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Climate change impacts and adaptation for dryland farming systems in Zimbabwe: a stakeholder-driven integrated multi-model assessment

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Abstract
Decision makers need accurate information to address climate variability and change and accelerate transformation to sustainability. A stakeholder-driven, science-based multi-model approach has been developed and used by the Agricultural Model Intercomparison and Improvement Project (AgMIP) to generate actionable information for adaptation planning processes. For a range of mid-century climate projections—likely to be hotter, drier, and more variable—contrasting future socio-economic scenarios (Representative Agricultural Pathways, RAPs) were co-developed with stakeholders to portray a sustainable development scenario and a rapid economic growth pathway. The unique characteristic of this application is the integration of a multi-modeling approach with stakeholder engagement to co-develop scenarios and adaptation strategies. Distribution of outcomes were simulated with climate, crop, livestock, and economic impact assessment models for smallholder crop livestock farmers in a typical dryland agro-ecological zone in Zimbabwe, characterized by low and erratic rainfall and nutrient depleted soils. Results showed that in Nkayi District, Western Zimbabwe, climate change would threaten most of the farms, and, in particular, those with large cattle herds due to feed shortages. Adaptation strategies that showed the most promise included diversification using legume production, soil fertility improvement, and investment in conducive market environments. The switch to more legumes in the farming systems reduced the vulnerability of the very poor as well as the more resourced farmers. Overall, the sustainable development scenario consistently addressed institutional failures and motivated productivity-enhancing, environmentally sound technologies and inclusive development approaches. This yielded more favorable outcomes than investment in quick economic wins from commercializing agriculture.

Keywords Climate change adaptation · Crop-livestock systems · Vulnerability · Poverty · Zimbabwe · Pathways and scenarios · Models

1 Introduction

In southern Africa, mixed crop and livestock systems are the predominant form of agriculture and source of income, and produce more than 80% of food in the region. Improving their productivity and resilience to climate change is challenging. Firstly, interventions need to be tailored to highly varied biophysical and socio-economic conditions (Giller et al. 2011; Antle et al. 2017; Descheemaeker et al. 2018). Secondly, development of market, technology, and services needs to be synchronized with consumption patterns and demand for food (Hazell and Wood 2008; Ingam 2017). Thirdly, most smallholder farm households (those with <2 ha rainfed land) in this region are resource poor, reliant on family labor, and exposed to multiple sources of risk (Harris and Orr 2014). These households have very little surplus for sale and seldom participate in markets, thus are highly constrained by limited capital.

A projected temperature rise by mid-century combined with a likely decrease in rainfall, greater rainfall variability, and highly vulnerable rural communities makes Southern Africa a hotspot of climate change (Christiaensen et al. 2007; Moyo and Nangombe 2015). The climate risks are compounded by a growing human population and significant disruptions to food and feed supply (Herrero et al. 2010; Campbell et al. 2017). The challenge is to find climate change adaptation options that also improve food security and livelihoods (Lipper et al. 2014). In smallholder mixed systems, farm diversification and sustainable intensification are often proposed as ways to achieve this (Descheemaeker et al. 2016; Whitbread et al. 2010). Progress has been made in developing improved crop varieties and livestock breeds, along with improved management, capitalizing on the synergies from crop-livestock integration, to increase resource-use efficiency, food and feed quantity and quality, and the entire system's overall productivity and stability (Blümmel et al. 2013; Garrett et al. 2017). Enhanced farm diversity (crops, livestock, off-farm activities) can help to disperse production and market risks, thus reducing the sensitivity to climate variability and economic risks.

In Zimbabwe, with more than 70% of the population depending on agriculture, sustainable intensification is high on the national agenda; knowledge is however scarce about climate change impacts to inform the road map for adaptation planning (Ministry of Agriculture 2019). Decision makers in Zimbabwe most importantly require information on vulnerability and adaption analyses that are context specific, while accounting for the main farming system components.

Earlier findings showed that impacts of business-as-usual pathways and incremental changes like fertilizer application, improved varieties, and forage production increased agricultural production but were not enough to substantially improve conditions of smallholder farmers (Masikati et al. 2015). Policy makers need actionable information to ensure future food security and allow farmers to capture economic opportunities, for example, through infrastructure development, market-oriented support and financial services (Thornton et al. 2009; Descheemaeker et al. 2016).

To address this need, the Agricultural Model Intercomparison and Improvement Project (AgMIP) developed a novel Regional Integrated Assessment (RIA) approach that combines multi-model simulations with expert knowledge to characterize the vulnerability to climate change and adaptation impacts in complex smallholder farming systems. It advances research on the use of forward looking decision support tools, for the design and implementation of effective policies towards climate proofing the agricultural sector.

Actual quantification of how many farmers in a population are indeed vulnerable to climate change, which characteristics distinguish them and why are they vulnerable, is still an open

question, which we aim to address here. Often, existing studies look at climate change effects and adaptation in current systems, but information as to what their effects could be in future systems is missing. This approach simulates distribution of outcomes for a population of farms in rural communities capturing the diverse farm types, household activities, and multiple crop and livestock farm activities. The development of scenarios to characterize current and future socio-economic and climate conditions allows us to assess agricultural systems under current and future conditions. The goal is to bring research closer to influencing decision processes towards more sustainable agricultural futures in the face of climate change.

2 Material and methods

2.1 Study area and agricultural systems

The study site in Nkayi District, Zimbabwe, is a dryland farming system, with communal land tenure. Rainfed agriculture (<650 mm average annual rainfall) with frequent droughts (occurring in two out of five years) and poor fertility of predominantly sandy loam soil, under continuous cultivation and limited input use, results in low agricultural productivity (Homann-Kee Tui et al. 2015; Supplementary Information (SI Figure 1). Poverty in Nkayi is the highest in the country, with over 76% of the rural population estimated to be below the international poverty line (USD1.25 per capita expenditure per day, at constant 2005 price), and more than 22% extremely poor (<USD1 per capita expenditure per day).

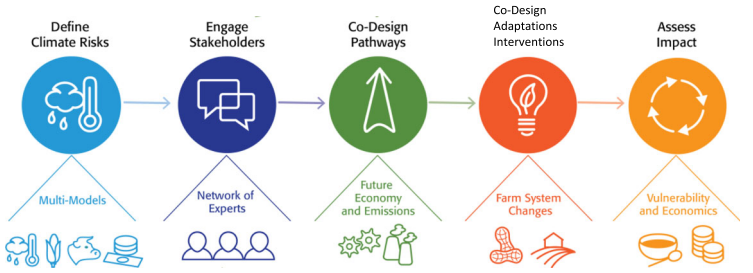
Agricultural systems in Nkayi are cattle-maize dominated (Homann-Kee Tui et al. 2015). Crop and livestock production are integrated, with crop residues being used as dry season feed resource, and livestock draft power and manure used for crop production. All farmers cultivate maize on individual fields (current yield ~0.7 t/ha); about a third of them produce groundnut (~0.4 t/ha) and another third produce small grains (sorghum current yield ~0.5 t/ha). Most used hybrid maize varieties (i.e., Sc401) and local small grains and legume varieties. Historically, maize yields attained 1.5 t/ha and 4.5 t/ha in the communal and commercial sectors, respectively; sorghum and groundnut yields reached 2.5 t/ha in the commercial sector (Ministry of Agriculture 2007). See Supplementary information for further details.

About 60% of the households keep cattle and/or goats and donkeys, local crossbreeds, primarily for draft power, organic fertilizer, and cash income. Livestock mortality rates often exceed 15%; milk yields are also low (<1.5 l/cow/day) and offtake rates are <10%. Despite dry season feed shortages and poor feed quality, less than 5% of farms produce forages for feed. Rural communities are heterogeneous and the different levels of resource endowments determine agricultural priorities and aspirations.

2.2 Simulation design for the Regional Integrated Assessment

The AgMIP RIA was calibrated for the Nkayi district of Zimbabwe as typical of low-input smallholder mixed crop-livestock farming system, which covers more than a third of the national area and is projected to expand under drier climates (Mugandani et al. 2012).

The research was carried out by a trans-disciplinary team comprised of researchers and provincial and national level experts and stakeholders, who, in an iterative process, co-developed pathways and adaptation interventions in the context of the local farming system



Simulation model outputs

Crops: APSIM, DSSAT, grain and stover yield
Livestock: LIVSIM, offtake and milk
Economics: TOA-MD, vulnerability, adoption, farm net returns, poverty impacts

Simulation model inputs

Number of farms: 160, extremely poor (0 cattle), poor (1-8 cattle), non-poor (>8 cattle)
Number of years: 30 years current, 30 years by mid century
Number of soil types: 3 (poor, medium and good soil fertility)
Number of crop varieties: 3 (local, high yielding, drought tolerant)
Number of livestock breeds: 1 (local cross breed)
Crop parameters: cultivar and management (sowing, fertilizer, density)
Livestock parameters: breed and management (feeding, herd management)
Economic parameters: household size, cropland and herd composition, income from crop and livestock activities and off-farm, price and productivity trends

Current world

Sensitivity to climate change
RCPs, GCMs
- **4.5, HD:** HadGEM2-AO
- **4.5, HW:** IPSL-CM5A-MR
- **8.5, HD:** R MPI-ESM-LR
- **8.5, HW:** CanESM2

Impact of improved management
Management options
- Step 1:Crop management improvement
- Step 2: Crop diversification, improved feed
- Step 3: Market incentives

Future worlds

Impact of climate change
RCPs, GCMs:
- **4.5, HD:** HadGEM2-AO
- **4.5, HW:** IPSL-CM5A-MR
- **8.5, HD:** R MPI-ESM-LR
- **8.5, HW:** CanESM2

RAPS:
- Business As Usual
- Sustainable Development
- Fast Economic Growth

Sensitivity analyses
- High price range
- Low price range

Impact of climate change adaptation
Adaptation options
- Switch to drought tolerant crop varieties

Fig. 1 Summary of simulation design used in the regional integrated assessment, in the current world, and different future worlds, defined by Representative Agricultural Pathways (RAPS), linked to Representative Concentration Pathways (RCPs), and Global Circulation Models (GCMs), Hot Dry (HD) and Hot Wet (HW) climate scenarios, in Nkayi District (adapted from Homann-Kee Tui et al. 2017)

(Figure 1). The validation of scenarios and modeling results at provincial and national levels brought local knowledge into the set up and interpretation of simulation experiments, and helped identifying priorities for policy development across local to national levels as discussed below.

The approach first captured sensitivity to climate change for this particular farming system and then assessed possible benefits from adaptation in a future with climate change. To account for uncertainty under future conditions, two socio-economic pathways (sustainable development (SDT), rapid economic growth (REG)) were developed as extension from global Shared Socio-Economic Pathways (SSPs) and linked to Representative Concentration Pathways (RCP 4.5, RCP 8.5) (Valdivia et al. 2021). Two downscaled Global Circulation Models (GCMs, hot dry (HD), hot wet (HW)), under each RCP, were used to simulate crop and livestock yields.

We applied the approach for a population of farms in Nkayi District. The simulations were calibrated with household-specific data collected by a study with 160 randomly selected farm households, including soil, crop and livestock types, input management, cultivated land, and herd and farm size. Three farm types were classified based on cattle ownership, which farmer consultations confirmed as main wealth determinant (SI Table 3). The extremely poor (0 cattle), poor (1–8 cattle), and non-poor (>8 cattle) represented 43%, 38%, and 19% of the population, respectively.

2.2.1 Current world: sensitivity to climate change and impacts of improved management

Climate projections To assess the sensitivity to climate change, the systems' responses were assessed to a set of downscaled GCMs, under two RCPs (RCP4.5 and RCP8.5) for mid-century (2040–2070, Ruane and McDermid 2017). Baseline climate data (1980–2010) were extracted from the agricultural modeling version of the Modern-Era Retrospective Analysis for Research and Applications dataset (AgMERRA; Ruane et al. 2015a). Mid-century climate projections were computed for 5 GCMs following the AgMIP enhanced delta approach that applied changes in mean temperature, precipitation, and carbon dioxide concentrations along with shifts in the variance of extreme temperatures and the frequency of rain events (Ruane et al. 2015b). For this paper, 2 out of the 5 GCMs were selected that represent hot/dry (HD) and hot/wet (HW) climate conditions, based on projections that higher temperatures are most likely, while precipitation change direction is uncertain (SI Figure 2, Table 1).

Improved management Improved management packages were designed as sets of interventions that could be realized within five years, to inform decisions about immediate solutions. The packages were developed through several workshops with 15–20 farmers each. Farmers with different cattle ownership defined options for changing farm configuration if access to markets and services were improved. These packages were then revised by experts from crop, livestock and economics disciplines to inform a set of crop, livestock, and economic model simulations. A 3-step approach was simulated, with each step illustrating the effects of further management improvements.

2.2.2 Future world: impact of climate change and adaptation

Plausible future conditions Scientists and experts from provincial and national levels co-developed three contrasting AgMIP Representative Agricultural Pathways (RAP) (Valdivia et al. 2021) to characterize plausible socio-economic and biophysical conditions of the agricultural sector by 2050 under which climate change might impact future farming systems (SI Table 2). The RAPs were paired with contrasting global socio-economic scenarios (Shared

Socio-Economic Pathways, SSPs, O'Neill et al. 2015) and Representative Concentration Pathways (RCPs). Global price and productivity trends that influence local context specific projections were obtained from the IMPACT global economic model (Robinson et al. 2016). This acknowledges that global drivers impact on local action, while there is uncertainty about future world conditions. The same GCMs as for the current world were imposed on the different future scenarios.

Adaptation packages Climate change adaptation options were identified according to their potential to address changes in temperature, precipitation, and CO_2 concentrations under future conditions. They consisted of switching to heat-tolerant long-duration cereal varieties (to retain cereal lifecycles) and to drought-tolerant legume varieties.

2.2.3 Integrated multi-model components

Crop simulations To assess the effects of changes in precipitation, carbon dioxide (CO_2), and temperature on crop grain and stover yields in response to field management, cultivar genetics, and soil conditions, two process-based models were used, the Agricultural Production Systems Simulator model (APSIM) (Holzworth et al. 2014) and the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al. 2019). Here we present APSIM results, the most extensively used crop simulation model for intervention strategies targeted at low-input smallholder farmers in Africa, under a wide range of management systems and conditions (see SI for DSSAT results; Homann-Kee Tui et al. 2021; Whitbread et al. 2010). The crop models were configured for the Zimbabwe context, using crop and soil data from field experiments in the same region (Masikati et al. 2013, Homann-Kee Tui et al. 2021). The models were calibrated for three types of sandy loam soils found in the study area characterized by organic carbon (OC) content (poor (OC<0.7%), medium good soils (>0.7% OC)) (SI Figure 4)), initial soil nitrogen, and other soil physical properties that include bulk density, plant available water capacity (Masikati et al. 2019). Crop production (grain and stover) and crop life cycles for maize, sorghum, groundnut, and mucuna (*Mucuna pruriens* (L.) DC.) were simulated for each farm for 30 years in the current period and 30 years centered around mid-century.

Livestock simulations Cattle production was simulated with the LIVestock SIMulator (LIVSIM, Rufino et al. 2009), which predicts monthly milk and meat production as well as herd dynamics. Based on information about feed, herd size, composition and management, and breed potential, the livestock model simulates the performance of every animal in the herd. The livestock model was calibrated and tested for the local breeds of the study area based on secondary data from research stations (Descheemaeker et al. 2018) (SI Figure 5). The model used feed availability information obtained from the crop models, whereas feed quality was based on data from the literature. The simulations did not account for effects of pests and diseases, or heat stress on livestock.

Economic analysis The TOA-MD model (Antle and Valdivia 2020) was used to simulate the distribution of possible changes in key indicators, vulnerability, adoption of technological changes, farm net returns, and poverty rates. Vulnerability is defined as the percentage of the population at risk of loss due to climate change (i.e., decrease of farm income). The model also

quantified the magnitude of the economic gains and losses (measured as the % of farm net returns that is gained or lost due to climate change). Technology adoption analyses estimated the proportion of households benefiting from improved management (during the baseline period) and benefiting from climate change adaptation (during the future period), compared to non-adoption. Farm net returns in a particular system state were compared with the expected farm net returns in an alternative system state. Impacts were measured as changes in net farm returns and headcount poverty rates.

Future socio-economic conditions were characterized, with qualitative assumptions on the role of women, and quantified using farming systems trends included in the RAPs (SI, Table 2; Table 3), and price and productivity trends from the IMPACT global economic model to project future prices and yields for the various crops and livestock activities (SI Table 4). These trends were reviewed and adjusted by experts and stakeholders to fit the local context of Zimbabwe. A sensitivity analysis using ranges of high and low output price assumptions was also conducted to account for the large variability in global price trends of key commodities (Nelson et al. 2014).

3 Results

We show results at field, farm, and population level. For field level (crops), we distinguish between three major soil types that are representative for the soils in the study area. For farm level (livestock), we distinguish between three farm types (extremely poor, poor, non-poor). Economic results represent the changes in mean outcomes in the population. The results are disaggregated by farm types, RCP (4.5 and 8.5), climate scenario (HD and HW) under current conditions, type of RAP (STD and REG) and price assumptions under future conditions.

3.1 Sensitivity to climate change in current agricultural systems

Overall, where productivity was currently low, climate change impacts were small, though varied by farm activities and farm types. Small crop yield changes under poor soil conditions are in part, due to limitations to productivity imposed by poor soil fertility and low fertilizer application rates typical of this region, as also reported in Masikati et al. (2019) (Figure 2, SI Figure 6). Maize yields were reduced in most climate change scenarios (up to 20%), mainly because the higher temperature accelerated phenological development, shortening the time for biomass accumulation. Higher-quality soils had higher yields, and the magnitude of climate change impacts was also larger. Impacts on groundnut were mostly positive (up to 10%), due to the response to CO_2 concentration, partially offsetting the effects of increased temperature. Yields in the HW scenarios were higher due to less water stress compared to HD conditions.

Milk production was affected by climate change due to altered on-farm crop residue production, rangeland productivity, and changes in cattle fodder intake resulting from that, with a decrease by up to 10% in the HD scenario. Details of fodder intake are reported in Descheemaeker et al. (2018). Rangeland productivity and resulting milk production were negatively affected in HD, and marginally increased in HW scenarios.

Non-poor farms, typically with larger stocking density, were more sensitive to feed gaps and were more negatively affected by climate change than poor farms, which typically have less animals per unit land (Figure 3, SI Figure 7). Impacts on offtake, manure production and

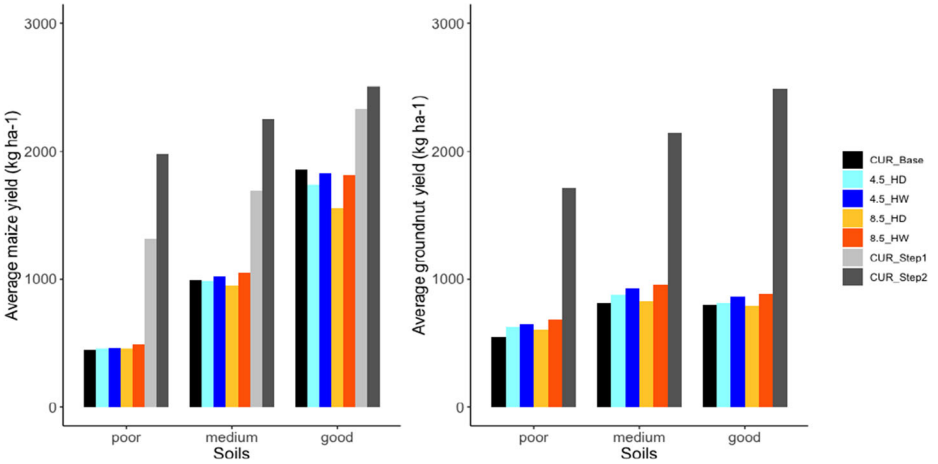


Fig. 2 Sensitivity to climate change of maize (left) and groundnut (right) in current farming systems on three soil types with varying quality, as simulated by APSIM. Baseline yields in the current climate (CUR_Base) are compared with yields under climate change for RCP 4.5 and 8.5, each for a hot-dry (HD) and a hot-wet (HW) climate scenario, and with current-climate yields under improved management in step 1 (only for maize) and step 2

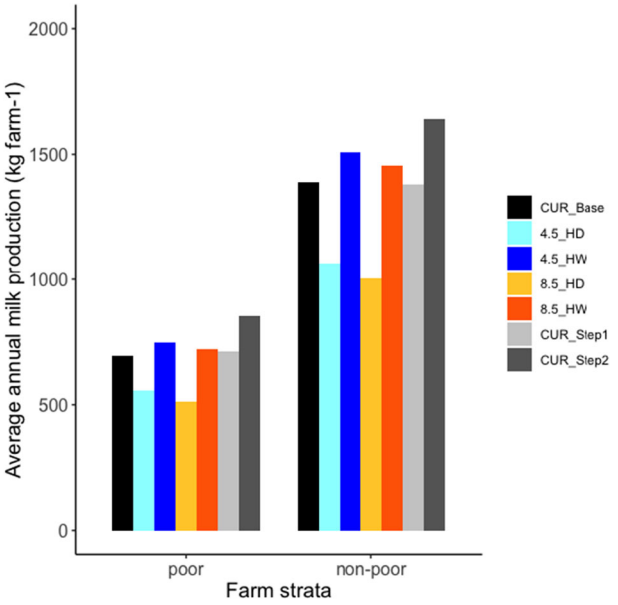


Fig. 3 Sensitivity to climate change of milk production in current systems of cattle-owning farm types (poor and non-poor only) as simulated by LIVSIM using APSIM results as input. Baseline milk production in the current climate (CUR_Base) is compared with production under climate change for RCP 4.5 and 8.5, each for a hot-dry (HD) and a hot-wet (HW) climate scenario, and with current-climate milk production under improved management in step 1 and step 2

mortality were in line with the impacts on milk production across climate scenarios and farm types.

Consequently, the non-poor lost up to 20% of their farm net returns compared to the poor and extremely poor who lost less than 5% (Figure 4). Extremely poor farms, mostly located on poorer soils, had very low production, and the magnitude of economic impact was therefore small. Most of these farmers were already in difficulty, with 94% below the poverty line. The non-poor with large cattle herds lost more under HD scenarios, due to larger feed deficits and yield reductions due to water stress. The magnitude of responses was larger under high-emission scenarios (RCP 8.5) than under low-emission scenarios (RCP 4.5).

About 85% of all farms were below the poverty line of USD1.25 per person per day and more than half the population was at risk of loss (i.e., vulnerable) due to climate change. Under the HD climate, a larger proportion of non-poor farms were vulnerable to climate change, mainly due to the effects of livestock feed deficits, whereas under a HW climate, they could improve their income (i.e., net economic impact is positive). For poor and extremely poor farmers, there was little change in poverty rates (<5%) as they already had been impoverished.

3.2 Benefits to improved management in current agricultural systems

Experts and stakeholders expressed strong interest and co-developed integrated interventions that have the potential to increase farm net returns and improve livelihoods. Improved management options dealing with the poor soils and low input levels were tested via three levels of interventions.

Step 1. Intensify maize and sorghum as staple crops and increase yields through improved management, using inorganic fertilizer (micro-dosing at 20 kg N/ha), manure (1100 kg/ha

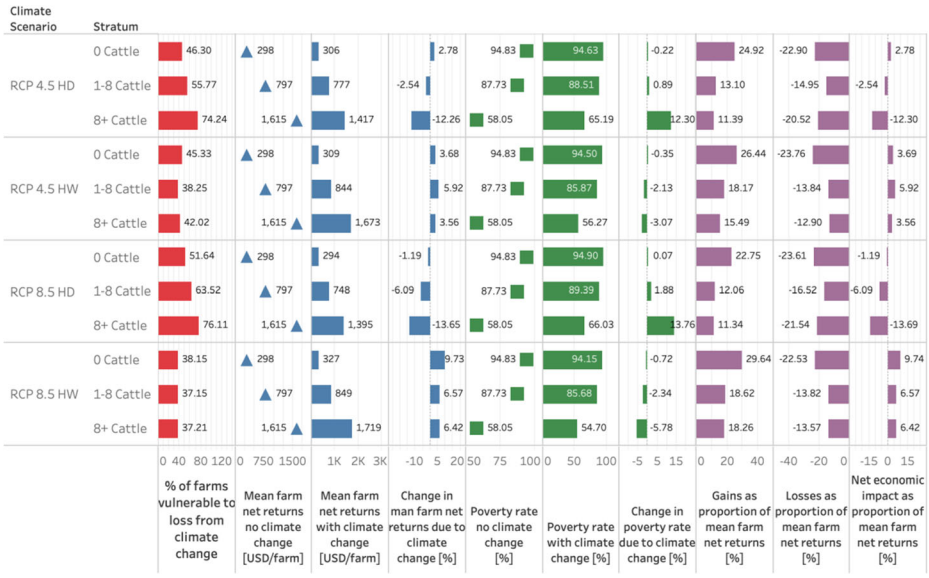


Fig. 4 Sensitivity to climate change (CC), for climate scenarios (hot/dry, hot/wet), emission scenario (RCP 4.5, RCP 8.5) and farm types in Nkayi, Zimbabwe, using APSIM results as input

for maize), improved certified varieties instead of retained crop varieties, and increased planting densities (30% higher than current density, up to 5.6 plants/m^2 on average).

Step 2. Following increased cereal productivity as a result of step 1, replace some of the cereals by legumes (groundnut and mucuna) on the land in excess of what is needed to fulfill staple food self-sufficiency (i.e., about 1100 kg cereals for a typical family of six). Improving groundnut management involved phosphorus fertilizer application, using existing improved high-yielding groundnut varieties, and increasing planting densities (40% higher than current density, up to 6 plants/m^2 on average). As compared to current cereal monocropping, cereal-legume rotations would improve soil properties, provide more nutritious feed for livestock, and thereby improve feed quality. We assume that groundnut shelling machines would be available to enable processing of larger volumes

Step 3. Focus on consolidating market opportunities and organizing groundnut sale. Farmers would switch from selling unimproved and non-shelled groundnut at a farm-gate price of USD 0.25/kg to targeting traders with aggregated volumes of improved shelled groundnut at USD 0.75/kg. Groundnut prices of USD 1.10 /kg are currently observed at urban markets.

The improved management packages increased maize and sorghum grain yields by more than 150% through the cumulative effects of better genetic potential, increased inorganic and organic fertilizer application, and changes in plant density in step 1 (Figure 2; SI Figure 6). In step 2, additional rotational benefits for maize and improved groundnut were obtained and groundnut yields increased by more than 200%.

Livestock benefited from improved feed supply through larger quantities and improved quality of crop residues (Figure 3, SI Figure 7). In step 1, more cereal stover was produced, but due to the poor feeding quality, this had only a small impact on animal productivity at roughly 6% improvement in milk production. As crude protein availability was the main limiting factor (Descheemaeker et al. 2018), the groundnut and mucuna stover produced in step 2 alleviated feed gaps more significantly, resulting in further improvements in animal productivity at about 30% improvement in milk production.

Economic analyses show high potential adoption rates for each of the three steps across the farm population (Figure 5). The gains in farm net returns and poverty reduction were high, from improved management packages and market revitalization. The poor increased net returns by up to 5-fold; the non-poor doubled their already higher net returns (compare base mean farm net returns in step 1 versus step 3 in Figure 5). Drawing on less resources and poor-quality soils, initial improvements appear as a jump in net returns, whereas for semi-intensified systems, the marginal rate of net returns decreases. The combination of these interventions halved poverty rates (from 85 to 45%), yet a large proportion of the population remained below poverty line, especially those without cattle.

3.3 Impact of climate change in future agricultural systems

The sustainability pathway (RAP SDT) assumed that public and private investments in inclusive value chains, coupled with improved access to technologies, markets, and services, led to diversified farming systems with tighter crop-livestock integration. Experts and

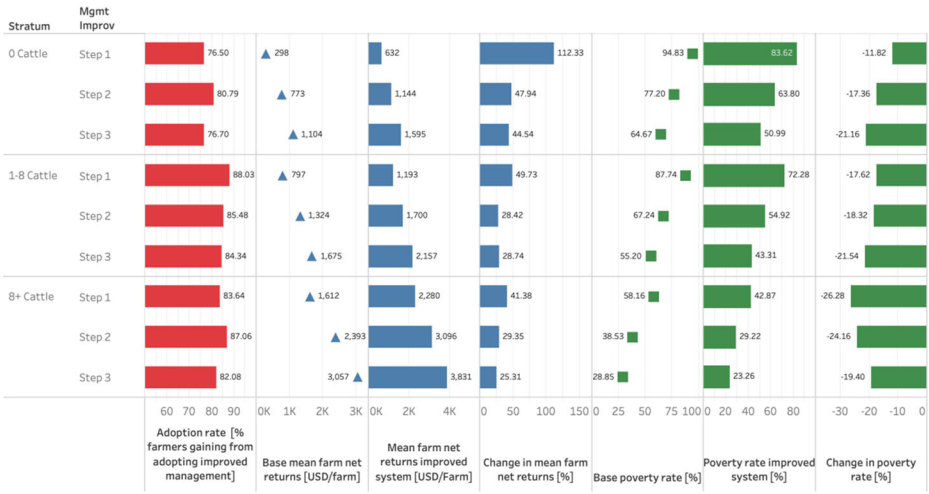


Fig. 5 Adoption, farm net returns, and poverty rates, by farm types and improvement steps, using APSIM results as input

stakeholders anticipated capacity gains for large parts of the population, including enhanced roles for women and improvements in food and nutrition security.

The rapid economic growth pathway (RAP REG) assumed that public and private investments maximized production in better-off farms, using innovative delivery systems, while the poor would seek off-farm income opportunities while maintaining minimal agriculture for their staple needs. Social standards being functions of market priorities, this resulted in larger numbers of poor and extremely poor households. Women and vulnerable groups were excluded from development.

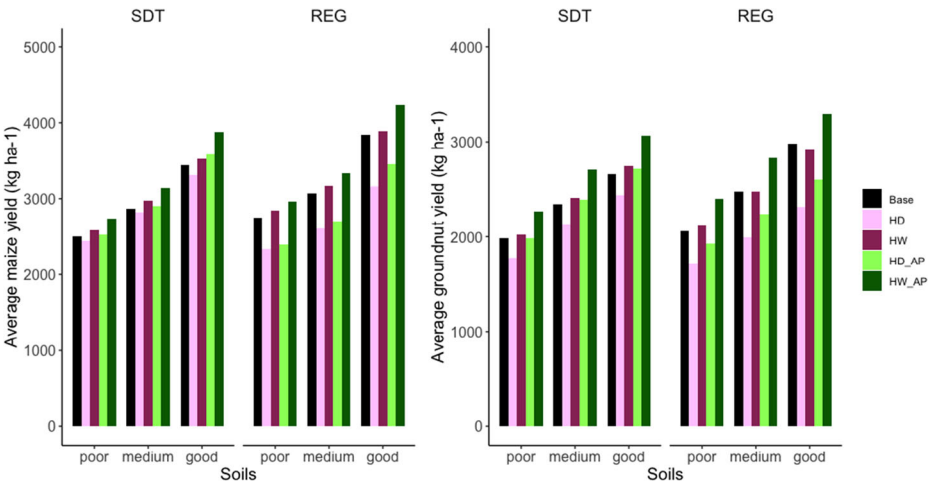


Fig. 6 Impacts of climate change and adaptation (AP) on maize (left) and groundnut (right) yields, on three soil types with varying quality, as simulated by APSIM for two contrasting RAPs (SDT sustainable development, REG rapid economic growth). Yields with no climate change (Base) are compared with yields under climate change for RCP 4.5 in SDT and 8.5 in REG, each for a hot-dry (HD) and a hot-wet (HW) climate scenario, and with the yields obtained with an adaptation package (AP)

Crop simulations show that soils play an important role and can act as buffer to reduce impacts of climate change on crop production (Fig. 6). Better soils under both climate scenarios HW and HD exhibited higher yields than the other two soils. Additionally better soils in combination with better climate in this case HW exhibited higher yields than the HD; hence, improved soils will be more important in the future for capitalizing on modified crop genetics and climate factors such as rainfall and CO2 for legumes in particular.

In contrast to crops, livestock production in future systems was less sensitive to climate change, for both RAP SDT and RAP REG. Compared to the current climate, milk productivity would increase by 5% in the HW scenarios and decrease by 22% and 13% under the HD scenarios of RAP REG and RAP SDT, respectively. The relatively small sensitivity was due to concentrates being fed to cattle to alleviate feed gaps. Hence, variation in rangeland and on-farm fodder production played a minor role and only non-poor farms with more animals were noticeably sensitive (Figure 7, SI Figure 9).

Households were less vulnerable to climate change in the future than today. In these future worlds, farmers were better off than today, influenced by the improvement of socio-economic conditions and the relative importance of different farm activities. The proportion of farms vulnerable to climate change under RAP SDT was lower as compared to RAP REG where maize was more predominant, with high rates of inorganic fertilizer (Figure 8).

The results in Figure 8 show that the HD scenario would decrease mean farm net returns across the two RAPs and price assumptions. The magnitude of the negative effects on farm net returns due to climate change is larger under the RAP REG. In contrast, the HW scenario shows positive net economic impact (i.e., the gains are larger than the losses in the population of farms),

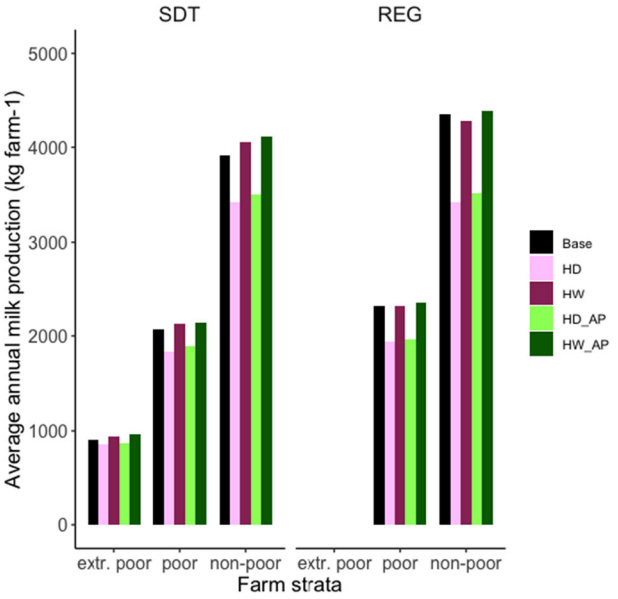


Fig. 7 Impacts of climate change and adaptation (AP) on milk production in cattle-owning farm types (extremely poor (with cattle only in the SDT RAP), poor, and non-poor), as simulated by LIVSIM using APSIM results as input for two contrasting RAPs (SDT sustainable development, REG rapid economic growth). Milk production with no climate change (Base) is compared with milk production under climate change for RCP 4.5 in SDT and 8.5 in REG, each for a hot-dry (HD) and a hot-wet (HW) climate scenario, and with milk production obtained with an adaptation package (AP)

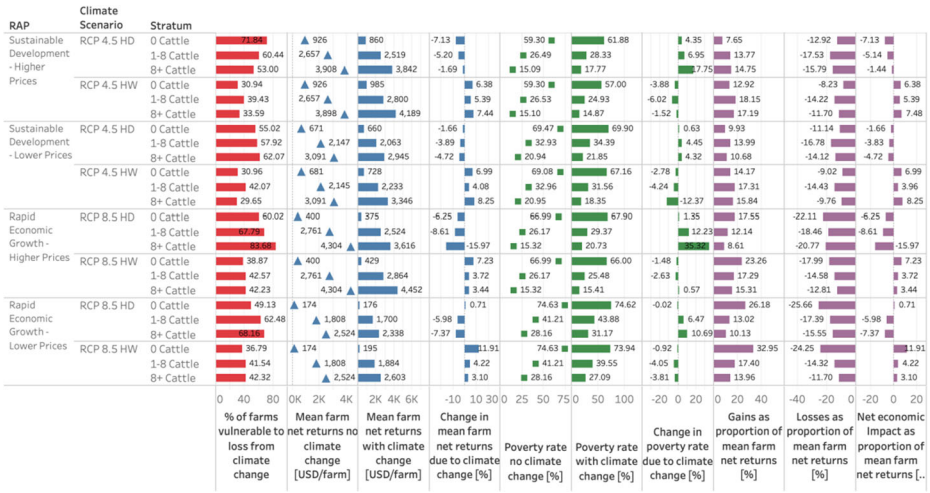


Fig. 8 Economic impacts of climate change by pathways (RAP SDT, RAP REG), price levels (1=high prices, 2=low prices), and farm types, using APSIM results as input

which can be explained in part by the higher crop yield increases with higher rainfall under high fertilizer applications and associated socio-economic conditions determined by the RAPs.

Furthermore, because of the different farm activities and endowments, farm types responded differently to climate change. Climate change effects were felt more by the "less poor." Feed gaps reduced milk yields and offtake which considerably reduced farm net returns of farmers with large herds of cattle. Poor and extremely poor farmers under RAP SDT produced more groundnut, which was less sensitive to climate change, whereas under RAP REG, they relied more on off-farm income. Poverty thus did not change much for those who already were poor.

While the development pathways seemed to offset the impacts of climate change and while the net economic impact (i.e., gains minus losses) was positive for some scenarios, the level of

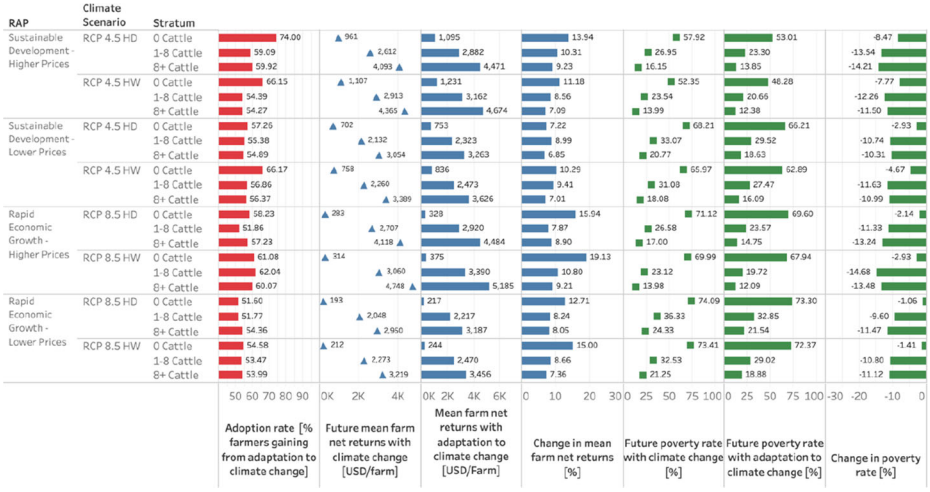


Fig. 9 Economic impacts of climate change adaptation, by pathways (RAP SDT, RAP REG) and price levels (1=high prices, 2=low prices), climate scenarios, and farm types, using APSIM results as input

vulnerability (i.e., the proportion of farmers at risk of having economic losses due to climate change) was still high (Figure 9). These results indicate that there is still need of designing climate change adaptation strategies to reduce vulnerability and improve farms resilience to climate change.

3.4 Benefits of climate change adaptation in future agricultural systems

Regaining life cycle and heat tolerance in maize were effective adaptation strategies with clear improvements compared to the non-adapted cultivars (Figure 6, SI Figure 8). Crop yields under RAP SDT had higher yields compared to RAP REG. Especially in non-poor farms cultivating on better soils, the responses of crop yields to temperature, water and nitrogen were positive as expected (Homann-Kee Tui et al. 2021, CTWN test). Similar results were obtained with a drought-tolerant groundnut variety, for which positive outcomes were projected, above the base yields across all soils and climate scenarios. Because of concentrate feeding in the future the impact of the crop adaptation package on livestock was negligible.

The economic benefits of switching to drought- and heat-tolerant crop varieties were small across RAPs and climate scenarios (Figure 9). This is explained by the small share of the farm-produced crop residues in the total livestock diet in the future systems where concentrate feeding plays an important role.

The results show that climate change adaptation benefited farmers, more under RAP SDT and high price assumptions. Mean farm net returns increased more for the extremely poor, with more land allocated to groundnut; price effects increased the importance of groundnut in overall farm net returns. However, in most cases the extremely poor did not step up into higher levels of livelihoods.

4 Discussion

This paper advances stakeholder-driven research approaches, with integrated multi-modeling simulations to generate actionable information for improved management and climate change adaptation. Researchers engaged with experts and stakeholders in the set up and validation of the modeling approach, which captured impacts on multiple farm activities and different farm types, and nuanced our understanding beyond what single-commodity analyses typically provide. The information can guide adaptation decisions for particular contexts and farming systems, like trajectories of resource constrained crop livestock farms in Zimbabwe where current poverty and vulnerability levels are rampant. Such forward-looking farming systems research is becoming more relevant as countries are increasing their commitments to climate change adaptation planning, while a quantitative understanding of vulnerability and adaptation impacts is lacking. As applied in various other contexts, our integrated assessments revealed what adaptation strategies are useful, where, and for whom, under plausible future conditions, co-constructed with stakeholders (Rosenzweig et al. 2021)

4.1 Reducing vulnerability to climate change

The simulations substantiate the benefits of tighter crop-livestock integration for enhancing biomass and nutrient flows within systems, resulting in improved farm incomes and food security outcomes (Homann-Kee Tui et al. 2015; Shikuku et al. 2017).

The sensitivity analyses showed that climate change impacts on crop yields under current conditions were generally small in Nkayi District, where productivity is already extremely low. Climate change impacts however manifest differently for different farm types and activities. A considerable number of resource-poor farms were vulnerable to climate change, even though crop responses to climate change impacts were small on the nutrient-depleted soils, a finding that is consistent with a study by Dimes et al. (2009). Furthermore, for poor households, limited yield response to management improvement can lock farms into low productivity (Tittonell et al. 2010). Efforts in restoring soil productivity must therefore be integrated with farm diversification and climate change adaptation, to counteract losses from climate change.

Soils play an important role in determining outputs of crop-climate interactions; they can buffer or aggravate climatic impacts. In our study, good soils consistently exhibited higher responses to positive influences such as increased rainfall and CO2 concentrations compared to poor soil yields under climate change scenarios. This confirms that good soils would be more important in future farming systems, hence a call for farmers in particular those with poor soils to invest in low cost but effective soil enhancement practices such as crop residue retention, use of animal manure, crop rotations, and agroforestry (Masikati et al. 2021; Smith et al. 2016).

Among the non-poor, more farms were vulnerable to climate change, compared to the poorer farms. Because non-poor farms had higher-quality soils, nutrient deficits were less severe so that crop growth was more sensitive to climate change and management improvements. Another important insight was that the better-off farms with relatively large livestock herds were more vulnerable due to severe feed gaps. Investing in more and higher-quality feed would narrow feed gaps in the dry season, resulting in better livestock condition, lower mortality, and higher productivity (Descheemaeker et al. 2018). Improving livestock disease control is critical to support the benefits from investments in feed. Farms that mitigate loss of livestock assets also have more options to compensate for losses in other farm activities, as livestock are used as on-farm capital and buffer in times of extreme events like droughts (Moll 2005).

The analysis of climate change under future scenarios shows that improving the conditions for farming can reduce vulnerability and half poverty by 2050. Our simulations illustrated that if farms would be expanding the area under high-value crops like legumes, given improved market access (inputs and outputs), they could derive substantial benefits from overall increased farm net returns and more nutrient dense foods. Transitioning towards sustainable development (RAP SDT), through crop diversification, soil rehabilitation, and livestock feed technologies, enabled by inclusive markets, was more profitable and provided more equitable benefits from agriculture than investing in rapid economic growth (RAP REG). Promoting diversification and integration of crop and livestock production is therefore not only critical to address current productivity constraints in smallholder farming systems, but also to adapt to future climates (Garrett et al. 2017).

4.2 Framing climate change in the context of socio-economic development

This study suggests that by improving the conditions for agriculture as part of transformational development processes, impacts of climate change could be better overcome (World Bank 2009; Falconnier et al. 2017). Enhancement of future agricultural productivity in drylands, through adoption of relevant technologies with support of appropriate institutions and dedicated policies, would make farmers better off than today, even under climate change. Investments in climate change adaptation are available now and would be less drastic, as most

components would have been incorporated in ongoing agricultural transformational programs, institutional barriers removed, making farming systems more resilient over time.

However, as our study shows, while transforming agricultural systems could help alleviate poverty, a high proportion of farms could still be trapped in poverty. There is need to acknowledge that climate change does not represent the main problem, but poor-quality soils, low input access and use, and low levels of resource endowments. It substantiates the need to link targeted climate resilience building interventions with social protection mechanisms (FAO and Red Cross Red Crescent Climate Centre 2019).

Limited access to labor creates short- and mid-term trade-offs in resource allocation (Giller et al. 2009). The diversification into higher value dual-purpose crops enhanced labor returns on food and feed per unit land (Homann-Kee Tui et al. 2015). In RAP SD, we considered a proportional increase in input costs, assuming that farmers set more land in value and feed livestock more, with mechanized field preparation, and less family labor. We also assumed that policies support women's control over production factors, improving their access to input and output markets and returns on labor, for food security and nutrition. Under RAP REG, for resource limited farms, off-farm activities were more important; women in particular were limited by labor force.

Discussion with experts and stakeholders helped to unpack the particular root causes and deeper structures that restrict shifting agriculture towards sustainability. In Zimbabwe, for instance, trade-offs were recognized between national resource allocations biased towards maize being a key staple in the region and attempts to diversify crops that are better adapted to harsh climates and poor soils typical for drylands. As was further observed, inconsistent support to small grain, legume, and livestock value chains further inhibit the uptake of sustainability enhancing technologies. In line with other studies, resulting non-functional markets transmit poor returns on the invested inputs, which has led to agricultural land being underutilized and limited interest of commercial fertilizer, seed, and feed industries in these fragile ecologies (Steiner and Franzluebbers 2009; Homann-Kee Tui et al. 2015). As a result, the uptake of nutrient recycling, seed systems, and dry season feeding technologies has also been slow. Providing decision makers with adequate information on gaps in policy formulation and clear recommendations on how to reach sustainability outcomes, as demonstrated in this study, is becoming an urgent matter to reduce vulnerability to climate change.

4.3 Influencing decisions towards sustainability pathways

In a developing country context like Zimbabwe, with years of economic depression, climate variability and change threaten food security and welfare. Climate change is not the cause of poverty; poverty rates were already high (e.g., Anseeuw et al. 2012). The rationale of this study was for science to work closer with policy makers and experts, through relevant networks, for the agricultural sector to be adapting more effectively. Policy-oriented research can help catalyze decisions for agricultural systems to change, with simulation modeling informing where what type of adaptation strategy can be deployed.

The use of simulation-modeling approaches combined with farming systems understanding can support and improve climate change adaptation planning (Holman et al. 2019). In this study, the multi-model approach was set up as part of an iterative process with experts and stakeholders to help prioritizing investments, by comparing impacts on vulnerability, farm net returns, and poverty rates, creating a learning environment for researchers and the users of research information (Valdivia et al. 2021; ICRISAT 2016). Comparison of multiple climate

scenarios and contrasting agricultural pathways embedded impacts in the context of uncertainty about possible gains and losses from adaptation (Pastor et al. 2020). This comparison process with experts and stakeholders allows verifying consistency in policy formulation and implementation, thus influencing decision processes at larger scale (O'Neill et al. 2015; Nilsson et al. 2017). Combining the simulation research with ongoing investigations on crop and livestock production allows building on existing social relations and systems understanding, and generates knowledge across disciplines and fields of expertise, as emphasized also in other studies (Falconnier et al. 2017).

The results can be used to extrapolate site-based assessments of expected climate change impacts to areas with similar conditions. This comparison process with experts and stakeholders allows verifying consistency in policy formulation and implementation (O'Neill et al. 2015; Nilsson et al. 2017), thus influencing decision processes at larger scale. Combining the simulation research with ongoing investigations on crop and livestock production allows building on existing social relations and systems understanding, and generates knowledge across disciplines and fields of expertise, as emphasized also in other studies (Falconnier et al. 2017).

Experts and stakeholders' point of views are important to direct research protocols to include important issues for specific context, e.g., crop responses for low input systems and near-term impacts of improved management. These interactions with stakeholders can provide useful insights on the barriers and limitations that need to be addressed. Through the verification of research results with experts and stakeholders, the analysis becomes more meaningful, with a closer science-policy interaction. In this study for example, it was recognized that more transformative change was required to lift people out of poverty; possible options were explored and how they would affect other system components, society, and environment. As others have observed, the use of simulation modeling can thereby facilitate new arrangements between researchers and users (Sterk et al. 2009; Knaggård et al. 2019).

5 Conclusions and next steps

Researchers and experts assessed ways to improve agricultural production in the face of climate change for typical dryland farming systems of Zimbabwe. Crop simulations highlighted the importance of soil, water, temperature, and nitrogen interactions in determining impacts of climate. Expanding groundnut and forage legumes as more climate resilient crops was an important strategy to buffer climate change impacts. At the lowest economic end, the returns were high on improving soil fertility management and on the use of currently neglected and potentially highly profitable crops such as groundnut.

The economic impact assessment showed that the proportion of farms vulnerable to climate change for poor households with poor soils was lower compared to non-poor households. The reason is that climate change impacts on farms with low yields and low incomes are relatively small compared to non-poor farms, because their yields and farm returns levels are already very low. Non-poor farms tended to lose more due to currently higher incomes.

This reaffirms the need for more transformative changes, addressing institutional failures, including non-functional output markets and unavailability and unaffordability of inputs. Investments in sustainability pathways (RAP SDT), with inclusive markets and value chains, were shown as important for all, as they halved poverty more effectively and led to more equitable benefits as compared to rapid economic growth pathways (RAP REG). The most positive impact of adaptation was also reached under RAP SDT, especially for the extremely poor.

This demonstrates that even with climate change, benefits can be reached by addressing the most stringent constraints in the socio-institutional context. By providing concrete messages to policy makers, who often make decisions without a credible evidence base, approaches like this support better-coordinated action and learning for sub-national and national decision and policy making. Use of pathways with integrated modeling approaches like the one presented in this study can bring research closer to influence decision- and policy-making processes, in order to create sustainable futures for smallholders in semi-arid Southern Africa.

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Declarations

Conflict of interest The authors declare no competing interests.

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