Chapter 5

Crop–Livestock Intensification in the Face of Climate Change: Exploring Opportunities to Reduce Risk and Increase Resilience in Southern Africa by Using an Integrated Multi-modeling Approach

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Introduction

The climate of Southern Africa is highly variable at most time-scales and follows a pronounced gradient with arid conditions in the west and humid conditions in the east. There is also a marked latitudinal rainfall distribution pattern, with the southern part having a low rainfall index and high variability and the northern part having higher annual rainfall and lower interannual variability (Kandji *et al.*, 2006). Over the last 100 years, temperatures have increased by about 0.5°C in the region and downward trends in rainfall have also occurred (Kandji *et al.*, 2006; Morton, 2007). There has also been an increase in drought events with over 15 drought events reported in the region between 1988 and 1992. The frequency and intensity of El Niño episodes have increased. Prior to the 1980s, strong El Niño events occurred every 10–20 years; between 1980 and 2000, the region experienced five episodes with the 1982–1983 and 1997–1998 episodes being the most intense of the century (Reason and Jagadheesha, 2005; Rouault and Richard, 2005). These episodes have contributed to stagnant or decreasing agricultural production and worsening food insecurity in the region (Kandji *et al.*, 2006). Unfavorable climatic conditions and projected climate change are among the major obstacles to achieving food security in the region and also have dire consequences for macro-economic performance.

Climate change impacts

Food insecurity in the region is further exacerbated by low crop production levels that are attributed to inherent low soil fertility and to continuous cropping without addition of adequate organic and inorganic fertilizers due to unavailability and high costs. Feed shortages (especially during the dry season), high incidence of diseases, and high mortality rates cause low livestock production. Undeveloped infrastructure, weak support systems, poorly developed markets, limited understanding of impacts of climate change on agricultural systems, and low investments in climate smart technologies exacerbate the vulnerability of the farming communities. Climate change impacts, when superimposed on the many structural problems in the region where most countries are unprepared or have inadequate adaptation strategies, can easily set-back possible developmental gains by affecting sectors such as agriculture, water resources, and infrastructure (Kandji *et al.*, 2006).

Although countries in Southern Africa are among those that have ratified the United Nations Framework Convention (UNFCCC), expertise in research related to climate change is limited and confined to a few institutions and individuals (Countries' Initial Communications on Climate Change, Malawi (2002), Mozambique (2003), and Zimbabwe (1998)). In the agricultural sector there is limited knowledge on the interactions between projected increases in CO_2, temperature and precipitation variations, and their combined effects on crop and animal production, which hence adds to uncertainties surrounding future smallholder farming systems (Thornton *et al.*, 2009; Countries' Initial Communications on Climate Change, Malawi (2002), Mozambique (2003) and Zimbabwe (1998)). It is imperative for research and development to understand these, as agriculture is the mainstay of the economy in most countries in Southern Africa, employing about 70% to 80% of the population in countries like Zimbabwe, Mozambique and Malawi (Countries' Initial Communications on Climate Change, Malawi (2002), Mozambique (2003) and Zimbabwe (1998)).

Rainfed agricultural production contributes about 35% of the GDP and about 35% to 40% of total export earnings in Southern Africa, excluding South Africa (Naab *et al.*, 2012). The agricultural sector is divided into two broad categories: Large commercial farms and smallholder farming systems. The former intensively use improved technologies and have high production levels, while the latter use limited external inputs and production is very low. The smallholder farmers constitute the majority (about 60% to 70%) of the farmers and are among the poorest and most vulnerable to climate change and variability in the region and the world (Morton 2007; Naab *et al.*, 2012; World Bank Report, 2009). Consequently these farmers face a double risk if adaptation measures are not taken; when there is crop failure there is no food available, and due to their dependency on agriculture for income, they would not have money to buy the food even if it is available on the market (Kandji *et al.*, 2006).

Measures to reduce the impact and risk of climate change in the region have been taken by regional organizations such as the Southern African Development Community (SADC). Since the 1992 drought events, SADC has established a task force under its Food Security, Technical, and Administrative Unit and also proposed a regional drought fund in 2002. At the national level, most countries in the region have established early warning systems that monitor national food supplies and seasonal weather patterns, including seasonal climate outlooks (Kandji *et al.*, 2006).

At the community level, farmers have developed coping strategies to deal with climate variability. Even though these might not be sufficient to deal with increased frequency of droughts, they can serve as useful starting points for interventions by research, government, and development agencies (Morton, 2007). Frequency of extreme events is projected to increase and such events might make timing of agricultural operations difficult and reduce incentives to invest in agricultural production. For example, if crops are damaged at different growth stages (Morton, 2007), replanting might not be a feasible option for smallholder farmers due to financial constraints.

Most studies done in the region have shown that temperatures are likely to increase by $>2°C$, and rainfall is likely to decrease (Dimes *et al.*, 2008; Kandji *et al.*, 2006; Morton, 2007; Thornton *et al.*, 2009; Walker and Schulze, 2008) and such changes will affect production of the main staple food, maize, in the medium and long term (Dimes *et al.*, 2008; Morton, 2007; Walker and Schulze, 2008). Although studies have been conducted at varying geographical and temporal scales, they fall short in capturing the complexity and site-specificity of the effects of climate change (Jones and Thornton, 2003). The effects of climate change differ geographically and can be crop-specific: A study in Tanzania showed that although climate change will have negative impacts on maize production, impacts on coffee and cotton, which are cash crops, may be positive (Agrawala *et al.*, 2003 in Morton, 2007). There is also little work done with regards to the effects of climate change on the biological processes of semi-arid crops and livestock (Thornton *et al.*, 2009; Zimbabwe's Initial Communications on Climate Change, 1998). Studies often elaborate on the communities' vulnerability and adaptation strategies (Jones and Thornton, 2003), but they fail to capture the heterogeneity and diversity within and among the communities and account for livelihood components such as off-farm income and remittances.

Agricultural production systems are complex, with various interacting biophysical (crops, livestock, soil, vegetation, climate) and socio-economic (markets, social institutions, off-farm income and remittances, local customs and policies) subsystems. Consequently, for research and development to have an impact on system efficiency, the potential intervention points need to be identified based on an understanding of the system's individual components and their interactions in space and time. Simulation modeling provides a valuable framework for systems analysis of crop–livestock systems. Component and systems modeling enables analysis of individual components of the complex systems and evaluation of complex interactions and overall systems efficiency.

The current study uses an integrated multi-modeling approach for *ex-ante* impact assessment of climate change and adaptation strategies in heterogeneous smallholder farmers' communities in a particular context. We assess the impact of climate change on crop and livestock production by looking at quantitative production with and without adaptations. We then integrate climate, crop, and livestock projections within the Tradeoff Analysis Model for Multi-dimensional Impact Assessment (TOA-MD; Antle, 2011; Antle and Valdivia, 2011) to assess the economic impacts of climate change and selected adaptation strategies. Here we take into account the heterogeneity of entire farm populations, while understanding that climate change and adaptations will affect households with different resource endowments and thus their ability to invest differently. We also integrate the impacts of projected economic development apart from climate change, by explaining plausible future scenarios. We discuss the costs and benefits of intensification (i.e., increased investments, diversity of activities, as well as economic opportunities) to determine efficient risk reduction strategies and increased resilience in the context of climate change. For our larger study we have considered three countries (Malawi, Mozambique, and Zimbabwe) in Southern Africa (see AgMIP final report); for this chapter, we focus on Zimbabwe.

Farming System Investigated

Settings and locations

The integrated assessment of farming systems was done for Nkayi in northwest Zimbabwe. The district is located between 19°00' south and 28°20' east. Crop production

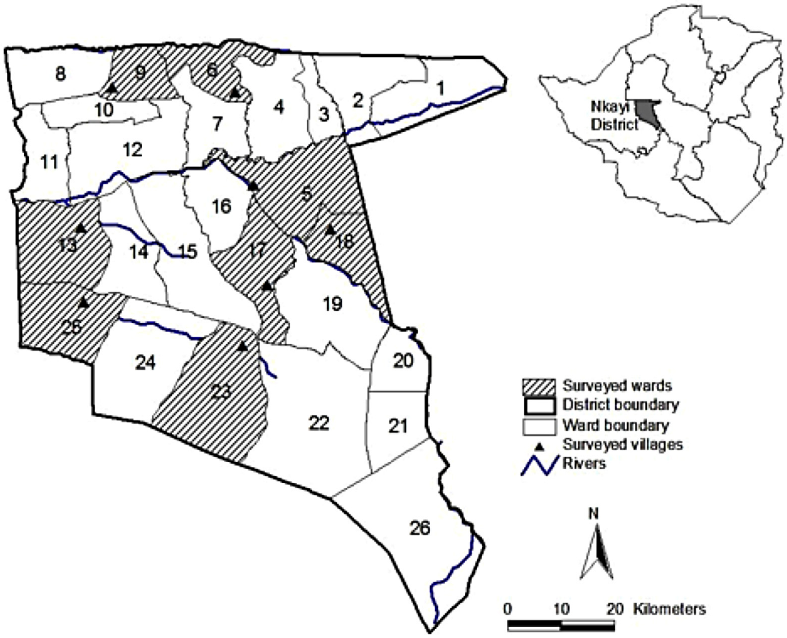

Fig. 1. Study area in Zimbabwe; gray shaded areas are the wards in which household surveys were done.

is rainfed, and average annual rainfall ranges from 450–650 mm. Rainfalls are erratic with a drought frequency of one in every five years (Rockström *et al.*, 2003). Long-term average maximum and minimum temperatures are 26.9°C and 13.4°C, respectively (Fig. 1). The soils vary from inherently infertile deep Kalahari sands, which are mainly nitrogen- and phosphorus-deficient, to clay and clay loams that are also nutrient-deficient due to continuous cropping without soil replenishment. Farmers use mainly a mono-cereal cropping system with addition of low amounts of inorganic and organic soil amendment. Natural pasture provides the basic feed for livestock, and biomass availability is seasonal. During the wet season feed quantity and quality is appreciable, while during the dry season there is low biomass of poor quality. The natural pastures are mainly composed of savannah woodlands, with *Aristida* species, *Eragrostis rigidia*, and *Heteropogon contortus* grass species (Homann *et al.*, 2007).

Crop–livestock farming systems

Mixed crop–livestock production systems are dominant in Zimbabwe (see Fig. 2). These farming systems are mainly based on maize, sorghum, groundnuts, and cowpeas as staple crops, combined with the use of communal range lands, fallow land,

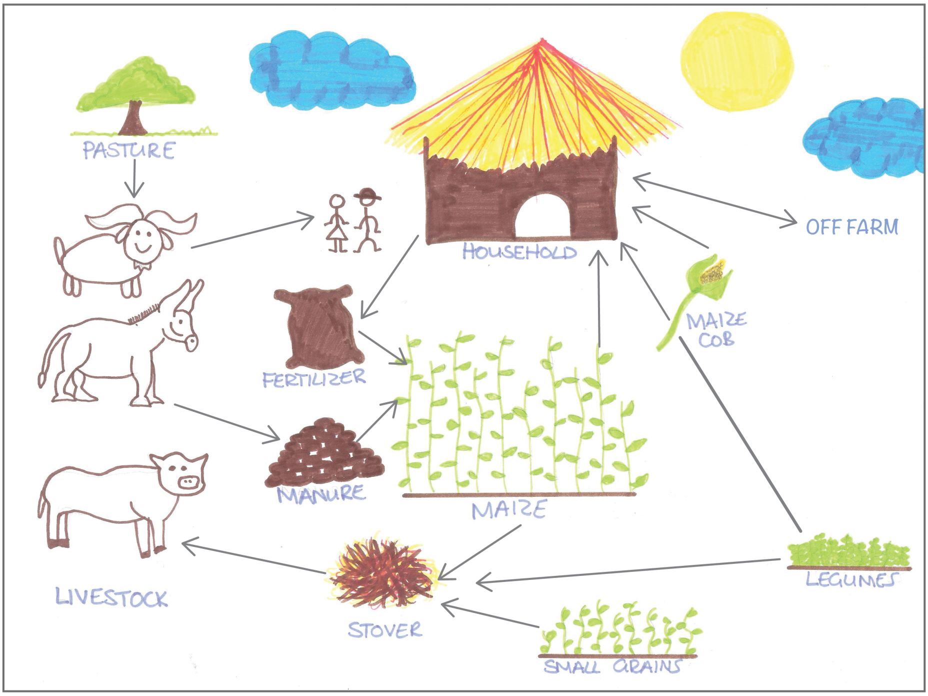

Fig. 2. Schematic representation of the predominant mixed crop–livestock farming systems in Zimbabwe, also found in large parts of Southern Africa.

and crop residues for livestock production. Household livestock holdings vary from a few to a hundred head per household, with varying ratios of cattle (*Bostaurus*), donkeys (*Equusasinus*), and goats (*Capra hircus*) (Bossio, 2009; Williams *et al.*, 2002). Livestock play an important role in these farming systems as they offer opportunities for risk spreading, farm diversification, and intensification, and provide significant livelihood benefits (Bossio, 2009; Williams *et al.*, 2002). Animals are kept to complement cropping activities through the provision of manure for soil fertility maintenance, draft power for cultivation, transport, cash, and food, while crop residues are used as adjuncts to dry-season feed (Masikati *et al.*, 2013; Peden *et al.*, 2009; Powell *et al.*, 2004; Williams *et al.*, 2002).

These systems evolve in response to various interrelated drivers, such as increased demographic pressure along with higher incomes earned by the urban populations, which results in a growing demand for crop and livestock products with the development of local and urban markets (Table 1; Homann-KeeTui *et al.*, 2013). This increased demand for crop and livestock products could benefit small-scale farmers as they gain access to markets, if they are able to intensify and diversify production in a sustainable way. This would reduce risk and increase resilience by

Table 1. National- and local-scale drivers that influence current farming systems in Nkayi, Zimbabwe.

National-scale drivers	
GDP *per capita* (average USD, 2003–2009)	422.3
Annual GDP growth (av. %, 2003–2009)	−6.4
Livestock (% agric. gross production, 2009)	44.8
Public spend on agriculture (av. %, 2003–2009)	8.6
Rural population (%, 2009)	62.2
Net imports (Mio USD, 2008)	
Maize	169.8
Milk	2.2
Local-scale drivers	
Rainfall (mm annual average)	650
Human density (2008, per km^2)	21
Main crops	Maize, small grains, legumes
Main livestock	Cattle, goats
Soil fertility and land management	Cattle, goats
Extension support	Fair
Market development	Fair

Source: Homann-Kee Tui *et al.* (2013).

providing farmers with diverse sources of income. Given that currently productive resources in these systems (although limited) are being used inefficiently, as evidenced by low production, a shift towards resilient and more productive systems is the key to future food security. Low production in smallholder farming systems is due to a combination of factors that include unfavorable climatic conditions, poor and depleted soils, environmental degradation, and low level of capital endowment that leads to limited uptake of improved technologies, in conjunction with failed sectorial and micro-economic policies (Kandji *et al.*, 2006; Morton, 2007; World Bank Report, 2009). Climate variability and change stressors, superimposed on the many structural problems in smallholders farming systems where there is not much support nor adequate adaptation strategies, can exacerbate food insecurity and increase vulnerability (Kandji *et al.*, 2006; Morton, 2007).

Stakeholder Interactions, Meetings, and Representative Agricultural Pathways

Stakeholder interactions and meetings

In this study, we engaged stakeholders in a process to design a set of plausible representative agricultural pathways (RAPs) for future economic development at the project site. The RAPs provide the parameters for the long-term projections of economic development. They are also a source of reference for predictions that affect smallholder farmers with limited market connections, in comparison with global model projections (e.g., IMPACT, SSP2_HGEM_DSSAT_5crop scenario, AGMIP reference scenarios). The stakeholder consultations were conducted as structured expert discussions at provincial level with six knowledgeable representatives from National Agricultural Research and Extension Systems (NARES), including government departments of crop and livestock production and agricultural economics. The discussions lasted about three to four hours. Separate talks were held with private sector representatives, including agrodealers and meat processors.

At the meeting with experts, the RAP concept was introduced, using the CCAFS national scenario (Ingram and Ainslie, 2011) as a visual aid to create a clear vision for the country, and to identify possible development scenarios and implications. To create an informed, engaged, and critical discussion and common understanding of the current situation, background material was shared and participants exchanged information on perceived poverty trends, major economic drivers for national and regional development, the role of agriculture, and major challenges and opportunities for agricultural development. A given list of indicators was extended, which included indicators that participants found relevant for the study case. Participants then agreed on a possible pathway; one that acknowledges the challenging economic conditions Zimbabwe is facing, but with positive assumptions for economic development. Participants used background information, their expertise, and their intuition to jointly define the RAP, including a catchy title, key indicators, magnitude of the changes, and rationale. Documentation of the narrative and the indicators was shared with the participants, experts, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) research team, and outside economists for review.

Representative agricultural pathways (RAPs)

Involvement of stakeholders by using a participatory approach is very important in assessing the climatic and non-climatic stressors on agricultural production systems. Stakeholder participation enhances collective knowledge and shared visions on how to manage natural resources to benefit communities effectively and to develop interventions aimed at improving farming systems. Interventions developed by using participatory approaches have a better chance of being accepted, appropriately planned, and maintained because they originate from a process that involves engagement rather than being a top–down process in which solutions are imposed from outside (e.g., without consultation or interaction). Dorward *et al.* (2003) found that low adoption could be attributed to lack of stakeholder participation in developing the technologies, and lack of consideration of market accessibility and incentives. In dealing with changing complex systems, natural resource management initiatives are increasingly turning towards participatory modeling procedures to integrate local, expert, and specialized stakeholder sources of knowledge effectively (Carberry *et al.*, 2003, Jones *et al.*, 2008; Masikati *et al.*, 2013).

Data and Methods of Study

The AgMIP integrated assessment approach was used to understand how crop and livestock productivity and net returns of the various farming activities would change under the different adaptation strategies in the current climate as compared to the mid-century climate scenario (2040–2070; Antle and Valdivia, 2013). This was done using climate, crop, livestock, and socio-economic models. To assess the sensitivity of the current farming systems to climate change we used climate data for mid-century (2040–2069) obtained from 20 GCMs under RCP8.5. For the full integrated assessment of the impacts and benefits of climate change on future agricultural production systems with adaptations and RAPs, we used mid-century climate data from five GCMs (E, I, K O, R). We assessed the impacts of climate change on maize production without adaptation strategies by using 20 GCMs, while the full integrated assessment was done with adaptation strategies by using five GCMs. For more information, see Table 2.

Table 2. Treatments and adaptation strategies used to assess the impacts and benefits of climate change on current and future crop production systems in Nkayi, Zimbabwe.

Treatments Used in Assessing the Sensitivity of Maize Production to Climate Change in Zimbabwe	
Production	Treatment
Crops	Maize production under farmer practice (low-input system), average fertilizer application: 3 kg/ha* and average manure application: 300 kg/ha*.
Adaptation Strategies Used for Integrated Assessment of the Impacts and Benefits of Climate Change on Future Agricultural Production Systems with Adaptations and RAPs	
District	Treatment
Nkayi	Maize production under micro-dose (17 kg N/ha). Maize under the recommended fertilizer application rate 52 kg N/ha. Maize under maize–mucuna rotation at 30% residues retention.

*ICRISAT Survey 2008. Crop residues obtained from the above crop production systems were fed to livestock as adjuncts to dry season feed.

Climate

Observed trends in temperature and precipitation

The climate of Southern Africa is highly seasonal with hot, wet summers and cool, dry winters. This is largely a function of the movement of the Intertropical Convergence Zone (ITCZ) and a semi-permanent high-pressure band located over the subtropical extent of the region that results from the descending limb of the Hadley circulation. During summer, the ITCZ is situated south of the equator and the high-pressure band to the south of South Africa. Summer rainfall is typically convective and may be linked to large-scale synoptic features like mesoscale convective systems, tropical temperate troughs, and thermal lows in the subtropics, which may form a close low pressure. Tropical cyclones may also impact Mozambique in the late summer. During winter, the northward movement of the ITCZ is accompanied by a northward movement of the high-pressure band over the region, which has subsiding air that causes dry, colder winters in the region.

1980–2010 baseline climate data construction

According to AgMIP climate data protocols, a baseline daily weather dataset (1980–2010) was produced based on the best available daily datasets with regard to geographical proximity, data length, and quality. Daily minimum and maximum temperatures, as well as rainfall, were used. For our study site, historical daily records were made available from Department of Meteorology, Zimbabwe and had nearly 50% missing data for temperatures and rainfall over 31 years at Nkayi station (19.00°S, 28.90°E).

Crop models require complete daily datasets as inputs. However, most climate datasets obtained from the meteorological departments in most countries in Southern Africa would be incomplete with regard to crop modeling requirements. The finished climate dataset for Nkayi consisted of observed and filled data (from AgMERRA, Ruane *et al.*, 2014) to form the station's baseline climate. Solar radiation (for APSIM; Agricultural Production Systems Simulator) and potential evapotranspiration (for DSSAT; Decision Support System for Agrotechnology Transfer) were not available in the station data and these were estimated on a daily time-scale by using temperature and rainfall from the baseline, latitude, and altitude. Each 31-year dataset was formatted according to AgMIP protocols to ensure data uniformity. To satisfy the point-based nature of the crop models as closely as possible, the baseline datasets were climate-corrected to create virtual climate stations at the location of each of the studied farms. The correction factors were extracted from the WorldClim monthly mean temperature and monthly total rainfall.

Maximum and minimum temperatures and rainfall were analyzed for historical averages, variability, and trends (Fig. 3 and Table 3). The station shows weak positive

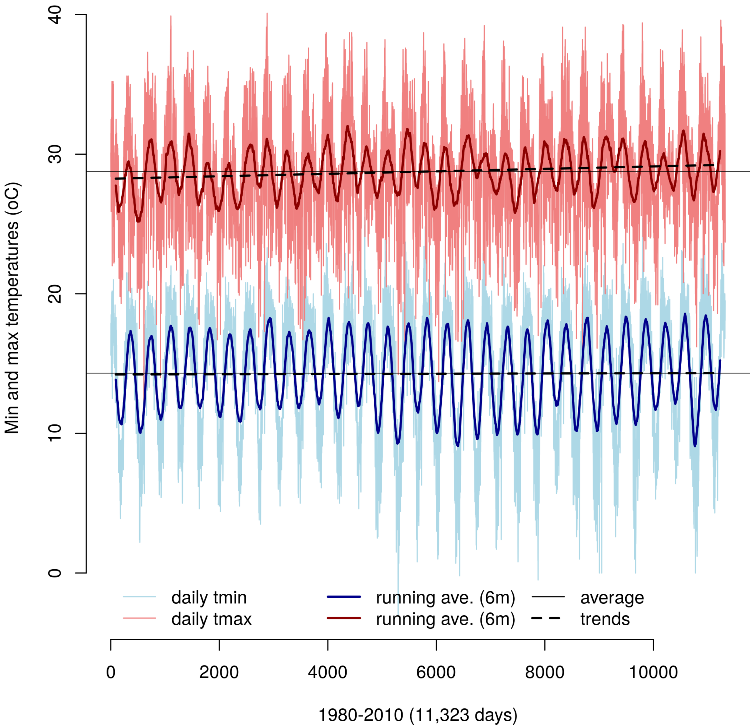

Fig. 3. Minimum and maximum temperature baseline trends for Nkayi, Zimbabwe (ZWNK). Maximum temperatures show an increasing trend over 1980–2010 (approx. 0.3°C per decade).

Table 3. Historical climate and annual trends of the Nkayi station.

Variable	Average	Highest	Lowest	Trend (°C or mm/year)
T_{min} (°C)	14.6	26.0	−2.9	0.0034
T_{max} (°C)	29.0	40.5	12.5	0.032
Rainfall (mm/day)	1.65	81.8	0	—

trends in both minimum and maximum temperature; however, these trends are not statistically significant.

Significance tests for delta method changes

The AgMIP global climate team uses a significance threshold of change. Based on the Z-test of significance, lower and upper significance thresholds are computed at each station, which rely on the 31-year baseline period. This bandwidth is used to categorize separately future temperature and rainfall projections that remain within expected statistical deviation, in opposition to those changing beyond the expected deviation, which hence suggests a climate change beyond natural variability.

The significant change amplitude is computed as 0.36 of the standard deviation of the monthly (growing season only) averages over the 31 years. This amplitude subtracted and added to the average gives respectively the lower and upper limits of significant change and plotted as dashed horizontal (rainfall) and vertical (temperature) dashed lines in Fig. 5.

Climate projections

Future projections of rainfall and temperature from 20 general circulation models (GCMs) were made under the RCP8.5 scenario for the period 2040–2070. The creation of the future climate datasets consisted of perturbing the baseline by following a delta approach. This study relies on daily future datasets that result from a monthly shift of daily mean temperatures and a monthly proportional variation of daily rainfall events. In each case, boundary conditions (e.g., large amplification of an extremely high-rain event) were tested and dealt with according to AgMIP standards (Rosenzweig *et al.*, 2014). The deltas were computed at the GCM grid-box scale, for each individual GCM, for each individual RCP, from the 30-year long baseline (1980–2009) to the 30-year-long future period. Each future scenarios is formatted as a standard *.AgMIP format, which can be translated automatically into the desired crop model format through the QuADUIAgMIP tool (Rosenzweig *et al.*, 2014).

Rainfall is projected to decrease over most of Southern Africa, particularly over the west and central regions, except over east South Africa and Mozambique where the change is uncertain (Fig. 4). Temperature is projected to increase across the whole region. Changes range from large increases inland (above 3°C in southwest Botswana and surrounding areas) to smaller increases in coastal areas. For our study site, the projections indicate a 5% to 10% decrease in rainfall and temperature increases of at least 3°C for the period 2040–2070.

It is important to understand climate future projections during the crop growing season since more than 90% of agriculture production is rainfed. For the Nkayi station for the months of October to March, the 20 GCMs show that temperatures are likely to increase (Fig. 5). Rainfall projections show both decreases and increases, which is partly due to the high complexity of rainfall simulation, and suggest less-clear future directions. Projected temperature increase is on average between 2–3°C, an increase that is projected across all months. There is no clear projected rainfall change except in the months of October and November where the majority of the GCMs project a slight decrease rainfall. There is much better agreement between GCMs in the temperature projections than in rainfall, as all

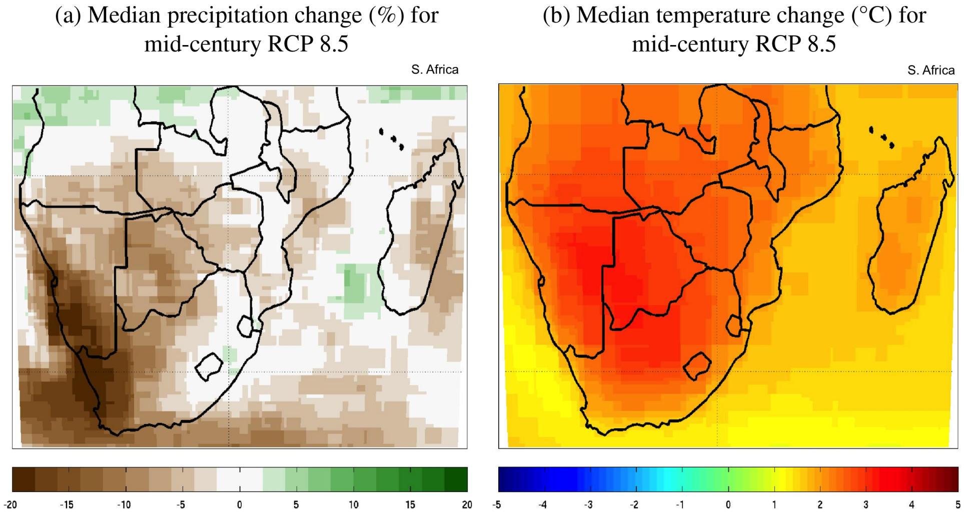

Fig. 4. Median precipitation (%) and temperature (°C) changes for mid-century (2040–2070) under RCP8.5 for Southern Africa.

the climate model projections lie outside the natural variability envelope during the rainy season for temperature. Nkayi is therefore projected to become warmer during the growing season with a possible reduction in early-season rainfall.

Crops

Crop model calibration (DSSAT and APSIM)

The predictive performance of the APSIM and DSSAT crop models was evaluated using on-farm experimental data obtained from ICRISAT research work under different projects in Nkayi (Homann-KeeTui *et al.*, 2013; Masikati, 2011). Both models were calibrated for maize and APSIM was also calibrated for the forage legume, mucuna (*mucuna pruriens*; Tables 4 and 5). Results were satisfactory (Figs. 6a–d) with an observed mean maize grain yield of 1115 kg/ha and simulated yields of 1185 and 1234 kg/ha for APSIM and DSSAT models, respectively. The root-mean-square error (RMSE) was 283 and 480 for APSIM and DSSAT. However, the models had a tendency to over-predict maize biomass (Figs. 6c, d) with a mean observed biomass of 2460 kg/ha and mean simulated biomass of 3385 and 3874 kg/ha for APSIM and DSSAT, respectively. For mucuna biomass (Fig. 6e) results were satisfactory with mean observed yields of 4263 kg/ha and a simulated yield of 4224 kg/ha with an RMSE of 165.

Both models (APSIM and DSSAT) were also evaluated for their ability to simulate maize grain yield variability across farming households (Fig. 6f). The models

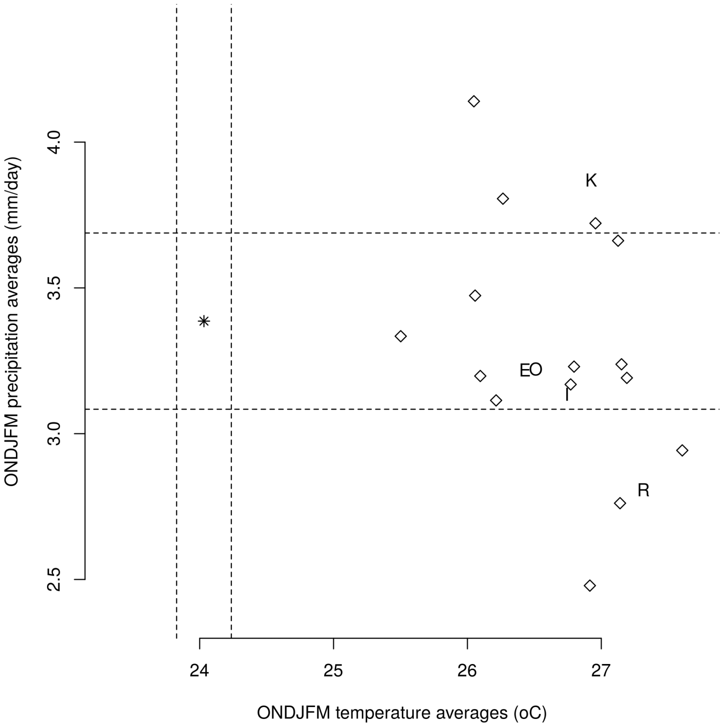

Fig. 5. Mid-century temperature and precipitation changes at Nkayi, Zimbabwe from 20 GCMs under RCP8.5. Dashed lines indicate the bounds of historical natural variability of rainfall. The * represents current baseline climate (1980–2010). GCMs represented by letters are used for full integrated assessment on impacts and benefits of climate change on farming systems with adaptations and RAPs.

Table 4. Genetic coefficients.

Crop	Maize		
Variety	SC 401		Mucuna
Crop models	DSSAT	APSIM	APSIM
Thermal time from emergence to end of juvenile stage (degree days)	230	230	Mucuna, long maturing variety and harvested at flowering stage.
Thermal time from silking to physiological maturity (degree days)	730	730	
Maximum possible number of kernels per plant	500	500	
Kernel filling rate (mg/day)	8	8	

Table 5. Soil initial conditions used for calibration of APSIM and DSSAT crop models. Soil samples were collected from experimental sites in December 2008 from Nkayi, Zimbabwe.

	Soil layer (cm)					
Parameter	0–15	15–30	30–45	45–60	60–75	75–100
Organic carbon (%)	0.52	0.43	0.35	0.30	0.21	0.21
*NO_3–N (ppm)	3.08	2.16	2.30	2.21	2.55	1.07
Air dry (mm/mm)	0.03	0.07	0.09	0.09	0.09	0.09
*LL 15 (mm/mm)	0.06	0.10	0.13	0.13	0.18	0.22
*DUL (mm/mm)	0.16	0.18	0.19	0.20	0.22	0.24
*SAT (mm/mm)	0.41	0.41	0.41	0.37	0.36	0.34
Bulk density (g/cm^3)	1.43	1.42	1.42	1.55	1.55	1.61

Source: Masikati (2011).
*NO_3-N = Nitrate–nitrogen, LL 15 = crop lower limit, DUL = drained upper limit, SAT = saturation

showed the capacity to simulate the middle yield range from the farming households but did not perform so well for the lower and higher ends, especially the DSSAT model. To offset the models' effects on projected future yields, the simulated yields were bias-corrected before doing the economic analyses; the biomass yields were also adjusted before they were fed to livestock.

After evaluation, the models were used to assess the impact of climate change on maize production with and without adaptations and the RAPs. Mucuna was evaluated as it was used as an adaptation strategy for the crop–livestock systems in Zimbabwe. However, only the APSIM model was used to assess the effects of mucuna on maize and livestock production, as routines required to harvest mucuna at the flowering stage are currently not available in the DSSAT model. The full integrated assessment included adaptation strategies, namely micro-dose application of fertilizer at 17 kg N/ha on total maize area, recommended rate of fertilizer application at 52 kg N/ha on the total maize area, and a mucuna strategy. The latter strategy consists of growing mucuna on one third of the maize area; the other third of the field would have maize that has 30% of total harvested mucuna residues in the soil, and feeding the remainder to cattle by using the LIVSIM model, while the final third would have maize under micro-dose treatment. It is important to note that the approach used for this study was mainly to assess the impact of year to climate variations on crop production, hence the residual effects of mucuna on subsequent maize were not taken into account in maize yield. The C:N ratio for mucuna used was 14 and the biomass was applied annually before planting (Capo-chichi, 2002).

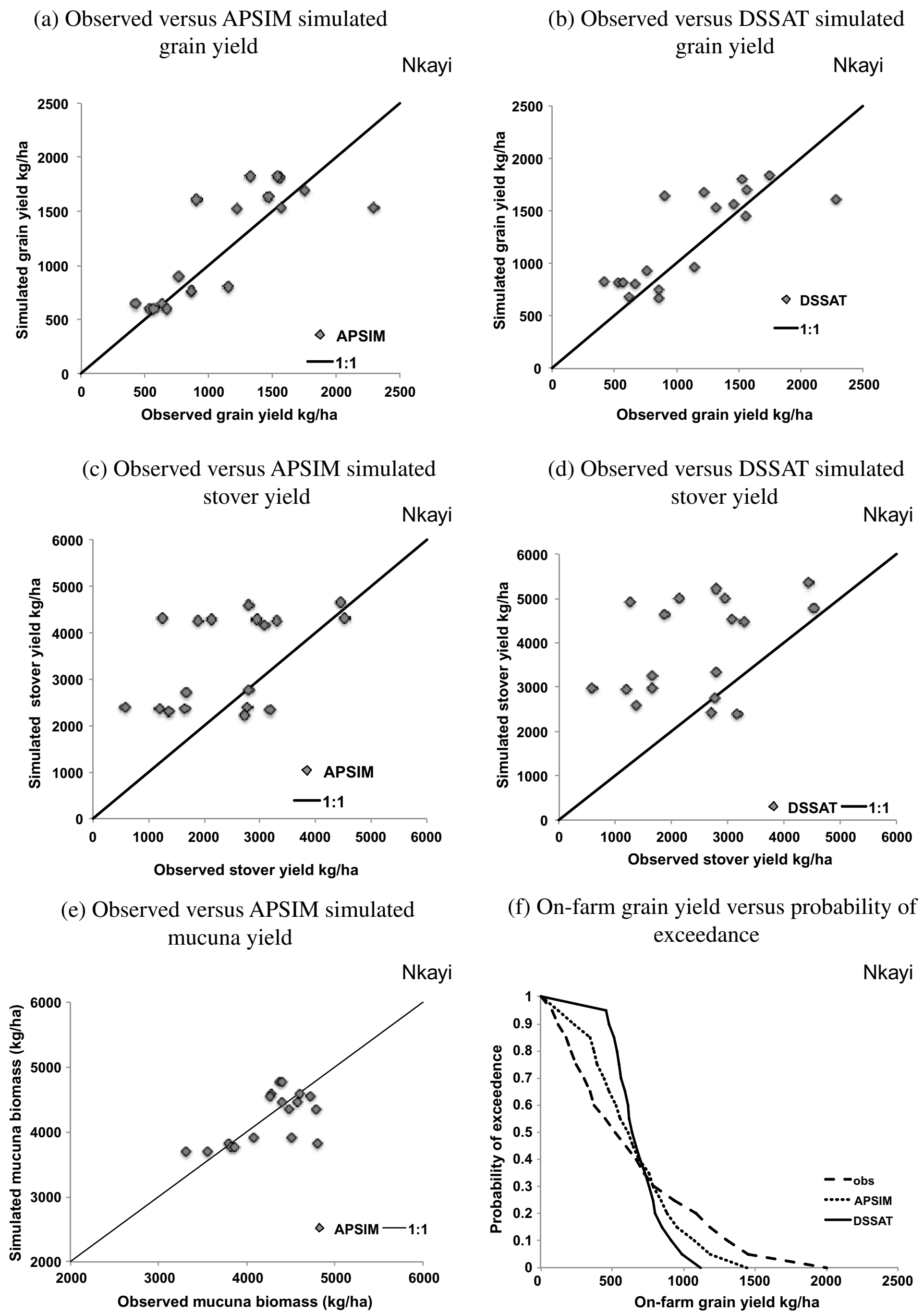

Fig. 6. APSIM and DSSAT crop model calibration by using (a–e) on-farm experimental data from Nkayi, Zimbabwe and (f) survey data, which show the distribution of observed and simulated maize grain yields across different farms.

Livestock

Household-level livestock production was modeled with LIVSIM (LIVestockSIMulator, Rufino *et al*., 2009). LIVSIM simulates production with a monthly time step, based on breed-specific genetic potential and feed intake, by following the concepts of Konandreas and Anderson (1982), and by taking into account specific rules for herd management. Energy and protein requirements are calculated based on AFRC (1993), whereas actual feed intake is simulated according to Conrad (1966). The simulated livestock production outputs used in this chapter included milk production and herd dynamics, such as animal sales, calving, and mortality rates.

The impact of climate change and the various adaptation strategies on livestock production was predicted based solely on simulated changes in on-farm feed production that resulted from the crop model runs. Livestock rely on community range-lands throughout the whole year and, in the dry season, crop residues constitute an important feed base component that help farmers to keep their animals alive and in reasonable condition (Fig. 7a; Masikati, 2011). However, the feed quality of the crop residues and of the dried grasses in the rangeland is low and the risk

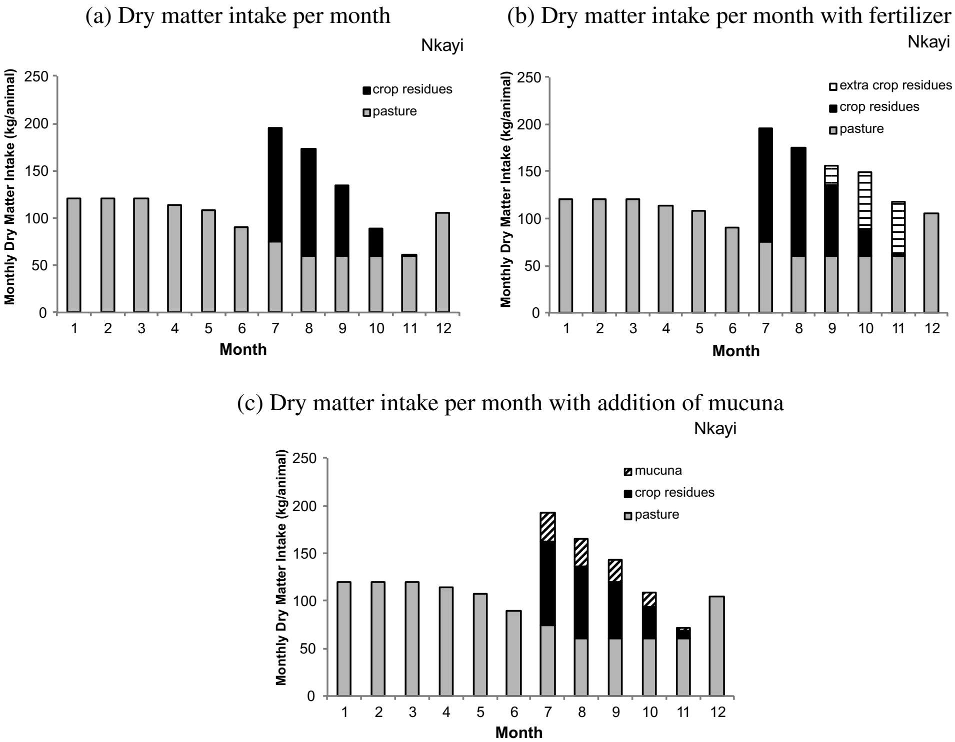

Fig. 7. Feedbase for cattle in Nkayi, Zimbabwe (a) in the baseline scenario, (b) with recommended fertilizer application to maize, and (c) with inclusion of mucuna on one third of the maize land.

of low crop production during dry years is relatively high. Therefore, feed gaps in the dry season are common, which leads to important inefficiencies in the livestock component of the system. On-farm feed production and composition change and the effects of these changes on livestock were simulated with LIVSIM for climate change and due to the various adaptation strategies. The effects of increased crop residue availability in the fertilizer adaptation strategies and of higher-quality feed in the mucuna strategy (Figs. 7 b, c), were investigated. Potential changes in rangeland productivity and direct effects of temperature on animal performance were not taken into account in this study.

Livestock model calibration (*LIVSIM*)

The LIVSIM model was earlier calibrated for Zimbabwean conditions and the Mashona breed, for which it is also used here (Rufino, 2008; Rufino *et al.*, 2011). Comparison of the simulated livestock outputs with the data collected from the households in the survey shows that the model predictions overestimated reported milk yields by, on average, 560 l per year. This difference can be accounted for by the milk consumption by calves, which is included in the model output and not in the values given by farmers.

Comparison of simulated with observed data on herd dynamics is more difficult than for milk. In reality, herd dynamics are influenced by factors that are not modeled, such as diseases and farmer decisions on, for example, selling, which may be influenced by sudden cash needs. However, simulated mortality and calving rates should at least correspond with the average observations across the households in a community. The average simulated mortality rate of 0.11 (across 30 years and 92 households) was within the range of the observed average and median values of 0.20 and 0.03, respectively, across the 92 households. The average simulated calving rate of 0.26 was similar to the observed 0.20.

The simulated average annual milk production varies greatly between households from 365 l to 2581 l, with an average of 1010 l per year under current climate and zero fertilizer (Fig. 8). These differences are largely explained by differences in herd size, ranging from 1–61 heads of cattle. Herd dynamics, including mortality and calving rates, are related to feed availability, which affects the animals' performance and health, and depends on the number of animals per cultivated area.

Economics

Survey data

The TOA-MD model (Antle and Valdivia, 2014) was used to simulate the economic tradeoffs between current and future climate and the selected adaptation strategies,

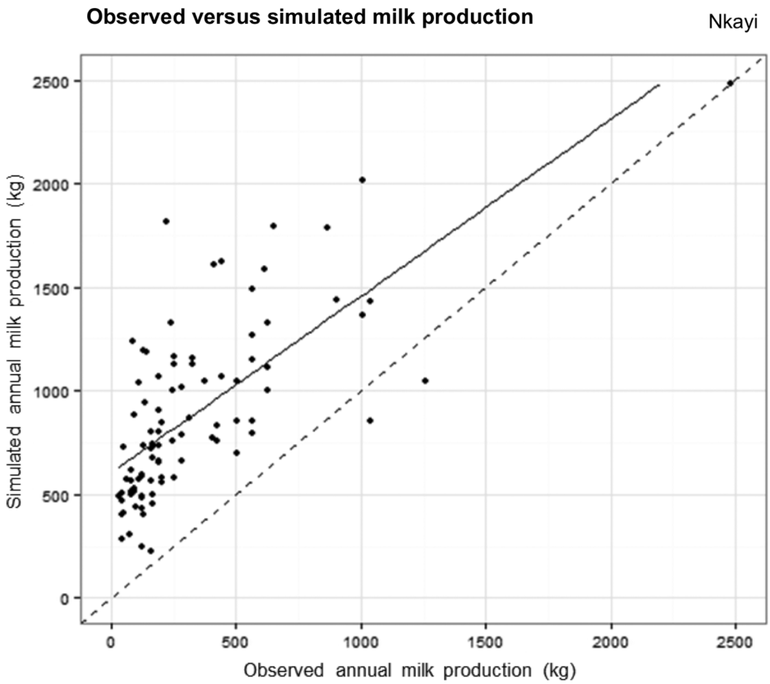

Fig. 8. Scatterplot of simulated vs. observed annual milk production for the households with cattle in Nkayi, Zimbabwe ($n = 92$).

as well as the associated economic outcomes for specific farming systems and their heterogeneous farm populations.

The model draws on various data sources:

- Household survey data: Household surveys conducted in 2011 with 160 farmers interviewed in eight villages assessed farm and household size, off-farm income, revenues from crops and livestock, and the costs of production. Complementarily, eight focus group discussions, one per each village surveyed, assessed agricultural output and input prices, perceived as normal prices during the observation year, not peak prices (Homann-KeeTui *et al.*, 2013).
- Biophysical model inputs: Crop and livestock simulations projected crop yields and livestock performance for the climate change and adaptation scenarios. They were matched with the crop and livestock outputs generated through the household survey through a bias-correction.
- RAPs: Stakeholder consultations were used to estimate exogenous growth rates and price trends for the future mid-term (2050s) scenarios.

For the assessment of net returns we estimated the monetary values of the multiple crop (grain and residues) and livestock (sale, draft power, manure, milk) outputs and valued the outputs used, consumed, or sold at opportunity costs, whereby internally used crop and livestock outputs were factored in as costs under the respective activities, by taking into account the local-user practices (Table 6). We modeled climate change and adaptation strategies for maize and cattle activities and used the RAP assumptions to account for the changes in other crops and other livestock activities, which included higher product prices, input uses, and input prices. We incorporated further relevant changes to the systems following the RAP assessments: Reduction of the farm-household cultivated land, increases in family and herd sizes, and less off-farm income.

Households were stratified into three categories based on cattle herd size, as this influences farmers' wealth status and their ability to invest in alternative technologies (Table 7).

RAPS narrative and development

We based the economic analysis on a representative agricultural pathway and scenario (RAPS) with the optimistic assumption that Zimbabwe will move out of the economic crisis towards positive economic development. By acknowledging the challenges and time required for institutional change, proactive governance and investments, we assume conservative projections. The goal of the RAPS is to unlock the potential for growth through integrated market-oriented crop and livestock production. Zimbabwe is stepping out of 15 years of economic crisis. The government seeks to promote market-oriented agricultural production and restore investor confidence. Severe liquidity constraints, however, restrict public and private investments. Local markets are not well integrated into international markets. Limited employment opportunities in urban areas reduce rural–urban migration. Climate change contributes to low and fluctuating crop yields. Tables 8 and 9 summarize the projected socio-economic changes, projected prices, and external growth rates for agricultural outputs and the narratives, which were based on the RAPS and used for the TOA-MD simulations.

Under these conditions, we assume 140% exogenous yield growth for maize as the predominant crop, and 135% growth for small grains and legumes (Table 9). Fodder crops were only recently introduced and no market exists; we therefore do not expect growth.

We assume 130% exogenous growth for cattle and 125% for small stock off-take, essentially by reducing mortality and improving livestock quality, and 10% increased milk, manure, and draft power production.

Low production and poor-quality produce contribute to a slow-down in producer price increases. Product price increases at international markets are not much transmitted to the local level. We assume price growth for maize grain and residues to

Table 6. Variables, reference prices and assumptions for the definition of crop and livestock revenues and variable costs, under farmer practice, fertilizer treatments, and maize mucuna rotation.

Variables	Units	Reference prices	Assumptions
			Crops
Revenues			
Maize grain	US$/kg	0.2	Village-market price for maize sales.
Other grain crops	US$/kg	0.25	Village-market price for small grain and legume sales. Higher prices as compared to maize were explained by higher labor cost.
Maize residues	US$/kg	0.04	Farmer-estimated price of crop residues, highest prices for legume residues. Crop residues are not sold. This price might reflect the labor for collecting the residues.
Other residues	US$/kg	0.02–0.08	
Mucuna residues — Feed equivalent — Mulch equivalent	US$/kg US$/kg	0.13 0.13	75% of equivalent feed value of mucuna biomass. 75% of equivalent fertilizer value of mucuna biomass.
Costs			
Estimated costs for external inputs	US$/year	Lump sum	Farmers individually estimated their total costs for external inputs in crop production during the observed year.
Draft power	US$/ha	20	Village price for animal draft power. Applied to the land cultivated by draft power.
Manure	US$/kg	0.04	Farmers estimated price of manure. Applied to the rates of manure use.
Mulch — Maize residues — Mucuna residues	US$/kg US$/kg	0.04 0.13	Farmers estimated price of maize residues for soil amendment. Equivalent fertilizer value of mucuna biomass as soil amendment.
Fertilizer non-subsidized	US$/kg	0.7	Village market price, assuming availability of fertilizer.
			Livestock
Revenues			
Draft power	US$/draft animal/day	3.3	Derived from local price for animal draft power (20US$/ha), and considering that a pair of oxen ploughs about 0.3 ha/day.

(*Continued*)

Table 6. (*Continued*)

Variables	Units	Reference prices	Assumptions
Milk	US$/l	1	Village-market price for milk.
Manure	US$/kg	0.04	Farmers estimated price of manure. This price might reflect the labor for collecting the manure.
Herd flows — Cattle	US$/kg live weight	1.3	Village-market price that reflects the average quality of cattle at markets in the communal farming sector.
— Other livestock	US$/kg live weight	1	Village-market price that reflects the average quality of goats at markets in the communal farming sector.
Costs			
Estimated costs for external inputs	US$/year	Lump sum	Farmers individually estimated their total costs for external inputs in livestock production during the observed year.
Feed			
— Crop residues	US$/kg	0.04	Farmers' estimated price of crop residues.
— Mucuna residues	US$/kg	0.13	Equivalent feed value of mucuna biomass.

be 110% and 103%, respectively, and for other crops grain and residues to be 110%. For cattle and small stock in the future we assume 15% and 10% price increase for live animal sales and 5% increase for the other products that are usually not traded. The influx of cheap imports also contributes to slow producer price growth. Input prices tend to remain high and inputs are not affordable for most smallholder farmers. Input support is limited to vulnerable households during recovery and rehabilitation. In these elements of the farming system that were not simulated by the crop and livestock models, future changes were estimated both with and without climate change.

Adaptation package

The adaptation package was purposely designed for resource-limited households under low and erratic rainfall conditions, with emphasis on low costs, which implies low risk, and by making use of locally available resources. We therefore first tested the effects of different fertilizer application rates (17kg N/ha, micro-dosing, and 52 kg N/ha, recommended rate) on subsequent maize, as well as organic fertilizer in a maize mucuna rotation.

Table 7. Base-system characteristics of 160 mixed farms used for the analysis, by farm type, in Nkayi, Zimbabwe.

Variables	Units	0 Cattle Mean	1–8 Cattle Mean	>8 Cattle Mean	Total Mean	Total Std. Dev.
Proportion in community	%	42.5	38.1	19.4		
Household members	People	5.9	6.9	7.4	6.6	2.5
Proportion of female-headed households	%	27.9	31.1	22.6	28.1	
Net returns (maize)	US$/farm	60	162	63	100	121
Net returns (other crops)	US$/farm	31	62	35	44	53
Net returns (cattle)	US$/farm	0	472	1347	443	586
Net returns (other livestock)	US$/farm	9	19	15	14	29
Off-farm income	US$/farm	220	300	294	265	217
Farms with maize	%	98.5	100.0	100.0	100.0	0.1
Maize area	Ha	1.1	1.4	1.8	1.3	0.8
Maize grain yield	kg/ha	497	826	675	657	531
Farms with small grains	%	23.5	32.8	41.9	30.6	46.2
Small grain area	Ha	0.7	0.7	1.0	0.8	0.8
Small grain yield	kg/ha	393	726	327	512	622
Farms with legumes	%	33.8	49.2	48.4	42.5	49.6
Legume area	ha	0.4	0.4	0.5	0.4	0.3
Legume yields	kg/ha	452	722	388	557	541
Cattle*	TLU	0	5.4	13.9	4.7	4.7
Other livestock*	TLU	0.3	0.5	1.6	0.6	0.9

*Herd size: cattle = 1.14 tropical livestock unit (TLU), donkeys = 0. 5 TLU, goats and sheep = 0.11 TLU.

The package that was finally applied across all types of households included the following components:

- Adoption of long duration maize varieties instead of short duration varieties, with grain yield increases between 8% and 18%, and residue increases between 5% and 11%.
- Converting one third of the maize land to maize–mucuna rotation, 30% of the mucuna biomass left on the fields as inorganic fertilizer for subsequent maize. 70% fed to cattle or available for sale.
- Application of micro-dosing (17kg N/ha) on one third of the maize field, second year after the maize mucuna rotation.

Table 8. Changes in socio-economic parameters, 2005–2050, based on the RAPS.

Parameter	Direction of change	Percentage change	Narrative
Family size	++	105	Restricted alternatives in urban areas reduce the rural–urban migration and result in more labor available in rural areas.
Farm size	− −	120	By using improved and labor-saving technologies, farm households will intensify production towards greater production on less land.
Herd size	++	115	Few farms will keep fewer animals in better conditions, the majority will diversify and this will lead to overall increases in livestock numbers
Off-farm income	–	110	Off-farm income has been playing an important role, the opportunities seem however increasingly restricted.

Note: ++ = medium increase, − − = medium decrease, – = small decrease.

Core Question 1: What Is the Sensitivity of Current Agricultural Production Systems to Climate Change?

Impact of climate change on crop production

Maize production in Nkayi, Zimbabwe

The APSIM and DSSAT crop models were used to simulate the effects of climate change on maize grain and stover production under the current farmers' practice (average fertilizer application of 3 kg N/ha). Both models predicted average yield reductions under most GCMs (Fig. 9a). Average simulated maize grain and stover yield reductions were –7% and –9% for APSIM, respectively, while for DSSAT they were –6% and –1%. Predicted yield reductions are not very pronounced under the current farmer practice as it is already a low-productivity system (due to depleted soils). The two crop models also agree on the shortening of days to flowering and maturity across the different GCMs. The APSIM model predicted a shortening of days to flowering and maturity of 11% and 12%, while DSSAT predicted 10% and 11%, respectively; the length of the maize growing period is projected to be shorter due to projected temperature increases which favors rapid crop development. Maize grain and stover yield reductions could mainly be attributed to increased temperatures coupled with reduced rainfall. See, for example climatic conditions under GCM R (Fig. 5) or GCM 18 (Fig. 9a).

Table 9. Current and projected producer prices and exogenous growth rates for agricultural outputs 2005–2050, without and with climate change, based on the RAPS.

		Without climate change		With climate change		
Outputs	Units	Projected price growth (%)	Projected exogenous growth (%)	Projected price growth (%)	Projected exogenous growth (%)	Narrative
Maize						
Grain	USD/kg	110	140	120	140	Village-market price for grain; residues are not traded. Most households have a food grain deficit; surplus for sale is limited. Maize remains the staple crop; intensification has large potential to contribute to growth, but depends on substantial investment.
Residues	USD/kg	103	140	105	140	
Other crops						
Small grains	USD/kg	110	130	115	130	Price increases of other crops are below maize. Groundnut prices can increase more than small grains. Growth potential is higher than for maize, and the contribution will increase.
Residues	USD/kg	103	130	105	130	
Legumes	USD/kg	110	130	115	130	
Residues	USD/kg	103	130	105	130	
Cattle						
Sales	USD/kg live weight	110	130	120	130	Live animals are being sold; milk; mainly for consumption; draft power and manure are in-kind exchanges. Investment in feed and improved management has great potential to reduce mortality, increase productivity and quality; little confidence however in producer price increases.
Milk	USD/l	103	110	105	110	
Draft	USD/draft animal/day	103	110	105	110	
Manure	USD/kg	103	110	105	110	
Other Livestock						
Sales	USD/kg live weight	110	120	110	120	New attention to other livestock will lead to productivity growth.
Milk	USD/l	105	110	105	110	
Manure	USD/kg	105	110	105	110	

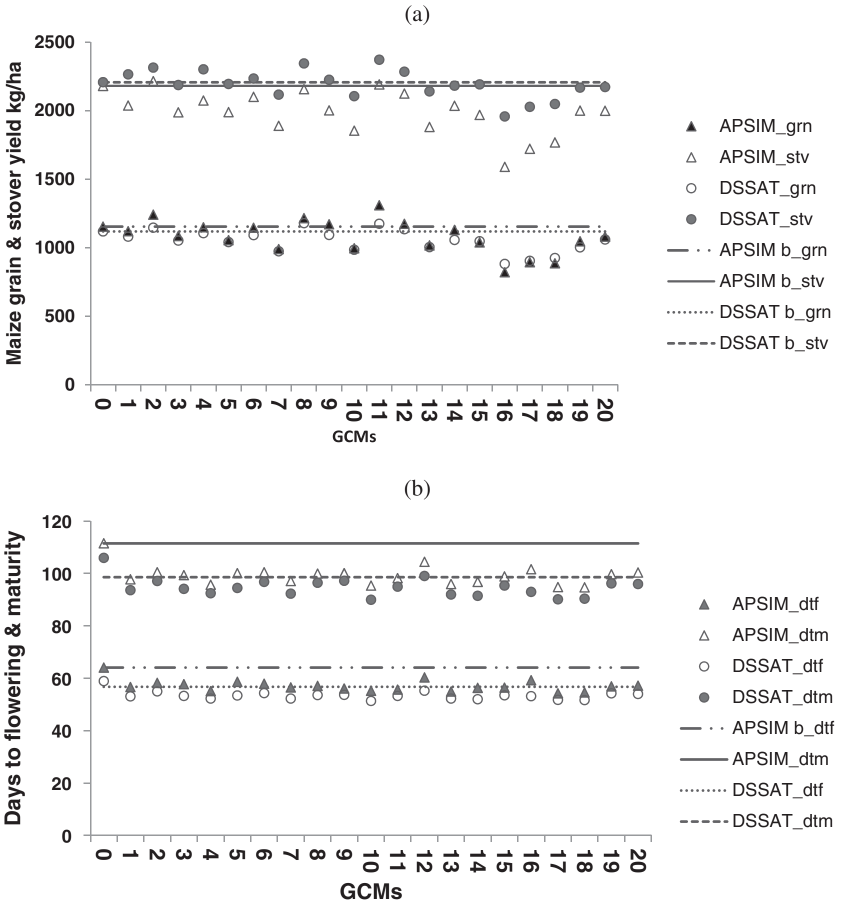

Fig. 9. Sensitivity of maize production to climate change in Nkayi, Zimbabwe. Twenty GCMs were used (A–K denoted by numbers 1–20; 0 denotes the baseline climate 1980–2010). RCP8.5 mid-century (2040–2070).

Impact of climate change on livestock production

Climate change and the uncertainty in the climate predictions do not exert a big influence on milk production, mortality rates (Fig. 10), or herd dynamics in general. Results for a typical farm in Stratum 2 (1–8 cattle) shown in Fig. 10 were very similar to the results for a typical farm in Stratum 3 (>8 cattle). Changes in stover yields under the various GCMs resulted in very minor reductions in annual milk production and slight increases in mortality rates (apart from GCM I). Apparently the predicted changes in stover production in the various climate change scenarios (Fig. 9a) were not large enough to be reflected in significant changes in livestock production.

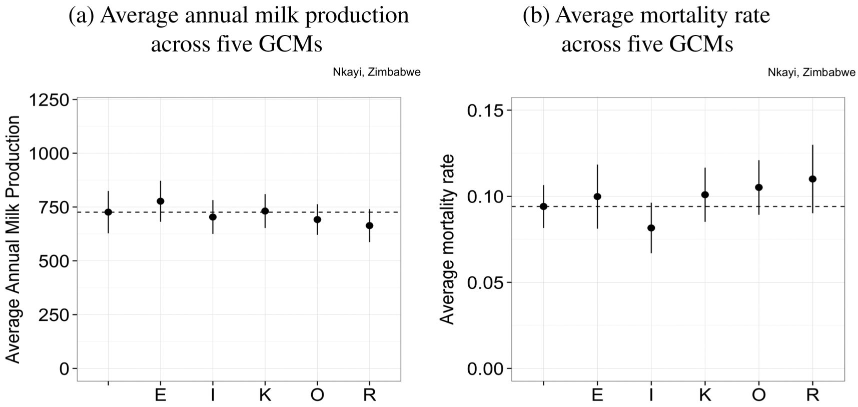

Fig. 10. Sensitivity of (a) milk production and (b) mortality rates to climate change for a representative farm in Stratum 2 in Nkayi, Zimbabwe. Five GCMs (denoted by their letters) are compared to baseline climate (1980–2010), represented by the first data-point and the dotted line. Dots represent average milk production and error bars the standard error around the mean across the 30 years of simulation.

Economic impact of climate change on current production systems

Here we assess the impact of climate change for current production systems. Figure 11 illustrates the projected percentage of farm households that lose from climate change, the percentage changes in the farm's net returns and *per capita* incomes, as well as the effects on poverty rates, for the different GCMs and also by farm type.

The results suggest that climate change impact varies in Nkayi, depending on the climate scenario. Under certain GCMs, especially GCM K, the wet scenario, more households (71%) tend to gain from climate change, while under others, especially GCM R, the dry scenario, more households (64%) tend to lose (Fig. 11).

The effect of climate change on the economic situation of the entire farm population is limited. The magnitude of gains and losses is relatively small, on average between –5% and 8% changes for the various economic indicators, including percentage change of farm net returns, percentage change of *per capita* incomes, and percentage change of poverty rates. Farm net returns of households without cattle can decrease by up to 10% (GCM R) or increase by up to 18% (GCM K). For those with large herds the returns decrease by up to 3% (GCM R) by or increase by up to 6% (GCM K). In absolute terms households lose up to 30 US$/farm (GCM R) or gain 50 US$/farm (GCM K). Households with large cattle herds lose most from climate change (between –50 and 90 US$ per farm net returns), as compared to those without cattle (between –10 and 20 US$ per farm net returns). *Per capita* income varies little among the household types.

The data also confirm that poverty is high in this community. According to this assessment, currently about 97% of the population lives on less than 1.25 US$ per

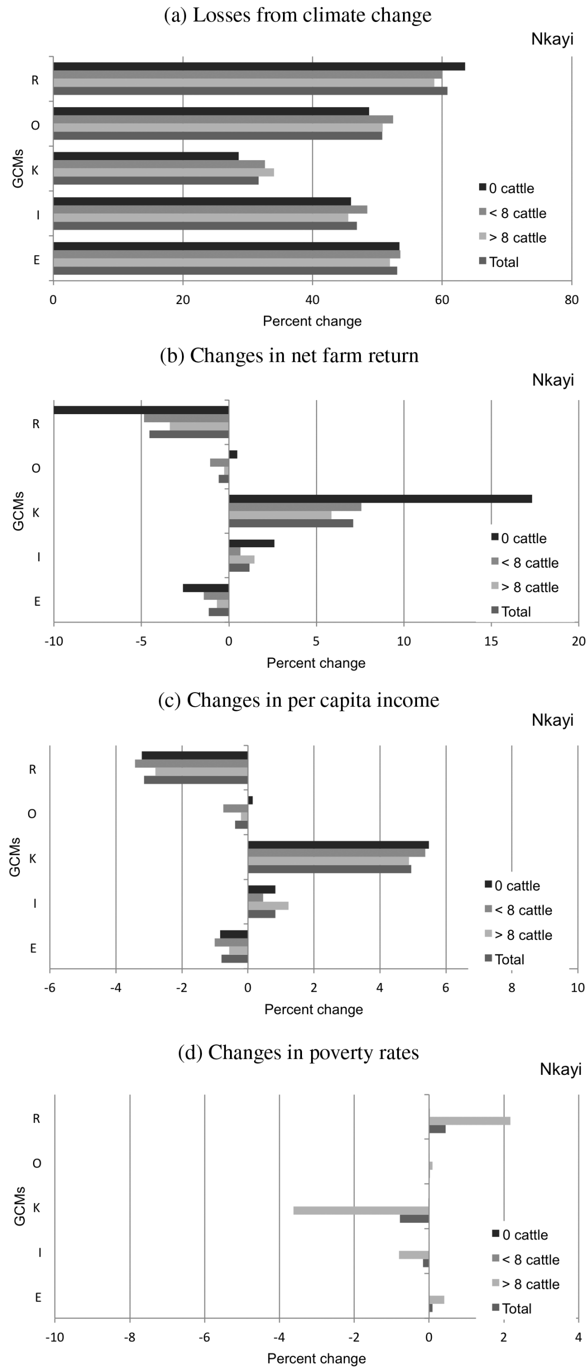

Fig. 11. Socio-economic indicators for estimating effects of climate change for current production systems: Percentages of potential losers from climate change, changes in farm net returns, changes in *per capita* income, and changes in poverty rates, by strata and climate model (GCMs R, O, K, I, and E).

person per day, most households live without or with only small cattle herds. Even with large herds, 91% of farm households are poor. Climate change does not change the proportion of households that are below the poverty line, on average between an increase of 1% and a decline of 1%. Farms with large cattle herds vary between an increase of poverty levels of 2% and a decline of 4%.

Core Question 2: What Is the Impact of Climate Change on Future Agricultural Production Systems?

Results and discussion

The impact of climate change on future agricultural farming systems in Nkayi is similar to that on the current farming systems, with slightly less negative influence than under current conditions (Fig. 12).

As for current production systems, climate change has limited influence on the economic situation of farm households for future production systems. Depending on the climate scenario, up to 67% of the households might gain from climate change (GCM K), or 64% might lose (GCM R). The magnitude of gains and losses (percentage change of farm net returns, percentage change of *per capita* incomes,

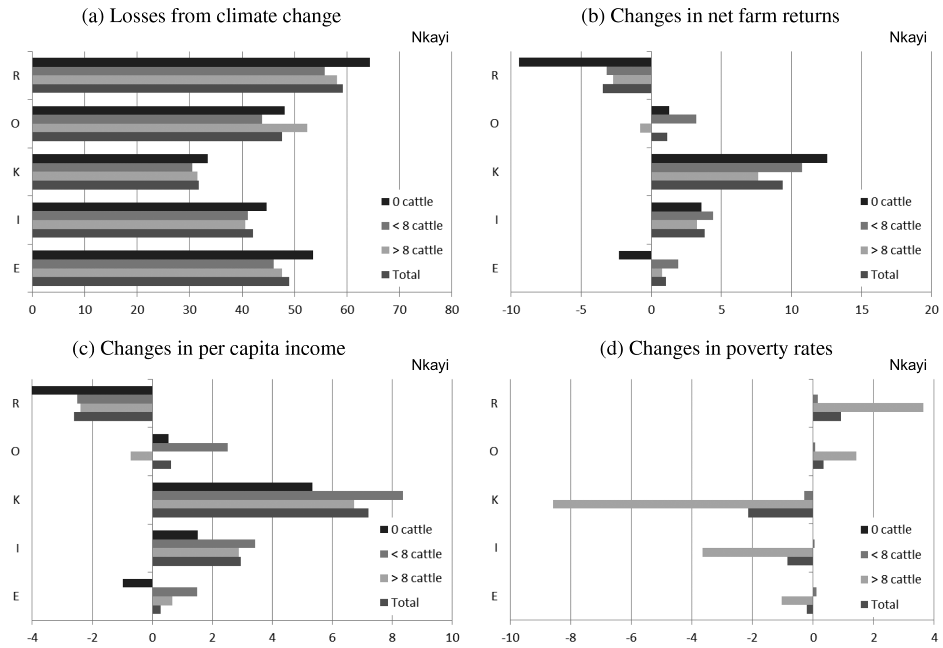

Fig. 12. Socio-economic indicators for estimating the effects of climate change for future production systems: Percentages of potential losers from climate change, changes in farm net returns, changes in *per capita* income, and changes in poverty rates, by strata and climate models (GCMs R, O, K, I, and E).

and percentage change of poverty rates) is also relatively small and varies between 4% loss and 9% gain for the various economic indicators. Those farms without cattle also experience greater changes in relative terms, between 10% loss and 13% gain. Those farms with large herds make greater gains in absolute terms, under GCM K up to 154 US$ per farm.

Despite the economic development, poverty rates are still high. About 90% of the population lives on less than 1.25 US$ per person per day, about 10% less than those under current production systems. Even with large herds, between 69% and 77% of farm households would be poor. Climate change does not much change the proportion of households above the poverty line of 1.25 US$ per person per day, while a large proportion of the farms will still be vulnerable to climate change. Across the total population poverty rates would change between 2% increase and 1% decline. Among the farms with large cattle herds, poverty rates would decline by 9% under GCM K and increase by 4% under GCM R.

Core Question 3: What Are the Benefits of Climate Change Adaptations?

Impact of adaptation on crop productivity

Benefits of organic and inorganic fertilizer application

Although the projected crop yield losses under the current farming practices are not substantial, use of soil amendments as adaptation strategies can offset the negative impact of climate change with mean yield gains ranging between 20% and 25% (Fig. 13). The use of organic amendments such as legume residues and low inorganic fertilizer application rates is less risky compared to high application of inorganic fertilizers. Application of high nitrogen fertilizers (recommended rate) shows very high variation over the years with yield changes ranging from –20 to >70%, while the use of lower rates (micro-dose) and use of legume residues (in this case mucuna) show lower variations, with yield changes ranging from –8% to >35% and –8% to >40 %, respectively. However, mean grain yields from the different treatments are similar, which shows that substantial benefits can be obtained from lower application rates, as increased temperatures and limited moisture would negatively affect crop production especially under high fertility treatments. In the study we used a maize–mucuna rotation system with application of 30% mucuna residues. The subsequent maize crop after mucuna would benefit from biological nitrogen fixation and also from the crop residues that are applied. Such adaptation strategies would benefit resource-poor farmers to improve main staple crop yields with minimal external inputs.

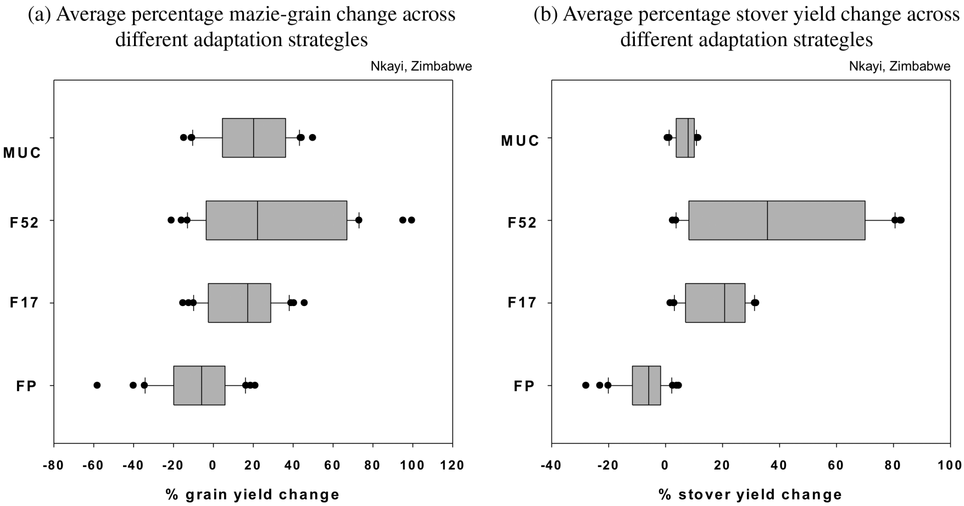

Fig. 13. Boxplots showing average percentage maize grain and stover yield change (five GCMs, mid-century, RCP 8.5) in Nkayi, Zimbabwe, under FP (farmer practice/no adaptation) and different adaptation strategies (F17: micro-dosing, F52: recommended fertilizer, MUC: maize–mucuna rotation system). The percentage change under adapted scenarios (F17, F52, and MUC) is calculated with respect to the non-adapted scenario under climate change while for the non-adapted scenario (FP) yield change is relative to FP under current climate.

Impact of adaptation on livestock production

Applying micro-dose fertilizer (F17) has a relatively minor effect on annual milk production for a typical farm with small cattle herds (1–8 cattle). The relative change fluctuates around the 0% line, except for a clearly positive change under GCM O (Fig. 14a). Under the recommended fertilizer application rate (F52) and the mucuna rotation (MUC) scenario, much clearer improvement in annual milk production are projected, around 20% and 25% improvement, respectively (Fig. 14a). With respect to mortality rates, the F17 scenario results in a strong improvement (decrease in mortality), which ranges from –20% to –50% change. However, with the F52 and MUC adaptations, an even stronger improvement can be achieved (Fig. 14b). The same trends were observed for a typical farm with large cattle herds, greater than eight cattle per household (not shown), even though the GCMs behave slightly differently than a farm with small cattle herds (in Fig. 10).

Impact of adaptation on farmer livelihoods

We first compared the effects of different fertilizer applications on farmers' livelihoods. According to the assumptions made in this analysis, the economic benefits from fertilizer applications are limited. The recommended fertilizer rates pay-off

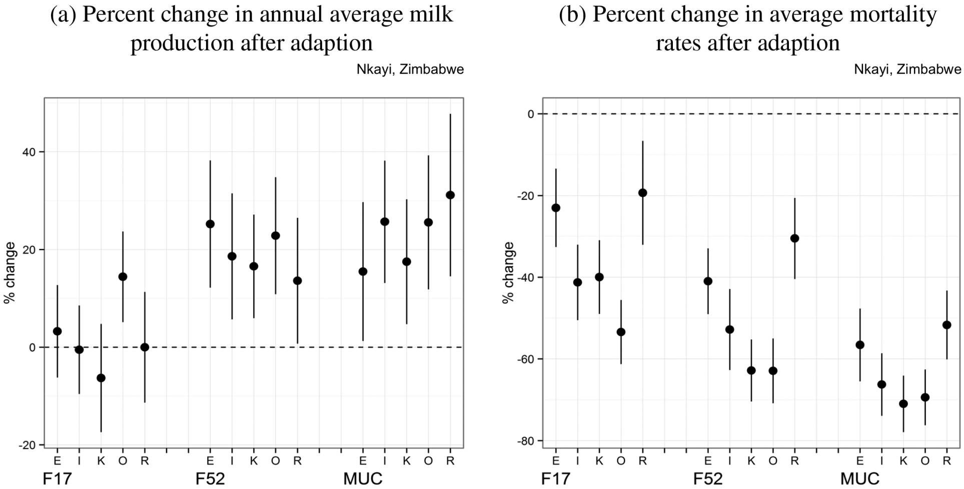

Fig. 14. Effect of adaptation options (F17: micro-dosing, F52: recommended fertilizer rate, MUC: mucuna rotation) on (a) annual milk production and (b) mortality rates for a medium farm in Nkayi, Zimbabwe. The percent change in the adapted scenario is calculated with respect to the non-adapted scenario in the future, with GCMs denoted by their letter. Dots represent the average change and error bars the standard error around the mean across the 30 years of the simulation.

under high-rainfall scenarios, through high yield increases for households with cattle. Under low-rainfall scenarios however, the low fertilizer application rates are more beneficial; especially poor households bear fewer costs and less risk.

In comparison, the maize–mucuna rotation is an alternative to fertilizer application for both high- and low-rainfall scenarios, but has its comparative advantage especially under low rainfall scenarios. Inclusion of mucuna is a low-cost/-risk alternative; especially poor households would adopt the technology and benefit from use of the organic fertilizer.

The adaptation package that was finally deemed appropriate for smallholder farmers under high-risk conditions comprised micro-dosing fertilizer application rates (F17) on one third of the farm's maize fields, a maize–mucuna rotation on the other two thirds, and switching to drought-tolerant maize with 10% to 18% yield increases. The following economic benefits can be expected (Table 10):

The adaptation package is likely to reduce vulnerability to climate change. Across the climate scenarios fewer households will be negatively affected by climate change. The proportion of households losing from climate change will possibly decrease, in ranges from 32% to 21% under the dry scenario GCM K or from 59% to 24% (GCM R). Almost 80% of the households will adopt the package. The adoption rates will be highest for households without cattle, assuming that they can convert the mucuna biomass to cash income.

Table 10. Socio-economic indicators and percentage changes in farm benefits from climate change adaptations for GCM K and GCM R.

	GCM K				GCMR			
Stratum	0 Cattle	1–8 Cattle	>8 Cattle	Total	0 Cattle	1–8 Cattle	>8 Cattle	Total
Adoption rates	95	69	73	79	94	65	72	76
Change in net returns	70	18	17	21	50	13	14	16
Change in *per capita* income	23	13	15	15	17	9	12	12
Change in poverty rate	0	−2	−18	−6	0	0	−14	−4

However, even though many households are likely to benefit, the magnitude of the benefits is relatively small. Farm net returns will increase by about 16% to 21%, and *per capita* incomes will increase by 12% to 15%. The overall poverty rate will be reduced by only 4% to 6%.

The economic benefits differ by farm types. Small farms without livestock make relatively little benefits from climate change adaptations. These farms might be adopting the technology package, but their benefits in absolute terms are rather small. Adopters make 100–180 US$ more farm net returns compared to non-adopters. The costs and benefits associated with the adaptation package tend to be more pronounced for larger farms. Adopters on medium (1–8 cattle) and better off farms (> 8 cattle) can increase their farm net returns from without adoption at about 900–1100 and 2000–2200 US$, to make with adoption higher net returns of 300–500 and 700–900 US$, respectively, but also face higher risk.

The selected adaptation package will not have a substantial impact on poverty levels. Overall poverty rates might be reduced by 4% to 6%. It will shift 14% to 18% of the larger farms to higher welfare levels, but not improve the welfare situation of the most vulnerable. For the majority of rural families, other solutions will have to be sought in and beyond agriculture.

In addition to the above we investigated food budgets (maize and other crops) for the different farm types under current and future production systems, and also under the adaptation package. Assuming food requirements of 120 kg maize per person per year, small farms without livestock can currently not cover their food needs from their own production. This food deficit will increase under climate change with and without the adaptation. The major challenge for these farmers is their high dependence on crop production, as long as no other income-generating activities are available to them. Small cropping areas, which are a consequence of limited labor and agricultural inputs and other factors, are a major constraint for them to increase production. These farmers will depend on safety support to sustain food security, unless functional markets will be developed that will allow them to sell high-value crops and use parts of that income to buy food. Livestock owners, in comparison, will maintain small surplus of food production, under climate change and with the adaptation package. They can thus afford to convert some land for fodder production without undermining immediate food security. They can supplement food losses through livestock sales. It is important to note the role of other crops, which include small grains and legumes, as they contribute to household food security and nutrition.

Conclusions and Next Steps

Climate projections for Southern Africa have shown that temperatures are likely to increase by >2°C, rainfall will be varied, and evaporation will increase in response to increased temperature. Such changes will affect production of the main staple food, maize, in the medium and long term. If current farmer practice (low-to-zero application of soil amendments) were continued into the future, farmers would, in some years, experience yield reductions >20%, with a mean yield change reduction being –5%. Livestock play an important role in the current farming systems. The projected climate conditions can also reduce feed availability and consequently livestock production, though livestock performance seems to be less influenced by climate change than crop performance. Consequently, smallholder farmers that depend on rainfed agriculture will face greater food insecurity and vulnerability if substantial adaptation measures are not taken. When there is a crop failure there is no food available, and especially those without livestock (43%) will face increasing food deficits and would not be able to buy food even if it is available on the market. In absolute terms, the losses from climate change are highest for households with livestock and large farms. This is because the economic value of the farm activities by these households is far greater than that of the poor; with larger areas of croplands and herds the sum of losses through climate change outweighs those of poor households.

This study has shown that adaptation measures contribute to economic gains from intensification and diversification. The use of low rates of inorganic and organic fertilizer and inclusion of forage legume crops of high-quality feed biomass can substantially reduce the effects of climate change on crop and livestock production. Feeding livestock increases the economic returns from livestock. This generates economic benefits that would allow farmers to purchase staple food and thus supplement the food deficits. Households without livestock could use the higher returns on high-value crops (e.g., mucuna, but also other cash crops) as a way to sustain food security — provided that food and feed markets are functional. For larger farms with livestock investment in food, feed crops can offset negative effects of climate change and transition some farms to higher levels of production and welfare.

An important result of the integrated assessments about the high and possibly overestimated poverty levels in Nkayi, Zimbabwe. These are likely to prevail in the future, if more drastic economic improvements are not made. National assessments in Zimbabwe (ZimVAC, 2013) acknowledge high poverty levels and food security in Nkayi (76% of the rural population below poverty line at <1.5 USD *per capita* expenditure per day; about 40% chronically food insecure). Reasons for overestimating poverty rates in this study could be that we did not take full account for off-farm activities. Other recent studies in Zimbabwe confirmed extremely low levels of cash income for the majority of the population (Dube *et al.*, 2014). Harris and Orr (2013) identified limited farm size and poor access to productive resources as major constraint for smallholder farmers raising income levels. Interventions that aim at improving the livelihoods of smallholder farmers in areas like Nkayi therefore have to go beyond food security and climate change adaptations, and capacitate farmers towards alternative livelihood activities. Alternative less risky, more profitable, and resilient products have to be identified and tested in the local context, e.g., livestock, cash crops, irrigation schemes. New initiatives shed light on the great potential and innovativeness of small and medium enterprises, which could facilitate farmer to market linkages from within the local context (Stepman *et al.*, 2014).

The RAP assessments set the bio-economic modeling results into the broader picture of economic development in Zimbabwe, based on current and future socio-economic trends. Stakeholders emphasized that government and agricultural policies will play a key role for promoting climate smart, resilient, and profitable agriculture in the future and that this has to go along with effective public and private investments in research and development. Stakeholders and farmers expressed a clear vision towards market-oriented agricultural production, supported by renewed investments in infrastructure and agricultural services and backed up by agricultural policies. Human population growth, which is associated with an increasing demand for quality food, was seen as a key driver for rural economic development. Product prices were not projected to increase much, given the interplay of increasing demand, higher production, and influx of cheaper imports. Similar trends are likely to be seen for inputs, increasing demand by a number of farmers, but also leading to revitalization of local processing industries.

The transition of the predominantly subsistence-oriented towards market-oriented smallholder farming system will, however, be slow, considering the existing challenges and barriers (e.g. low capital endowment, incomplete agricultural policy framework, need for institutional change to govern, regulate and enforceme). By addressing these as Anseeuw *et al.* (2013) suggest, future approaches will be oriented towards integration of the agricultural sector, by stepping out from subsistence towards economic development, promoting market linkages and limited-input support programs, with investments from both public and private sectors. Based on these assumptions, farmers will find incentives to invest in improved crop and livestock technologies. At the farm level, a switch from high risk towards more diversified crop and livestock production and marketing, and better integration of livelihood activities on- and off-farm will reduce farmer vulnerability to climate-induced shocks such as dry spells, droughts, and flash floods as well as market shocks (e.g., price fluctuations). Improved integration on- and off-farm needs to go beyond technical options; there is a need to promote other pathways for sustainable low-cost and -risk intensification, supported by better integrated services and production-to-market linkages. As the results from climate change adaptation have shown, the interventions need to be tailored to farm type. Poor farmers can benefit from proactive and innovative investments in functional food and feed markets, and provide services beyond immediate food security. Larger farms can spearhead market-oriented production and sustain product flows.

Women will continue to play a critical role in farm management. Labor migration of men and high rates of female-headed households have contributed to women becoming important decision-makers on the farm, on issues of production, marketing, and sales of products. Recent ICRISAT studies have illustrated that women gained influence and knowledge with market-development processes, and were not marginalized as is often assumed. With more drastic changes there is new emphasis on gender-sensitive approaches to capacitate farmers to adapt and innovate, which ensure that women and men are involved in the full range of production to market activities.

At the community level, greater awareness of more extreme climatic conditions and a more integrated agricultural-development approach will be required in order not to aggravate possible negative impacts of climate change, but to lead to improved control and management of natural resources and land use. In the short term, despite investments in agriculture, the combination of increased population pressure, fragile environments, and poor institutional regulations will result in further degradation of soils, water, and landscape. Institutional and technological improvements, to govern, regulate, and enforce communal natural resource use will take time, but need to be established in the mid-term, to offset negative consequences of degradation (Siziba, personal communication).

The promotion of multi-stakeholder engagement will improve communication on context-specific investment opportunities, e.g., new attention to "marginal" crops and livestock, market requirements, and services needed.

Major message for stakeholders

For farmers to be more resilient in the future, policymakers need to understand the projected economic trends along with the impacts of climate change on farming systems, associated uncertainties, and favorable adaptation strategies. The major challenge in Zimbabwe is lack of expertise to generate such knowledge that can be shared with decision-makers with regard to impacts of climate change on different sectors, including agriculture. Other challenges are how to convince decision-makers in the face of great uncertainties and how to bridge the gap between scientific and traditional perception of climate change (Tadesse, 2010).The approach we used in AgMIP was mainly aimed at addressing such issues as we engaged with stakeholders during the RAP development process for possible future production scenarios that would assist farmers in adapting and evaluating possible benefits across different farmer categories. It is therefore important for us to take another step and see how we could generate information that can also be used to support forecasting seasonal food production, famine early-warning systems, redefining agroecological zones and recommending adaptations that are specific for agroecological zones.

The AgMIP regional integrated assessments can also provide information about possible radical system shifts towards more productive and sustainable options, e.g., from maize–cattle systems towards more diversified maize–legumes–cattle–small-stock systems. Farmers can adapt to the impacts of climate change more specifically by changing management practices or crop choices, as well as considering other inputs such as chemical treatments and irrigation. It is important, however, for decision-makers to understand that there are conditions that need to be met such as input availability, access to markets with attractive prices, as well as infrastructure and functional institutions that would enable farmers to invest in agricultural production. Multi-stakeholder engagement in policy formulation is critical, to ensure the representation of interests and requirements by public and private sectors. More process-oriented planning and structured interactions among stakeholders is needed, with the goal of reconstructing the agricultural sector and transitioning to more resilient and profitable farming systems. Such planning processes should include a common vision as the foundation; technology choices informed by bio-economic models; functional markets to catalyze positive change; solutions based on farmers' choices and from within local contexts; and research and development to engage in those agricultural pathways.

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