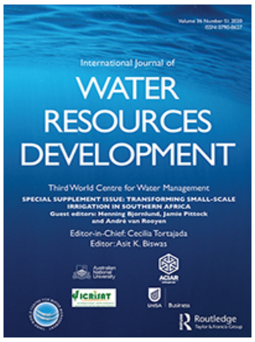

International Journal of Water Resources Development

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/cijw20

The dynamics between irrigation frequency and soil nutrient management: transitioning smallholder irrigation towards more profitable and sustainable systems in Zimbabwe

Martin Moyo , André Van Rooyen , Henning Bjornlund , Karen Parry , Richard Stirzaker , Thabani Dube & Mthulisi Maya

To cite this article: Martin Moyo , André Van Rooyen , Henning Bjornlund , Karen Parry , Richard Stirzaker , Thabani Dube & Mthulisi Maya (2020) The dynamics between irrigation frequency and soil nutrient management: transitioning smallholder irrigation towards more profitable and sustainable systems in Zimbabwe, International Journal of Water Resources Development, 36:sup1, S102-S126, DOI: 10.1080/07900627.2020.1739513

To link to this article: https://doi.org/10.1080/07900627.2020.1739513

INTERNATIONAL JOURNAL OF WATER RESOURCES DEVELOPMENT
2020, VOL. 36, NO. S1, S102–S126
https://doi.org/10.1080/07900627.2020.1739513

Routledge
Taylor & Francis Group

The dynamics between irrigation frequency and soil nutrient management: transitioning smallholder irrigation towards more profitable and sustainable systems in Zimbabwe

Martin Moyo[a], André Van Rooyen[a], Henning Bjornlund[b], Karen Parry[b], Richard Stirzaker[c], Thabani Dube[a] and Mthulisi Maya[a]

[a]Matopos Research Station, International Crop Research Institute for Semi-arid Tropics, Bulawayo, Zimbabwe; [b]School of Commerce, University of South Australia, Adelaide, Australia; [c]CSIRO Agriculture, Canberra, Australia

ABSTRACT
Successful irrigated agriculture is underpinned by answering two critical questions: when and how much to irrigate. This article quantifies the role of the Chameleon and the Wetting Front Detector, monitoring tools facilitating decision-making and learning about soil-water-nutrient dynamics. Farmers retained nutrients in the root zone by reducing irrigation frequency, number of siphons, and event duration. Water productivity increased by more than 100% for farmers both with and without monitoring tools. Transitioning smallholder irrigation systems into profitable and sustainable schemes requires investment in technology, farmers and institutions. Importantly, technologies need embedding in a learning environment that fosters critical feedback mechanisms, such as market constraints.

ARTICLE HISTORY
Received 21 July 2019
Accepted 28 February 2020

KEYWORDS
Irrigated agriculture; soil and moisture monitoring tools; adaptive management; Zimbabwe

Introduction

Globally, farming needs to transition from lower- to higher-yielding systems, which are profitable and sustainable and provide food security for growing populations (Tilman et al., 2011). In sub-Saharan Africa, agriculture is mostly rainfed and undertaken by smallholder farmers who face frequent dry spells and droughts. Food production in sub-Saharan Africa over the past two decades has been insufficient, with decreasing output per unit of input (FAO et al., 2018). Agricultural water management is important for crop production, especially in southern Africa, where there is increasing pressure on land due to climate variability and greater food demands (Yokwe, 2009).

Irrigation presents an opportunity for sustainable intensification, increasing crop yields and improving resilience to climate shocks, especially in southern Africa, which is experiencing increased rainfall variability. Irrigation uses 60–70% of all withdrawn water to produce about 40% of the world's food (Portmann et al., 2010). Without irrigation, global cereal production would decrease by 20%, with climate change and population growth further emphasizing the increasing importance of irrigation (Easterling, 2007). Irrigation has the potential to increase crop water productivity (WP) – producing more crops with

CONTACT Martin Moyo M.Moyo@cgiar.org

less water (Cai et al., 2011). But there is a need to explore opportunities to improve the efficiency, sustainability and productivity of irrigation (Tilman et al., 2011).

Zimbabwe has made a significant investment in irrigation development compared to other countries in the Southern Africa Development Community (Mtisi & Nicol, 2003). About 20% of Zimbabwe's agricultural production is under irrigation, mostly in semi-arid areas where irrigation is necessary for agriculture to be productive (Government of Zimbabwe, 2012; Rukuni, 1984). The total developed irrigation area in the country is estimated at 206,590 ha, of which 132,370 ha is currently irrigated (Department of Irrigation Development, 2012). However, water is becoming scarce due to increasing demands from agricultural (82% of water), domestic and industrial uses (15%) and mining (3%) (Jacobs et al., 2013).

The return on investments in smallholder irrigation has been unsatisfactory. The functionality of these schemes has largely remained low, resulting in infrastructure decay and calls for rehabilitation and revitalization of schemes (Jacobs et al., 2013). In Zimbabwe, market, production and WP barriers are the root causes of reduced productivity and profitability in existing and new smallholder irrigation schemes. They include infrastructure deficiencies, unfavourable land tenure, small landholdings, poor management, inadequate access to markets, and lack of technical knowledge for managing water and irrigation infrastructure (Inocencio et al., 2007; Moyo et al., 2017; Mutiro & Lautze, 2015). Many schemes have also been developed to increase food security through growing staple crops, but the financial returns are insufficient to justify the costs of running and maintaining the infrastructure (Bjornlund et al., 2017).

The transition from inefficient subsistence systems towards market-oriented production systems requires a paradigm shift among irrigators, irrigation management committees (IMCs) and policy-makers (Van Rooyen et al., 2017). Institutional and system rigidity, reinforced by IMC strategies, inhibits flexible water delivery and contributes significantly to a deterioration in crop WP, which is target 6.4 of the Sustainable Development Goals.

This article explores the role of the Chameleon and the FullStop Wetting Front Detector (WFD) as monitoring tools to help farmers decide when and how much to irrigate. Results are communicated of a project implemented between 2013 and 2017 and using two complementary entry points: the monitoring tools, and agricultural innovation platforms (AIPs) which strengthen social networks. Collectively, the interventions achieve a transformational change of smallholder irrigation schemes towards sustainable irrigation communities (Figure 1).

The tools were introduced to assist in farmer decision-making and learning about when and how much to irrigate, and how to manage fertilizers (Stirzaker et al., 2017). However, it is important to acknowledge that improving crop production on smallholder farms cannot be achieved simply by introducing appropriate technology, no matter how good that technology is. The failure of smallholder irrigation schemes is not solely a water challenge. The causes span policy (e.g., weak institutions), environmental (e.g., salinity and waterlogging), social (e.g., lack of agronomic and irrigation knowledge), financial (e.g., farmers' inability to support scheme maintenance) and technical (e.g., infrastructure) barriers.

The complex nature of smallholder irrigation schemes means that the challenges and solutions are highly interconnected. Transitioning these complex systems into profitable, equitable and economically sustainable schemes requires investment not only in smart technologies but also in the farmers, institutions and value-chain network (Figure 1). Thus,

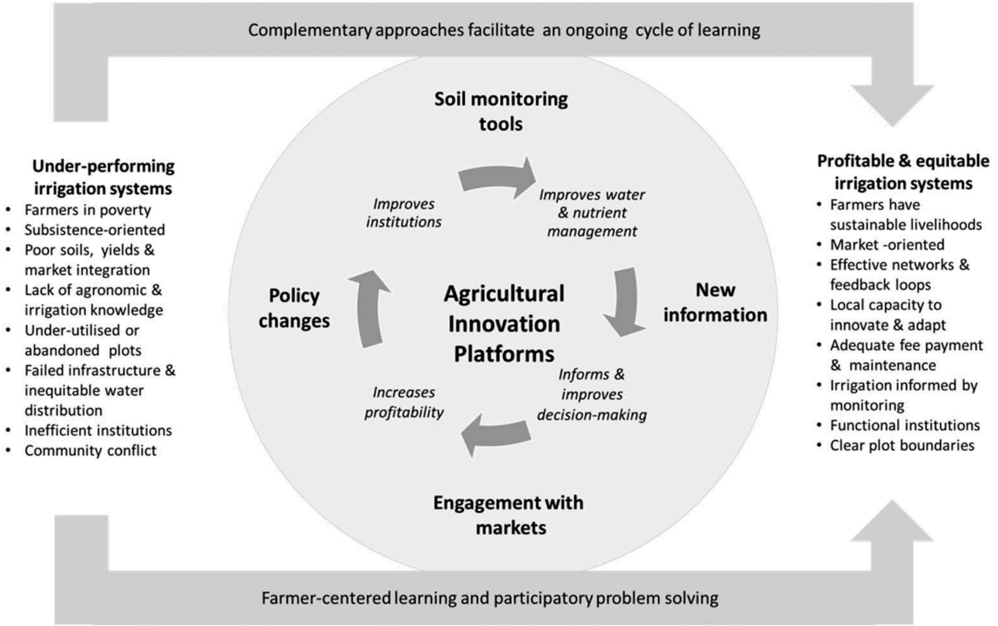

Figure 1. Transitioning underperforming smallholder irrigation schemes in Africa towards profitable and equitable irrigation systems (Bjornlund et al., 2018).

the AIPs were introduced to bring key stakeholders together to develop solutions to the broader challenges that restrict profitability (Van Rooyen et al., 2017). The AIP process facilitates farmer learning about management, crop choices and market integration and augments the learning from the soil and nutrient monitoring (Bjornlund et al., 2018).

This article focuses on the role and influence of the soil moisture and nutrient monitoring tools; the role of the AIP process is detailed elsewhere (Parry et al., 2020; Van Rooyen et al., 2020).

Reducing water use in smallholder irrigation systems in Zimbabwe

More frequent and intense drought and flood events will create water availability challenges and increase the need for efficient integrated systems of capture, storage and use (Ronco et al., 2017). Irrigation, therefore, is increasingly important to mitigate against climatic variability and support year-round crop production (Moyo et al., 2017). Hence, irrigation is a key strategy in Zimbabwe's Food and Nutrition Security Policy (Government of Zimbabwe, 2012).

Irrigation is often presented as a panacea for semi-arid areas; however, it is also vulnerable to rainfall variability and climate change, and many complexities influence its success (Mosello et al., 2017). An inadequate and insecure water supply impacts irrigated agriculture, which leads to water stress and reduced crop yield and quality (Senzanje et al., 2003). In most schemes, irrigation scheduling is inefficient and inflexible. Water is not managed to maximize yield and profit, and the consequence is loss of production capacity (productivity losses). Despite well-documented inefficiencies, smallholder irrigation in Zimbabwe mainly uses flood systems (Mosello et al., 2017). Current irrigation efficiencies are often below 50%, as much of the diverted water is lost in the conveyance system or through inefficient application (Jägermeyr et al., 2015).

Understanding soil moisture management by answering 'when and how much to irrigate' is key to improving irrigation management and water-use efficiency (Jacobs et al., 2013; Senzanje et al., 2003). The recommended approach for optimal root-zone soil water management includes irrigation scheduling through soil moisture monitoring (Van der Laan et al., 2015). This helps fine-tune the timing and amount of water applied, based on the root-zone moisture, crop water consumption, and crop development stage (Stevens et al., 2005), and it optimizes production, minimizes nutrient leaching and prevents other environmental harms (Van der Laan et al., 2015). Flexible irrigation scheduling, which supplies water when it is most needed by crops, is not practised in most smallholder irrigation schemes. This is because farmers lack soil moisture monitoring tools and training and expertise in appropriate timing, which has resulted in excessive irrigation in most situations (Samakande et al., 2004).

Soil moisture monitoring equipment ranges from simple mechanical sensors to multi-depth continuous recording electronic sensors with web-based data access. Each has strengths and shortcomings. Despite the advantages of irrigation scheduling tools, their adoption remains limited, especially in Africa (Myeni et al., 2019; Stevens et al., 2005; Stirzaker, 2006). The main reasons for non-adoption by smallholder farmers include complexity and difficulty of applying the technology, economic costs, and perceptions that accurate scheduling provides little benefit (Olivier & Singels, 2004). In practice, farmers often irrigate with fixed amounts, or at a constant interval, with little regard to variability in weather conditions and actual crop water requirements. Importantly, Zimbabwean farmers are not charged per unit of water; rather, a constant annual price per land unit is paid, which provides no incentive to use less water or to use it more effectively.

Methodology

Study location

Zimbabwe is divided into five agro-ecological regions, known as natural regions, based on the rainfall regime and number of growing days in a season (Vincent & Thomas, 1961). The study was carried out at Mkoba and Silalatshani irrigation schemes, in Zimbabwe's semi-arid areas, Natural Regions III and IV, respectively (Table 1). Rainfall in the arid and semi-arid regions is inadequate and too erratic and unreliable for dryland farming, making supplementary irrigation necessary for productive agriculture. Both Silalatshani and Mkoba are communal irrigation schemes. The land is government owned and governed under Communal Land Act 20 of 1982, according to which the Rural District Councils allocate land for occupancy and use (Sithole, 2002). The schemes were selected based on a set of criteria to ensure that the project could be implemented, such as the District Authority's willingness to collaborate and site accessibility (for the project to be cost-effective) and the ability to test the project interventions' effectiveness in improving agronomic practices, institutional capacity to generate long-term changes, and overcoming market barriers.

Table 1. Irrigation scheme characteristics (Moyo et al., 2017).

	Mkoba	Silalatshani (Landela)
Year constructed	1968–69	1968
Location	Gweru Rural District (19°22′ 0.07″ S, 29°32′ 13.4″ E)	Insiza District (20°47′ 22″ S, 29°17′ 44.59″ E)
Farmers	75	212
Irrigated area (ha)	10.1	47.7
Main crops	Maize, sugar beans, leafy vegetables	Maize, wheat, sugar beans
Legal structure	By-laws	By-laws
Access to land	State-owned, chief allocates	State-owned, chief allocates
Soils	Mostly sandy soils	Mostly loamy sands
Annual rainfall (mm)	650–900	450–650
Climatic characteristics	Mid-season dry spells and high temperatures are a common feature	Severe dry spells and seasonal drought are very common
Irrigation method	Flood	Flood

Description of tools

The WFD and the Chameleon (together called ‘the tools’ hereinafter) were developed to build learning around soil water and solute monitoring among farmers, researchers and extension workers in developing countries (Stirzaker et al., 2017). The WFD was originally developed as an irrigation scheduling tool, to observe how deep water has penetrated the soil after an irrigation event (Stirzaker et al., 2010; Stirzaker, 2003). It consists of a funnel-shaped device with a mechanical indicator above the soil surface (Figure 2). Usually two are used, buried at different depths. As soil moisture penetrates the soil profile, it collects in the funnel, and the indicator pops up to alert the farmer that water has reached that level. A water sample can then be extracted using a syringe to measure salinity and nitrates.

Recently, the WFD has been used more as a solute monitoring tool than an irrigation scheduling tool (Van der Laan et al., 2010). The nitrate in the water sample is measured using nitrate test strips, and an electrical conductivity meter measures the salt levels (Figure 2).

The Chameleon soil-water sensor (Figure 3) was developed as a complementary tool to the WFD. It is meant to guide farmers in the best irrigation timing by providing interactive learning about the dynamics and complex interactions between irrigation, soil moisture and nutrient leaching when combined with data from the WFD.

The Chameleon consists of a sensor array and a portable hand-held reader, which can be used with any number of sensor arrays. Each array has three (new models) or four sensors (older models) permanently installed at three depths in relation to the root zone of the crops being grown (Stirzaker et al., 2017).

The current version of the reader also stores data and then automatically uploads them to the internet (when it connects to wi-fi), where it is recorded and stored on the Virtual Irrigation Academy platform for future analysis (Virtual Irrigation Academy, 2019). Once the reader is connected to the sensor array, it displays soil moisture at each depth as a coloured light.

🔵 Blue: the soil layer is wet.
🟢 Green: the soil layer is moist.
🔴 Red: the soil layer is dry.

The Chameleon measures soil tension, so the colours have the same meaning regardless of soil type (Stirzaker et al., 2017). The three lights show soil water conditions from the

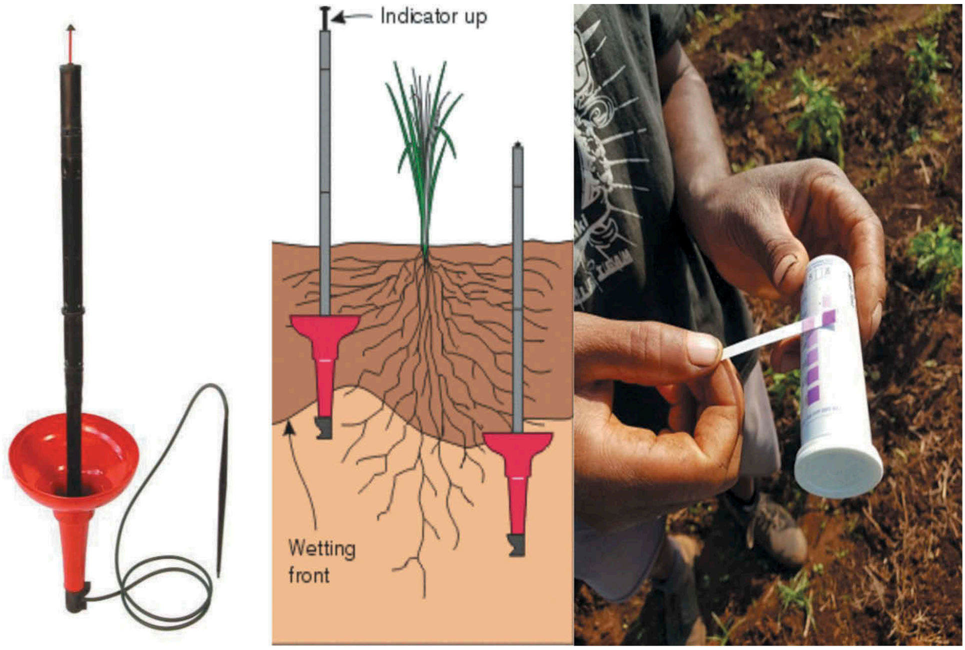

Figure 2. Wetting Front Detectors are placed at two depths in the ground and facilitate the testing of nitrate in the field (Virtual Irrigation Academy, 2019).

Figure 3. Chameleon soil moisture sensors and reader (Virtual Irrigation Academy, 2019).

top to the bottom of the root zone (Stirzaker et al., 2017). The farmer notes the colours in their field book (see Data Collection section), so they are available for their irrigation and

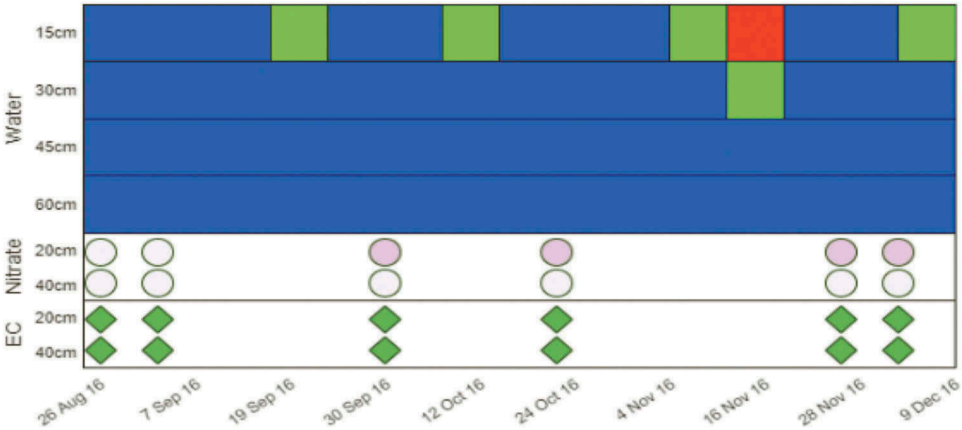

Figure 4. Seasonal patterns of soil moisture, nitrate and electrical conductivity for one farmer's maize crop at Silalatshani (Virtual Irrigation Academy, 2019).

fertilizer decision-making and comparison over time (see Virtual Irrigation Academy, 2019, for more detail).

Successive readings through the season provide a colour pattern that can be used to make reasonable inferences about irrigation management, rooting depth, water, and nitrate adequacy and leaching when combined with the WFD. Figure 4 is a typical example of how the soil water, nitrate and salinity data are displayed at Virtual Irrigation Academy (2019) for a 2016 maize crop on one plot at Silalatshani. The four rows in the upper part of the diagram show the soil moisture levels measured by Chameleon sensors at 15, 30, 45 and 60 cm depths.

The predominance of blue, especially at 45 and 60 cm depths, means the soil was consistently wet. There were only four brief periods when slight drying was observed (green) and significant depletion only at 15 cm depth in mid-November (red). The nitrate levels are shown by the circles. Nitrate levels were moderate in the topsoil (pink = 50–100 mg/L) and low in the deeper layer (white = 0–25 mg/L). The salt levels, shown as diamonds, were low at both depths (less than 0.4 dS/m).

Data collection

Data collection encompassed several sources and methods, as outlined in Table 2 and described in the remainder of this section: the project's baseline household survey (2014); data from the soil moisture monitoring tools and records in farmers' field books for the 2016/17 season; the end-of-project household survey (2017); and measurement of irrigation water discharge.

Soil monitoring and farmers' field books

In 2014, at each scheme, 20 irrigators (of the 75 and 100 in Mkoba and Silalatshani, respectively) were given two WFDs and a Chameleon sensor array. Two of the 20 irrigators at each site acted as field assistants and were trained to instal the tools, monitor nutrients and soil moisture, and help other irrigators with record keeping. They were selected by

Table 2. Overview of the data collection processes.

Data collected	Method	Date or frequency of collection	Sample size (no. of farmers) Mkoba	Silalatshani
Baseline irrigation amount and frequency before tools were introduced	Baseline household survey	February 2014	68	100
Changes in irrigation amount and frequency for farmers with tools (2017)	Farmer field books	Weekly during the 2016/17 season	12	18
Changes in irrigation amount and frequency for farmers without tools	End-of-project household survey	February 2017	35	60
Rainfall at the schemes	Farmer field books	Daily during the 2013/14 and 2016/17 seasons	12	18
Baseline yield for all farmers	Baseline household survey	February 2014	68	100
Yield for farmers with tools at the end of the project	Farmer field books	February 2017	12	18
Yield for farmers without tools at the end of the project	End-of-project household survey	February 2017	35	60

other irrigators in their respective schemes, as it was thought they could easily learn to operate the tools and facilitate learning by other farmers.

The field assistants were given a Chameleon reader, a pocket electrical conductivity meter and nitrate test strips. They were required to visit the plots each week, take the Chameleon soil water measurement, and record whether the WFDs had collected a water sample. If so, the sample was removed using a syringe, and they tested and recorded the conductivity and nitrate measurements.

With the tools, a field book was provided to the 20 farmers, so that they could record the soil monitoring data, their learning experiences and the reasons for any diversions from their 'normal' irrigation schedule. The field book was also used to record on-farm agronomic practices (crop planted, date of planting, number of weedings, date of fertilizer application, harvesting of plots), input costs, yields, output prices and income. The Chameleon and WFD data were recorded weekly, which facilitated important learning about the soil-water nutrient dynamics and enabled farmers to make changes to their water and nutrient management.

Data on changes in irrigation frequency, nutrient monitoring and yields were collected from the farmers who had the tools at the end of the project (12 at Mokba and 18 at Silalatshani). These data were used to calculate WP (see next section). Data was also collected from farmers without the tools (35 and 60 farmers at Mkoba and Silalatshani, respectively), using an end-of-project household survey, which was used to calculate WP (see next section).

Measuring and calculating water discharge

The farmers' plots are 0.1 ha at Mkoba and 0.5 ha at Silalatshani. They are 100 m long, 10 m wide at Mkoba, and 50 m wide at Silalatshani. At Mkoba, there are typically 10 furrows in a 0.1 ha plot; at Silalatshani there are 50 furrows. Farmers use six to nine polyethylene irrigation pipes (40 mm diameter) to siphon water from the canals into the irrigation furrows; they stop and move on to the next furrow when the water reaches three-quarters of the length of the field.

Since the water is supplied to the fields by open canals and gravity, it is difficult to measure the irrigation water applied to each plot. Measurements were taken at the beginning and end of the project (2014 and 2017) to determine the amount of irrigation water typically applied per plot and estimate field-level water usage. The water used was measured by recording the time taken to fill a 25 L bucket (positioned at field level) five times from a single siphon (Figure 5) and then computing an average discharge. The average time it took the water to reach three-quarters of the field was also recorded. This measurement was used to calculate the total amount of water used per irrigation event and per season, using three formulae:

discharge rate = V/T

where V is the volume of water in litres and T is the time taken for the siphon to fill the 25 L bucket

total water use per event = siphon discharge rate × duration of event × number of siphons × number of furrows

total irrigation water use per season = total water use per event × number of events in the season.

Calculating water productivity

WP is defined as the yield divided by the water (irrigation and rainfall) consumed to grow the crop and is an accepted way to measure the efficiency of on-farm water use (Kassam et al., 2007; Perry, 2011; Perry et al., 2009). In this study, WP is used to compare the productivity and performance of individual farmers growing the same crop.

Figure 5. Measuring irrigation water discharge.

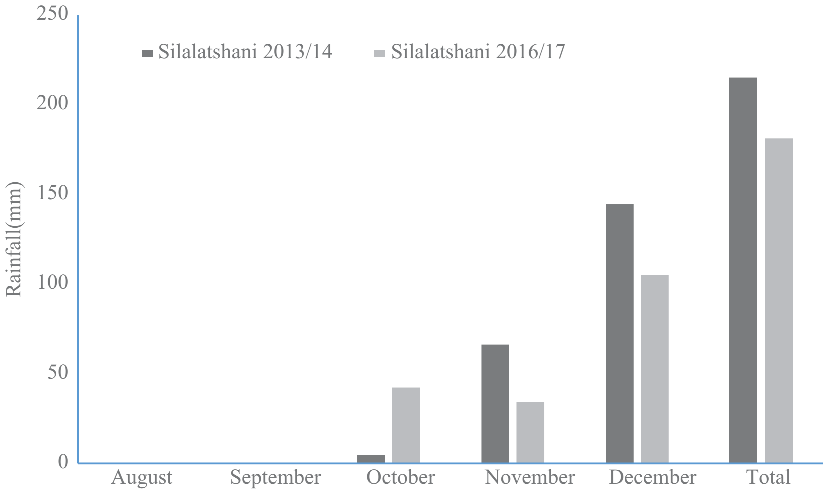

Figure 6. Rainfall during the study period at Silalatshani.

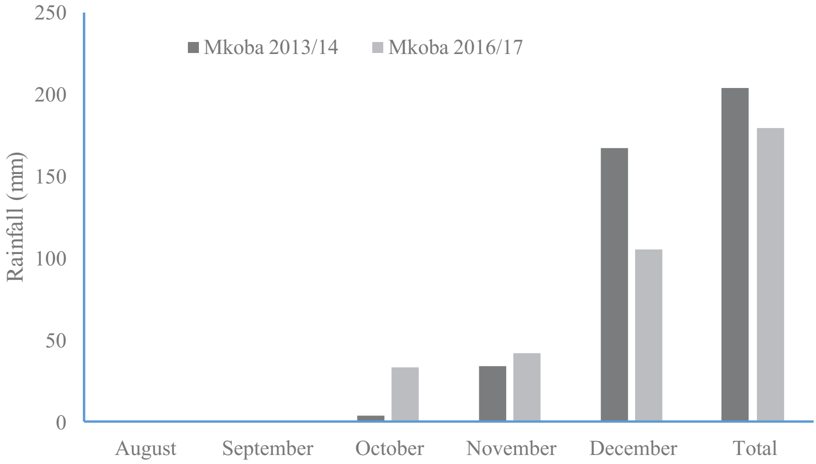

Figure 7. Rainfall during the study period at Mkoba.

WP was calculated by dividing grain yield by the gross volume of irrigation water and total rainfall (gross water use) during the growing season (Figures 6 and 7). The maize crop (*Zea mays* L., SC727 variety) was planted at both schemes in August 2016, harvested at physiological maturiy and grain dried to 12.5% moisture content. Each farmer collected the yield from a 10 m × 10 m plot. The yield of maize cobs from each plot was placed in 50 kg sacks, and the number (to the nearest half sack) was recorded in the field books. Spot checks were made to quantify the weight of threshed grain in a 50 kg bag to convert the number of bags to a grain yield per ha. Typically, a 50 kg bag of maize cobs contained 25 kg of grain. The yield from the plots was then extrapolated to a per hectare basis.

During the growing season, the number of irrigation events, the number of siphons used, and the duration of the irrigation events were recorded in farmers' field books. These were then used to calculate the amount of water used for a maize crop (Table 3):

Table 3. Changes in irrigation practices and water productivity from using the tools.

		Without tools				With tools			
		Mkoba		Silalatshani		Mkoba		Silalatshani	
Variables	Units	2013/14	2016/17	2013/14	2016/17	2013/14	2016/17	2013/14	2016/17
Irrigation events per season	#	20	10.5	18	7.7	20	8.1	18	8.5
Siphons used	#	7	5	9	8	7	5	9	8
Time taken to irrigate plot	hours	2	1	4	2	2	1	4	2
Irrigation per event	mm	30	11	30	13	30	11	30	13
Days between irrigation events	#	7	13.3	7	16.3	7	17.3	7	14.9
Irrigation events per season for maize production	#	20	10.5	18	7.7	20	8.1	18	8.5
Irrigation water applied per season	mm	1089	204	779	148	1089	157	779	164
Total rainfall per crop growing season	mm	204	179	216	204	204	179	216	204
Rainfall + irrigation	mm	1293	384	995	352	1293	337	995	368
Grain maize yield	kg/ha	2500	2664	2000	3356	2500	3354	2000	4693
Water productivity	kg/m^3	0.19	0.69	0.20	0.95	0.19	1.00	0.20	1.28

Source: Authors' own data.

$$WP = \frac{Crop\ Yield\ (kg)}{\text{Water applied to produce that yield m3}(i.e. \sum Water\ Applied + \sum Rainfall)}$$

where WP is the water productivity (kg/m^3).

Household surveys

Two household surveys have been undertaken; a baseline survey in 2014 and an end-of-project survey in 2017. The latter was done to investigate how the knowledge from the soil water and solute monitoring had been used and how the tools had influenced farmers' irrigation practices. The 20 farmers with the tools were included the survey. Selected results are compared to data collected in the baseline household survey, as reported in Moyo et al. (2015, Table 2).

The survey was administered to key decision-makers from the household. When two key informants were available, the survey was conducted with both at the same time. The survey was carried out by the researchers and a team of experienced enumerators. This team underwent a five-day training workshop prior to administering the survey. The survey was field tested and subsequently refined. Administering the survey generally took close to two hours. The team used local extension officers and scheme leaders to facilitate farmer participation.

The intention was to interview all the farmers that were part of the baseline survey: 68 from Mkoba and 100 from Silalatshani (Moyo et al., 2015). However, some attrition was encountered, and only 54 respondents were interviewed at Mkoba and 84 at Silalatshani in 2017. Of these respondents, 35 and 60 represented households without the tools in Mkoba and Silalatshani, respectively. Quantitative data were augmented by observations and reflection by the research team.

Data analysis

The survey data were entered and analyzed in SPSS and Microsoft Excel. The results were tested for normality using ANOVA, and descriptive statistics (means, standard deviation, standard errors and frequencies) were produced.

Results

Effect of soil monitoring tools on water productivity in maize production

The results of the end-of-project household survey and farmer field books show evidence of farmer-to-farmer learning at both schemes. Both the farmers with and those without the Chameleon and WFD lengthened the period between irrigation events and reduced the number of siphons used per irrigation event and the duration of the event (Table 3). This reduced the amount of water used, and saved time, for both sets of farmers.

WP increased for all farmers from the 2013/14 season to the 2016/17 season (Table 3). It is important to note that when the tools were introduced the WP was the same for those with and without the tools.

WP in the 2013/14 season was 0.19 kg/m^3 and 0.20 kg/m^3 at Mkoba and Silalatshani, respectively (Figure 8). In the 2016/17 season, this improved to 1.00 kg/m^3 and 1.28 kg/m^3

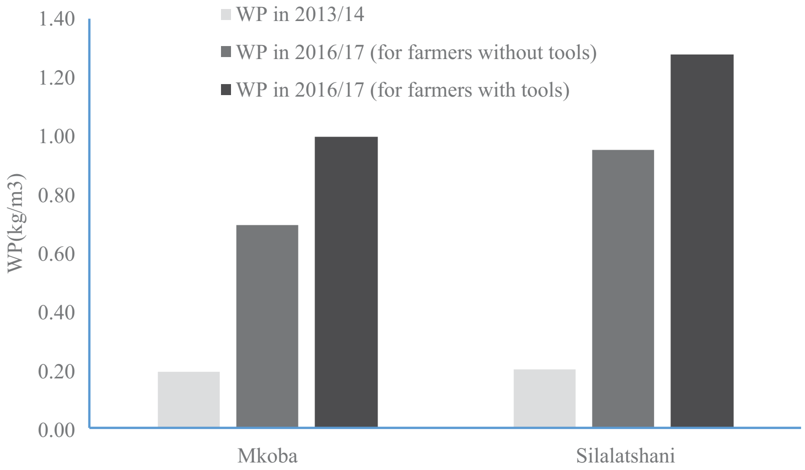

Figure 8. Water productivity (WP) before and after the introduction of the tools, for farmers with and without tools.

(for farmers with the tools) and to 0.69 kg/m^3 and 0.95 kg/m^3 (for farmers without the tools) at Mkoba and Silalatshani, respectively.

Relative value of rainfall and irrigation water in maize productivity

For the Mkoba farmers in the 2013/14 season, a total of 1089 mm (Table 3) of water was used for maize production, with rainfall and irrigation accounting for 16% and 84%, respectively. In the 2016/17 season, the proportion of irrigation water declined from 84% to 47% for farmers with the tools and from 84% to 53% for farmers without the tools, as farmers started skipping irrigation events.

The evidence from the field books data and from the end-of-project household survey presented in Table 3 shows that farmers both with and without tools increased the time between irrigation events and reduced the number of siphons used and the duration of the event, reducing the irrigation water used. The rainfall proportion of water input increased from 16% to 53% and from 16% to 47% for farmers with and without the tools, respectively (Figure 9). The proportion of rainfall water used in maize production increased, despite a decline in total rainfall during the growing period in 2016/17 compared to the 2013/14 season (Figures 6 and 7).

At Silalatshani, the rainfall in the 2016/17 growing season was 204 mm, compared to 216 mm in the 2013/14 season (Table 3). In the 2016/17 season (in comparison to the 2013/14 season), the proportion of irrigation water declined from 78% to 44% for farmers with the tools and from 78% to 42% for farmers without the tools, while the rainfall proportion increased from 22% to 56% and from 22% to 58% for farmers with and without the tools, respectively (Figure 9). Similarly, in Mkoba the proportion of rainfall water used in maize production increased, despite less total rainfall during the growing period in 2016/17 than in the 2013/14 season.

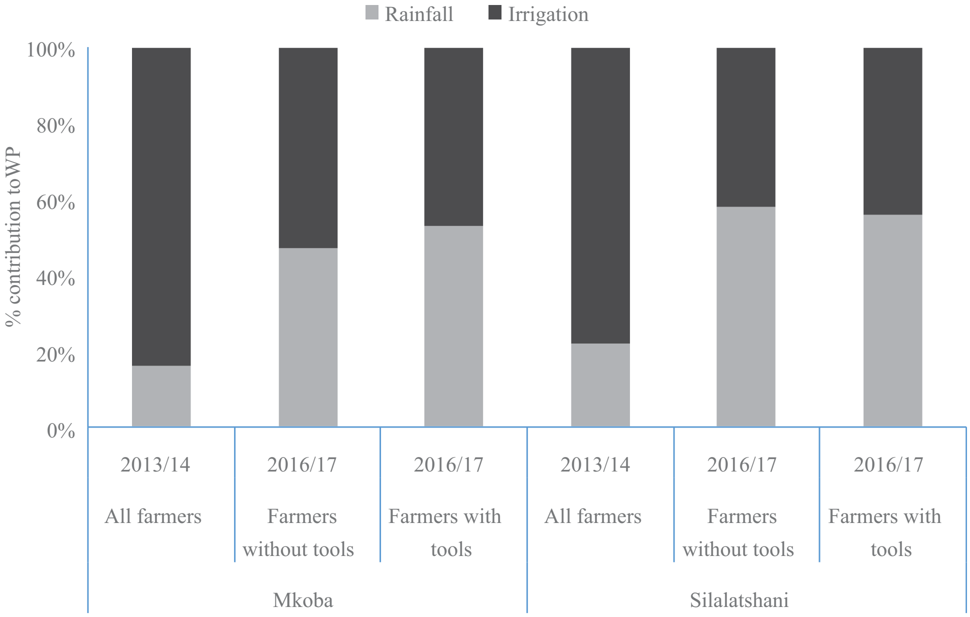

Figure 9. Relative contribution of rainfall and irrigation water to WP.

Monitoring tools and their influence on irrigation practices

Despite only 20 irrigators at each scheme having the monitoring tools, 96% and 89% of the surveyed households (at Mkoba and Silalatshani, respectively) were aware of them (Table 4). This has resulted in social learning, which is evidenced by the fact that changes in decision-making and action (and higher yields and income) also took place among farmers without tools as a result of observing and interacting with those that had the tools (Table 4). Farmers had a clear understanding that the tools help improve irrigation water management: to create awareness of moisture in the root zone and enable them to irrigate at the point of crop water need, using water more wisely.

Farmers know what the tools measure and what they are used for: 86% and 70% at Mkoba and Silalatshani, respectively (Table 5). The difference in proportion here is probably due to the higher density of tools in Mkoba than in Silalatshani. Farmers know that the Chameleon measures how wet or dry the soil is, and that the WFD is used together with the Chameleon to provide information on soil nutrients. This shows that farmers have integrated the knowledge gained from the monitoring tools to generate a better understanding of their farming system.

Comparing households' response to the Chameleon, 50% and 71% (with tools) and 56% and 51% of households (without tools) (where each pair of percentages is for Mkoba and Silalatshani, respectively) reported changing their farming practices. The proportion of households changing in response to the WFD was 70% and 45% (with tools) and 30% and 35% (without tools) for Mkoba and Silalatshani, respectively (Table 6). Approximately 90% of those who made changes in response to the Chameleon reduced their irrigation frequency. Major changes made in response to the WFD were to the timing and mode of fertilizer application. Although unquantified, farmers have reduced the quantity of fertilizer applied.

Table 4. Households' awareness and knowledge of the monitoring tools. All figures are percentages.

Engagement, awareness and changes	Mkoba With tools (n = 20)	Mkoba Without tools (n = 48)	Silalatshani With tools (n = 20)	Silalatshani Without tools (n = 80)
Households with soil monitoring tools	37		20	
Households aware of the tools (excluding those with tools)	–	96	–	89
Households that have reduced time taken to irrigate	40	44	47	28
Households that have reduced irrigation frequency	45	53	70	49
Households that know about the tools:				
Are aware of changes farmers have made because of the tools	100	79	100	66
Know what tools measure and what they are used for	100	77	100	63
Households that have made changes because of their learning from the:				
Chameleon	50	56	71	51
Wetting Front Detector	30	41	35	24
Households that changed practice from using the tools and also increased yields	70	94	67	84
Households that changed practice from using the tools and also increased income	30	50	83	46

Source: Authors' own data (end-of-project household survey).

Table 5. Households' knowledge about the tools (what the tools measure and what they are used for). All figures are percentages.

	Mkoba	Silalatshani
Farmers who know what the tools measure and what they are used for	86	70
Chameleon		
How easy it is for plant to access water	50	42
How wet or dry the soil is	80	86
Blue = wet	72	83
Green = wet but drying	74	81
Red = dry, irrigate	72	83
Different depths relative to plant root zone	35	44
Consist of reader and sensor array	41	41
WFD		
Rate of nutrient loss	22	39
Use two depths	37	54
Used together with the Chameleon	37	54
Pops up when full	57	85
Amount of solute in water	34	42

Farmers' benefits and well-being increases

Farmers reporting changes in yield and income during the project period report increased yields of 25% or more for their major irrigated crops, for 86% and 76% of households at Mkoba and Silalatshani, respectively (Figure 10). Income increases of 25% or more were reported by 43% of households at Mkoba, and 56% at Silalatshani. These findings confirm that yield and therefore income can increase despite a lower frequency and duration of water supply and fertilization (Table 6). Note that the maize WP data relate to the farmers' main crop, whereas the survey data relate to all crops grown in the last four years.

The higher income has led to self-reported more spending; 40% of farmers at Mkoba and Silalatshani are spending more money than they did four years ago on many activities to improve household well-being, including irrigation, farm inputs, food, education, and within the home (Figure 11). Spending on education, food and other household needs are

Table 6. Changes made by farmers in response to monitoring tools. All figures are percentages.

	Mkoba		Silalatshani	
	With tools	Without tools	With tools	Without tools
Changed their farming practices based on what they learned from the Chameleon	50	56	71	51
Reduced irrigation frequency	45	51	63	46
Reduced the time to finish irrigating the plot	40	15	25	13
Reduced the amount of water used to irrigate	35	15	35	12
Changed their farming practices as a result of what they learned from the Wetting Front Detector	70	30	65	35
Reduced the quantity of fertilizer applied	55	18	45	8
Split fertilizer, applying small doses more frequently	44	6	45	6
Synchronized the timing of fertilizer application with nutrient availability in the soil (based on the Wetting Front Detector)	41	6	45	3
Reduced irrigation frequency	10	15	13	9

the main incentives for change. Therefore, these are critical indicators for sustainable change in systems: greater investment in food and greater productivity, learning and education is a direct route out of poverty (Oxford Poverty and Human Development Initiative, 2018). This increase in spending also reflects higher confidence in the community to accumulate or improve assets.

Use of the Chameleon and WFD (the tools) and changes in conflict

There is evidence that bringing all the irrigation stakeholders together (including farmers, extension, market players, irrigation engineers, and institutions that govern water and the

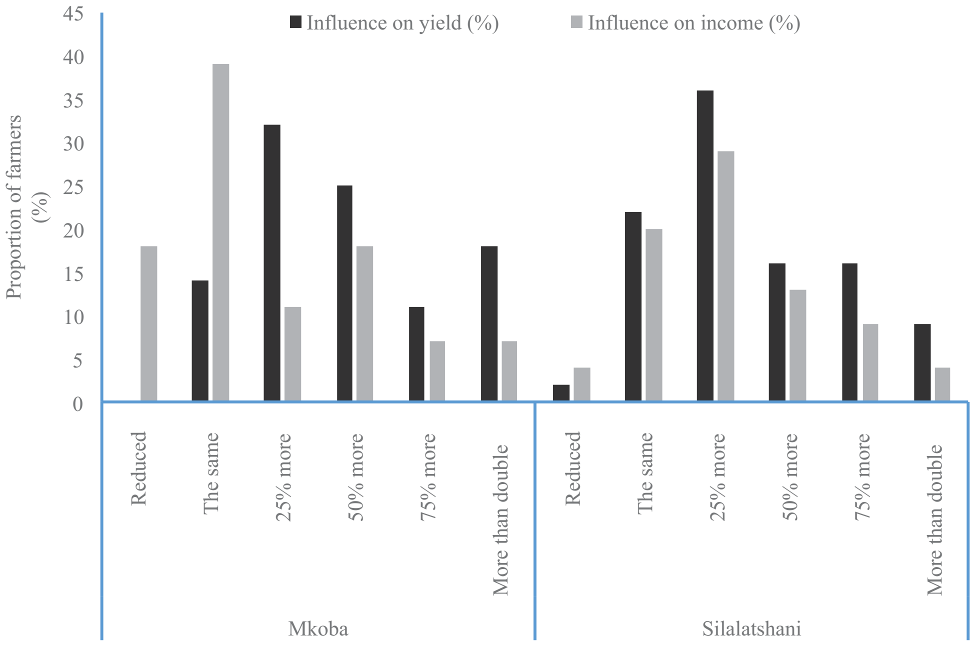

Figure 10. Influence of changes on households' yield and income (for those reporting changes).

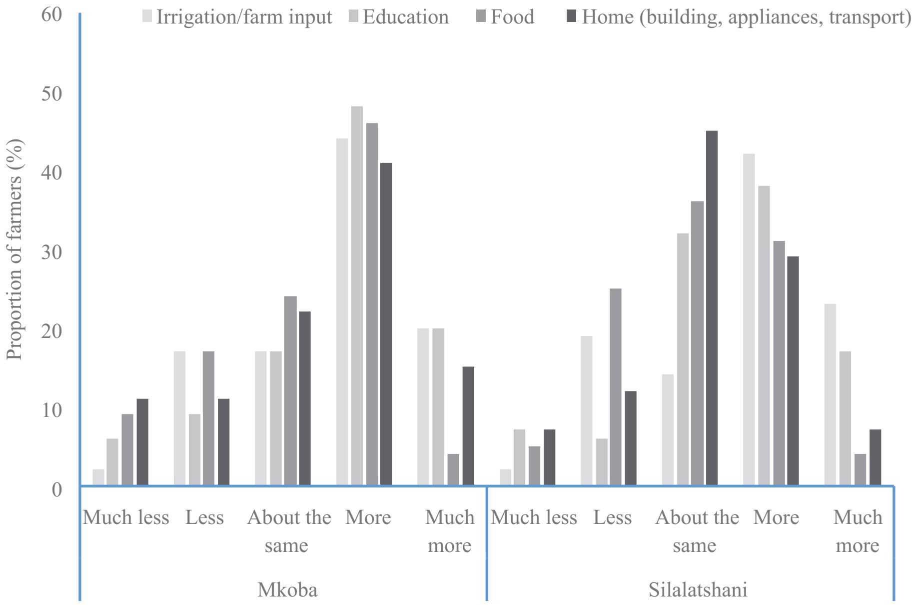

Figure 11. Changes in household spending patterns in the last four years (showing the proportion of farmers now spending on different activities compared to four years ago).

communities in the study areas) through the AIP process and using the tools has reduced the level of water-related conflict within the scheme and between irrigators and other water users (Figure 12). The Chameleon and WFD increased time between irrigation

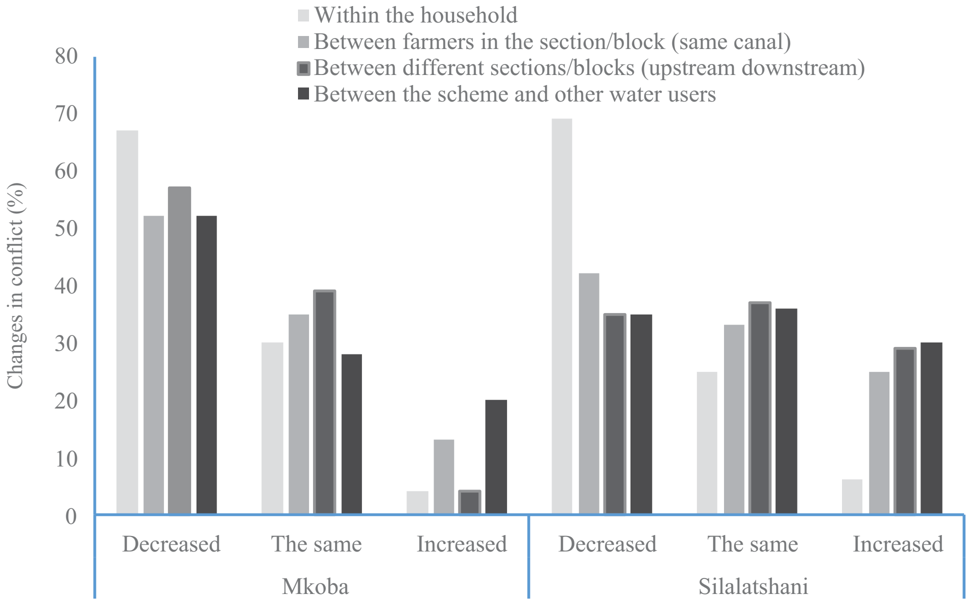

Figure 12. Households' perceptions of changes in conflict within the scheme over the last four years.

events, reducing the amount of water used. Consequently, there was less competition for water among irrigators, and more water in the storage dams. This led to less conflict among irrigators.

Discussion

The data indicate that these tools can answer the question of when to irrigate, and how much. Irrigation influences the availability of nutrients in the root zone, which is critical to the success of irrigated agriculture. The outcome of better water and nutrient management is that farmers begin to make informed decisions, which generates confidence and trust and helps manage risk. The findings indicate a cascading array of transformative changes, where impacts at the plot level have influenced household well-being and scheme productivity. This has resulted in important flows of information between the bio-physical and socio-economic aspects of the irrigation system. These dynamics are presented in the influence diagram of Figure 13. The linearity implied here simplifies a more complex system; it elicits the complexity of the smallholder systems and how there are feedback loops that directly and indirectly contribute to improve the productivity and profitability of the irrigation systems.

This research shows that soil monitoring tools and associated learning can improve the WP of irrigated agriculture, which is critical to improving water management under climate variability and predicted climate change (Target 6.4 of the Sustainable Development Goals). The maize WP results in this study are comparable to other WP results in similar environments. WP of 0.67 kg/m^3 has been reported for maize grown using conventional fertilizers under rainfed conditions in the Chihota Communal Lands (Marondera, Zimbabwe), where soils are predominantly sandy (Guzha et al., 2005). Pazvakavambwa and Van der Zaag (2000) found WP of 1.5 kg/m^3 for maize under irrigation for smallholder farmers in loamy sandy areas in Nyanyadzi, Zimbabwe.

The schemes are transforming farming from being almost totally dependent on irrigation water (as farmers were irrigating on a weekly basis regardless of rainfall) to farmers now only irrigating to supplement rainfall to meet crop water requirements. The proportion of rainfall used by crops has increased as the amount of irrigation decreased, especially in the sandier Mkoba scheme. This suggests that rainfall is much better utilized than before. In the 2016/17 season, the proportion of rainfall used in maize production increased, despite a decline in total rainfall. This illustrates the value of the tools as climate-smart technologies. Using the Chameleon to assess soil moisture, the contribution of rainfall can now be factored into decision-making on whether or not to irrigate, and this is a critical paradigm shift in how many farmers, and support services, view the role of irrigation systems. Better WP is critical to help transition existing unproductive systems to more productive systems and may well justify investments in increasing the area under irrigation (Senzanje et al., 2003).

The tools provide an effective learning environment for farmers to understand soil and water dynamics, which informs their decision-making on irrigation scheduling and improves yields (Parry et al., 2020). In this way, the tools could be a breakthrough towards more adaptive irrigation practices, which have been limited in Africa. One of the greatest hindrances to adoption has been the complexity of monitoring tools. The Chameleon overcomes this with a highly intuitive interface, eliminating the need for calibration for

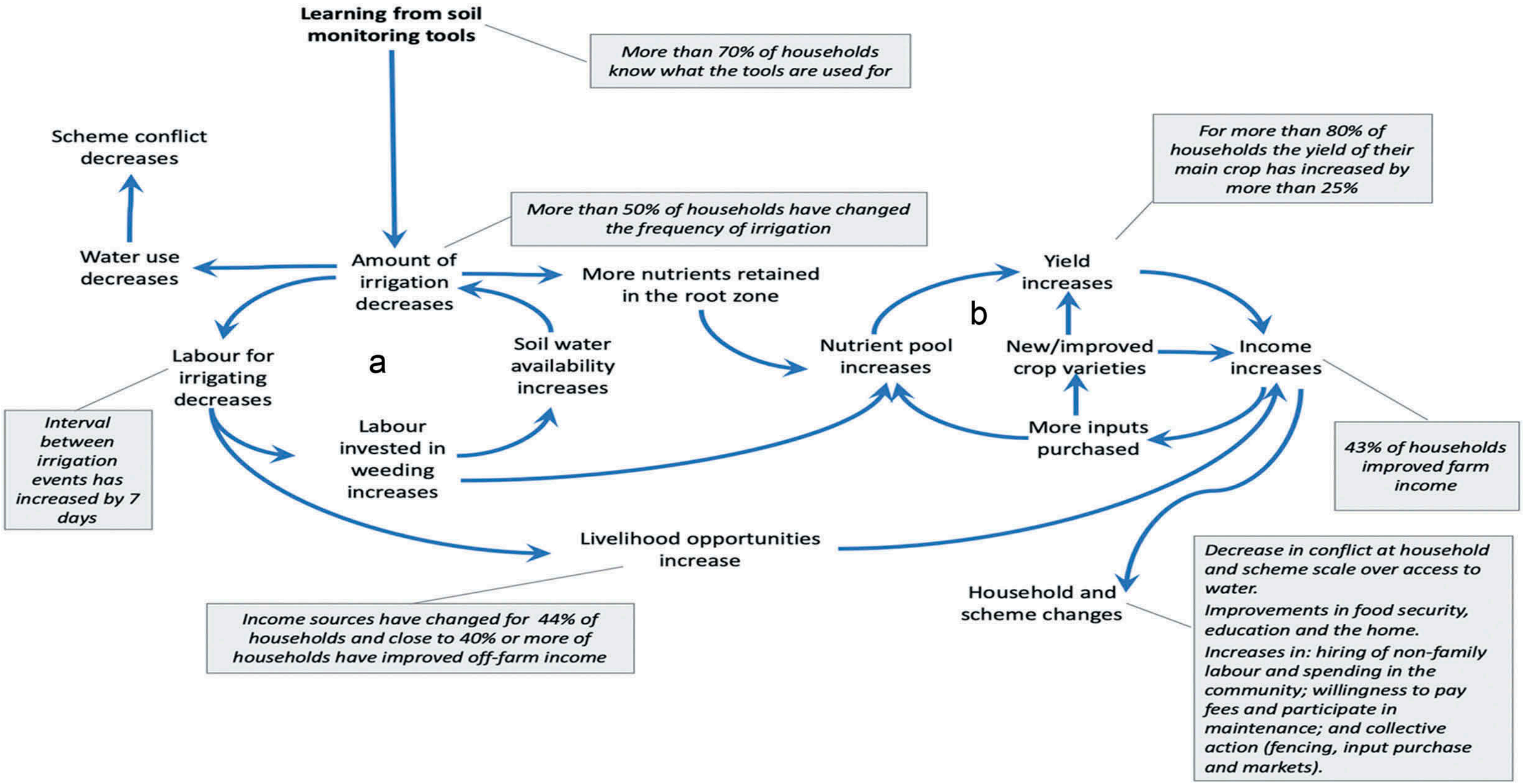

Figure 13. Influence diagram illustrating the systemic changes brought about by the soil moisture and nutrient monitoring tools (Loop A) and the AIP (Loop B) at Silalatshani irrigation scheme (Van Rooyen et al., 2020).

different soil types and temperature and providing immediate information on soil moisture and nutrients. The immediacy of feedback on the impact of previous irrigation and rainfall events facilitates decision-making at the plot level (Van Rooyen et al., 2020). The tools offer most of the irrigation scheduling advantages identified by Stevens et al. (2005), enabling farmers to schedule watering to minimize crop water stress and optimize yields.

The findings of this study suggest that the high proportion of behavioural change is the direct result of two independent feedback mechanisms reducing water use: the availability of nutrients in the root zone and subsequent increased yields; and the significant labour saving from reduced irrigation, which allows more time for weeding and other livelihood activities. More weeding reduces competition for water and nutrients, increasing the water and nutrient pool for crops and further increasing yields. Using the tools increased the interval between irrigation events, reducing the amount of water used. This reduced competition for water among farmers and thus reduced conflict over water at various levels within and beyond the irrigation scheme (Van Rooyen et al., 2020).

We find that these tools are people-centred, facilitating experimental and social learning suitable for smallholder irrigators. Farmers both with and without the tools reduced their irrigation frequency and increased WP. Farmers learnt that skipping irrigation events had no adverse effect on crop performance, and as confidence grew, they skipped irrigation opportunities more often. Farmers entered a process of experimental learning, and over time also reduced the number of siphons used and the duration of irrigating.

Note that a relaxation of the IMC’s strict scheduling rules, stimulated by the AIP, was critical in allowing farmers to experiment with different watering schedules. These findings strongly suggest that behavioural change resulted from the introduction of the monitoring tools, which open the possibility for experimentation and learning, particularly social learning (e.g., new irrigation frequencies) (Parry et al., 2020); and from having mechanisms, such as an AIP, to address contextual barriers.

Learning from the monitoring tools (*A* in Figure 13) makes a critical contribution to overall system efficiency, but it may not be enough to maintain the positive interactions and outcomes (Van Rooyen et al., 2020). With more water and nutrients resulting in higher yields, there is a dire, but often neglected, need to ensure the functioning of input and output markets and the associated information flows between these markets and farmers. Increasing the yields of crops with low market potential and low gross margins will only result in more waste and still no resources to pay for water, inputs and other household needs. Thus, enterprise selection and associated market linkages are critical.

The AIP played a critical role in facilitating the experimental learning from using the tools. Although this article’s focus is not on the AIP (*B* in Figure 13), AIPs were instrumental in stimulating the learning around gross margins; integrating private-sector players into the AIP; establishing links between farmers and input and output markets; and facilitating information flows (Van Rooyen et al., 2020). This resulted in better market engagement with farmers able to sell their more profitable produce at higher prices, generating the income that allowed greater investments in inputs and other livelihood needs. This loop in the influence diagram is critical, as greater market engagement is the major driver of the changes in the behaviour observed in *A*. Without better market access, post-harvest losses will negate all the efforts in system improvements. If higher yields do not increase household benefits, the system cannot be sustained. Through this project, farmers reported higher yields associated with higher incomes, but this only happens if farmers also increase their investment in agriculture.

All too often research and development projects neglect the incentives required for large-scale behavioural change to take place, such as farmers' need to spend on education, health, food and nutrition, which are the non-monetary measures of deprivation experienced by poor people and components of the Multidimensional Poverty Index (Oxford Poverty and Human Development Initiative, 2018). Better household assets indicate substantial improvements in the quality of life and basic living standards. These are important indicators and should be measured to assess the real impact of rural research and development projects (Burney & Naylor, 2012).

The foregoing statements regarding sustainability are reinforced by the fact that more farmers are willing and able to pay for water and to engage in scheme maintenance (Figure 13), which was part of the farmers' future vision, articulated in the first AIP meeting (Van Rooyen et al., 2017). Earlier, we postulated that hardware decay is a symptom of dysfunctional systems. This suggests that the main challenge faced by smallholder irrigation schemes in the developing world, especially those managed by governments, is the contradictory objectives of the governments who oversee them, the IMCs who manage them and the irrigators who eke out a living on them. Governments want to ensure food security, a concept that isolates schemes from market engagement; and without incomes from markets, farmers can neither pay their water bill nor invest in inputs to meet basic livelihood requirements. This results in system failure. Irrigated plots produce as little as or less than dryland plots; costs and levies accumulate; infrastructure is not maintained, and decays; and farmers abandon the most limiting resource irrigation schemes offer: water (Moyo et al., 2017). Transforming schemes from subsistence to market-oriented production systems is the minimum requirement to achieve sustainable and profitable smallholder irrigation systems (Bjornlund et al., 2017). Soil monitoring is a valuable tool, but its implementation needs to be understood in the current context of a scheme. Whilst the 'fit' may be appropriate (cheap, simple to use and providing useful information), it might not be adopted for the long term if other systemic barriers are not addressed.

Conclusions

Soil moisture and nutrient monitoring tools provide the data farmers need to make decisions about when to irrigate, which results in efficient use of rainfall, irrigation water and fertilizer, and greater production. Putting these tools in the hands of farmers was a critical entry point in facilitating this change, as learning leads to behavioural change when the right incentives are in place. Transferring irrigation decision-making from authorities (such as the IMC) to farmers allows local-level experimentation and learning and sets the scene towards co-management. The IMCs allowed the farmers to irrigate as and when they needed (following the colours from the tools). This single intervention in the system (tools provision and facilitating learning) has multiple outcomes, including higher yield, better water use and better labour utility, all contributing to human well-being and to environmental sustainability targets. However, for this to have its full impact, policy-makers must institute processes and improve capacity to allow farmers and support services to maximize the benefits from the learning. This includes supporting farmers to make their own decisions, informed by appropriate information, rather than continuing a top-down approach to scheme management. Policy-makers should facilitate processes that allow local-level experimentation and learning. Further, development of new irrigation schemes should allow flexible water delivery to plots based on soil water monitoring, as described in this article.

The use of the monitoring tools has brought numerous anticipated and unexpected impacts and outcomes, which has produced a strong set of incentives for technology adoption and adaptation: farmers have essentially turned a water-saving device into a labour-saving device. Significant water savings have resulted from 'rich' innovations in how watering of the plots can be reduced: changing the frequency of irrigation, as well as reducing the number of siphons and the duration of irrigation events. The tools offer the means of maximizing the benefit of rainwater.

There is evidence that the schemes behave like complex adaptive systems. To bring about large-scale systemic changes in smallholder irrigation in Africa, there must be a move from linear technical approaches (such as fixing hardware only) towards more holistic systems approaches that require understanding the incentives for change (for all actors, but farmers in particular). This project clearly illustrates that there are relatively simple interventions to increase water productivity, reduce nutrient leaching, and increase crop yields and profitability, but only if these technologies are embedded in a wider learning environment where other important feedback mechanisms, such as labour constraints and market opportunities, are addressed.

Acknowledgments

This research was part of project Increasing Irrigation Water Productivity in Mozambique, Tanzania and Zimbabwe through On-Farm Monitoring, Adaptive Management and Agricultural Innovation Platforms and funded by the Australian Centre for International Agricultural Research [grant no. FSC/2013/006]. The project was also supported by the CGIAR Research Program on Water, Land and Ecosystems and CGIAR Fund Donors.

Disclosure Statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Australian Centre for International Agricultural Research [LWR-2016-137], CGIAR Research Program on Water, Land and Ecosystems, and CGIAR Fund Donors.

ORCID

Martin Moyo http://orcid.org/0000-0002-5496-7554
André Van Rooyen http://orcid.org/0000-0003-2035-049X
Henning Bjornlund http://orcid.org/0000-0003-3341-5635
Karen Parry http://orcid.org/0000-0003-0045-6967

Richard Stirzaker http://orcid.org/0000-0001-6956-4179
Thabani Dube http://orcid.org/0000-0001-6394-8083

References

Bjornlund, H., Parry, K., Pittock, J., Stirzaker, R., Van Rooyen, A. F., Moyo, M., Mdemu, M., de Sousa, W., Cheveia, E., Munguambe, P., Kimaro, E., Kissoly, L., Chilundo, M., Zuo, A., & Ramshaw, P (2018). *Transforming smallholder irrigation into profitable and self-sustaining systems in southern Africa*. Technical Report. K-water and the International Water Resources Association (IWRA).

Bjornlund, H., Van Rooyen, A., & Stirzaker, R. (2017). Profitability and productivity barriers and opportunities in smallholder irrigation schemes. *International Journal of Water Resources Development*, *33*(5), 685–689. https://doi.org/10.1080/07900627.2017.1326881

Burney, J. A., & Naylor, R. L. (2012). Smallholder irrigation as a poverty alleviation tool in sub-Saharan Africa. *World Development*, *40*(1), 110–123. https://doi.org/10.1016/j.worlddev.2011.05.007

Cai, X., Molden, D., Mainuddin, M., Sharma, B., Ahmad, M.-D., & Karimi, P. (2011). Producing more food with less water in a changing world: Assessment of water productivity in 10 major river basins. *Water International*, *36*(1), 42–62. https://doi.org/10.1080/02508060.2011.542403

Department of Irrigation Development. (2012). Unpublished draft 1 of National irrigation policy and strategy and regulatory measures (2012–2032). Harare: Ministry of Agriculture Mechanisation and Irrigation Development.

Easterling, W. E. (2007). Climate change and the adequacy of food and timber in the 21st century. *Proceedings of the National Academy of Sciences*, *104*(50), 19686–19690. https://doi.org/10.1073/pnas.0710388104

FAO, IFAD, UNICEF, WFP and WHO. (2018). *The state of food security and nutrition in the world 2018: Building climate resilience for food security and nutrition*. FAO.

Government of Zimbabwe. (2012). *Zimbabwe Agricultural Investment Plan (ZAIP: 2013–2018): A comprehensive framework for the development of Zimbabwe's agriculture sector*.

Guzha, E., Nhapi, I., & Rockstrom, J. (2005). An assessment of effect of human faeces and urine on maize production and water productivity. *Physics and Chemistry of the Earth.*, *30*(11–16), 840–845. https://doi.org/10.1016/j.pce.2005.08.028

Inocencio, A., Kikuchi, M., Tonosaki, M., Maruyama, A., Merrey, D., Sally, H., & de Jong, I. (2007). *Costs and performance of irrigation projects: A comparison of sub-Saharan Africa and other developing regions*. Research Report 109. International Water Management Institute. https://doi.org/10.1094/PDIS-91-4-0467B

Jacobs, C., Chitima, M., van 'T Klooster, K., & Bwanali, K. (2013). *Determinants of the productivity and sustainability of irrigation schemes in Zimbabwe & pre-investment framework* (Final report 30 May 2013). Alterra, Department of Irrigation and JICA Expert.

Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., & Lucht, W. (2015). Water savings potentials of irrigation systems: Global simulation of processes and linkages. *Hydrology and Earth System Sciences*, *19*(7), 3073–3091. https://doi.org/10.5194/hess-19-3073-2015

Kassam, A. H., Molden, D., Fereres, E., & Doorenbos, J. (2007). Water productivity: Science and practice. Introduction. *Irrigation Science*, *25*(3), 185–188. https://doi.org/10.1007/s00271-007-0068-x

Mosello, B., Oates, N., & Jobbins, G. (2017). *Pathways for irrigation development: Policies and irrigation performance in Zimbabwe*. PRISE working paper. http://prise.odi.org/research/pathways-for-irrigation-development-policies-and-irrigation-performance-inzimbabwe/

Moyo, M., Moyo, M., & van Rooyen, A. (2015). *Increasing irrigation water productivity in Mozambique, Tanzania and Zimbabwe through on-farm monitoring, adaptive management and Agricultural Innovation Platforms: Mkoba and Silalatshani irrigation schemes in Zimbabwe* (FSC-2013-006). ANU.

Moyo, M., van Rooyen, A., Moyo, M., Chivenge, P., & Bjornlund, H. (2017). Irrigation development in Zimbabwe: Understanding productivity barriers and opportunities at Mkoba and Silalatshani irrigation schemes. *International Journal of Water Resources Development*, *33*(5), 740–754. https://doi.org/10.1080/07900627.2016.1175339

Mtisi, S., & Nicol, A. (2003). *Caught in the act: New stakeholders, decentralisation and water management processes in Zimbabwe*. Institute of Development Studies, University of Sussex.

Mutiro, J., & Lautze, J. (2015). Irrigation in southern Africa: Success or failure? *Irrigation and Drainage*, *64*(2), 157–298. https://doi.org/10.1002/ird.v64.2

Myeni, L., Moeletsi, M., & Clulow, A. (2019). Present status of soil moisture estimation over the African continent. *Journal of Hydrology: Regional Studies*, *21*, 14–24. https://doi.org/10.1016/j.ejrh.2018.11.004

Olivier, F. O., & Singels, A. (2004). Survey of irrigation scheduling practices in the South African sugar industry. *Proceedings of the South African Sugar Technologists Association*, *78*, 239–244.

Oxford Poverty and Human Development Initiative. (2018). *Global multidimensional poverty index 2018: The most detailed picture to date of the world's poorest people*. University of Oxford.

Parry, K., van Rooyen, A., Bjornlund, H., Kissoly, L., Moyo, M., & Chilundo, M. (2020). The importance of learning processes in transforming smallholder irrigation schemes. *International Journal of Water Resources Development*.

Pazvakavambwa, G. T., & Van der Zaag, P. (2000, November 1–2). The value of irrigation water in Nyanyadzi smallholder irrigation scheme, Zimbabwe. *Proceedings of the 1st WARFSA/Water Net/GWP symposium: Sustainable use of water resources*, Maputo.

Perry, C. (2011). Accounting for water use: Terminology and implications for saving water and increasing production. *Agricultural Water Management*, *98*(12), 1840–1846. https://doi.org/10.1016/j.agwat.2010.10.002

Perry, C., Steduto, P., Allen, R. G., & Burt, C. M. (2009). Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. *Agricultural Water Management*, *96*(11), 1517–1524. https://doi.org/10.1016/j.agwat.2009.05.005

Portmann, F. T., Siebert, S., & Döll, P. (2010). MIRCA2000: Global monthly irrigated and rainfed crop areas around the year 2000. A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, *24*(1), GB1011. https://doi.org/10.1029/2008GB003435

Ronco, P., Zennaro, F., Torresan, S., Critto, A., Santini, M., Trabucco, A., & Marcomini, A. (2017). A risk assessment framework for irrigated agriculture under climate change. *Advances in Water Resources*, *110*, 562–578. https://doi.org/10.1016/j.advwatres.2017.08.003

Rukuni, M. (1984). *An analysis of economic and institutional factors affecting irrigation development in communal lands of Zimbabwe*. Doctoral dissertation, University of Zimbabwe.

Samakande, I., Senzanje, A., & Manzungu, E. (2004). Sustainable water management in smallholder irrigation schemes: Understanding the impact of field water management on maize productivity on two irrigation schemes in Zimbabwe. *Physics and Chemistry of the Earth*, *29*(15–18), 1075–1081. https://doi.org/10.1016/j.pce.2004.08.009

Senzanje, A., Samakande, I., Chidenga, E., & Mugutso, D. (2003). Field irrigation practice and the performance of smallholder irrigation in Zimbabwe: Case studies from Chakohwa and Mpudzi irrigation schemes. *Journal of Agriculture, Science and Technology*, *5*, 1–21.

Sithole, E. (2002). Gender analysis of agrarian laws in Zimbabwe: A report. Prepared for Women and Land in Zimbabwe. http://www.kubatana.net/docs/women/wlz_gen_analysis_agrilaws_zim_0207.pdf

Stevens, J. B., Duvel, G. H., Steyn, G. J., & Marobane, W. (2005). *The range, distribution and implementation of irrigation scheduling models and methods in South Africa*. Report No. 1137/1/05. Water Research Commission.

Stirzaker, R., Mbakwe, I., & Mziray, N. (2017). A soil and water solute learning system for smallholder irrigators in Africa. *International Journal of Water Resources Development*, *33*(5), 788–803. https://doi.org/10.1080/07900627.2017.1320981

Stirzaker, R. J. (2003). When to turn the water off: Scheduling micro-irrigation with a wetting front detector. *Irrigation Science*, *22*(3–4), 177–185. https://doi.org/10.1007/s00271-003-0083-5

Stirzaker, R. J. (2006). *Soil water monitoring: State of play and barriers to adoption*. Irrigation Matters Series 01/06. CRC for Irrigation Futures.

Stirzaker, R. J., Stevens, J. B., Annandale, J. G., & Steyn, J. M. (2010). Stages in the adoption of a wetting front detector. *Irrigation and Drainage*, *59*(4), 367–376. https://doi.org/10.1002/ird.v59:4

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, *108*(50), 20260–20264. https://doi.org/10.1073/pnas.1116437108

van der Laan, M., Jumman, A., & Perret, S. R. (2015). Environmental benefits of improved water and nitrogen management in irrigated sugar cane: A combined crop modelling and life cycle assessment approach. *Irrigation and Drainage*, *64*(2), 241–252. https://doi.org/10.1002/ird.v64.2

van der Laan, M., Stirzaker, R. J., Annandale, J. G., Bristow, K. L., & Du Preez, C. C. (2010). Monitoring and modelling draining and resident soil water nitrate concentrations to estimate leaching losses. *Agricultural Water Management*, *97*(11), 1779–1786. https://doi.org/10.1016/j.agwat.2010.06.012

van Rooyen, A., Moyo, M., Bjornlund, H., Dube, T., Parry, K., & Stirzaker, R. (2020). Identifying leverage points to transition dysfunctional irrigation schemes towards complex adaptive systems. *International Journal of Water Resources Development*. https://doi.org/10.1080/07900627.2020.1747409

van Rooyen, A., Ramshaw, P., Moyo, M., Stirzaker, R., & Bjornlund, H. (2017). Theory and application of agricultural innovation platforms for improved irrigation scheme management in southern Africa. *International Journal of Water Resources Development*, *33*(5), 804–823. https://doi.org/10.1080/07900627.2017.1321530

Vincent, V., & Thomas, R. G. (1961). *An agricultural survey of southern Rhodesia (now Zimbabwe), Part 1. Agro-ecological survey*. Government Printers.

Virtual Irrigation Academy (2019). *The Virtual Irrigation Academy*. https://via.farm/

Yokwe, S. (2009). Water productivity in smallholder irrigation schemes in South Africa. *Agricultural Water Management*, *96*(8), 1223–1228. https://doi.org/10.1016/j.agwat.2009.03.012