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Balancing co-benefits and trade-offs between climate change mitigation and adaptation innovations under mixed crop-livestock systems in semi-arid Zimbabwe

Sabine Homann-Kee Tui[1*], Roberto O. Valdivia[2], Katrien Descheemaeker[3], Gevious Sisito[4], Elisha N. Moyo[5] and Farai Mapanda[6]

Abstract

Achieving Zimbabwe's national and international commitments to food systems transformation and climate resilience building is of high priority. Integrated simulation-based research approaches developed under the Agricultural Model Intercomparison and Improvement Project (AgMIP) are important sources of evidence to guide policy decisions towards sustainable intensification. Through the identification of economically viable, socially inclusive and environmentally sustainable development pathways, the analysis in this study evaluates co-benefits and trade-offs between climate change adaptation and mitigation interventions for vulnerable smallholder crop-livestock holdings in the semi-arid regions of Zimbabwe. We explore how climate effects disrupt the livelihoods and food security for diverse farm types, the extremely vulnerable and those better resource endowed but facing high risks. In an iterative process with experts and stakeholders, we co-developed context specific development pathways. They include market-oriented adaptation and mitigation interventions and social protection mechanisms that would support the transition towards more sustainable intensified, diversified and better integrated crop-livestock systems. We assess the trade-offs associated with adoption of climate-smart interventions aimed at improving incomes and food security but that may have consequences on GHG emissions for the different pathways and farm types. The approach and results inform the discussion on drivers that can bring about sustainable intensification, and the extent to which socio-economic benefits could enhance the uptake of emission reducing technologies thereof. Through this strategy we evaluate interventions that can result in win–win outcomes, that is, adaptation-mitigation co-benefits, and what this would imply for policies that aim at transforming agri-food systems.

Keywords Climate change adaptation, Mitigation, Sustainable intensification, Food security, Social equity, Simulation modelling, Multi-stakeholder approaches, Mixed crop-livestock systems, Zimbabwe

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*Correspondence:
Sabine Homann-Kee Tui
shomannkeetui@gmail.com
Full list of author information is available at the end of the article

Background

Climate change and other shocks urge transformation towards equitable, inclusive, climate resilient and sustainable agriculture and food systems in Sub-Saharan Africa (Agra 2022; von Grebmer et al. 2022). At high levels of poverty, food insecurity and vulnerability, climate impacts amplify threats to agriculture; women and female-headed households face negative consequences of climate disproportionally and transformation therefore aims to address gender and social disparities associated with smallholder agriculture (Huyer and Partey 2020).

Countries are exploring different pathways to achieve their Sustainable Development Goals (SDGs), and the Nationally Determined Commitments (NDCs) and National Adaptation Plans (NAPs), as part of the Paris Agreement (Crumpler et al. 2021). The Agriculture, Forestry and Other Land Use (AFOLU) sector constitutes a high priority for mitigation and adaptation. Through their updated NDCs countries are making stronger ledges to reduce GHG emissions in agriculture, through more inclusive planning process. At the same time, adaptation measures are highlighted as national priority, to address the vulnerabilities to climate change, and the objectives of reducing poverty and food insecurity for the attainment of their vision 2030 and related SDGs (World Bank 2021). Depending on a countries' priorities, policy and decision makers need to look at strategies and actions in agriculture to address low productivity levels. Interventions aimed at increasing income and food security, such as livestock development, may be achieved at the cost of increasing GHG emissions. Policy makers need to evaluate these trade-offs to set priorities for research, development and investment (Rojas Downing et al. 2017; Liu et al. 2021).

Zimbabwe for instance, largely depends on smallholder mixed crop-livestock systems and semi-arid areas cover the largest shares of land. Semi-arid areas are expanding under the influence of climate change, where agricultural production is vulnerable (Manatsa et al. 2020). Interventions in these areas tend to focus on cropping systems to increase food security, however these regions are characterized by depleted soils and water shortages which limit the potential gains (GOZ 2022). Trends show a decline in crop production, against an increase in small stock production (www.faostat.org/faostat). Enhancing the role of climate smart livestock production would be critical to improve farm profitability, adaptation and resilience, through interventions that improve productivity and thereby also reduce GHG emission intensities (FAO 2019). Balancing the economic benefits from crops and livestock, notably income, input services, nutrition, and risk mitigation, with a reduction of GHG emissions would support the objectives of reducing poverty and food insecurity for the attainment of related SDGs by 2030 (Lipper et al. 2014). Improved management decisions that raise the nutritional status of cattle and goats, feed quality and digestibility, along with health systems and market development can reduce emissions and increase farm incomes (Thornton et al. 2009; Herrero et al. 2015).

To advise countries and farming systems on the direction for climate change mitigation, adaptation and development, science-informed evidence generation is becoming more critical, guiding stakeholder engagement, policy and investment planning and decisions (van Braun et al. 2021; Bezner-Kerr et al. 2022). Sustainable intensification frameworks are being developed to achieve synergies in mitigation and adaptation supporting advancements in income and food security, and social equity (Suckall et al. 2015; Smith et al. 2017; Reisinger et al. 2021).

This study builds on a recent multi-model assessment that illustrated impacts of climate change and adaptation on mixed crop-livestock systems in Zimbabwe (Homann-Kee Tui et al. 2022). The study showed how climate smart sustainable intensification strategies, crop diversification and integration with livestock production, improved economic benefits and reduced inequality among farm types (strata). We are advancing the multi-model research, by analysing co-benefits and trade-offs that sustainable intensification and socio-economic development can create while emphasizing a stronger role of livestock, with environmental impacts, as expressed in changes in GHG emissions. The underlying research question is to what extent can changes in agricultural priorities towards intensified and climate resilient crop-livestock systems create mitigation-adaptation co-benefits, through context specific adaptations packages that can also lead to mitigation benefits, and reduce socio-economic and environmental trade-offs?

Study area

Agriculture in Zimbabwe Agriculture is driven by smallholder farmers, employing more than 80% of the economically active population in rural areas and contributing about 20% to the country's GDP (ZIMSTAT 2019). Poverty and food insecurity levels are high, as most farmers depend on rainfed agriculture, dominated by maize; Zimbabwe is amongst the 10 countries worldwide most exposed to the risks and vulnerabilities to climate change (IEP 2021). Higher temperatures accelerate plants' phenological development, shortening the time for biomass accumulation, reduced crop yields and change in rangeland plant diversity (Hatfield and Dold 2018). Less rain implies water stress. Despite a large livestock population, 75% found in the semi-arid areas, and increasing demand for livestock products, livestock productivity is extremely low (Ndlovu et al. 2020). In marginal areas, and for small livestock in particular, market development and technical support to the livestock sector have been inadequate (Van Rooyen and Homann 2009).

Climate variability and change The map in Additional file 1: Appendix 1 illustrates agro-ecological zones and major farming systems in Zimbabwe, with semi-arid areas and semi-extensive to extensive crop-livestock systems covering more than 70% of the country. Current temperatures are fairly high and rainfall is low and erratic (< 650 mm annual average) in these areas. Climate projections foresee increasing temperatures across the cropping season along with a likely decrease in rainfall, prolonged dry spells, higher variability of rainfall, and more extreme climate events, with drier agro-ecological zones expanding (Moyo et al. 2018; Moyo 2020; Manatsa et al. 2020).

Agricultural and climate policies Zimbabwe's agricultural policy frameworks commit to improve the agricultural sector through commercialization and addressing welfare of smallholder farmers (NDS1, Comprehensive National Agricultural Policy Framework (2018–2030); National Agricultural Policy Framework (2012–2032); Agricultural Gender Mainstreaming Guideline (2021); The Livestock Growth Plan (2020).

Zimbabwe also scales up efforts in addressing climate change (National Climate Change Response Strategy (2017), National Climate Policy (2017), Low Emission Development Strategy (2020–205), Zimbabwe Long Term Low Green House Gas Emission Development Strategy (2020–2050) and Gender Action Plan (2020).

According to Zimbabwe's Long term Low Emission Development Strategy (LEDS), Zimbabwe contributes about 0.045% to the global GHG emissions (GOZ 2022). The total national GHG emissions are estimated at 60.7 Mt CO_2 eq., while total national GHG removals are estimated at 22.8 Mt CO_2 eq., giving a net total of 37.9 Mt CO_2 eq (MECTHI 2022). The AFOLU sector contributes about 71% of the national total emissions. Within the AFOLU sector, conversion of forest land to grassland contributes highest emission (41%), followed by emissions from conversion of forest land to cropland (18%), biomass burning (12%), enteric fermentation (10%), and direct N_2O emissions from managed soils (9%). From the LEDS, the GDP contribution of the AFOLU sector was anticipated to grow annually by around 10% between 2021 and 2030. In the past, the Energy sector used to be the major contributor to emissions but was overtaken by the AFOLU sector as the country's industrial development slowed down due to macro-economic challenges over the past two decades.

The country through its revised NDCs commits to 40% reduction of GHG emissions per capita by 2030, conditional on international support (GOZ 2021). The largest abatement potential to reduce GHG emissions is expected to come from AFOLU (47%), addressing low resource-use efficiency and high GHG emission intensity due to high deforestation and land degradation, yield-gaps, low productivity of crops and livestock (GOZ 2021). Conservation agriculture including indirect beneficial impacts on livestock, increased natural forest, increased plantation of forests and reduced burning of rangelands and forests were identified as major mitigation measures (MECTHI 2022). Efforts to include livestock feeding in mitigation measures, however, have been excluded owing to the lack of available data and implementation agents.

Data and research approach

This study advanced the Agricultural Model Intercomparison and Improvement Project (AgMIP) Regional Integrated Assessment (RIA) approach that investigates economic impacts of climate change, by assessing the trade-offs of mitigation and adaptation innovations for particular agricultural systems and farm types. To identify just, economically viable and environmentally sustainable development pathways, the analysis integrates climate, crop, livestock and economic data and models. They were applied to under future climate and socio-economic scenarios.

The study used inputs from the AGMIP-RIA framework applied to the crop-livestock systems in Nkayi District, Zimbabwe (Homann-Kee Tui et al., 2022). Household survey and secondary data were used to characterize household and farm production activities and to calibrate and run crop and livestock simulation models. Socio-economic pathways and co-developed context-specific adaptation strategies with stakeholders, including consultations, validation, and feedback, were used to design the simulation experiments that are the basis of this study. Details are found in Homann-Kee Tui et al. (2022).

Regional Integrated Assessment (AgMIP RIA) Throughout the RIA research process, scientists work in collaboration with experts and stakeholders, to characterize agricultural systems, set priorities, identify indicators and co-design pathways, adaptation and mitigation strategies, review and validate research results, and identify ways to disseminate the information to users (Antle et al. 2017; Rosenzweig et al. 2021).

Representative Agricultural Pathways (RAPs) Different pathways were co-developed in an iterative process with experts and stakeholders to compare climate change, adaptation and mitigation impacts under plausible future conditions (Valdivia et al. 2021). National RAPs capture agricultural development policies and climate specific policies of the agricultural sector (e.g., vision 2030 for sustainable development). Sub-national RAPs, characterize future socio-economic and biophysical conditions under which climate change might impact future agriculture scenarios, for a particular agricultural system.

Three future pathways were contrasted, BAU (Business as Usual), SD (Sustainable Development) and UD (Unsustainable Development) with different priorities attributed to climate change adaptation and mitigation supporting agricultural development, and different extent of coherence in implementation strategies (Fig. 1; Homann-Kee Tui et al. 2021a, b). BAU portrayed a future where agricultural systems remained stuck at low levels of productivity, weak institutions and poor policy implementation cementing poverty and food insecurity. Under UD, trade-offs with social and climate issues, aggravated poverty and inequality.

In contrast, following SD was associated with sustainable intensification strategies appropriate for the particular farming systems in Nkayi district, crop diversification and integration with livestock, social inclusion mechanisms, and market access improving productivity and profitability, supported by adaptation and mitigation interventions.

Adaptation interventions In correspondence to the socio-economic scenarios, climate change adaptation and mitigation interventions were co-designed with farmers, experts and stakeholders, for mixed crop-livestock agricultural systems in Nkayi District (Table 1).

Under BAU and UD, given limited resources and inconsistent integration and implementation of climate policies, the adaptation strategy was merely a switch to drought tolerant crop varieties and using crop residues to feed livestock (A1).

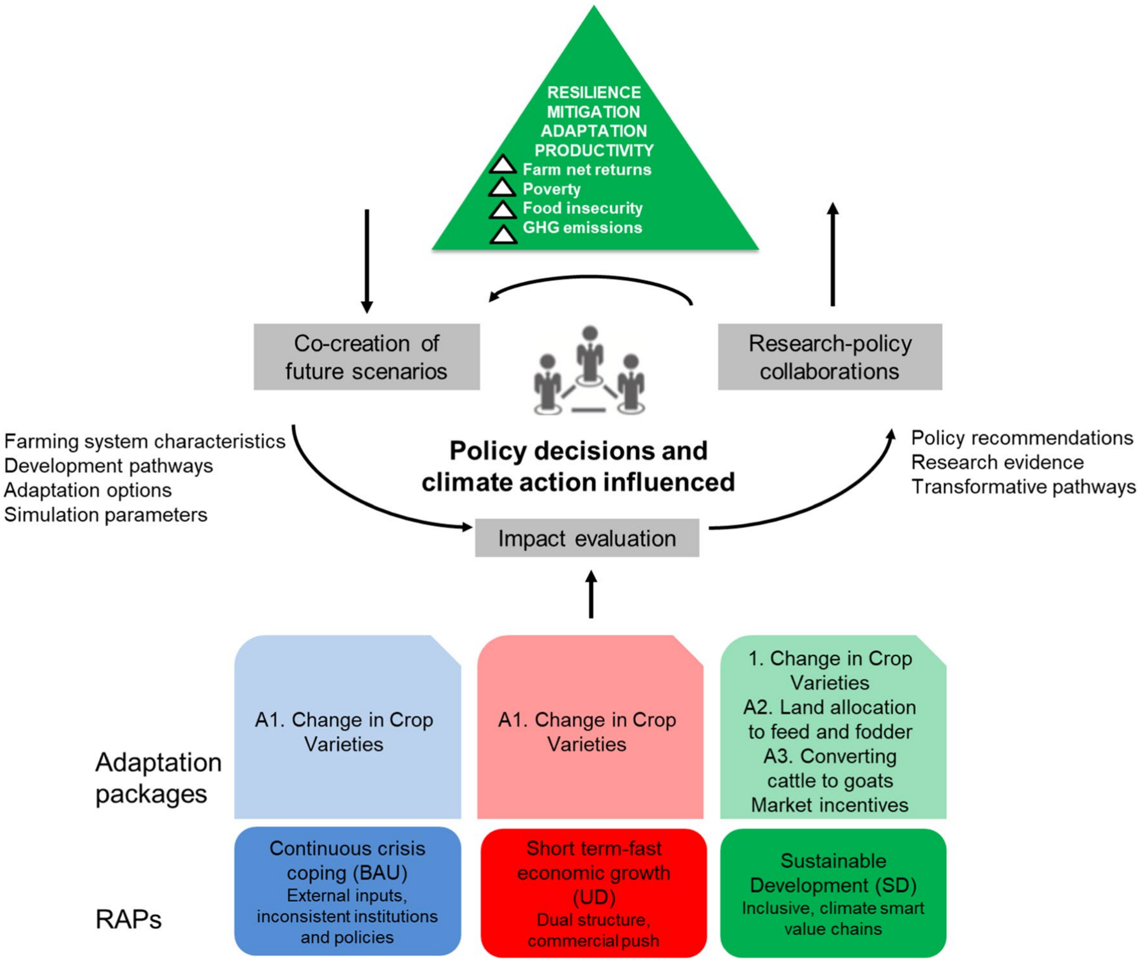


Fig. 1 Research design: Evaluation of co-benefits and trade-offs from climate adaptation and mitigation innovations, using integrated scenario approaches (RAPs, adaptation packages), to influence policy decisions and climate action, for sustainable futures, with equitable, profitable and environmentally proof farms

Table 1 Simulation parameters used in the economic trade-off analysis

	Business-as-usual (BAU)			**Unsustainable development (UD)**			**Sustainable development (SD)**		
Productivity trends (%)									
Maize	2.08			2.08			2.26		
Sorghum	1.51			1.51			1.62		
Groundnuts	1.25			1.25			1.32		
Cattle	1.45			1.45			1.55		
Goats	1.04			1.04			1.13		
Price trends (%)	No CC		With CC	No CC		With CC	No CC		With CC
Maize	1.19		1.26	1.19		1.26	1.25		1.29
Sorghum	1.23		1.34	1.23		1.34	1.19		1.29
Groundnuts	1.3		1.32	1.3		1.32	1.32		1.33
Cattle	1.06		1.08/1.07	1.06		1.08/1.07	1.18/1.11		1.2/1.12
Goats	1.06		1.07	1.06		1.07	1.19		1.2
Stratum	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Cultivated land (ha)	1.8	2.4	3.2	0.9	3.5	4.8	1.8	2.8	3.7
Herd size (TLU)	0	6	13.4	0	8.8	22	3.5	8	19.6
Family size (persons)	6.2	7.3	7.6	6.5	6.2	6.6	6.5	7.6	8.1
Off-farm income (USD)	956.5	1031.1	1097.7	1304.3	1031.1	1097.7	1043.4	1124.8	1197.8
Cropland allocation (%)									
Maize	50	56	55	100	50	35	40	35	35
Sorghum	32	28	30	0	0	15	10	15	15
Groundnut	18	16	15	0	20	20	30	20	20
Mucuna	0	0	0	0	30	30	20	30	30
Inorganic fertilizer (kg N/ha)									
Maize (11.6**)	11.6	11.6	11.6	18	48	48	18*	18*	18*
Sorghum (0**)	0	0	0	0	30	30	18*	18*	18*
Groundnut (0**)	0	0	0	0	0	0	0	0	0
Manure (kg/ha)									
Maize (2366**)	0	2366	2366	0	0	0	1100	2200	2200
Sorghum (0**)	0	0	0	0	0	0	0	0	0
Groundnut (0**)	0	0	0	0	0	0	0	0	0
Cattle offtake (%)	5	5	5	20	20	20	20	20	20
Goat offtake (%)	5	5	5	20	20	20	20	20	20
Improved feeding regime									
Cattle stock feed (kg)	0	0	0	0	1	1	0	0.5	0.5
Cattle residues, maize, mucuna, leucaena (kg)	0	0	0	0	1.5	1.5	0	0.55/0.45/0	0.55/0.45/0
	Adaptation and mitigation options								
A1. Change in crop varieties	Shift to drough tolerant varieties			Shift to drough tolerant varieties			Shift to drough tolerant varieties		
A2. Change in cropland allocation (%)	Crop diversification			Crop diversification			Crop diversification		
Maize	no change			no change			18	18	18
Sorghum	no change			no change			18	18	18
Groundnut	no change			no change			25	25	25
Mucuna	no change			no change			17	17	17
Leucaena	no change			no change			22	22	22

Table 1 (continued)

	Adaptation and mitigation options				
A3. Change in herd composition, offtake	Shift cattle to goats	Shift cattle to goats	Shift cattle to goats		
Herd composition			All HH convert half their cattle to goats		Half HH convert all cattle to goats
Cattle offtake (%)	no change	no change	20	20	20
Goat offtake (%)	no change	no change	35	35	35
Further improved feeding regime (kg/animal/day)					
Cattle stock feed (kg)	no change	no change	0	0.5	0.5
Cattle residues, maize, mucuna, leucaena (kg)	no change	no change	0	0.4/0.3/0.3	0.4/0.3/0.3

HH household, *TLU* tropical livestock unit, *Cattle* = 1.14 TLU, goats and sheep = 0.11 TLU

*Consider residual effects of cereal legume rotation

**N/manure application under current conditions

Whereas under SD, two transformative interventions were simulated as part of the adaptation package, strengthening the comparative advantage of livestock in the mixed agricultural systems:

A2. shifting cropland to fodder production to improve livestock productivity and resource use efficiency at farm level, and

A3. Shifting cattle to goats, supported by increases prices as market incentives for goat products, and given the small size, low metabolic necessities, and effective reproductive potential, goats are easier for farmers to keep and adapt to a drier climate. Local mixed breeds were maintained, assuming that they are well adapted to the harsh environment, and benefits can be achieved through a combination of improved feed and water management, structured markets and support services that motivate increased offtakes.

Under SD and its adaptation package the soil fertility and cattle feed amendments were also more pronounced:

Soil fertility regimes:

(i) Baseline: Inorganic fertilizer and livestock manure on maize

(ii) Future RAP SD: Minimum rates of inorganic fertilizer on maize and sorghum, combined with organic fertilizers, livestock manure and residual effects of legumes in cereal crop rotation.

Cattle feeding regimes, goat feeding remained constant:

(iii) Baseline: Basic crop residues

(iv) Future RAP SD: Improved feeding, in which cattle get concentrates and mucuna besides crop residues

(v) Future RAP SD + adaptation: further improved feeding in which cattle get concentrates, mucuna and leuceana pods besides crop residues

Multi-model set up The multi-model and multi-scale ex ante assessment framework integrated 4 climate scenarios representing low and high emission scenarios with hot and wet conditions (HW and HD, RCP 4.5 IPSL-CM5A-MR and HadGEM2-AO, and HW and HD, RCP 8.5 CanESM2 and RMPI-ESM-LR), considered the most likely climate scenarios for this region, two crop models (ASPIM Holzworth et al. 2014, and DSSAT Hoogenboom et al. 2019a, b, for grain and biomass; here we refer to the APSIM results as validated for low input farming systems, for DSSAT results for comparison see the Additional file 2: Appendix 2), one livestock model (LIVSIM, Descheemaeker et al. 2018, for offtake, manure and milk), as well as the TOA-MD model for economic ex ante impact assessment (Antle and Valdivia 2020; Valdivia et al. 2021). The projected timeline referred to baseline conditions (1980–2010) and mid-century (2040–2070).

Economic impact assessment The multi-dimensional Trade-off Analysis, estimated the impacts of climate change and adaptation innovations on socio-economic and environmental outcomes using a characterization of the various household and farm production (Antle and Valdivia 2021). The distributional impacts were estimated across a population of farms in the Nkayi district. The study used simulation outputs from the AgMIP study in Homann-Kee Tui et al. (2022), informing the current time-period (1980–2010), and the future (2000–2030). A range of economic and food security indicators (The models project the future value and distribution of economic indicators (vulnerability, adoption rates, farm net returns, poverty rates, income-based food security) were projected by capturing the important household, on-farm and off-farm activities and characteristics, including bio-physical conditions like soil fertility, crop and livestock management, crop production, herd sizes and off-takes, cultivated land, herd, and farm size. The population of farms were stratified by type of farms as stratum 1: 'extremely resource poor, small herds' (42%), stratum 2: 'resource poor, medium herds' (36%), and stratum 3: 'non-resource poor, large herds' (12%). This enabled us to differentiate impacts of climate change, adaptation and mitigation on incomes and equity in a heterogeneous farm population.

Assessment of greenhouse gas emissions (GHG) GHG emissions were calculated following the International Panel on Climate Change (IPCC) guidelines using the Tier 1 and Tier 2 methods (IPCC 2006) where data availability allowed. Emissions from enteric fermentation in livestock were calculated following the Tier 2 methods for cattle, and Tier 1 for other livestock types, where animal numbers were multiplied with their standard methane emission factors. For cattle, the energy requirements for maintenance and different activities (pregnancy, lactation, work, growth) of the different animal types were considered together with the feed-dependent methane conversion factor. The values for these parameters were derived from the IPCC report using information on body weight, lactation and growth.

Emissions from animal waste and manure management were calculated with the Tier 1 methods. For methane, this consisted of multiplying the animal numbers of different types with their specific methane emission factor. For N_2O emissions from collected manure, we considered both direct and indirect (after volatilization) N_2O emissions by applying the IPCC emission factors and loss fractions for dry lot and solid storage to stall-fed and other feeding regimes respectively.

Tier 1 methods were also used for the emissions from managed soils, where we considered direct N_2O emissions from N inputs to agricultural soils, including the application of synthetic fertilizer, animal manure and crop residues left as mulch. Direct N_2O emissions from urine and dung deposition during grazing were also considered. Indirect N_2O emissions were included for atmospheric deposition from volatilized N and for leaching and runoff losses.

Under these assumptions goats had higher CH_4 emissions per TLU compared to cattle. Due to lack of more detailed information, we used the tier 1 approach for goats. As such, the amount of goat emissions was fixed per animal, and would not change with improved feeding. Hence the herd composition (cattle/goat ratio) influenced the emissions in the different scenarios. All emissions were converted to CO_2 equivalents and summed up.

Results

Increasing farm productivity and climate impacts

Farms differ in capacity to increase productivity. Currently, in Nkayi District, 78% of the farms are categorized as resource poor (small and medium herd sizes), growing crops under poor soils and with low input use. The impacts of climate change on maize and sorghum productivity were therefore small comparatively. Only the 12% non-resource poor farms (large herd sizes) on soils with better fertility had higher crop yields, hence, the magnitude of losses due to climate change were larger for this group.

In areas with poor soil fertility and low fertilizer application rates, crop productivity was low and climate change impacts were small (Fig. 2). Changes in maize yields ranged from − 27 to 22%, while changes in sorghum yields ranged from − 19 to 13% and groundnuts from − 19 to 43%. Groundnuts tended to benefit from climate change, as higher CO_2 concentrations offset the impact of increased temperature. Cattle production responded more negatively to climate impacts (− 38 to 10% change in offtake, − 30 to 9% in milk production) because of climate change impacts on reduced crop biomass and rangeland production. In addition, climate change was likely to have a negative impact on feed quality due to changes in rangeland species composition. Supplementary feeding reduced the negative impacts of climate change on cattle outputs.

Under future conditions, soils were assumed to be more fertile. Under SD scenarios, experts projected that greater importance would be attributed to soil improvement, through diversification into climate resilient high-yielding dryland legumes (groundnut and forages) and organic soil fertility management, resulting in higher crop yields as compared to BAU and UD, characterized by higher reliance on external inputs and weak institutions. Under these conditions, soils were more productive, which resulted in larger losses due to climate change. Maize productivity increased but lead to higher losses from climate change; diversification into small grains was supported by smaller losses from climate change, groundnut productivity responded less negatively under climate change. The resource-poor benefited relatively more from improved crop production.

As for livestock, supplementary feeding was key to reduce losses to climate change. Feed deficits affected farms with larger cattle herd sizes more negatively. Hot dry conditions reduced feed intake of livestock and therewith livestock productivity, which increase with the

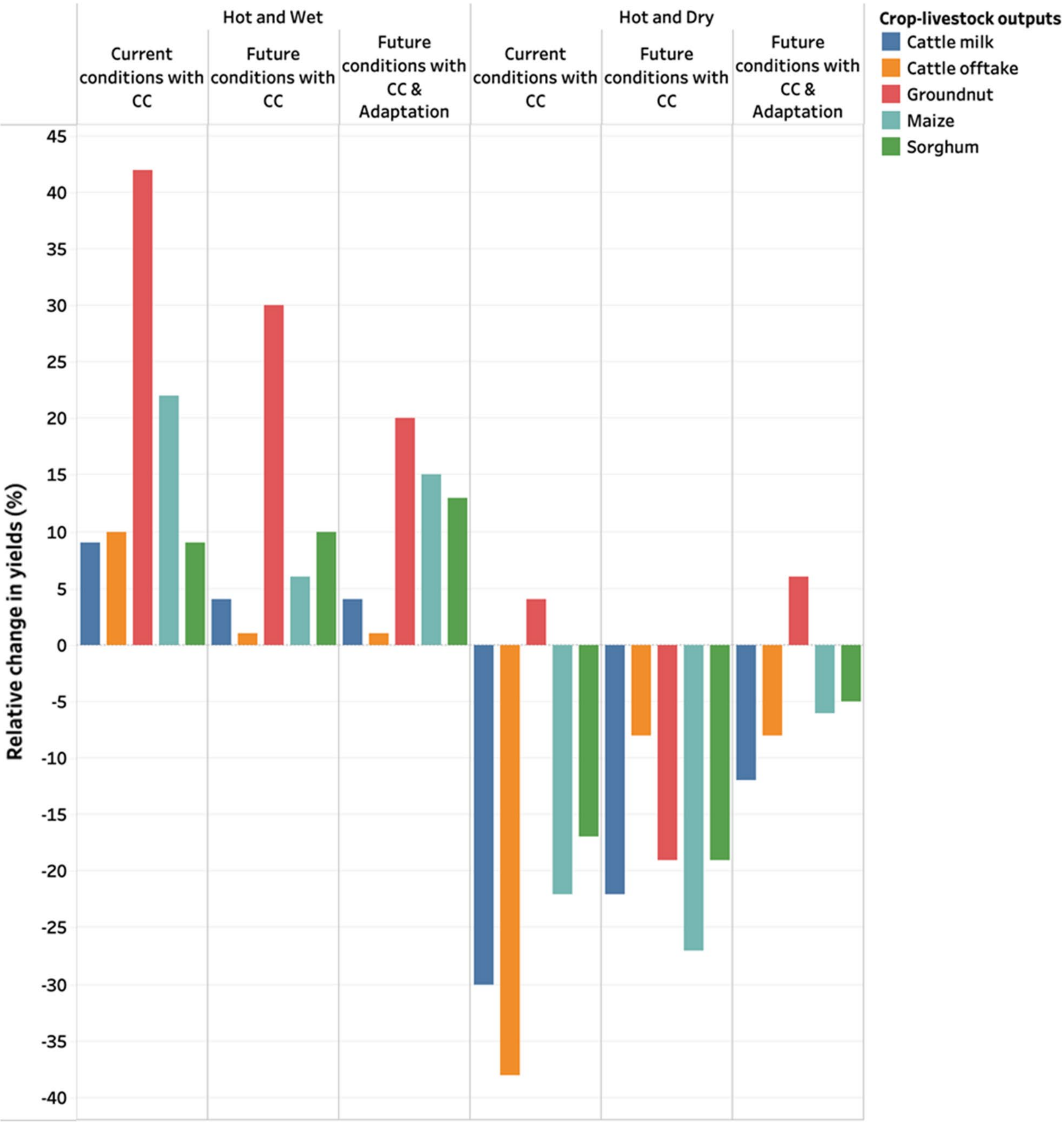


Fig. 2 Impacts of climate change (CC) and adaptation: relative change in yields (%) for crops and livestock outputs, under current and future conditions and hot and wet (HW) and hot and dry (HD) climate scenarios, Nkayi District

probability of more dry years. Under hot wet conditions, the impacts of climate change were small.

SD addressed strategic bottlenecks in livestock production. Firstly, supplementary feed (crop residues, forage, supplements) improved livestock productivity. Secondly, mechanized crop cultivation, renting ploughing services, reduced the burden on cattle and therefore more productive animals available. Thirdly, improved market access with 15% price incentive raised off-take levels. A national restocking strategy in response to the increasing demand for livestock provided every household with at least five cattle. Under BAU and UD resource-poor farmers remained excluded from keeping cattle.

Future agricultural development and impacts of climate change

The choice of development pathways resulted in different economic impacts due to the factors and trends of each pathway. Following a sustainable development pathway (SD) resulted in greater economic impacts and higher emission trade-offs as compared to Business As Usual (BAU) and Unsustainable Development (UD) (Figs. 3, 4).

Under SD farms had double the average annual farm net returns as compared to farms under UD and BAU, as farms with more livestock and diversified crop production generated higher income (2548, 1165, 801 USD, respectively). Under SD food insecurity was more effectively reduced, about 23% of the farms could not afford an appropriate food basket; under UD and BAU more than half the population were food insecure. 35% of the farms were below poverty line under SD, as compared to around 70% under UD and BAU.

Important to note that SD more effectively increased NR for all farm strata. SD increased NR for stratum 1 as a large group of resource poor farms, compared to current conditions, would have started keeping cattle and thereby graduated to improving incomes and livelihoods.

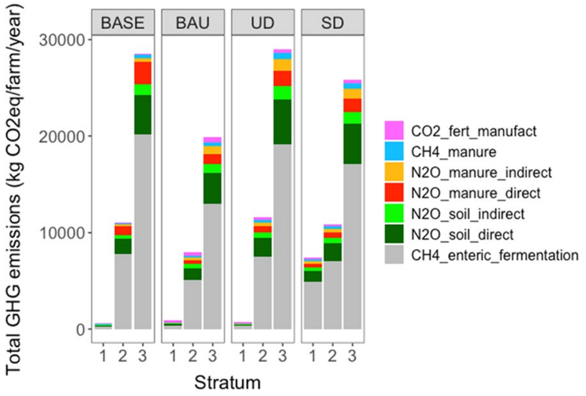


Fig. 4 Impact of agricultural development on emission levels on farm types (stratum 1 farms with no livestock, stratum 2 farms with 1–8 cattle, stratum 3 farms with > 8 cattle) in Nkayi District, Zimbabwe, by Representative Agricultural Pathway (RAP) [Business as Usual (BAU), Sustainable Development (SD) and Unsustainable Development (UD)], using APSIM results as inputs

Whereas under BAU and UD stratum 1 had small changes in NR, hence poverty rates remained high compared to strata 2 and 3. Average annual farm net returns

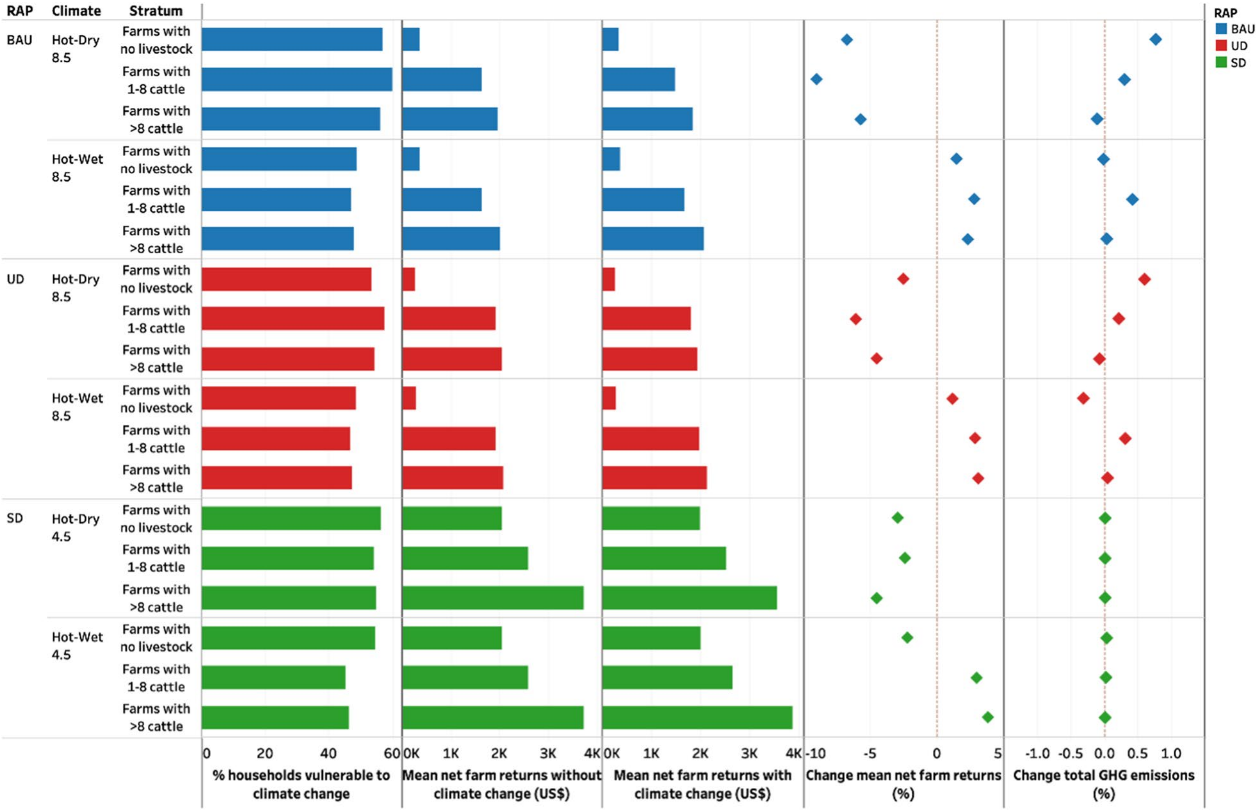


Fig. 3 Economic impacts of future climate change and changes in emission rates on farm types in Nkayi District, Zimbabwe, by Representative Agricultural Pathway (RAP) [Business as Usual (BAU), Sustainable Development (SD) and Unsustainable Development (UD)], using APSIM results as inputs

for resource poor farms were estimated at 2044, 277 and 365 USD for SD, UD and BAU respectively. Among the resource poor, under SD 24% of the farms were food insecure, and 70% under UD and BAU. High levels of poverty remained a cardinal problem for UD and BAU, with small gains for resource poor farms, and 84 and 92% of households living below poverty line as compared to 39% under SD.

Enteric fermentation emission levels for cattle keepers changed from 1350 to 1600, CO_2 equivalent (eq.) per unit TLU under current management reflecting poor livestock productivity and low off-take rates, to half the emissions per TLU under SD with improved supplementary feed and higher offtake. However, at the herd level, total emissions were highest for SD (13,890 CO_2eq. per herd), as compared to UD and BAU (12,900 and 8970 CO_2eq. per herd). This is because under SD, providing resource poor farms with at least 5 cattle increased the overall herd size and hence the total emissions.

Despite higher farm incomes under the development pathways, vulnerability levels were still high when climate change is accounted for. Across all scenarios more than 50% of all households were at risk of losing from climate change. As illustrated in Fig. 3, 55–60% of the farms were vulnerable and would lose from climate change during hot dry years, and about 50% during hot wet years. The relative impacts of climate change on yield and income levels were however small. As expected, the changes in emissions induced by climate change were below 2%, for the various emission indicators. Total GHG emissions under SD were not different across the farm types, while under BAU and UD, GHG emissions varied across farm types, although the changes were small.

Mitigation adaptation co-benefits

To avoid losses from climate change, adaptation interventions were tested. Under SD deliberate efforts were made to strengthen the livestock driven pathway and reduce emissions. Figure 5 illustrates trade-offs and synergies between changes in economic benefits from adaptation as compared to changes in emissions.

A1. Change in crop varieties The impacts of adaptations by merely switching cereal and legume crops to drought tolerant crop varieties had limited impact on crop and livestock productivity. Changes in economic impacts were therefore small; when about half the population

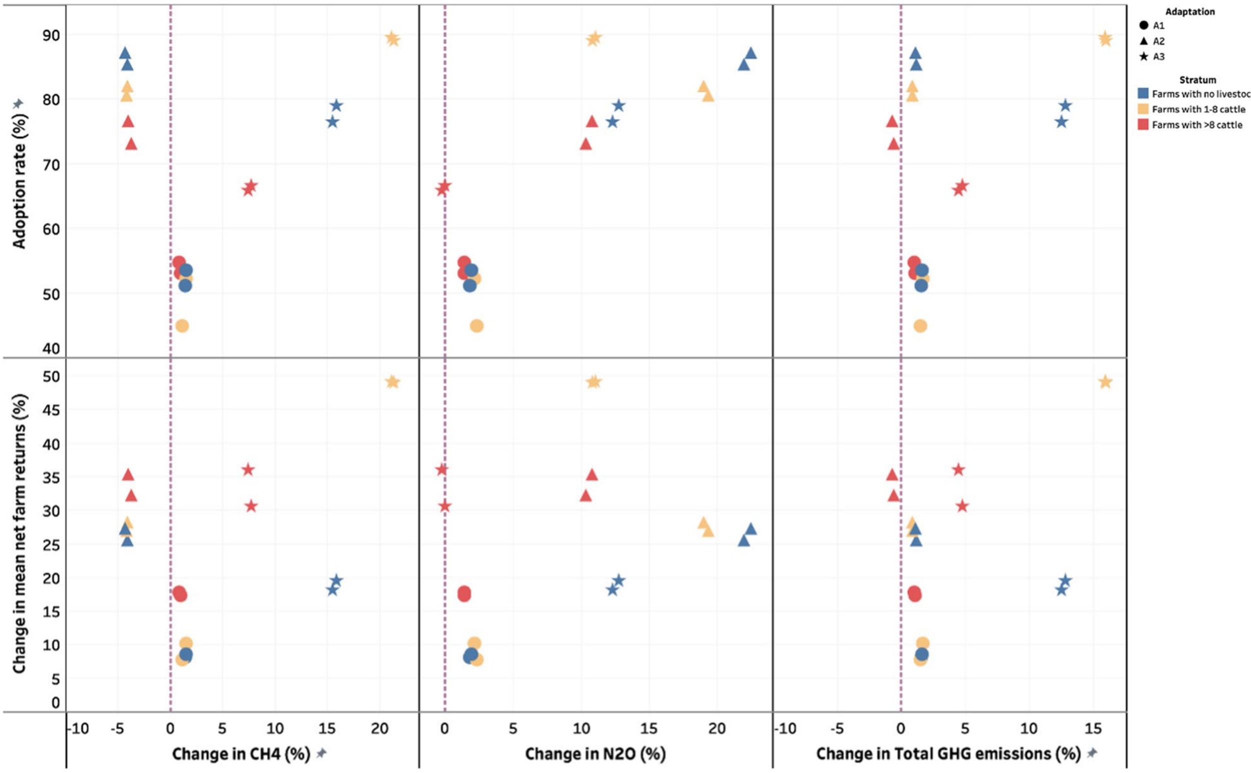


Fig. 5 Potential adoption rates and changes in mean net farm returns of climate change adaptation, and changes in net returns and emission rates by farm type in Nkayi District, Zimbabwe, for Adaptation Strategy A1, A2, and A3, and under the Sustainable Development (SD) pathway, using APSIM results as inputs. Additional file 3: Appendix 3 shows comparative results using APSIM and DSSAT results as inputs and the Business as Usual (BAU) and Unsustainable Development (UD) pathways

adopt these technologies, farm net returns increase by around 20%.

The environmental footprint was also small as reflected in negligent changes in emission rates (Fig. 5).

A2. Land allocations to feed and fodder Improving the quality and quantity of feed supply, by converting land into high-yielding Leucaena, was a way to further increase cattle productivity per TLU and organic soil amendment. More than 80% of the farms adopted this package and farm net returns increased by 27, 29 and 34%, to USD 2514, 3319 and 4920 for farms of stratum 1, 2 and 3 respectively, those with large cattle herds in particular benefited the most. Food insecurity was reduced to 15%, while poverty rates were reduced to 23%.

Along with more substantial increases in incomes, the improved feed base reduced the herds' methane from enteric fermentation emissions by less than 5%, and increased N_2O by 10–20%, and CO_2 emissions by 15–20%.

A3. Converting cattle to goats Next, shifting cattle to goats supported by a market incentive of 15% higher output price and increased offtake rates, this package was attractive to 81% of the farms. It increased farm net returns by 19, 51 and 32%, to USD 2365, 3878 and 5770, for stratum 1, 2 and 3, respectively. This meant that income benefits by switching from cattle to goats were not lost for farms in strata 2 and 3; resource poor farmers would benefit more by not switching cattle to goats. Food insecurity rates were at 15%, poverty rate at 23%, being similar to A2.

Shifting cattle to goats however resulted in trade-offs with environmental consequences. It increased CH_4 enteric fermentation emissions by about 15 to 20% for farms with small and medium herds, and 5% for those with large herds, negating the emission reductions through land allocation to feed and fodder. This can be explained by the fact that goats had higher emissions per TLU compared to the better-fed cattle in the future scenarios. For goats we were following the IPCC Tier 1 approach, multiplying animal numbers with their standard methane emission factor (5 kg CH_4/head/year), resulting in 50 kg CH_4/TLU/year, irrespective of the scenario. For cattle, we were following the IPCC Tier 2 approach, so that enteric fermentation emissions varied with the feeding regime in the scenario. In the current system, enteric fermentation emissions per TLU amounted to 61.86 kg CH_4/year/TLU. With better feeding the emissions dropped to 31.7 kg CH_4/year/TLU in all future systems (BAU, UD and SD), and even further with adaptation to 29.65 kg CH_4/year/TLU. Because of the differences in emissions between livestock types the herd composition (cattle/goat ratio) also influenced the emissions in the different scenarios. N_2O levels increased for those with small and medium herds by around 10%, while those with large herds did not contribute to increasing N_2O. The CO_2 levels were reduced by 15 to 20% across all farm strata.

Figure 5 illustrates the impacts of the various adaptation strategies:

- A1, switch to drought tolerant varieties, resulted in low adoption rates and small increases in mean farm net returns, and small increases in GHG emissions, in comparison to A2 and A3.
- A2, shift to fodder production, showed higher adoption rates, which led to larger increases in mean farm net returns. GHG emissions varied across the type. For instance, for CH_4 was a win–win condition as Ch_4 decreased and net returns increased. Emissions of N_20 increased. The total GHG emissions showed socio-economic and environmental gains for some strata.
- A3, shift from cattle to goats, had much higher adoption rates for stratum 2, and yet lower adoption rates for stratum 1 and stratum 3 than under A2. Farm net returns for stratum 1 and stratum 3 are comparable to A2, and higher for stratum 2. However, trade-offs were higher, as GHG emissions increased.

The strata differed in terms of impacts of adaptation strategies, priority for adaptation:

- Stratum 1: A2 showed highest adoption rate, with highest increases in net returns, and small total GHG increase, but decrease in CH_4. A2 clearly is the priority strategy.
- Stratum2: A2 showed high adoption rate and increased the net returns with small increase in total GHGs (also decrease in CH_4). A3 had higher mean net returns but also higher GHG emissions. Depending on the countries' goals, economic development, or emission mitigation, A2 or A3 would be prioritized.
- Stratum 3: A2 lead to clear win–win outcomes, with high adoption rates, high increase in mean net returns and decrease in GHG emissions, although small. A3, in comparison, had lower adoption rates, change in net returns similar to A2, and GHGs (Ch4 and total GHGs) increased more in A3 than A2.

Discussion

For Zimbabwe to achieve its SDGs, reducing poverty, improving food security and addressing the situation of the extremely poor and vulnerable are of top priority, and the country views climate change as a direct threat to its socio-economic development. The agricultural sector has set climate change adaptation as a national priority, demanding policy direction at the highest level. At the same time, the sector seeks opportunities for climate change mitigation, limiting global temperature raise to below 1.5 °C. The sector has a strong interest to promote and scale co- benefits from climate change adaptation and mitigation in support of its socio-economic goals, and requires that such action is supported by finance, capacity-building, technology development and transfer (Figs. 6, 7).

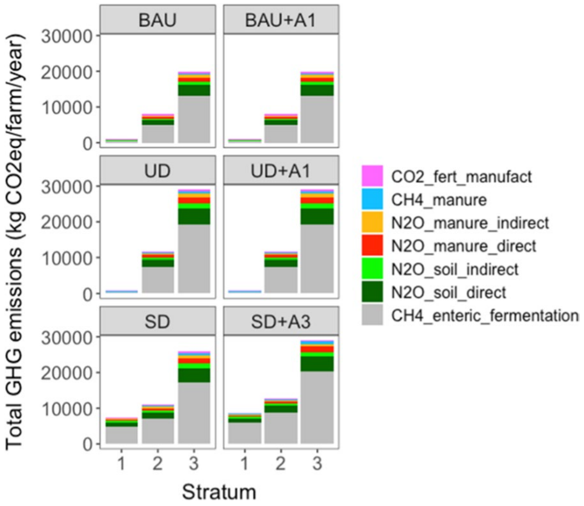


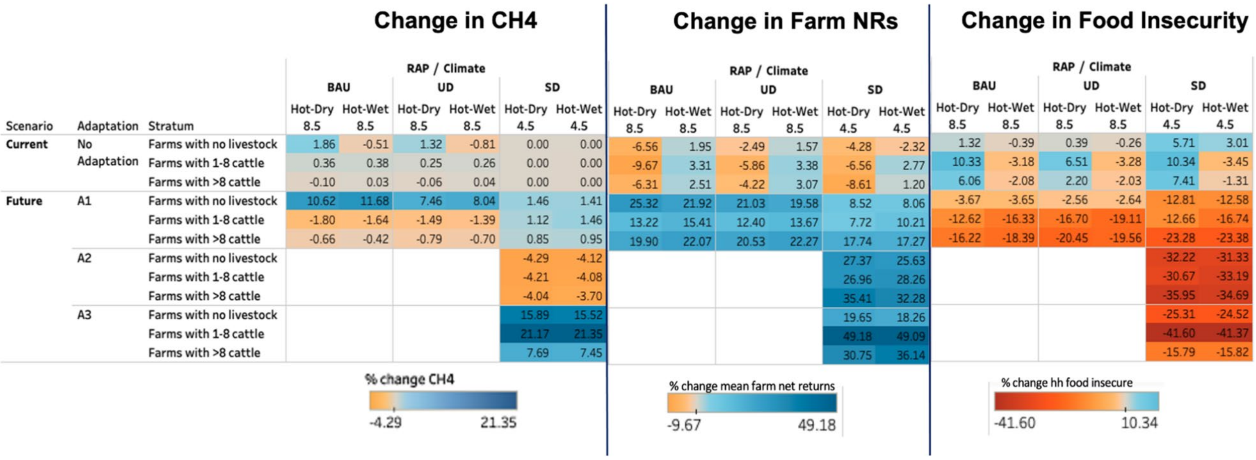
Fig. 6 Impact of future climate change adaptation on absolute emission levels by pathways [Business as Usual (BAU), Unsustainable Development (UD) and Sustainable Development (SD)], and farm types in Nkayi District, Zimbabwe, using APSIM results as inputs. For SD, only the last step in the adaptation (A3) is shown. A1 and A2 take intermediate positions

The results of this study are intended to help better understanding the impacts of climate change, adaptation and mitigation interventions, how they interact and how they can be balanced, with consideration of vulnerable groups, under local contexts and priorities, while supporting sustainability outcomes (income, food security and environment). Research can thereby support climate smart decisions, depending on what the priorities are for a country like Zimbabwe, for its policy makers and local stakeholders, to achieve SDGs and contribute to the NDCs and NAPs. This can bring about greater synergies among agricultural policies, climate action and humanitarian efforts.

Challenges of climate change and co-benefits from climate change mitigation and adaptation

Zimbabwe enters its commitments about reducing GHG emissions at a point, where the food systems already are in crisis. This is in the face of a future with climate change and an increasing demand for food and livestock-based food products (Badiane and Makombe 2022). To harness the potential for creating co-benefits from mitigation and adaptation, there is need for strategies and decisions that help to reduce GHG emissions and address the vulnerabilities, without compromising production and adaptation.

As this study has shown, significant gains can be made from climate smart interventions in Zimbabwe's semi-arid areas, through improved farm productivity and incomes from dryland crops and livestock in combination with decreasing emission intensity and Nitrogen



Change in CH4

			RAP / Climate					
			BAU		UD		SD	
Scenario	Adaptation	Stratum	Hot-Dry 8.5	Hot-Wet 8.5	Hot-Dry 8.5	Hot-Wet 8.5	Hot-Dry 4.5	Hot-Wet 4.5
Current	No Adaptation	Farms with no livestock	1.86	-0.51	1.32	-0.81	0.00	0.00
		Farms with 1-8 cattle	0.36	0.38	0.25	0.26	0.00	0.00
		Farms with >8 cattle	-0.10	0.03	-0.06	0.04	0.00	0.00
Future	A1	Farms with no livestock	10.62	11.68	7.46	8.04	1.46	1.41
		Farms with 1-8 cattle	-1.80	-1.64	-1.49	-1.39	1.12	1.46
		Farms with >8 cattle	-0.66	-0.42	-0.79	-0.70	0.85	0.95
	A2	Farms with no livestock					-4.29	-4.12
		Farms with 1-8 cattle					-4.21	-4.08
		Farms with >8 cattle					-4.04	-3.70
	A3	Farms with no livestock					15.89	15.52
		Farms with 1-8 cattle					21.17	21.35
		Farms with >8 cattle					7.69	7.45

% change CH4
-4.29 21.35

Change in Farm NRs

			RAP / Climate					
			BAU		UD		SD	
Scenario	Adaptation	Stratum	Hot-Dry 8.5	Hot-Wet 8.5	Hot-Dry 8.5	Hot-Wet 8.5	Hot-Dry 4.5	Hot-Wet 4.5
Current	No Adaptation	Farms with no livestock	-6.56	1.95	-2.49	1.57	-4.28	-2.32
		Farms with 1-8 cattle	-9.67	3.31	-5.86	3.38	-6.56	2.77
		Farms with >8 cattle	-6.31	2.51	-4.22	3.07	-8.61	1.20
Future	A1	Farms with no livestock	25.32	21.92	21.03	19.58	8.52	8.06
		Farms with 1-8 cattle	13.22	15.41	12.40	13.67	7.72	10.21
		Farms with >8 cattle	19.90	22.07	20.53	22.27	17.74	17.27
	A2	Farms with no livestock					27.37	25.63
		Farms with 1-8 cattle					26.96	28.26
		Farms with >8 cattle					35.41	32.28
	A3	Farms with no livestock					19.65	18.26
		Farms with 1-8 cattle					49.18	49.09
		Farms with >8 cattle					30.75	36.14

% change mean farm net returns
-9.67 49.18

Change in Food Insecurity

			RAP / Climate					
			BAU		UD		SD	
Scenario	Adaptation	Stratum	Hot-Dry 8.5	Hot-Wet 8.5	Hot-Dry 8.5	Hot-Wet 8.5	Hot-Dry 4.5	Hot-Wet 4.5
Current	No Adaptation	Farms with no livestock	1.32	-0.39	0.39	-0.26	5.71	3.01
		Farms with 1-8 cattle	10.33	-3.18	6.51	-3.28	10.34	-3.45
		Farms with >8 cattle	6.06	-2.08	2.20	-2.03	7.41	-1.31
Future	A1	Farms with no livestock	-3.67	-3.65	-2.56	-2.64	-12.81	-12.58
		Farms with 1-8 cattle	-12.62	-16.33	-16.70	-19.11	-12.66	-16.74
		Farms with >8 cattle	-16.22	-18.39	-20.45	-19.56	-23.28	-23.38
	A2	Farms with no livestock					-32.22	-31.33
		Farms with 1-8 cattle					-30.67	-33.19
		Farms with >8 cattle					-35.95	-34.69
	A3	Farms with no livestock					-25.31	-24.52
		Farms with 1-8 cattle					-41.60	-41.37
		Farms with >8 cattle					-15.79	-15.82

% change hh food insecure
-41.60 10.34

Fig. 7 Average change in CH_4 from enteric fermentation emissions, under future climate change and adaptation by pathways, and farm stratum [Business as Usual (BAU), Unsustainable Development (UD) and Sustainable Development (SD)], and farm strata in Nkayi District, Zimbabwe, using APSIM results as inputs losses (Herrero et al. 2016; Notenbaert et al. 2020). Chang et al. (2020) also showed that improving production efficiency is most critical to mitigation effects and should be prioritized where emission intensities are high.

The emission results of this study tally with other similar studies. The emission levels of 62 kg CH_4/year/head of cattle (base), and 30–32 kg CH_4/year/head of cattle (improved feeding) are comparable with those by Doelman et al. (2018), showing between 25 and 66 kgCH_4/year/head of cattle. The emissions per farm in our study were higher as compared to a study in Rwanda, 1000–4000 kg CO_2 eq./farm/year, due to larger cropland and herd sizes in Zimbabwe (Paul et al. 2018). The total GHG emissions in relation to herd sizes were similar.

Methane (CH_4) as the greatest emitter needs to be addressed by mitigation efforts, through feed technologies. It is mostly feed quality that will impact CH_4 emissions from enteric fermentation. Simulation results showed that emission intensities could be halved per unit animal by diversifying crops into legumes and improving the feeding regimes for livestock, better integration of crops with livestock. For Zimbabwe currently holding a national herd of about 5,478,648 cattle heads (MLAFWRS 2021), this would imply a reduction of 4.1 10^6 ton CO_2eq per year, and this exceeds the requirement to reduce enteric fermentation by 2.3 10^6 ton CO_2eq per year. The role of co-benefits through development of the livestock sub-sector needs to be adequately acknowledged in the LEDS, as well as the likely increases in livestock ownership associated with economic development, urging investment in feed as mitigation strategy.

More robust GHG accounting methods are required, identification and prioritization of mitigation options, as in the case of this study to justify livestock feed as mitigation option. This requires improvement of approaches and models to measure and estimate livestock emissions more accurately. Experiments are needed to get data on emissions for specific contexts, breeds, feeding strategies, improved accounting methods and trainings on inventories, as otherwise GHG calculations are based on assumptions that not always are representative of local conditions.

Due to the lack of adequate GHG accounting methods, using IPCC default factors for enteric fermentation and manure emissions could be inaccurate, especially for goats, where systems specific metrics have not been developed, and systems specific management nuances such as feed improvement cannot be captured. Shumba et al. (2023) also found that GHG emissions from Conservation Agriculture practices were lower than the default IPCC emission values. At the same time, possible reductions of losses in crop and livestock production and post-harvest tend to be underreported. GHG emission reductions could be done more significantly with improved livestock management as presented in the adaptation and mitigation interventions in this study (Shikuku et al. 2017; Zhu et al. 2021). More accurate quantification of impacts and benefits would involve inherent resource flows and how better recycling of nutrients can reduce GHG emissions.

Furthermore, investments in specific innovations, adaptation and mitigation strategies leading to co-benefits are inclined towards sectors or emission sources where quantification and monitoring of the benefits is relatively easy and where the economic and political risks are low, such as conservation agriculture (FAO 2018). Often the focus is on crop production, notably maize as the predominant crop where assessment methods are advanced, whereas interventions and assessment tools for alternative dryland cereals and legumes, livestock and full farm analyses are not adequately developed (Graham et al. 2022). This disadvantages the livestock sub-sector, and small stock species, already increasing in trends, and the resource poor and women depending on, and such as goats.

Identification and prioritization of mitigation and adaptation co-benefits using ex-ante impact analyses

As Zimbabwe enhances its efforts to achieve its SDGs, creating co-benefits that balance mitigation and adaptation priorities is becoming more important. The ex-ante impact analyses presented in this study contributes to the development of robust tools, that help decisions to transition from potential 'lose–lose' to 'win–win' between social, economic and environmental outcomes. As this study showed, without adaptation all farms would lose from climate change, whilst climate change itself and climate scenarios had no impact on GHG emission levels. The outcomes of adaptation differed depending on policy priorities and trade-offs, (1) policies prioritizing incomes and food security and therefore boosting the importance of livestock had trade-offs with increased emissions (2) adaptations with least emissions, uptake of drought tolerant varieties and crop diversification to provide more quality livestock feed had limited impacts on reducing poverty and climatic risk. To guide decisions towards 'win–win' goals, there is need to integrate those priorities, under socio-economically acceptable and environmentally sound pathways.

The combination of (1) development pathways determining the conditions that need to be in place for the socio-economic conditions to improve in future, with (2) adaptation strategies composed of sustainable intensification interventions, and (3) farm types led to different levels of synergies and trade-offs. The simulation results illustrate:

- A1. Technical interventions that merely promote drought tolerant crops, had limited impacts on farm incomes, food security and in reducing climate risks, for all farm types. Reducing the environmental impacts of economic development was also small. As reflected in low adoption levels, this intervention is not a priority for Zimbabwe.
- A2. Promoting feed and fodder technologies had greater economic impacts through more productive livestock and offset the environmental impacts. This adaptation package created win–win outcomes for all strata. For the benefits to materialize, they should be implemented along with complementary interventions in livestock health and development of structured markets, as defined in the SD pathway.
- A3. Policies that prioritize incomes, food security and resilience would therefore boost the importance of livestock, despite trade-offs with increased GHG emissions. If mitigation is not a priority since Zimbabwe is a low emitter, switching from cattle to goats would increase farm net returns for those farm types with medium and large sized herds and thus be a priority, provided that adequate feed, health and market systems are established.

The simulation modelling results can also assist to better understand the behaviour of farming systems that determines the outcomes of climate smart interventions. In the case of mixed crop-livestock systems in semi-arid Zimbabwe, with typically low nitrogen input use and hence low farm productivity, especially among resource-poor farms, impacts of climate change on crop yields increase when farmers commence soil fertility improvements (Falconnier et al. 2020). This study has shown that if soil fertility was improved higher levels of maize yields were achieved, but the risks of losses emanating from climate change effects were also higher. Whereas small grains had smaller losses from climate change and higher productivity associated to the adaptation strategies, supporting diversification to drought tolerant small grain varieties. Groundnut was generally less affected by climate change and provides valuable residues for improving soil health and feed for livestock, while also considered as a 'women's crop that benefits low-income households (Orr, et al. 2016). The risk of losses in cattle productivity increased especially with the likelihood of more dry years.

The results resonated with findings that farmers started intensifying feed management, use of crop residues to improve livestock feed and enhance manure productivity, attributed crop residues more for livestock feed than soil amendment, driven by increasing demand for livestock products, and as alternative feed resources decrease (Valbuena et al. 2015). Improving access to feed and feed management, dual purpose crops, feed and fodder varieties, local livestock feed rations, is also critical for the impacts of health and genetic interventions to pay off, as well as to preempt further degradation of rangelands (Shikuku et al. 2017; Notenbaert et al. 2020). The priority of crop residue biomass used as livestock however constitutes a trade-off with GHG emission reduction through conservation agriculture, which relies on the full implementation of all three principles, minimum tillage combined with intercropping and rotation, and residue retention (Corbeels et al. 2019; O'Dell et al. 2020). Perennial multi-purpose crop and fodder varieties are being promoted as possibility to reduce such trade-offs (Snapp et al. 2019).

Implications for policy-makers

Policy interventions aiming at implementing co-benefits from reduced GHG emissions and adaptations that reduce climate risks will be crucial to support sustainable intensification in the context of climate change. Policy makers and local stakeholders need to decide to what extend they want to reduce GHG emissions from the agricultural sector and formulate mitigation strategies to do so, as compared to a situation where mitigation is not a priority, and farmers livelihoods and poverty reduction and food security outcomes are more important. The approach presented in this study allows us to look at the trade-offs among the multiple outcomes, mitigation, adaptation and development, important for decisions on intervention priorities. The question to policy makers and local stakeholders would be as to what is their desired pathway to achieve SDGs, and what are the implications for NDCs and NAPs leading to climate action?

The study underpins the critical importance of forward-looking research-based evidence to support Zimbabwe's ambitions and aspirations with a better understanding of the impacts of climate change and co-benefits on interventions at farm and community level. Importantly, the study illustrates the need for coherent and plausible agricultural development pathways across sub-national to national levels. The focus was on semi-arid farming systems that are important and vulnerable and require more adequate support through national programs. The study illustrates heterogeneity in farm populations in these areas and that distributional impacts of climate change and adaptation within communities need to wary of the implications for the extreme poor (Stringer et al. 2014; England et al. 2018). Social protection interventions were highlighted to be part of climate smart intervention planning to ensure that women and other vulnerable groups accrue the requisite benefits from adaptation, improved agricultural markets, services and financial tools (Gilligan et al. 2022).

As experts and stakeholders in Zimbabwe also highlighted, forward looking research and improving researcher, experts and stakeholder networks and capacity must be used more effectively to enhance climate smart intervention planning and policy coordination (Homann-Kee Tui et al. 2021a, b; Sixt et al. 2022). Building knowledge and capacity at local level is critical, to understand context specific vulnerabilities to climate change, co-create and validate climate smart interventions that are sensitive to local specific requirements, and ensuring that national policies enable local action and resolutions feeding into national processes, rather than constraining or being an obstacle (Madajewicz et al. 2021). Stakeholder participation, inclusion of women and other vulnerable groups, in early stages and throughout agricultural development and climate policy scenario processes must be placed at the center of adaptation objectives to address and not deepen multi-faceted vulnerabilities (Eriksen et al. 2021; Gilligan et al. 2022). In Zimbabwe the Rural District Council Act and the Traditional Authority act are existing instruments that outline inclusive planning frameworks and provide procedures that should be used to mobilize grassroot level participation, as decisions about uptake and hence sustainability are made by the communities (Nare 2021). This acknowledges that countries and administrative units also differ in their capacity to engage in reducing emissions and increasing incomes in agriculture.

Zimbabwe's climate policy advocates for integrated and participatory climate research instruments, sound data-based simulation modelling and rigorous analyses, to inform vulnerability assessments and adaptation innovations, inter-agency coordination, as these support access to climate finance. This study through the collaborative research approach brings research-based evidence closer to policy decisions, with a climate rationale and evidence for current and future vulnerabilities and impacts (Homann-Kee Tui et al. 2022; Valdivia et al. 2021). Reflecting on co-benefits and trade-offs can help to unpack conflicting drivers, at national and sub-national levels, and identify root causes for limited adaptation innovations and not being implemented. For scalable technical innovations enabling institutional innovations are required (Sartas et al. 2020). They need to facilitate higher returns on systems improvement, for increasing systems productivity and reducing emission intensities (Gerber et al. 2013; Herrero et al. 2016).

Conclusions

Strategies to harness mitigation and adaptation co-benefits are important to guide policy decisions towards a win–win among sustainability outcomes (i.e., income, food security and environment). The AgMIP RIA assessment illustrates the emission challenges for agricultural systems in semi-arid Zimbabwe and explores income, food security and environmental trade-offs, as an attempt to inform policies that enable co-benefits, while promoting food security and poverty alleviation.

Forward looking research as presented in this study needs to be further developed, to adequately inform socially inclusive climate smart policy and intervention planning, include and address the trade-offs between policy priorities, and use feedback from implementation in particular agricultural systems. The evidence can be used to continuously reflect and prioritize investments and capacity to generate new forms of knowledge, technologies and agricultural support services that meet emerging development challenges arising from increased climate variability as well as other drivers. This can be aligned with regular assessments on possible climate-related shifts in the viability of farming systems, and to understand barriers to adaptation to climate change, including human, institutional and financial barriers.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-023-00165-3.

Additional file 1. Zimbabwe's' agro-ecological zones (Manatsa et al., 2020).

Additional file 2. ASPIM and DSSAT model-based results for potential changes in mean net farm returns, poverty rates, food insecurity and emission impacts of climate change adaptation, by pathways [Business as Usual (BAU), Unsustainable Development (UD), Sustainable Development (SD)], climate scenarios (Hot Dry and Hot Wet, for RCP 8.5 and 4.5, and farm strata, in Nkayi District, Zimbabwe.

Additional file 3. Potential adoption rates and changes in mean net farm returns of climate change adaptation, and changes in net returns and emission rates by farm type in Nkayi District, Zimbabwe, for adaptation strategy A1 under Business as Usual (BAU), and Unsustainable Development (UD) pathways, using APSIM results as inputs.

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Author contributions
SH-KT: Leading the design and writing of most of the manuscript, with inputs to economic analyses and stakeholder engagement during the scenario

development. RV: Guided the economic analyses, provided most of the graphics and reviewed the manuscript. KD: Provided the livestock and GHG simulation modelling, provided graphs, and reviewed the manuscript. GS: Provided the economic simulation modelling, inputs to scenario development and policy analyses and relevance in the national context. ENM: Inputs to climate scenario and policy analyses and relevance in the national context. FM: Inputs on national priorities and reviewed parts of the manuscript

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Availability of data and materials
The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Declarations

Ethics approval and consent to participate
The manuscript did not present studies on humans.

Consent for publication
All authors consented to the publication of this manuscript.

Competing interests
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential competing interests.

Author details
[1]International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Chitedze Research Station, Lilongwe, Malawi. [2]Department of Applied Economics, Oregon State University, Corvallis, USA. [3]Plant Production Systems, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands. [4]Department of Livestock Research and Pastures, Matopos Research Institute, PB K 5137, Bulawayo, Zimbabwe. [5]Climate Change Management Department, Ministry of Environment, Climate, Tourism and Hospitality Industry, 11th Floor, Kaguvi Building, Harare, Zimbabwe. [6]Department of Soil Science and Environment, University of Zimbabwe, Mt Pleasant, P.O. Box MP167, Harare, Zimbabwe.

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References

AGRA. Africa Agriculture Status Report. Accelerating African Food Systems Transformation Issue 10. Nairobi, Kenya: Alliance for a Green Revolution in Africa (AGRA).2022. https://agra.org/resource-library/africa-agriculture-status-report/.

Antle JM, Valdivia, RO. TOA-MD: Trade-off analysis model for multi-dimensional impact assessment of agricultural systems. 2020. https://agsci.oregonstate.edu/tradeoff-analysis-project/webform/toa-md-software. Accessed 23 Feb 2022.

Antle JM, Valdivia RO. Trade-off analysis of agri-food systems for sustainable research and development. Q Open. 2021;1(1):qoaa005.

Antle J, Homann-Kee Tui S, Descheemaeker K, Masikate M, Valdivia, RO. Using AgMIP Regional Integrated Assessment Methods to Evaluate Climate Impact, Adaptation, Vulnerability and Resilience in Agricultural Systems. In: Zilberman D, Lipper L, McCarthy N, Asfaw S, Branca G (eds) Climate Smart Agriculture - Building Resilience to Climate Change. Natural Resource Management and Policy 52. Springer, Rome. 2017. https://doi.org/10.1007/978-3-319-61194-5_14.

Badiane O, Makombe T. Beyond a Middle-Income Africa: Transforming African Economies for Sustained Growth with Rising Employment and Incomes. ReSAKSS Annual Trends and Outlook Report 2014. 2015. International Food Policy Research Institute (IFPRI). 2022. https://doi.org/10.2499/9780896298927.

Bezner Kerr R, Hasegawa T, Lasco R, et al. Food, Fibre, and Other Ecosystem Products. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Pörtner HO Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem B, Rama B (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. 2022. https://doi.org/10.1017/9781009325844.007.

Chang J, Peng S, Yin Y, Ciais P, Havlik P, Herrero M. The key role of production efficiency changes in livestock methane emission mitigation. AGU Adv. 2020. https://doi.org/10.1029/2021AV000391.

Corbeels M, Cardinael R, Naudin K, Guibert H, Torquebiau E. The4per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. Soil Tillage Res. 2019;188:16–26.

Crumpler K, Abi Khalil R, Tanganelli E, Rai N, Roffredi L, Meybeck A, Umulisa V, Wolf J, Bernoux M. 2021 (Interim) Global update report—Agriculture, Forestry and Fisheries in the Nationally Determined Contributions. Environment and Natural Resources Management Working Paper No. 91. Rome, FAO. 2021. https://doi.org/10.4060/cb7442en.

Descheemaeker K, Zijlstra M, Masikati P, Crespo O, Homann-Kee TS. Effects of climate change and adaptation on the livestock component of mixed farming systems: a modelling study from semi-arid Zimbabwe. Agric Syst. 2018;159:282–95. https://doi.org/10.1016/j.agsy.2017.05.004.

Doelman JD, Stehfest E, Tabeau A, et al. Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land-based climate change mitigation. Global Environ Change. 2018. https://doi.org/10.1016/j.gloenvcha.2017.11.014.

England MI, Dougill AJ, Stringer LC, Vincent KE, Pardoe J, Kalaba FK, Mkwambisi DD, Namaganda EA, Afios S. Climate change adaptation and cross-sectoral policy coherence in southern Africa. Regional Environ Change. 2018. https://doi.org/10.1007/s10113-018-1283-0.

Eriksen SE, Schipper LF, Scoville-Simonds M, Vincent K, Adam HN, Brooks N, Harding B. Adaptation interventions and their effect on vulnerability in developing countries: help, hindrance or irrelevance? World Development Review. 2021;141:105383. https://doi.org/10.1016/j.worlddev.2020.105383.

Falconnier G, Corbeels M, Boote K, et al. Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa. Global Change Biol. 2020. https://doi.org/10.1111/gcb.15261.

FAO. The future of food and agriculture, alternative pathways to 2050. 2018. http://www.fao.org/3/I8429EN/i8429en.pdf. Accessed 23 Nov 2022.

FAO. Five practical actions towards low-carbon livestock. Rome. 2019. https://www.fao.org/3/ca7089en/ca7089en.pdf.

Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, et al. Tackling climate change through livestock—a global assessment of emission and mitigation opportunities. Rome: FAO, Rome. 2013. http://www.fao.org/3/a-i3437e.pdf.

Gilligan DO, Devereux S, Tenzing J. Social protection: Designing adaptive systems to build resilience to climate change. In 2022 Global Food Policy Report: Climate Change and Food Systems. Chapter 6. Washington, DC: International Food Policy Research Institute (IFPRI). 2022. https://doi.org/10.2499/9780896294257_06

GOZ (Government of Zimbabwe). Zimbabwe Revised Nationally Determined Contribution. 2021. Harare.

GOZ (Government of Zimbabwe). Zimbabwe Long-term Low Greenhouse Gas Emission Development Strategy (2020–2050) 2022. Harare.

Graham MW, Butterbach-Bahl K, du Doit CJL, et al. Research progress on greenhouse gas emissions from Livestock in Sub-Saharan Africa falls short of national inventory ambitions. Front Soil Sci. 2022;2:927452. https://doi.org/10.3389/fsoil.2022.927452.

Hatfield JL, Dold C. Climate Change Impacts on Corn Phenology and Productivity. In: Eds: Armanullah and Fahad, S. Corn. 2018. https://doi.org/10.5772/intechopen.76933.

Herrero M, Wirsenius S, Henderson B, Rigolot C, Thornton P, Havlik P, De Boer I, Gerber PJ. Livestock and the environment: what have we learned in the past decade? Annu Rev Environ Resour. 2015;40:177–202. https://doi.org/10.1146/annurev-environ-031113-093503.

Herrero M, Mayberry D, Van de Steeg J. et al. Understanding livestock yield gaps for poverty alleviation, food security and the environment. 2016. LiveGaps Final Report. https://cgspace.cgiar.org/handle/10568/93009.

Holzworth DP, Huth NI, de Voil PG, et al. APSIM—evolution towards a new generation of agricultural systems simulation. Environ Model Softw. 2014;62:327–50.

Homann-Kee Tui S, Masikati P, Descheemaeker K, Sisito G, Francis B, Senda T, Crespo O, Moyo EN, Valdivia R. Transforming Smallholder Crop–Livestock Systems in the Face of Climate Change: Stakeholder-Driven Multi-Model Research in Semi-Arid Zimbabwe. In: Handbook of Climate Change and Agroecosystems: Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research (In 2 Parts). Vol. 5, 217–276. 2021a. World Scientific Publishing Company. World Scientific Publishing. [Rosenzweig, C, Mutter CZ, Mencos Contreras E (eds.)].

Homann-Kee Tui S, Sisito G, Moyo EN, Dube T, Valdivia R, Madajevicz, M. Climate resilient agricultural systems in Zimbabwe: enhancing science—policy collaboration. Policy Brief 38, ICRISAT, Hyderabad. 2021b. http://oar.icrisat.org/11934/.

Homann-Kee Tui S, Descheemaeker K, Masikati P, Sisito G, Valdivia R, Crespo O, Claessens L. Climate change impacts and adaptation for dryland farming systems in Zimbabwe: a stakeholder-driven integrated multi-model assessment. Clim Change. 2022. https://doi.org/10.1007/s10584-021-03151-8.

Hoogenboom G, Porter CH, Boote KJ, Shelia V, Wilkens PW, Singh U, White JW et al. The DSSAT crop modeling ecosystem. In: Advances in crop modelling for a sustainable agriculture. Burleigh Dodds Science Publishing, Cambridge. 2019a. p. 173–216

Hoogenboom G, Porter CH, Boote KJ, Shelia V, Wilkens PW, Singh U, White JW et al. 'The DSSAT crop modeling ecosystem', Advances in crop modelling for a sustainable agriculture. 2019b. 173–216. Burleigh Dodds Science Publishing Cambridge, UK.

Huyer S, Partey S. Weathering the storm or storming the norms? Moving gender equality forward in climate-resilient agriculture. Clim Change. 2020. https://doi.org/10.1007/s10584-019-02612-5.

IEP (Institute for Economics & Peace). Ecological Threat Report 2021: Understanding Ecological Threats, Resilience and Peace, Sydney. 2021. http://visionofhumanity.org/resources.

IPCC (Intergovermental Panel on Climate Change). Guidelines for national greenhouse gas inventories. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (Eds.). 2006. Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan.

Lipper L, Thornton P, Campbell BM, Baedeker T, Braimoh A, et al. Climate smart agriculture for food security. Nat Climate Change. 2014. https://doi.org/10.1038/nclimate2437.

Liu S, Proudman J, Mitloehner FM. Rethinking methane from animal agriculture. CABI Agric Biosci. 2021;2:22. https://doi.org/10.1186/s43170-021-00041-y.

Madajewicz M, Hathie I, Homann-Kee Tui S. et al. Supporting national climate change planning for agriculture in Ghana, Senegal and Zimbabwe: A report from baseline stakeholder interviews and surveys. A Mid-Project Technical Report of the CLARE Program for the International Development Research Center (IDRC). 2021. Canada.

Manatsa D, Mushore TD, Gwitira I, Wuta M, Chemura A, Shekede MD, Mugandani R, Sakala LC, Ali LH, Masukwedza GI, Mupuro JM, Muzira NM. Revision Of Zimbabwe's Agro-Ecological Zones. 2020. Harare.

MECTHI (Ministry of Environment, Climate, Tourism and Hospitality Industry). Fourth National Communication to the United Nations Framework Convention on Climate Change. 2022. Harare.

MLAFWRS (Ministry of Lands, Agriculture, Fisheries, Water and Rural resettlement). First round crop and livestock assessment report 2020/2021 season. 2021. Harare. https://fscluster.org/zimbabwe/document/first-round-crop-and-livestock-1.

Moyo EN, Mugabe FT, Ndebele-Murisa MR, Makarau A. CMIP5 GCM Selection for future climate simulations over Zvishavane, Zimbabwe. In: Petrik D, Ashburner L (Eds). Conference Proceedings of Adaptation Futures 2018. Adaptation Futures 2018. University of Cape Town, Cape Town. 2018. https://openbooks.uct.ac.za/uct/catalog/view/20/27/935.

Moyo EN. Analysis of climate dynamics, climate model selection and impacts on maize production for the Gutu, Chirumhanzu and Zvishavane districts in Zimbabwe. PhD Thesis. 2020. CUT Library, Chinhoyi.

Nare L. Bottom—up approach to community development in action: a practical demonstration by LIPS Zimbabwe. Project report. Unpublished. 2021. ILRI. Harare.

Ndlovu C, Mayimele R, Wutete O, Ndudzo A. Breeding of goats: an indigenous approach to enhancing opportunities for smallholder farmers in Inyathi, Zimbabwe. Int J Livestock Prod. 2020;11(3):91–101.

Notenbaert A, Groot CJ, Herrero M, Birnholz C, Paul BK, Pfeifer C. Towards environmentally sound intensification pathways for dairy development in the Tanga region of Tanzania. Reg Environ Change. 2020;20:138. https://doi.org/10.1007/s10113-020-01723-5.

O'Dell D, Eash NS, Hicks BB, Oetting JN, Sauer TJ, Lambert DM, Thierfelder C, Muoni T, Logan J, Zahn JA, Goddard JJ. Conservation agriculture as a climate change mitigation strategy in Zimbabwe. Journal of Agricultural Sustainability. 2020;18(3):250–65. https://doi.org/10.1080/14735903.2020.1750254.

Orr A, Tsusaka T, Homann Kee-Tui S, Msere H. What do we mean by 'women's crops'? Commercialisation, gender, and the power to name. J Int Dev. 2016. https://doi.org/10.1002/jid.3224.

Paul BK, Frelat R, Birnholz C, Ebong C, Gahigi A, Groot H, et al. Agricultural intensification scenarios, household food availability and greenhouse gas emissions in Rwanda: ex-ante impacts and trade-offs. Agric Syst. 2018. https://doi.org/10.1016/j.agsy.2017.02.007.

Reisinger A, Clark H, Cowie AL, Emmet-Booth J, Gonzalez Fischer C, Herrero M, Howden M, Leahy S. How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? Phil Trans R Soc. 2021;379:20200452. https://doi.org/10.1098/rsta.2020.0452.

Rojas-Downing MM, Pouyan Nejadhashemi A, Harrigan T, Woznicki SA. Climate change and livestock: impacts, adaptation, and mitigation. Clim Risk Manag. 2017. https://doi.org/10.1016/j.crm.2017.02.001.

Rosenzweig C, Mutter CZ, Mencos Contreras E (Eds.) Handbook of Climate Change and Agroecosystems Vol. 5—Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research, in 2 Parts. Series on Climate Change Impacts, Adaptation, and Mitigation. World Scientific. ISSN (print) 2021. p. 2517–7451.

Sartas M, Schut M, Proietti C, Thiele G, Leeuwis C. Scaling readiness: science and practice of an approach to enhance impact of research for development. Agric Syst. 2020. https://doi.org/10.1016/j.agsy.2020.102874.

Shikuku KM, Valdivia RO, Paul BK, Mwongera C, Winowiecki L, Läderach P, Herrero M, Silvestri S. Prioritizing climate-smart livestock technologies in rural Tanzania: a minimum data approach. Agric Syst. 2017;151:204–16. https://doi.org/10.1016/j.agsy.2016.06.004.

Shumba A, Chikowo R, Corbeels M, Six J, Thierfelder C, Cardinael R. Long-term tillage, residue management and crop rotation impacts on N_2O and CH_4 emissions from two contrasting soils in sub-humid Zimbabwe. Agric Ecosyst Environ. 2023. https://doi.org/10.1016/j.agee.2022.108207.

Sixt GN, Hauser M, Blackstone NT, Engler A, Hatfield J, Hendriks SL. A new convergent science framework for food system sustainability in an uncertain climate. Food Energy Security. 2022. https://doi.org/10.1002/fes3.423.

Smith A, Snapp SS, Chikowo R, Thorne P, Bekunda M, Glover J. Measuring sustainable intensification in smallholder agroecosystems: a review. Glob Food Secur. 2017;12:127–38. https://doi.org/10.1016/j.gfs.2016.11.002.

Snapp S, Rogé P, Okori P, Chikowo R, Peter B, Messina J. Perennial grains for Africa: possibility or pipedream? Exp Agric. 2019;55:251–72. https://doi.org/10.1017/S0014479718000066.

Stringer LC, Dougill AJ, Dyer JC, Vincent K, Fritzsche F, Leventon J, et al. Advancing climate compatible development: lessons from southern Africa. Reg Environ Change. 2014. https://doi.org/10.1007/s10113-013-0533-4.

Suckall N, Stringer LC, Tompkins EL. Presenting triple-wins? Assessing projects that deliver adaptation, mitigation and development co-benefits in rural sub-Saharan Africa. Ambio. 2015;44:34–41. https://doi.org/10.1007/s13280-014-0520-0.

Thornton PK, Van De Steeg J, Notenbaert AM, Herrero M. The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. Agric Syst. 2009;101:113–27. https://doi.org/10.1016/j.agsy.2009.05.002.

Valbuena D, Homann-Kee Tui S, Erenstein O, Teufel N, Duncan AJ, Abdoulaye I. Identifying determinants, pressures and trade-offs of crop residue use in mixed smallholder farms in Sub-Saharan Africa and South Asia. Agric Syst. 2015;134:107–18. https://doi.org/10.1016/j.agsy.2014.05.013.

Valdivia R, Homann-Kee Tui S, Antle J, Subash N, Singh H, Nedumaram S, Representative Agricultural Pathways: A Multi-Scale Foresight Process to Support Transformation and Resilience of Farming Systems. In: Handbook of Climate Change and Agroecosystems: Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research (In 2 Parts) (Vol. 5). World Scientific Publishing. 2021. [Rosenzweig, C., C.Z. Mutter and E. Mencos Contreras (eds.)].

Van Rooyen A, Homann-Kee Tui S. Promoting goat markets and technology development in semi-arid Zimbabwe for food security and income growth. Short Notes Trop Subtropical Agroecosyst. 2009;11(1):1–5.

Von Braun J, Afsana K, Fresco LO, Hassan M. Science for Transformation of Food Systems: Opportunities for the UN Food Systems Summit. Scientific Group for the United Nations Food Systems Summit 2021. 2021. https://sc-fss2021.org/.

Von Grebmer K, Bernstein J, Wiemers M, Reiner L, Bachmeier M, et al. Global Hunger Index 2022, Food Systems Transformation and Local Governance. Welthungerhilfe and Concern Worldwide, Dublin and Bonn. 2022. https://www.concern.net/knowledge-hub/2022-global-hunger-index.

World Bank. Climate Risk Profile: Zimbabwe. The World Bank Group. Washington. 2021. https://climateknowledgeportal.worldbank.org/sites/default/files/2021-05/14956.

Zhu Y, Merbold L, Leitner S, Wolf B, Pelster D, Goopy J, Butterbach-Bahl K. Interactive effects of dung deposited onto urine patches on greenhouse gas fluxes from tropical pastures in Kenya. Sci Total Environ. 2021. https://doi.org/10.1016/j.scitotenv.2020.143184.

ZIMSTAT. Zimbabwe poverty report 2017. 2019. Zimbabwe National Statistics Agency. Harare.

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