LETTER

Tackling climate risk to sustainably intensify smallholder maize farming systems in southern Africa

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Abstract

Sustainable intensification (SI) of low input farming systems is promoted as a strategy to improve smallholder farmer food security in southern Africa. Using the Limpopo province South Africa as a case study (four villages across a climate gradient), we combined survey data (140 households) and quantitative agronomic observations to understand climate-induced limitations for SI of maize-based smallholder systems. Insights were used to benchmark the agroecosystem model Agricultural Production System sIMulator, which was setup to ex ante evaluate technology packages (TPs) over 21-seasons (1998–2019): TP0 status quo (no input, broadcast sowing), TP1 fertiliser (micro dosing), TP2 planting density (recommended), TP3 weeding (all removed), TP4 irrigation, TP5 planting date (early, recommended), and TP6 all combined (TPs 1–5). An additional TP7 (forecasting) investigated varying planting density and fertiliser in line with weather forecasts. Input intensity levels were low and villages expressed similar challenges to climate risk adaptation, with strategies mostly limited to adjusted planting dates and densities, with less than 2% of farmers having access to water for irrigation. Simulations showed that combining all management interventions would be expected to lead to the highest mean maize grain yields (3200 kg ha$^{-1}$) across villages) and the lowest harvest failure risk compared to individual interventions. Likewise, simulations suggested that irrigation alone would not result in yield gains and simple agronomic adjustments in line with weather forecasts indicated that farmers could expect to turn rainfall variability into an opportunity worth taking advantage of. Our study emphasises the need for a cropping systems approach that addresses multiple crop stresses simultaneously.

1. Introduction

Food security remains a major challenge in Africa, as food production is not on par with population growth. These uncomplimentary trends are added to for southern Africa through devastating drought events (Braimoh 2020) and about 60% of the population live in rural areas and rely on rainfed agriculture for income (Nhamo et al 2018). Such farming systems are commonly low yielding with assessed yield gaps of up to 80% at a sub-regional level (Mueller et al 2012, Kassie et al 2014). Farmers in southern Africa...
need to be better able to cope with the challenges and make use of the opportunities of climate variability. If not addressed, the challenge of adapting to greater variability may prove impossible for many (Cooper et al. 2008).

The improvement of agricultural production is often referred to as sustainable intensification (SI), i.e. increasing productivity per hectare land with maximum resource use efficiency (Cassmann and Grassini 2020). The topic is multifaceted but might provide some ways to tackle complex farming challenges (Foley et al. 2011). Research has shown that increased resource inputs in line with good agricultural practices can reduce yield gaps, although, due to many factors, experimental SI gains are not always transferred to the farm (Andersson et al. 2013, Magombeys et al. 2018, Vanlauwe and Dobermann 2020). A key reason typically given is that climate risk leads to farmers being risk averse, reducing input to avoid huge losses in dry years that can lead to large yield gaps in favourable years (Hoffmann et al. 2018a). The low-income nature of smallholder systems means many cannot afford to waste fertiliser (Rurinda et al. 2020) and rates lower than the recommended (around 50 kg ha$^{-1}$) can provide better economic rates of return (Dimes 2005, Twomlow et al. 2006). Data from a 22 000-household study across six countries in sub-Saharan Africa (SSA) found agricultural inputs are rarely combined (Sheahan and Barrett 2017), highlighting that smallholder farmers often miss out on opportunities for complementarity input investments.

Total water-driven crop failures in some regions of southern Africa do occur, particularly in El Niño years (McNally et al. 2019). As a result, some propose that intensification in southern Africa may only be possible through widespread irrigation (Cassmann and Grassini 2013). Others argue that irrigation-based solutions face too many adoption barriers related to investment and maintenance, suggesting rainwater-based approaches to be more appropriate (Rockström et al. 2009, 2010). However, the design of any intervention measure should not bypass the complex stresses and risks smallholders face in real-world farming (Bjornlund et al. 2020), especially in the semi-arid tropics (Monteith and Virmani 1991). In general, there is a lack of available data to collectively describe stresses and agricultural risks in a manner that allows for standard agronomic rule development. Estimating the potential of different interventions is therefore challenging, especially when working within a single discipline. Integrated approaches can be insightful but must include stakeholder participation to avoid application failure (Magombeys and Taigbenu 2011).

On-farm observations, biophysical sampling and in-depth interviews and surveys are research methods that can complement one another. For this study, on-farm observations offered both farmer and researcher the opportunity to delve into the specifics of the crop management system. Researchers who have spent time with farmers are unlikely to deny the embodied knowledge gained from such experiences. It is this joint experience that facilitates the combination and use of multiple information sources for collaborative output. Qualitative data can complement quantitative data if translated and used appropriately providing framing for scenario analyses. Although on-farm experimentation can test scenario effects, these are time and labour intensive. Crop models can offer insights into cropping system interactions, but often lack the incorporation of farm management stresses such as pests and diseases (Monteith and Virmani 1991, Röller et al. 2018), which necessitates a deeper understanding of specific farming challenges. In a meta-analysis on agricultural water management for smallholders in the Limpopo River Basin, Magombeys et al. (2018) highlight the importance of context-specific guidance, advocating for advice on seasonal rainfall forecasts linked to inputs and cultural farming practices. This is in line with Fallon et al. (2019) who confirm that farmers in Limpopo were more interested in weather forecasts after the 2015–16 El Niño season. Farmers showed a lack of awareness and understanding of how useful forecasts could be. While insightful and innovative assessments have been made on irrigation potential for the region (e.g. Magombeys and Taigbenu 2011, Moyo et al. 2020, Parry et al. 2020), a comparison to management adaptation based on forecasts has not been made. A context-specific quantification that illustrates the pros and cons of seasonal forecasts combined with good agronomic practice is therefore needed. While multidisciplinary approaches have been implemented in the study region, our combination of data sources is unique.

With the strengths and weaknesses of each information source in mind, we combined surveys, on-farm observations and in-depth interviews, and modelling to answer the following questions for smallholder maize-based farming systems in the Limpopo province, South Africa:

(a) What are the current adaptation challenges for smallholders in improving the productivity of maize systems?
(b) What are existing adaptation responses to climate variability and drought events for maize cultivation systems?
(c) What is needed to increase maize productivity and reduce the risk of poor and failed harvests through improved water use via seasonal forecasts or irrigation?
2. Materials and methods

2.1. Case study region: climatic conditions and cropping system

The study took place in the Limpopo province, South Africa, a region characterised by the highest share of smallholder farms and level of food insecurity throughout the country (Sikora et al. 2020, Rötter et al. 2021). Common smallholder production is dominated by maize (Zea mays L.), supplemented with legumes such as peanut (Arachis hypogaea), Bambara nut (Vigna subterranea), cowpea (Vigna unguiculata), and some horticultural crops on plots of around 1 ha. Broadcasting seeds by hand is the most common sowing method.

Climate conditions differ spatially and range from a warm desert climate (BWh according to Köppen classification) in the West, to a warm semiarid (BSH) to humid subtropical climate (Cwa) in the East (Engelbrecht and Engelbrecht 2016). The rainy season occurs during the summer and autumn (November to May) and is the main maize cropping season; the winter period (June to August) is characterised by extended dry spells. In addition to the strong spatial variability, a strong difference between seasons exists in the region, at times caused by El Niño–Southern Oscillation (Moeletsi et al. 2011, Reason and Smart 2015).

We selected four villages that represent a climate gradient for arable farming (figures 1 and S1: Gabaza, Mafarana, Ndengeza, and Selwane). Although Gabaza and Mafarana are neighbouring villages and have the same climate we treat them as different due to soil variability. All villages are part of an ongoing research project SALLnet (www.uni-goettingen.de/de/592566.html) (Rötter et al. 2021). All research activities within the project relevant to the results presented were approved by the ethical research committee at the University of Limpopo (UL).

2.2. Smallholder survey

A household survey was conducted between February and May 2019 in Ndengeza (40), Mafarana (25), Gabaza (25), and Selwane (50) (140 total, not including pretesting in two different villages). For each household the responsible person for farm management, often the household head, was interviewed. The survey included general household characteristics combined with socio-economic aspects as well as information on resource endowment and agricultural activities. Questions focused on perceived effects of extreme weather and adverse climate events on agricultural production and management as well as drought adaptation measures for maize production and implementation barriers.

2.3. On-farm agronomic sampling: farm management, maize harvests, and soil sampling

In April and May 2019 (maize harvest time), 103 smallholder maize plots (1 m$^{2}$; figure 2) from 40 farms throughout four villages (Gabaza: 21; Mafarana: 29; Ndengeza: 33; Selwane: 20) were assessed on the management aspects needed to set up the Agricultural Production System Simululator (APSIM). Farms were chosen based on whether farmers were in the field harvesting maize (purposeful sampling: Patton 1990). Plots representative of the entire field in terms of maize plant density, development, and health were selected for sampling. Observations included maize plant density, weed cover and type, as well as a rated assessment of cob health per plant (0.0 = poor to 1.0 = good). Maize grain yields are reported at 12.5% moisture content. Simultaneous to these observations, semi-structured in-depth interviews with farmers provided insight into land preparation methods, sowing times, maize genotypes used, soil amendments, weed and residue management. As an example of how this information helped design the simulation study: in-depth interviews revealed that sowing took place after 2–5 d of consecutive rainfall, which spanned a sowing window of 15 November to 15 February (table S2). Farmers mentioned machinery (tractors and ploughs) and manual labour shortage as limitations for weed clearing and seedbed preparation.

All maize plants within the plots were harvested by hand for grain yield. Samples were dried in ovens at 60 °C for 48 h before being weighed at the UL, Polokwane. Soil was sampled for each plot with an auger (as deep as possible at 15 cm intervals) for organic carbon (OC), total nitrogen (N) and soil texture (figure 3). While OC and total N were quantified via elemental analysis at the Georg-August-Universität, Göttingen, soil texture was assessed by hand (Amelung et al. 2018). Based on texture and OC measurements, permanent wilting point, field capacity and bulk density were estimated based on methods detailed by Minasny and Hartemink (2011). Rooting depth was estimated during soil sampling for each plot through the maximum soil penetration possible with a soil auger.

2.4. Crop modelling

2.4.1. Overview

This study used APSIM, which simulates crop development and growth on a daily time step as affected by temperature, radiation, and water and nutrient supply. For this, soil N, phosphorous and water dynamics are calculated (Probert et al. 1998, Wang et al. 2014, Whitbread et al. 2017). APSIM has been applied in many studies in SSA (e.g. Whitbread et al. 2010, Hoffmann et al. 2020). Table S1 highlights additional evaluations related to aspects of this study.
Figure 1. Climate characteristics of the villages studied in the Limpopo province, including maximum and minimum temperature, potential evapotranspiration (Priestly–Taylor approach) and rainfall (October to May, 1998–2019). Source: NASA POWER data (https://power.larc.nasa.gov/). Lines represent the median, the middle 'box' the inter-quartile range (50% of scores for the group), and the whiskers the lower and upper quartiles (25% respectively).

Figure 2. Georeferenced maize system biomass, grain harvest and soil sampling in Mafarana, farm five, plot one, 2 May 2019.
2.4.2. Model: benchmarking setup
To benchmark the model for the smallholder sites, APSIM was set up to simulate the period June 2018 to September 2019, spanning one cropping season lasting from October to May. Soil properties were surveyed and estimated as described above (2.3). For the layers below rooting depth, constant soil texture was assumed. Soil OC was halved every 30 cm (Dagliesh et al. 2016). Observed maize yields from the 2019 on-farm harvest (2.3) were used to benchmark APSIM for each village at farm level. Weeds were included using a generic summer grass (summer period) and a winter dicot (winter period). Weed cover and removal was based on a visual assessment of each plot through the agronomic observations. As initial N was not measured, a sensitivity analysis approach was implemented using four values ($N_{\text{min}}$ 53, 58, 63, 68 kg ha$^{-1}$ for the profile) realistic for the scenario (Hoffmann et al. 2020). Initial soil water was set to 60% full (filled from top) and run from June, 4 months prior to the sowing window allowing for a sufficient spin-off period. Farmers sowed when it rained for 2–5 d consecutively (source: on-farm, in-depth interviews) and explained in which week this was for the 2018–19 season. All remaining management aspects, such as density, were based on agronomic observations (2.3; figure 2). Together, 103 soils from four villages (Gabaza, Mafarana, Ndengeza, Selwane) led to 412 simulations in total. Figure 4 presents the observed versus simulated data for the benchmarking exercise.

2.4.3. Model: simulation experiment
APSIM was setup with weather data from June 1998 to September 2019 (21 seasons: October to May) for each village using soil properties from the benchmarking setup. Along the lines of Palosuo et al. (2021), we created seven hypothetical technology packages (TPs) that optimised one or more dimensions of management based on the information gathered from farmers during interviews:

- TP0 Status quo
- TP1 Fertiliser
- TP2 Plant density
- TP3 Weeding
- TP4 Irrigation
- TP5 Planting date
- TP6 All combined
- TP7 Forecasting

For further details, please refer to the supplementary material (S1 and table S2).
3. Results

3.1. Farmer perceptions of adaptation strategies and related barriers

The most prominent adaptation measures perceived by respondents across villages (n = 140) included altering the planting date (mid-November to mid-February) of maize (80%) and using weather forecasts (74%) (figure 5)—consistently the top two adaptations. Fertiliser (21%) and supplementary irrigation (2%—ranked lowest) as adaptation measures ranked low. While the ‘Use of extension service’ is important from a systems perspective, it is difficult to incorporate into the simulations as we cannot be sure of the management changes it would lead to. Similarly, although ‘Livestock sale’ can influence crop-livestock farming systems, this economic adaptation was not applicable for our study. A lack of knowledge (about adaptation measures: 97%), finance (for irrigation infrastructure: 96%), or support (governmental: 80%) were the main adaptation barriers. Others included crop diversification, related to Sorghum as an alternative to maize, such as: lack of information (42.9%) and pests (31%).

3.2. Effects of the different technological packages

Simulated status quo yields were the lowest across all villages, averaging 1060 kg ha\(^{-1}\) (data not shown) (simulation period: 1998–2019). Thirty-five per cent of all status quo harvests were below 500 kg ha\(^{-1}\) (harvest failures). While the definition of a harvest failure is context specific, this threshold is based on average observed maize yields across all villages from 2019 of just over 1400 kg ha\(^{-1}\) (figure 4). The threshold 500 kg ha\(^{-1}\) is around 33% of the average observed maize yields for the region, as used by Snapp et al (2018) for a study of smallholder maize farmers in Malawi. The simulation of a recommended planting density (2.7 m\(^{-2}\)) did not improve maize yields across villages (1070 kg ha\(^{-1}\)). Simulated fertiliser, weeding, planting date, irrigation and forecasting TPs led to similar overall yields ranging between 1400 and 1700 kg ha\(^{-1}\). Larger gains were made through all combined (3200 kg ha\(^{-1}\)).

Similar to maize productivity, harvest failure risk (<500 kg ha\(^{-1}\)) was not reduced through planting density simulations alone (36% versus 34% for status quo—average across villages). Fertiliser alone slightly reduced risk to 30%. As with productivity, weeding and planting date simulations led to similar results, reducing the risk to around 20%. Forecasting performed worse in terms of harvest failure risk (34%), but this is misleading, as input (fertiliser and seed) was minimised when predicted rainfall was low. Although irrigation alone did not lead to high overall yields, harvest failure risk decreased to 13%. Irrigation alone led to the highest simulated in-season drainage in all villages (figure S2).

Combining all simulated management interventions nearly eliminated the risk of harvest failure (2%). Only 15% (of 2%) were absolute harvest failures at 0 kg ha\(^{-1}\), which occurred in Ndengeza (five times) and Selwane (once) in the 2002 and 2003 seasons.
Figure 5. Perceived smallholder adaptation strategies and barriers from all four villages: Gabaza (n = 25), Mafarana (n = 25), Ndengeza (n = 40) and Selwane (n = 50).

The largest simulated yield increases from the status quo were from all combined (table 1, figures 6 and S3—all villages). Simulations conducted for Selwane experienced the most substantial yield increase of 279%, followed by Mafarana (+189%), Ndengeza (+188%) and Gabaza (+178%). All combined led to larger yield increases than the sum of all other individual TP increases, except for forecasting (Gabaza: +146%; Mafarana: +140%; Ndengeza: +178%; Selwane: +235%). In terms of absolute highest yields, 70% were from the all combined TP (across villages), ranging from around 5500 to 5900 kg ha$^{-1}$.

The absolute highest yield was from forecasting (6200 kg ha$^{-1}$).

The most simulated harvest failures occurred in Selwane, which was consistent for the majority of TPs (table 1). Combining all management interventions reduced harvest failures for all villages, followed by irrigation in all villages, except Selwane—here weeding and planting date performed better. Weeding and planting date were consistently good at reducing harvest failures when compared to the status quo. While fertiliser led to good yields compared to the status quo and other individual TPs, it did not reduce harvest failure risk as much as, for example, weeding in all instances.

4. Discussion

In line with other studies (Magombeyi and Taigbenu 2011, Cammarano et al 2020, Hoffmann et al 2020), assessed current smallholder maize yield levels were low (figure 4), with drought a key threat to production (figure 6). However, production faces additional abiotic and biotic limitations, meaning interventions that single out management practices do not lift yields as much as when practices are combined (figures 6 and S3). For example, in our simulations, we found fertiliser alone increased yields across villages by around 38%—in line with Magombeyi et al (2018) at 31% with manure and inorganic...
Table 1. Simulated maize grain yield means (kg ha$^{-1}$) with standard deviation and statistical groups (letters) following ANOVA ($p$-value 0.05) and the Tukey post-hoc HSD (honestly significant difference) test. Different letters indicate significantly different yields over the simulated period. Group ‘a’ contains the highest yield within villages and group ‘e’ the lowest. This is followed by percentage of failed harvests (<500 kg ha$^{-1}$) and the percentage difference from the status quo TP.

| Technological package | Gabaza Mean yield (kg ha$^{-1}$) (SD) | Mafarana | Ndengeza | Selwane |
|-----------------------|--------------------------------------|---------|---------|---------|
| Status quo            | 1281 (911) d; 27; NA                  | 1116 (918) de; 30; NA                   | 1042 (972) d; 38; NA                   | 816 (733) e; 42; NA |
| Fertiliser            | 1528 (1147) c; 27; +19                | 1257 (1147) de; 31; +13                | 1558 (1285) c; 32; +50                | 1370 (1087) c; 29; +68 |
| Planting density      | 1289 (977) d; 30; +1                  | 1114 (1031) e; 38; +0                 | 1049 (965) d; 37; +1                  | 848 (724) e; 39; +4  |
| Weeding               | 1691 (998) c; 13; +32                 | 1544 (1058) c; 17; +41                | 1431 (1085) c; 25; +42                | 1238 (826) c; 20; +60 |
| Irrigation            | 2047 (765) b; 2; +60                  | 1881 (751) b; 0; +69                  | 1435 (932) c; 19; +38                 | 1063 (810) d; 31; +30 |
| Planting date         | 1716 (992) c; 13; +34                 | 1306 (924) d; 22; +17                 | 1536 (1044) c; 24; +47                | 1415 (969) bc; 23; +73 |
| All combined          | 3568 (1045) a; 0; +178                | 3224 (1092) a; 0; +189                | 3006 (1283) a; 4; +188                | 3092 (1215) a; 3; +279 |
| Forecasting           | 1962 (1658) b; 25; +53                | 1531 (1585) c; 41; +37                | 1852 (1618) b; 34; +78                | 1601 (1549) b; 35; +96 |
Figure 6. Simulated maize grain yield means (kg ha$^{-1}$) from four villages in the Limpopo province based on the status quo management (TP0), and seven technological packages (TPs: TP1–7) from the driest (320 mm in 2003), an average (600 mm in 1998), and the wettest (1200 in 2000) seasons in terms of in-season rainfall from the entire simulation period (1998–2019 seasons). The dashed lines at 1000 and 3000 kg ha$^{-1}$ are for visual guidance only. Bars represent the grain yield means. Dots illustrate the distribution of simulated yields, their colour indicates the water holding capacity (WHC, mm) of the specific soil and location.

fertiliser—compared to around 200% for all combined. As expected, irrigation was the basis for system improvements from the status quo, as TP4 was the only individual TP to substantially reduce harvest failure risk other than all combined, which included irrigation. This is in line with Andersson et al. (2013) and Magombeyi et al. (2018), who report irrigation to increase yields between around 30%–95% for farmers in the Limpopo River Basin (compared to our 30%–69% for irrigation alone). We showed that providing tactical input in line with a simple weather index can result in better matching resource use to potential yield (figure S3). Although yields in low rainfall years were low, this was in line with input. For example, low input (1.6 plants m$^{-2}$ and 2 kg ha$^{-1}$ fertiliser) in the strong El Niño year of 2015 (harvest of 2016) (table S3) led to a simulated average of 100 kg ha$^{-1}$ across villages. This was less than the 350 kg ha$^{-1}$ across villages from the status quo but forecasting used little input.

4.1. Smallholder intensification limitations and opportunities

Survey results suggested that fertiliser was not used, and supplementary irrigation not seen as an adaptation measure. It is not clear, however, whether this is purely due to financial restrictions or a potential lack of awareness about technological advancements around infrastructure and use. Around 95% of respondents across villages reported a lack of funding for irrigation infrastructure as the second highest ranked barrier overall (figure 5). Average
annual household income across villages was around 5000 United States Dollars (USDs, converted 2019 exchange rate, World Bank Data 2021) and the cost of installing a borehole-sourced drip-irrigation system for 1 ha in Ndengeza was said to be around 2500 USD (survey data not shown). However, irrigation costs vary depending on water source and technology. Ottoo et al (2018) showcase small and deep-well solar-powered irrigation pumps starting at around 250 USD in Ethiopia, highlighting potential misconceptions that are important to clarify and may hold farmers back from adaptations. Farmers who irrigated in Ndengeza had off-farm income through civil-service employment, in line with Olofsson (2019), explaining the willingness to invest. Similar findings were reported in Tanzania (Jah et al. 2020). This indicates that where water resources are available, irrigation infrastructure subsidies could reduce this barrier and develop an avenue for farmers to improve production. In a study of smallholder farming systems in KwaZulu-Natal, South Africa, Chipfupa and Wale (2019) promote governmental subsidies for initial irrigation infrastructure that are repaid by farmers over time. However, a lack of running and maintenance cost support can cause such initiatives to fail (personal communication: representative of the Water Research Commission, South Africa, SALL-net stakeholder workshop 2021). Any related schemes should be accompanied by the integration of water-monitoring tools as presented by Stirzaker et al. (2017) and Moyo et al. (2020). This enabled farmers to make their own informed decisions about irrigation scheduling, leading to higher water-use efficiency. Adaptive irrigation practices even spread to farmers without soil–water monitoring tools, highlighting the need for policy to facilitate local-level experimentation and learning, which should be strongly linked to farmer-trusted networks (Cooper et al. 2008). Andersson et al. (2013) estimated external water harvesting techniques to provide a maximum of 176 mm per season in the Limpopo basin. Our simulated irrigation use ranged from 100 to 380 mm, demonstrating potential, but also limitations. Only around 4 to 6 per cent of smallholder farmers irrigate in SSA (Wiggins and Lankford 2019). While previous attempts to expand irrigation may have failed, leading to scepticism, improved access to finance, infrastructure, technological advances and an improved understanding of effective and sustainable irrigation means it has potential in parts of the continent. Substantial irrigation expansion opportunities and benefits for SSA smallholders are highlighted by Xie et al. (2014), who emphasise the need for a multifaceted approach that includes sustainable finance models.

Respondents expressed interest in weather forecasts as a key adaptation method (74% across villages), but they are currently not used. Fallon et al. (2019) even found commercial farmers in Limpopo to not use forecasting services due to limited information and communication from providers, and a poor understanding of how to link information to management. Other than planting date adjustments, leaving some land fallow (51% across villages) was the only management adjustment used (figure 5)—more so in Ndengeza and Selwane (68% and 62%) compared to Gabaza and Mafarana (26% combined). It is important to note that leaving land fallow can also be the result of a lack of labour. As current management adaptation options were limited, due to financial and information-based restrictions, simple, cultural practices hold the most immediate promise, especially if combined.

4.2. Linking surveys and crop models for a systems approach to crop management

Vanalauwe and Dobermann (2020) argue that simple agronomic practices should be addressed first and can lead to the ‘top priority’ of increasing crop yields and investment return. Our simulation study is in agreement with this, with the highest absolute yields resulting from the forecasting TP at just over 6000 kg ha$^{-1}$ (across villages), although yield variation was high as it was dictated by rainfall and inputs (seed and fertiliser). Without investing in irrigation systems or fertiliser above 70 kg ha$^{-1}$ urea N, high simulated yields were achieved through good timing and simple agronomy. The highest simulated forecasting yields are in line with those of commercial maize for Limpopo (white as opposed to yellow maize), which peak at just over 6000 kg ha$^{-1}$ (1986–2014) (Department of Agriculture, Forestry and Fisheries and Department of Rural Development and Land Reform South Africa: www.statista.com). Commercial yields average just under 3000 kg ha$^{-1}$, which are higher than simulated forecasting means and closer to those of all combined across villages. The lowest simulated mean (status quo: 1060 kg ha$^{-1}$ across villages) is in line with Andersson et al. (2013) for a comparable TP for the same system and region.

Simulated all combined means across villages were highest at around 3000 kg ha$^{-1}$, which required the most amount of input (table S2). Regardless, the ‘bundle’ of management interventions was best for harvest failure risk reduction, but not necessarily to fulfil yield potential or be resource-use efficient (figure 6). This is more complex than looking at pure yield values alone and best assessed when all inputs (e.g. labour and finance) are accounted for. While insights from Magombeyi and Taibenu (2011) highlight the economic benefit potential of irrigation for the study region, what needs to be clear is that good agronomy is key if benefits are to be maximised. For example, while simulated irrigation reduced interannual yield variability it was limited by soil fertility. Due to the high WHC of Ndengeza, good yields were simulated in the driest year (figure 6), potentially due to water stored at lower layers. Even planting date and no irrigation simulations were effective in this...
scenario, stressing the importance of soils. The high variability of soils within villages means findings are site specific, highlighting the significance of farmer knowledge about such aspects. Implementing higher weeding intensity also proved to be an effective soil–water management method, particularly for Selwane (table 1). Magombeyi et al (2018) also found weeding led to slightly higher yields than fertiliser under low rainfall conditions in similar systems. Important to note is that simulated Irrigation required increased biotic stress management in our study (weeding), demonstrating the ‘hidden costs’ of some interventions.

As agriculture accounts for about 70% of water use in southern Africa (Mabhaudhi et al 2018), expansion could require reallocation from current uses. Over irrigation must also be addressed as it can leach soil nitrate. Our simulations showed that Irrigation alone (no fertiliser) led to lower yields in average and wet years compared to the dry (figure 6). Linked to high simulated in-season drainage for Irrigation alone (figure S2), the effect of nutrient leaching can be attributed to an oversupply of water. This threat should not be underestimated and highlights the need to provide a management ‘package’. In a study of similar cropping systems in neighbouring Zimbabwe and Mozambique, Stirzaker et al (2017) observed farmers half their irrigation treatments after using soil–water and nitrate monitoring tools which visualised the impact over irrigation can have on soil nutrients.

While forecasting can achieve high yields without irrigation, the lack of stability is a problem for farmers under prolonged drought. Under such conditions, no agricultural water management technology other than irrigation can offset the effects of such extreme conditions (Magombeyi et al 2018). Our results suggest that adaptation discussions move beyond the simple rainfed versus irrigated debate and towards an adaptive approach that combines the two through a systems perspective on management—especially with increased intra-seasonal variability in the region (Thomas et al 2007). Jägermeyer et al (2016) found large-scale implementations of even low-tech integrated crop–water management to substantially reduce global food gaps and climate-related smallholder system risks. Key is developing the knowledge and skill to dynamically optimise several management solutions. Further studies could assess combinations of intra-seasonal forecasting and irrigation with split fertiliser applications, utilising new insights into climate predictions (Silvério and Grimm 2021). Linking infrastructure and management developments to advances in disciplines such as plant breeding also has great potential, e.g. through genotypes that make use of below-ground space.

Rockström et al (2010) predicted that rainfed agriculture will play a dominant role in the medium term. Linked to the fact that smallholder irrigation was largely non-existent in the region, this prediction continues to hold substantial weight. Our simulation results and the work of specialists in the study region (e.g. Xie et al 2014, Stirzaker et al 2017, Magombeyi et al 2018, Wiggins and Lankford 2019, Bjornlund et al 2020, Moyo et al 2020, Parry et al 2020) demonstrate the potential of irrigation if approached in a context-specific manner. However, in the short-term and with existing infrastructure, seasonal weather forecasts combined with simple management adjustments could help farmers enjoy bumper harvests and avoid inefficiencies. Key is the promotion of such insights to empower farmers and quash related misconceptions.

5. Conclusion

We investigated a data-scarce farming scenario through a multidisciplinary approach leading to insights into the SI of low input smallholder dryland crop production in southern Africa.

Production improvements under climate risk require a systems approach and must be based on the combination of synergetic management practices. Tackling climate risk for low input systems could be achieved through making use of the opportunities of climate variability through adaptive management combinations including supplementary irrigation in low-rainfall years. Irrigation can help farmers manage risk, but is only efficient when the related costs, e.g. labour for biotic stress management and fertiliser inputs, can also be covered. With climate projections set to exacerbate, the need for adaptability, focussing on dynamic skills combined with simple agronomic practices seems the most empowering and efficient way forward.

Data availability statement

The data that support the findings of this study are available upon request from the authors.

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Ethical statements

Before the survey and on-farm sampling work a meeting was organised in each village to explain the
research aims and procedures. This offered participants, including household heads and village elders, the opportunity to ask questions and discuss the research. Participants were reminded of the conditions before each interaction and asked again for consent.

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