ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Investing in sustainable intensification for smallholders: quantifying large-scale costs and benefits in Uganda

To cite this article: Luigi Piemontese *et al* 2022 *Environ. Res. Lett.* **17** 045010

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

Investing in sustainable intensification for smallholders: quantifying large-scale costs and benefits in Uganda

Luigi Piemontese[1,2,*], Rick Nelson Kamugisha[3,4], Jennie Barron[5], Joy Margaret Biteete Tukahirwa[3], Nicole Harari[6] and Fernando Jaramillo[7]

1 Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden
2 Department of Agriculture, Food, Environment and Forestry (DAGRI), Università degli Studi di Firenze, Firenze, Italy
3 Uganda Landcare Network (ULN), Uganda
4 College of Agriculture and Environmental Sciences (CAES), Department of Extension and Innovation Studies, Makerere University, Kampala, Uganda
5 Department of Soil and Environment, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden
6 Centre for Development and Environment, University of Bern, Switzerland
7 Department of Physical Geography, Stockholm University, Stockholm, Sweden
* Author to whom any correspondence should be addressed.

E-mail: piemonteseluigi@gmail.com

CrossMark

OPEN ACCESS

RECEIVED
8 June 2021

REVISED
4 February 2022

ACCEPTED FOR PUBLICATION
4 March 2022

PUBLISHED
18 March 2022

Keywords: Uganda, agriculture, sustainable intensification, archetype analysis, smallholder farming, sustainability science

Supplementary material for this article is available online

Abstract

In Uganda, upgrading smallholder agriculture is a necessary step to achieve the interlinked sustainable development goals of hunger eradication, poverty reduction and land degradation neutrality. However, targeting the right restoration practices and estimate their cost-benefit at the national scale is difficult given the highly contextual nature of restoration practices and the diversity of small-scale interventions to be adopted. By analysing the context-specific outcomes of 82 successful case studies on different sustainable land and water management (SLWM) in Uganda, we estimated that out-scaling of existing successful practices to 75% of agricultural land would require a one-time investment of US$ 4.4 billion from smallholders. Our results show that, besides the many social and environmental benefit commonly associated to SLWM, a wide outscale of SLWM could generate US$ 4.7 billion every year, once the practices are fully operational. Our context-specific estimates highlight the profitability of investing in smallholder farming to achieve the sustainable development goals in Uganda, with geographical differences coming from specific social-ecological conditions. This study can guide sustainable intensification development by targeting the most suitable SLWM practices and plan for adequate financial support from government, investors and international development aids to smallholder farming.

1. Introduction

Land degradation is a major challenge for achieving the sustainable development goals (SDGs) in Uganda [1]. Unsustainable farming practices, exacerbated by climate change [2], are the main cause of land degradation, which altogether contribute to keep agricultural productivity low [3]. Agriculture is a backbone of the country's economy, accounting for 25% of the gross domestic product (GDP) and providing the livelihood of about 70% of the population, which comprises smallholder farmers [4]. Government of Uganda's modernization plan of agriculture estimated the cost of land degradation at the rate of 4%–12% of GDP per year [5, 6], of which 85% is due to soil erosion reducing agricultural yields (around US$ 600 million per year) [7]. Over 90% of arable land is degraded in the highlands districts of Kabale and Kisoro [7].

In order to reverse the unsustainable rates of land degradation and achieve the SDGs, agriculture sector has to transform from the source of the problem to its solution [8, 9]. Sustainable agricultural intensification through sustainable land and water management (SLWM), if widely adopted, has the potential to mitigate climate change, reverse land degradation and increase food production [8, 10]. SLWM practices such as agroforestry, intercropping and conservation tillage can contribute to CO_2 sequestration, conserving water in the soil and increasing soil fertility and eventually increasing yields and farmers wellbeing [11, 12].

Many technologies and approaches adopted locally have demonstrated that investing in SLWM significantly increases crop yields, although with mixed economical outcomes [13, 14]. The World Overview of Conservation Approaches and Technologies (WOCAT) documented more than 50 cases of implementation of SLWM across Uganda and thousands cases globally [15, 16], finding that the large majority (93%) reported a positive or very positive cost/benefit ratio in the long term [17]. However, despite the documented benefits, the widespread adoption required to reverse land degradation is limited by the establishment costs, which represent an unbearable burden for most farmers [18, 19].

Rough estimates suggest that a large-scale investment plan for US$10 billion to $20 billion per year for 10–15 years is needed for all Africa to support smallholders in the adoption of more sustainable agricultural practices [20]. However, no national cost-benmefit estimates are currently available to inform the extent and convenience of investing in SLWM. In fact, performing a national-scale cost-benefit analysis of smallholder adoption of SLWM is particularly challenging since every practice has a different impact on the environment, effect on crop production and a different cost depending on the local social-ecological conditions [21]. Nonetheless, this information is crucial to unlock the necessary investments to smallholders as donors and investors need to know the costs and benefits of SLWM before considering investing [22].

In this paper, we provide a first national-scale estimate of the costs required to adopt context-specific SLWM practices across Uganda and the potential benefits in terms of income increase generated by the large-scale adoption from smallholders. We use evidence from 82 case studies of implementation of different SLWM practices across Uganda and a mixed qualitative-quantitative approach based on archetype analysis to provide context-specific generalization of local evidence. Archetype analysis is a methodological approach that allows to synthesize knowledge among cases and delineate areas for transferability of outcomes [23, 24]. Archetype analysis has been used to find recurrent solutions between multiple cases [25, 26] and, when applied to spatial data, to identify patterns of social-ecological conditions that allow for context-sensitive transferability of outcomes [27–29].

In the following sections we describe how we identify the common set of SLWM from case studies and how we out-scale this information to the country scale using archetype analysis. Finally, we present our results and discuss how the benefits could exceed the costs, thus informing on the profitability of investing in smallholders to support the widespread adoption of SLWM in Uganda.

2. Data and methods

The case-based data for the analysis are 82 case studies, of which 51 from the WOCAT database and 31 cases collected by the authors during fieldwork. The case studies contain information on the types of SLWM practices implemented in Uganda along with their establishment and maintenance costs, and the crop production increase resulting from the adoption of these practices (see detailed WOCAT case studies description in supplementary material). The 31 complementary cases were collected by *in-situ* interviews in November/December 2019, following WOCAT standards, in the four main Ugandan regions to increase data coverage and resolution (see case studies location in figure 2). The objectives of the case studies are diverse and generally related to multiple goals, such as land restoration, soil erosion control and crop and income increase and diversification. We use this multi-purpose set of practices since our approach is geared towards estimating costs and benefits based on 'real-life' SLWM practices, tailored to their specific goals and boundary conditions.

2.1. Evidence-based bundles of SLWM practices

To out-scale the outcomes of local case studies, we first identify the most suitable set of SLWM practices (bundles). We consider the 12 most adopted SLWM practices: mulching, trenches, terraces, agroforestry, intercropping, vegetation strips, check dams, water harvesting, soil and water conservation, manure, zero grazing and integrated crop-livestock. Since every case study includes more than one practices, we delineate the most recurrent sets of practices by using hierarchical clustering [19, 30] (i.e. grouping the cases that have similar sets of SLWM practices), using the Gower dissimilarity matrix [31] to handle categorical data. We use the NbClust function in *R*, which provides the aggregated results of 30 indices, to select the optimal number of clusters in line with previous works with similar clustering methods [19, 30].

2.2. Spatial social-ecological archetypes

We delineate the spatial social-ecological archetypes (i.e. archetypes from now on) using hierarchical clustering by following the methodology of Rocha *et al* [30]. The archetypes encompass districts with similar social-ecological conditions based on 15 spatial social-ecological indicators, with every district belonging to only one archetype. We selected the same indicators used by Piemontese *et al* [32], as they represent context-specific conditions of agriculture at large scale, enriching it with additional indicators available at national scale, such number of farmers organizations and coverage of agricultural extension services. We also checked for correlation between the 15 indicators, setting a threshold of 0.7 as reference for excluding correlate indicators and found no significant correlation. The 15 indicators are listed with source references in table S3 in supplementary material (available online at stacks.iop.org/ERL/17/045010/mmedia). The final list of indicators comprises annual cumulated precipitation, precipitation seasonality, aridity, soil quality, slope, elevation, agricultural labour, remoteness, farm size, extension services, number of farmers organizations, gender gap, GDP per capita, rural poverty and education.

2.3. National costs and benefits calculation

After identifying both bundles and archetypes, we use equation (1) to calculate both costs and benefit (CB) at the national level. The first step is calculating c_x/c, which is the percentage of case studies belonging to each bundle (x) within every archetype (A). We then use this relative distribution of bundles to out-scale the average costs and crop production increase from the case studies $\overline{\mathrm{CB}_x}$. We calculate CB at the national level as a weighted average of CB in every archetype, using the relative distribution of bundles as weight

$$\mathrm{CB} = \sum_{A=1}^{3}\sum_{x=1}^{n}\frac{c_x}{c}\times\overline{\mathrm{CB}_x}\times 100. \quad (1)$$

For example, if three out of ten total cases in an archetype (c) belong to bundle x, then both CBs of bundle x in that archetype (A) account for 30% of the total average CB of that archetype.

Since the benefits in equation (1) are calculated in terms of national crop production increase (at the district level), increase we estimate the income increase by multiplying the crop production increase by the national average farm-gate prices of the nine main food crops in Uganda: Beans, Banana, Maize, Cassava, Sweet and Irish Potato, Millet, Plantain and Sorghum (see table SX and sections S3 and S4 in supplementary material). Finally, we calculate cumulative values of costs and income increase at the archetype scale by summing up their district-level values within each archetype.

We base our analysis on the assumptions that (a) the outcomes of the reported case studies can be replicated in areas with similar social-ecological conditions defined by the archetype analysis; (b) all the crop production increase is sold in local markets (c) under current average farm-gate prices.

3. Results

3.1. Evidence-based bundles of SLWM in the national context

The cluster analysis of the case studies reveals the emergence of six bundles of SLWM practices in Uganda (figure 1). Four out of six bundles are determined mostly by a single practice (after which we chose to name the whole bundle), while two bundles present a more diverse set of practices.

In the 'Agroforestry' bundle, agroforestry is the most frequent practice, implemented alongside trenches, grass strips and terraces. This bundle is the most complex one, presenting the highest number (9) and diversity of practices. Agroforestry is often implemented with multipurpose trees that provide timber, fodder, nitrogen fixation, shade to crops, cycle nutrients and diversify production, while terraces, trenches and grass strips are cross-slope measures used to reduce soil erosion and increase water retention in the soil. The other complex bundle is Integrated crop-animal production, composed of conservation practices, manure and zero grazing to reduce overgrazing, close the nutrient cycle and restore degraded land. The 'Trenches' bundle comprises the cases where trenches are the main practice, rarely implemented with check dams and conservation while the 'Mulching' bundle contains mainly mulching, but also intercropping and agroforestry as secondary practices. The bundle 'Intercropping' is also mostly implemented as a standalone practice, but sometimes combined with agroforestry and trenches and in the 'Rainwater harvesting' bundle the practice of the name dominates and is marginally accompanied by trenches.

Regarding the archetypes of socio-ecological conditions, the clustering of districts resulted in five archetypes (see supplementary figure S4 for detailed representation of archetypes). The three archetypes hosting case studies—the Northern, the Central and the Highlands, all together cover the 75% of total agricultural land of Uganda (figure 2(b)). The Northern archetype spans from the border with South Sudan to the foot of Mont Elgon in Eastern Uganda. It is the driest part of the country and the one with the poorest soil conditions. Despite having low access to market, this archetype shows higher access to extension services and above average education. The Highlands is the most humid archetype and with relatively good soil quality which includes the districts with highest average slopes and altitude; it is better connected to markets then the Northern archetype, high labour availability, but low access to extension services. The Central archetype covers all districts in central Uganda and expands into the lowland districts of western Uganda, which present relatively humid hydroclimatic conditions and below-average labour availability and education.

With the exception of the bundle 'Trenches' in the Central archetype, all SLWM bundles are adopted within the three archetypes with case studies (figure 2(a)). Trenches are mostly implemented in the Highlands (in blue) together with 'Agroforestry & trenches', because of the high average slope. In the Northern archetype, where cattle keeping is the traditional activity, 'integrated crop-animal production' is the most frequent bundle, followed by 'intercropping' and 'Mulching'. Finally, in the Central archetype all

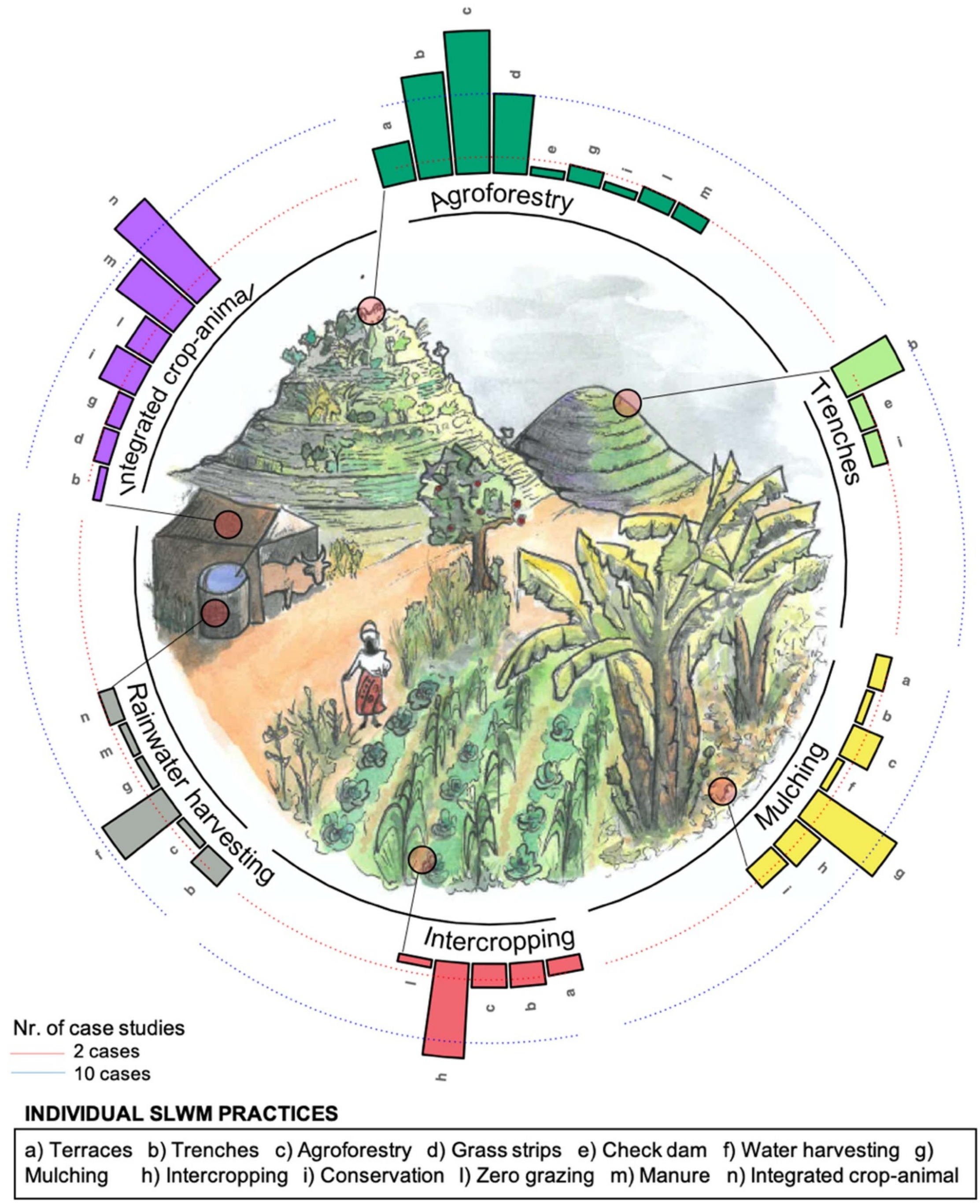

Figure 1. Bundles of SLWM in Uganda constructed from case studies ($n = 82$). The outer bar plot shows the distribution of practices in each bundle (number of case studies on the y axes). The painting in the inner circle is an artistic representation of the bundle of practices in a farming landscape and visualizes the meaning of the bundles within the Ugandan landscape.

SLWM practices seem to have equal relevance apart from trenches, which are only adopted along with agroforestry.

4. Estimating CBs of of scaling SLWM in Uganda

When considering the profitability of SLWM to the national scale, implementation in the Northern archetype shows the highest costs and lowest production increase, while the Highlands shows the highest increase in productivity and low establishment costs (figure 3). However, not all the bundles appear to be cost-effective. For instance, in the Northern archetype, 'Integrated crop-animal production' is the most expensive bundle (three kUSD per hectare of establishment costs) but does not provide the highest production increase. On the other hand, the second and third most implemented bundles—'Mulching' and 'intercropping'—are the ones providing the highest production increase with a relatively low investment (below one kUSD per hectare). In the

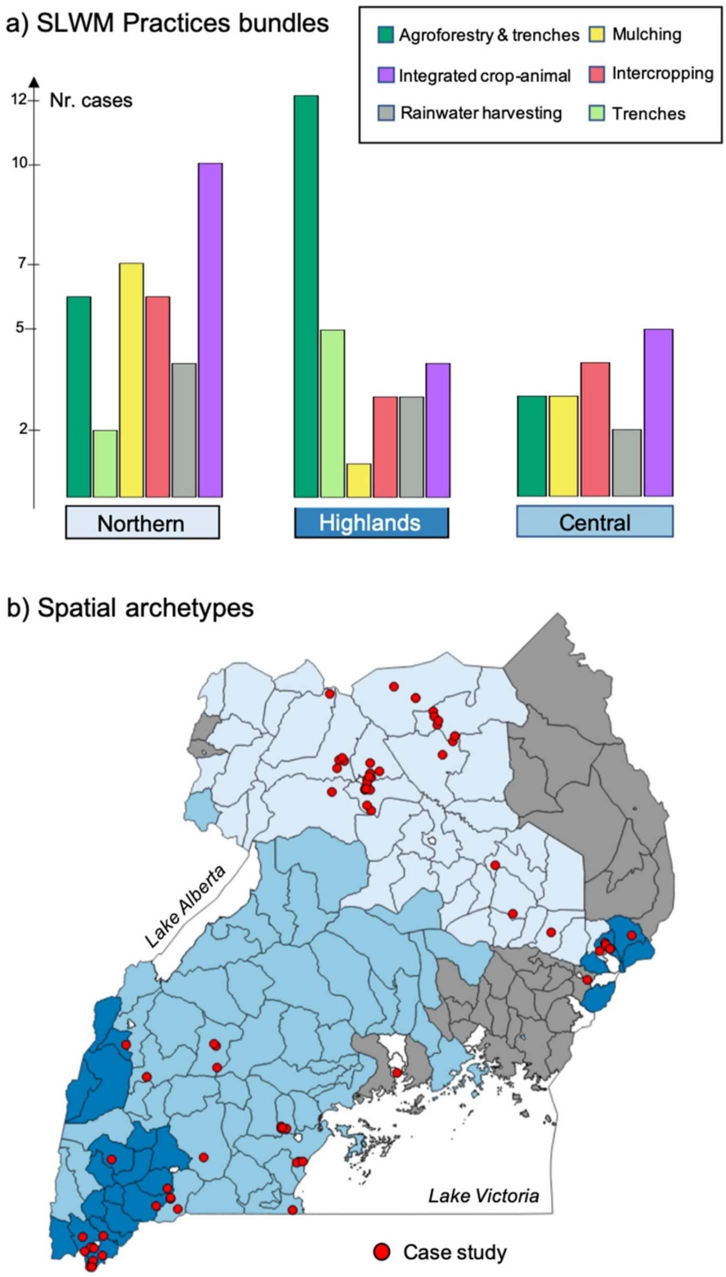

Figure 2. Distribution of (a) SLWM bundles in the three archetypes hosting case studies and (b) districts grouped within the archetypes, including case studies location (red dots). The grey-coloured archetypes do not contain case studies.

Highlands, the most frequent bundles ('Trenches' and 'Agroforestry') are the most profitable, showing a crop production increase of about 6–7 times the production before SLWM at lower costs compared to other bundles (about 400 US$ per hectare).

'Mulching' is the most cost-effective practice in the Central archetype, with average crop production increase of three times the production before SLWM implementation.

To implement these bundles of SLWM practices on every hectare of current agricultural land would cost in total 4.4 billion USD, with the highest share in the Northern archetypes (around 3 billion USD) and the implementation costs are the lowest in in the Highlands (0.2 billion USD). Once fully operational, the implemented SLWM could generate in total an annual income increase of 4.7 billion USD (assuming that the resulting produce would be sold at the market under current prices). For instance, in the Central and Highlands archetypes, the annual income increase would be of 1.5 and 5.5 times the establishment costs respectively (figure 4). Only in the Northern archetype the establishment costs would overrun the income increase (almost double). Maintenance costs are generally low compared to the potential income increase, ranging from 2% in the Highland archetype to the 32% in the Northern archetype.

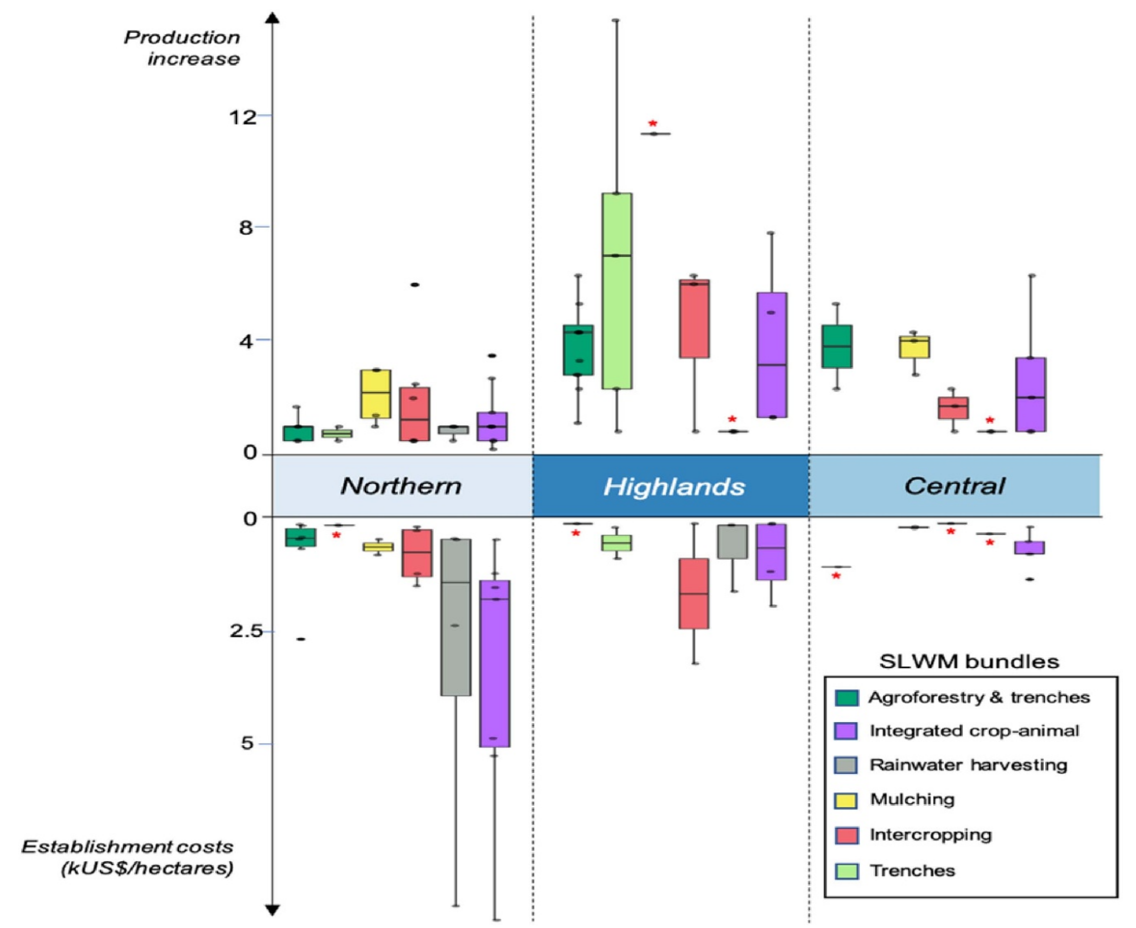

Figure 3. Crop production increase (compared to current production) and establishment costs (in kUS$ per hectare) for the six SLWM bundles in the three archetypes hosting case studies. Red asterisks indicate bundles with only one case or no cases (in which case the average cost among bundle was used).

5. Discussion

Our analysis identifies six sets of practices that are the most commonly adopted in current successful implementations, depicting evidence-based bundles of sustainable farming practices in Uganda. Promoting these practice bundles is more likely to result in higher adoption rates among farmers as they suit the specific social-ecological contexts of the archetypes. In fact, while other assessments aim at maximizing the reveniews [33], here we provide an estimate based on real-life SLWM implementation, which usually have multiple social-ecological goals including improving food security, increasing diversity, increasing water retention and reducing land degradation. This approach differs from the conventional top-down selection and spread of agricultural innovation that often neglect socio-economic conditions, originating from purely biophysical research studies. These types of estimate tend to out-scale one-fits-all solutions which are demonstrated to fail in complex restoration projects, which instead need a better fit with the local social-ecological contexts [34, 35]. For example, a recent soil erosion risk assessment based on biophysical modelling estimated that terraces and strip-cropping are the most effective practices in reducing soil degradation if widely adopted in Uganda [36]. However, in our analysis, terraces appear to be marginally adopted, and mostly in combination with agroforestry and other cross-slope measures in the highlands archetype. The reason for this mismatch is that terraces have the highest potential from a soil erosion-risk reduction perspective, but in real life they are difficult to implement as they are labour intensive, expensive and require frequent maintenance [37]. Instead, farmers might opt for less effective practices that better fit their farming style and needs [38]. This is the case of trenches, which are frequent in the highlands archetypes because easier to implement and embedded in the historical landscape [39]. Hence, trenches and vegetation strips provide a first cost-effective step for farmers, that might eventually encourage further adoption of terraces [40]. On the other hand, one of the surprising hints of this study is that less cost-effective practices might result in higher adoption rates because of their socio-cultural fit. This is the case of integrated crop-animal production in the Northern archetype, where cattle keeping is a traditional activity.

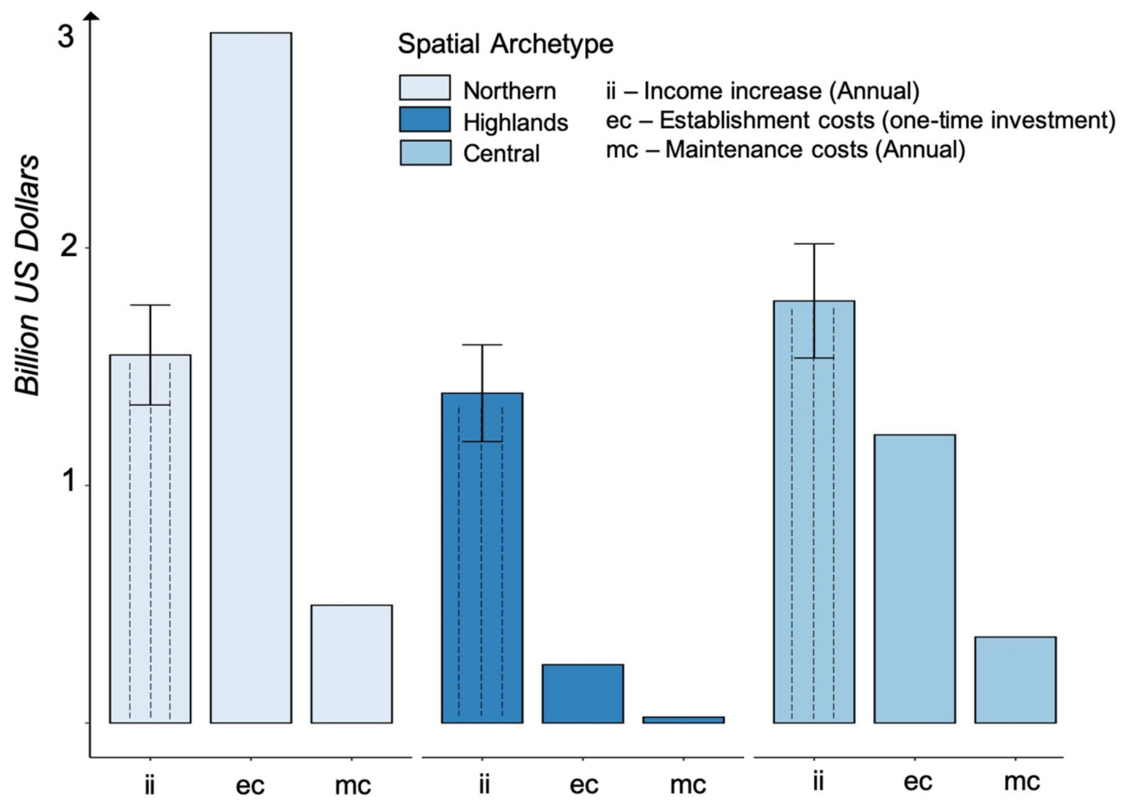

Figure 4. Cost-benefit analysis of out-scaling SLWM in Uganda. Establishment costs as one-time investment and annual maintenance costs as well as annual income increase (dotted bars) of implementation of SLWM in the three archetypes hosting case studies. The annual income increase is calculated for both low-range and high-range farm-gate price to provide a measure of uncertainty.

Apart from describing the social-ecological suitability of SLWM at the sub-national scale, another key insight of our results show that also the investment cost vary depending on the type of practice and the sub-national social-ecological conditions. In view of these results, estimates based on contextual out-scaling, like the one presented in this work, can provide a more reliable basis for nation-wide adoption estimates of SLWM when compared to standardized top-down approaches. Usually, large-scale assessments do not account for local variations in investment costs and local conditions, relying on coarse assumption of uniform investment cost per hectare at the national or even continental scale. For example, large-scale estimates in sub-Saharan Africa (SSA) found a total investment of 1–2 billion US$ for expanding irrigation in Uganda [41], assuming a flat investment cost of 1000 US$ US$ ha^{-1} across SSA countries. Another study [33] found a one-time investment of 4.2 billion US$ with a combination of small and large-scale irrigation schemes, considering an average investment cost of 600–1000 US$ ha^{-1} in every SSA country. The World Bank [42] estimated the cost of widespread adoption in drylands of different SLWM from smallholder farms, small-scale irrigation and large-scale irrigation assuming an average cost per hectare across SSA of $250–$500, $4500 and $12 000 respectively, and using average crop increase estimate. With this premises, they estimated a total required investment of 1.2 billion US$ only in the Ugandan drylands (which is a marginal part of Ugandan agriculture). However, scholars stress how the returns on investment are highly dependent on local conditions [13, 43]. These studies found that investments in water harvesting pay back in 4–5 years on average, but that the actual time to return the investment can vary significantly depending on local social-ecological conditions (e.g. access to market and number of harvests per year), ranging from 2 to 15 years. Our results well compare with these findings, showing a return time on investment ranging roughly from three to five years (considering that most practices need about 2–3 years before being fully operational [17]).

The major contribution of our context-sensitive approach highlights that almost any investment in SLWM can be profitable in most of Uganda, while specific condition need to be set in place for Northern Uganda. In fact, all SLWM practices are cost effective, particularly in the Highlands archetype, except for integrated crop-animal production and rainwater harvesting in the Northern archetype. While, at first glance, this might suggest to direct investments on the highlands, which is one of the most populated areas of Uganda, this should not discourage investments in the Northern archetype. In fact, the general higher costs and lower returns in the Northern archetype can be explained by the particularly fragile post-conflict conditions of this area [19]. National policies could facilitate investment (e.g. with indirect investments in infrastructures or land tenure reforms) to let the Northern archetype out of the poverty trap, which keeps SLWM underadopted and less cost effective.

However, the bottom-up nature of our mixed qualitative-quantitative approach bring some limitations to our assessment. Some costs reported in our case studies seem suspiciously low compared to average costs from literature reported in other assessments (see establishment costs in highlands and central archetypes in figure 3). This might be because some cases do not report the family labour as a cost, which represent a major cost item in SLWM. This mismatch might therefore bring to underestimating the final costs. However, it is worth noticing that the income increase is calculated by considering the nine major crops produced in every district, thus leaving out other potential income increase coming from the increased production of other locally-relevant crops. This conservative assumption might produce underestimated benefits, thus potentially balancing the previous underestimated costs, leading to a more realistic overall cost-benefit estimate.

Furthermore, our analysis is based on a limited number of cases (i.e. 82) not uniformly distributed across the country, because of time and field accessibility constrains. Therefore, we might have overlooked some specific local conditions, eventually affecting the final cost-benefit estimates. This limitation might be addressed by enriching the case database and eventually update the final analysis. However, we do not expect the results to be of different order of magnitude since the CB are fairly comparable with other estimates reported in this section [42]. In fact, although the required total investment is higher than any other previous financial effort documented in Uganda, it is of similar magnitude of investments in SLWM in other East-African countries; for example Ethiopia invested USD 1.2 billion per year over the past ten years [44]. A call for a comprehensive SLWM investment framework that support smallholders with tens of millions of dollars over a 5–10 years period is already in place [45], and although original smallholders funding schemes are being tested in East Africa [46, 47], more are still needed. Governments and local authorities should implement policies that remove disparities between large-scale agricultural companies and smallholder farmers in access to land, access to market and contractual disputes [48], thus removing power asymmetries and favour smallholder-inclusive investments. These policies could likely encourage private investments funds—e.g. in the form of impact investments, philanthropic funding or carbon finance [46]—to support smallholders or farmers organizations with direct investments needed to achieve the major shift towards SLWM agriculture.

6. Conclusions

We analysed the cost-effectiveness of different SLWM documented in 82 case studies across Uganda and used archetype analysis to out-scale context-specific practices in three archetype covering 75% of Uganda's agricultural land. Overall, the potential long-term benefits largely exceed the implementation costs of SLWM. Besides the environmental and personal barriers to the adoption of SLWM, smallholders need substantial financial support to start off SLWM interventions. However, we show that the amount of funding needed to incentivize SLWM is lower than the one required for large-scale irrigation and other conventional agricultural development strategies, that might result in higher environmental impact and lower social benefit for local communities. The income increase generated with SLWM, especially in the Central archetype and highlands of Uganda, would pay off the investment in less than one year once fully operative, resulting even more beneficial in the long run, with maintenance costs being one fifth of the annual increased income. The added value of the presented analysis is the evidence-based assessment, which considers geographically varying, real-life CBs, thus providing a more contextual and realistic estimate to guide transformative policies. These results should enhance awareness of decision makers and private investors on the urgency and profitability of investing in smallholders SLWM interventions, beyond the highly valuable social and environmental benefits of such farming practices.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This research was funded by the Swedish Research Council (VR, Project 2015-06503) and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning FORMAS (942-2015-740). We thank the WOCAT for making the case studies available. Finally, we thank the Uganda Landcare Network for helping during the fieldwork in Uganda.

ORCID iDs

Luigi Piemontese https://orcid.org/0000-0002-1600-5450
Jennie Barron https://orcid.org/0000-0002-3292-3438
Fernando Jaramillo https://orcid.org/0000-0002-6769-0136

References

[1] Research Institute (IFPRI) 2008 *Linkages between Land Management, Land Degradation, and Poverty in Sub-Saharan Africa the Case of Uganda* (Washington DC: International Food Policy Research Institute) (https://doi.org/10.2499/9780896291683RR159)
[2] Piemontese L, Fetzer I, Rockström J and Jaramillo F 2019 Future hydroclimatic impacts on Africa: beyond the Paris agreement *Earths Future* **7** 748–61
[3] Barbier E B and Hochard J P 2018 Land degradation and poverty *Nat. Sustain.* **1** 623–31
[4] UN Environment 2017 State of the environment report—Uganda (UNEP—UN Environment Programme) (available at: www.unenvironment.org/resources/annual-report/state-environment-report-uganda)
[5] Mugyenyi O, Kaggwa R, Kisaame K E and Solomon S 2011 Marginalization of environment and natural resources sub-sector 26
[6] Ministry of Foreign Affairs 2006 Uganda's plan for the modernisation of agriculture (available at: www.netpublikationer.dk/um/6207/html/chapter02.htm)
[7] Olson J and Berry L 2003 Land degradation in Uganda: its extent and impact
[8] Abraham M and Pingali P 2020 Transforming Smallholder Agriculture to Achieve the SDGs *The Role of Smallholder Farms in Food and Nutrition Security* (Berlin: Springer) p 41
[9] Rockström J *et al* 2017 Sustainable intensification of agriculture for human prosperity and global sustainability *Ambio* **46** 4–17
[10] Dougill A and Stringer L 2017 19th EGU General Assembly (EGU2017) Vienna, Austria 23–28 April 2017 *Challenges for Sustainable Land Management through Climate-Smart Agriculture* vol 19 p 12638
[11] FAO 2013 *Climate-smart Agriculture Sourcebook* (Rome: FAO)
[12] FAO 2017 *B7-3 Sustainable Soil and Land Management for CSA in Practice | Climate Smart Agriculture Sourcebook* (Rome: Food and Agriculture Organization of the United Nations)
[13] Bouma J A, Hegde S S and Lasage R 2016 Assessing the returns to water harvesting: a meta-analysis *Agric. Water Manage.* **163** 100–9
[14] Banadda N 2011 Gaps, barriers and bottlenecks to sustainable land management (SLM) adoption in Uganda *Afr. J. Agric. Res. Spec. Rev.* **525** 3571–80
[15] Liniger H and Schwilch G 2002 Enhanced decision-making based on local knowledge *Mt. Res. Dev.* **22** 14–18
[16] Schwilch G, Bachmann F and de Graaff J 2012 Decision support for selecting SLM technologies with stakeholders *Appl. Geogr.* **34** 86–98
[17] Giger M, Liniger H, Sauter C and Schwilch G 2018 Economic benefits and costs of sustainable land management technologies: an analysis of WOCAT's global data *Land Degrad. Dev.* **29** 962–74
[18] Shiferaw B and Holden S T 2000 Policy instruments for sustainable land management: the case of highland smallholders in ethiopia *Agric. Econ.* **22** 217–32
[19] Piemontese L *et al* 2021 Barriers to scaling sustainable land and water management in Uganda: a cross-scale archetype approach *Ecol. Soc.* **26** 6
[20] Rockström J and Falkenmark M 2015 Agriculture: increase water harvesting in Africa *Nat. News* **519** 283
[21] McElwee P *et al* 2020 The impact of interventions in the global land and agri-food sectors on nature's contributions to people and the UN sustainable development goals *Glob. Change Biol.* 26 4691–721
[22] FAO 2016 *Informing Future Interventions for Scaling-up Sustainable Land Management* (Rome: Food and Agriculture Organization of the United Nations (FAO)) pp 40
[23] Oberlack C *et al* 2019 Archetype analysis in sustainability research: meanings, motivations, and evidence-based policy making *Ecol. Soc.* **24** 26
[24] Sietz D *et al* 2019 Archetype analysis in sustainability research: methodological portfolio and analytical frontiers *Ecol. Soc.* **24** 34
[25] Oberlack C, Tejada L, Messerli P, Rist S and Giger M 2016 Sustainable livelihoods in the global land rush? Archetypes of livelihood vulnerability and sustainability potentials *Glob. Environ. Change* **41** 153–71
[26] Neudert R, Salzer A, Allahverdiyeva N, Etzold J and Beckmann V 2019 Archetypes of common village pasture problems in the South Caucasus: insights from comparative case studies in Georgia and Azerbaijan *Ecol. Soc.* **24** 5
[27] Václavík T *et al* 2016 Investigating potential transferability of place-based research in land system science *Environ. Res. Lett.* **11** 095002
[28] Rocha J, Malmborg K, Gordon L, Brauman K and DeClerk F 2018 Mapping social ecological systems archetypes *bioRxiv* 299693
[29] Václavík T, Lautenbach S, Kuemmerle T and Seppelt R 2013 Mapping global land system archetypes *Glob. Environ. Change* **23** 1637–47
[30] Rocha J, Malmborg K, Gordon L, Brauman K and DeClerck F 2020 Mapping social-ecological systems archetypes *Environ. Res. Lett.* **15** 034017
[31] Gower J C and General A 1971 Coefficient of similarity and some of its properties *Biometrics* **27** 857–71
[32] Piemontese L *et al* 2020 Estimating the global potential of water harvesting from successful case studies *Glob. Environ. Change* **63** 102121
[33] You L *et al* 2011 What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach *Food Policy* **36** 770–82
[34] Mahajan S L *et al* 2019 Systems thinking for planning and evaluating conservation interventions *Conserv. Sci. Pract.* **1** e44
[35] Turschwell M P *et al* 2020 Multi-scale estimation of the effects of pressures and drivers on mangrove forest loss globally *Biol. Conserv.* **247** 108637
[36] Karamage F, Zhang C, Liu T, Maganda A and Isabwe A 2017 Soil erosion risk assessment in Uganda *Forests* **8** 52
[37] Amsalu A and de Graaff J 2007 Determinants of adoption and continued use of stone terraces for soil and water conservation in an Ethiopian highland watershed *Ecol. Econ.* **61** 294–302
[38] Vanclay F and Lawrence G 1994 Farmer rationality and the adoption of environmentally sound practices; A critique of the assumptions of traditional agricultural extension *Eur. J. Agric. Educ. Ext.* **1** 59–90
[39] Kassie M, Shiferaw B and Muricho G 2011 Agricultural technology, crop income, and poverty alleviation in Uganda *World Dev.* **39** 1784–95
[40] Miiro R and Tibezinda J 1998 Factors that affect the sustainability of terraces in Kabale district *MUARIK Bull.* **1** 51–56
[41] You L Z 2008 *Irrigation Investment Needs in Sub-Saharan Africa* (Washington DC: World Bank)
[42] Christopher Ward 2016 *Improved Agricultural Water Management for Africa's Drylands* (Washington DC: The World Bank) (https://doi.org/10.1596/978-1-4648-0832-6)
[43] Ngigi S N, Savenije H H G, Rockström J and Gachene C K 2005 Hydro-economic evaluation of rainwater harvesting

and management technologies: farmers' investment options and risks in semi-arid Laikipia district of Kenya *Phys. Chem. Earth* ABC **30** 772–82

[44] Adimassu Z, Langan S and Barron J 2018 *Highlights of Soil and Water Conservation Investments in Four Regions of Ethiopia* (Colombo: International Water Management Institute (IWMI)) (https://doi.org/10.5337/2018.214)

[45] FAO 2009 Country support tool for scaling-up sustainable land management in sub-Saharan Africa

[46] Fränkl L, Madden K and Silber T2019 Mapping financial mechanisms for enhanced rainfed agriculture in Africa Stockholm International Water Institute (SIWI)

[47] Van Leeuwen J and Feinberg M 2018 Impact investing in Africa: a case study on East Africa (available at: www.wilsoncenter.org/publication/impact-investing-africa-case-study-east-africa)

[48] West J J and Haug R 2017 The vulnerability and resilience of smallholder-inclusive agricultural investments in Tanzania *J. East. Afr. Stud.* **11** 670–91