Soil as a water resource: Some thoughts on managing soils for productive landscapes meeting development challenges

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ABSTRACT

Humanity is facing fundamental challenges in the anthropocene on how to produce food, fodder and fibre, in an era of increasingly limited resources. Freshwater and healthy soil systems are fundamental in this, and in particular in areas with high rainfall variability soils with low inherent nutrient status and people with marginal resources to invest in their local landscape production resources. This paper argue that soil and water management for healthy soil systems and availability of soils moisture (green water) are a first step towards transforming landscapes to more productive and sustainable, and yet an untapped opportunity in particular in sub-Sahara Africa and South Asia semiarid and sub-humid tropical areas. Three examples of transforming landscapes in India, Burkina Faso and Tanzania serve to inform on processes of change initiated by managing soil health and water in landscape. Changes have been achieved over 15-30 years, although not always towards an healthy state of the landscapes. Positive change has been achieved with significant internal and external investments, added knowledge and awareness, and through coupled soil nutrient and soil water interventions. Soil science academics can contribute to adoption of 'green' water management as a lever to accelerate improved production, productivity and sustainability of crops and surrounding ecosystem services in currently low yielding and unsustainable landscapes.

INTRODUCTION

As a global community we are facing unprecedented challenges to address sustainability and development in an era of accelerating degradation of our life support systems. Ways to identify and enable processes for more desired change are urgently needed at landscape scales where local people manage soils for water and biomass, and where policies and economical systems provides incentives for various desired and/or undesired changes. Rockstrom et al (2009) recently illustrated this through the concept of the planetary boundaries, proposing that several key boundaries have already been exceeded such as biodiversity, climate change and biogeochemical thresholds whilst others are being approached in the current anthropocene. This biophysical concept was further complement with indicators of the social economic boundaries showing the dimensions of human wellbeing such as poverty alleviation, health and social security issues (OXFAM, 2011). These challenges at global scales are very often merged also at regional and landscape scales, setting development in a number of biophysical and social-economic operational challenges. This short paper builds on a presentation at AGROENVIRON 2012, focusing on the opportunities that are yet to be realized to address sustainable development in rural developing contexts such as in sub-Sahara Africa (SSA) and parts of South Asia (SA), with high incidence of poverty. The objective is to argue for a re-framing of the often over(?) emphasis by research on constraints and problem analysis in soil and water management. To accelerate development and put the vast body of research knowledge into use, also researchers need to move to an approach to identify opportunities, states and processes to transform landscapes and contributions to income generation and wellbeing in sustainable ways. The short paper makes a brief re-visit to recent global to national analyses on the state of water and soil constraints and the effect on crop yields in SSA and SA. It then describes 3 landscapes in various degree of transformation which used soil and water management as entry points for change. The paper concludes on some thoughts on the role of soils and water management for further research developments needed to accelerate the transformations into productive landscapes in SSA and SA.

ROLE OF WATER FOR FOOD AND DEVELOPMENT

Fresh water is fundamental to a wide range of ecosystem services that supports human wellbeing. One of the most critical is the requirement of water for providing biomass, whether agricultural crops or others, such as forests, and grasslands sustain additional food, fodder and fibre. Numerous analyses suggest that freshwater is and will continue to be a fundamental constraint to development and food production. At a global scale the CA (2007) recently proposed that out of the 110 000 km^3 y^{-1} rainfall on land areas, approximately 4.5 % is appropriated for rainfed agriculture and livestock production, and 2% is appropriated for irrigation (Fig 1). In addition, 56% of water is appropriated for the non-agricultural landscapes that supports forests, grassland and other non-farmed areas, which still provides a range of water-dependent ecosystem produce for economic and livelihood gains (e.g. UNEP 2011). The recent FAO-SOLAW (2011) assessment show that multiple constraints related to soils, and rainfall hamper the potential of yield in particular parts of the world, i.e., there continues to be justification for zooming into global 'hotspots' of poverty, water constraints and soil limitations.

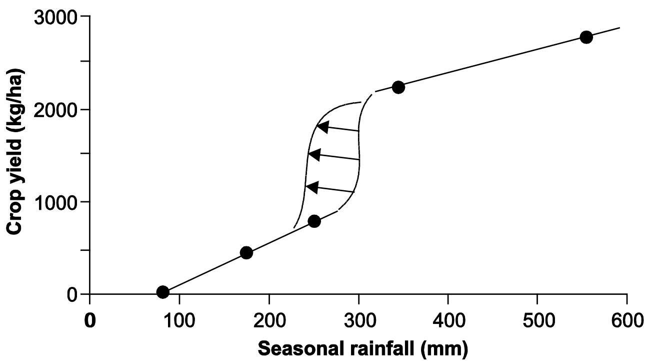

Figure 1. Opportunity in moving the yield level by soil and water management strategies in current low yielding smallholder farming systems in SSA and SA (modified after Enfors et al 2011).

MANAGE SOILS TO MANAGE WATER

A fundamental challenge in agricultural production and water management has been to change a perceived understanding of which type water in the landscape produce our food: is it the rainfed so-called 'green' water, which derive from soil moisture, or is it irrigated, largely supported by appropriation of surface and/or groundwater, and so called 'blue'? This is important as the 'green' water and blue water domains are managed, govern and provide fundamentally different opportunities to be addressed. The Comprehensive Assessment of Water Management for Food (CA, 2007) changed a paradigm by presenting the values of area, water appropriation and food production from 'green' (rainfed) and 'blue' (irrigated) water resources (table 1).

Table 1: Summary of crop land, fresh water appropriation and food produce for green and blue water according to the Comprehensive Assessment of Water Management for Food (CA, 2009).

	Total	Green water	Blue water
Land area (million ha)	1314	70%	30%
Fresh water appropriation ($km^3\ y^{-1}$)	7130	80%	20%
Food produce	-	60%	40%

Essentially, rainfed productions remains the key source for food, fodder and fibre globally, and in particular so in areas with major rural livelihood systems living around or below the poverty line of USD 1.25 day^{-1} , such as South Asia and sub-Sahara Africa (IFAD, 2011).

Country-level analysis by Rockstrom et al (2010) developed a better understanding for which countries do have scope for further 'green' water and/or 'blue' water developments. Using scarcity for not just 'blue' water alone (i.e., as discussed by Rijsberman, 2006, often set to 1000 $m^3\ cap^{-1}\ y^{-1}$), it is clear that various countries can be sorted by the 'green' –'blue' water management opportunity framework in order to address current and future food security issues at national level. Although only accounting for calorific needs in balanced diet, the analysis presented can be seen as a guide towards where in the 'green' –'blue' matrix different opportunities exist (Table 2).

Table 2: Example of countries sorted after green –blue water resource availability per capita per year (data after Rockstrom et al 2009)

	Green water available	Green water constraint
Blue water available	LKA;NER;SEN;KEN; ZWE;MLI;TZA;SLV	PRK;KOR;EGY;BGD
Blue water constraint	IRQ;IND;CHN;MWI; TJK;TUR;AZE;BFA; ETH;AFG;MDA;DJI; SVK;ALBY;CZE; ARM;NPL;UZB;SYR; CHE;TUN;DEU;DNK ;TWN;LSO;UGA; SVN;	RWA;BDI; IRN; PAK; ISR;JOR;QAT

In this matrix, some countries nearing 'blue' water scarcity still have 'green' water opportunities, whereas other countries may actually be scarce of both types of water resources. What is evidently clear is that a range of countries are nearing 'blue' water scarcity. In these countries the current and future options for addressing national food security and income generation through biomass through 'blue' water management and investments in for example irrigation are limited in scope. Whereas the countries in the realm of 'blue' water scarcity, but still with 'green' water availability, are areas which have significant scope to manage soils to manage water for current and future food, fodder and fibre needs. In these countries, the efforts and investments in rainfed agriculture will be key in closing food demand –supply (for own consumption or for income) in the short term, especially for the countries in low-middle income band which still house significant parts of population in subsistence and semi-subsistence agricultural livelihood systems. And the starting point in addressing rainfed agriculture will be to manage soil health, i.e., the physical-chemical and biological aspects of soils towards sustainable and productive states.

A particular opportunity in soil management for 'green' water presents itself in areas with current low crop yield but with a potential to produce better i.e., so-called yield gaps (explored by for example Singh et al 2009). Such areas and farming systems currently dominate smallholder farming systems in parts of SSA, South Asia and Latin America. Evidently, there is a range of biophysical as well as social factors that limit current yield levels. But if concentrating on soil and water management factors, multiple analyses from field to modeling show that there is often a real opportunity to shift yields from below current 1 t ha^{-1} to 2-4 times higher yields with enhanced rainfall infiltration, nutrient management and timely sowing, weeding and harvesting in particular in areas with rainfall of 200-400 mm $season^{-1}$ (e.g., Rockstrom et al, 2007; Barron & Okwach, 2005; Fox et al, 2005; Pandey et al, 2001; Pandey et al, 2000; Kahinda et al, 2007; Andersson et al, 2011) (Fig. 1). The reason for this is that in this rainfall regime, agricultural dryspells due to natural rainfall variation within and between seasons have direct impact limiting final quality and quantity of yields (Barron et al, 2003). In these rainfall regimes, enhancing soil water availability to bridge agricultural dryspells are key as a first management effort to enhance crop yields. However, as soon as crop water availability is secured, nutrients for plants constraint growth (e.g., Breman et al, 2001), especially in many tropical and sub-tropical soils which are inherently weathered and prone to further erosion when put into agricultural production. Whereas Fig 1 presents a threshold in addressing yields in the 200-400 mm $season^{-1}$ rainfall regimes, there are other threshold features operating at different time and spatial scales in soil properties such as available water storage capacity (pore volume distribution) or nutrient availability (i.e., governed by a combination for physical, chemical and biological properties (e.g., Kibblewith et al, 2008). Lahmar et al (2012) showed such principal threshold features relating to soil degradation –regeneration for Sahelian conditions under conservation tillage. A major challenge for managing soils for water and crops are the cross-scale impacts and ability to sustained benefits (i.e., the yield shift in Fig.1 this paper versus Fig. 1 in Lahmar et al, 2012). On a seasonal time step, water availability for a crop can be enhanced almost instantly through improved soil management (tillage, infiltration structures such as pits, zai, bunds etc.), and nutrient availability by adding inorganic and /or organic nutrients. But a long-lasting and sustainable healthy soil that bridges dryspells can only be achieved through investments in soil and nutrient management, often not stabilized until more than 10-20 years due to the challenge of building the chemical and biological soil properties, including soil organic matter, in tropical semiarid and sub-humid areas.

TRANSFORMING LANDSCAPES WITH SOIL AND WATER INTERVENTIONS

Despite there being a substantial opportunity in increasing production and productivity in particular in 'green' water dependent food, fodder and fibre, there is also an increasing awareness and consensus that any current and future production need to be done aligned with other users, uses and demand of soil and water resources. Both soils and water are fundamental in a range of ecosystem services and functions, which benefit humans and economies at local to global scales. A first step is to explore soil and water issues in agriculture as integral parts of a social and ecological system at landscape scale. What is occurring and changing on farmers' fields always have impacts beyond the field and household scale. Increasing production and productivity with soil management for water will have benefits and dis-benefits for various ecosystem services and users of these services, as yields are improved on the field.

To ensure we manage not only the agricultural part of landscapes in a productive manner we must assess how soils and water can be as productive as possible whilst generating the crops, biomass and other ecosystem services we demand. Landscapes (meso-scale 1- 10 000 km^2 where local people still can form physical linkages to landscapes and its management) range from severely degraded to highly productive from a human perspective. A landscape in balance is where the agricultural production is in balance without negatively affecting other provisional, regulating, supporting and cultural ecosystem services (Foley et al 2005; Gordon et al, 2010). However, some landscapes are highly productive, but not necessarily in balance. A particular example can be some high intensity mono-cropped agricultural systems with high input of energy and nutrients (and knowledge) and low biodiversity. In Fig 2, the principal components relating to soils and water are shown as these resources underpin not only crop yields but also a range of ecosystem functions on and off the farmer fields depending on management.

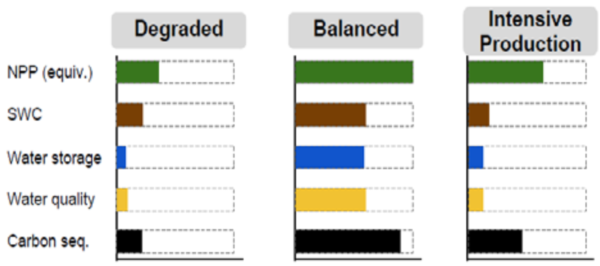

Figure 2. States and processes relating to soil and water resources in productive landscapes systems in SSA and SA, indicating principal characteristics and possible levels of health (full bar=highest potential)(figure after Barron & Keys, 2011).

In the previously identified areas where development needs and 'green' water management merge as a real opportunity to address multiple needs, there are a range of examples that can help us understand process that change landscapes into the three mentioned categories. Learning from these examples will inform the debate on which opportunities exist, what potential trade-offs may emerge and how to ensure the process of transformation stays ion desired trajectory of development and sustainability without undermining future opportunities.

Examples of transforming semi-arid landscapes: Indian watershed with community organization and state subsidy

The transformations of rural India has been remarkable over the last 40 years , but still a 230 million Indians live in poverty in rural areas (IFAD, 2012), largely dependent on subsistence farming for their livelihood and income. Yet, the India national government, and state governments make substantial economic efforts to develop rural areas alongside the overall developments of India. The Kothapally micro-watershed (hydrologic boundary 2.9 km^2, political boundary 4.7 km^2), Musi basin, Andhra Pradesh, is an example of ta watershed subject to these development efforts. Dryspells are frequently affecting yields: 5-7 days long dryspells occur 3-8 times per season. Soils are shallow vertisols with less than 1m root depth. (More details are available in Garg et al 2011, and Garg et al, accepted). Before 2000, this watershed was considered severely degraded, with extreme sensitivity to the natural rainfall variability in such a semi-arid location. However in 1999-2000 a significant effort started to rehabilitate common and private land through a range of *in-situ* and *ex-situ* water harvesting (soil and water conservation) measures, i.e., 'green' water management efforts through soil management. Through these efforts, the watershed now contains numerous infiltration bunds and vegetation strips slowing downs surface runoff, and more than 15 check dams recharging shallow groundwater. Through this recharged shallow groundwater, and increased rainfall infiltration various changes have been made to the crop system in Kothapally. The soil nutrient management became a viable investment when soil water was improved, and crops no longer affected by natural occurring dryspells. The recharge of shallow groundwater enabled positioning of shallow wells nearby fields which are utilized for supplemental irrigation, especially for a dry season crop. Availability of water for irrigation enable switching to a higher value crop (cotton) generating more income for farmers (Fig. 3). Soil erosion estimated by modeling was significantly reduced from an average of 22 t ha^{-1} y^{-1} for pre-2000 watershed state, to a level of 2.2-4.5 t ha^{-1} y^{-1} for post -2000 state (Garg et al 2011). Thus, the efforts to improve the 'green' water in the landscape resulted in overall higher production and productivity (per unit land and per unit water). The main drawback is a significant reduction of water outflow from the watershed to downstream users. From an average of 19% of seasonal rainfall in normal years in the degraded state, the flow has been reduced to 10% for a transformed state of the Kothapally watershed. This reduction was larger in dry years, and may ultimately hamper downstream users for agriculture, and domestic water supply to Hyderabad urban area (Garg et al , accepted).

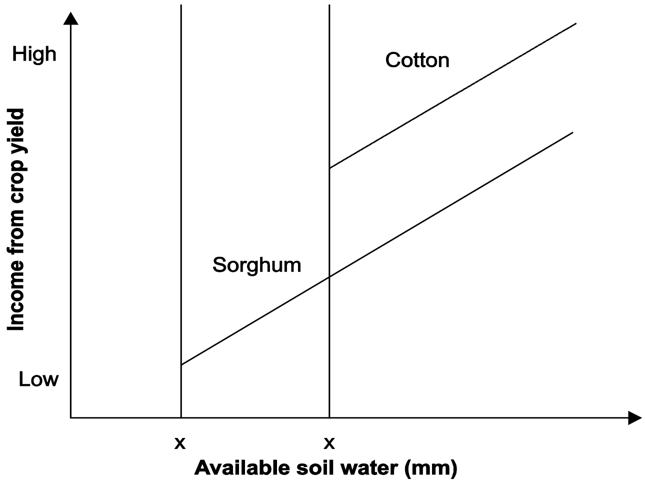

Figure 3.Principal benefit of shift in crop systems enabled by 'green' water management strategies in Kothapahlly, Andrha Pradesh (figure after Karlberg 2010)

Examples of transforming landscapes: Peri-urban Burkinabe watershed with small reservoirs

The Nariarle watershed is a rural-peri-urban watershed of 1000 km^2 on the outskirts of Ouagadougou, Burkina Faso. It has over the last 50 years undergone major changes in landuse from natural dry forest and savannah with 16% agricultural use, to being 72% agricultural today. In addition, rainfall has changed significantly, and last 20 year average is near 160 mm y^{-1} less than previous 20-year period. A third major change is the estimated quadrupled population over the last 40 years. Alongside these major human and biophysical changes, a number of soil and water management structures have been changing the landscape, the soils and the water resources. The main change is the construction of small dams and reservoirs (Fr. 'petit barrages') to store water in the landscape for multiple benefits to agriculture, livestock and human wellbeing. Current storage is approximately 2%of total average seasonal volume of rainfall. The use of water in the dams has lately developed into small and medium size agro-business, enabling farmers to intensively crop high value vegetables for urban market demand. Irrigation currently only covers 2% of the watershed, and does not necessarily imply an overall increase in biomass production at landscape level, as most land is still under low yielding rainfed production. By exploring various water and soil management strategies, from improved rainfed production with long-term soil and water management strategies (incl. nutrients), to intensify or expand irrigation land (Barron et al, forthcoming). In Fig. 4, the impact on water outflow from Nariarle is show for various modeled strategies. According to this, an improved rainfed cropping system would increase long-term yields of sorghum, millet and maize by 3-4 times from current yields of 0.8-1.2 t ha^{-1}, benefitting all farmers in the watershed, whilst reducing outflow from watershed by 9% from current state. By intensifying the irrigation area alone (by adding one more crop during dry season), the same impact on water flows is achieved, whilst only a handful of farmers can benefit from this strategy.

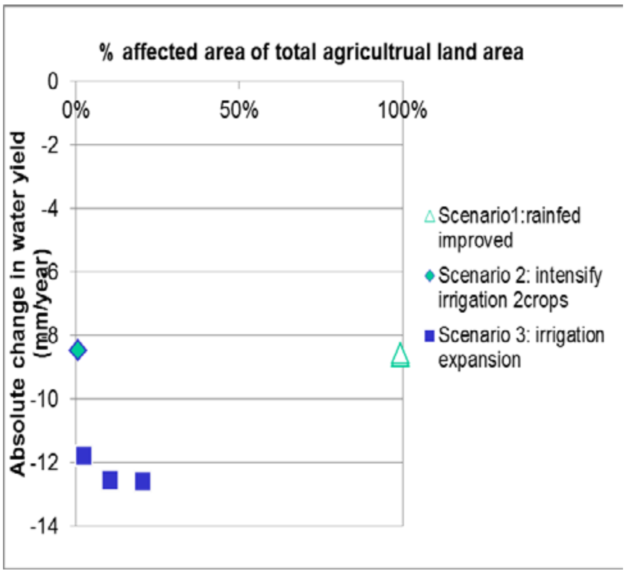

Figure 4. Impact on water outflow of various startegies to intensify agricultural production in Nariarle watershed, Burkina Faso.

Thus, there is an equity dimension in the transformation of the landscape. By enabling improvement in the 'green' water management, more farmers can potentially benefit, achieving more equitable distribution of growing wealth. However, this potential is yet largely unrealized as the current rainfed yields remain at a low 0.8-1.2 t ha^{-1} and most re-investments by framers into the farming enterprise is focused around the high value market produce of vegetables along the small reservoir banks, with challenging implication for water quality and human health by the intense use of pesticides and fungicides.

Examples of transforming landscapes: In a degraded state in rural Tanzania

The Makanya catchment (320 km^2) is in a rural location of the Pangani basin, NE Tanzania. Enfors & Gordon (2007) presented a social-environmental summary of the watershed developments over the last 50 years. This showed that despite increasing population pressure with +200% over the time period, (the so-called 'more people –less erosion', cf. Tiffen et al, 1994) investments in soils and land has not taken place. In fact, Enfors & Gordon (2007) suggest that a number of untimely top-down and bottom-up opportunities have failed to realize the landscape potential, and possibly set the social-ecological system into a degrading spiral caused by an increasing drypsell occurrence, degraded soils in rainfed ('green' water) production, over-utilisation of the limited spate irrigation system, and reduced off-farm ecosystem service loss, which disable coping mechanisms when crop yields are failing (Enfors, 2009). The overall impact is a landscape on slow degradation with farmers having limited opportunity to raise necessary investments for putting 'green' water management into practice, even if the potential benefits of increased yields have been shown (Enfors et al, 2011; Makurira et al, 2011). Such improved yields with better food security and income, may even release the current pressure on off-farm land and associated ecosystem services, enabling a slow change towards a higher production state of the landscape as a whole.

In summary the three watersheds discussed here are at different levels of transformation towards new states of landscape productivity and livelihood opportunity (Table 3). Clearly both the Indian example and the Burkinabe example are in a progressively better state, supporting more people largely enabled by restoring soil health and water resources in the landscape, i.e., managing soils for 'Green' water. In the Indian case, this approach was a starting point in enabling desired trajectories in landscape productivity. In the Burkinabe example, addressing rainfed agriculture and 'green water management is a yet an untapped opportunity in a landscape with escalating demands on the available 'blue' water resources. In the Tanzania case, a major effort may be needed to avoid collapse into a further degraded state of both agriculture and of off-farm ecosystem services. But as discussed by Barron & Keys (2011) it does not necessarily mean that the social ecological systems are more resilient. They may have shifted resilience of livelihoods from on subsistence farming highly dependent rainfall variability, towards depending on markets and associated price fluctuations, - both for inputs as well as outputs.

PUTTING RESEARCH INTO ACTION AND ENABLING CHANGE

This paper presents some of the global contexts on water and food, and the role of soil and water management, -in particular 'green' water, may play in transforming landscapes to more productive states and trajectories for human wellbeing. There is an urgent need to put our vast research knowledge on soil and water management into practice together with users of landscapes, as well as developers and investors. We must enable these changes and realize the existing untapped potentials in producing food, fodder and fibre for a growing global population. The most imminent changes are of course needed in currently poverty affected areas, possibly in landscapes in a degraded state, with low yielding agro-eco systems and poorly functioning ecosystems at large.

As the examples of three watersheds illustrates, there are multiple ways to leverage landscapes into positive and more desired trajectories of development and sustainability. Multiple levers are needed: only addressing 'green' water through better soil and water management is likely needed to be addressed in a context of impacts and benefit distributions, as well as investments and markets.

It is clear that the soil and water technologies at hand, combining soil and water management must be addressed with soil nutrients to realize the full yield (biomass) potential. Addressing water holding capacity and soil water infiltration alone (i.e, the key 'green' water levers) may not enable the most productive use of the water for crops. The consistent divide between academics, for example soil and land courses versus water courses, do not

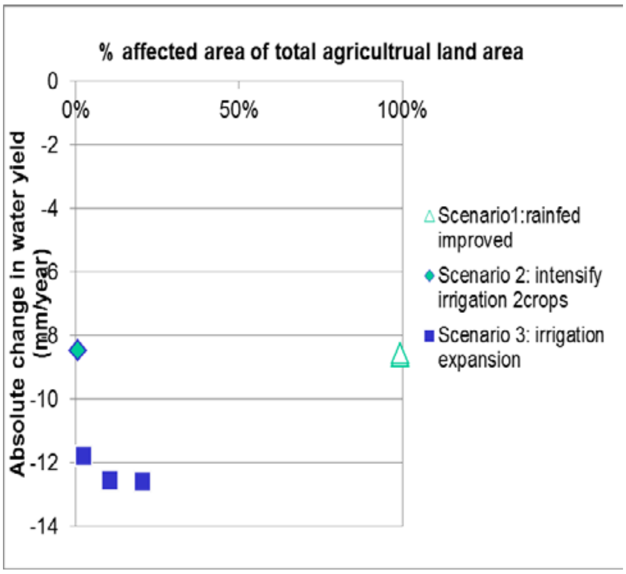

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Table 3: State and change of example watersheds in India, Burkina Faso and Tanzania (after Barron, forthcoming)

Location	Degraded	Balanced	High Intensity	Comment
Kothapally (IND)	Pre 2000		Post 2000	Production and productivity shift initiated through 'green' water management efforts at landscape scale enabled by internal and external investments
Nariarle (BKF)	Pre 1990?		2010	Part productivity and production increase by 'green' and 'blue' water management efforts enabled by external investments into small reservoirs
Makanya (TNZ)	Pre 1990; today			Possibly shifting into a more severe landscape productivity level with deteriorating green and blue water resources, and negative impacts on surrounding ecosystem services

necessarily help integration and finding holistic solutions to improve landscape productivity. Researchers in soil and water need to merge into better systems approach in science, as well as in communication of science, to ensure the sectorial divide move also beyond academics.

Secondly, the transformation of landscapes through 'green' water requires substantial investments at various scales. The Indian example subsidized labour,- the most costly investment in transforming the Kothapally watershed. In the Burkinabe example, an upfront large external (donor) investment was made in the construction in small reservoirs. Manually shaping landscapes with bunds, terraces and earth dams are time and energy consuming. Even if labour is at current low cost, researchers should be challenged to find technology solutions and crop- crop-livestock systems that can be implemented with less labour (energy) input and still achieve the productivity goals to scale.

A third point is the need for new knowledge and awareness to achieve change and map out possible impacts and alternatives. Often local knowledge is rich about local conditions and can maintain a landscape through its social networks. But a change in crop –crop/livestock system will have social and ecological opportunities and impacts which need to be decided upon: what trade-offs are acceptable within and beyond the landscape? For whom? Ensuring access to new knowledge is key to 'frog leap' development, and to manage emerging positive and negative impacts within and beyond the local setting so to stay on course.

Finally, an immediate action for researchers to contribute to putting research knowledge into practice would be to assist in developing 'best bet business models' for investments in 'green' water management. Synthesizing the knowledge in local and global contexts, map the opportunities and possible impacts, and suggest the value of public, private and individual investments needed may be an immediate action to be taken. The soils science research community has the knowledge needed to help policy and investors realize the opportunities in soil and water management for productive landscapes in development.

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