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Sustainable intensification of small-scale agriculture in the upper Blue Nile basin: Multi-criteria optimization of rainwater management strategies

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Abstract: Using a multi-criteria optimization technique for system analysis, this paper quantitatively characterizes baseline production activities, resource management and environmental relationships of the mixed crop–livestock farming system at the Jaba micro-watershed, upper Blue Nile Basin, to get insights that inform sustainable intensification of small-scale agriculture. The paper characterizes and models system relationships at a landscape scale under the business as usual land use and resource management scenario (including rainwater management), in the light of social, economic and environmental sustainability indicators (employment, farm income and sediment loss and water generation, respectively). The analysis is based on optimization technique that weighs the socio-economic and environmental costs and benefits of current land use and resource management practices at spatial and temporal scales, using farm level survey data. The results show that, under the business as usual scenario, the crop sub-sector will remain the major source of farm income and rural employment. Agricultural income, though trending positively, will not significantly drift from its current level, indicating the limited possibility for rural income growth from agricultural activities under the current pattern of land use, resource management and socio-economic circumstances. Land has the highest shadow price (while such price is low for labour), showing that land scarcity, unlike abundant labour, limits the possibility for extensive farming and agricultural income growth in the area. The environmental cost of agricultural income growth is considerable, showing a clear trade-off between agricultural income growth and the natural resource base that supports agriculture. The socio-economic and biophysical consequences of alternative innovations towards such end can be simulated by introducing respective scenarios into the quantified baseline relationships. The social, economic and environmental consequences of alternative rainwater management strategies can be simulated for technology selection, prioritization and targeting.

Key words*:* Sustainable intensification; integrated innovations; system analysis; landscape; optimization; upper Blue Nile.

Media grab: There is a need for land use change in the Upper Blue Nile Basin to get poverty reducing and ecologically sustainable outcomes from small-scale agriculture.

Introduction

Rainfed areas have potential for intervention schemes that can be operated locally and targeted at smallholder farmers to improve livelihood resilience (FAO 2008). One of such schemes is rainwater management (RWM), which refers to capturing, storing and using rainwater for productive and consumptive purposes (Rockstrom et al. 2007). Rainwater management provides adaptive mechanism to upgrade rainfed agriculture and to improve livelihood resilience in areas where water related constraints to food production are important sources of risk (Oweis and Hachum 2009). It improves resilience of rural livelihoods in the event of climate change and rainfall variability. Provided that it is complemented with other interventions, there is optimism that better management and use of rainwater provide a dependable option for productivity growth and livelihood resilience in rainfed agriculture, including reduction in crop failure risk due to short dry spells (de Fraiture et al. 2009; Zemadim et al. 2011).

Rockström et al. (2010) suggest for a paradigm shift in agricultural water management in favour of a focus on a catchment scale, which offers the best opportunities for water-related investments to build resilience in small scale agricultural systems and to address trade-offs between water for food and other ecosystem functions and services. There is a growing shift of focus towards watersheds (landscapes) as entry points for water governance and management. As a result, watersheds have become increasingly useful planning and intervention units for integrated management of land and water resources (Argent et al. 1999). Integrated watershed management (addressing social, economic and ecological aspects as multiple objectives pursued in a watershed) has recently become a useful concept of analysis for environmental management and sustainable development (Pastakia and Oza 2011). The approach promotes the use of soil, water and vegetation resources to obtain optimum and sustainable benefits without undermining the capacity of the natural resources and the ecosystem to regenerate and sustain itself. The concept underscores the importance of considering the economic, social and ecological costs and benefits in assessing alternative management strategies.

Method

Optimal RWM strategies in a landscape can be identified using multi-criteria optimization techniques which identify and quantify RWM strategies that enable achieving multiple objectives in a landscape. Optimization techniques applied to natural resource management permit identifying the optimal values for decision variables (land use types and soil and water management practices) that lead to the achievement of a management goal (Quintero et al. 2006). The optimal relationships and benefits identified for a base period can serve as baseline scenarios to be compared against simulated results for alternative management scenarios.

This paper applies the concept of landscape approach to RWM in a crop–livestock mixed rainfed agriculture as adaptive strategy to build livelihood resilience. Using a multi-criteria optimization technique, the paper quantifies optimal socio-economic and biophysical relationships for Melka micro-watershed located in the Blue Nile subbasin, Ethiopia. Alternative RWM scenarios can be developed and their impacts can be simulated *ex-ante* to guide decision-making at farm, community, watershed and policy levels. The costs of environmental services, such as payment for environmental services, can be estimated to inform management options. The paper contributes to the environmental management and climate change adaptation literature by applying the concept of landscape approach to RWM for upgrading rainfed agriculture.

The optimization model uses income, employment, sediment and water generation as important socio-economic and biophysical indicators to address the social, economic and environmental objectives pursued in a watershed. It is necessary to optimize indicators on each of these objectives in order to make production, development and livelihoods sustainable. Technologies and livelihood development strategies that fail addressing such issues are unlikely to be sustained in the long-run. The model was conditioned in such a way that available land resource in the three zones of the watershed is fully utilized for agriculture, grazing and tree planting purposes as important land use types. Consequently, the model optimizes activities on 7.94 ha in the upper zone, 8.80 ha in the middle zone and 3.92 ha in the lower zone (a total of 20.66 ha). Such land sizes in each zone at which the model optimizes are the same as the land size used in the model's land size input. This is an indicator that the model reproduces the baseline situation and is valid for simulation.

Results and discussion

At optimal level, the baseline activities in the three zones of the micro-watershed generate a total net income of USD 404,790 over a 10 years period (2011/12–2020/21) for the rural dwellers. Agriculture will continue as the major source of rural income. Annual income generated from agriculture will be irregular, though trends positively. Crops are the major sources of agricultural farm income, followed by dairy and meat products. Income generated from dairy and meat products is more stable than that from crops. Moreover, agriculture will remain the major source of employment opportunities. The sector will generate a total of 3847 employment opportunities for contracted labour over the ten years period.

Production activities will generate water and sediment as positive and negative externalities, respectively. The annual average level of water and sediment produced as a result will remain steady around 13235 mm and 2538 (t/ha), respectively. As can be seen, the environmental cost in terms of sediment loss is high, showing a clear trade-off between income generation and resource conservation.

The baseline results in the Jaba micro-watershed show an important feature that income generated in the coming ten years will basically remain where it is today, except minor rise. Maintaining the current crop–livestock mixed farming system and land use pattern will ensure achieving only the current income level, with no meaningful shift to high level rural income. Under such scenario, per capita income level will perhaps decline as a result of a rising population size in the area. This suggests the need for alternative management practices that enhance productivity growth in the micro-watershed.

The optimal net farm income level for the business as usual scenario provides a benchmark for comparative analysis purpose on the feasibility and marginal impact of alternative management practices. The optimal levels of farm income and environmental externalities imply that alternative management practices in the micro-watershed (rainwater management, soil conservation, land use change etc.) will be economically feasible and environmentally sustainable if the net income they generate exceeds or is equal to the baseline income level and the negative (positive) environmental externalities are reduced to below (increased to above) the baseline average.

Income growth in a watershed can be constrained both by resource limitations and high production costs. Acquiring additional resources and undertaking extra activities are costly to farmers. Identifying the resources that constrain income growth in a watershed and the real value of such resources helps devising mechanisms that help cost reduction and productivity growth per unit resource. Shadow prices provide estimate of additional costs required to acquire a unit of extra resource (land, energy, protein etc.) and to produce a unit of extra output (crop, milk, meat etc.). Accordingly, the scarcest or constraining resources tend to have high shadow prices. Such resources have high limiting role against income growth. Provided that the optimization model is based on real socio-economic and biophysical data, the calculated shadow prices reflect the real market value of resources and cost of activities.

Land is the scarcest resource and most important constraint in Jaba micro-watershed. As a result, income growth in the micro-watershed will be limited because of land scarcity. Acquiring a hectare of land for different activities costs USD 23813 in the upper zone, USD 17495 in the middle zone and USD 24272 in the lower zone. Labour is not a limiting factor of production in the area and has a shadow price USD 1.77/man-day. Energy supply (shadow price USD 145/thousand megacal) is more limiting than protein supply (shadow price USD 0/ton) for livestock production. Meat production is more expensive than dairy production, which, in turn, is more expensive than crop production.

Conclusion and recommendation

Optimization results for the business as usual scenario in Jaba micro-watershed mimic reality on the ground. They show that agriculture will continue as the major source of rural income in the coming years and as the major employment provider. Much of agricultural income will be generated from the crop sub-sector, followed by income from the livestock sub-sector. Agricultural income will be sustained around its current level, without showing major positive change. Agricultural income enhancing efforts in the area will be constrained by land shortage as the most important limiting factor. This is reflected in the high shadow price for land, while it is low for labour. This suggests the need for interventions that promote intensive (land saving) agriculture combined with more labour use. Potential impact of alternative RWM and land use practices as intensification and climate change adaptation strategies can be assessed by extending the analysis of this paper to such scenarios.

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