input context have been made. Soil-crop models (DSSAT, APSIM) have been calibrated to reproduce local varietal diversity (Gbegbelegbe et al., 2017; Akinseye et al., 2017; Adam et al., 2018), and the impact of complex interactions between cereal residue, soil type and climate on residue mineralization, in tropical environment in sub-humid Brazil (Maltas, 2007), sub-humid Ghana (MacCarthy et al., 2015), semi-arid Benin (Amouzou et al., 2018) and sub-humid Southern Zambia (Corbeels et al., 2016). Recently, the STICS model was also calibrated to simulate green manure decomposition and the effect on subsequent crop in the tropical context of sub-humid Madagascar (Ranaivoson et al., forthcoming). The study showed that the formalisms for residue decomposition built into the model, initially developed for temperate regions, was relevant for tropical conditions: accurate simulation of the release of nitrogen through the decomposition of the incorporated legume was achieved. STICS was also calibrated for simulating sorghum-cowpea intercropping systems in rainfed conditions in West Africa (Traoré et al., forthcoming and Ganeme et al., in prep). Competition and complementarity between crops for light, water and nitrogen uptake were well reproduced by the model: (i) cowpea and sorghum aboveground biomass was smaller in intercropping than in sole cropping, and (ii) cowpea biomass decreased more strongly than sorghum biomass, and this feature was reproduced by the calibrated model. Despite a reduction in sorghum and cowpea yield, land equivalent ratio of the intercropping for aboveground biomass was greater than one in the additive intercropping systems (Traoré et al., forthcoming).

These recent progress in modeling key processes in low-input systems are promising, but the challenges ahead are substantial. For example, the calibration and validation of STICS-intercrop revealed prospects for improvement. The model, so far, can only simulate intercropping for interrow systems and cannot deal with more complex configurations implemented by farmers (e.g. inter- or within-hill, Ganeme et al., 2021). Traoré et al. (forthcoming) showed accurate simulation of water dynamics, but inaccurate simulation of competition for nitrogen between the cereal and the legume. Pest and disease are not yet properly considered in most crop models (Savary et al., 2019). Phosphorus deficiency, legumes, traditional crops such as pearl millet or teff are also not accurately represented.

2.2 Effect of climate change on livestock and grazing land

In low-input systems, crop-livestock integration is widespread and provides several benefits to smallholder farmers (e.g. traction, manure, saving) (Descheemaeker et al., 2016). Livestock and climate change are closely interconnected as on the one hand livestock is a significant contributor to greenhouse gas emissions (FAO, 2006), and on the other hand livestock is drastically impacted by climate change (Rojas-Downing et al., 2017). While the mitigation of greenhouse gas emissions is indeed a high priority in developed countries with intensive livestock production systems, adaptation remains the priority for smallholder farmers, as climate change strongly affects their livestock systems.

2.2.1 Impact of climate change on livestock productivity and adaptation strategies

Increase in temperature and higher frequency of drought affect feed quality and quantity when livestock systems rely on cropland and grazing land. With high temperature, feed intake and ruminant digestion are reduced (Yadav et al., 2013). Reproduction is also affected by high temperature (e.g. Wolfenson and Roth, 2019) through, e.g. disruption of oocyte development and alteration of ovarian follicular growth dynamics. Reproduction is a 'luxurious phenomenon' appropriate when animals are in a favorable environment (Chauhan and Ghosh, 2014). Fertility rate reduction is a coping strategy for animals, which can affect directly farm viability. Livestock disease outbreaks will also become more frequent under a warmer and wetter climate (Sejian et al., 2016). Climate change may favor living conditions of disease vectors and tick-borne disease, rift valley fever and bluetongue will likely affect more cattle. Parasitic diseases will also be more frequent or affect larger geographical areas, in regions where rainfall will increase.

Climate change adaptation options for low-input livestock systems can follow three overall strategies, being risk management, diversification and sustainable intensification (Descheemaeker et al., 2016). Grazing management, including seasonal herd migration, adjustment of stocking densities and rotational grazing, and weather-based index insurance schemes (Greatrex et al., 2015) are typical examples of risk management strategies that allow adapting to increased climate variability and a higher frequency of extreme events. Adapting to the increasing incidence of heat and drought stress can also be achieved through diversifying with breeds and livestock species that are better adapted to these circumstances. Tighter crop-livestock integration (e.g. improved residue and manure management, inclusion of fodder legume) and diversification of household income sources, including off-farm income, can

cushion low-input systems against climate shocks. Sustainable intensification that is targeted at increasing animal productivity is a promising strategy as it also helps in reducing greenhouse gas emission, expressed per kg of animal product. In particular, feed gaps in the dry season are a major cause of livestock inefficiency, with animals losing weight and becoming more susceptible to diseases. These feed gaps could be addressed through cultivating fodder legume crops (e.g. *Mucuna pruriens*) that produce high quality biomass and provide rotational benefits to other crops (Descheemaeker et al., 2018), or through using feed concentrates. If heat, drought and water stress can be managed, the introduction of more productive breeds is also an option.

For all the reasons mentioned above, milk and meat productivity, and household food security, will be affected by climate change. In addition, changes in the suitability of agro-ecological zones for keeping certain types of animals, may impact the configuration of entire farming systems, with repercussions on crops, grazing lands and herder livelihoods.

2.2.2 Modeling key processes of particular relevance for livestock and grassland low-input systems

Livestock simulation models can be used to evaluate the effect of climate change on animal performance. The LIVSIM model (LIVestock SIMulator, Rufino et al., 2009) has been used extensively for smallholder cattle systems in a range of environments, including Zimbabwe (Rufino et al., 2011; Descheemaeker et al., 2018), Kenya (Rufino et al., 2009) and Mali (de Ridder et al., 2015), and for small ruminant systems in Nigeria (Amole et al., 2017). LIVSIM calculates the performance of each individual animal in the herd on a monthly basis, according to its genetic potential, feed availability and quality, and herd management. Model outputs include milk and manure quantity and nutrient content, animal body weight and herd dynamics, including birth rate, offtake rate and mortality. LIVSIM has been used to evaluate the effects of altered feed availability due to climate change and adaptation on livestock in mixed systems in a semi-arid area of Zimbabwe (Descheemaeker et al., 2018). Taking into account differences between temperate and (sub-)tropical husbandry systems, a recent modification called LIVSIM-mod (Bateki and Dickhoefer, 2020) accurately represented voluntary feed intake capacity, growth and lactation, and metabolizable energy requirements for maintenance and weight gain of cattle in low-input tropical systems.

Studies assessing the impact of climate change on crops mostly focused on grain yield with little attention to biomass. Yet crop residues are an important feed source for livestock and for other household uses like fuel, composting, building), and as a mulch to protect the soil and recycle nutrients (Valbuena et al., 2012). Crop residues are indeed an important feed source in sub-humid

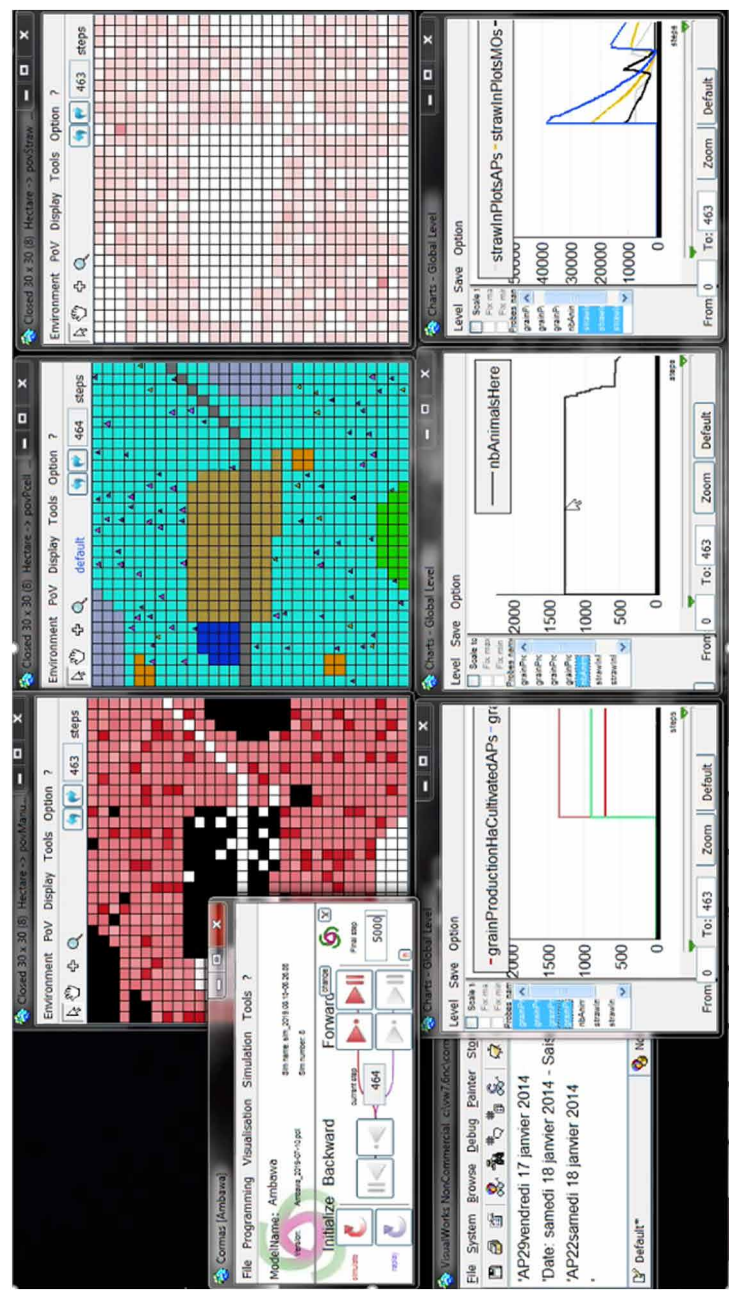


Figure 3 Example of agent-based model exploration of the effect of mulching at landscape scale (windows on the upper side are amount of manure deposited (left) during free-grazing of crop residue (right) with cattle mobility moving in the cropping land (center). Windows on the lower side are respectively crop yield (left), number of animals in the landscape (center, decreasing when cattle starts to leave the village) and crop residue decreased during the dry season).

and semi-arid areas during the dry season. Historically, livestock are authorized by common-law to graze on cropland after harvesting, which also benefits crop producers thanks to manure deposition during the livestock corralling. While the effect at field scale of crop residue mulching on yield is well-documented, in such a context of cattle mobility, spatially explicit models combining both biophysical and managerial modules are needed to understand biomass flows and correlated fertility patterns. The AMBAWA model (Berre et al., 2021) can simulate at village level the impact of an increasing share of cropland with residue mulching on cattle mobility and soil fertility (Fig. 3). Regardless of mulch effect on soil (from no effect to doubling of yield), yields are always decreasing at landscape scale if mulch is used, as cattle have to leave the landscape and manure is therefore lost for soil fertility in the village. Such complex feedbacks need to be accounted for when analyzing the impact of climate change on low-input farming systems.

In a context of cattle mobility in sub-humid and semi-arid areas, biomass inflows and outflows at farm scale are highly influenced by fodder seasonality and cattle mobility. Indeed, modeling biomass inflows and outflows in farm households allows identifying contrasted types of biomass management but does not tackle farms' interaction and inputs from grazing land at landscape scale (Assogba et al., 2022). As such, more research is needed in (i) livestock science to understand physiological processes governing feed and water intake during droughts and (ii) environmental sciences to better explore changes in feed quantity and quality in remote grazing land used during transhumance. Assouma et al. (2018) and Lo Seen et al. (1995) provide useful examples.

2.3 Effect of climate change on agroforestry

Agroforestry systems are characterized by the integration and management of trees with crop and livestock. Agroforestry has been pointed out by the Intergovernmental Panel on Climate Change as a key option to respond to climate change and land degradation while simultaneously improving global food security (IPCC, 2019). In SSA, where around 40% of people in rural areas live in landscapes with more than 10% tree cover (Zomer et al., 2014), agroforestry is a traditional and major land-use system and has long been recognized as a solution to address climate change (Mbow et al., 2014). Depending on agroclimatic situations and socio-economic environments, different types of agroforestry systems occur in SSA: e.g. Sahelian parklands systems, Kenyan rotational woodlots or intercropping systems in Malawi (Dagar et al., 2020).

2.3.1 Impact of climate change on trees and agroforestry productivity and adaptation strategies

Rainfall and temperature influence tree growth (Sanogo et al., 2016), tree density and tree species diversity (Gonzalez et al., 2012). Strong wind can

increase flower dropping and hence reduce fruit production. Climate change is expected to change the current distribution of tree species in SSA. For instance, using ensemble suitability mapping, Kindt (2018) assessed the distribution of over 150 tree species with future climate. The authors showed a huge reduction of suitability areas by 2050 for most of the tree species being planted and managed today. In the Sahelian areas, a decline in tree density and tree cover is already observed, particularly in cultivated areas with high population density (Brandt et al., 2016; Hiernaux et al., 2022). This decline was attributed to climate change (Gonzalez et al., 2012).

In SSA, agroforestry systems provide an array of ecological, economic and cultural services (Sinare and Gordon, 2015; Kuyah et al., 2016; Miller et al., 2017). The expected impacts of climate change on trees in agroforestry systems can reduce their provision of ecosystem services. First, it can have a direct impact on food security. Large tree species (e.g. shea fruits, baobab fruits) have high nutritional values and households use them in coping with seasonal food shortages. Fruit yields of these trees could decrease with climate change. Second, indirect impacts of climate change on household food security and livelihoods can be expected. Trees are a source of products, income and energy (e.g. fruits, wood, charcoal) and services (e.g. microclimate amelioration, medicine) that contribute to household adaptation to climate change (Koffi et al., 2017; Bayala et al., 2014; Sida et al., 2018; Reed et al., 2017).

2.3.2 Modeling keys processes of particular relevance for agroforestry

Agroforestry models have been developed over the past decades. Due to the complexity of agroforestry systems that include interactions between crops and trees, those models have mainly been used to predict field-scale performance (Luedeling et al., 2016). None of them have been used to assess performance at farm level in SSA. Examples of such models applied at field-scale are WaNuLCAS (Van Noordwijk and Lusiana, 1998) or HyPAR (Mobbs et al., 1999). Attempts have been made to develop models to assess the economic costs and benefits of agroforestry systems at farm scale in Europe (Farm-SAFE, Graves et al., 2011). Other approaches have been proposed to assess the productivity of agroforestry systems at landscape and farm scales in SSA. Leroux et al. (2020) developed a remote sensing-based statistical model accounting for vegetation productivity and tree density to predict millet yields in Senegalese *Faidherbia albida* parklands (Fig. 4). The authors evidenced that millet yield increased with woody cover up to 35% in the surrounding landscape of agricultural fields. Then, using an integrated landscape approach relying on remote sensing data and recent advances in data analysis methods, they showed that the tree

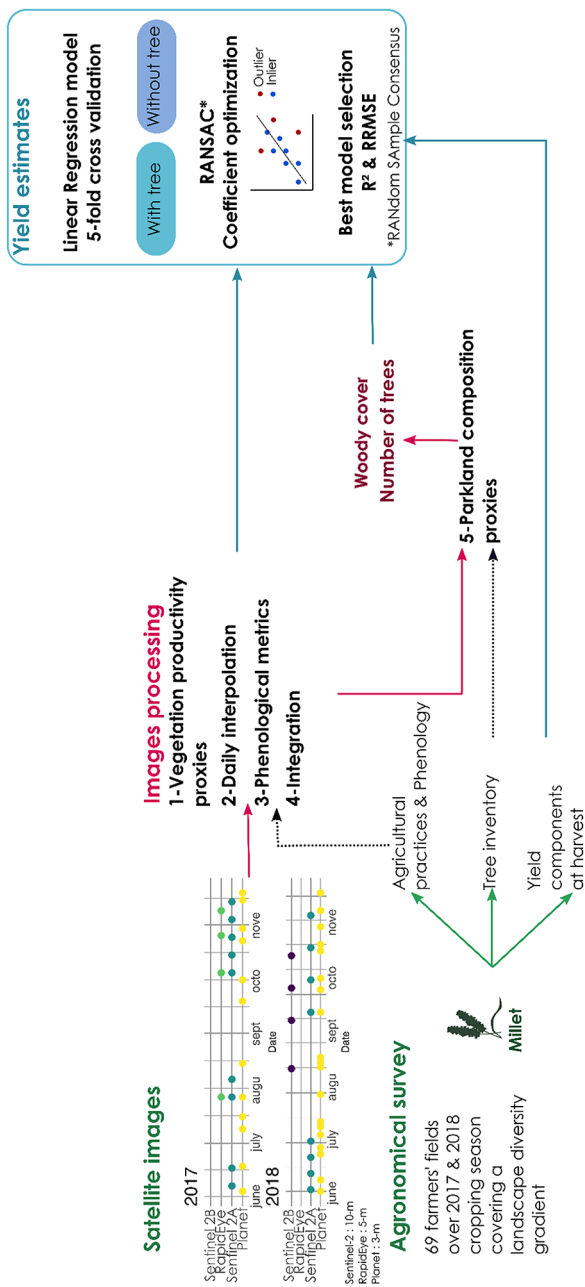


Figure 4 Methodology developed in Leroux et al. (2020) for improving millet yield estimation considering the tree component using a remote sensing-based model.

species diversity contributed mainly indirectly to household food security through the provision of ecosystem services regulating and supporting crop production (Leroux et al., 2022).

3 Toward an integrative perspective

After a review of recent progress and challenges remaining to capture the effect of climate change in the different components of low-input farming systems, it is now important to consider the integration of these different components. In this section we highlight the main approaches that address the effect of climate change at farming systems level rather than at individual component level.

3.1 Coupling models to assess climate change effect at farm scale

In order to understand climate change impacts and the effects of adaptation and mitigation options on mixed farming systems, a systems approach considering the interactions between farm components and processes at different scales is needed. The Agricultural Model Intercomparison and Improvement Project (AgMIP) Regional Integrated Assessment (RIA) approach links climate, crop, livestock and economic data and models for assessing the effect of climate change and adaptation options on heterogeneous farm populations. This modeling framework was run for a multi-farm assessment to capture the heterogeneity existing on a specific site, and to link different components of the farming systems. Results from contrasting Global Circulation Models (i.e. climate models used for future climate explorations) were used as input in two crop growth models (APSIM and DSSAT) to simulate effects on crop yield and (fodder) biomass production. The crop model results were used as input in the livestock model LIVSIM (Rufino et al., 2009), which allowed the simulation of field and herd level productivity. Both crop and livestock results fed into the TOA-MD model, which estimated economic performance at farm level (Claessens et al., 2012). This approach was carried out for different regions across the world, ranging from Africa (West, East and Southern) to Asia (Pakistan, Southern India and Indo Gangetic-Basin).

In West Africa, the impact of climate change was investigated on farmers' livelihoods under current production systems using Nioro, located in the South of the Groundnut Basin of Senegal as a case study. Nioro agriculture consists of predominately smallholder rainfed farms cultivating a range of cereals (millet, maize and sorghum) and legumes (peanut and cowpea) in rotation. Livestock plays a significant role in the functioning of the overall system through its dependence on crop residues as feed, and provision of manure to the cropping system. Fallow tends to disappear under population pressure. Very few farmers apply mineral fertilizers. As a result, average yields of cereals and peanut are

low. The economic estimation of climate change impact on farming systems was done with the TOA-MD and uses inputs from two crop models (DSSAT and APSIM), which generated data through 10 GCMs (five for a 'high emissions' scenario in which little climate change mitigation happens in the future, RCP 8.5, and five for a 'medium emissions' scenario in which some climate change mitigation happens, RCP 4.5). Outcome variables such as vulnerability, defined as the proportion of households negatively affected by climate change, mean net farm returns, per capita income and poverty rates, were considered. With DSSAT simulations, the percentage of vulnerable farms varied between 24% and 59% across GCMs and RCPs. The lowest values were recorded for the cool/wet and middle scenarios. The hot/dry scenario presented the highest level of farm vulnerability. With APSIM simulations, the percent of vulnerable farms was between 42% and 49% (Fig. 5a).

Using the same approach for three farm types in semi-arid Zimbabwe, crop sensitivity to climate change in the current agricultural systems was relatively small, due mainly to poor soil fertility and low fertilizer application rates, causing severe nutrient stress. The observed small yield decline was attributed to increased temperature accelerating phenological development, and exacerbated by drought stress in the hot-dry climate. As "non-poor" farms (farmers above the poverty line) cultivated maize on better soils and with more fertilizer input, their maize was more sensitive to yield loss compared with the less-endowed farms. Livestock productivity was affected through altered production of crop residue and rangeland biomass, influencing feed intake, ranging from a slightly positive to a negative effect in the hot-wet and the hot-dry climate respectively. Non-poor farms, typically with larger stocking density, were more sensitive to feed gaps, and more strongly impacted by climate change than poor farms (Descheemaeker et al., 2018). At farm level, the simulated change in farm net returns depended on the climate and the farm type. 95% of the extremely poor households was currently below the poverty line. Their low-input production system was not sensitive to climate change, and only 40–50% of these farmers would lose (a little). In the group of best-endowed farmers, who cultivate better soils and keep more cattle, about 75% faced reduced returns in the hot-dry scenario, which increased the poverty rate from 60% to 65% of the households (Fig. 5b).

As described above, in order to assess the effect of climate change at farm scale or landscape scale, it is a common approach to first assess the effects at the component-level (climate change on crop or livestock or tree) based on general circulation models (GCM) climatic simulation, and then feed the outputs of one model into the next model in the chain. However, this raises the question of uncertainty propagation where uncertainty in data used to feed one model can lead to very high uncertainty in the outputs of subsequent models in the chain. Indeed, Corbeels et al. (2018) underlined that the variability in

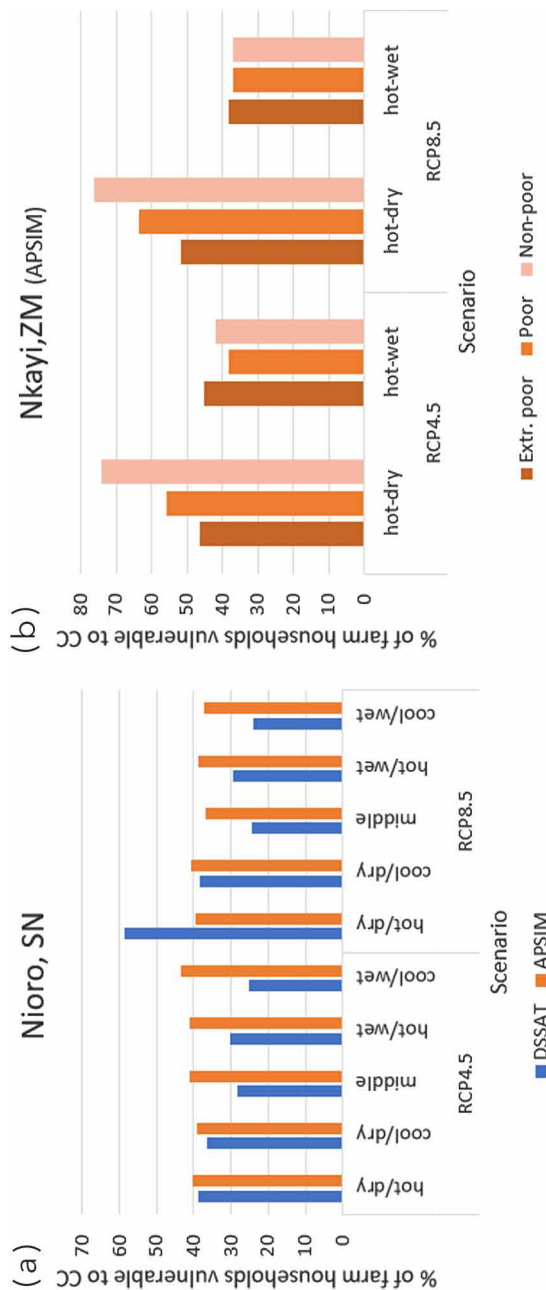


Figure 5 Percentage of farm households vulnerable to climate change (a) when considering two crop models in Nioro, Senegal and (b) according to different farmers type in Nkayi, Zimbabwe.

simulated yields arising from the use of several GCMs was stronger than the simulated yield variation that could be attributed to management adaptation. Recent ensemble modeling approaches allow to capture the uncertainty due to the GCM used (Tao et al., 2018) and crop model structure (Falconnier et al., 2020). Hence, as generated climatic data, simulated crop yield and zootechnical performance are all uncertain and the output of a farm-scale model fed with these data should be considered carefully.

3.2 Accounting for farmer decision-making in models

The AgMIP framework does not consider farmers' decision-making and farmers' preferences for different farming options nor does it account for farmers' adaptations in response to their perception of climate change. Optimization models can be used to represent farmers' decision-making. In such approaches, farms are modeled as managed by rational decision-makers (the farmers) who decide to select different farming options to achieve their goals under different constraints (cash, labor, land; Fig. 6). Using an optimization model, Wineman and Crawford (2017) found that farmers in Zambia will likely shift their choices of technologies and crops with climate change, but calorie production from crops would still decrease by 1-5%, depending on farm type. They identified that land-constrained farmers would have a high probability to fall below a minimum of calorie threshold and that autonomous adaptation would probably not be enough to offset yield losses. Boansi et al., (2021) identified with the use of an optimization model that rainfall shocks will lead to a decrease in total farm income in Ghana by 7.3-45.5%, and impact more the income and food consumption of 'asset poor farmers' who cannot cope by selling livestock.

Optimization models allow interactions between crop, tree, livestock, household and off-farm activities to be considered. Moreover, such models account for the seasonality of farming activities: by dividing a year in key periods of time, the effect of climate change on seasonal availability of farm resources (labor, forage, cash, grain for sale or self-consumption) can be analyzed and the effect on farm level indicators (e.g. income, food security) assessed.

Farmers' rationality to maximize their utility (i.e. what is important for them, e.g. profit, yield, costs, work, food security) is assumed in optimization models. Waldman et al. (2020) pinpointed that in an uncertain, changing context, these farm models represent the decision-making of farmers in an overly simplistic manner. They are used to quantify the effects of climate change in an ideal world where farmers have full knowledge of the farming options, and on the effects of climate change on these options. Assuming full rationality of farmers implies the risk to overestimate farmer adaptation to climate change. Farmers are not necessarily utility-maximizers, for example, they may not choose the

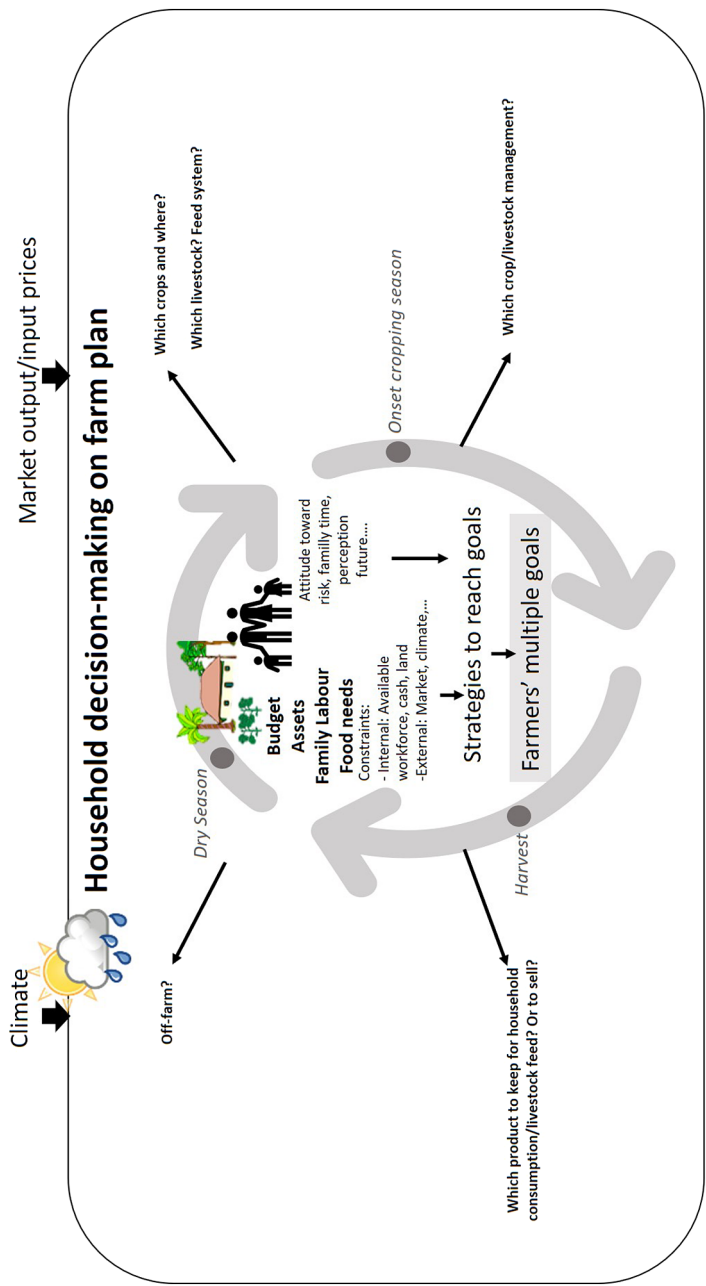


Figure 6 Representation of the key factors to consider when modeling household decision-making at farm level.

best option on every attribute, but rather make fast decisions on the option that performs best on their most important attribute (Waldman et al., 2020). Decision-making is also more complex than only utility maximization and could be linked to perceived risk, beliefs and values (Zhang et al., 2020). The perception that farmers may have of climate change may be biased, and the adaptations they may make as a result of this perception of climate change may be hard to predict. Lastly, climate change will be only one driver of change among others, such as input/output price fluctuation, policy interventions on e.g. agriculture, livestock, family planning (Falconnier et al., 2018; Assogba et al., 2022).

As climate change will generate more risks, e.g. income fluctuations (Adzawla et al., 2020), it is important to consider such risk in farmer decision-making. Accounting for risk means to assess farmer risk-aversion (see e.g. use of a lottery game in Eckel and Grossman, 2008), their perception of that risk (sometimes biased, because people tend to better remind extreme events), to identify the origins of this risk (flood, drought, delayed onset of rainy season, etc.), and the variability of performances under climate change for current systems and adaptation strategies (Huet et al., 2022).

3.3 Co-design adaptations with decision-makers

The heterogeneity of smallholder farms in large parts of SSA requires climate adaptations that are flexible and adapted to local agro-ecological and institutional conditions and to farmers' willingness and ability to invest. Models are essential tools for assessing the performance of farming systems and exploring the multidimensional effects of their adaptation, as shown in the previous sections. However, for model results to be useful in supporting decision-makers choices, modeling exercises need to be conducted in collaboration with the decision-makers so that criteria relevant to them are included in the assessment.

Decision-makers, ranging from farmers to policymakers, need science-based information to design interventions that address climate change and underpin transitions toward more sustainable farming system. AgMIP used a stakeholder-driven, integrated modeling approach to generate actionable information for policy planning processes (Homann-Kee Tui et al., 2021). Local experts and stakeholders were engaged in participatory workshops in which model results were presented and discussed, and future development pathways (called Representative Agricultural Pathways, RAPs; Valdivia et al., 2021) and adaptation options were co-designed. The process was iterative, which allowed for consecutive refinement of RAPs and adaptation options. For example, a first round of model runs for a Zimbabwean case showed that,

whereas individual crop and animal productivity increased with adaptation options, whole-farm effects on food security and income were limited and would not allow to lift the majority of farmers out of poverty. Indeed, constraints related to farming system characteristics (e.g. small farm sizes, low soil fertility) and institutional barriers (e.g. absence of market incentives, poor access to inputs) were more important than climate change effects and impeded a shift toward more sustainable systems. Hence, in a second round of RAP adaptation, stakeholders and researchers co-designed future system changes that would enable farmers to earn a better living than today, even under climate change, through the adoption of relevant technologies (e.g. integrated soil fertility management, better husbandry of more productive livestock breeds) with support of appropriate institutions (e.g. functioning markets, insurance) and dedicated policies (e.g. on input and output prices, land tenure) (Homann-Kee Tui et al., 2021).

Farmers perceive strong risks from climate variability and extreme events (Huet et al., 2020), which leads to reduced investments and input use. As such, low-risk subsistence activities lower farm productivity and profit, resulting in an impact that may be stronger than that of changes in mean climate. Moreover, when a shock/hazard happens, a common coping strategy by smallholders is to sell assets (e.g. livestock, land, farming material) (Wichern et al., 2022) with prolonged impacts on income and food security and an increased likelihood of smallholders falling into poverty traps as a result. To cushion smallholder farmers against these risks, it is important to co-design relevant adaptation options with them. However, participatory processes of co-learning and co-design are challenging because farmers and researchers use different mental models of reality. Scientists rely on weather records of past meteorological data, while farmers often rely on their perception of how the climate may have changed over time. Meteorological data and farmers' perception do not necessarily align: while farmers of central Mali perceived an increase in the frequency of dry spells, the analysis of past climate data did not show such an increase (Traore et al., 2021). This investigation of the consistency between farmers' perception and weather record is crucial, as farmers' inaccurate perception of climate change can lead to maladaptation (Grothmann and Patt, 2005).

Mismatch between perception and actual weather record can be linked to the fact that perception is biased with possibly over-emphasis of recent extreme events (Marx et al., 2007), or it may also arise from the fact that scientists use indicators of climate change that do not match with the indicators used by farmers. The analysis of the link between farmers' perception of climate change and effective implementation of adaptation strategies is also crucial, as it may illustrate areas where farmers need stronger support. For example, farmers acutely perceived the increase in temperature in central Mali (an increase also

shown by the analysis of historical data), yet they fell short at designing and implementing specific adaptation in their field to address this rising constraint (Traore et al., 2021). Continuous interactions between farmers and researchers are needed to develop a common understanding of the impact of climate change on crops and to design site-specific adaptation strategies.

4 Conclusion

Modeling the effect of climate change in low-input farming systems still faces some challenges. First, at component level, we notice the unbalance in studies carried out in low-input systems. In terms of modeling, much more is done for cropping systems than for livestock and let alone the agroforestry component. This can certainly be attributed to the difficulty in capturing relevant processes and acquire data for low-input systems. Even for crop models, as they have first been developed for industrialized countries, when applied to low-input cropping systems, the number of processes that have to be accounted for drastically expands (i.e. water, nutrient and biotic constraints). For livestock and agroforestry component, new approaches are needed to capture the complexity of the component in low-input systems. We described a few promising attempts to address this void, but we stressed the importance of data collection in this context to account better for these constraints. With respect to modeling livestock and agroforestry components, there are novel approaches that help model important processes, i.e. agent-based modeling to represent the importance of biomass management at landscape scale, or use of remote sensing to quantify the effect of trees on crop productivity and food security. Further integration of agroforestry and livestock modeling with cropping system modeling will help account for the crop-livestock-tree integration that is so crucial for farmers of the South to adapt to climate change.

Second, there is an urgent need for farm-level models to assess climate change impacts. Such approach will permit to go beyond point-based crop modeling and coupling of input-outputs from one model to another. Impact at farm level is more than the sum of the impacts on the separate components. Unfortunately, too little is done at this level. Coupling climate, crop, livestock and economic models is a step forward. But it raises the issue of propagation of uncertainty from component to component and of integrating farm-level decision-making. It is (very) challenging to predict farmers' adaptation decisions to the effects of climate change as climate is one driver of farm change among many others (market, policies, labor supply, Mertz et al., 2009). A better understanding of farmers' climate change perception, risk-aversion and livelihood strategies can result from more interdisciplinary research involving agronomists and social scientists.

Finally, we can mention farm-level constraints (e.g. farm size) and entry points (e.g. intensification) that can easily offset climate change impact. But often family farmers have more urgent issues to solve before thinking about future climate change, and that might prevent them from acting against climate change. Hence, we argue, in our last section, on the importance of including decision-makers, including farmers, in modeling exercises to co-design adaptation strategies to climate change. Their involvement will allow first to create a constructive dialogue on the effect of climate change on farming systems, and second to better represent in farm models key factors, and finally to co-design locally relevant adaptation strategies.

5 Where to look for further information

5.1 Further reading

- For more information on effect of climate change on crop models, see the book chapter by Adam, M., Boote, K. J., Falconnier, G. N., Porter, C., Rezaei, E. E. and Webber, H. 2020. Modeling the effects of climate change on agriculture: a focus on cropping systems, in: *Climate Change and Agriculture*, Deryng Delphine (Ed.). Burleigh Dodds Science Publishing, Cambridge.
- For more information on a livestock model applied to tropical conditions, see Bateki, C. A. and Dickhoefer, U. 2020. Evaluation of the Modified LIVE-stock SIMulator for Stall-Fed Dairy Cattle in the Tropics. *Animals* 10, 816. <https://doi.org/10.3390/ani10050816>.
- For more information for agroforestry modeling, please have a look at <https://worldagroforestry.org/output/wanulcas-model-water-nutrient-and-light-capture-agroforestry-systems>.

5.2 Major international research projects work on integrative approaches

- AgMIP: <http://www.agmip.org/>.
- Big data and crop modeling groups (CGIAR initiative): <https://bigdata.cgiar.org/communities-of-practice/crop-modelling/>.

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