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A soil water and solute learning system for small-scale irrigators in Africa

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ABSTRACT

Better yields of high-value crops are necessary for a profitable irrigation industry in sub-Saharan Africa. We introduced two simple tools, the Chameleon soil moisture sensor and the FullStop wetting front detector, which represent soil water, nitrate and salt levels in the soil by displaying different colours. These tools form the basis of an experiential learning system for small-scale irrigators. We found that farmers quickly learned from the tools and changed their management within a short time. The cost of implementing a learning system would be a small fraction of that of building or revitalizing irrigation schemes.

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Introduction

Irrigation in sub-Saharan Africa has, for the most part, failed to live up to its potential. Irrigated land is currently less than 5% of the total cultivated area, and expansion has been slow. During a 40-year period when the irrigated land in China and India increased by 57 million ha, irrigated land in sub-Saharan Africa increased by just 4 million ha (World Bank, 2008). Many irrigation schemes have fallen into disrepair; up to two-thirds of the land with existing irrigation infrastructure in Mozambique lies unused (Chilundo, Brito, & Munguambe, 2004), and over half of the smallholder schemes in South Africa that rely on pumping are no longer operational (van Averbeke, Denison, & Mnkeni, 2011). Historically, irrigation projects in sub-Saharan Africa have been more expensive than in other developing regions, and had a lower probability of generating a return on investment (Inocencio et al., 2007). As a consequence, investment in irrigation by donors during the mid-1990s had fallen to just one-tenth of what it was two decades prior (World Bank, 2008).

Yet there are also positive signs for irrigation in the region. Svendsen, Ewing, and Msangi (2009) report that despite the small area of irrigation, the value of irrigated agriculture in sub-Saharan Africa is about 25% of the total agricultural output. Land and water resources are available for a large expansion of the irrigated area (Xie, You, Wielgosz, & Ringler, 2014). The emergence of the private irrigation sector shows great promise (de Fraiture & Giordano,

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2014; Wichelns, 2014), and annual net revenues of USD 40 billion could flow from the development of small reservoirs and the use of motorized pumps, benefiting hundreds of millions of farmers (Giordano, de Fraiture, Weight, & van der Bliek, 2012). In their review of irrigation as a poverty alleviation tool for sub-Saharan Africa, Burney and Naylor (2012) argue that too many technologies offered to small-scale farmers offer such marginal benefits that they will not get farmers out of poverty, but that irrigation can help farmers break the "multi-scale poverty trap".

Inocencio et al. (2007) found that irrigation projects in sub-Saharan Africa are not intrinsically more expensive or less successful than anywhere else, provided that a number of lessons are heeded. These lessons include: (1) allocating more funds towards better technical assistance, design and management in the construction phase; (2) better agricultural support, institution building, and training of agency staff and farmers after the construction phase; and (3) moving operation and maintenance from the sole responsibility of government to more fully involving the farmers. Donor funding for irrigation projects has increased since the mid-1990s (World Bank, 2008), and a renewed commitment to irrigation has been captured in the Comprehensive Africa Agriculture Development Programme (CAADP, 2009). The Malabo Declaration, signed by the heads of state and government of the African Union in June 2014, records "efficient and effective water management systems notably through irrigation" as one of their commitments for ending hunger in Africa by 2025. In short, the physical resources, financial backing and political will are in place to realize a rapid increase in irrigated area in sub-Saharan Africa. The extent to which this will translate into a profitable irrigation sector hinges on: (1) good water governance; (2) farmer access to functioning markets; and (3) the agronomic and water management skills of the small-scale irrigator. This article explores point 3 above and describes the use of soil water and nutrient monitoring tools that could underpin a learning system necessary to increase the profitability of small-scale irrigation in Africa.

A learning system

The Comprehensive Africa Agriculture Development Programme (CAADP, 2009, p. 24) lists one of the key elements for successful water management projects as "people-centred learning":

> Based on innovative and participatory adult learning methods, this involves guided practical field-based investigations through which land users learn for themselves.... They also learn how to identify ways of addressing these challenges through observation, testing and monitoring of different treatments as well as reviewing and sharing findings through subgroups and plenary discussions within common interest groups.

Traditionally, irrigation has not been taught this way. The FAO produced a set of training manuals to support smallholder irrigation in the 1980s, with *Irrigation Water Needs* (Training Manual No. 3) dealing with the principles for calculating irrigation requirements (Brouwer & Heibloem, 1986). The manual is divided into two parts, with Part 1 intended for use by "village level extension workers" and Part 2 by "irrigation technicians at the village and district levels". The information is laid out simply, with tables, charts and worked examples to determine potential crop water use and effective precipitation, and hence irrigation requirements. Similarly, in a comprehensive manual for training extension advisers to small-scale farmers in South Africa, Stevens and Buys (2012) use quantitative estimates of the crop, climate and soil parameters that interact to produce an irrigation requirement. For example, estimates of potential evaporation, crop coefficient, effective rainfall, allowable soil moisture depletion and rooting depth are all required as inputs to calculate the required irrigation amount. Each variable needs to be measured or estimated, and is associated with uncertainty, and thus prone to error. But even if the final answer is the correct one, it might be impractical for a farmer to implement in real-world situations. How does a farmer, for example, apply 27 mm of irrigation when flooding a field from an earthen canal?

The crux of the problem is that scientists and farmers operate from very different mental models. The mental model of scientists is based on theory, which enables clear communication among specialists, and quantification and extrapolation of basic principles to new situations. The mental models of the farmers are built around their experience and local knowledge (Abel, Ross, & Walker, 1998). Farmers use their experience to build a mental construct that allows them to predict what might happen next and react accordingly. When an extension worker tries to tell farmers to change their irrigation practice, the message is filtered through the farmers' mental model and may be distorted or ignored if the extension message conflicts with farmers' experience or understanding (Abel et al., 1998).

Although the training of irrigation extension workers falls overwhelmingly within an engineering paradigm, as evidenced by the manuals above, there are calls to move towards an experiential learning system more likely to fit the mental models of the farmers. In their 2012 report, 'Coping with Water Scarcity', the Food and Agriculture Organization (FAO, 2012, p. xv) comes up with the following summary:

> Planning and management systems need to be flexible, adaptive and based on continuous social and institutional learning. Adaptive management recognizes the high level of uncertainty associated with future situations, and places emphasis on flexible planning that allows regular upgrading of plans and activities. Such a level of responsiveness is only possible if information and knowledge are updated, and if monitoring and information management systems continually provide decision-makers with reliable information.

There are clearly two ways of tackling the irrigation knowledge problem. The method favoured in training materials is a first-principles approach requiring climate, crop and soil data that are manipulated through a set of calculations to provide a predicted irrigation volume to farmers. The alternative, going under the term people-centred learning, experiential learning or adaptive management, requires observation, monitoring and feedback. If the latter is deemed to be the way forward for small-scale irrigators, how would it be put into practice? What can farmers observe to give themselves reliable feedback and stimulate learning?

Visual cues such as wilting are unreliable indicators of crop stress; in some cases yield can be reduced before wilting is observed, and in others, periods of midday wilting have no impact on yield (Stirzaker, Hayman, & Sutton, 1996). Observation of the soil surface can also be misleading, as a dry crust frequently overlays a moist root zone. Farmers obviously get some feedback from their water management and crop performance; even if the water applied is not quantified, experience would be accumulated by observing crop growth during periods of supplying more or less than average water. Our aim is to structure adaptive management of irrigation by providing tools that fit the mental models of the farmers so as to engage them in a learning-by-doing approach.

Methodology

Given that we are working with farmers with low literacy and numeracy, we are building an appropriate suite of tools to foster understanding around soil water and solute management through experiential learning. We start with three questions:

(1) What is the least information a farmer needs to make a better irrigation decision?
(2) What is the simplest way to provide it?
(3) How do we move from data, to understanding, to knowledge?

We have developed two tools to help irrigators who have little prior understanding of soil water dynamics. The first tool, the FullStop wetting front detector, is a funnel-shaped device buried in the soil with an indicator above the soil surface (Stirzaker, 2003). Water infiltrates the soil; the wetting front is the boundary between the wet soil above and the drier soil below. How deep the wetting front moves into the root zone is a function of the amount of water applied, the soil type and the initial soil water content. If the wetting front reaches the buried funnel, some of the infiltrating water is intercepted. As water moves down the funnel, the soil water content increases as the cross-sectional area of the funnel decreases, until saturation occurs. This water flows through a filter and into a reservoir, activating the magnetically latched indicator at the soil surface. The soil water sample captured by the detector can be extracted for monitoring of electrical conductivity and nitrate.

The Chameleon soil moisture sensor consists of an array of three or four sensors that are permanently installed at different depths in the soil. A portable hand-held reader is connected to each sensor array and displays the soil moisture as coloured lights (Stirzaker, 2014). Each depth is represented by a light, and each light can be blue (wet soil), green (moist soil) or red (dry soil). The lights give a picture of soil water conditions from the top to the bottom of the root zone. Successive readings through the season give a colour pattern that illustrates the wetting and drying of the soil, the depth of rooting and how well irrigation or rain refills the soil. The Chameleon measures soil tension, so that the colours have the same meaning for the farmer, regardless of the soil type. Both the Chameleon and the FullStop are described more fully at the Virtual Irrigation Academy website, https://via.farm/.

Soil nitrate and salt status is measured in the water sample captured by the FullStop. Most of the nitrogen available to the plants is in the form of nitrate, a negatively charged molecule that largely moves with the water and which is highly susceptible to leaching in irrigated situations (van der Laan, Stirzaker, Annandale, Bristow, & Preez, 2010). Using the water sample from the FullStop, nitrate was measured in the field using colour test strips (Merckoquant nitrate test strips, Merck, Germany). Salt build-up is also a major problem in irrigated areas, and electrical conductivity is monitored using a pocket meter (EcoTestr EC High, Eutech, Singapore).

The above tools were evaluated in two irrigation schemes in Zimbabwe, two in Mozambique and one in Tanzania (Table 1; described more fully in Moyo, van Rooyen, Moyo, Chivenge, & Bjornlund, 2017; de Sousa et al., 2017; Mdemu, Mziray, Bjornlund, & Kashaigili, 2017). At each scheme, 20 farmers were selected and each was provided with two FullStops and four Chameleons. A team member at each site was trained on how to install the equipment and take measurements and provided with a Chameleon reader, a pocket electrical conductivity meter and nitrate test strips. They were required to visit the schemes each week, take a Chameleon measurement, and record whether the FullStops had collected a water

Table 1. The scheme, main crops monitored, and placement depths of FullStop wetting front detectors and Chameleon soil moisture sensors.

Scheme	Irrigation method	Crops monitored	Wetting front depths (cm)	Chameleon depths (cm)
Kiwere, Tanzania	Gravity flood	Tomatoes	20, 50	20, 30, 40, 50
Silalatshani, Zimbabwe	Gravity flood	Maize	20, 40	15, 30, 45, 60
Mkoba, Zimbabwe	Gravity flood	Maize	20, 40	15, 30, 45, 60
Boane, Mozambique	Pump flood	Maize, cabbage	20, 40	15, 30, 45, 60
Khanimambo, Mozambique	Pump flood	Cabbage, onion	20, 40	15, 30, 45, 60

Table 2. The colour patterns used to illustrate water, nitrate and salt levels in the soil.

	Colour	Approximate value	Meaning
Water	Blue	<25 kPa	Soil layer is wet
	Green	25–50 kPa	Soil moisture is adequate for most plants
	Red	>50 kPa	Soil layer is dry
Nitrate	Light pink	<25 mg/L	Nitrate level is low
	Mid-pink	25–100 mg/L	Nitrate level is good
	Purple	>100 mg/L	Nitrate level is high
Salt	Green	<2 dS/m	Salinity acceptable for most plants
	Orange	2–4 dS/m	Salinity a potential problem
	Red	>4 dS/m	Salinity too high for most plants

sample. If so, the sample was removed using a syringe, the conductivity recorded and the nitrate measured on the test strip. The water, nitrate and salt readings were plotted weekly to produce colour patterns which communicated the information that would prompt farmers to take appropriate action (Table 2).

The study aimed to get answers to the following questions from the monitored data:

(1) Do the tools detect obvious problems with water, nitrate and salt status at each scheme (sites too dry, nitrate deficient or soil salty)?
(2) Can farmers understand the water, nitrate and salt colour patterns and act on the information?
(3) What constraints prevent farmers from acting on the monitored information?
(4) What is the value to the farmer of saving water?
(5) How is learning promoted through monitoring and observation of the colour patterns?

A project member visited the sites weekly or bi-weekly to discuss the monitored data with farmers. Farmers were not advised to change practice at any time, but only told what the colours mean, as described in Table 2. For example, blue at all depths means the soil is probably too wet, whereas red at all depths means the soil is probably too dry. At the end of the first cropping cycle in February 2015, 20 farmers from Kiwere were interviewed and asked four questions about their experience of using the Chameleons and FullStops: (1) What practices have you changed? (2) What are your future plans? (3) What are the key lessons learned? (4) What issues remain unclear? Each farmer was allowed to make one contribution under each question. A few months later, 10 of the farmers were brought to a workshop to discuss their experiences in greater detail with the project team.

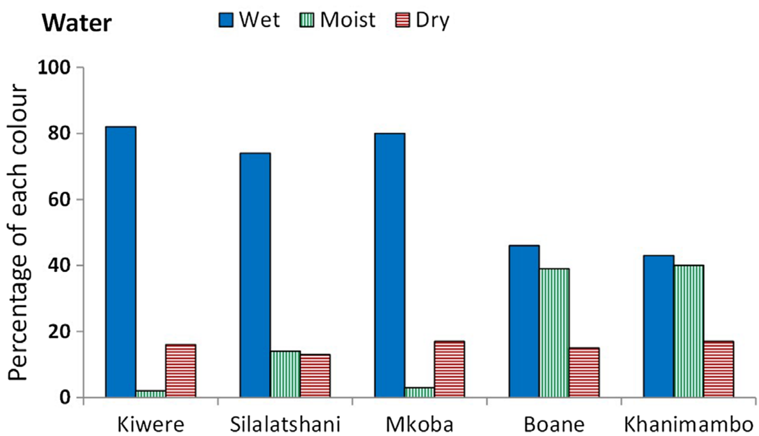

Figure 1. Soil water conditions at each scheme: the percentage of blue (wet), green (moist) and red (dry) colours reported on the Chameleon soil moisture sensors, based on the following number of readings: Kiwere 944, Silalatshani 400, Mkoba 456, Boane 584, Khanimambo 284.

Results

We give a general overview of water, nitrate and salt conditions at all schemes below, as well as the constraints farmers experience in managing water and the potential value to the farmer of saving water. A more in-depth evaluation of the farmers' understanding of the water and nitrate patterns is given for the Kiwere scheme in Tanzania, where the focus groups were held. The final question expressed above, about how learning occurs, is dealt with in the discussion section.

Do the tools detect obvious problems with water, nitrate and salt status at each scheme (sites too dry, nitrate deficient or soil salty)?

Farmers reported the Chameleon colours once or twice per week. To get a high-level overview of soil moisture conditions, the percentages of blue, green and red lights from the Chameleon were averaged at each scheme. Apart from the two Mozambican schemes, Chameleon sensors showed blue (wet soil) over 70% of the time, and all sites showed red (dry soil) less than 20% of the time (Figure 1). Given that four depths were monitored, red at all four depths would be a certain indicator of water stress, and this only occurred after irrigation ceased at the end of the season. The Mozambican schemes which relied on pumping did show more green (moist soil, approximately 25–50 kPa), but it is unlikely that the crops were seriously affected by water stress. Although farmers at all schemes complained of problems with irrigation infrastructure, the supply of water to planted crops appears to have been sufficient.

There is a lot of information in the literature about how soil water tension affects crop yield, but much less information about soil nitrate. Generally crops appeared to have an adequate amount of nitrate in the soil in the early crop stages, and less as the season progressed, due to crop uptake and leaching (Figure 2). As will be seen later, there was evidence that nitrate was being leached due to over-irrigation. Salt was not a problem at any monitored sites, although Silalatshani and Kiwere did show signs of waterlogging and salt accumulation in low-lying parts of the scheme (Figure 3).

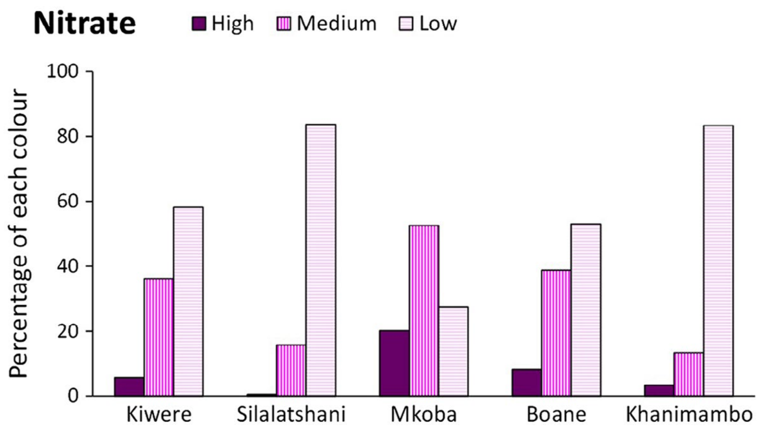

Figure 2. Soil nitrate concentrations at each scheme: the percentage of high, adequate and low nitrate colours reported from the FullStop wetting front detector samples, averaged over both depths, based on the following number of readings: Kiwere 337, Silalatshani 203, Mkoba 179, Boane 49, Khanimambo 30.

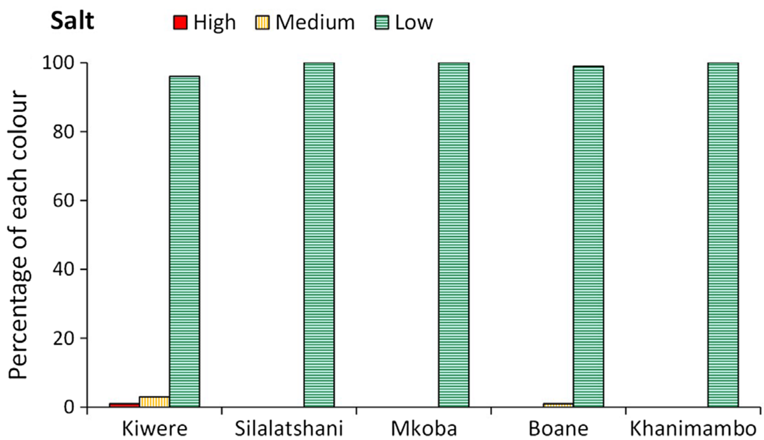

Figure 3. Soil salinity conditions at each scheme: the percentage of high, medium and low salt colours reported from the FullStop wetting front detector samples, averaged over both depths, based on the following number of readings: Kiwere 336, Silalatshani 200, Mkoba 155, Boane 128, Khanimambo 77.

Can farmers understand the water, nitrate and salt colour patterns and act on the information?

The above question is asked with respect to the Kiwere scheme in Tanzania, which provided the most comprehensive feedback following the production of a tomato crop. The Chameleon showed that all farms recorded blue at all depths for most of the season. All 20 farmers interpreted the information correctly and responded by reducing irrigation. Farmers reported that they would continue monitoring into the future, and some requested sensors for crops they grew other than tomatoes. Many farmers gave their views on how they responded to Chameleon colours, and none reported that they were unclear on how to interpret the information (Table 3).

Table 3. Responses to the Chameleon soil moisture sensor at Kiwere Irrigation Scheme. Each farmer could make one contribution under each of the four headings ($n = 20$).

Things changed	Reduced irrigation (20)
Future plans	Continue to monitor for irrigation management (13)
	Add more sensors to other crops (4)
	Apply fewer irrigations (3)
Lessons learned	How to respond to the Chameleon colours (15)
	More water available for downstream irrigators (2)
	Can recognize over-irrigating (1)
	Soil can look dry on top but there is sufficient water below (1)
	Water stays in the soil longer than I thought (1)
Unclear issues	None (20)

Table 4. Responses to the FullStop wetting front detector at Kiwere Irrigation Scheme. Each farmer could make one contribution under each of the four headings ($n = 20$).

Things changed	No change (11)
	Stop irrigating when indicator flag pops up (4)
	Apply fertilizer more often (2)
	Increase amount of fertilizer (1)
	Observe levels of nitrogen fertilizer (1)
	Used manure, not fertilizer (1)
Future plans	Change type and/or timing of fertilizer (7)
	Apply fertilizer when readings are low (3)
	Plan to use manure (2)
	Mix organic and chemical fertilizer (2)
	Need more information (2)
	Reduce irrigation (1)
	Monitor nitrate levels (1)
Lessons learned	Understand changes in soil nitrogen (8)
	Fertilizer goes down with the water (4)
	When the FullStop flag is up there is enough water (3)
	Apply fertilizer when nitrogen is low (2)
	Manure stays in the soil longer (1)
	Decide when to apply fertilizer (1)
	Nitrogen levels decrease as crop grows
Unclear issues	Not sure which fertilizer to use (7)
	Need more training (5)
	None (3)
	How to get rid of salinity (2)
	Why do crops look green when nitrogen is low? (1)
	How best to manage nitrogen fertilizer (1)
	Why does nitrogen change so fast? (1)

The response to the FullStop was very different (Table 4). Most reported that they had not changed behaviour in response to the FullStop, and only three reported that there were no unclear issues. Of most interest was the range of concerns that the FullStop brought to the surface. Some farmers were observing the FullStop as a device that alerted them to over-irrigation. Others recognized they may have a salt problem. However, the majority of the responses revolved around the fate of soil nitrate and how it related to the type of fertilizer (organic or chemical).

What constraints prevent farmers from acting on the monitored information?

Monitoring data is only valuable if farmers can understand them and act on their new knowledge. The farmer has two options in responding to Chameleon data: to change the amount of water at each irrigation, or to change the frequency of irrigation events. If a farmer only has access to water once per week, then they are unlikely to miss the opportunity to irrigate unless they are convinced their whole root zone is wet. However, if water is available several times per week, then skipping an irrigation event in response to persistent blue indicators is an option. Farmers at Kiwere and Sililatshani schemes could generally get water on demand. At Mkoba, all farmers have to agree on the irrigation schedule because they share the same canal that carries water one day per week. The pumped schemes in Mozambique should have access more or less on demand, but in practice there were problems relating to pump breakdowns and disagreements on how to share pumping costs if multiple plots were watered at the same time.

Changing the amount of water applied at one time may not be easy under flood irrigation. If the irrigated plot is long, such as the 100 m lengths at Silalatshani, siphons are left running until the water reaches the other side of the field. Thus once the decision is made to irrigate, there is a certain minimum amount of water that needs to be applied, regardless of the starting conditions shown by the Chameleon. Farmers do have the opportunity to add more siphons, apply water more quickly and potentially reduce the amount of water applied at one time. The small size of the individual farmer plots at Kiwere gave much greater control over irrigation, but also meant that each irrigation event put greater demands on labour.

The Kiwere farmers did exploit the flexibility of their system and make major changes to their irrigation management. The focus groups revealed that farmers were most concerned about the rapid drop in soil nitrate levels early in the season. One farmer had started to skip scheduled irrigations and noticed that the new crop growth was greener and more luxuriant. The practice spread to the other farmers, and the concept of over-irrigation quickly became the common perception. At the start of the season, just under half the farmers irrigated twice per week, and the others three or four times per week. By the end of the season, most farmers irrigated once per week, and none irrigated more than twice per week. Given that this was the dry season, and assuming that each irrigation event applies a similar amount of water, reductions in water use could be estimated by the change in the number of irrigation events, as shown in Table 5.

Farmers do have control over nitrate management through applications of fertilizer and manure, but it is very difficult to manage nitrate in the root zone. Nitrate management is inextricably linked to irrigation management, and unless farmers can reduce over-irrigation, they will continue to leach nitrate from their soils. Since almost all farmers apply fertilizer to their fields, they do have the ability to time applications in response to soil nutrient levels, provide smaller side-dressing more often, or change to organic sources. Salt management is linked to the problem of over-irrigation at the scheme scale. All schemes have relatively fresh irrigation water, so salinity will only be a problem in lower-lying parts of the schemes where water tables have risen due to sustained over-irrigation in the past.

Table 5. Change in number of irrigations

Change in number of irrigations per week	Percentage drop in irrigation	Number of farmers
3 to 2	33%	3
4 to 2	50%	5
2 to 1	50%	9
3 to 1	66%	3

Table 6. The cost of inputs, gross margins and the cost of water as a percentage of input costs. All dollar amounts in US dollars.

Scheme	Crop	Water	Fertilizer	Other costs	Crop income	Gross margin	Water/input costs (%)
Kiwere	Tomato	$6	$205	$1,583	$3,447	$1,654	0.3%
	Maize	$6	$170	$726	$1,738	$ 836	0.6%
Mkoba	Maize	$12	$907	$484	$1,170	–$233	1%
Silalatshani	Maize	$56	$907	$484	$1,170	–$277	4%
Boane	Tomato	$145	$135	$451	$1,691	$960	20%
	Cabbage	$177	$180	$1,129	$4,003	$2,518	12%
	Maize	$151	$108	$450	$1,935	$1,227	21%

What is the value to the farmer of saving water?

Gross margins were calculated following interviews with farmers from Kiwere and Boane, with the input costs separated into water, fertilizer and other costs, such as ploughing, seeding, weeding, crop protection and harvesting. In the case of the two Zimbabwe sites, Mkoba and Silalatshani, we used the gross margins prepared by AGRITEX, the local extension agency and the local water charges. For the Boane site, which required diesel for pumping, water costs were 12–21% of total input costs, depending on the crop grown. For the rest of the sites, the cost of water was trivial compared to other input costs (Table 6). The Zimbabwe government extension agency calculates a negative gross margin for producing a 3 t/ha irrigated maize crop, yet production of irrigated maize is still promoted to farmers.

Discussion

We did not seek to demonstrate, through a controlled trial, that the scientific application of irrigation monitoring tools would increase productivity. Instead, we sought to introduce what we believed to be user-friendly tools to a subset of irrigators on a scheme. We told farmers the meaning of the colour output from the tools (Table 2), but we did not tell them what colour patterns they should aim for. Our objective was to see (1) whether the tools identified obvious problems, such as fields that were too dry, nitrate deficient or salty; (2) whether farmers could understand the information and act on it; and (3) whether the farmers' response to the information could generate value for the individual or benefits to the scheme as a whole.

At the Kiwere scheme in Tanzania, farmers asked the project leader whether they could keep the Chameleon reader at the scheme and take readings more frequently than the once-a-week visit from the project officer allowed. In focus group meetings, several farmers asked whether they could get their own readers, and asked for more sensors for different crops. Clearly they needed more information than the project could provide and were using it in their management. During a project visit to Zimbabwe in July 2015, it was farmers, not extension workers, who demonstrated the monitoring tools to local and international visitors. Moreover, the farmers volunteered their own interpretations of what colours they should aim for, demonstrating how the data were being applied in their specific context.

Many of the comments in Table 4 revealed perceptive observations around nutrient management, such as (1) nitrate lasts longer in the soil from organic sources of nitrogen, (2) nitrate levels can drop surprisingly quickly, and (3) crops can look green with no nitrate in the soil. The above scenarios tend to occur for the following reasons: (1) animal manures continue to mineralize during the season, releasing nitrate, whereas nitrogen fertilizers are easily leached; (2) a few leaching events due to over-irrigation can quickly strip the soil of nitrate; and (3) once a crop is growing quickly, all the nitrate is taken up by the plants, leaving little in the soil. These observations revealed astute understanding, and there is no way these topics could have been discussed without the experiential learning of the farmers themselves.

Initially we planned to spend at least one year familiarizing the farmers with the tools and making sure they understood the information before suggesting changes. But the farmers made changes well before we expected. Two farmers in the downstream section of Kiwere reported that there was more water available for downstream farmers since the project had begun (Table 3). A focus group of 10 farmers was assembled over a two-day period to explore this and related claims. Given that less than 10% of the farmers on the scheme had access to the tools, how could there be an impact at the scheme scale? The farmers explained that many of them had become convinced that skipping irrigation events was beneficial, and tended to watch those farmers who had monitoring equipment. The net result was that upstream irrigators used less water, leaving more for the downstream irrigators.

The focus group revealed that the idea of skipping irrigation events had started with one farmer, who had observed: "If the *kinyonga* [Swahili for Chameleon] is always blue, then the *bendera* [Swahili for FullStop] will go white." This is a reference to the nitrate test strip, which can rapidly change from purple (high N) to white (low N) under conditions of over-irrigation. This farmer had observed that new growth of his tomato crop was greener after skipping irrigation, and had made the conceptual breakthrough that applying more water to insure against stress was a poor strategy. The practice quickly spread, and the benefits were apparently self-evident to the other farmers.

The response by the Kiwere farmers stands out against the generally poor adoption of soil water monitoring equipment in Africa (Annandale, Stirzaker, Singels, van der Laan, & Laker, 2011). Studies on the early adoption of the FullStop wetting front detector by farmers in South Africa found that all 54 farmer or extension workers found it easy to understand, and 82% believed that it helped them reach their irrigation goals (Stirzaker, Stevens, Annandale, & Steyn, 2010). A follow-up study by Stevens and van Heerden (2013) compared the detector with six other scheduling aids in South Africa and found that it ranked in the top two for factors such as ease of using the method/tool, ease of making decisions based on the method/tool, and improvement of productivity. Despite these favourable statistics, the interest by small-scale farmers usually ended with the project funding, and the thousands of detectors sold mostly went to the large-scale sector. We potentially face the same problem with the learning system described here: tools distributed free of charge with some technical support give no guarantee of ongoing impact.

But two factors distinguish this project from the earlier efforts. First, a single intervention such as a wetting front detector is not sufficient to catalyze the necessary level of farmer engagement. The FullStop raised as many questions among farmers as it solved (Table 4), and it was the combination of tools, in particular the nitrate measurements from the FullStop and the water readings from the Chameleon, that stimulated the farmers to change. Second, the project had a focus on governance and market issues in small-holder irrigation schemes (van Rooyen, Ramshaw, Moyo, Stirzaker, & Bjornlund, 2017) as well as technical issues such as soil and water monitoring. Such broad-scale intervention appears critical in catalyzing and sustaining action by farmers.

The question then becomes, is the monitoring cost-effective, thus allowing its spread to other farmers and schemes? Apart from the two sites paying for fuel for pumps, there is little benefit to farmers in saving water. The amount paid for water is minimal, and costs are levied by area, not the amount of water applied. Typically, irrigation water is applied to excess, as evidenced by the global area of waterlogged and salinized land. Applying more water than the crops need is a form of cheap insurance for the farmer, and is in many cases cheaper than monitoring (Stirzaker, 1999). Although this study did not have treatment and control crops from which an economic case could be made, a survey of Kiwere farmers revealed that tomato and onion yields had doubled since they started monitoring. Farmers also revealed that the substantial time saved in not irrigating was incredibly valuable, as it allowed them to spend more time tending their crops or attending to small businesses off the farm.

The Chameleon system is still in late-prototype form, and although it is inexpensive to build, the final cost will depend somewhat on the commercial business model. Even if it is produced cheaply enough for farmers to purchase, the supply chain will not be easy. Thus it is necessary to look at the social benefits at the scheme scale that might add to any private benefit captured by an individual farmer. For example, farmers reported less conflict over water when using the monitoring tools. At one scheme the extension workers reported that farmers with unlevelled fields take longer to complete an irrigation, which slows down the rotation of filling header canals, resulting in other farmers not getting water on time. Extension workers expressed interest in using the tools to demonstrate to farmers the benefits of levelling in an attempt to reduce the management problems they faced at the scheme level.

The example of the downstream irrigators at Kiwere illustrates a similar issue, that the Chameleon colour patterns can highlight inequities at the scheme level that can be addressed through the rules of the user association. A zonal irrigation manager in Tanzania alerted us to the value of the information at a higher scale. He had oversight of 100 schemes, all clamouring for infrastructure upgrades from a very limited budget. He believed that general Chameleon patterns within schemes and across different schemes could help prioritize investment, because persistent red would show that the infrastructure, or the way it was used, could not supply farmers with water in a timely way. Lastly, a senior irrigation bureaucrat left one project meeting saying that he had the information he needed. He had been called to a meeting with government ministers representing the hydropower sector, wildlife and tourism, concerning disputes over water availability in a water-stressed basin. He needed to show that the irrigation sector had plans in place to minimize its abstraction of water and justify its use (Table 7).

Table 7. Interest in the tools by irrigation stakeholders operating at different scales

Scale	Interest	Opportunity
Farmer	Crop yield	Avoid crop water stress and nitrate leaching
Extension worker	Demonstrate good practice	Encourage land levelling and shorten the time taken for each irrigation event so the next section can be supplied with water
Water user association	Equity of water distribution	Feedback as to whether different parts of a scheme obtain water when required
Zonal manager	Rehabilitation of schemes	Identification of schemes with infrastructure contributing to poor water distribution
Government agency	Stewardship of common resources	Demonstration of learning systems to achieve best practice

Finally we must address the last objective of the article: How is learning promoted through monitoring and observation of the colour patterns? The introductory section laid out reasons why we must move from a curriculum-based training approach to an experiential-learning approach. The learning process described by Kolb (1984) fits the experience of the farmers in this study. With the Chameleon, they have concrete experience of the colours representing the soil water status. Reflecting on these colour patterns they came up with a new conceptualization: that they were applying too much water and that this led to nitrate leaching. This new understanding was acted upon by skipping one or more irrigation events per week. The new irrigation plan would then generate a different colour pattern, and the learning cycle would continue.

The above represents individual learning, which is likely to be a fairly slow process. 'Social learning' is increasingly being invoked as necessary for sustainable water resources management. Ison, Röling, and Watson (2007) contend that relying on scientific knowledge alone is insufficient for water management problems that involve multiple stakeholders, complexity, uncertainty and conflict, and that social learning is required to build a shared understanding. Pahl-Wostl et al. (2007) conclude that social learning is fundamental to implementing socially, environmentally and economically sustainable water resources management. Yet there has been some confusion as to the exact meaning of the term 'social learning', as it goes well beyond the familiar topics of participatory action research and other multi-stakeholder approaches (Reed et al., 2010).

Wals (2007, p. 39) considers that the point of social learning is not to prescribe what people ought to know or how they should behave, but to find out what people want to know and learn. He asks:

> How can social learning build upon people's own knowledge, skills and, often alternative, ways of looking at the world? How can the dissonance created by introducing new knowledge, alternative values and ways of looking at the world become a stimulating force for learning, creativity and change? How can people become more sensitive to alternative ways of knowing, valuing and doing, and learn from them? How do we create spaces or environments that are conducive to this kind of learning?

Reed et al. (2010) list two criteria necessary as evidence of social learning: demonstration that change has taken place among individuals, and that the change goes beyond individuals and spreads to the wider community of practice. Based on this definition, we can conclude that the monitoring tools and the learning platform at https://via.farm/, where the data can be visualized and discussed, show the beginnings of the process of social learning in the small-scale irrigation community. We provide evidence that farmers at Kiwere were gaining new insights into water and solute management (Tables 3 and 4), and changed behaviour in response to the new knowledge (Table 5), and that the knowledge spread to other farmers beyond the 10% actively involved in the project. We also found out that other stakeholders, such as extension workers, water user associations, irrigation engineers and government officials, were all showing interest in what the farmers were doing (Table 7).

This interest in water information at different scales is at the heart of building a learning system for small-scale irrigators. Though farmers can derive some benefits from their own management changes at the plot scale, greater benefits can be realized when the rules for water access are equitable and transparent, infrastructure is better maintained, and schemes can show they are good stewards of their land and water resources. This mix of private and social benefits may also facilitate a way of funding the learning system and the necessary tools. The question is: What proportion of the thousands of dollars per hectare spent on infrastructure should be allocated to building a learning system to use the infrastructure?

Conclusion

Across five irrigation schemes in three countries, we found that farmers could keep the root zones wet enough to enable high crop yields. Soil nitrate levels were also adequate, at least at the start of the season. In most cases high yields were not obtained, probably because excess irrigation leached nutrients beyond the root zone. Farmers were able to understand and interpret the colour patterns from the Chameleon soil moisture sensors and the nitrate patterns from the FullStop wetting front detectors. We recorded substantial change in irrigation management at one scheme in response to these patterns, leading to much higher yields. These management changes spread to farmers outside the group directly involved in the project, and interest in monitoring also spread from farmers to extension workers and managers of irrigation schemes.

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