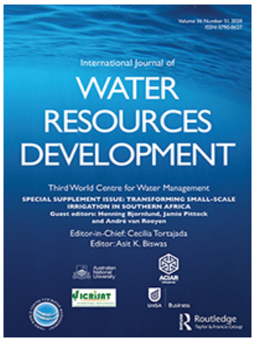

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Identifying leverage points to transition dysfunctional irrigation schemes towards complex adaptive systems

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ABSTRACT
This article explores the value of Ostrom's socio-ecological systems framework and Meadows's leverage point hierarchy, as structured diagnostics, to define systemic problems and avoid approaches based on linear thinking. These frameworks were applied as an ex post analysis of an irrigation scheme in Zimbabwe, drawing on the scheme's baseline condition and the intervention outcomes. Strong leverage points, particularly those driving feedback mechanisms and institutional design, interacted with other intervention points, initiating systemic change. This analysis suggests that dysfunctional schemes can be transitioned towards complex adaptive systems by using agricultural innovation platforms to identify systemic challenges and intervention points.

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Small-scale irrigation; complex adaptive systems; leverage points; system diagnostics; Zimbabwe

Introduction

Dryland agriculture alone cannot feed sub-Saharan Africa's population of 1 billion people (United Nations, 2019). In semi-arid areas, where water is a critical constraint, irrigation is an obvious solution to increase crop production and food security, manage drought risk and stimulate income generation. These propositions have resulted in widespread investment in irrigated agriculture, especially in small-scale systems. However, the total irrigated land in sub-Saharan Africa accounts for only 6.5 M ha, or 16.6% of the total potential irrigated land; thus, there is scope to increase irrigated food production (FAO, 2016). The main objective driving investments by governments and funding agencies is to grow enough staples and improve food security for the 23.2% of the sub-Saharan Africa population that is undernourished (FAO et al., 2018).

The relationship between irrigation and higher food security and income appears obvious; however, two critical factors complicate this assumed linear relationship. First, while irrigation may solve the challenges related to drought, it radically increases the diversity of skills and expertise required of farmers, governance systems and policy makers. Second, the capital invested in developing irrigation schemes is large; moreover, continued investment in infrastructure maintenance is often not factored into overall planning, and producing staples on small plots does not produce sufficient profit to pay for the maintenance of infrastructure.

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There is a rich literature describing the factors that contribute to the poor performance of small-scale irrigation schemes, including socio-economic, institutional, technical, political and design factors; poor farmer participation; and lack of input and output markets (Bembridge, 2000; Denison & Manona, 2007; Fanadzo et al., 2010; Fanadzo & Ncube, 2018; Machethe et al., 2004; Mutiro & Lautze, 2015). Southern Africa has not escaped this unfortunate scenario, with 40% of irrigation schemes regarded as unsuccessful and government-managed schemes, in particular, exposed to failure (Mutiro & Lautze, 2015). Pritchett and Woolcock (2004) described common problem-solving approaches, such as food security in dry areas, as a mechanistic 'needs-supply-civil service' paradigm, which often becomes the next problem. This paradigm refers to the linear and reactionary response of large donors and governments to perceived needs, such as food insecurity. These authors describe how investments in large-scale irrigation systems often fail, as mechanistic approaches create problems that override anticipated benefits. The result is often referred to as the build-neglect-rebuild syndrome (Suhardiman & Giordano, 2014), as there are significant challenges in the 'civil service supply' paradigm when responding solely to the 'needs' of the people (see also Harrison, 2018; Mutambara et al., 2016).

Although the factors leading to system failure are diverse, decaying infrastructure is a highly visible symptom, and a common and immediate point of intervention. However, soft issues such as capacity building, institutional arrangements and water management should be addressed alongside infrastructure rehabilitation to ensure sustained scheme improvement (Fanadzo, 2012; Fanadzo & Ncube, 2018; Lozano et al., 2010).

Despite the significant challenges faced by externally funded government-managed irrigation schemes (Harrison, 2018; Pritchett & Woolcock, 2004), the critical contribution that irrigated agriculture can make to rural economic development remains undisputed. Therefore, numerous African governments and development partners, such as the World Bank and FAO, continue to declare their intentions to significantly invest in irrigated agriculture, including the rehabilitation of existing large schemes.

The question is, how do we transition existing schemes and design new schemes to be functional and sustainable systems? This article argues that a fundamental paradigm shift is needed among designers and managers of irrigation schemes: to shift from an 'external prescriptive process' (identification of problems, and planning of interventions and management) towards adaptive management by internal and external stakeholders, involving wider networks, innovation, learning and self-organization. Though irrigated agriculture has been the focus of influential system thinkers, their approaches have not been widely adopted by practitioners and policy makers. The next section introduces three concepts: complex adaptive systems, to illustrate how small-scale irrigation systems should function; Ostrom's (2007) socio-ecological-systems (SESs) framework for analyzing irrigation systems and identifying critical challenges; and Meadows's (1999, 2009) list of places to intervene in complex systems to illustrate the leverage potential of interventions in irrigation schemes. In a later section, these concepts are then applied to the Silalatshani irrigation scheme in Zimbabwe as a case study, to develop an understanding of the challenges faced by dysfunctional irrigation systems and how the interventions of the Transforming Irrigation in Southern Africa (TISA) project helped transition the schemes towards complex adaptive systems.

Understanding complexity in socio-ecological systems

Complex adaptive systems are robust, open systems consisting of many interacting components and/or actors with the capacity to share, conserve and process resources and/or information. This capacity forms the basis of learning, adaptation and self-organization. They often live 'on the edge of chaos', where the system maintains enough structure to process information but fluctuates such that new information is always created. A critical characteristic of complex adaptive systems is their ability to evolve through the interactions of actors and components, the changing nature of the social, economic and physical environment, and the initial conditions. These initial conditions can lead to lock-in or path dependency – where the system's path remains defined by the initial conditions and the dynamics of rules and decisions – from which escape in the short term is highly unlikely without external interference. Left to their own devices these systems would eventually collapse completely (Holling, 2001). Ostrom (2009) emphasized the importance of decentralized control, as rigid or excessive rules restrict experimentation and adaptation. Systems that can evolve and self-organize exhibit *emergence*, which is defined as new or novel system configurations and behaviours. Consequently, a complex system is larger than the sum of its components, presenting a compelling reason to transition irrigation schemes to complex adaptive systems.

In large complex systems, subsystem interactions are typically controlled by positive and negative feedback mechanisms. Therefore, the subsystems cannot be studied in isolation (Spielman et al., 2009), as this changes their functioning and interactions with other actors and/or processes. The interactions and feedback mechanisms contribute to the unpredictable nature of complex systems – hence the difficulty of studying them.

Ostrom (2007) developed a nested, multi-tier framework to diagnose the problems and potentialities in SESs and support interdisciplinary research. Variables that affect the patterns of interactions and outcomes in complex systems are identified. This article draws on Meinzen-Dick's (2007) adaptation of this framework for irrigation schemes and a further adaptation by McGinnis and Ostrom (2014). The SES framework provides a structure for analyzing the interactions and outcomes in focal action situations and is organized around several first-tier variables: resource systems; resource units and outputs of the system; actors within the system; and governance systems (Figure 1). Decomposing each of these into second-tier variables enables further analysis. The variables are nested in a larger socio-economic and ecological context which affects the interactions and outcomes and enables 'diagnosticians to match governance arrangements to specific problems embedded in' this wider context (Ostrom, 2007, p. 15181).

The capacity to adapt and respond to changing conditions is absent in many irrigation systems. This is primarily due to the limited interaction between the actors and the limited flow of information and resources between components. The latter is determined by the central control imposed by governance structures, which does not allow experimentation and learning, such as national umbrella-type policies and rigid rules enforced by irrigation management committees (IMCs). These influences suggest that small-scale irrigation systems have the characteristics of complex systems; but many are not functioning as complex adaptive systems. This article argues that by identifying critical barriers and effective systemic interventions, small-scale schemes can transition towards complex adaptive systems.

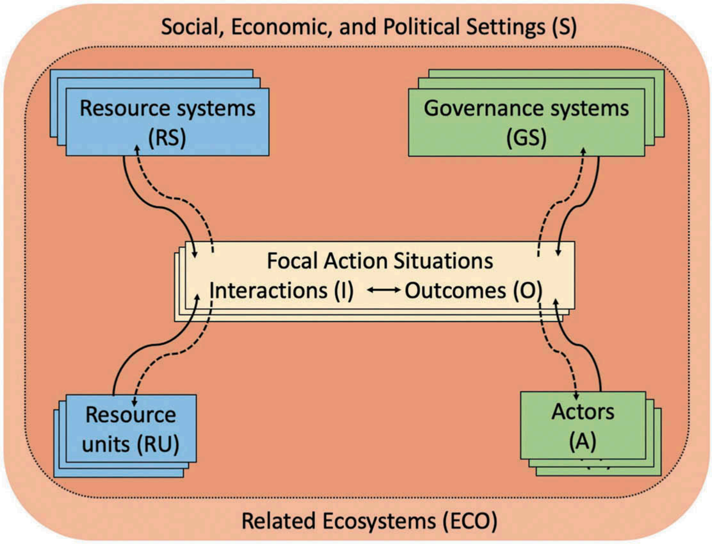

Figure 1. Socio-ecological-systems framework (McGinnis & Ostrom, 2014).

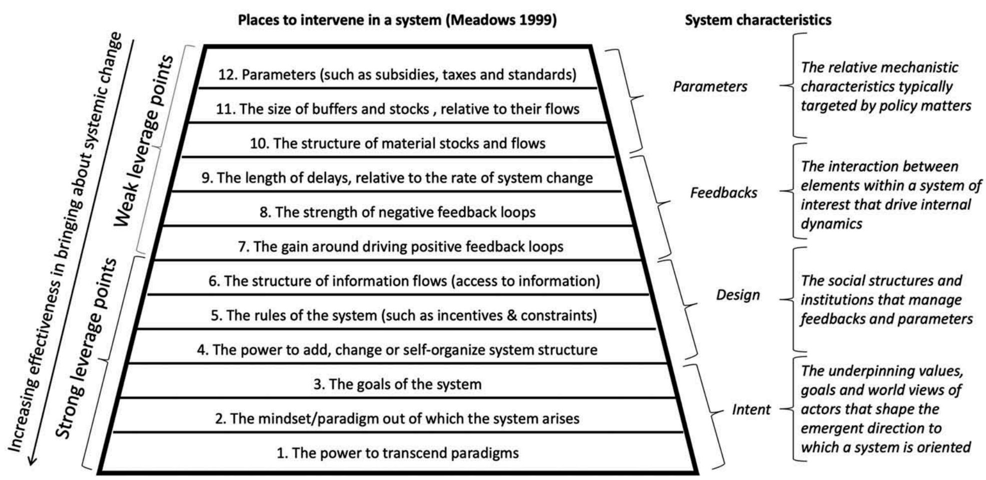

Figure 2. Intervention points and systems characteristics (adapted from Abson et al., 2017).

Leverage potential of interventions in irrigation systems

Meadows (1999, 2009) proposed a hierarchy of 12 intervention points, in increasing order of effectiveness, for leveraging change in complex systems. She argued that the capacity of an intervention to bring about systemic change depends directly on the characteristics of the system the intervention acts on, so some interventions may have better leverage (causing systemic change), while others may have less (inducing only small or localized changes).

Systems researchers have defined *leverage points* as places where small interventions will bring about large changes in other parts of the system (Meadows, 1999, 2009). Abson et al. (2017) grouped this hierarchy into four classes of system characteristics that interventions can influence: parameters, feedback, design and intent (Figure 2). We use the term *intervention points* (IntP) to refer to the places where projects intervene in systems, without any judgement on the intervention's capacity to change the system. While Meadows ordered leverage points from 'shallow' to 'deep', we use the terms *weak* and *strong* to refer to the capacity of an IntP to leverage change in other parts of the system: IntPs range from weak (IntP 12) to strong (IntP 1).

The parameters: the relative mechanistic characteristics of systems

IntP 12: Constants, parameters, numbers (such as subsidies, taxes standards). These can be constraints that influence the flow of resources. Projects and policies often operate at this level, where it is easy to work but the capacity to leverage systemic change is very weak (Abson et al., 2017). In irrigation they include the amount of water available, irrigation frequency, seed and fertilizer rates, and levies paid for water and land.

IntP 11: The size of buffers and other stabilizing stocks, relative to their flows. Buffers are the 'slack' in a system and are influenced by the size of the corresponding stock. They offer very weak leverage. In irrigation, they include the size of the reservoir or the capacity of the night storage dams relative to the outflows; the water holding capacity of the soil; and soil nutrient pools.

IntP 10: The structure of material stocks and flows and nodes of intersection. This is the physical structure of a system which determines the flow of units and influences the systems' buffers (IntP 11). Physical structure is critical for system functioning, but is rarely a leverage point, as it can only be changed by rebuilding. The real leverage is having proper design in the first place. In irrigation, structure includes the design of the infrastructure; size and capacity of night storage dams; the canal system and number of plots serviced; mode of water supply, application and control; and frequency and volume of water released from dams or drawn from rivers. Much of this is planned and designed without the participation of the eventual irrigators and managers.

This group of intervention points has weak capacity to leverage systemic change. To improve the management of irrigation schemes, engineers and agronomists develop crop production strategies and cropping calendars, and provide guidelines such as seeding rates and fertilizer application rates. However, this is often without reference to the goals, and there is little or no interaction with other components of the system, such as market access, profitability and related information flows, or the relationship between watering schedules and crop type, growth stage and rainfall.

Feedbacks: The interactions between system components that drive the internal dynamics

IntP 9: The lengths of delays, relative to the rate of system change. Delays in feedback cause systems to oscillate, by overshooting or undershooting a goal, and destabilize the system. Delays can leverage change but are themselves not easily changed. For example, in irrigation there can be delays between rainfall events and reservoirs being replenished;

between crop needs and when water reaches plots; and between crop production, marketing and income from markets. Critically, there are delays between when information is needed and when it is received (IntP 6).

IntP 8: The strength of negative feedback loops, relative to the impacts they are trying to correct. Negative feedback acts as a control to balance the growth resulting from positive feedback and helps keep system's states within safe limits. These could be good places to leverage change, but they are often ignored because they are difficult to implement. In many small-scale irrigation schemes there are no negative feedback mechanisms controlling the amount of water going to a crop. The assumption is that the more you irrigate, the better the crop will grow. Negative feedback develops when farmers reduce irrigation frequency knowing that excess water leaches expensive nutrients.

IntP 7: The gains driving positive feedback loops. Positive feedback is self-reinforcing and a strong leverage point, so it is usually more effective than increasing negative feedback. In irrigation, this includes improving input supply and market access to increase yields and income, and stimulating reinvestment of profit in production.

Feedbacks provide stronger leverage points because they link different system components, driving their dynamics or stabilizing their interactions. For instance, advocating greater fertilizer application without reducing the rate at which it leaches beyond the root zone will not increase yields. Similarly, if higher yields do not translate into increased incomes – because, for example, markets are not functioning – proper agronomic practices have no value and will not be implemented. Feedbacks offer stronger leverage than parameters, because they often link and influence the variables associated with IntPs 10–12. Interventions focussing on the feedbacks within a system will generate changes elsewhere in the system, increasing the capacity to bring about change.

Design: the social structures and institutions that manage the feedbacks and parameters

IntP 6: The structure of information flows. Adjusting who does and does not have access to information has relatively strong leverage. In irrigation, this would include information on agronomic practices, crop water requirements, fertilizer management in relation to irrigation frequencies, seed quality, market requirements, and price information and enterprise selection.

IntP 5: The rules of the system (such as incentives, punishments and constraints). Rules define system boundaries, scope, and codes of conduct. They can be absolute (physical laws), explicit (policies and procedures), or implicit (social norms). Rules are strong leverage points in creating self-organizing systems by enforcing good rules and changing or eliminating inappropriate rules. In irrigation, they include IMC rules and other policies, such as the type of crop to grow; strict irrigation schedules; inappropriate land tenure systems; and controlled markets.

IntP 4: The power to add, change, evolve or self-organize system structure. Self-organization occurs when the internal organization of a system becomes more complex without direction or guidance from an outside source. This is a strong leverage point. In irrigation it includes local-level group formation, collective action to negotiate new market integration, new irrigation frequencies, and developing new institutions or co-management.

Design characteristics are the framework within which systems function. Should there be no flow of information on water and fertilizer use or on markets, proper agronomic practices cannot develop, and crop failure may occur. With no feedback loops between users and markets, no learning takes place, and users may end up in poverty traps. Rules can break down a system's efficiency if access to resources (land, water and information) is inequitable; broken feedback loops or skewed information flows constrain the development or functioning of a system. Tenure structures, IMCs and fee payments will break down without the positive feedback of good services and other incentives. Governments and their agents insisting on farmers' growing unprofitable staple crops may drive irrigators away from their plots. By its nature, interventions in this group can have very strong leverage, as they trigger changes elsewhere in the system; but interventions here can be very difficult to implement directly.

Intent: the underpinning values, goals and worldviews of actors that shape the emergent direction to which a system is oriented

IntP 3: The goals of the system. These are leverage points for the entire system, not just the separate components, but they are difficult to implement. In government-controlled irrigation schemes, goals and policies to grow staple crops for food security may not reflect the cash and livelihood needs of farmers. Changing the goals of the system affect almost everything else in the system, and will therefore have significant consequences – good or bad.

IntP 2: The mindset or paradigm out of which the system (its goals, structure, rules, delays and parameters) arises. A paradigm is the set of collective experiences, beliefs and values that affect how the members of an organization perceive reality. This is the second-strongest leverage point. If the paradigm is to achieve food security through self-sufficiency in irrigation schemes, then most projects and programmes will aim to maintain this status. Hence, interventions are often targeted at parameters and buffers, such as recommendations regarding seed and fertilizer rates, to increase production. Often seed and fertilizer are handed out for free, negating the necessary feedbacks between input and output markets, and ultimately self-sufficiency as well. Changing this paradigm can lead to significant systemic changes.

IntP 1: The power to transcend these paradigms. The most powerful leverage point is the ability to change paradigms. By objectively evaluating paradigms, leaders can transcend entrenched mental models and enable radical change. In irrigation, the most fundamental change might be from subsistence agriculture to market-oriented production, or from government-managed to co-management or even full autonomy, by forming new independent organizations. To effect this, all actors need to transcend the paradigm: farmers, the government, and donor agencies and their support services. Similarly, if the private sector does not take note of the power of small-scale irrigators, the necessary transition will take much longer.

Intent influences all other groupings of system characteristics, generating changes in all system components, so interventions focussed on intent are the most powerful leverage points. But because these are the most difficult IntPs, they are the least used in rural development.

Case study: Silalatshani irrigation scheme, Zimbabwe

As a pilot project, TISA set out to test the impact of two interventions in irrigation schemes in southern Africa (2013 to 2017). The project introduced agricultural innovation platforms (AIPs), and two soil moisture and nutrient monitoring tools ('the tools'). The baseline conditions at the schemes and TISA's processes and outcomes are described extensively elsewhere (Bjornlund & Pittock, 2017; Moyo et al., 2020, 2017). Only the critical features and outcomes are summarized in this section.

The Silalatshani irrigation scheme is one of five schemes that are part of the TISA project. The Landela block of the Silalatshani irrigation scheme is used as a case study to analyze system improvement through the lens of the SES framework and the IntPs used by TISA. First, the project's interventions and key outcomes are summarized. The case study continues by using the SES framework to analyze Silalatshani's water resources and cropland as separate resource systems, and tables of the second- and third-tier variables are presented as a diagnostic of Silalatshani's baseline condition at the project's inception. Narratives of the baseline and intervention situations are included, with links to Meadows's intervention points and their ability to leverage systemic change, to illustrate how the system dynamics and interactions are changed. There is a final section on how the water resources and cropland systems interact to generate larger system outcomes.

TISA interventions and key reported outcomes

Project interventions

The AIP is a multi-stakeholder process used to define the challenges (Figure 3) and opportunities faced by the scheme. In Silalatshani, the AIP facilitated the development of a 'status quo' scenario, and a collective or common vision for the scheme (Van Rooyen et al., 2017). The AIP actors then developed a pathway from 'where we are' to 'where we want to be', which helped: identify critical barriers to address before the project could proceed, such as outstanding water bills and tenure constraints (Bjornlund et al., 2017; Van Rooyen et al., 2017); highlight institutional issues, training and capacity development, and development of market links; and create a learning platform to increase the footprint of the project in the local context. Critically, the AIP also increased links and information flow between actors and allowed them to understand their contribution to the functioning of the larger system.

The tools included a Chameleon soil moisture monitoring tool and the FullStop Wetting Front Detectors (WFD), which were developed by CSIRO (Stirzaker et al., 2017). These were made available to 20 farmers through the AIP process to assist with water management challenges (Figure 3) and to stimulate a learning process (Moyo et al., 2017). The Chameleon is a highly sophisticated device that measures soil water at three different depths, but with a user-friendly interface. When connected to a sensor array, three LEDs show either blue for wet, green for moist or red for dry. This allows farmers to adjust irrigation frequency for optimal plant growth based on soil moisture. The WFD shows

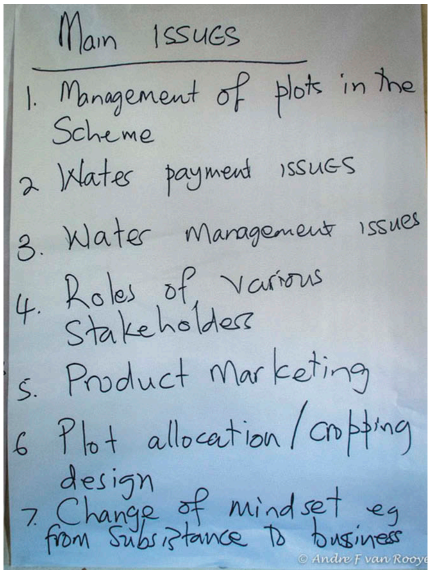

Figure 3. The main issues in Silalatshani irrigation scheme, Zimbabwe, as identified during the first agricultural innovation platform.

farmers when water has reached the depth of the device, and also allows water to be extracted to measure salinity and the nutrient status within and beyond the root zone of a particular crop. Integrating the results from these tools allows farmers to balance irrigation frequency, to maintain sufficient root-zone moisture without leaching nutrients beyond this zone. Farmers understood this dynamic, and it created much excitement at the prospect of higher efficiency for expensive fertilizer. A critical characteristic of these tools is that the information required to make decisions was given to farmers and was accessible when they needed it most (Moyo et al., 2020).

Systemic changes from TISA's interventions

The systemic changes brought about by the tools and the AIP are illustrated in Figure 4. Farmers learnt to trust the tools, and they skipped irrigation opportunities when they realized their crops were not dying. Farmer-to-farmer learning spread these positive impacts across the scheme (Moyo et al., 2020; Parry et al., 2020). Reduced irrigation was immediately reinforced by the time saved, which could now be spent on weeding and further reduced the need to irrigate and apply fertilizer. This double feedback loop resulted in much greater yields, which could now be sold to markets opened up by the AIP process. The higher income from markets provided both the incentives and the resources to reinvest in fertilizers and improved varieties. Training on gross margin analysis allowed various actors to learn more about enterprise selection, such that irrigation managers relaxed the rules about which crops could be grown (Figure 5), and the IMC relaxed the rigid irrigation schedules based on farmer feedback on water requirements. With higher incomes, farmers were able to pay water fees, which reduced conflict between water users and between

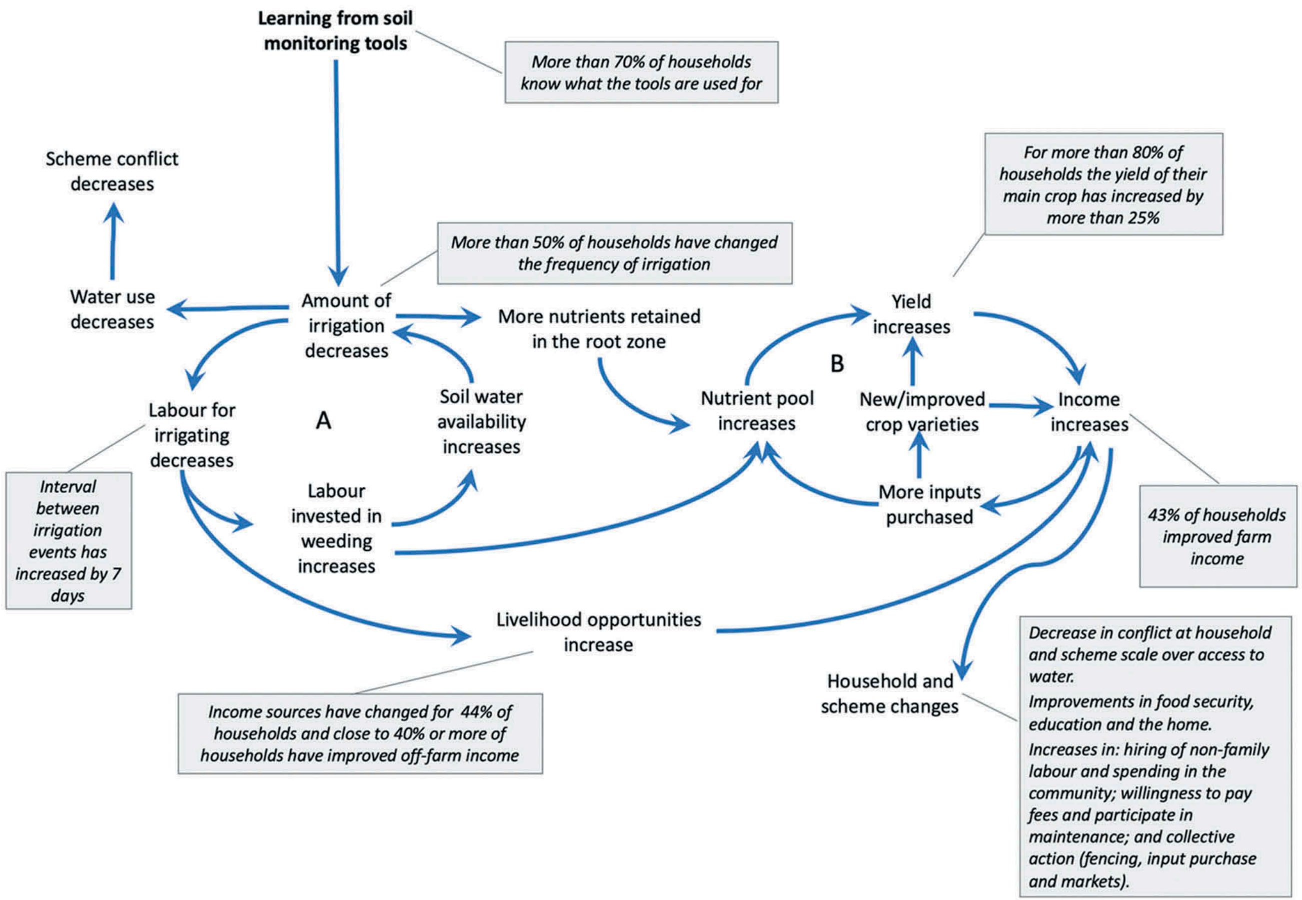

Figure 4. Influence diagram illustrating the systemic changes brought about by the soil moisture and nutrient monitoring tools (Loop A) and the agricultural innovation platform (Loop B) at Silalatshani irrigation scheme.

water users and the IMC. This allowed increased cooperation between farmers, which allowed them to collectively maintain the canals and to organize themselves to erect a fence to protect their crops against livestock.

The interventions used in TISA were not strategically selected with respect to Meadows's intervention points. Rather, the project was designed as a two-pronged approach to ensure that higher yields were linked to better markets, and also that higher water productivity brought immediate and direct benefits to farmers (Bjornlund et al., 2018; Bjornlund & Pittock, 2017). The AIP specifically identified critical and immediate barriers, such as water management and water payments which were in arrears with the Zimbabwe National Water Authority (ZINWA), but also identified other systemic challenges, like the top-down decree of the cropping calendar (Van Rooyen et al., 2017). Thus, the work of the AIP provided a larger contextual environment for critical system analysis, developing opportunities to create change and realize real and tangible returns in the marketplace (Moyo et al., 2020).

Analysis of water resource system

Baseline situation: challenges, interactions and outcomes

The water resource system baseline condition at Silalatshani is presented in Table 1. Silalatshani Dam is relatively large, supplying water to the irrigation scheme, local mines and urban centres. During AIP discussions, ownership and responsibility for maintenance of headworks and canals were greatly disputed (RS4, I4 in Table 1). Although farmers pay to irrigate, the price is fixed and not related to the volume of water used, so there has been no incentive for efficient water use (S5). Strong governance systems existed within various organizations, applying strict rules and consequences for non-compliance. ZINWA controls water allocation to the scheme (GS1) and would cut supply at critical production times if bills are not paid, and AGRITEX and the IMC enforce strict and rigid irrigation scheduling (GS5). Farmers fear losing access to plots if these rules are not followed. The regional district council (local government) determine access to plots and succession of plot ownership (GS4), so they hold considerable power. The cropping calendar represented rigid operational rules (CS5), prescribing the type of crop and agronomic practices. Irrigators were unable to change the rules (GS6), with the IMC having strong constitutional powers (CS7). The monitoring and sanctioning processes (CS8) were also rigid, so irrigators had no information to contest or contribute to the irrigation scheduling and water management decision making. Rules and regulations were enforced, and irrigators were locked in a rigid system, with no opportunity to experiment with different crops and markets or adapt and learn about improved irrigation strategies. This left them with little information (A7), and they had no opportunity to lobby for change (I6). The outcome was unsustainable: overuse of water, resulting in significant impact on the ecological performance of the system. With limited knowledge of the system and water availability on a weekly basis, farmers maximized water use opportunities. This resulted in the night storage dam running dry (RS5, 7) and poor supply for tail-end users, and thus conflict between users and between users and authorities (I4). Water use efficiency was low (O1b), and because of nutrient leaching, yields were also low (O1d). Because of the specific tenure arrangements (U2c) and low actual economic value of water, there were many unused plots. This resulted in low cropping intensity (O1c) and

Table 1. Baseline conditions of second- and third-tier variables of the water resources system of the Silalatshani irrigation scheme. Critical variables are in ***bold italics.***

Social, economic and political settings (S)

S1, Economic development: ***Limited***. S2, Demographic trends: Outmigration. S3, Political stability: Unstable. S4, Government settlement policies: Unclear. S5, Market incentives: ***No price incentives for more efficient use of water***. S6, Media organization: None.

Resources system (RS)

RS1 Sector: Water
RS2 Clarity of system boundaries: Clear boundaries of main dam and canals
RS3 Size of irrigation system: Large dam with multiple users (agriculture, mining and urban centres)
RS4 Water infrastructure
RS4-a Headworks: ***Good but decaying***
RS4-b Channels: ***Not maintained – conflict over responsibility***
RS4-c Control structures: ***In disrepair – conflict over responsibility***
RS4-d Roads: Poor
RS4-e Communications: Reasonable mobile coverage
RS5 Scarcity: ***High due to overuse***
RS6 Equilibrium properties
RS7 Predictability of supply
RS7-a Seasonal: Reasonable
RS7-b Interannual: Low as a result of rainfall variability
RS8 Storage characteristics: Main dam with five night storage dams
RS9 Location: Matabeleland South, ***far from markets***

Governance system (GS)

GS1 Government organizations: Well-structured and functioning: AGRITEX, ZINWA, Regional District Council
GS2 NGOs: Various
GS3 Structure of user groups: Scheme, block, farmer groups
GS4 Property rights:
GS4-a Property rights to infrastructure: ***Rigid, but inefficient and unclear***
GS4-b Property rights to water: Weak
GS5 Operational rules: ***Clear but rigid set of rules on water allocation and scheduling***
GS6 Collective-choice rules: ***Low capacity to change rules or develop new rules***
GS7 Constitutional rules: ***IMC has set rules but some are unclear and lack enforcement provisions***
GS8 Monitoring and sanctioning processes: ***Strong at the ZINWA level but weak at the IMC level***

Resource units (RU)

RU1 Resource unit mobility: All water is contained in the dam, and the scheme is the final destination; no downstream users
RU2 Water availability, by season: Available throughout the year
RU3 Hydrologic interaction among irrigation units:
RU3-a Interaction within a system: Interactions between five blocks
RU3-b Interaction between systems: None
RU4 Economic value of output: ***High perceived value, but farmers have low ability to realize the economic value of the resource***
RU7 Spatial and temporal distribution of water: ***Controlled by governance systems according to the set irrigation schedule***

Actors (A)

A1 Number of users (total and in local units):
A1-a Whole system: 400 in whole scheme.
A1-b Local units: 120 in Landela block
A2 Socio-economic attributes of users:
A2-a Wealth: Relatively poor
A2-b Heterogeneity: Both men and women, most local people of similar ethnicity
A2-c Land tenure: Based on traditional systems, under local governance control
A2-d Stability of group: Stable
A3 History of irrigation: 50 years
A4 Location (residence relative to canals): Silalatshani growth point
A5 Leadership: Strong local leaders
A6 Shared norms/social capital: Relatively good
A7 Knowledge of irrigation: ***Poor understanding of water-nutrient dynamics***
A8 Dependence on irrigation: Farmers also have dryland plots; perception is that users are highly dependent on the resource
A9 Technology used: ***Flood irrigation, no soil moisture or nutrient measurements***

Interactions (I)

I1 Water use by diverse users: ***Users maximize use when water is in the canal according to schedule***
I2 Information sharing:
I2-a Information on resource use: ***Limited information to share***
I2-b Information on conditions of resource: Limited
I3 Deliberation processes: Weak in comparison to IMC
I4 Conflicts among users: ***High at various levels***
I5 Investment in maintenance: ***None***
I6 Lobbying activities: None, as users have no relevant information and no power to change the system; limited ability to self-organize/collective action?

Outcomes (O)

O1 Socio-economic performance
O1-a Equity of water distribution: ***Low***
O1-b Water use efficiency: ***Low***
O1-c Cropping intensity: ***Low***
O1-d Yields: ***Low***
O1-e Value of output: ***Low***
O2 Ecological performance measures
O2-a Waterlogging: Present in parts of the scheme
O2-b Salinity: Localized
O3 Externalities to other systems: ***Cannot pay water bills***

Related ecosystems (ECO)

ECO1, Climate patterns: Erratic. ECO2, Pollution patterns: limited. ECO3, Flows into and out of local irrigation systems: Limited.

poor scheme performance. The overall inefficiencies of the system manifested in low income, and farmers being unable and unwilling to pay water bills (O3).

Interventions

Soil water and nutrient monitoring tools allow farmers to determine soil moisture before they irrigate (A7). This has been made possible within the framework of the AIP, giving farmers an opportunity to decide on the frequency of irrigation at individual plot level. The Chameleon intervened specifically at IntP 6, but also at IntPs 7 and 9. The Chameleon provided immediate information about the need to irrigate. When irrigation was not required, farmers could choose to use the time saved to weed their plots, which further reduced the need to irrigate, as weeds were no longer consuming valuable water and nutrients. The Chameleon provided reliable information on soil moisture when farmers required it (IntP 6), allowing them to skip irrigation events. Farmers now had reliable information (U7) and increased their collective action to affect the governance systems at various levels (I3). This ultimately provided information that farmers used to negotiate irrigation scheduling with their IMC, which then changed the operational rules (GS5). The consequent water savings lead to further positive interactions: for example, less irrigation increased the relative storage capacity (RS8) of water and therefore the predictability of the system (RS7a). This improved the spatial and temporal distribution of the resource (RU7), reducing conflict (I4) and increasing willingness to self-organize in response to the higher perceived value of the resource unit (RU4) through its interaction with the cropland resource system.

The Chameleon provided information on soil moisture, driving the gains around positive feedback loops (IntP 7). The WFD provided information that nutrients were leached from the system and irrigation water should be reduced, which provided the negative feedback loop to keep the system within functional limits (IntP 8). This provided further positive feedback by maintaining the nutrient levels in the root zone, which interacts positively with the cropland system.

The Chameleon and WFD were introduced to improve the mental models of the irrigators in the system (A7) and to improve management based on real-time measurements of soil moisture and nutrient levels, as opposed to rigid guidelines or rules (GS5). These represent examples of IntPs 7–9 (all feedbacks), which triggered a series of interactions between other second-tier system variables and led to positive social and ecological performance outcomes (O1, less conflict, more collective action; ECO3, water and nutrient savings). Moreover, the self-organization resulting from these impacts influenced IntPs 10–12, leading to positive system outcomes such as canal maintenance and the erection of fences by users themselves. As noted earlier, the rehabilitation of infrastructure (IntP 10) is not a strong leverage point; but through self-organization, users are now maintaining their own canals and constructing fences around the Landela block, as envisioned at the initial AIP meeting (Van Rooyen et al., 2017).

Analysis of cropping resource system

Baseline situation

The cropping resource system baseline condition at Silalatshani is presented in Table 2. Low crop yields (RS5) and thus incomes (RU4) were the most critical challenges faced by

Table 2. Baseline conditions of second-and third-tier variables of the cropping system of the Silalatshani irrigation scheme. Critical variables are in ***bold italics.***

Social, economic and political Settings (S)

S1, Economic development. S2, Demographic trends. S3, Political stability. S4, Government settlement policies. S5, Market incentives: Limited price incentives for staple crops. S6, Media organization.

Resources system (RS)	**Governance system (GS)**
RS1 Sector: Cropland	GS1 Government organizations: Well-structured and functioning: AGRITEX, IMC
RS2 Clarity of system boundaries: Clear boundaries between plots and ownership	GS2 NGOs: Various
RS3 Size of resource system: ***Plot sizes are small, 0.5 ha.***	GS3 Network structure: ***Poor***
RS4 Human-constructed facilities: Irrigated plots	GS4 Property-rights systems: ***Rigid, but inefficient***
RS5 Productivity of system: ***Low***	GS5 Operational rules: ***Rigid rules; irrigation schedule, cropping calendar***
RS6 Equilibrium properties: Disequilibrium	
RS7 Predictability of system dynamics: High	GS6 Collective-choice rules: ***Low capacity to change rules***
RS8 Storage characteristics: Limited	GS7 Constitutional rules: ***IMC has set rules***
RS9 Location: Matabeleland South, Zimbabwe	GS8 Monitoring and sanctioning processes: ***Strong***
Resource units (RU) – crops grown	**Actors (A)**
RU1 Resource unit mobility: n/a	A1 Number of users: 120 in Landela block, 400 in whole scheme
RU2 Growth or replacement rate: Two growth crops per year	A2 Socio-economic attributes of users: relatively poor
	A3 History of use: 50 years
RU3 Interaction among resource units: Potential positive interaction between legumes and cereals	A4 Location: Silalatshani growth point.
	A5 Leadership/entrepreneurship: Strong local leaders
RU4 Economic value: ***Low value of staple crops***	A6 Norms/social capital: Relatively good
RU5 Size: ***Low production because of small plots***	A7 Knowledge of SES/mental models: ***Poor***
RU6 Distinctive markings: n/a	A8 Dependence on resource: Not fully dependent; users also have dryland plots where they can grow staple crops and want to grow cash crops on irrigated plots
RU7 Spatial and temporal distribution: Low	
	A9 Technology used: ***Limited use of mechanization, little use of improved crop varieties, extensive use of fertilizer***
Interactions (I)	**Outcomes (O)**
I1 Harvesting levels of diverse users: n/a	O1 Social performance measures: ***Low***
I2 Information sharing among users: ***Limited***	O2 Ecological performance measures: ***Low crop productivity, low crop diversity, low resilience***
I3 Deliberation processes: ***Weak***	
I4 Conflicts among users: ***High***	O3 Externalities to other SESs: ***Often dependent on handouts and food distribution programs***
I5 Investment activities: ***Low***	
I6 Lobbying activities: ***None***	

Related ecosystems (ECO)

ECO1, Climate patterns: ***Erratic.*** ECO2, Pollution patterns: Low. ECO3, Flows into and out of focal SES: Limited.

irrigators. This situation was amplified by the small plot sizes (RS3). Low system efficiency was directly related to the poor performance of the water resource system, but exacerbated by poor enterprise selection, which was enforced by the governance systems' operational rules (GS5). The cropping calendar controlled which crops should be planted (Figure 5) and dictated staple crop production, regardless of the profitability of the enterprise. While staples are primarily consumed by the farmers, the excess is available for sale; but income is low, because the market price of staples is minimal (RU4), leaving no resources to pay water bills and buy inputs for the next season. Therefore, water bills were significantly in arrears (Van Rooyen et al., 2017), with ZINWA (GS5 in the water system) often shutting off the water supply at critical times of the production cycle (GS8). With little incentive to invest in irrigated agriculture, many irrigators left Silalatshani. Also, the tenure system (GS4) was too rigid to change ownership on a continuous basis, so the scheme had an occupancy rate of less than 30% at the beginning of the project (U2c, Table 1). The overall outcome was that irrigators remained poor (O1): with limited inputs, the system was unable to perform, leaving farmers and the larger system very vulnerable. As farmers had access to dryland plots for staple crop production, they were not highly

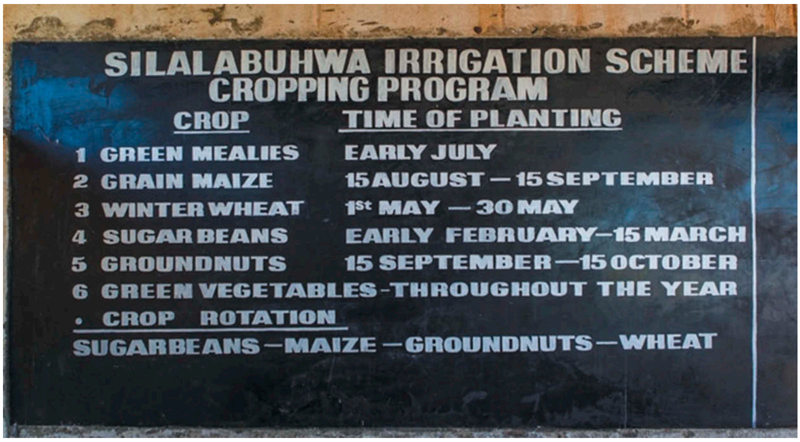

Figure 5. The cropping calendar in place in Silalatshani irrigation scheme since the scheme's development 1968.

dependent on the irrigated cropland. The diversity of crops grown was low (O2), and with little income, farmers were highly vulnerable and sometimes dependent on food aid (O3). It was later learnt that Silalatshani was regarded as one of the most difficult schemes in Zimbabwe and ran the risk of total collapse and closure.

Interventions

From the first AIP meeting (18 November 2013), it was clear that changing the cropping system to allow farmers to engage in more lucrative enterprises should be one of the first tasks of the AIP. A gross margin analysis training session for extension officers was organized (RU4). The strategy was to illustrate the unprofitable nature of the cropping system (and resulting ZINWA arrears) and the overall inefficiency of the system's subsistence goal. The project itself could not change local policies and institutions, so the aim of the intervention was to change the rules of the systems indirectly (IntP 5) through better knowledge of the system's efficiencies and profitability. As a result, extension officers questioned the adherence to the cropping calendar and released the pressure on farmers to follow the rules of the system (GS5). The AIP also linked farmers to input and output markets (IntP 7), so they received relevant information and had direct contact with buyers (A7).

Interactions between the two resources systems

The interaction between the water resources and cropping systems resulted in numerous feedback mechanisms being established. For example, improvement in nutrient dynamics and input management resulted in higher yields, and market links translated the higher yields into higher profitability (RU4). Better profits made reinvestment in crop production possible, creating positive feedback and illustrating the interaction between interventions. Stimulating such interactions led to changing the rules of the systems (IntP 5) and gave irrigators the power to add, change and self-organize the structure of the system. This represents a stronger intervention point (IntP 4). Better enterprise selection increased farm income and strengthened these interactions. Thus there are clear interactions and feedback mechanisms – between the better agronomic practices and crop selection and market integration, and the incentives to invest in better agronomic practices – with the returns on investment potentially contributing to the ecological, economic and social sustainability of the system.

General discussion

The SES framework provides a comprehensive structure to analyze the second- and third-tier system variables and contributes to understanding the interactions between the resource system, resource units, governance systems, actors and outcomes. However, the interactions between these components do not always lead to linear or predictable outcomes.

Linear versus systemic interventions

Table 3 lists several common problems in agricultural systems and typical linear project interventions meant to resolve them. In reality, linear relationships seldom exist in complex systems, and responses to problems rarely have the desired outcome, because when one problem is resolved, related or new barriers may continue to prevent progress. It is essential to engage in a process that helps all parties understand how the different problems are related and for them to develop, own and implement solutions. This can be done by reflecting on how different problems interact and how interventions that affect one problem influence other components of the system. This would negate the 'needs-supply-civil service' paradigm (Pritchett & Woolcock, 2004) and other linear interventions based on linear thinking.

Relationship of TISA interventions, leverage points and system variables

The application of the SES framework has illustrated the challenges associated with the system's variables. In this section, we explain how the project's interventions addressed these challenges, and discuss where Meadows's leverage points influenced the first–tier variables. The first group of leverage points, parameters (IntPs 10-12) influence the resource units and resource systems; the feedbacks (IntPs 6 – 9) influence the interactions; and the design (IntPs 4, 5) and intent (IntPs 1 – 3) influence the governance system and actors (Figure 6).

Table 4 aligns TISA's interventions with Meadows's leverage points and the second-tier resource system variables being influenced (from Tables 1 and 2). The table also shows actors' incentives to change, observed changes in behaviour, and the immediate and direct impacts. Understanding actors' incentives to change is critical in developing a facilitating environment for positive change. Although TISA intervened in relatively few places, the interventions indirectly affected other parts of the system (Table 3), which were quantified in an end-of-project survey (Moyo et al., 2020).

TISA had no direct intervention in the scheme's 'parameter' characteristics (IntPs 12–10) (Table 4). This is where many projects intervene because it is easy to change parameters such as free or subsidized inputs, the frequency of irrigation, or the capacity of the night storage dams. However, these interventions often do not address the cause of

Table 3. Common 'problems' in agricultural development, typical linear project interventions, and the systemic solutions of the Transforming Irrigation in Southern Africa (TISA) project.

Issue/Problem	Typical linear project interventions	TISA's systemic solutions
Decaying headworks (RS4, Table 1)	Rehabilitate infrastructure, assuming this will increase productivity, food production and income	Infrastructure decay indicates either a lack of incentive or ability to maintain infrastructure. Ability could relate to technical know-how or lack of resources or management skills. The capacity to pay and the incentive to engage in scheme maintenance emerges with the transition from subsistence to market-oriented production.
Market access (RS9, Table 1),	Link farmers to markets, often through short-term contractual arrangements	The real problem may be that farmers should (also) grow high-value products for which there is a demonstrated demand. Silalatshani's farmers, to a large extent, changed to higher-value crops.
Low productivity (RS5, Table 2)	Provide handouts such as seeds and fertilizer	During the first AIP meeting, farmers asked for inputs. On closer inspection, farmers were using expensive organic and chemical fertilizers. The problem was that the fertilizer was leached beyond the root zone. Hence, adding more fertilizer would not improve yields.
Farmers' knowledge of the system is poor (A7, Table 2)	Train farmers in agronomic practices to improve productivity	Training alone will not be effective if farmers have no markets for their products, or if they cannot put their training into practice, e.g. by changing their enterprise or their irrigation scheduling. Training should be reinforced with applied learning, better decision making and clear feedback mechanisms to maintain and advance newly acquired knowledge.
Poor or inappropriate governance systems (GS, Tables 1 and 2)	Superficial policy analyses and associated policy briefs are written, and discussions aimed at institutional and policy reform	The IMC initially asked for more authority to enforce its bylaws to make farmers pay the ZINWA water bill, and adhere to the cropping calendar. Strengthening the rules is not the answer; this project shows that farmers are willing to pay for water, if irrigation is profitable and they have the money to do so. The transition from subsistence to a market-oriented paradigm also addressed these issues. Policies need to address the cause, not just the effect.

the problem, and are rarely maintained beyond a project's lifetime (Abson et al., 2017). Changing irrigation frequency without the associated learning would have been met with significant resistance from farmers. Similarly, enforcing payments for water without higher income would have driven more farmers away from the scheme. Changing the capacity of the night storage dams (a buffer) to increase water availability (IntP 11) would have been extremely costly and could have increased water use without increasing yields. The project did not have the intent or the resources to work on infrastructure (IntP 10). However, while canal ownership and maintenance were significant points of contention during the first AIP meeting, farmers are now taking care of the canal maintenance and addressing IntP 10. Scheme maintenance and rehabilitation is typically the main intervention in irrigation projects, but many of these interventions continue to fail. This represents weak leverage, as feedback mechanisms are not triggered that would provide the incentive and capacity of the system to maintain infrastructure. While infrastructure maintenance is critical for efficient production, it is not enough on its own. TISA's interventions associated with IntPs 10–12 were indirect and the result of interventions at stronger IntPs.

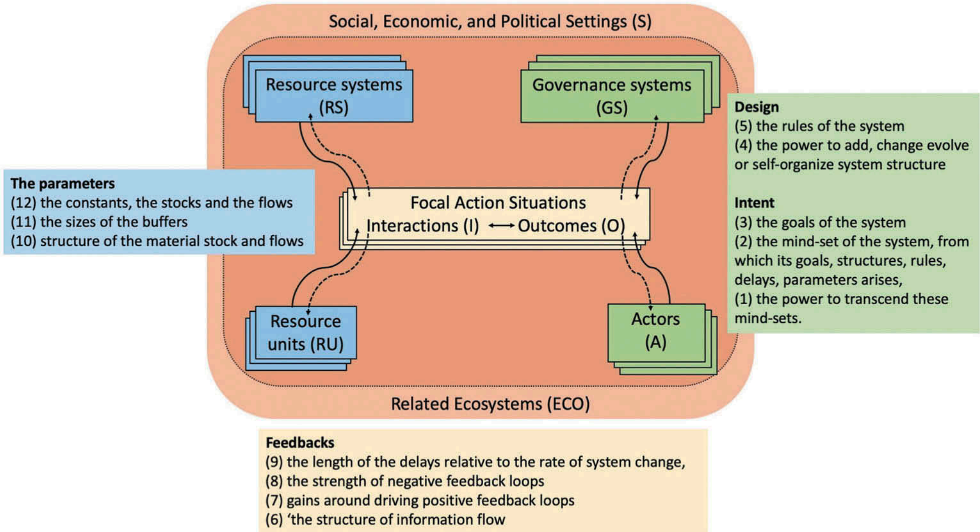

Figure 6. The socio-ecological-systems framework and where Meadows's intervention points influence the first-tier variables.

TISA's interventions were not focused directly on addressing delays in feedback (IntP 9) in the system, but farmers using the tools received immediate feedback to improve their decision making. Other feedbacks between enterprise selection and market returns (IntP 9) took longer but were important in improving farmers' knowledge of the system. The gains from establishing positive feedbacks (IntP 7) were critical for improving water management, while the positive returns from markets reinforced investments in inputs and increased income. Before the introduction of the WFD, there was no negative feedback (IntP 8) to reduce water use, and farmers oversupplied water and flushed nutrients through the root zone. By understanding the dynamics between irrigation and nutrient flows, irrigators developed a critical negative feedback mechanism, which maintained the system within the boundaries of optimal crop production.

Interventions related to system design require more thought and are more difficult to implement. However, the potential impact of better information flows and changing rules is very powerful. The tools were introduced to structure information flows to provide information to guide decision making on irrigation (IntP 6). Neither the AIP nor project personnel suggested that farmers change their water or fertilizer application rates, but based on the feedback from the tools, farmers reduced their irrigation frequency (Moyo et al., 2020). In fact, users negotiated new approaches to the timing of water supply with the IMC to change the strict rules around irrigation scheduling (IntP 5). The cropping calendar presented another debilitating set of rules, and was changed based on the learning from the gross margin analysis training. This training resulted in a significant flow of information, which ultimately negated the need for a cropping calendar – a clear indication of how information from within can be used to change the rules and design of the system.

Interventions that aim to influence the system's intent are the most powerful leverage points but also the most difficult to implement. TISA did not directly work in this area, apart from farmers articulating changes of mindset during the first AIP (Figure 3). The

Table 4. Alignment of interventions by the Transforming Irrigation in Southern Africa (TISA) project with leverage points, second-tier resource system variables and incentives, and outcomes.

System characteristic	Leverage point	Resource system variables	TISA interventions	Incentive to change	Change in behaviour	Immediate or direct impact	Indirect and other systemic outcomes
Parameters	12. Constants, parameters, numbers						More water available; farmers able and willing to pay fees; farmers adjust fertilizer rates
	11. The sizes of buffers and other stabilizing stocks, relative to their flows						The capacity of the night storage dam is no longer a limiting factor
	10. The structure of material stocks and flows						Farmers maintain infrastructure; fewer unused plots
Feedbacks	9. The lengths of delays, relative to the rate of system change						No delay in information; farmers water on demand
	8. The strength of negative feedback loops	RS: Water RU3b: Interactions between systems (fertilizer management)	Wetting Front Detectors and agricultural innovation platform (AIP): Training, learning interaction with other actors	Users: More efficient fertilizer management resulted in savings on inputs and increased yields	Users: Manage fertilizer better	Higher yields, lower fertilizer costs	Less irrigation, less nutrient leaching
	7. The gain around driving positive feedback loops	RS: Cropland RU4: Economic value of output (market links)	AIP: Training, learning interaction with other actors	Users: Higher incomes	Users: Engaged and learn from market information; produced crops of higher quality and value at the right time and negotiated better prices with buyers	Better incomes; greater willingness and capacity to pay for water	

(*Continued*)

Table 4. (Continued).

System characteristic	Leverage point	Resource system variables	TISA interventions	Incentive to change	Change in behaviour	Immediate or direct impact	Indirect and other systemic outcomes
Design	6. The structure of information flows	RS: Water RU2: Water availability (water management)	Chameleon & AIP: Training, learning interaction with other actors	GS: More efficient water use, leading to better production capacity, lass conflict between GS and users Users: less leaching of fertilizers, higher yields, labour savings	GS: Prepared to engage with users to relax the rules regarding irrigation scheduling Users: Less frequent irrigation; negotiate changes in water supply	Significant saving of water; less leaching of nutrients	
	5. The rules of the system	RS: Cropland GS5: Operational rules (cropping calendar)	Gross margin analysis: Training, learning, interaction with other actors	GS: Realized that to increase the efficiency of the system and to increase the capacity of users to make water payments they needed to change the rules Users: Higher profits from better enterprise selection	GS: relaxed rules on cropping calendar Users: Grow more profitable crops	Transition from subsistence to market-oriented production	
	4. The power to add, change, evolve or self-organize system structure	RS: Cropland RU4: Economic value (enterprise selection)	AIP and gross margin analysis: Training, learning and interaction with other actors	Users: Knowing that fertilizers will not leach and profitable crops will provide good returns raises yields and incomes	Users: Selected profitable crops	Higher income	
Intent	3. The goals of the system						Transitioned from subsistence to more market-oriented production
	2. The mindset or paradigm out of which the system arises						Paradigm changed from maintaining minimum livelihoods to economic growth
	1. The power to transcend paradigms						Department of Irrigation supported out-scaling of the work throughout Mat North.

most critical mindset change expressed was the need to transition from a subsistence to a market-oriented or economic-development paradigm. Within the subsistence paradigm, actors typically intervene with technologies and strategies such as seed and fertilizer handouts, which keep farmers locked in a state of dependence. In contrast, the economic-development paradigm is focused on improving irrigation system efficiency by creating economic incentives through higher production and market links. This incentive through the TISA project resulted in farmers reoccupying previously abandoned land. Higher income allows reinvestment in production (labour, inputs and information) and provides a feedback mechanism that maintains economic and environmental sustainability.

More recently, in October 2017, high-level officials were involved in a TISA workshop where the end-of-project results were presented to plan a large up- and out-scaling strategy (phase two of TISA). At this workshop, it was evident that most governance systems (GS) actors had made the paradigm shift from subsistence and food security to a market-oriented goal. This is because farmers are now able to grow enough staples on part of their land (irrigated or dryland) to ensure food security through self-sufficiency, and/or to the knowledge that food markets function well enough to allow farmers to purchase staples from the income generated by cash crops. So, with the right amount of communication and sharing of relevant information, TISA had indirect outcomes even at the highest leverage points.

Systemic change through intervention-point interaction

Both Meadows (1999, 2009) and Abson et al. (2017) suggest that using IntPs with stronger leverage will interact with IntPs that have weaker leverage, which is supported by this study. Working with the system's feedback mechanisms resulted in outcomes at the level of parameters; while influencing design had impacts at the level of feedbacks and parameters. There is also evidence that TISA's interventions resulted in changes at intervention points with the most leverage: the system's intent. Many users, governance actors, NGOs and even private-sector players have changed their perceptions of the goals of the system. Silalatshani and many other schemes in Zimbabwe were developed based on a strong subsistence / food security paradigm. Central control dictated which staples should be produced during which season (Figure 5), with the IMC controlling irrigation scheduling. As a result of the project there was a clear change in this paradigm, with all actors now focusing on market-oriented production systems. As a result, TISA is now out-scaling the project to many more irrigation schemes in Matabeleland North. This illustrates actors' capacity to transcend the paradigm – up to and including the director of irrigation. Interestingly, and as mentioned earlier, this change in paradigm was articulated during the first AIP in Silalatshani (Figure 3), because farmers themselves felt trapped in the subsistence paradigm and aspired to more efficient market-oriented production systems with returns on investment.

Towards a structured transition process

If small-scale irrigation schemes are complex systems, then the goal should be to transition them towards complex adaptive systems. Developing adaptive capacity is essential; therefore, actors within and between subsystems must be enabled to share, conserve and process large amounts of information. This requires free and effective communication between all actors, not only between irrigators. This allows the system to effectively manage the flow of resources: water, nutrients, inputs and outputs. Experimentation and learning need to guide enterprise selection, and provide farmers with the incentive to invest in production. This requires a flow of information between output markets, farmers and extension officers, giving farmers the necessary production knowledge to supply quality produce that meets market demand.

Ostrom (2007) warned against central control in systems, because it prevents experimentation and learning, resulting in lock-in or path dependence, and ultimately preventing the system from evolving in response to external conditions and opportunities. Previously in Silalatshani, the central control of the government prevented farmers from experimenting and responding to market information or changing what the system produced. Central control should be devolved to lower-level coordination, as in Silalatshani, where the cropping calendar is no longer in use. Similarly, flexible scheduling is critical so irrigators can set their own water scheduling based on their own information and on external influences, such as rainfall. Devolving the power of decision making, based on the information provided by the tools, allows farmers' mental models to develop and evolve in response to their water and market requirements. These changes would never have occurred in Silalatshani if the local governance system had not realized the value of releasing control over irrigation water supply and which crops to grow, allowing farmers to experiment, learn and organize in response to actual irrigation needs and market demands. In return, information is gathered that can be used to increase system efficiency.

Figure 7 illustrates how actors are engaged with farmers in irrigation systems. (A) represents the norm, where most actors exert their influence from outside the arena where farmers operate. Here all decisions, rules and support strategies are developed with minimal farmer consultation, or none. This central control does not allow the evolution of new strategies or institutions. Initially there are clear boundaries between organizations and farmers, with all rules, prices and support mechanisms decided externally and most often imposed without effective consultation or feedback from farmers. This may all be done in good faith, but based on the assumption that farmers cannot resolve their own challenges, process and integrate information, or become strong partners in their own development. (B) illustrates a reconfiguration of the same actors. Here, all the actors are in the same arena, and strategies and institutions can evolve based on consultation and interaction, the integration of different types of information, and experimentation. This configuration puts farmers in the decision-making arena, where they can contribute to the development of local rules and institutions, and where their needs and aspirations are considered in the development of goals and objectives for the larger system. In this new constellation of actors, farmers can negotiate terms of engagement and can experiment and learn based on multidirectional flows of information between numerous actors. Here different types of information can be integrated to generate new mental models, and feedback can trigger new adaptations and further refinement of the system.

In Silalatshani, farmers processed information, and new information resulted in better decision making and lower water use. Numerous unanticipated and critically important outcomes were observed: less conflict between users, and between users and governance systems; and more trust, group cohesion, and cooperation. With the

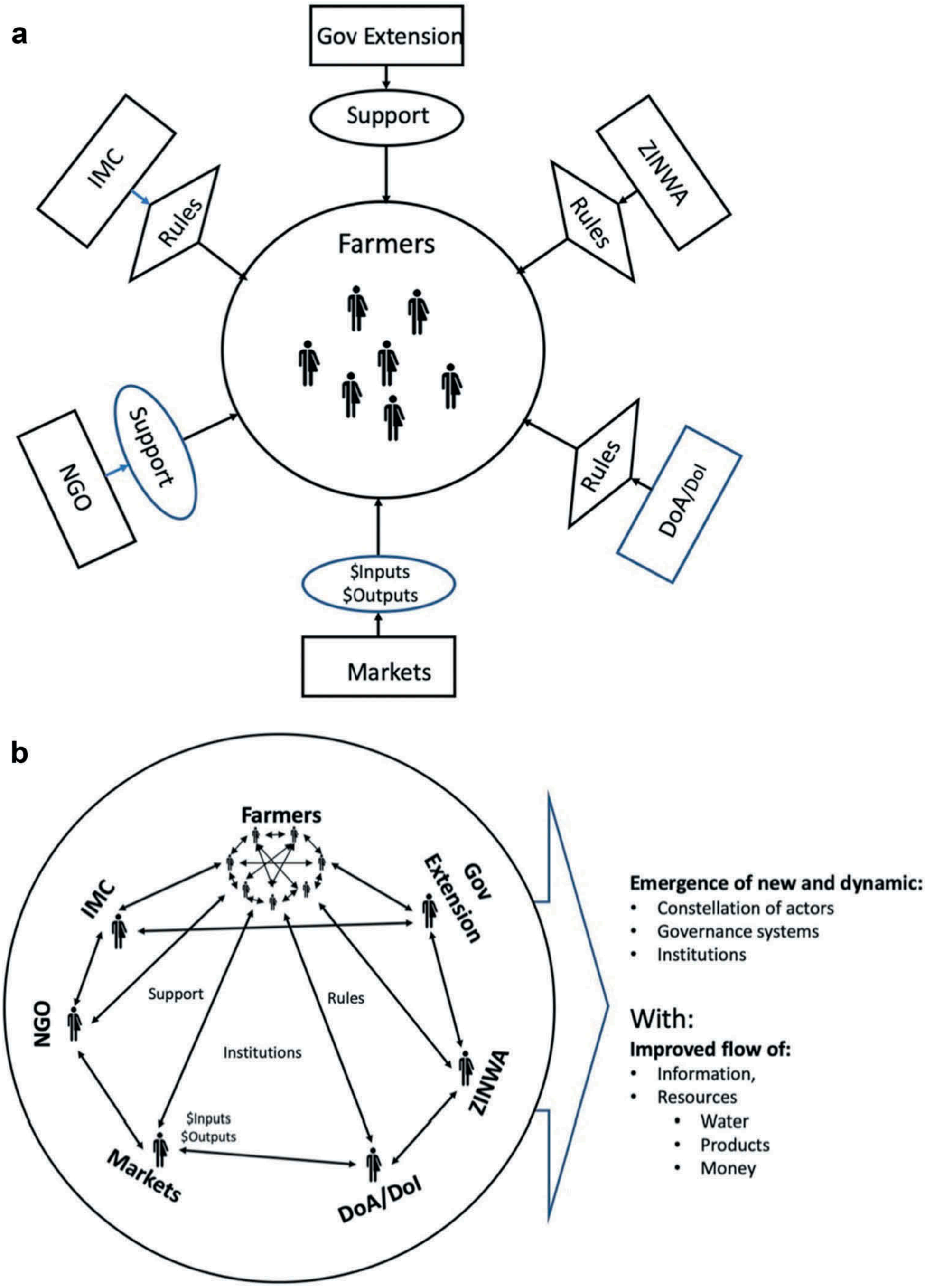

Figure 7. (A) How actors are commonly configured in small-scale irrigation schemes. (B) Better configuration of actors in the same arena.

resources now available, farmers initiated their own collection systems to procure materials and contributed labour to maintain canals and erect a fence to protect the crops from livestock. These examples of self-organization are highly encouraging, and illustrate high-level systemic changes and a transition towards complex adaptive systems.

The capacity to adapt to changing conditions is missing in many small-scale irrigation systems. This is primarily due to the limited interaction between actors and the central control of governance structures. Improving the effective communication and flow of information by developing new configurations of existing and even new actors will put farmers in the interaction arena. They will then not be mere recipients of externally determined rules and institutions, which is critical to stimulate transformative change. Generating strong networks based on trust and transparent flow of relevant information will increase, reducing the need for strong central control that prevents systems from evolving in response to the interactions.

Multi-stakeholder processes such as AIPs can be used as a structured diagnostic process to conduct an in-depth analysis using the SES framework and participatory problem analysis; consult with all parties to determine the relationships and interactions between problems; reconfigure the constellation of actors for effective communication and flow of information; determine the intervention points within the feedback and design groups that would address the variables in the SES framework relating to the problem and their root causes; and identify and develop interventions that drive the gains around positive feedbacks, and establish negative feedbacks where possible (to hold positive drivers within reasonable limits). Within the system's design characteristics, the focus of interventions should be on information flows and a thorough analysis of the rules and institutions, as it is important to determine where these aspects may be preventing proper dynamics between actors and components. To ensure effective feedback, a monitoring and evaluation process is paramount. This article offers a structured process as a starting point to stimulate further discussion. Implicit in a diagnostic approach is that irrigation schemes differ in their context, size, issues and extent of functionality, and various interventions need to be identified to suit the circumstance and produce the strongest impact. Though TISA's interventions have stimulated many changes, it is recognized that the duplication of these interventions elsewhere may not have similar impacts. The process we followed, however, will help diagnose the systemic challenges in existing schemes and guide the planning of new schemes beyond the development of infrastructure and irrigation schedules.

Conclusion

We find that dysfunctional irrigation schemes can be transitioned towards complex adaptive systems by offering appropriate technologies, a thorough diagnostic approach, wide stakeholder involvement, and careful selection of strong but achievable interventions. Although this *ex post* analysis is substantiated by hindsight, it provides evidence of how the SES analytical framework can be used in conjunction with Meadows's leverage points to develop an understanding of a system's major systemic challenges. TISA's interventions primarily addressed the system's feedbacks and design characteristics. The AIP played an important role in facilitating better communication and understanding between all the actors in the system. This is critical to identify new opportunities and to establish or strengthen relationships, to increase experimental learning and the adaptive capacity of the system.

This analysis supports Meadows's (1999) and Abson et al.'s (2017) assertion that intervention points with strong leverage can interact with and effect change elsewhere in the system. However, there is also evidence that interventions with weaker leverage can also effect change at levels with stronger leverage, with many of the system's actors changing their perceptions of the system's goals and rules. All actors now have a market-oriented production focus, supported by a more responsive irrigation schedule and abandonment of the cropping calendar. These changes have supported further out-scaling. Interventions that leverage change at other places in the system constitute valuable leverage points.

The interventions used in this project facilitated two transitions: from a centrally controlled system where actors had little opportunity to interact, experiment and learn, to a system where all actors are learning, new strategies are emerging, and farmers are able to self-organize and take charge of their production systems and infrastructure maintenance; and from a subsistence orientation to a market-oriented production paradigm where farmers are able to plan, invest and produce effectively in response to market information. We argue that this was possible because the project intervened at different but complementary and strong intervention points, most of which also unlocked barriers (leveraged change) in other places in the system. The question that now remains is how to identify strong interventions *a priori* and trigger synergies between them.

AIPs can be used to reconfigure the actors to allow effective communication and flow of information. Once problems, and their relationship with other problems, are identified using the SES framework, the focus should be on identifying interventions in the feedback and design groups to facilitate the dynamics between all the variables. Collective development of interventions that enhance positive feedbacks is essential – and the establishment of negative feedback, where possible – to keep positive drivers within reasonable limits. Within the design group, the focus should be on information flows and a thorough analysis of the rules and institutions, as it is important to determine where these aspects may be limiting interaction between actors and components. Strong monitoring and evaluation procedures should guide the process.

Two important considerations arise for the research and development community from this article: use structured diagnostics to identify systemic problems and the dynamics between these problems in complex systems; and think carefully about the best possible intervention points to generate/leverage systemic change – refrain from designing interventions based merely on linear thinking.

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