Barriers to implementing poverty alleviation through livelihood strategies: a participatory analysis of farming communities in Ethiopia's Upper Blue Nile Basin

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***Abstract*—** Poverty is multi-dimensional global challenge that impedes individual and community capacities to satisfy basic needs. These capacities are shaped by locally configured institutional and biophysical processes that are often hidden from external researchers and practitioners. To explore this worldwide aspect, we adopt participatory rural appraisal (PRA) methods to expose barriers to implementing livelihood strategies to address poverty in Ethiopia's upper Blue Nile basin, where 85% of the population are subsistence farmers reliant on local ecosystem services (ES). We identify local barriers to poverty alleviation in three steps. First, we classify major ES-livelihood interrelationships among communities of Debre Mawi catchment in upper Blue Nile. Secondly we assess ongoing struggles in these interrelations using combined biophysical and social assessment criteria to evaluate how poverty relates to current patterns of ES management. The analysis identifies complex interdependencies between livelihoods and regulating (crop pest controls), provisioning (water, land, and feed availability, soil fertility) and cultural (top-down ES management, population growth) ES that create bottlenecks to effectively 'lock in' poverty. Thirdly, we identify potential new ES management strategies, focused on dry season water availability. We conduct participatory field experiments on rooftop water harvesting to show this is a promising approach for increasing water availability to enhance agricultural production. Depending on the rooftop area, our modelling suggests that farmers can improve household income by US$136 to 14876 from 5 months beef fattening and US$69 to 7704 from 4 months sheep fattening. Except these specific livelihood strategies, the findings are replicable to the world's ES-dependent regions.

***Keywords*—** Debre Mawi, Ethiopian highlands, livelihood strategies, poverty, water harvesting

1. Introduction

Poverty, defined as a lack of basic capacity to participate effectively in society, is now recognized as a global challenge to sustainable development (Morton et al., 2017). It is a multi-dimensional phenomenon that is experienced in different ways, but is concentrated in rural areas of low and middle income countries, where about 90 % of people depend on agriculture for their livelihoods (FAO, 2005; IFAD, 2011; Roser, 2015; Mphande, 2016). In these settings, relations between agriculture and ecosystem services (ES) – i.e. the benefits humans derive from ecosystems – are often complex and highly interdependent (Jalan and Ravallion, 1998; Amberber et al., 2020). As tackling global poverty reduction is recognised as an international policy priority (IFAD, 2011), scientific research and policy initiatives need to focus upon these agriculture-ES interrelations, particularly as there is growing consensus that targeting agriculture and ES-dependent rural areas in developing counties potentially offers the best prospects for large-scale poverty reduction (Oakley and Clegg, 1998; Bebbington, 1999; Barder, 2009; Daw et al., 2011; Dile et al., 2013; Fisher et al., 2013).

In Africa as a whole and Ethiopia in particular, respectively over half and 96% of the population are subsistence farmers living in rural areas that rely on local ES for their livelihoods (Bationo et al., 2006; OPHI, 2014). The Ethiopian highlands feed 88% (Lemma, 2004) of the national population through mixed farming (crop production and livestock keeping) (Headey et al., 2014). This is one of Africa's most densely populated regions, and is also endowed with many supporting ES, including rich biodiversity (Hamza and Iyela, 2012) and relatively abundant surface and groundwater. It is located within the upper Blue Nile Basin (UBNB), which provides 85% of the net surface water flow for Sudan and Egypt (Bayabil et al., 2010). Despite the area's physical resources, food availability per capita has decreased recently due to the degradation of water and soil ES (Ali and Surur, 2012). This trend has increased poverty: most people in UBNB now experience food self-insufficiency (i.e., they cannot produce enough to cover fully their subsistence), which is a characteristic of extreme poverty (Diouf et al., 2002). Poverty alleviation has been very slow over the last decade as "little attention has been paid to understanding of the ways in which ES actually do contribute to poverty alleviation" (Suich, et al., 2015, p.137).

This context warrants research to explore how the use of local ES in poverty alleviation strategies can be optimised. Currently a gap exists in our understanding of the local barriers to more sustainable utilisation of ES (Suich, et al., 2015). Moreover, little work to date has framed ES for livelihood improvement through the concept of social-ecological systems (Ostrom, 1998; Pinho et al., 2014). Social-ecological systems are closely intertwined human-biophysical units with their own specific interrelations and interdependencies, within which ES play a vital role. In this context, Daw et al. (2011, p. 372) notes how 'the existence of trade-offs between different ES due to social-ecological dynamics has been emphasized by several authors, but despite extensive research on the Ethiopian highlands, to our knowledge no studies exist that conceptualize this region as a social-ecological system in relation to ES supported poverty alleviation (Amberber et al., 2020).

This study seeks to address these gaps by developing a grounded understanding of people's livelihoods in relation to ES provision (Chambers, 2012) in the Debre Mawi catchment of the UBNB, based on participatory rural appraisal (PRA) of the local barriers preventing poverty alleviation. We define barriers as constraints that prevent people from benefitting optimally from ES to improve their livelihood. We identify them and potential ameliorative livelihood strategies in three steps. First, using individual and community-level interviewing and workshops, we classify main ES-livelihood interrelationships among communities of the Debre Mawi catchment. Then we assess ongoing struggles in these interrelations by using a combination of biophysical and social assessment criteria to evaluate how poverty relates to current patterns of ES management. The analysis identifies complex interdependencies between livelihoods and regulating (crop pest controls), provisioning (water, land and livestock feed availability, soil fertility) and cultural (local top-down ES management, population growth) ES that act as bottlenecks to effectively 'lock in' poverty by limiting individual and community capacities to diversify traditional livelihood strategies based on farming. On this basis we then identify potential ES management strategies to improve agricultural livelihoods, focused on boosting water availability during the dry season.

The paper is structured as follows: Section 2 briefly reviews the recent literature on PRA and livelihood strategies (LS). We then introduce the study area and research methodology in sections 3 and

4 respectively. Section 5 then presents and discusses the results and, followed by conclusions and recommendations in section 6.

2. Participatory Rural Appraisal and Livelihood Strategies – examining 'hard-to-view' barriers to poverty alleviation

Limited access to formalized knowledge-related processes and phenomena, such as data on the state of ecosystem services, or awareness of the increasing range of public policies seeking to protect or to manage ES integrity, can be barriers to poverty reduction (Daw et al., 2011, p. 370; Amberber et al., 2020). Often, collective decision making processes and local informal institutional norms, beliefs and attitudes play significant roles in facilitating or impeding pathways to poverty alleviation (Bewket, 2007; Singh and Chudasama, 2020). These informalities can be much more difficult to discern for external actors such as scientists. PRA is a particularly useful suite of qualitative research approaches with which to uncover these hard-to-access or hard-to-reach processes or phenomena (Campbell, 2001). PRA emerged among development practitioners (Martin and Sherington, 1997; Chandra, 2010) to "enable local (rural or urban) people to express, enhance, share and analyse their knowledge of life and conditions, to plan and to act" (Chambers, 1994). This includes locally-specific decision making processes on resource management and community coping strategies for poverty alleviation that seek to address altered patterns of ES use in response to changing climatic (eg. drought, flooding) or environmental conditions (eg. deterioration of ecosystems), and their impact on individual and/or community livelihoods. PRA approaches include semi-structured interviews, focus groups, community workshops and participant observation, offering a methodological toolkit for focal communities to present, share and analyse their everyday knowledge and experiences (Abbot, 1996). The interplay between these methods enables researchers and communities to learn from each other by building on indigenous knowledge (Martin and Sherington, 1997) and lived experiences of people to co-produce ways of addressing poverty alleviation for specific socio-ecological systems. Notably, PRA helped the identification of livelihood strategies to address poverty alleviation among individuals and communities in the Debre Mawi.

Livelihood strategies are the diverse practices and actions used by people to meet their socio-economic needs and aspirations (Khatiwada et al., 2017). Strategies are often dynamic in response to changing environmental and social pressures, and can include overlapping activities affecting production, consumption and collaboration. In agricultural communities, livelihood strategies may include diversification or introduction of new business enterprises to raise income or alleviate poverty (Barrett et al., 2001). A key feature in their development in poverty affected rural areas is access to ES and the flexibility and adaptability of local institutions to respond to environmental change expeditiously (Tittonell, 2014). Mobilising indigenous knowledge of ES is also crucial in developing livelihood strategies that meet sustainability objectives.

3. Study Region

The upper Blue Nile basin in Ethiopia, (34°33'–39°45'E and 7°49'–12°42' N) is one of the major tributaries of the Nile River (Mellander et al., 2013) and comprises a total area of 180 000 km^2. It has a tropical highland monsoon climate with a main rainy season between June and September (Gondo et al., 2010). Mean annual rainfall ranges between 800 to 2200 mm, while average minimum and maximum temperatures are respectively 11°C and 26°C. The high precipitation rate and emanating ES, gives the basin a high potential for agriculture, hydroelectric power development and ecotourism, especially around the Lake Tana. Lake Tana is the main source of the Blue Nile River, and the largest and third largest lake respectively in Ethiopia and the Nile basin. Despite this potential most subsistence farmers are food self-insufficient. As a result, the existing ES-livelihood relationship needs to be improved to maximize poverty alleviation, through appropriate interventions that support adequately the ES-livelihood relationship. This requires an in-depth situation analysis, which can be achieved through participatory research. We focus specifically on ES management processes in one of the headwaters of the Blue Nile basin, i.e., the Debre Mawi watershed, which we consider representative of the basin and wider highlands of the world.

The Debre Mawi watershed is situated in the headwaters of the Blue Nile, about 30 km south of Lake Tana (between 11ºº20'13" and 11º21'58" N, and 37º24'07" and 37º25'55" E). The watershed's total area is 716 hectares (ha), elevation ranges between 1950–2309 metres, and slopes vary from 8 to 30% (Fig. 1). The maximum annual temperature occurs in March–April, ranging from 22–29ºC, with minimum temperature in November–December, with an annual range of 5 to 12ºC over the measurement period of 1996 to 2005. The watershed has a unimodal rainfall regime with an average annual rainfall of 1238 mm (Zegeye et al., 2010). June, July, August and September receive the largest shares of annual rainfall. The watershed is characterized as mountainous, highly rugged and dissected topography with steep slopes (Guzman et al., 2013) and has variable soil losses (Tebebu et al., 2010; Tilahun et al., 2013; Tebebu et al., 2015; Zimale et al., 2016; Tebebu et al., 2017). Particularly, fertile topsoil has been lost due to rill erosion (Zegeye et al., 2010) from cultivated land.

Rain-fed mixed farming is practiced here by about 85% of subsistence farmers. More than 70% of the land is cultivated (Amare et al., 2014) for teff, maize, finger millet, grass pea, bread wheat, food barley, potato and field lupin (*Lupinus albus)* production. Farmers keep livestock for different purposes, with cattle for traction, and sheep and goats for the market.

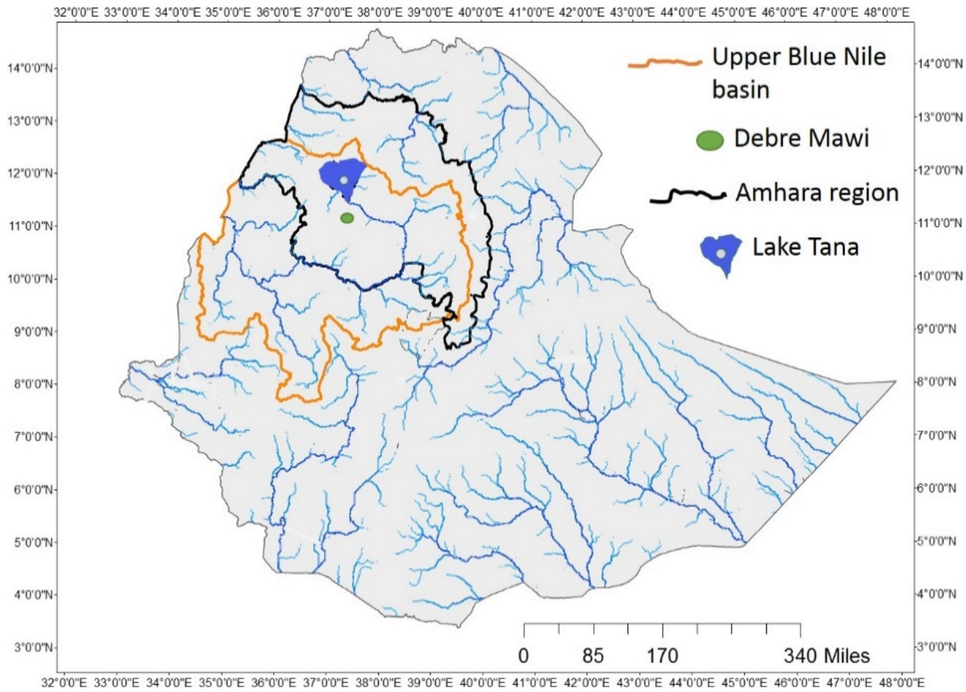

Fig. 1. Location of the Debre Mawi watershed within the upper Blue Nile basin, Ethiopia.

4. Research Methodology

Through detail situation analysis using PRA for data collection, and data analysis applying descriptive statistics using SPSS software, first ES and livelihood relationships trends, including status of poverty based on formal and informal (local) poverty indicators, were identified at Debre Mawi; next, livelihood impediments and improved options were classified. Then the applicability of improved livelihood strategies were evaluated applying field experiment; experimental data used for strategies comparison were computed using simple models and compared applying analysis of variance. Finally cost-benefit analysis was employed to select best livelihood strategy (ies) from the suggested options.

4.1. Participatory Rural Appraisal

This research finds out barriers of poverty alleviation first, then poverty lock-in challenging strategies using PRA. Following Fentahun and Gashaw (2014), a detailed situation analysis of the study area was conducted in 2015 using various participatory methods, including household questionnaires, semi-structured interviews with key informants, open community meetings, and small focus group discussions. These participatory techniques were complemented with detailed field observations through transect walks and ES mapping with farmers. Based on the outcomes of these survey methods, community-researchers participatory mental model framework was designed aiming to improve ES management to livelihood and environmental sustainability.

To avoid bias in this participatory approach, we used systematically a combination of tools, which included household surveys, semi structured interviews, focus group discussions, and mapping of ES on the ground by farmers followed by checking of the map elements on the ground through transect walks. Maps were copied on the paper and then reviewed, and if necessary revised, with focus group members. Based on the outcomes of these survey methods, we designed a participatory mental model framework for community member and researchers to jointly analyse potential improvements to ES – livelihood interactions. In our data analysis process, commonly mentioned major problems and solutions in the above mentioned tools were considered as the real (unbiased) major problems and solutions. In addition to using a combination of tools, a detailed explanation of the purpose of the study and its relevance for local development were explained, at the start of each session, in the hope that this would promote honest and correct answers from the farmers.

Household surveys: To select the most representative respondents a random sampling method was used, taking account of gender, and following the rule of thumb (Yount, 2006) for sample size determination (Fig. 2). Yount (2006) states that the sample sizes can be 100, 10, 5, 3 and 1 percent for 0−100, 101–1000, 1001–5000, 5001−10 000 and >10 000 population sizes respectively for comprehensive, large number survey questions. This survey was conducted to collect information using close ended questions.

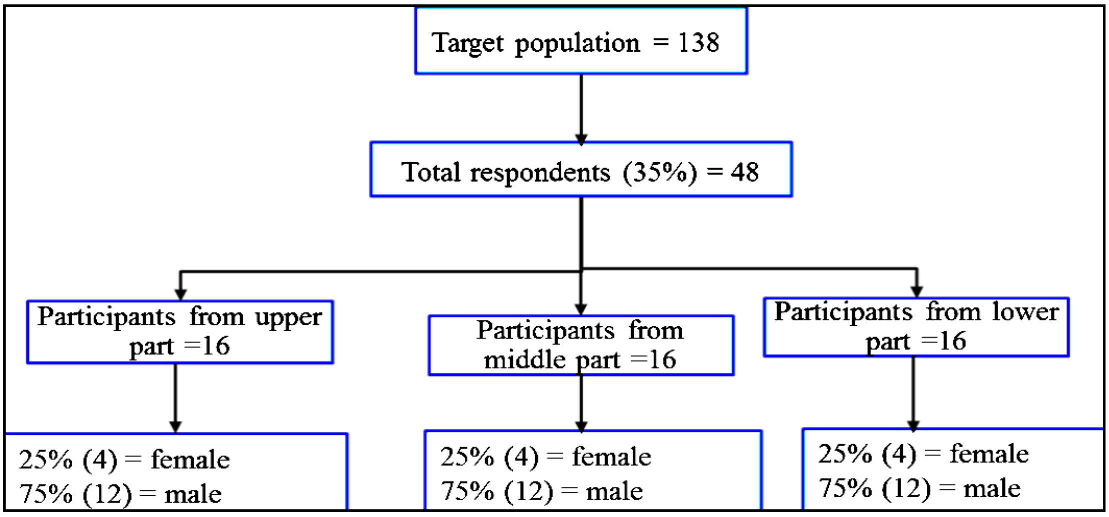

Fig. 2. Overview and statistics of selected household respondents: respondents were selected from residents of upper, middle and lower landscape positions; the number of respondents in three parts of the case study was the same; in each part respondents' composition was determined as 75% male and 25% female purposively; then respondents in each gender group of each part of the watershed were selected using random sampling.

Semi structured interviews: Six farmers were selected for interviewing based on their extensive knowledge and experience of dry land arable farming and livestock management, their familiarity with the challenges posed by ES provisioning issues, and their availability and willingness to participate in the research. These farmers were interviewed to gather information using open ended questions.

Focus group discussions and field observations: Three focus groups were convened, each consisting of 5-7 farmers from the three parts of the Debre Mawi watershed (5, 7 and 6 representatives in upper, middle and lower parts respectively) mainly from the interview sample. Participants were selected using purposive sampling, which assumes the composition of the group as fairly homogeneous (active farming representatives) but is sensitive to gender differences. A transect walk was undertaken with participants along the boundary of the 716 ha watershed. This was done to observe, experience, and make sense of how participants perceived and conducted ES management practices, and to help researchers to better apprehend the challenges farmers faced. One representative from each focus group with good knowledge of the boundary of the watershed participated in this transect walk. Each group then assisted during mapping the ES on the ground using available local materials such as stone, ash, leaves, branches and grass by participant who had taken part in the first transect walk. Once the mapping was complete, participants were interviewed on supplemental questions in group to complement the information mentioned in their map (Supplementary material Fig. S1). A second transect walk was then completed to collect biophysical data to supplement farmers' perceptions and field observations. In total therefore, three transect walks were completed in three parts of the watershed (Supplementary material Fig. S2). Mapping and transect walk activities provided the necessary data to prepare a watershed level ES base map. Once complete, this was presented to community representatives from the three focus groups to verify the mapping process and to provide an opportunity for discussion, revision and amendment (Supplementary material Fig. S3). By highlighting results of previous discussions, observations and interviews, the resulting situation analysis was complemented by cognitive mapping (i.e., a participatory mental model framework designed by community and researchers about the ES management for livelihood improvement) through another focus group discussion. Lastly strategies considered by farmers as most promising were identified for further analysis, on the basis that potentially they might improve current ES management and enhance farming livelihoods while also minimizing current patterns of resource degradation.

Survey data analysis: The data collected as part of the situation analysis was analysed using quantitative and qualitative methods as appropriate. The questionnaire survey data was analysed applying descriptive statistics particularly frequency analysis using SPSS software, with focus group discussions, field observations and semi-structured interviews examined and summarized in relation to the quantitative data.

4.2. Evaluation of Livelihood Strategies

The PRA was implemented in 2015, and field experiments were conducted during the 2016 wet season, to evaluate the applicability of one of the livelihood strategies (poverty lock-in challenging strategies). For the purpose of this study, the Debre Mawi watershed was divided into three parts based mainly on rainfall spatial variability, which was a criterion suggested by interviewees. Two common rooftop designs were used for collecting rainwater: surrounding and rectangular (Fig. 3). To gather representative evidence on water harvesting for the whole Debre Mawi watershed, six (3 surrounding and 3 rectangular) experimental rooftops were selected per village. Rooftops were chosen in degraded sites where high overland flow generation was expected to reduce runoff that causes soil loss. 18 rooftops (6 per village, i.e., 6 x 3) were selected for this experiment with surface areas ranging between 70.5 m^2 and 155 m^2. The total rooftop area is 2067 m^2. Barrels were used to collect the rainfall on rooftops through a system that connects rooftops to barrels; the rainwater depth in the barrel was recorded after every storm event from June to October 2016 (during the rainy season). Then the volume of harvested water was determined as the product of water depth in the barrel and its area. The spatial variability and rooftop design effects on the amount of harvested rainwater (HRW) were analysed using one-way ANOVA and t-tests respectively at the 95% confidence level. For future HRW simulation, a simple equation (the product of rooftop area, precipitation and runoff coefficient) was calibrated using the 131 observed HRW volumes, and its simulation efficiency was evaluated using coefficient of determination (R^2) and Nash Sutcliffe efficiency (NS).

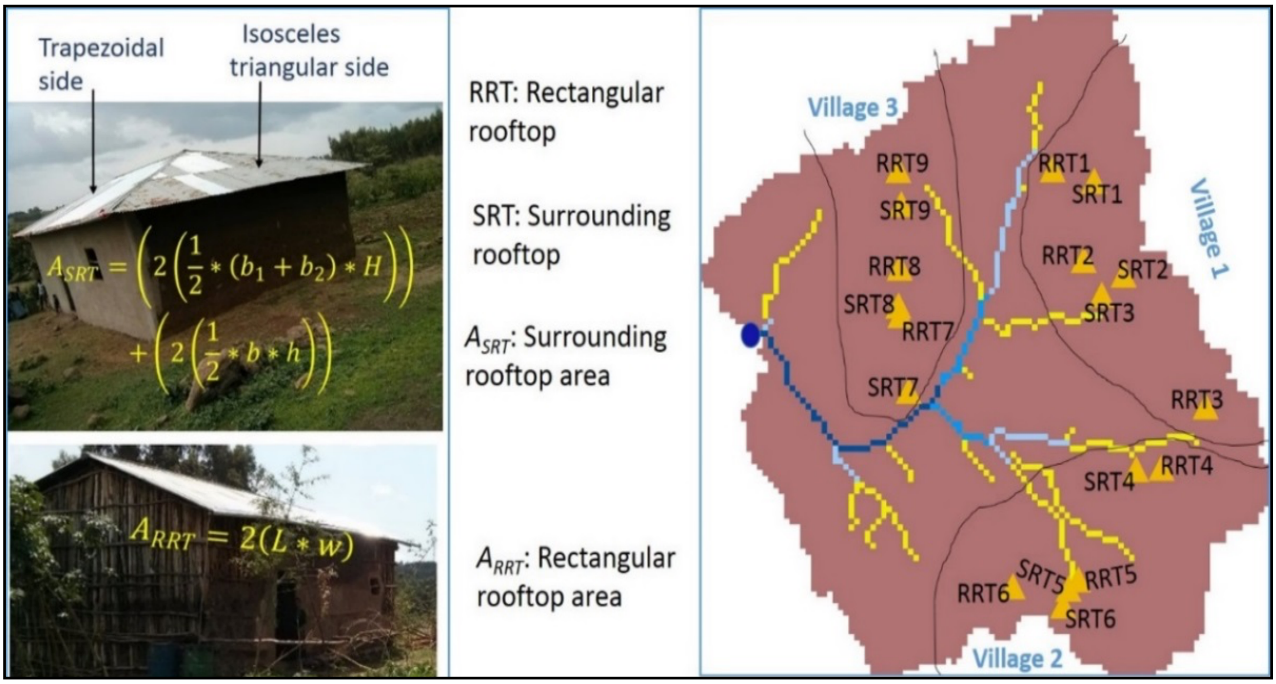

Fig. 3. Designs of experimental rooftops and their locations at the Debre Mawi.

Subsequently, water requirements were determined. Irrigation and fattening were potential farming practices. Crop water requirement (CWR) was determined using the CROPWAT 8.0 software developed by FAO, based on the FAO Irrigation and Drainage Paper 56 (FAO, 1998; Surendran et al., 2015), and the animal drinking water requirement was determined from the literature. In the study region, the mean daily water consumption of beef cattle is 40 l and of sheep is 10 l per animal (Sileshi et al., 2003; Ward and McKague, 2007; Birhan and Manaye, 2013). Before determining crop area and number of animals that can respectively be irrigated and produced using rooftop water harvesting, the household water demand for domestic use that needs to be supplemented by HRW was calculated as follows:

$$HRW_{du} = WD_{du} - WA_{ews} \qquad (1)$$

where HRW_{du} is harvested rainwater need for domestic use (m^3), WD_{du} is total water demand for domestic use (m^3) and WA_{ews} is water amount from existing sources, hand dug wells (m^3); the last two were determined using PRA research method.

The cropland area for irrigation and the number of animals for fattening were then calculated based on the rest amount of harvested rainwater. Lastly, a comparison of the cost-benefit ratio (CBR) was made of the resulting four livelihood enhancing strategies, namely: potato irrigation, hot pepper irrigation, sheep fattening and beef cattle fattening followed by selection by ranking; the higher the CBR, the better the strategy for livelihood improvement. The cost that was considered in this analysis includes the following elements: pond installation (geo-membrane and plastic sheet for pond covering), water collection system installation cost, seed and animal purchase cost for irrigation and fattening respectively.

The benefits are described as the gross returns from these irrigation and fattening practices. For these farming strategies, the farmers will use family labour that technically also involves an opportunity cost. The time farmers spend on these practices is time they cannot spend on other things before, because it is free time between their two successive rain fed cropping calendars.

$$CBR_{Ind.option} = \frac{\sum Benefit}{\sum Cost} \qquad (2)$$

where $CBR_{Ind.option}$ is benefit to cost ratio of individual option, for example, potato irrigation. For a scenario to be beneficial, the CBR has to be greater than 1.

5. Results and Discussion

5.1. Ecosystem Services and Livelihood Relationships Trends in Debre Mawi Watershed

The PRA approach revealed 10 main types of natural capital that provide ES for the focal communities (Table 1). The most important from a livelihood perspective were water, land for cultivation, and animal feed. However, the analysis revealed that due to land degradation, farmers were unable to benefit from four of the total 10 landscape elements mentioned in Table 1. Wild plants and animals have largely disappeared because of deforestation, with scrub and woods cleared to provide agricultural land expansion for the increasing population (Ebenezer, 2015). Wetlands and amenity lands have either been converted to arable land or swallowed up by gully erosion; these have formed in valley bottoms after deforestation in upland parts of the catchment (Tebebu et al., 2010). Currently, the main livelihood strategies are arable production and oxen management for ploughing. Water resources, cultivated land and pasture land are thus the key natural capitals for the focal communities (Table 1).

5.2. Status of Poverty in the Debre Mawi watershed

The livelihood or poverty status of the community was analysed based on a range of local and general indicators derived from the survey research and existing studies. Of the seven commonly grown crops in the case study, maize has largest production followed by teff (Fig. 4). Farmers prefer to grow teff as it is a cash crop that yields the highest income, which is needed to purchase fertilizer for subsistence crops. The cost of fertilizer is very high and teff grain income is not sufficient to purchase adequate levels of fertilizer. As a result, yields are low and virtually all people are poor and suffer food insecurity. Particularly, malnutrition is a serious problem as the local diet largely consists of only maize (Fig. 7). In addition, the level of educational attainment was low, and health and wellbeing were poor (Table 2). Illiteracy is one factor that exacerbates poor agricultural production, since illiterate farmer particularly who is not able to read "would not be able to manufacture, investigate and communicate improved information about agriculture to boost his production'' (Masood et al., 2012).

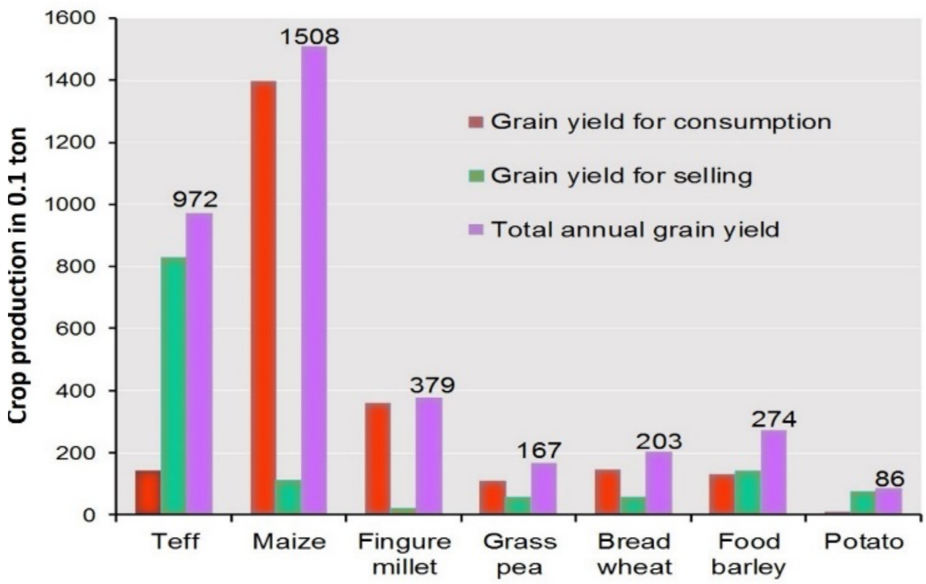

Fig. 4. Purpose of crop production in Debre Maw: annual grain production for consumption and selling.

Table 1

Main natural resources and essential ESS for the focal communities. Feed is a general term which can include pasture (grass grazed by animals) and other types such as hay, crop bran and straw. Green water is the rainwater that falls directly on the land (field), whereas blue water refers to surface and groundwater can be consumed for production and other services such as cleaning. A church is of course a manmade structure, but we consider it an ES because farmers consider various the landscape futures in their decision to build the church. For instance, it should be at the top of hill, allow for tree growth, and have holy water available close to it. Holy water is the water which is sanctified by a priest for the purpose of the blessing of persons, places, and objects, or as a means of repelling evil.

Natural capitals	ES for the local community	ES Category
Water resources	Water for drinking, sanitation, irrigation	Provisioning

(blue water)		
Cultivated land	Crop yield for food, income and animal feed	Provisioning
Pasture land	Feed (food & income), income (selling hay), hut thatching	Provisioning
	Land cover (conserve water and soil)	Regulating
Forest land	Wood products (fuel, construction)	Provisioning
	Land cover (conserve water and soil)	Regulating
	Shelter for wild animals, nutrient cycling, adds organic matter to soil	Supportive
Green water	Sources of all water such as water for drinking, sanitation, irrigation, swimming, and growth of forest, grass and other plants	Provisioning, supportive, regulating (green water helps land covers to grow, hence the land covers reduce soil loss and runoff)
Stone	Reduce soil erosion and keeps soil fertility	Regulating
	Income generation (selling of stone)	Provisioning
Church	For praying, to resolve conflicts (spiritual)	Cultural
Wild plants	Food from non-timber products	Provisioning
Wild animals	Food	Provisioning
	Green grass for livestock during dry season	Provisioning
Wetlands		
Recreational landscape (fields)	Horse riding, ball and other cultural playing at flattened ever green fields	Cultural

Table 2
Farmers' education and health services access.

	Variables	% of respondents (N=48)
Education of household heads	Illiterate	72
	Can read and write	10
	Grade 1-4	4
	Grade 5-8	10
	Religious knowledge	4
Health centre (clinic)	'In the Debre Mawi clinic, we have mostly been told that our health problem is beyond their expertise as well as facility; thus, we need to look for another place which is far; visiting far health centres is not a good option as there is no money to pay for these distance facilities'	100

Based on the survey results, local community identified that wealth status is the main local indicator of poverty. This wealth status intern has four main indicators (Table 3; Fig. 5): the size of their land holding (main), number of oxen, amount of savings and ownership of assets (eg., flour mill, eucalyptus tree plots). If the farmer has land scarcity, his daughter cannot marry; because he cannot give her the required area of land for local marriage; but this is one opportunity for girls to join school. The saving was derived based on interview outcomes: the sources are selling of 'teff' grain yield and eucalyptus wood, except a few farmers whose additional income source is off-farm activity (mainly from flour mill). Using these criteria, no respondent can be considered wealthy, i.e., all are poor in Debre Mawi.

Table 3
Wealth status indicators in the study area.

Wealth status	Wealth indicators			
	Land size (ha)	Oxen (No)	Saving (Birr)	Others (type)
Rich	>3	2−3 pairs	≥20000−30000	flour mill, eucalyptus
Medium	1.5–3: main factor	not mandatory	not mandatory	not mandatory
Poor	<1.5: main factor	not mandatory	not mandatory	not mandatory

Considering local and general indicators, poverty is endemic in the watershed despite of the agricultural potential of the area. Here the important driving forces of poverty are population growth, the minimal level of household assets, and a 'top-down' governmental approach to ES management (FAO, 2003). In interview, a farmer told us that "currently seven households hold the land area that was owned by one farmer 20 or 30 years ago. As a result, they practice continuous cultivation, ploughing on sloping terrains and planting of the non-native eucalyptus tree species, have all increased ES degradation. The first two activities aggravate crop yield reduction through loss of organic matter and soil erosion, while eucalyptus is usually planted along streams, reducing water availability by decreasing flow to streams (Chanie, et al., 2013; Mhiret et al., 2020). Most farmers own a small plot of land and a few oxen (Figs. 5 and 6), which limit the opportunities to move out of poverty.

In the literature, various reasons have been given for the poverty of Ethiopian farmers, but poor ES management is typically considered as the main contributory factor (Gashaw et al., 2014; Kabuya, 2015; Zerga, 2015). Particularly the current situation in the study area indicates that people are living in poverty because of increasing pressures related to erratic rainfall and population growth (Gray and Mueller, 2012; Singh, et al., 2013; Misra, 2014; Sinore et al., 2018). The farmers have tried to improve their livelihood especially through cropland expansion but this has often resulted in aggravating land degradation. At the same time, top-down government-led approaches that have been implemented to improve livelihood and environment (Cohen and Lemma 2011; Gashaw, 2015), but often had adverse effects, which have been attributed to a lack of planning at the local level considering social-ecological context (Haile et al., 2006; Cohen and Lemma, 2011). In the Debre Mawi watershed, a contour furrow installed in 2013 in the valley bottom initiated a large gully (Mhiret et al., 2019). Hence, land degradation and poverty have been increasing through time despite of efforts of the local community and top-down interventions (Bewket, 2007; Meheretu et al., 2014; Sinore et al., 2018). This needs detail analysis to find barriers and improved ES management strategies of poverty alleviation.

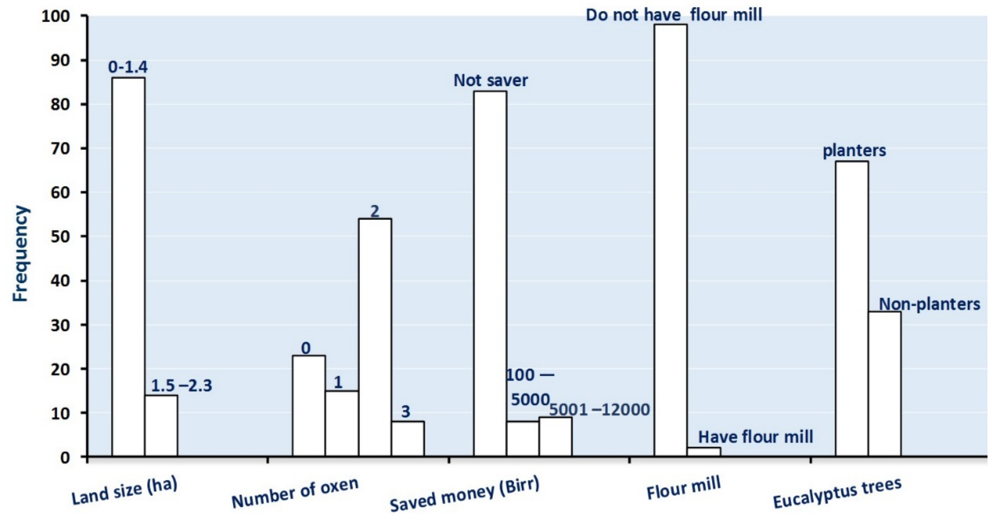

Fig. 5. Wealth status indicators and current farmers, relationship, in Debre Mawi (N=48).

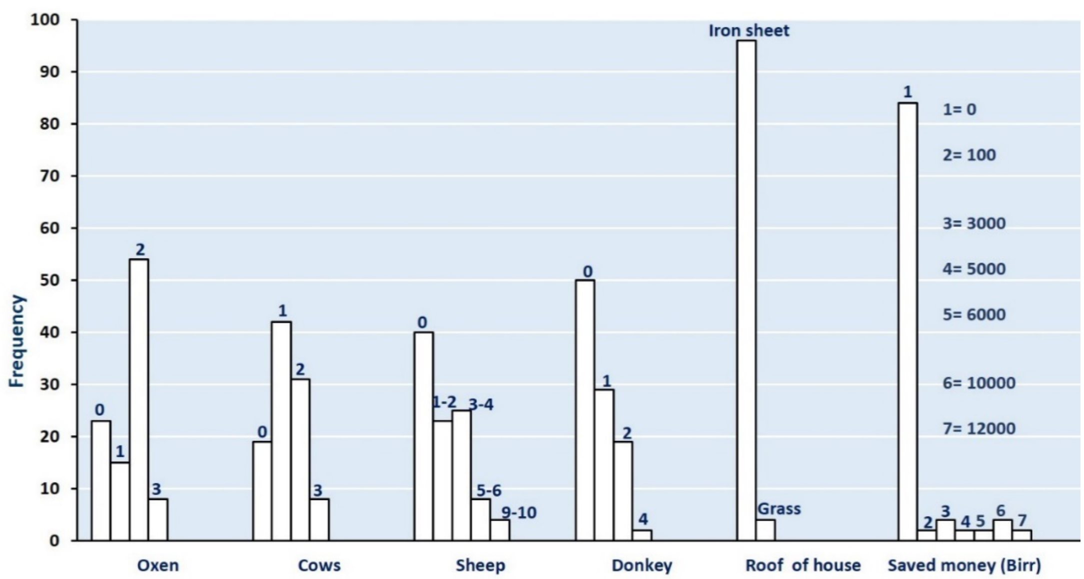

Fig. 6. Main household assets as obtained from the PRA activities.

5.3. Major Bottlenecks to a More Sustainable Use of ES in the Debre Mawi Watershed

In this study, we found eight more specific bottlenecks: water scarcity, soil erodibility, crop pests, unoptimised strategies, soil fertility declining, land scarcity, feed shortage and poor animal breed. These issues were ranked based on their importance to community livelihoods (Fig.7). Despite the study region's abundant surface and groundwater (Bayabil et al., 2010), water is in short supply (Stokes, 2010) during the dry season (for 6 months). Due to shrinking land availability (Regassa et al., 2010; Tschopp et al., 2010; Minale, 2013) and increasingly erratic rainfall, most farmers (96%) wanted to diversify their crop production using irrigation, but limited water availability prevents this possibility (Stokes, 2010). Water scarcity also affects livestock productivity: stream volume decreases over time, and most are completely dry during January–May.

Soil erosion, which increases with decreasing organic matter and varies as soil type and slope (Lal, 1985; Ali and Surur, 2012; Geta et al., 2013; Tebebu et al., 2017), and crop pests such as pea aphid (*Acyrthosiphon pisum*) (Wale et al., 2003) and rodents are a second bottlenecks for poor farmers. These are the main causes of crop failure (90 and 69% of the responses, respectively). Most farmers cultivate the upslope in the rainy season (Dagnew et al., 2015); as these lands are exposed to surface runoff, top soil erodes, resulting in reduced soil depth; in addition, gullies form in the periodically saturated lower regions with vertisols (Natarajan et al., 2010; Tebebu et al., 2010; Zegeye et al., 2016, 2018). Saturated soils have little strength, and once a gully is initiated, the gullies expand rapidly due to slumping banks (Amare et al., 2019). Gully erosion is especially active in the lower regions of the Debre Mawi watershed, with several rapidly expanding 6 m deep and 25 m wide gullies.

The predominant cropping strategy chosen by farmers is the third factor leading to poverty lock-in. Farmers insist on rainy season crops, especially cereals production and keeping some cattle even though they (100%) have known that the production from both sectors decreases over time (Bishaw, 2009; Gecho et al., 2014; Mekasha et al., 2014; Gebremedhin and Tesfaye, 2015; Yosef and Asmamaw, 2015). Decreased soil fertility due to loss of organic matter (Geta et al., 2013; Tebebu et al., 2017), land shortage, feed scarcity and inappropriate cattle breeds are the fourth set of factors that inhibit farmers' livelihoods. All farmers in the sample recognised that their cultivated land was infertile, requiring high fertilizer application. As a result of rising demand, fertilizer price increases. Virtually all farmers commented on this point, with one noting, "our current land cannot give any yield without fertilizer; if fertilizer was not available, "we will stop production and die". This is challenging for all farmers as their cash resources are seldom sufficient to cover fertilizer purchases (Croppenstedt et al., 2003). Next to water scarcity, feed scarcity due to intrusion of gullies in grazing lands is the most significant factor affecting livestock productivity (Dejene et al., 2014; Mekasha et al., 2014; Beriso et al., 2015).

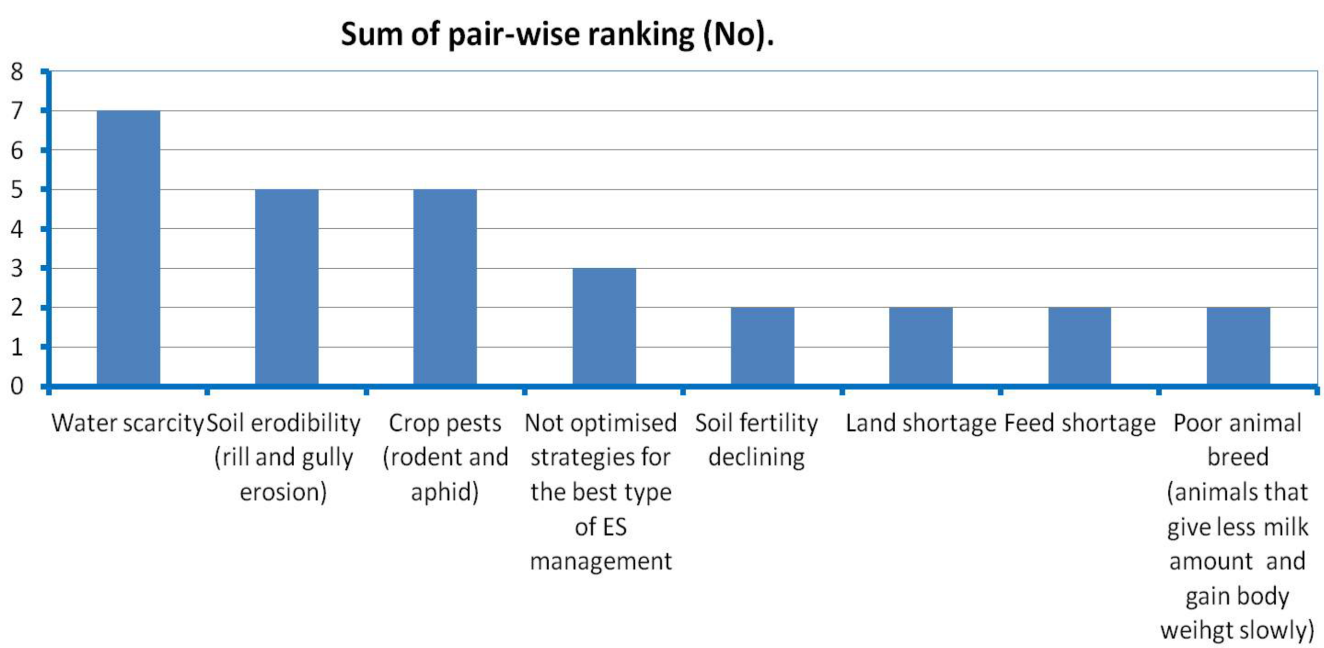

Fig.7. Major bottlenecks to benefit from ES.

5.4. . Main Biophysical Processes Perpetuating Poverty

We found three biophysical processes that can be classified as bottlenecks that lead to poverty lock-in. These processes are soil erosion by rain water (runoff), drying of streams and climate change (erratic rainfall). Rill (Zegeye et al., 2010) and gully (Tebebu et al., 2013; Dagnew et al., 2015; Zegeye et al 2016, 2018) erosion types are serious land degradation problems, threatening farmers' livelihoods in the watershed (Guzman et al., 2013). Drying of streams also causes a decline in provisioning ES, especially provided by livestock. Lastly, change in climate is thought to affect ES derived from crops (96% respondents), and was the major reason of crop failure over the last five years after severe soil erosion. In focus group discussions, farmers reported that "in 2015 cropping season rain fell unexpectedly at flowering stage of our most popular, income generating crop (teff). Consequently, yield of teff reduced by 50% from the usual harvest per household".

Considering the above major bottlenecks and biophysical ES degradation processes, improved livelihood strategies (section 5.5) with their optimal management options (section 5.6) were identified unlike the suggestion of Cohen and Lemma (2011),i.e., 'fertilizer and soil and water conservation interventions to improve livelihood'.

5.5. Livelihood Strategies to Reduce Existing Bottlenecks in Debre Mawi

Strategies to reduce or remove bottlenecks were analysed. The best options were selected using the Debre Mawi watershed as a case study to make use of the participatory cognitive map of ES management developed in this paper. By considering the information in sections 5.3 and 5.4 the cognitive map of the researchers-community participatory mental model, which considers the long-term livelihood and environmental sustainability, was developed. This model presents the steps of actions, contributions of relevant stakeholders, challenges and solutions for each step, and how participatory knowledge generation and exchange work for sustainable development (Fig. 8). This approach is flexible and can be adopted in similar regions of the world. In the focus group discussion, the most frequently mentioned bottom-up strategies to escape poverty (Kristjanson and Kuan, 2006; Schneider and Gugerty, 2011) identified by participants are listed in Table 4. Most farmers wish to produce horticultural crops at least in their homesteads using irrigation to mitigate the crop failure risk of a changing climate and generate income for fertilizer purchase. The second strategy mentioned was livestock fattening. However, lack of water during the dry season was found as a major problem. There is insufficient water for domestic consumption as well, indicating a solution to the water availability issue is urgently required.

5.6. Management Options at the Local Level

Managing water availability is a key requirement to improve livelihoods and make them more sustainable (Table 4; Fig. 8). Fig. 8 presents the link between current livelihood issues (bottlenecks), their consequences, and possible mitigation strategies; besides, it highlights how participatory knowledge generation and exchange could contribute by combining possible stakeholders, solutions and challenges for sustainable development. Typically, the study area is now facing serious soil erosion due to intense precipitation and drought in the same year. As a counter measure to unpredictable rainfall, land shortage and severe soil erosion, rainfall-runoff harvesting appears to be an effective option (Gatot et al., 2001). It could help store water in the rainy season to raise crop production in dry spells, control runoff (decrease erosion rate), conserve the excess runoff water for livestock and improve farmers' income and food security. Currently, most cropping land in the uplands has been covered by in situ rainwater harvesting methods such as bunds, vegetative barriers and trenches to conserve soil and water. Farmers consider that this rainfall-runoff harvesting might also improve groundwater recharge in the lower catchment, but direct rainwater-runoff harvesting has rarely been attempted. Hence, to select optimally appropriate livelihood strategy (ies) from the list identified in Table 4, rainwater-runoff harvesting supported livelihood strategies were compared, applying comparative advantage analysis as mentioned in Section 5.7.

Table 4
Strategies to move out of poverty, and their required management options.

S/N	Strategy type	Required management options in their ranks order		
1	Crop diversification using irrigation	Water availability (1)	High value crops (2)	Market opportunity creation (3)
2	Animal fattening	Water availability (1)	Enough feed (2)	Improved breed (3)

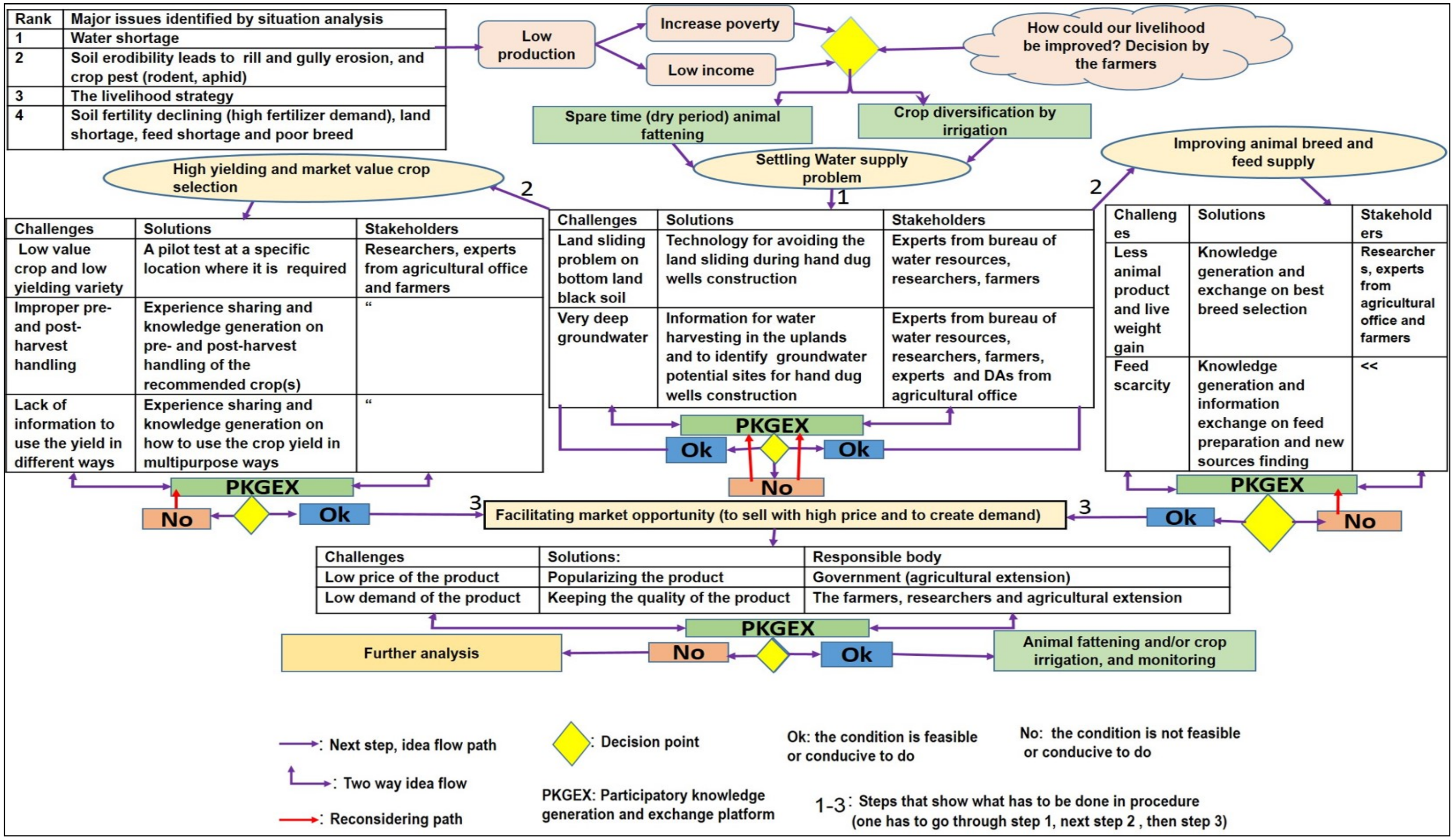

Fig. 8. Cognitive map of the researchers-community participatory mental model about the ES management for livelihood improvement in Debre Mawi

mitigate major bottleneck, i.e., water scarcity, and to experiment with implementation of a participatory knowledge co-creation process to support this strategy. It focuses on rooftop water harvesting, which is considered as a potentially viable strategy. The largest and smallest amounts of harvested rainwater (HRW) using the experimental rooftops were respectively 140 and 71 m³. Fig. 9 shows high correlation (up to 0.98) between the total HRW volume and rooftop size during the observation period (15 Jun 2016–23 October 2016). For further comparison, the data was normalized as the ratio of sum of HRW volume to rooftop area. Using this ratio, one-way ANOVA and t-test respectively confirm that the HRW amount is not affected by spatial or rooftop design variations (Tables 5 and 6) at Debre Mawi.

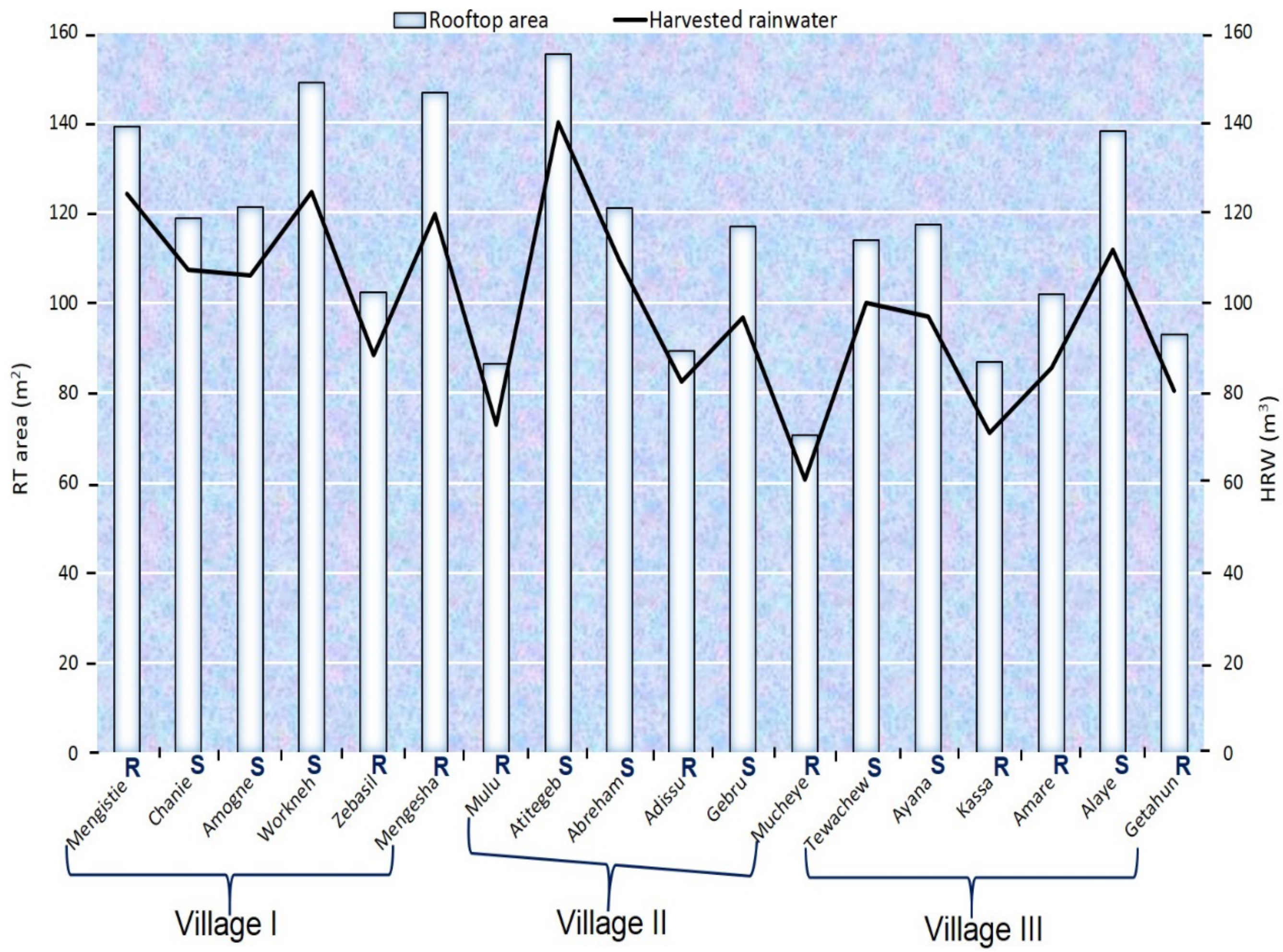

Fig. 9. Rooftop, RT and harvested rainwater, total HRW relationships; household heads of experimental rooftops; *R*: rectangular, *S*: surrounding.

deviations from the means, *MS* (mean squares): average variations, are found by dividing sum of squares by the corresponding degrees of freedoms, *F-calc* (f-calculated): between groups variance/within group variance, *P-value*: the probability of getting a result at least as extreme as the one that was actually observed, given that the null hypothesis is true.: *F-crit* (f-critical): is found in the table considering significance level (α: alpha=0.05) and the degrees of freedoms of numerator and denominators respectively *df* of between groups and *df* of within group, if *f-calc* is greater than *f-crit*. Then the null hypothesis is rejected.

RT design	Source of Variation	SS	df	MS	F-calc.	P-value	F-crit.
Rectangular	Between groups	0.002	2	0.001	0.74	0.52	5.14
	Within groups	0.007	6	0.001			
	Total	0.009	8				
Surrounding	Between groups	0.003	2	0.001	0.96	0.43	5.14
	Within groups	0.009	6	0.001			
	Total	0.011	8				
Watershed level	Between groups	0.004	2	0.002	2.01	0.17	3.68
	Within groups	0.016	15	0.001			
	Total	0.021	17				

Table 6

Determination of rooftop design effect on rooftop rainwater harvesting using t-test (*sd*: standard deviation, *t-calc*: calculated t-value, *t-crit*: critical t value and *P-value*: as mentioned in Table 5).

Location	Rooftop design	Mean	SD	t-calc	t-crit	P-value
Village 1	Rectangular	0.86	0.04	0.47	2.78	0.66
	Surrounding	0.87	0.03			
Village 2	Rectangular	0.88	0.04	0.07	2.78	0.95
	Surrounding	0.88	0.04			
Village 3	Rectangular	0.84	0.02	0.11	3.18	0.92
	Surrounding	0.84	0.04			
Watershed level	Rectangular	0.86	0.03	0.26	2.12	0.80
	Surrounding	0.86	0.04			

The 15 June to 23 October 2016 record showed that the total rainfall amounts in villages 1, 2, and 3 were respectively 1072, 1036 and 987 mm which were homogeneous. But there was daily rainfall amount difference between the three villages except between village 2 and 3 (Fig. 10) as respondents believed that there is a daily storm event difference during the wet season between these villages. The farmers in Debre Mawi said that “when the rain rains in village 1, it does not rain in village 2 and/or 3 and vice versa, mostly; but the annual rainfall amount in the three villages is similar”.

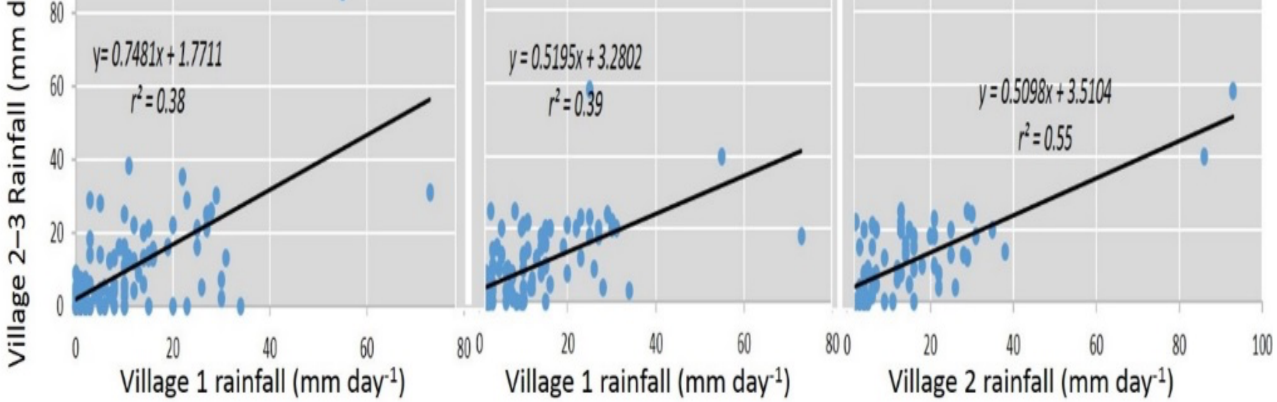

Fig. 10. Correlation of daily rainfall between the 3 studied villages (15 June to 23 October 2016).

The wet season period (15/6/2016 to 23/10/2016) data indicates the observed and simulated harvested rainwater values are strongly correlated. The simulation efficiency of the equation is in the acceptable range (Enku and Melesse, 2014; Fig. 11). Including experimental rooftops, the total rooftop area in the watershed is 2.38 ha. The 2005 to 2015 data indicate that the mean annual rainfall is 1193 mm. Therefore, the total possible harvested rainwater using rooftops is around 23 thousand cubic meters.

In the Debre Mawi catchment, most farmers want to cultivate potato and hot pepper for subsistence needs (Amede and Delve, 2008) and fatten sheep and beef cattle for income generation (Amistu et al., 2016; Bezabih et al., 2016) in the dry season. Sheep and beef need to be fattened for 4–5 months respectively to achieve a good market price (Animut and Wamatu, 2014; Wolde et al., 2014). To capture higher market premia available during the Ethiopian Easter, farmers usually start fattening sheep in January and beef cattle in December to sell in May for the Easter holiday.

The CROPWAT outputs show that irrigation water requirements during the dry season is 0.44 m^3 m^{-2} for potato and 0.41 m^3 m^{-2} for hot pepper. The average water consumption of beef and sheep as found from literature (Table 7) is respectively 40 and 10 l per animal per day (Sileshi et al., 2003; Ward and McKague, 2007; Birhan and Manaye, 2013). However, before harvested rain water, HRW, is used for irrigation and fattening, domestic use has to be satisfied. Farmers are using hand dug wells for domestic use (human and their animals' consumption). These wells supply only 20% of the household water requirement. In this study we estimate that farmers need 48 m^3 more water per household on average for their domestic use in dry period than what hand dug wells can provide (Eq 1 under section 4.2; Table 8). Hence, the net minimum, mean and maximum HRW that can be used for fattening and/or irrigation is 10.7, 31.1 and 227.5 m^3 respectively (Table 8). On average, this net HRW helps farmers irrigate around 70.8 m^2 of potatoes, 76 m^2 of hot peppers, and to fatten 26 sheep and 5 beef (Table 9).

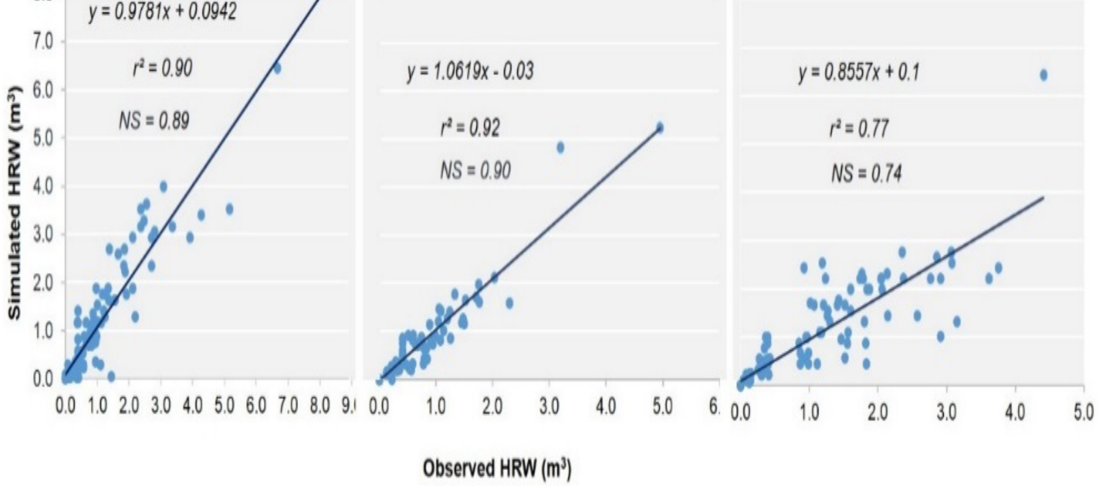

Fig. 11. Comparison of the observed and simulated amounts of harvested rooftop water (HRW) for the rainy period (15/6/2016 to 23/10/2016).

Table 7
Crop water requirement (CWR) and animal drinking water requirement (DWR) in the different strategies of livelihood improvement.

Crop	Planting date	Harvest date	Irrigation water application	Irr.req (mm)	CWR (m^3 m^{-2})
Potato	15-Dec	23-Apr	14 times	439.7	0.44
Pepper	15-Dec	18-Apr	13 times	406.2	0.41
Animal	Starting date for fattening	Selling date	Daily water requirement, DWR (m^3)	Days for fattening	Total DWR per animal (m^3)
Sheep	1-Jan	1-May	0.01	120	1.2
Cattle	1-Dec	1-May	0.04	150	6

5.7.2. Economic Analysis of Livelihood Strategies

Farmers will use family labour and will not allot money for labour cost to this potato and hot pepper production. To fatten animals during this dry season, farmers can also use family labour and feed farm by-products such as crop residue, straw, hay, crop bran and local breweries by-products (Berhanu et al., 2009; Animut and Wamatu, 2014; Halala, 2015), which are cost-free. Chanie (2014) did a comparative advantage analysis of three crops grown in the same area but with different inputs requirements such as fertilizer, labor, seed and different outcome (yield and income). He selected the profitable crop using cost-benefit analysis (i.e., if the benefit to cost ratio is greater than one, the crop management is profitable). Following his methodology, we draw the cost-benefit analysis to compare HRW supported livelihood strategies mentioned above, to select productive option(s). The cost-benefit analysis proves fattening is more profitable than crop irrigation as the cost-benefit ratio (CBR) of return benefits to fattening costs relations is greater than one in all (Table 10). The farmers with the least assets can be most profitable in beef fattening. The second profitable option for this group of farmers is sheep fattening. The average amount asset possessing farmers at the watershed level can be most profitable by beef fattening; their second option is sheep fattening. The farmers with the greatest assets can generate the highest profit by sheep fattening,

consumers at household level in Debre Mawi. (eg.some households fiche minimum amout of water (5.4 m³ during this dry period) fro communal and dug wells while some fiche 18.9 m³ (i.e., the maximum amount); here average household water demand for farmers' domestic use in dry period than what hand dug wells can provide is 48 m³.

Water sources/consumers	Minimum	Maximum	Mean	Daily per capita water requirement, *DWR* (m^3)
Hand dug wells, WA_{ews} (m^3)	5.4	18.9	12.24	
Consumers				
Family member (No)	2	8	5	0.005
Cattle (No)	0	10	6	0.04
Sheep (No)	0	10	3	0.01
Donkey (No)	0	4	1	0.04
HRW_{du} (m^3)	0	107.1	48.06	
Harvested rain water, HRW (m^3 $year^{-1}$)	10.7	334.6	79.2	
NHRW (m^3)	10.7	227.5	31.14	

Table 9

Crop area and animal number can be supplied by harvested rainwater.

Pathways out of poverty	Crop/Animal type	Dry period water demand per unit crop or animal (m^3)	Number of animals or crop area that the NHRW can supply		
			10.7 m^3	31.14 m^3	227.5 m^3
Crop	Potato (area)	0.44	24.3 m^2	70.8 m^2	517 m^2
	Hot pepper (area)	0.41	26.1 m^2	76 m^2	555 m^2
Fattening	Sheep (No.)	1.2	8	26	189
	Beef cattle (No.)	6	1	5	37

Table 10
Benefit–cost analysis of pathways to poverty reduction in the study area (potato and hot pepper irrigation and beef cattle and sheep fattening).

Pathway options	Potato irrigation			Hot Pepper irrigation			Sheep fattening			Beef fattening		
HRW supply (m^3)	10.7	31.1	227 .5	10.7	31.1	227 .5	10.7	31.1	227 .5	10.7	31.1	227.5
Crop area/animal No.	24.3	70.8	517.0	26.1	76.0	555.0	8.0	26.0	189.0	1.0	5.0	37.0
Crop production (kg/ha)	33300	33300	33300	7600	7600	7600						
Ave. crop yield (kg)/animal (No.)	80.9	235.8	1721.6	19.8	57.8	421.8	8.0	26.0	189.0	1.0	5.0	37.0
Average unit price (birr/kg or animal)	10	10	10	20	20	20	1500	1500	1500	15000	15000	15000
Gross return (Birr)	809.2	2357.6	17216.1	396.7	1155.2	8436	12000	39000	283500	15000	75000	555000
Geo membrane cost	4515	4515	4515	4515	4515	4515	4515	4515	4515	4515	4515	4515
Plastic sheet for pond covering	240	240	240	240	240	240	240	240	240	240	240	240
Installation cost	1675	2285	9675	1675	2285	9675	1675	2285	9675	1675	2285	9675
Required seed (kg)/animal (No.)	5.0	14.7	107.3	0.5	1.0	1.5	8.0	26.0	189.0	1.0	5.0	37.0
Seed/animal unit cost	15	15	15	20	20	20	500	500	500	5500	5500	5500
Total seed/animal cost	75	221	1610	10	20	30	4000	13000	94500	5500	27500	203500
Total cost (Birr)	6505	7261	16040	6440	7060	14460	10430	20040	108930	11930	34540	217930
BCR	0.1	0.3	1.1	0.1	0.2	0.6	1.2	1.9	2.6	1.3	2.2	2.5
Net return (Birr)	-	-	1177	-	-	-	1570	18960	174570	3070	40460	337070

6. Conclusion and Recommendation

This paper presents an integrated participatory rural appraisal and participatory field experiment that notes how local ES management can address poverty alleviation in the Debre Mawi catchment of the upper Blue Nile. We identified local barriers to poverty alleviation in three steps. First, we classified the main ES-livelihood interrelationships among communities of the upper Blue Nile. Secondly, we assessed ongoing struggles in these interrelations using combined biophysical and social assessment criteria to evaluate how poverty relates to current patterns of ES management. Our analysis confirms complex interdependencies between livelihoods and regulating (crop pest controls), provisioning (water, land and livestock feed availability, soil fertility) and cultural (local top-down ES management, population growth) ESS that create bottlenecks to effectively 'lock in' poverty by limiting individual and community capacities to diversify traditional farming.

Out of the eight major bottlenecks we identified in the Debre Mawi watershed, dry season water shortage is the primary issue that limits farmers' chances of developing alternative livelihood sources. We have also identified three highly dynamic biophysical processes: gully erosion, drying up of streams, and unpredictable rainfall that lead to pronounced poverty lock-in. On this basis, we identified potential ES management strategies to improve agricultural livelihoods, focused on boosting dry season water availability.

From a range of potential strategies identified using the PRA approach, the most important community-focused solutions are crop diversification using potato and hot pepper irrigation and fattening livestock (sheep and cattle). We have argued that lack of water availability is the main limiting factor for irrigation of vegetables and fattening, which needs to be resolved first. We, therefore, recommend that water harvesting and installation of hand-dug wells for the upper and lower catchments respectively may have a high potential for improving community ES management. In the upper catchment, surface and groundwater access is nil, and soil erosion is severe. Hence, a feasibility analysis of water harvesting should be focusing on the degraded uplands. We have argued here that for such areas, rainfall on the rooftops of houses can be harvested for dry season use. Groundwater accessibility assessment should be feasible in the lower catchments, particularly given upstream soil and water conservation (SWC) measures on groundwater recharge. All these findings were derived from participatory work undertaken with the focal communities.

Poverty alleviation needs to ensure that it focuses on the poorest segment of society. Their experiences and priorities must be taken into account in formulating any livelihood strategy. Therefore, we recommend further research to determine the practicalities of rainfall-runoff harvesting in the uplands and detailed analysis of groundwater potential for hand-dug wells installation. Livestock and crop water requirements also need further study. Furthermore, it should be possible to integrate accessible water resources with productive crop and livestock management. Based on the situation analysis, the main near future research components in our case study should be (1) determination of the volume of rainfall−runoff that can be harvested (2) analysis of the spatial and temporal variation of groundwater and especially locating the volcanic dikes that prevent the lateral flow of groundwater (Alemie et al., 2019) and (3) selecting the best ESS management options. To turn our research into an example of "best practices" and allow replication in the upper Blue Nile basin and other highland worldwide regions, we explore a practical example of using water harvesting using a participatory field experiment. We used 18 households' rooftops where data was collected by farmers. Based on data from 2016, on average, each household can harvest 79.2 m^3 rainwater per year.

Lastly, we compared four rooftop water harvesting supported livelihood scenarios such as potato and hot pepper irrigation, and beef and sheep fattening, using combination of data analysis tools such as CROPWAT and FAO Penman–Monteith. Out of the total mean HRW amount, 48 m^3 supplies the domestic (household) needs, while the remaining 31m^3 can be used for irrigation and/or fattening (for new livelihood improvement strategies). From the tested scenarios, the best option for poverty alleviation is animal fattening using rooftops water harvesting instead of crop irrigation. Based on their rooftop size and household domestic water consumption that reduces and increases respectively amount of harvested water for fattening and/or irrigation, the farmers can obtain a profit of US$136 up to $149 from five months of cattle fattening and US$69 to $77from four months of sheep fattening.

This research aimed to address the recurrent academic debates on how to support agricultural livelihoods and poverty alleviation and to implement participatory methods (particularly on how to include local knowledge in the decision-making process of ES management). Scientific debates have been focused on the ES-livelihood relationships since the 1970s in Ethiopia. But in much past research, the involvement of the farmers was essentially limited. Indigenous knowledge and farmers' competence to solve their problems have usually been underestimated and given less emphasis in the design of land management practices (Bewket, 2007). As a result, some of the introduced technologies are usually ineffective in increasing short-term benefits and are not maintained without further governmental intervention in the study region. Haile et al. (2006) pose that top-down interventions are mostly not technically feasible, ecologically sound, economically viable and socially acceptable for the specific local community. Bewket (2007) suggests that future interventions should carefully pursue a farmer-participatory approach.

Our case study is representative of Ethiopian and African highlands and focuses on the issue of rural focal community livelihoods and ES relationships. The potential of leveraging ES as a means to alleviate poverty is receiving increasing global scientific attention. Hence our findings, especially our social-ecological contextualization based on a bottom-up approach, are replicable to the Ethiopian, African and other international ES supported rural communities.

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