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

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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 SDGs 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.

Introduction

Land degradation is a major challenge for achieving the Sustainable Development Goals (SDGs) in Uganda¹. Unsustainable farming practices, exacerbated by climate change², are the main cause of land degradation, which altogether contribute to keep agricultural productivity low³. Agriculture is a backbone of the country's economy, accounting for 25% of GDP and providing the livelihood of about 70% of the population, which comprises smallholder farmers⁴. 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

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3 reducing agricultural yields (around US\$ 600 million per year)⁷. Over 90% of arable land is
4 degraded in the highlands districts of Kabale and Kisoro⁷.
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6 In order to reverse the unsustainable rates of land degradation and achieve the SDGs,
7 agriculture sector has to transform from the source of the problem to its solution^{8,9}.
8 Sustainable agricultural intensification through SLWM, if widely adopted, has the potential
9 to mitigate climate change, reverse land degradation and increase food production^{8,10}. SLWM
10 practices such as agroforestry, intercropping and conservation tillage can contribute to CO₂
11 sequestration, conserving water in the soil and increasing soil fertility and eventually
12 increasing yields and farmers wellbeing^{11,12}.
13

14 Many technologies and approaches adopted locally have demonstrated that investing in
15 SLWM significantly increases crop yields, although with mixed economical outcomes^{13,14}.
16 The World Overview of Conservation Approaches and Technologies (WOCAT) documented
17 more than 50 cases of implementation of SLWM across Uganda and thousands cases
18 globally^{15,16}, finding that the large majority (93%) reported a positive or very positive
19 cost/benefit ratio in the long term¹⁷. However, despite the documented benefits, the
20 widespread adoption required to reverse land degradation is limited by the establishment
21 costs, which represent an unbearable burden for most farmers^{18,19}.
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24 Rough estimates suggest that a large-scale investment plan for US\$10 billion to \$20 billion
25 per year for 10–15 years is needed for all Africa to support smallholders in the adoption of
26 more sustainable agricultural practices²⁰. However, no national cost-benefit estimates are
27 currently available to inform the extent and convenience of investing in SLWM. In fact,
28 performing a national-scale cost-benefit analysis of smallholder adoption of SLWM is
29 particularly challenging since every practice has a different impact on the environment, effect
30 on crop production and a different cost depending on the local social-ecological conditions²¹.
31 Nonetheless, this information is crucial to unlock the necessary investments to smallholders as
32 donors and investors need to know the costs and benefits of SLWM before considering
33 investing²².
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36 In this paper, we provide a first national-scale estimate of the costs required to adopt context-
37 specific SLWM practices across Uganda and the potential benefits in terms of income
38 increase generated by the large-scale adoption from smallholders. We use evidence from 82
39 case studies of implementation of different SLWM practices across Uganda and a mixed
40 qualitative-quantitative approach based on archetype analysis to provide context-specific
41 generalization of local evidence. Archetype analysis is a methodological approach that allows
42 to synthesize knowledge among cases and delineate areas for transferability of outcomes^{23,24}.
43 Archetype analysis has been used to find recurrent solutions between multiple cases^{25,26} and,
44 when applied to spatial data, to identify patterns of social-ecological conditions that allow for
45 context-sensitive transferability of outcomes^{27–29}.
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47

48 In the following sections we describe how we identify the common set of SLWM from case
49 studies and how we out-scale this information to the country scale using archetype analysis.
50 Finally, we present our results and discuss how the benefits could exceed the costs, thus
51 informing on the profitability of investing in smallholders to support the widespread adoption
52 of SLWM in Uganda.
53

54 55 **Data and Methods**

56
57 The case-based data for the analysis are 82 case studies, of which 51 from the WOCAT database
58 and 31 cases collected by the authors during fieldwork. The case studies contain information
59 on the types of SLWM practices implemented in Uganda along with their establishment and
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3 maintenance costs, and the crop production increase resulting from the adoption of these
4 practices (see detailed WOCAT case studies description in supplementary material). The 31
5 complementary cases were collected by in-situ interviews in November/December 2019,
6 following WOCAT standards, in the four main Ugandan regions to increase data coverage and
7 resolution (see case studies location in Figure 2). The objectives of the case studies are diverse
8 and generally related to multiple goals, such as land restoration, soil erosion control and crop
9 and income increase and diversification. We use this multi-purpose set of practices since our
10 approach is geared towards estimating costs and benefits based on “real-life” SLWM practices,
11 tailored to their specific goals and boundary conditions.
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14 ***Evidence-based bundles of SLWM practices***

15 To out-scale the outcomes of local case studies, we first identify the most suitable set of SLWM
16 practices (bundles). We consider the 12 most adopted SLWM practices: mulching, trenches,
17 terraces, agroforestry, intercropping, vegetation strips, check dams, water harvesting, soil and
18 water conservation (SWC), manure, zero grazing and integrated crop-livestock. Since every
19 case study includes more than one practices, we delineate the most recurrent sets of practices
20 by using hierarchical clustering^{19,30} (i.e. grouping the cases that have similar sets of SLWM
21 practices), using the Gower dissimilarity matrix³¹ to handle categorical data. We use the
22 NbClust function in R, which provides the aggregated results of 30 indices, to select the optimal
23 number of clusters in line with previous works with similar clustering methods^{19,30}.
24
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26 ***Spatial social-ecological archetypes***

27 We delineate the spatial social-ecological archetypes (i.e. archetypes from now on) using
28 hierarchical clustering by following the methodology of Rocha et al, 2020³⁰. The archetypes
29 encompass districts with similar social-ecological conditions based on 15 spatial social-
30 ecological indicators, with every district belonging to only one archetype. We selected the same
31 indicators used by Piemontese et al, 2020³², as they represent context-specific conditions of
32 agriculture at large scale, enriching it with additional indicators available at national scale, such
33 number of farmers organizations and coverage of agricultural extension services. We also
34 checked for correlation between the 15 indicators, setting a threshold of 0.7 as reference for
35 excluding correlate indicators and found no significant correlation. The 15 indicators are listed
36 with source references in table S3 in supplementary material. The final list of indicators
37 comprises annual cumulated precipitation, precipitation seasonality, aridity, soil quality, slope,
38 elevation, agricultural labour, remoteness, farm size, extension services, number of farmers
39 organizations, gender gap, GDP per capita, rural poverty and education.
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44 ***National costs and benefits calculation***

45 After identifying both bundles and archetypes, we use Equation 1 to calculate both costs and
46 benefit (CB) at the national level. The first step is calculating c_x/c , which is the percentage of
47 case studies belonging to each bundle (x) within every archetype (A). We then use this relative
48 distribution of bundles to out-scale the average costs and crop production increase from the
49 case studies \overline{CB}_x . We calculate CB at the national level as a weighted average of CB in every
50 archetype, using the relative distribution of bundles as weight.
51
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53 Equation 1
$$CB = \sum_{A=1}^3 \sum_{x=1}^n \frac{c_x}{c} * \overline{CB}_x * 100$$

54 For example, if 3 out of 10 total cases in an archetype (c) belong to bundle x, then both costs
55 and benefits of bundle x in that archetype (A) account for 30% of the total average costs and
56 benefit of that archetype.
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3 Since the benefits in Equation 1 are calculated in terms of national crop production increase (at
4 the district level), increase we estimate the income increase by multiplying the crop production
5 increase by the national average farm-gate prices of the nine main food crops in Uganda: Beans,
6 Banana, Maize, Cassava, Sweet and Irish Potato, Millet, Plantain and Sorghum ((see Table SX
7 and section S3 and S4 in supplementary material). Finally, we calculate cumulative values of
8 costs and income increase at the archetype scale by summing up their district-level values
9 within each archetype.
10

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

19 **Evidence-based bundles of SLWM in the national context**

20 The cluster analysis of the case studies reveals the emergence of six bundles of SLWM practices
21 in Uganda (Figure 1). Four out of six bundles are determined mostly by a single practice (after
22 which we chose to name the whole bundle), while two bundles present a more diverse set of
23 practices.
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27 In the “Agroforestry” bundle, agroforestry is the most frequent practice, implemented alongside
28 trenches, grass strips and terraces. This bundle is the most complex one, presenting the highest
29 number (9) and diversity of practices. Agroforestry is often implemented with multipurpose
30 trees that provide timber, fodder, nitrogen fixation, shade to crops, cycle nutrients and diversify
31 production, while terraces, trenches and grass strips are cross-slope measures used to reduce
32 soil erosion and increase water retention in the soil. The other complex bundle is Integrated
33 crop-animal production, composed of conservation practices, manure and zero grazing to
34 reduce overgrazing, close the nutrient cycle and restore degraded land. The “Trenches” bundle
35 comprises the cases where trenches are the main practice, rarely implemented with check dams
36 and conservation while the “Mulching” bundle contains mainly mulching, but also
37 intercropping and agroforestry as secondary practices. The bundle “Intercropping” is also
38 mostly implemented as a standalone practice, but sometimes combined with agroforestry and
39 trenches and in the “Rainwater harvesting” bundle the practice of the name dominates and is
40 marginally accompanied by trenches.
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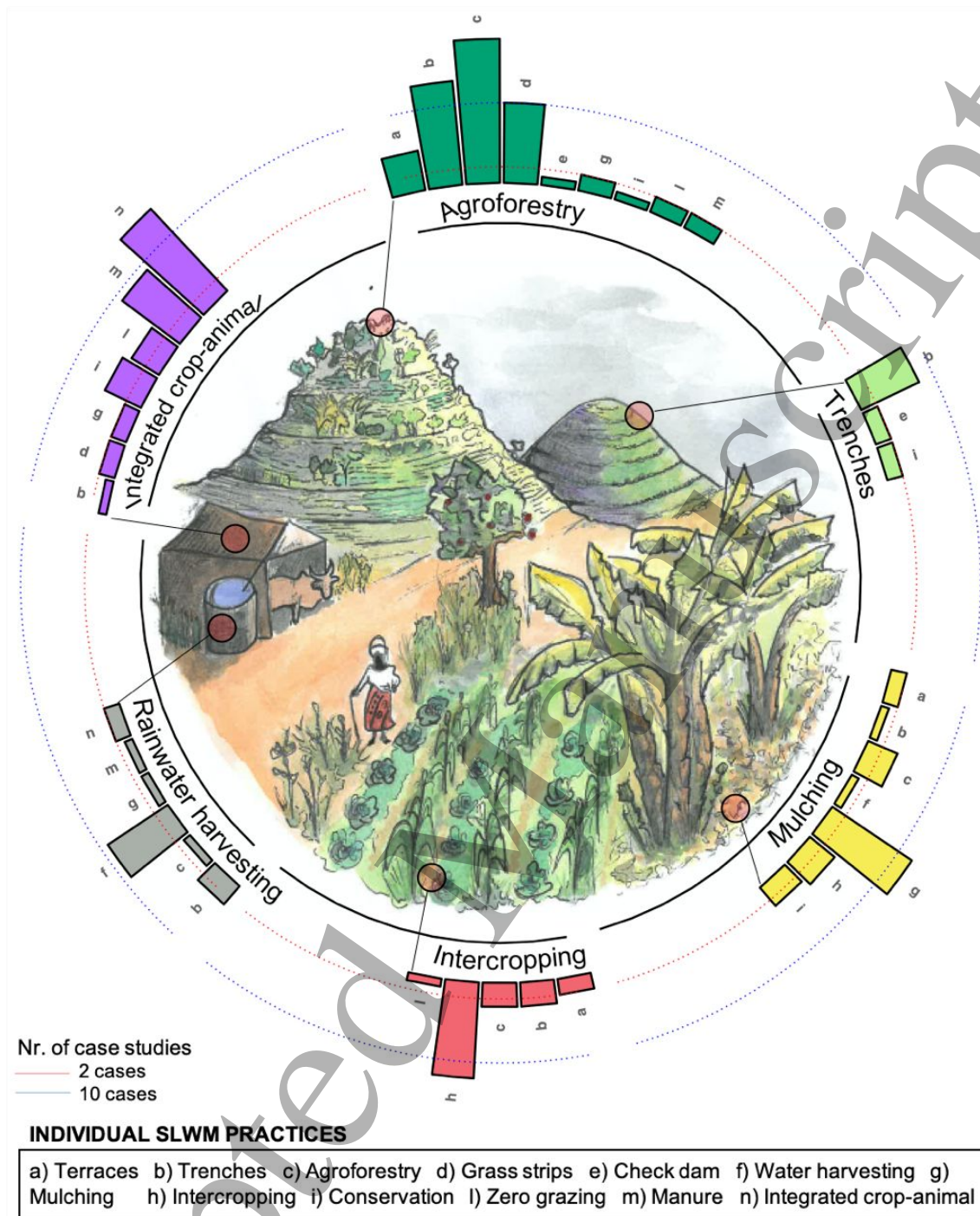
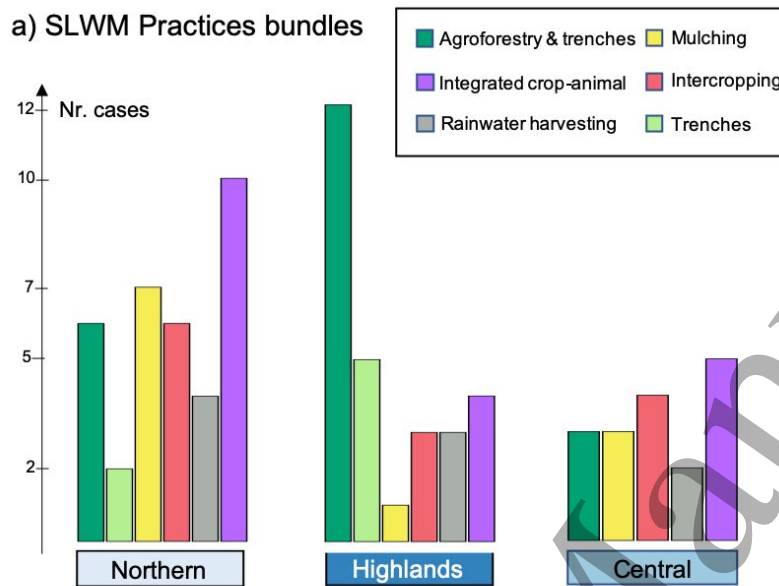


Figure 1: Bundles of SLWM in Uganda constructed from case studies (n=82). The outer bar plot shows the distribution of practices in each bundle (number of case studies on the y axes). The painting in the inner circle is an artistic representation of the bundle of practices in a farming landscape and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

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 2b). 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 than 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.



b) Spatial archetypes

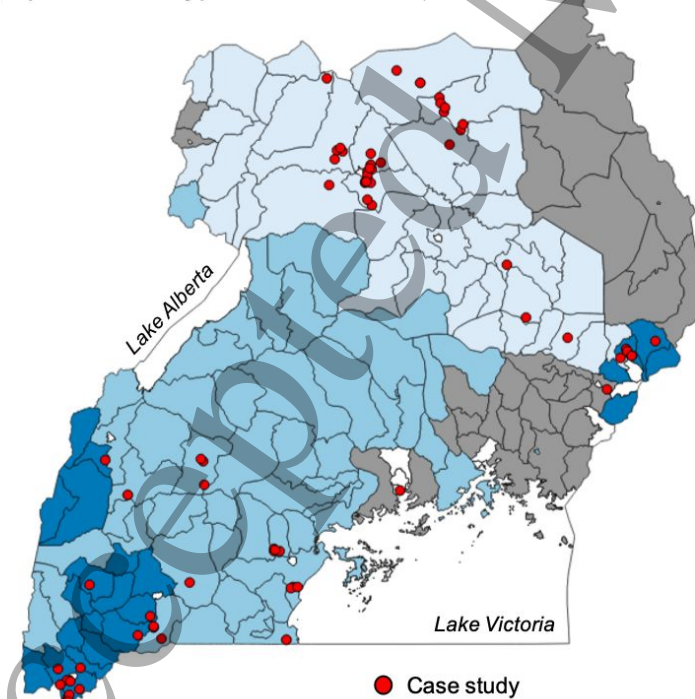


Figure 2: Distribution of (a) SLWM bundles in the three archetypes hosting case studies and (b) districts grouped within the archetypes, including case studies location (red dots). The grey-coloured archetypes do not contain case studies.

With the exception of the bundle “Trenches” in the Central archetype, all SLWM bundles are adopted within the three archetypes with case studies (Figure 2a). 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 SLWM practices seem to have equal relevance apart from trenches, which are only adopted along with agroforestry.

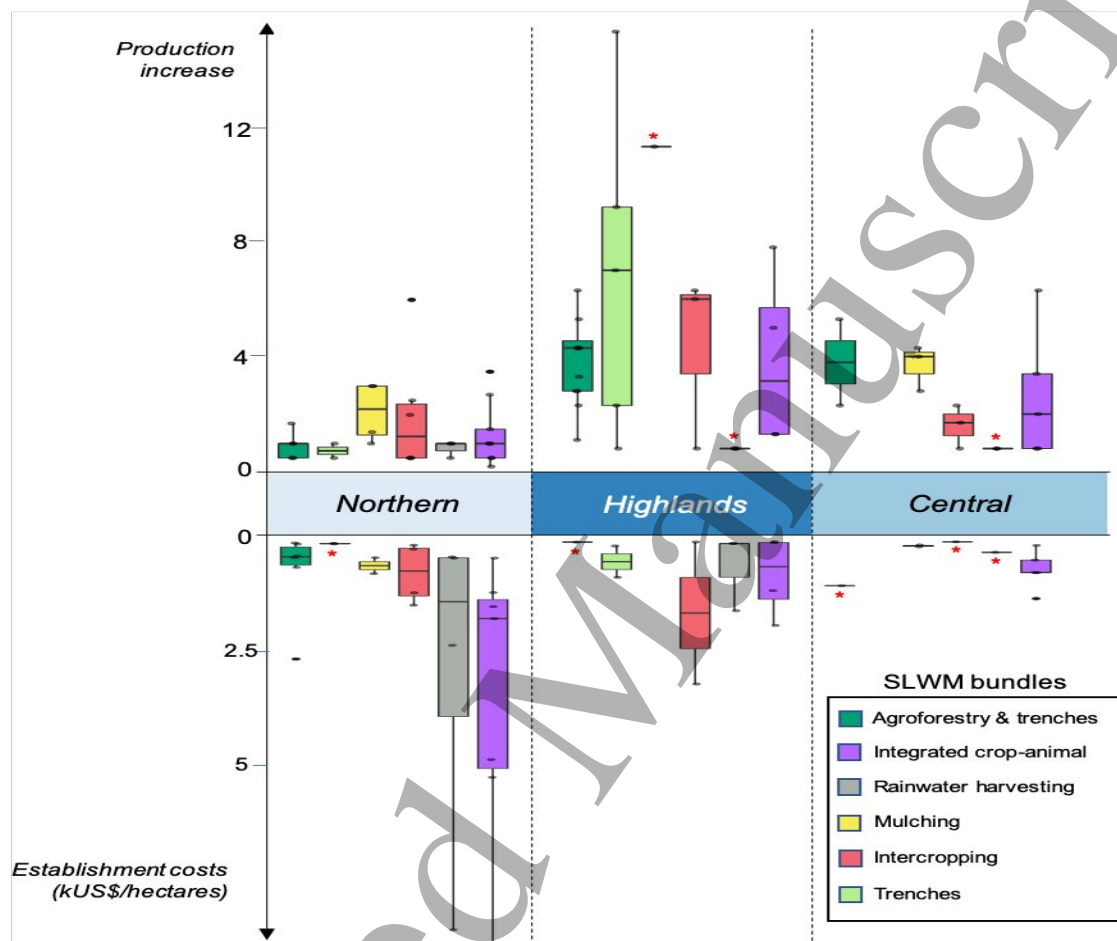


Figure 3: Crop production increase (compared to current production) and establishment costs (in kUSD per hectare) for the six SLWM bundles in the three archetypes hosting case studies. Red asterisks indicate bundles with only one case or no cases (in which case the average cost among bundle was used).

Estimating costs and benefits 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 (Fig3). 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 (3 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 1 kUSD per hectare). In the 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.

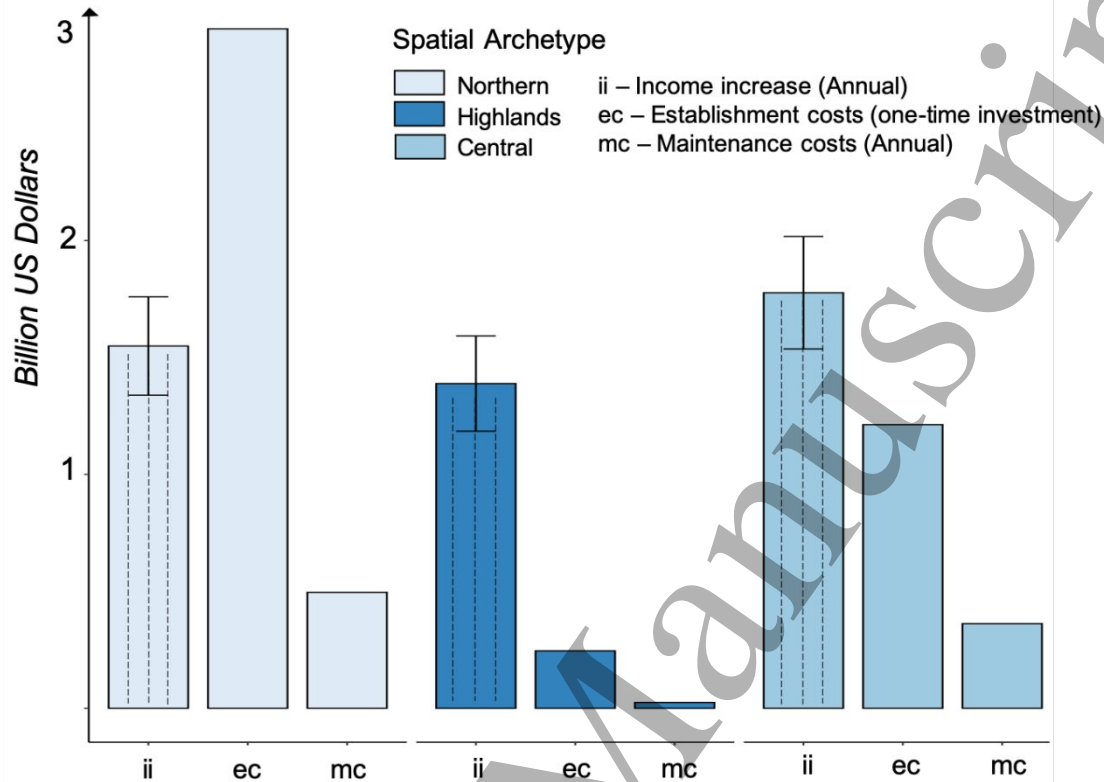


Fig4: Cost-benefit analysis of out-scaling SLWM in Uganda. Establishment costs as one-time investment and annual maintenance costs as well as annual income increase (dotted bars) of implementation of SLWM in the three archetypes hosting case studies. The annual income increase is calculated for both low-range and high-range farm-gate price to provide a measure of uncertainty.

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 (Fig4). 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.

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 revenues³³, 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 Uganda³⁶. 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 maintenance³⁷. Instead, farmers might opt for less effective practices that better fit their farming style and needs³⁸. This is the case of trenches, which are frequent in the highlands archetypes because easier to implement and embedded in the historical landscape³⁹. Hence, trenches and vegetation strips provide a first cost-effective step for farmers, that might eventually encourage further adoption of terraces⁴⁰. 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.

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 to 2 billion US\$ for expanding irrigation in Uganda⁴¹, assuming a flat investment cost of 1,000 US\$ US\$/ha across SSA countries. Another study³³ 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 in every SSA country. The World Bank⁴² 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, \$4,500 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 to 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,

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3 showing a return time on investment ranging roughly from 3 to 5 years (considering that most
4 practices need about 2-3 years before being fully operational¹⁷).
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6 The major contribution of our context-sensitive approach highlights that almost any investment
7 in SLWM can be profitable in most of Uganda, while specific condition need to be set in
8 place for Northern Uganda. In fact, all SLWM practices are cost effective, particularly in the
9 Highlands archetype, except for integrated crop-animal production and rainwater harvesting
10 in the Northern archetype. While, at first glance, this might suggest to direct investments on
11 the highlands, which is one of the most populated areas of Uganda, this should not discourage
12 investments in the Northern archetype. In fact, the general higher costs and lower returns in
13 the Northern archetype can be explained by the particularly fragile post-conflict conditions
14 of this area¹⁹. National policies could facilitate investment (e.g. with indirect investmsts in
15 infrastructures or land tenure reforms) to let the Northern archetype out of the poverty trap,
16 which keeps SLWM underadopted and less cost effective.
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19 However, the bottom-up nature of our mixed qualitative-quantitative approach bring some
20 limitations to our assessment. Some costs reported in our case studies seem suspiciously low
21 compared to average costs from literature reported in other assessments (see establishment
22 costs in highlands and central archetypes in Figure 3). This might be because some cases do
23 not report the family labour as a cost, which represent a major cost item in SLWM. This
24 mismatch might therefore bring to underestimating the final costs. However, it's worth
25 noticing that the income increase is calculated by considering the nine major crops produced
26 in every district, thus leaving out other potential income increase coming from the increased
27 production of other locally-relevant crops. This conservative assumption might produce
28 underestimated benefits, thus potentially balancing the previous underestimated costs,
29 leading to a more realistic overall cost-benefit estimate.
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32 Furthermore, our analysis is based on a limited number of cases (i.e. 82) not uniformly
33 distributed across the country, because of time and field accessibility constrains. Therefore,
34 we might have overlooked some specific local conditions, eventually affecting the final cost-
35 benefit estimates. This limitation might be addressed by enriching the case database and
36 eventually update the final analysis. However, we do not expect the results to be of different
37 order of magnitude since the costs and benefit are fairly comparable with other estimates
38 reported in this section⁴². In fact, although the required total investment is higher than any
39 other previous financial effort documented in Uganda, it is of similar magnitude of
40 investments in SLWM in other East-African countries; for example Ethiopia invested USD
41 1.2 billion per year over the past 10 years⁴⁴. A call for a comprehensive SLWM investment
42 framework that support smallholders with tens of millions of dollars over a 5–10 years period
43 is already in place⁴⁵, and although original smallholders funding schemes are being tested in
44 East Africa^{46,47}, more are still needed. Governments and local authorities should implement
45 policies that remove disparities between large-scale agricultural companies and smallholder
46 farmers in access to land, access to market and contractual disputes⁴⁸, thus removing power
47 asymmetries and favour smallholder-inclusive investments. These policies could likely
48 encourage private investments funds – e.g. in the form of impact investments, philanthropic
49 funding or carbon finance⁴⁶ – to support smallholders or farmers organizations with direct
50 investments needed to achieve the major shift towards SLWM agriculture.
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54 **Conclusions**

55 We analysed the cost-effectiveness of different SLWM documented in 82 case studies across
56 Uganda and used archetype analysis to out-scale context-specific practices in 3 archetype
57 covering 75% of Uganda's agricultural land. Overall, the potential long-term benefits largely
58 exceed the implementation costs of SLWM. Besides the environmental and personal barriers to
59 the adoption of SLWM, smallholders need substantial financial support to start off SLWM
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3 interventions. However, we show that the amount of funding needed to incentivize SLWM is
4 lower than the one required for large-scale irrigation and other conventional agricultural
5 development strategies, that might result in higher environmental impact and lower social
6 benefit for local communities. The income increase generated with SLWM, especially in the
7 Central archetype and highlands of Uganda, would pay off the investment in less than one year
8 once fully operative, resulting even more beneficial in the long run, with maintenance costs
9 being one fifth of the annual increased income. The added value of the presented analysis is the
10 evidence-based assessment, which considers geographically varying, real-life costs and
11 benefits, thus providing a more contextual and realistic estimate to guide transformative
12 policies. These results should enhance awareness of decision makers and private investors on
13 the urgency and profitability of investing in smallholders SLWM interventions, beyond the
14 highly valuable social and environmental benefits of such farming practices.
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