

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

The nexus between integrated natural resources management and integrated water resources management in southern Africa

Stephen Twomlow^{a,*}, David Love^{a,b}, Sue Walker^c^aICRISAT-Bulawayo, Matopos Research Station, P.O. Box 776, Bulawayo, Zimbabwe^bWaterNet, P.O. Box MP600, Mount Pleasant, Harare, Zimbabwe^cDepartment Soil, Crop and Climate Sciences, University of Free State, P.O. Box 339, Bloemfontein, South Africa

ARTICLE INFO

Available online 10 July 2008

Keywords:

INRM

IWRM

Green water

Blue water

ABSTRACT

The low productivity of smallholder farming systems and enterprises in the drier areas of the developing world can be attributed mainly to the limited resources of farming households and the application of inappropriate skills and practices that can lead to the degradation of the natural resource base. This lack of development, particularly in southern Africa, is of growing concern from both an agricultural and environmental perspective. To address this lack of progress, two development paradigms that improve land and water productivity have evolved, somewhat independently, from different scientific constituencies. One championed by the International Agricultural Research constituency is Integrated Natural Resource Management (INRM), whilst the second championed predominantly by Environmental and Civil Engineering constituencies is Integrated Water Resources Management (IWRM). As a result of similar objectives of working towards the millennium development goals of improved food security and environmental sustainability, there exists a nexus between the constituencies of the two paradigms, particularly in terms of appreciating the lessons learned. In this paper lessons are drawn from past INRM research that may have particular relevance to IWRM scientists as they re-direct their focus from blue water issues to green water issues, and vice-versa. Case studies are drawn from the management of water quality for irrigation, green water productivity and a convergence of INRM and IWRM in the management of gold panning in southern Zimbabwe. One point that is abundantly clear from both constituencies is that 'one-size-fits-all' or silver bullet solutions that are generally applicable for the enhancement of blue water management/formal irrigation simply do not exist for the smallholder rainfed systems.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

Increasing water productivity is a growing concern and objective within the international research and development community (CAWMA, 2007). This objective is encapsulated in the statement made Kofi-Annan at the UN Millennium Summit in September 2000, 'we need a blue revolution in agriculture that focuses on increasing productivity per unit of water – more crop per drop' (Quoted by Falkenmark and Rockström, 2004). This increased productivity is a necessary condition for agricultural producers to make better use of available water and protect its quality, while enhancing food production and income in a sustainable manner, especially in water-limited communities.

Modern crop varieties offer high yields; however, the larger share of this potential yield can only be realised with good crop management. This focus is particularly pressing in the SAT of

southern Africa (Love et al., 2006b; Twomlow et al., 2006). Despite the rising levels of adoption of improved maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench), pearl millet (*Pennisetum glaucum* (L.) R.Br.), and groundnut (*Arachis hypogaea* L.), per capita grain production continues to decline (Ryan and Spencer, 2001). Smallholder crop yields remain in the range of 500–1000 kg of grain per hectare (ICRISAT survey data for southern Africa, 2003–2006), with seasonal yield variation a function of seasonal rainfall (Fig. 1, Mugabe pers. comm.). Concomitant with poor rainfall, a major constraint to crop production is poor soil fertility, caused by inherently poor soil quality and inappropriate soil management practices (Mapfumo and Giller, 2001; Sanchez, 2002; Vanlauwe et al., 2003). Throughout Africa, negative nutrient balances for nitrogen and phosphorus have been found consistently in smallholder farming systems (Roy et al., 2003).

The slow rate of rural development, particularly in southern Africa, is of growing concern from both an agricultural and environmental perspective. To address this slow progress, two development paradigms to improve land and water productivity have evolved, somewhat independently, from different scientific

* Corresponding author.

E-mail addresses: S.Twomlow@cgiar.org, twomlowtravel@yahoo.com (S. Twomlow).

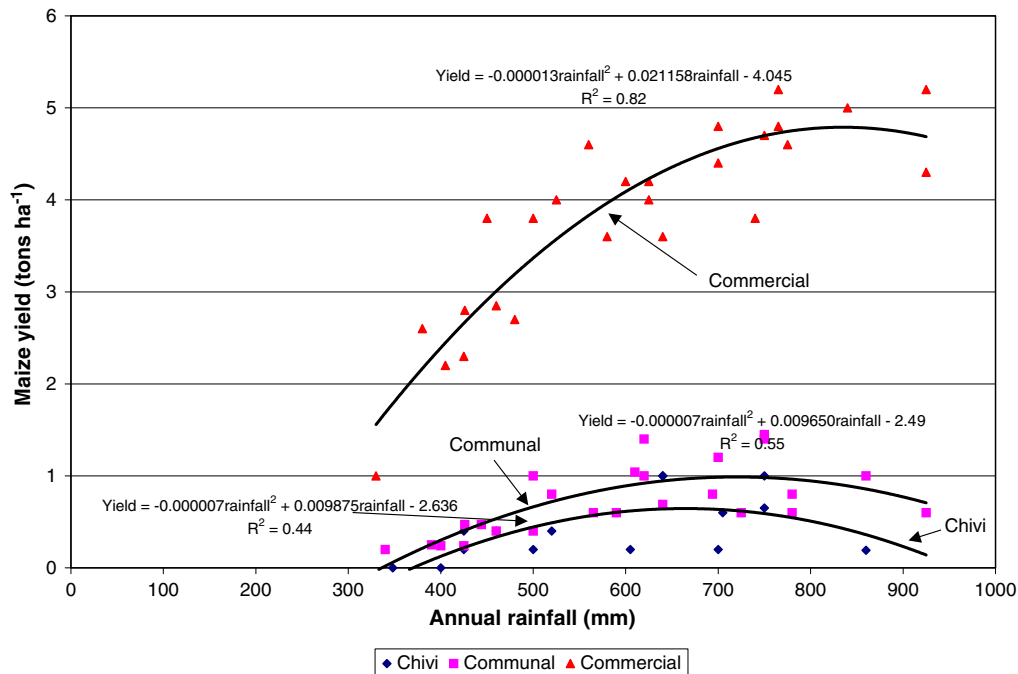


Fig. 1. Variation in average rainfed maize grain yields with annual rainfall as affected by resource status of the farming system. \blacktriangle Average maize yields from Zimbabwe's commercial farms. \blacksquare Average maize yields from Zimbabwe's communal farms, \blacklozenge Average maize yields from Chivi communal area (source Mugabe pers. comm.).

constituencies. One championed by the International Agricultural Research constituency is Integrated Natural Resource Management (INRM), whilst the second championed predominantly by Environmental and Civil Engineering constituencies is Integrated Water Resources Management (IWRM). The two paradigms have similar objectives of working towards the millennium development goals of improved food security and environmental sustainability and there exists a nexus between the constituencies of the two paradigms, particularly in terms of appreciating the lessons learned by each. In this paper, lessons are drawn from past INRM research that may have particular relevance to IWRM scientists as they redirect their focus from blue water issues to green water issues, and vice-versa, with a particular focus on southern Africa.

2. The need for new concepts and operational principles

2.1. Introduction

Good management of natural resources is key to good agriculture and rural development (Ryan and Spencer, 2001; Greenland et al., 1998; Twomlow, 2003; Pender et al., 2006; Pretty et al., 2006). This is true everywhere and is particularly true in the SAT, where over-exploitation of fragile or inherently vulnerable agroecosystems is leading to the degradation of land, soil and water resources. This degradation results in declines in food production and increasing hunger and poverty. Modern crop varieties offer high yields; however, the larger share of this potential yield can only be realised with good crop management (Twomlow et al., 2008a). A plethora of INRM and IWRM technologies have been developed over the years, but adoption has been poor for various technical, environmental, socio-economic and institutional reasons. Table 1 summarises what is currently known about the adoption of INRM/IWRM technologies, whilst Table 2 summarises some of the institutional and organizational constraints that have been identified. Alternative technologies that will address some of the issues facing the farmers are promoted by both INRM and IWRM. However, due to various constraints such as external conditions,

Table 1

What we know about the adoption of Integrated Natural Resource Management (INRM) and Integrated Water Resource Management (IWRM) practices (adapted from Barrett et al., 2002)

- Farmers have different needs/constraints according to the external conditions they face and their internal characteristics. Therefore, the identification of a large number of INRM/IWRM technologies or a basket of INRM/IWRM technological options is critical for reaching a large number of farmers and communities
- There is an inherent dilemma between deliberate targeting of technologies to areas and social groups most likely to adopt and benefit from those technologies and the desire to make technology dissemination more demand driven
- The adoption of innovation processes by individual farmers and groups of farmers is often more important than the adoption of individual technologies
- INRM practices that improve soil fertility, raise production and prove profitable options do exist
- Farmers who recognise natural resource problems are not always induced to invest in improved INRM/IWRM practices
- Working-capital constraints or high opportunity costs of capital commonly limit investment in improved INRM/IWRM practices. The linking of high value cash crops to cash investment therefore helps make such investments attractive
- Farmers will find ways to adopt/adapt new INRM/IWRM technologies into their farming system when incentives are sufficiently high from their perspective
- Improved INRM/IWRM technologies generally fail to be adopted by women farmers and poor farmers at the same rate as male farmers who enjoy greater wealth, education and socio-economic power. Where adoption by disadvantaged groups does take place concerted efforts have been made to reach these groups
- Few studies on the social cost and benefits of resource degradation or improvement

lack of available finance, and social differences farmers have not readily implemented them. Low adoption leads to low impact and failure to reach the goals of agricultural research investments (Ryan and Spencer, 2001; Freeman et al., 2002; Harwood et al., 2006. Love et al., 2006b; Pretty et al., 2006), and the MDGs (UN Millennium Project, 2005).

There are two main reasons for low impact of research and development (R&D) investments and why smallholder farmers

Table 2

Common organizational problems in Natural Resource Management Research that also apply to Water Resource Management Research (adapted from Ashby, 2003)

- Lack of representation of key stakeholders in research process
- Participation is not developed around clearly specified rights, roles and responsibilities
- Mechanisms of accountability among participants are lacking, especially the accountability of researchers
- Process too often corrupted by hidden agendas
- Conflicts of interest are not made explicit or negotiated
- Transaction costs of participation exceed the benefits to the participants, particularly households with low resource endowment
- Feedback mechanisms, such as monitoring and evaluation of the research process, are not in place so that learning about how to improve the process is minimal or slow

often do not invest in new technologies. First is the relative profitability and associated risk of the new technology under moisture limited and variable climatic conditions (Table 1). The second is the need for site-specific innovations that address farmer and market preferences and the diversity in the policy and institutional constraints, all of which affect adoption (Table 1) (Pender et al., 2006).

2.2. Alternative conceptual frameworks and models of integration

Both biophysical and socioeconomic factors are crucial in shaping research strategies and priorities (Harwood et al., 2006; Kassam, 2006; CAWMA, 2007). Research in developing countries has evolved in different phases. Agronomists and breeders have long been aware of genotype–environment interactions and the need to tailor technologies for specific eco-regions and the impacts of climate on the catchment and agricultural systems (Table 3). There is now a growing realisation that R&D efforts should be demand-driven and respond to the needs and priorities of smallholder farmers (van der Zaag, 2005; Love et al., 2006b; Twomlow et al., 2008a), their support agents (Twomlow et al., 2008b), as well as consumers and markets (Pender et al., 2006). Developing widely adaptable, acceptable products requires participatory approaches that involve end-users, stakeholders and target groups at all stages of technology development. It also requires proper monitoring and evaluation that will help draw lessons from experience – reflective learning in project cycle parlance (Fig. 2). A coalition of strategic partners, with complementary skills, is also needed for scaling

out desirable innovations. A brief review of the different integrating models and their evolution is provided below.

2.3. The integrated natural resource management paradigm within international agricultural research (adapted from Twomlow et al., 2008a, b)

INRM is an attempt to build a new agricultural research and development paradigm to meet the challenges and opportunities outlined above. Campbell et al., 2001 defined INRM as ‘a conscious process of incorporating the multiple aspects of natural resource use (be they biophysical, sociopolitical or economic) into a system of sustainable management to meet the production goals of farmers and other direct users (e.g. food security, profitability, risk aversion) as well as the goals of the wider community (e.g. poverty alleviation, welfare of future generations, environmental conservation)’. This new paradigm attempts to integrate various, but not necessarily multi-disciplinary, participatory research and development paradigms that include:

– Participatory plant breeding	– Participatory action research
– Farming systems research	– Farmer-led on-farm trials
– Farmer field schools	– Integrated pest and disease management
– Community-based NRM	

The five key elements of the INRM paradigm are summarised in Table 4 and the linkages between principles are illustrated and summarised in Fig. 3.

In essence, INRM tries to harmonise the complementary but often conflicting goals facing farmers of using natural resources for production while considering environmental protection and maintaining the sustainability of any agricultural system.

There is a vast literature on INRM and on technology evaluation and adoption. Some recent publications include Barrett et al., 2002; Campbell and Sayer, 2003; CIMMYT, 2003; Douthwaite et al., 2003; Harwood and Kassam, 2003; Perez and Tschinkel, 2003; Pound et al., 2003; Shiferaw and Freeman, 2003; Shiferaw et al., 2005; Harwood et al., 2005, 2006; Campbell et al., 2006. The focus of much of this literature is on the integration of socio-economic

Table 3

Effect of climate variability on pearl millet crop performances and Integrated Genetic Natural Resource Management (IGNRM) options in Mali (adapted from Hausmann and Gerard, pers comm.)

Climate parameters	Effects on crops and natural resources	IGNRM options
Late onset of rains	Shorter rainy season, risk that long-cycle crops will run out of growing time	Early-maturing varieties, exploitation of photoperiodism, P fertilizer at planting
Early drought	Difficult crop establishment and need for partial or total re-sowing	P fertilizer at planting, water harvesting and runoff control, delay sowing (but poor growth due to N flush), exploit seedling heat and drought tolerance
Mid-season drought	Poor seed setting and panicle development, fewer productive tillers, reduced grain yield per panicle/plant	Use of pearl millet variability: differing cycles, high tillering cultivars, optimal root traits, etc.; water harvesting and runoff control
Terminal drought	Poor grain filling, fewer productive tillers	Early-maturing varieties, optimal root traits, fertilizer at planting, water harvesting and runoff control
Excessive rainfall	Downy mildew and other pests, nutrient leaching	Resistant varieties, pesticides, N fertilizer at tillering
Increased temperature	Poor crop establishment (desiccation of seedlings), increased transpiration, faster growth	Heat tolerance traits, crop residue management, P fertilizer at planting (to increase plant vigor), large number of seedlings per planting hill
Unpredictability of drought stress	See above	Phenotypic variability, genetically diverse cultivars
Increased CO ₂ levels	Faster plant growth through increased photosynthesis, higher transpiration	Promote positive effect of higher levels through better soil fertility management
Increased occurrence of dust storms at onset of rains	Seedlings buried and damaged by sand particles	Increase number of seedlings per planting hill, mulching, ridging (primary tillage)
Increased dust in the atmosphere	Lower radiation, reduced photosynthesis	Increase nutrient inputs (i.e. K)

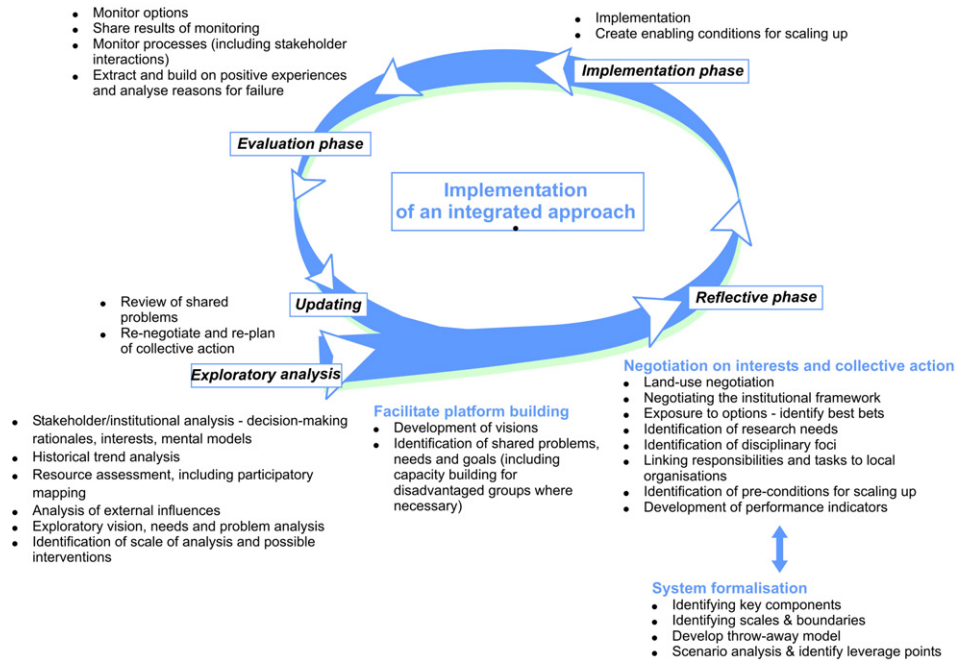


Fig. 2. An idealised learning cycle in R&D for natural resource management (Campbell et al., 2006).

Table 4

Five key elements of Integrated Natural Resource Management (adapted from Douthwaite et al., 2003)

<p>(1) <i>Learning together for change</i> NRM must be based on a continuous dialogue among stakeholders. Natural resource management is like jazz—it needs constant improvisation, each band member knows the weaknesses and strengths of the others, and they all learn how to play together. Researchers cannot remain exclusive: they need to engage in action research to develop appropriate solutions together with resource users. In this process researchers and resource users: (a) define subsystems, (b) reflect and negotiate on future scenarios, (c) take action, (d) evaluate and adapt attitudes, processes, technologies and practices</p> <p>(2) <i>Multiple scales of analysis</i> INRM attempts to integrate research efforts across spatial and temporal scales. This is because ecological and social processes take place over different time scales ranging from minutes to decades. Slow changing variables restrict the dynamics of more rapidly cycling processes, and vice versa. As the system evolves, the dynamics of the different variables may experience sudden changes that reorganize the system. Usually these changes arise when the system reaches specific thresholds. In these reorganization points, it is impossible to predict how the system will self-organize. Understanding a system, rather than just describing it, usually requires studying that system plus other systems with which it interacts. Systems modelling is a practical approach to deal with variables that change more slowly than the length of a project. Modeling can also help farmers and other natural resource managers explore different scenarios, identify preferred ones, and then negotiate how to achieve them</p> <p>(3) <i>Plausible promises</i> INRM needs a practical problem-solving approach that delivers tangible outputs. There must be motivation for farmers to work together with researchers. This motivation comes from ideas and technologies that make a ‘plausible promise’ of being beneficial to farmers. Working together builds trust and leads to further learning, from which other possibilities flow. Monitoring and evaluation and impact assessment can help identify and improve what is working</p> <p>(4) <i>Scaling out and up</i> INRM runs the risk of being criticised for only producing local solutions. However, if natural resource systems are characterised adequately (e.g. according to exogenous drivers as in the IITA Benchmark Area Approach – Douthwaite et al., 2003) then INRM can yield results that have application across broad ecoregional domains. While most INRM technologies cannot be scaled-out, some can be, together with the learning processes that allow rural people to identify and adapt new opportunities to their environments. INRM recognises a difference between scaling-out (where an innovation spreads from farmer to farmer, community to community, within the same stakeholder groups) and scaling-up, which is an institutional expansion from grassroots organizations to policy makers, donors, development institutions, and other stakeholders key to building an enabling environment for change. The two are linked: scaling-out occurs faster if INRM projects plan and invest in engaging with stakeholders who can help promote project outputs and create an enabling environment for them. Iterative learning cycles that take place in participatory technology development processes can also help create an enabling environment through interaction, negotiation and co-learning among different stakeholders</p> <p>(5) <i>Evaluation</i> Evaluation is key to adaptive management because it provides the real-time feedback necessary for constant improvisation, learning and improving performance. Evaluation also provides data for further negotiation between stakeholders, and for resource allocation decisions. Stakeholders should agree on plausible strategies on how research will contribute to developmental change and then regularly monitor implementation of these strategies to feed into the learning cycle. Success criteria and indicators, agreed early on in a project, are the basis for impact assessment and negotiation amongst stakeholders for resource allocation decisions</p>
--

and biophysical issues, with little focus on the integration of the genetic dimension (Twomlow et al., 2008a). Omission of the genetic component (both crop and livestock) in improved management of agroecosystems is contrary to the wider consensus to link natural resource management with livelihood strategies of smallholder farmers and other resource users.

2.4. The integrated water resources management paradigm (IWRM)

IWRM is a systems approach to water management, recognising the need to manage the entire water cycle and its inter-connectiv-

ity (Fig. 4). It stands on four fundamental principles: (i) water is a vulnerable and finite resource and must be managed sustainably, (ii) water is a (special) economic good, (iii) management of water resources should be done in a participatory manner and (iv) gender equity should be promoted in water resource management (ICWE, 1992; Savenije, 2002; Murenga, 2003). So IWRM and INRM share many of the same physical parameters and the systems concepts, yet operate at a different level in the grand scheme from a biological cell to the whole earth, which can each be seen as a system. Both try to promote utilisation yet balance within the system, with INRM having the farmer or household at its centre and IWRM hav-

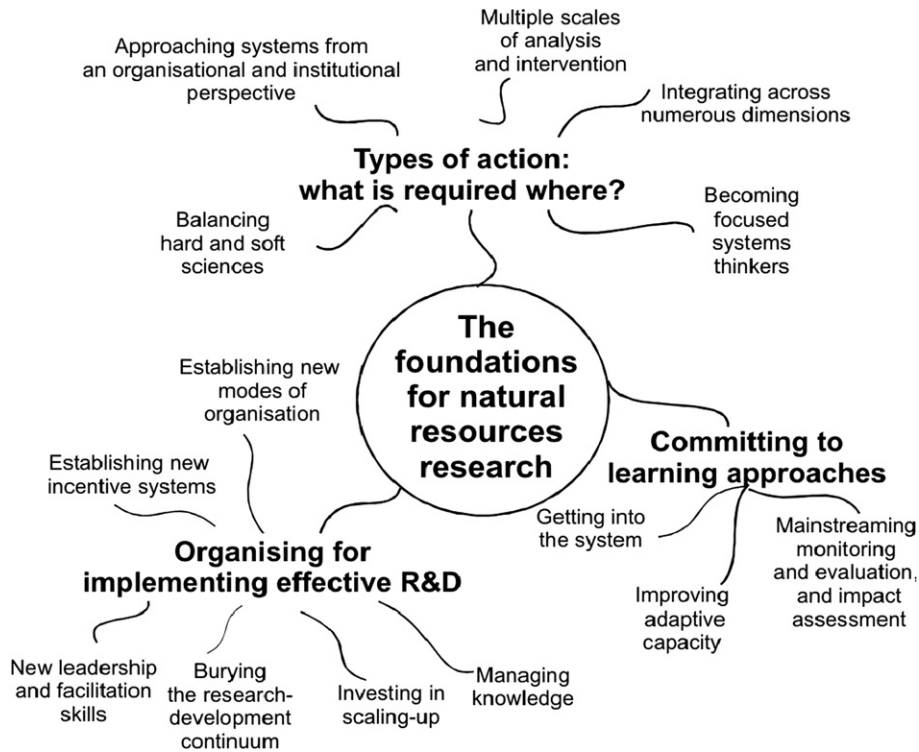


Fig. 3. The principles for more effective Integrated Natural Resource Management (Campbell et al., 2006).

ing the hydrological catchment as the basic unit and addressing water utilisation by a wider range of people living in the whole catchment.

Both INRM and IWRM recognise their subjects of research as complex systems, that is systems consisting of a large number of components that are richly and non-linearly interconnected (Figs. 3 and 4). The emergent properties of the system are not primarily a result of the nature of the components, but of the nature of inter-connections (Cilliers, 1998). Such complexity requires research that is transdisciplinary and often transinstitutional (Bawa, 1997; Carnoy, 1998; Love et al., 2004). This is what is known as mode 2 knowledge production (Gibbons et al., 1994; Jansen, 2000).

One key difference that has arisen between purely INRM and purely IWRM studies is the issue of the scale or boundary for analyses and interventions. It is a fundamental IWRM principle that the basic unit is the catchment (hence the term “integrated catchment management”), while many INRM studies use a unit with social boundaries (e.g. village or household) as the scale for analysis (Lovell et al., 2002). Table 5 summarises the biophysical and institutional boundaries that might be considered when addressing issues of scale. The use of IWRM approaches at the catchment scale could be considered a special case of the ecodistrict. Boundaries are central to INRM and IWRM because they specify the area over which jurisdictions apply, as well as the roles to which particular actors are assigned. Within this context there is also a need not only to understand the management and technical differences between irrigated and rainfed agriculture, but also the differences between formal and informal irrigation in semi-arid regions (Table 6).

3. Case studies

3.1. Need for water resources assessments prior to food security interventions

Many rural development initiatives, notably the Millennium Project, target the smallholder-farming sector and emphasise irri-

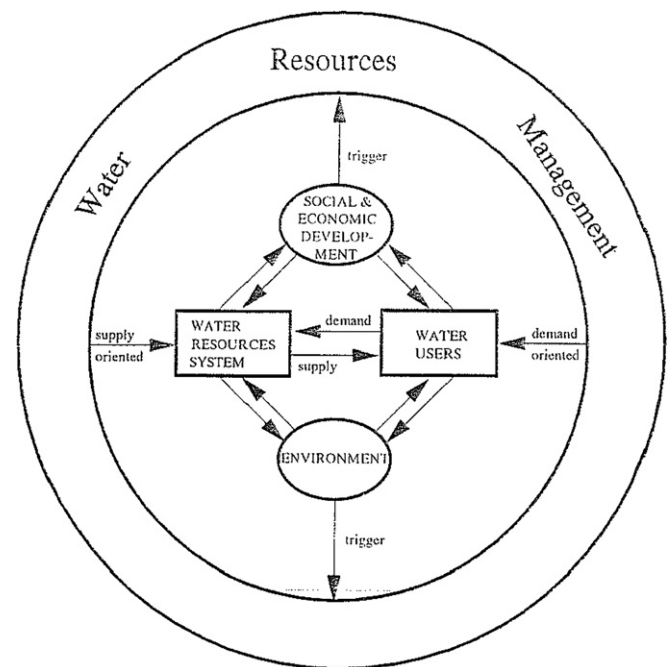


Fig. 4. Schematic representation of Integrated Water Resources Management (adapted from Koudstaal et al., 1992).

gation (UN Millennium Project, 2005). However, water resource availability is limited in southern Africa (e.g. Mazvimavi, 2004; Nyabeze, 2004) and this imposes a constraint on some food security interventions (Love et al., 2006b). Promoting irrigation technologies in the absence of an assessment of access to the required water can result in a partial failure of the intervention (Moyo et al., 2006), and this is where IWRM needs to play a greater role.

Table 5

Hierarchical levels of observation to address issues of scale from ecological and social perspectives (Twomlow, 2003)

Ecological boundaries	Social boundaries
<i>Ecozone</i> : Based on broad-scale physiography and vegetation, controlled by climate, e.g., dry savannah	<i>Regional and national</i> Community and ethnic grouping
<i>Ecoregion</i> : Subdivision of ecozone regional climate, surface topography, vegetation, e.g., commercial versus subsistence farming	
<i>Ecodistrict</i> : Land resource area parent material, surface topography, e.g., major drainage basin	
<i>Soil landscapes</i> : Dominant landscape component, e.g., major soil unit that influences land use – catenas	<i>Communities</i> Villages and chieftainships
<i>Farm unit (ecosite)</i> : E.g., cropping system or grazing, gradients in soil fertility	<i>Private and communally held property</i>
<i>Plot/quadrat (ecoelement)</i> : E.g., comparisons of change within and between farms	
<i>Microsite</i> : Characterization of soil biophysical attributes	

Table 6

Comparison of rainfed and irrigated agriculture in semi-arid regions (source: Twomlow (2003))

	Irrigated		Rainfed	
	Informal	Formal	Traditional	Water harvesting
Cost	Moderate	High	Low	Moderate
Structures	Some	Large	No	Possibly
Management				
Control	Farmer	Scheme	Farmer	Farmer
Technology	Indigenous + new	New	Indigenous	Indigenous + new
Inputs/outputs	Moderate	Moderate	Moderate	Low
Adoptability	Farmer initiated	Imposed	Accepted	New/accepted
Reliability	Increased	Variable	Poor	Increased
Flexibility	Flexible	Limited	Limited	Good
Crops	Very wide	Wide	Limited	Wide
Crop stress	Some	Absent	Present	Some
Salinity	Some	Present	Absent	Absent
Social				
Land tenure dynamics	Established	Changes	Established	Changes
Market outlets	Yes	Essential	Yes	Yes

3.2. Water quality management for irrigation

Salinity is a major challenge to irrigation and is a common problem in the alluvial aquifers of the Limpopo Basin. Many alluvial aquifers, especially smaller aquifers and those on river bank flood plains are characterised by high levels of sodium and chloride. This is an ambient condition, related to the geology of the aquifers, and threatens irrigated agriculture in the form of equipment or crop failure. It necessitates the characterisation of boreholes and other water points as suitable or unsuitable for irrigation prior to interventions such as drip kit distribution (Love et al., 2006a). The Lower Mzingwane alluvial aquifer is one such system, where agricultural production is constrained by salinity that increases significantly at the end of the dry season. During drought years, recharge is expected to be less and if the drought is extended water levels in the aquifers drop substantially, increasing salinity problems (Love et al., 2007). Catchment level management of the water quality problems is required to develop a balance between low salinity surface water released for recharge, high salinity water in the flood plains aquifer, and high salinity return flows from irriga-

tion on the flood plains and this can be best achieved via an IWRM approach.

3.3. Green water productivity

Much of the current thinking about green water productivity has been developed by Rockström et al. (2007), with a strong emphasis on actual green water flows (evapotranspiration) and how we might improve productivity via different management interventions (i.e. INRM). Fig. 5, adapted from Rockström et al. (2007), with additional data taken from the work of Ncube et al., 2007 presented in Fig. 6, indicates that when doubling yields from 1 to 2 t/ha in semi-arid tropical agro-ecosystems, green water productivity may improve from approximately 3500 m³/ton to less than 2000 m³/ton. This, as is correctly argued, is a result of the dynamic nature of water productivity improvements when moving from very low yields to higher yields. At low yields, crop water uptake is low and evaporative losses high, as the leaf area coverage of

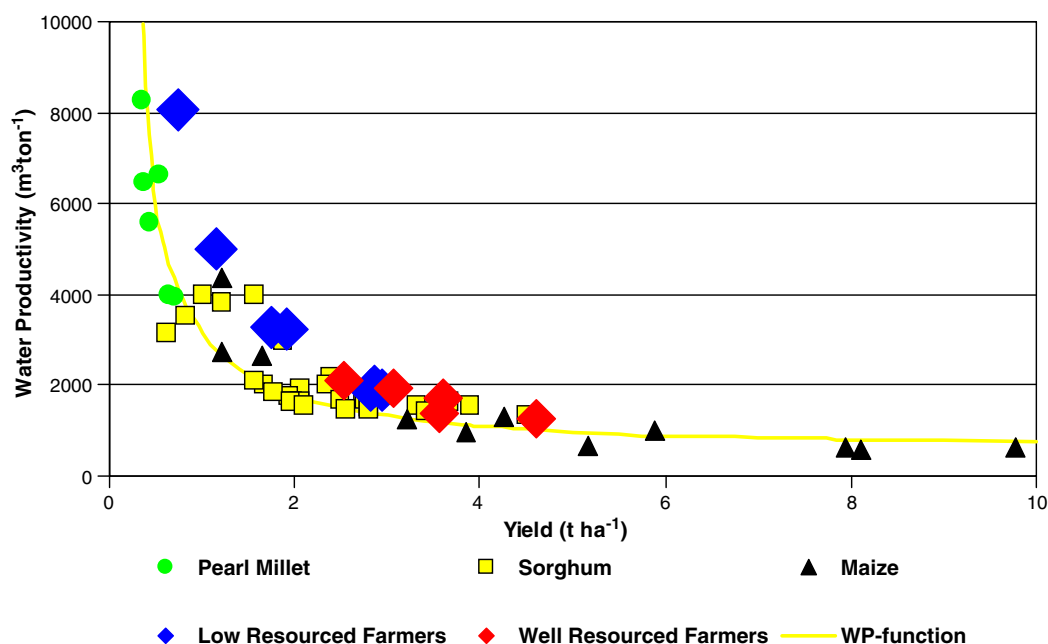


Fig. 5. Dynamic relationship between water productivity and yield for cereal crop under (i) various management and climatic conditions (adapted from Rockström et al., 2007) compared to (ii) low and well resource status of household for the same climatic conditions but different management (adapted from Fig. 6, Ncube et al., 2007).

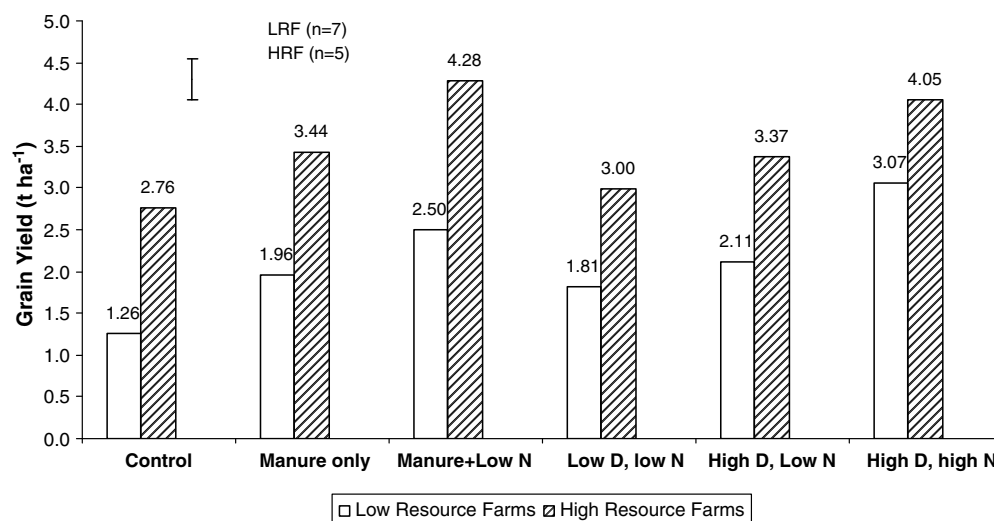


Fig. 6. Mean maize grain yield, 2003/04 season (Mkhubazi, Tsholotsho, Zimbabwe) in response to a range of soil fertility amendments for low and well resourced Farms. 1. Control plot with no soil fertility amendments. 2. Manure only. 3. Manure + Low N (25 kg ha⁻¹ ammonium nitrate). 4. Low D, low N (25 kg ha⁻¹ of Compound D and ammonium nitrates). 5. High D, low N (150 kg ha⁻¹ Compound D and 25 kg ha⁻¹ of ammonium nitrate). 6. High D, high N (150 kg ha⁻¹ of Compound D and ammonium nitrates). Error bars represent standard errors of differences between means of the treatments (source Ncube et al., 2007).

the soil is low. Together this results in high losses of water as evaporation from soil. However, little of this work was undertaken on-farm and none of it takes cognizance of the resource endowment of households and how this might influence crop management decisions and the residual fertility of a household's fields (Tittonell et al., 2005a, b; Zingore et al., 2007; Ncube et al., in press).

A good understanding of the farming systems is essential to develop appropriate technological interventions to manage water and fertility (Twomlow et al., 2006; Mupangwa et al., 2006; Pretty et al., 2006). Some studies have been conducted to assess the dynamics (including nutrient management and resource allocation) of smallholder farming systems (Defoer et al., 1998; Briggs and Twomlow, 2002; Tittonell et al., 2005b; Zingore et al., 2007). Most of these were however conducted in medium to high rainfall areas. The few studies that have been conducted in the semi-arid regions of Africa were carried out in West Africa (Mortimore and Harris, 2005), close to a large urban population with strong market drivers and focused on nutrient flows. Data on resource allocation and use patterns in the semi-arid regions of southern Africa is limited to a few case studies (Scoones, 1997, 2001; CAWMA, 2007; Ncube et al., in press). Future work must take account of this, as crop responses to similar management interventions can differ markedly by resource group, as is shown in Fig. 6 (Ncube et al., 2007), and can have major impacts on the water productivity (Fig. 5).

3.4. INRM/IWRM convergence in the management of gold panning in rural areas

Gold panning is an intractable socio-environmental problem common in the rural areas many developing countries (MMSD, 2002), where the co-occurrence of poverty and easily extractable alluvial gold leads to this livelihood strategy as an inevitable outcome. It is associated with a wide variety of negative impacts, including social problems within rural communities such as violence and prostitution, as well as erosion and chemical pollution (Maponga and Ngorima, 2003), especially the release of toxic mercury into water bodies, soils and air (Spiegel et al., 2006). Gold panners vaporise mercury out of the gold mercury-amalgam, in order to recover the mercury (Love, 2002). A variety of studies in Zimbabwe have approached the problem. Shoko and Love (2005) adapted

the INRM paradigm "CAMPFIRE model" to the management of gold panning and emphasise social structures, such as the village, as the point of analysis for management interventions. Zwane et al. (2006) applied the IWRM paradigm catchment planning model and focused on the hydrological catchment as the point of analysis for management interventions. Thus, both approaches were used in this same catchment area in parallel studies.

There are important lessons to be learned from the application of both approaches to this type of problem. Both approaches converge in emphasising (i) community participation in management activities and decisions: the community-based natural resource management approach, (ii) functional decentralisation and (iii) transdisciplinary intra-governmental collaboration. The first emphasis encourages local ownership of the legal framework and saves monitoring costs (Shoko and Love, 2005; Tunhuma et al., 2007). The second leads to decision-making at the lowest appropriate level, where more context-specific details of the issue under consideration are available – or even obvious (Jaspers, 2003; Nare et al., 2006). The third allows for more informed decision-making and for harmonisation of different policies that may have different origins but address the same problem (Zwane et al., 2006). Furthermore, the case of gold panning shows that valid analysis of socio-environmental problems can (and should) be made at different spatial and disciplinary scales, and lessons drawn at each of these scales.

4. Concluding comments

Agricultural production systems in the SAT are very complex and have evolved over generations in order to adapt to high variability and diverse biotic and abiotic stresses. In a risk-prone environment of southern Africa's smallholder sector, the nexus between rural poverty, population pressure and agro-ecosystem degradation (Templeton and Scherr, 1999; Scherr, 2000) further complicates the application of research results to the real world livelihood situations. The relative importance of land, labour and water as factors in production also vary according to the population densities in a given catchment system. Also, the R&D strategy will have to vary according to the relative importance and scarcity of land, labour, water and capital. Where land is scarce (e.g. Malawi) and labour is relatively abundant, research should focus on

technologies that improve land/water productivity and use labour to generate employment. However, labour-saving options that also improve land/water productivity may be needed in areas of low population density where labour markets are poor and HIV/AIDS has become a major issue (e.g. Zambia and Zimbabwe). Both of these situations can benefit from applying both of the integrated management approaches, while searching for the optimisation of the systems.

Social and economic diversity and failure to capture farmer/consumer preferences and market requirements are key factors constraining the adoption of innovations despite the scientific proof that they could be of benefit. Individual farmers and government ministries may have non-complementary (and sometimes conflicting) economic, social and environmental objectives but both INRM and IWRM could be used as complimentary approaches. Farmers' economic and environmental objectives might depend on their comparative advantages and vulnerabilities to shock; this in turn is determined by natural resource endowments, market access, government policies and social entitlements. Again these could benefit from both integrated management approaches. For example, with unreliable or imperfect markets, farmers may not be in a position to adopt profitable and marketable varieties. The opportunities for intensification, diversification and commercialisation of production will vary accordingly (Pender et al., 2006). In remote SAT areas that are poorly integrated to markets, perishables and high-value input-intensive crops may not be appropriate; whereas farmers closer to urban centers, processing plants and marketing points may benefit from such technologies. This could be tested using either integrated management approaches depending on the scale or focus of the study. Also, comparative advantages are relatively dynamic, varying over time depending on changing infrastructure and market conditions. This will necessitate different R&D strategies for the short, medium and long-term; and periodic evaluation and refinement of growth opportunities and research priorities.

In addition to markets, property rights, pricing policies and institutional arrangements can also influence the profitability and uptake of new innovations. Vulnerability to drought and other risks will differ across farm households depending on wealth, access to resources and ability to smooth consumption over time. Again these could benefit from both (INRM & IWRM) integrated management approaches. Different groups of rural households may have differing capacities for buffering and managing risk and may require different types of technological and policy interventions (see Fig. 6 for example). When the benefits from resource investments are unequally distributed or externalities affect the flow of benefits captured by farmers, it can hamper adoption and investment on such technologies. For example, households in the upper and downstream reaches of a watershed may have different incentives for land and water management investments, which can be assessed by either INRM or IWRM. Yet it is essential that each understands the needs of the other, and the off-site implications of future management decisions, particularly those taken in the upper catchments that influence flows to the lower reaches (CAWMA, 2007). Likewise, developing integrated pest management options requires collective, coordinated action amongst a group of farmers to combine occasional use of pesticides with crop rotation or intercropping of different crops or varieties and reduce pest resistance (Singh and Trivedi, 2005). Similarly, men and women farmers may have different constraints and priorities and preferences. Labour-deficient households or those affected by AIDS may require special attention and targeting (Yamano and Jayne, 2004). Technology development needs to be fully cognizant of client needs and growing conditions in a given target region.

Even when technologies are profitable under a given biophysical environment, uptake may be limited by policies and institu-

tional factors including production and market risk (especially among risk-averse farmers). While developing new technologies, it is important to diagnose needs and limiting factors – biophysical and socioeconomic constraints, biotic and abiotic stress factors, resource conditions and market, policy and institutional factors – at a range of levels. Experience has shown that a narrow disciplinary or commodity approach that fails to integrate all these dimensions will not succeed.

It is in the essence of complex systems that no single approach can do justice to describing the system (Cilliers, 1998), nor is it likely that an intervention based on one disciplinary approach will be fully successful. INRM and IWRM both offer transdisciplinary approaches that can do justice to natural systems. However, the difference in scale of analysis between the two approaches is likely to influence the outcomes of such analyses and the interventions recommended (see Hattingh et al., 2007). It is therefore important not to rule out either paradigm in approaching a natural system problem or policy.

References

- Ashby, J., 2003. Introduction: uniting science and participation in the process of innovation – research for development. In: Pound, B., Snapp, S., McDougall, C., Braun, A. (Eds.), *Managing Natural Resources for Sustainable Livelihoods: Uniting Science and Participation*. IDRC and Earthscan Books, London, pp. 1–15.
- Barrett, C.B., Place, F., Aboud, A.A. (Eds.), 2002. *Natural resources management in African agriculture: understanding and improving current practices*. CABI Publishing in Association with ICRAF. 335 p.
- Bawa, A.C., 1997. Knowledge production and research strategies in South Africa. In: Cloete, N., Muller, J., Makgoba, M.W., Ekong, D. (Eds.), *Knowledge, Identity and Curriculum Transformation in Africa*. Maskew Miller Longman, Cape Town, pp. 43–52.
- Briggs, L., Twomlow, S.J., 2002. Organic material flows within a smallholder highland farming system of South West Uganda. *Agriculture, Ecosystems and Environment* 89, 191–212.
- Campbell, B.M., Sayer, J.A. (Eds.), 2003. *Integrated Natural Resource Management: Linking Productivity, the Environment and Development*. CABI Publishing UK in Association with CIFOR, 315 p.
- Campbell, B.M., Sayer, J.A., Frost, P., Vermeulen, S., Ruiz-Perez, M., Cunningham, A., Ravi, P., 2001. Assessing the performance of natural resource systems. *Conservation Ecology* 5 (2), 22. <<http://www.consecol.org/vol5/iss2/art22/index.html>>.
- Campbell, B., Hagmann, J., Stroud, A., Thomas, R., Wollenberg, E., 2006. *Navigating amidst complexity: guide to manage R&D interventions for improving livelihoods and the environment*. Center for International Forestry Research, Bogor, Indonesia. p. 82.
- Carnoy, M. 1998. Higher education in a global innovation economy. Globalisation, Higher Education, High Level Training and National Development Conference. Centre for Higher Education Transformation and Human Sciences Research Council, Pretoria, South Africa, May 1998.
- CAWMA, 2007. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London.
- Cilliers, P., 1998. *Complexity and Postmodernism: Understanding Complex Systems*. Routledge, New York, p. 337.
- CIMMYT -SPIA. 2003. Why has impact assessment research not made more of a difference? Summary Proceedings of an International Conference on Impact of Agricultural Research and Development, 4–7 February 2002, San José, Costa Rica, organized by the CGIAR's Standing Panel on Impact Assessment (SPIA) and CIMMYT.
- Defoer, T., De Groote, H., Hilhorst, T., Kante, S., Budelman, A., 1998. Participatory action research and quantitative analysis for nutrient management in southern Mali a fruitful marriage? *Agriculture Ecosystems and Environment* 71, 215–228.
- Douthwaite, B., Delve, R., Ekboir, J., Twomlow, S.J., 2003. Contending with complexity: the role of evaluation in implementing sustainable natural resource management. *International Journal of Agricultural Sustainability* 1, 51–68.
- Falkenmark, M., Rockström, J., 2004. *Balancing Water for Humans and Nature: The New Approach in Ecohydrology*. Earthscan, London.
- Freeman, H.A., Rohrbach, D.D., Ackello-Ogutu, C. (Eds.), 2002. *Targeting Agricultural Research for the Development of the Semi-arid Tropics of Sub-Saharan Africa*. Summary Proceedings of a Workshop, 1–3 July 2002, Nairobi, Kenya.
- Harwood, R.R., Kassam, A.H. (Eds.), 2003. *Research Towards Integrated Natural Resources Management: Examples of Research Problems, Approaches and Partnerships in Action in the CGIAR*. Interim Science Council, CGIAR, Washington DC, USA, p. 168.
- Harwood, R.R., Kassam, A.H., Gregersen, H.M., Ferres, E., 2005. Natural resources management research in the CGIAR: the role of the Technical Advisory Committee. *Experimental Agriculture* 41, 1–19.

- Harwood, R.R., Place, F., Kassam, A.H., Gregersen, H.M., 2006. International public goods through integrated natural resources management research in CGIAR partnerships *Experimental Agriculture* 42, 375–398.
- Hattingh, J., Marre, G.A., Ashton, P.J., Leaner, J.J., Turton, A.R., 2007. A trailogue model for ecosystem governance. *Water Policy* 9 (Suppl. 2), 11–18.
- Gibbons, M., Limoges, C., Nowotny, H., Schwartzmann, S., Scott, P., Trow, M., 1994. *The New Production of Knowledge: the Dynamics of Science and Research in Contemporary Societies*. Sage, Thousand Oaks. p. 192.
- Greenland, D.J., Gregorgy, P.J., Nye, P.H. (Eds.), 1998. *Land resources: on the edge of the Malthusian precipice*. *Philosophical Transactions of the Royal Society and CAB International*. p. 180.
- ICWE, 1992. *The Dublin Statement and Report of the Conference. International Conference on Water and the Environment: Development Issues for the 21st Century*. World Meteorological Organization. Geneva. <<http://www.wmo.ch/pages/prog/hwpr/documents/english/icwedece.html>> (accessed 22.04.08).
- Jansen, J.D., 2000. Mode 2 knowledge and institutional life: taking Gibbons on a walk through a South African university. In: Kraak, A. (Ed.), *Changing Modes: New Knowledge Production and its Implications for Higher Education in South Africa*. Human Sciences Research Council, Pretoria, pp. 156–171.
- Jaspers, F.G.W., 2003. Institutional arrangements for integrated river basin management. *Water Policy* 5, 77–90.
- Kassam, A.H., 2006. Receptivity to social research by the CGIAR. *Experimental Agriculture* 42, 1–12.
- Koudstaal, R., Rijsberman, F., Savenije, H.H.G., 1992. Water and sustainable development. *Natural Resources Forum* (November, 1992), 277–290.
- Love, I., 2002. *The Chemistry of Gold Extraction in Zimbabwe*. Zimbabwe Science News.
- Love, D., Jonker, L., Rockström, J., van der Zaag, P., Twomlow, S., 2004. The Challenge of Integrated Water Resource Management for Improved Rural Livelihoods in the Limpopo Basin – an Introduction to WaterNet's First Network Research Program. In: *Fifth WaterNet/WARFSA/GWP-SA Symposium*, Windhoek, Namibia, November 2004, pp. 106–107.
- Love, D., Moyce, W., Ravengai, S., 2006a. Livelihood challenges posed by water quality in the Mzingwane and Thuli river catchments, Zimbabwe. In: *Seventh WaterNet/WARFSA/GWP-SA Symposium*, Lilongwe, Malawi, November 2006, p. 32.
- Love, D., Twomlow, S., Mupangwa, W., van der Zaag, P., Gumbo, B., 2006b. Implementing the millennium development food security goals – challenges of the southern African context. *Physics and Chemistry of the Earth* 31, 731–737.
- Love, D., Owen, R.J.S., Uhlenbrook, S., van der Zaag, P., Moyce, W., 2007. The lower Mzingwane alluvial aquifer: managed releases, groundwater – surface water interactions and the challenge of salinity. In: *Eighth WaterNet/WARFSA/GWP-SA Symposium*, Lusaka, Zambia, November 2007, p. 8.
- Lovell, C., Mandoondo, A., Moriarty, P., 2002. The question of scale in integrated natural resource management. *Conservation Ecology* 5 (2), 25 [online] <<http://www.consecol.org/vol5/iss2/art25>>.
- Mapfumo, P., Giller, K.E. 2001. *Soil Fertility Management Strategies and Practices by Smallholder Farmers in Semi Arid Areas of Zimbabwe*. International Crops Research Institute for the Semi Arid Tropics (ICRISAT) with permission from the Food and Agricultural Organization (FAO). Bulawayo, Zimbabwe and Rome, Italy, 60 p.
- Maponga, O., Ngorima, C.F., 2003. Overcoming problems in the gold panning sector through legislation and education: the Zimbabwean experience. *Journal of Cleaner Production* 11, 147–157.
- Mazvimavi, D., 2004. *Estimation of Flow Characteristics of Ungauged Catchments: Case study in Zimbabwe*. Ph.D. dissertation. Wageningen University and International Institute for Geo-Information Science and Earth Observation, Delft, ITC Eschede, 176 p.
- MMSD (Minerals, Mining and Sustainable Development Project) 2002. *Breaking New Ground: Minerals, Mining and Sustainable Development*. Earthscan, London, 364 p.
- Mortimore, M., Harris, F., 2005. Do small farmers' achievements contradict the nutrient depletion scenarios for Africa? *Land Use Policy* 22, 43–56.
- Moyo, R., Love, D., Mul, M., Twomlow, S., Mupangwa, W., 2006. Impact and sustainability of low-head drip irrigation kits, in the semi-arid Gwanda and Beitbridge Districts, Mzingwane Catchment, Limpopo Basin, Zimbabwe. *Physics and Chemistry of the Earth* 31, 885–892.
- Mupangwa, W., Love, D., Twomlow, S.J., 2006. Soil–water conservation and rainwater harvesting strategies in the semi-arid Mzingwane Catchment, Limpopo Basin, Zimbabwe. *Physics and Chemistry of the Earth* 31, 893–900.
- Murenga, K., 2003. The impact of integrated water resources management on poverty alleviation. In: *Fourth WaterNet/WARFSA Symposium*, Gaborone, October 2003, 12 p.
- Nare, L., Love, D., Hoko, Z., 2006. Involvement of stakeholders in the water quality monitoring and surveillance system: the case of Mzingwane catchment. *Physics and Chemistry of the Earth* 31, 707–712.
- Ncube, B., Dimes, J., Twomlow, S., Mupangwa, W., Giller, K., 2007. Raising the productivity of smallholder farms under semi-arid conditions by use of small doses of manure and nitrogen: a case of participatory research. *Nutrient Cycling in Agroecosystems* 77, 53–67.
- Ncube, B., Twomlow, S., Dimes, J., van Wjick, M., Giller, K., in press. Farm characteristics and soil fertility management strategies in smallholder farming systems under semi-arid environments in Zimbabwe. *Soil Use and Management*.
- Nyabeze, W.R., 2004. Estimating and interpreting hydrological drought indices using a selected catchment in Zimbabwe. *Physics and Chemistry of the Earth* 29, 1173–1180.
- Pender, J., Plaice, F., Ehuie, S., 2006. *Strategies for Sustainable Agricultural Development in the East African Highlands*. EPTD Discussion Paper No. 41. Environment and Production Technology Division International Food Policy Research Institute 2033 K Street, N.W. Washington, DC, 20006 USA, 89 p.
- Perez, C., Tschinkel, H., 2003. Improving watershed management in developing countries: A framework for prioritizing sites and practices. *AgREN Network Paper No. 129*, July 2003, London. ODI, UK, 15 p.
- Pound, B., Snapp, S., McDougall, C., Braun, A. (Eds.), 2003. *Managing Natural Resources for Sustainable Livelihoods: Uniting Science and Participation*. IDRC and Earthscan Books, London, UK.
- Pretty, J., Noble, A., Bossito, D., Dixon, J., Hine, R., Penning de Vries, F., Morison, J., 2006. Resource-conserving agriculture increases yields in developing countries. *Environmental Science and Technology*. doi:10.1021/es051670d.
- Rockström, J., Wani, S., Hatibu, N., 2007. Managing water in rainfed agriculture. In: *CAWMA. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London, UK: Earthscan and Colombo, Sri Lanka: International Water Management Institute, pp. 315–348.
- Roy, R.N., Misra, R.V., Lesschen, J.P., Smalling, E.M., 2003. Assessment of soil nutrient balance. Approaches and methodologies. *FAO Fertilizer and Plant Nutrition Bulletin* 14. Food and Agriculture Organization, Rome.
- Ryan, J., Spencer, D., 2001. Challenges and opportunities shaping the future of the semi-arid tropics and their implications. *Draft White paper*, March 2001. Patancheru, A. P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics, 143 p.
- Sanchez, P., 2002. Soil fertility and hunger in Africa. *Science* 225, 2019–2020.
- Savenije, H.H.G., 2002. Why water is not an ordinary economic good, or why the girl child is special. *Physics and Chemistry of the Earth* 27, 741–744.
- Scherr, S., 2000. A downward spiral? Research evidence on the relationship between poverty and natural resource degradation. *Food Policy* 25, 479–498.
- Scoones, I., 1997. Landscapes, fields and soils: understanding the history of soil fertility management in southern Zimbabwe. *Journal of Southern African Studies* 23, 615–634.
- Scoones, I., 2001. Transforming soils: the dynamics of soil-fertility management in Africa. In: Scoones, I. (Ed.), *Dynamics and Diversity: Soil Fertility and Farming Livelihoods in Africa*. Earthscan, London, pp. 1–44.
- Shiferaw, B., Freeman, H.A. (Eds.), 2003. *Methods for assessing the impacts of natural resource management research*. In: *Summary Proceedings of an International Workshop*, 6–7 December 2002, ICRISAT, Patancheru, India. Patancheru, India: ICRISAT.
- Shiferaw, B., Freeman, A., Swinton, S.M. (Eds.), 2005. *Natural Resource Management in Agriculture: Methods for Assessing the Economic and Environmental Impacts of Management Practices*. CABI International, Wallingford.
- Shoko, D.S.M., Love, D., 2005. Gold panning legislation in Zimbabwe – what potentials for sustainable management of river resources. In: Mathew, K., Nhapi, I. (Eds.), *Water and Wastewater Management for Development Countries*. IWA Water and Environmental Management Series. IWA Publishing, London, pp. 499–512.
- Singh, A., Trivedi, T.P., 2005. Creation of visible impact of integrated pest management in selected crops. In: *Proceedings of the National Seminar on Pesticide Residues and their Risk Assessment*, 20–21 January, 2005, National Institute of Nutrition, Hyderabad, pp. 137–144.
- Spiegel, S., Shoko, D.S.M., Tesha, A., Love, D., Veiga, M., 2006. Legal and policy approaches to address mercury hazards in Africa: an analysis of government strategies in the small-scale mining sector. *International Conference on Mercury as a Global Pollutant*, Madison, USA, August 2006.
- Templeton, S.R., Scherr, S.R., 1999. Effects of demographic and related microeconomic change on land quality in hills and mountains of developing countries. *World Development* 27, 903–918.
- Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., Giller, K.E., 2005a. Exploring diversity in soil fertility management of smallholder farms in western Kenya – I. Heterogeneity at region and farm scale. *Agriculture Ecosystems and Environment* 110, 149–165.
- Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., Giller, K.E., 2005b. Exploring diversity in soil fertility management of smallholder farms in western Kenya – II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. *Agriculture Ecosystems and Environment* 110, 166–184.
- Tunhuma, N., Kelderman, P., Love, D., Uhlenbrook, S., 2007. Environmental Impact Assessment of Small Scale Resource Exploitation: the case of gold panning in Zhulube Catchment, Limpopo Basin, Zimbabwe. In: *Eighth WaterNet/WARFSA/GWP-SA Symposium*, Lusaka, Zambia, November 2007, p. 47.
- Twomlow, S.J., 2003. Soil and water: the flesh and blood of semi-arid agriculture in Africa. In: Waliyar, F., Collette, L., Kenmore, P.E. (Eds.) *Beyond the Gene Horizon: Sustaining Agricultural Productivity and Enhancing Livelihoods through Optimization of Crop and Crop-associated Biodiversity with an Emphasis on the Semi-arid Tropical Agroecosystems*. Summary Proceedings of a Workshop, 23–25 September 2002. Food and Agriculture Organization of the United Nations (FAO), Patancheru, Patancheru 502 324, Andhra Pradesh, India, Teme di Caracalla, Rome 00100, Italy, pp. 36–65.
- Twomlow, S.J., Steyn, J.T., du Preez, C.C., 2006. *Dryland farming in southern Africa*. Chapter 19. In: *Dryland Agriculture*, second ed. Agronomy Monograph No. 23. American Society of Agronomy, Madison, Wisconsin, pp. 769–836.
- Twomlow, S., Shiferaw, B., Cooper, P., Keatinge, J.D.H., 2008a. Integrating genetics and natural resource management for technology targeting and greater impact

- of agricultural research in the Semi-Arid Tropics. *Experimental Agriculture* 44, 235–256.
- Twomlow, S., Mugabe, F.T., Mwale, M., Delve, R., Nanja, D., Carberry, P., Howden, M., 2008b. Building adaptive capacity to cope with increasing vulnerability due to climatic change in Africa – a new approach. *Physics and Chemistry of the Earth* 33 (8–13), 780–787.
- UN Millennium Project, 2005. Halving Hunger: It Can be Done. Report of the Task Force on Hunger. Earthscan, New York.
- Van der Zaag, P., 2005. Integrated water resources management: relevant concept or irrelevant buzzword? A capacity building and research agenda for Southern Africa. *Physics and Chemistry of the Earth* 30, 867–871.
- Vanlauwe, B., Bationo, A., Carsky, R.J., Diels, J., Sanginga, N., Schulz, S., 2003. Enhancing the contribution of legumes and biological nitrogen fixation in cropping systems: Experiences from West Africa. In: *Grain Legumes and Green Manures for Soil Fertility in Southern Africa: Taking Stock of Progress*. Waddington, S.R. (Ed.) Proceedings of a Conference held 8–11 October 2002 at the Leopard Rock Hotel, Vumba, Zimbabwe. Soil Fert Net and CIMMYT-Zimbabwe, Harare, Zimbabwe, 246 pp.
- Yamano, T., Jayne, S., 2004. Measuring the impacts of working-age adult mortality on small-scale farm households in Kenya. *World Development* 32, 91–119.
- Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture Ecosystems and Environment* 119, 112–126.
- Zwane, N., Love, D., Hoko, Z., Shoko, D., 2006. Managing the impact of gold panners within the context of integrated water resources management planning: the case of the Lower Manyame Subcatchment, Zambezi Basin, Zimbabwe. *Physics and Chemistry of the Earth* 31, 848–856.