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Luigi Piemontese Sustainable Land and Water Management for a Greener Future

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Large-scale insights in support of Agroecological Intensification

Luigi Piemontese

Doctoral Thesis in Sustainability Science at Stockholm University, Sweden 2020

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Academic dissertation for the Degree of Doctor of Philosophy in Sustainability Science at Stockholm University to be publicly defended on Friday 20 November 2020 at 13.00 in rum 306, hus 2 B, Roslagsvägen 101, Kräftriket.

Abstract

The challenge of producing more food in times of climate change, degraded land and scares water resources is calling for a radical transformation of agriculture. Sustainable agricultural intensification is the process of increasing the productivity of farms while preserving functional ecosystems. A range of sustainable land and water management (SLWM) practices and approaches to sustainable intensification have been successfully implemented at the local scale during the last decades, but adoption rate remains low due to a variety of barriers and lack of effective approaches from authorities at larger scales (national to global). Despite the wealth of local successes, promoting and realizing the widespread uptake of SLWM requires large scale understanding of the potential and challenges of adoption of SLWM, which is currently lacking. This thesis bridges outcomes of successful implementation of SLWM from local cases to large scale social-ecological patterns, showing where and what is the potential of SLWM to contribute to sustainable agricultural intensification and the barriers to achieve it. The methodological approach and the results presented in this thesis aim at providing insights to improve current assessments of sustainable intensification of agriculture and practical guidance to planning, policy making and funding interventions to promote the widespread adoption of SLWM.

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“Though the problems of
the world are
increasingly complex,
the solutions remain
embarrassingly simple.”
– Bill Mollison (1978)

"Conservation is a state
of harmony between
[wo]man and the land."
– Aldo Leopold (1935)

Abstract

The challenge of producing more food in times of climate change, degraded land and scarce water resources calls for a radical transformation of agriculture. Sustainable agricultural intensification is the process of increasing the productivity of farms while preserving functional ecosystems. During recent decades, a range of sustainable land and water management (SLWM) practices and approaches to sustainable intensification have been successfully implemented at the local scale. However, adoption rates have remained low due to a variety of barriers and lack of effective approaches from authorities at larger scales (national to global). Despite the wealth of local successes, promoting and realizing the widespread uptake of SLWM requires large scale understanding of the potential and challenges of adoption of SLWM, which is currently lacking. This thesis bridges outcomes of successful implementation of SLWM from local cases to large scale social-ecological patterns, showing where and what is the potential of SLWM to contribute to sustainable agricultural intensification and the barriers to achieve it. The methodological approach and the results presented in this thesis provides insights to improve current assessments of sustainable intensification of agriculture and practical guidance to planning, policy-making and funding interventions to promote the widespread adoption of SLWM.

Sammanfattning

Utmaningen att producera mer mat i tider av förändrat klimat, försämrade jordar och knappa vattenresurser kräver en radikal transformation av jordbruket. Hållbar intensifiering av jordbruket är en process som innebär att öka produktiviteten på gårdarna samtidigt som ekosystemens funktion bevaras. För att åstadkomma hållbar intensifiering av jordbruket har flertalet hållbara mark- och vattenförvaltningsmetoder (sustainable land and water management, SLWM) implementerats lokalt med goda resultat under de senaste decennierna. Dock har upptaget av dessa metoder förblivit lågt sett över nationell till global skala på grund av ett antal barriärer och bristfälliga åtgärder från myndigheter. Trots de många lokala, lyckade exemplen, saknas fortfarande en förståelse för SLWM-metodernas storskaliga potential och utmaningar. För att åstadkomma ett bredare upptag av dessa metoder krävs att denna förståelse förbättras. Denna avhandling kopplar samman lokala exempel av lyckad implementering av SLWM-metoder med storskaliga social-ekologiska mönster. Därigenom visas var och i vilken utsträckning det finns potential för att SLWM-metoder kan bidra till hållbar intensifiering av jordbruket och vilka barriärerna mot lyckad implementering kan vara. Det metodologiska tillvägagångssättet och resultaten som presenteras i denna avhandling har som mål att ge insikter för att förbättra gällande bedömningar av hållbar intensifiering av jordbruket. Dessutom presenteras praktisk vägledning till planering, beslutsfattande och finansieringsinterventioner som är ämnade att gynna ett brett upptag av SLWM-metoder.

Riassunto

Produrre cibo in maniera sostenibile in tempi di cambiamenti climatici, degradazione dei suoli e crescente scarsità idrica, richiede una radicale trasformazione del modo di fare agricoltura. L'intensificazione sostenibile è un processo che consente di aumentare la produzione agricola mantenendo la complessiva funzionalità dell'ecosistema. Le varie pratiche agricole che consentono tale intensificazione sostenibile sono state adoperate con successo in molti casi a piccola scala nel corso degli ultimi decenni, ma l'adozione estensiva di tali pratiche rimane ardua a causa di una inefficace strategia di promozione su larga scale (da nazionale a globale). Nonostante i molti successi documentati a livello locale quindi, promuovere e realizzare la diffusione di pratiche sostenibili richiede una profonda conoscenza delle potenzialità e degli ostacoli al raggiungimento di tale potenzialità a livello nazionale e globale, che rimangono ad oggi sostanzialmente inesplorate. Questo lavoro di dottorato presenta stime globali e nazionali, mostrando dove e quale sia il potenziale delle pratiche di intensificazione sostenibile sull'aumento della produttività agricola. Questi risultati vengono prodotti collegando i successi documentati da casi a piccola scala con le caratteristiche del contesto socio-ecologico a larga scala. Sia l'approccio metodologico che i risultati di questa tesi di dottorato vogliono proporre una visione alternativa alle attuali stime di intensificazione sostenibile e, ove opportuno, fornire una guida pratica alla pianificazione, al finanziamento e alla realizzazione di interventi in supporto alla diffusione di pratiche agricole sostenibili.

LIST OF PAPERS

I. **Future Hydroclimatic Impacts on Africa: Beyond the Paris Agreement.** Piemontese, L., Fetzer, I., Rockström, J., Jaramillo, F., 2019. Earths Future 7, 748–761. https://doi.org/10.1029/2019EF001169

II. **Estimating the global potential of water harvesting from successful case studies.** Piemontese, L., Castelli, G., Fetzer, I., Barron, J., Liniger, H., Harari, N., Bresci, E., Jaramillo, F., 2020a. Glob. Environ. Change 63, 102121. https://doi.org/10.1016/j.gloenvcha.2020.102121

III. **Unpacking the barriers to adoption of sustainable land and water management in Uganda.** Piemontese, L., Kamugisha, R., Tukahirwa, J.B., Tengberg, A., Pedde, S., Jaramillo, F., 2020b. *Ecology and Society (in review)*

IV. **Sustainable intensification of agriculture in Uganda: quantifying large-scale investments for small-scale farmers.** Piemontese, L., Jaramillo, F., 2020. *Manuscript*

Contributions to the papers

My contribution **I-IV**: Idea generation, data collection, data analysis, paper preparation and writing as leading author.

PAPERS OUTSIDE THE THESIS

Bennich, T., Maneas, G., Maniatakou, S., Piemontese, L., Schaffer, C., Schellens, M., Österlin, C., 2020. Transdisciplinary research for sustainability: scoping for project potential. Int. Soc. Sci. J. https://doi.org/10.1111/issj.12245.

Gleeson, T., Wang-Erlandsson, L., Porkka, M., Zipper, S. C., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S, Piemontese, L. et al (2020). Illuminating water cycle modifications and Earth system resilience in the Anthropocene. Water Resources Research, 56, e2019WR024957. https://doi.org/10.1029/2019WR024957

Gleeson, T., Wang-Erlandsson, L., Zipper, S., Porkka, M., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S., Piemontese, L., Gordon, L., Rockström, L., Oki, T., Sivapalan, M., Wada, Y., Brauman, K., Flörke, M., Bierkens, M., Lehner, B., Keys, P., Kummu, M.-, Wagener, T., Dadson, S., Troy, T., Steffen, W., Falkenmark M., and Famiglietti, J. The Water Planetary Boundary: Interrogation and Revision. One Earth, 10.1016/j.oneear.2020.02.009, 2, 3, (223-234), (2020).

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Fetzer, I; Piemontese, L; Rocha Gordo, J, Martín-López, B. A guide to navigating methods for studying social-ecological systems. Book chapter: Statistical analysis. *Accepted.*

Introduction

Agriculture, through land-cover modifications and irrigation, is currently the world's largest driver of environmental change (Tilman et al., 2001) and the single most impactful human activity on the planet that accounts for over 70% of global freshwater consumption (Campbell et al., 2017; Jaramillo and Destouni, 2015, 2014). Environmentally-damaging farming practices includes massive land use changes such as deforestation, grassland conversion to agriculture land and large-scale irrigation.

Land use changes have significantly altered the volume of evaporated moisture in the atmosphere (Gordon et al., 2003), which changes the intensity and patterns of precipitation (Keys et al., 2012) thus affecting local water availability (Destouni et al., 2013). Precipitation and evapotranspiration changes have fundamental implications for human wellbeing, especially in areas of rainfed agriculture where precipitation is the only source of water for natural vegetation and crops. For example, shifts in evapotranspiration can lead to the redistribution of water resources up to the global scale (Gordon et al., 2005), increasing the risk of desertification in some of the global food production hotspot such as the Sahel (Wang-Erlandsson et al., 2018).

A growing global population further increases demand for food production, which poses a great challenge for the sustainable development of humanity: Agriculture needs to become more productive, while reducing its environmental impact on the planet. This problem is often framed as "sustainable intensification of agriculture" (Rockström et al., 2017).

Current debate on sustainable intensification of agriculture

Despite the widely acknowledged need to sustainably increase agricultural productivity, the way of achieving such "intensification" has been contested, polarizing the debate on future agriculture between a biotechnological and an agroecological perspective (Bernard and Lux, 2017; Garnett et al., 2013). The first perspective relies heavily on external inputs, including expansion of irrigation water, use of artificial fertilizers, pesticides and large-scale crop monocultures to increase productivity. The guiding principles behind this paradigm are the same that lead to the "Green revolution" – i.e. the modernization of agriculture between the 1920s and 1960s (Evenson, 2003).

While a biotechnological approach increases the food production per unit of land, it does not address the already critical impact of agriculture on environmental processes. This approach also neglects the socio-economic context of farming in developing countries where agriculture represents the livelihood of the majority of the population (Pretty, 2008). Negative consequences of this approach include land and water grabbing, leading to the potential depletion of water resources and limiting accessibility of food and natural resources for local people (Johansson et al., 2016; Rulli and D'Odorico, 2014).

On the other hand, the perspective of agroecological intensification provides a more holistic approach that embraces the social and ecological processes around agriculture. With this holistic approach, agriculture changes from a source of global environmental change to a beneficial social-ecological process that ensures human wellbeing in a safe planet (Altieri et al., 2017; Bernard and Lux, 2017; Loos et al., 2014; Rockström et al., 2017). The paradigm of sustainable intensification resonates with the definition of sustainable intensification proposed by Pretty (1997), who first introduced the concept in the context of smallholder farms in Sub-Saharan Africa. The agroecological intensification aims at creating and maintaining productive agro-ecosystem with no or little external inputs, as well as managing local land and water resources with the use of a wide range of farming practices (FAO, 2017; Mitiku et al., 2006). As opposed to the biotechnological approach, agroecological intensification often builds on local knowledge and active farmers engagement and participation in the design, implementation and ownership of the practices to build the long term sustainability of local communities (Altieri and Rosset, 1996).

Principles and practices of agroecological intensification

The agroecological approach aims at intensifying the productivity of farms by encouraging the retention of water and recycling of organic matter within the farm. Especially in small-scale low-income farms, precipitation is the only source of water for plants, which makes them particularly susceptible to hydroclimatic changes and extremes. When precipitation reaches the ground, only part of it infiltrates into the soil contributing to crop growth. Part of the remainder precipitation runs off feeding rivers and lakes, and the rest evaporates back to the atmosphere (Figure 1).

In broad terms, this partition of precipitation is governed by atmospheric water demand (i.e. the evaporative energy) and soil conditions (i.e. porosity, soil cover). Both of these elements determines the final amount of water available to crops (i.e. soil moisture). Change in climate conditions affects the partitioning of water (i.e. hydroclimatic change). These conditions cause a potential increase in evaporation and change in precipitation pattern and intensity (Budyko, 1963), leaving agriculture increasingly exposed to drought and floods (Destouni et al., 2013).

To cope with the negative effects of hydroclimate change, farmers can use agroecological principles to maximize water productivity (i.e. the amount of precipitation contributing to plant growth) by promoting precipitation infiltration in the soil and limiting evaporation and excessive runoff. (Liniger et al., 2011; Liniger and Mekdaschi Studer, 2019; Pretty et al., 2003). The span of practices building on agroecological principles is very broad, including the collection of rainfall and runoff in ponds or small dams to be used as supplementary irrigation; the use of organic or non-organic material for mulching to avoid soil evaporation and cross-slope measures (e.g., terraces and trenches – Figure 2) to collect excessive runoff, limit soil erosion and increase infiltration (see **Paper II** and **paper IV** for a thorough description of SLWM practices).

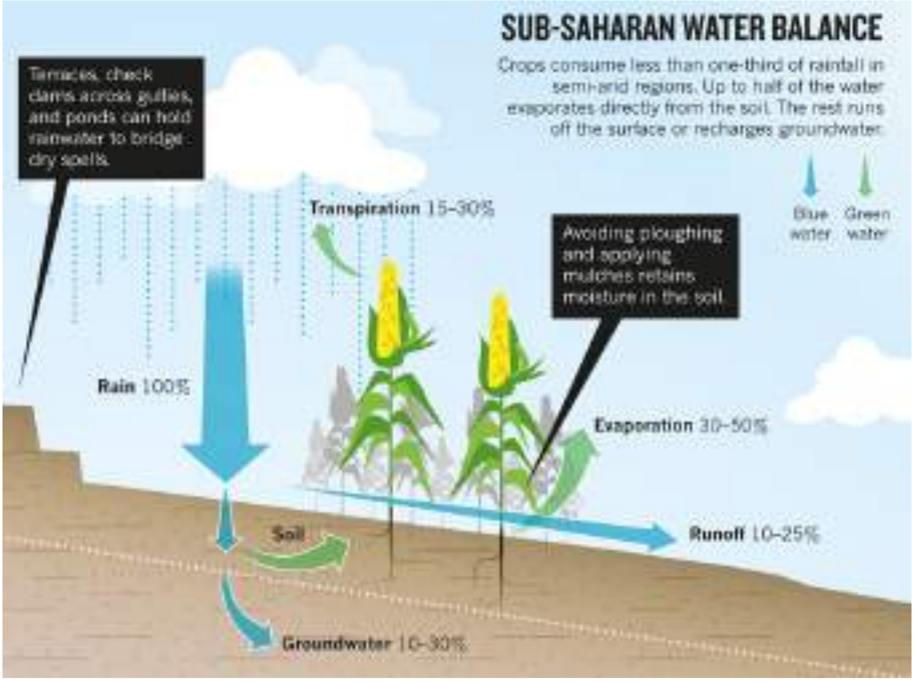

Figure 1. In-field water balance using the green-blue water framework and the role of farming practices to increase water productivity, from Rockström and Falkenmark (2015).

The scientific literature developed throughout the past decades refers to these practices with different terms, depending on the disciplinary lens. For example, in agriculture and development research, common terms are "soil and water conservation" and "conservation agriculture" (Adimassu et al., 2017; Rockström et al., 2009), while in water resources research terms as "water harvesting", "agricultural water management" and "green water management" are more frequent (Botha et al., 2015; Christopher Ward, 2016; Oweis and Hachum, 2006). Recently, the same practices are often rebranded as "climate-smart agriculture" to emphasize the positive impact of these practices for adaptation to and mitigation of hydroclimatic extremes such as floods and droughts (FAO, 2017; 2014).

In this work, the farming practices built around agroecological principles are framed under the overarching term of "Sustainable land and water management"

(SLWM) that embraces all the above. The term "sustainable" is explicitly mentioned to emphasize the social and ecological dimensions of farming (Chartres and Noble, 2015; Khan and Hanjra, 2008).

Sustainable land and water management in Sub-Saharan Africa

Agriculture in Sub-Saharan Africa is managed by smallholders in 80% of the farmland and employs on average more than 50% of the labour force. In Eastern Africa, agriculture employs up to 70% of the population (Altieri et al., 2008), thus constituting the main livelihood for millions of people. Nevertheless, the large water and nutrient gaps caused by poor farming practices, climate change and low access to resources (e.g. inputs and irrigation) restricts crop production far from its potential (Pradhan et al., 2015; Rosa et al., 2018).

Figure 2. Examples of a common SLWM practices in Uganda – trenches in coffee and banana plantations in the left and right pictures respectively, taken during the fieldwork in Masaka district, Uganda, December 2019.

To increase agricultural productivity, in the last decades international development agencies and donors have promoted the implementation of SLWM with encouraging results (Adimassu et al., 2019; Biazin et al., 2012; Douxchamps et al., 2014; Karpouzoglou and Barron, 2014; Rockström and Falkenmark, 2015). A wealth of local case studies of SLWM have demonstrated success in increasing crop production and quality, improving the livelihoods of smallholder farmers in different social-ecological contexts (Karpouzoglou and Barron, 2014; Oweis and Hachum, 2006; Stroosnijder, 2009). In some arid and sub-humid countries of Sub-Saharan Africa such as South Africa, Kenya and Tanzania, small scale water harvesting has improved the stability of crop yields, increasing productivity from 1 ton per hectare to 3-4 tons (Botha et al., 2015; Rockström and Falkenmark, 2000). In Uganda, a country with widespread land degradation but with favourable agro-climatic conditions (Banadda, 2011), conservation agriculture increased yields by 50–100% (Ellis-Jones and Tengberg, 2000; Pretty, 1999), while trenches and terraces in the most degraded highlands have increased crop production of at least 20-50% (WOCAT, 2019).

Nevertheless, the widespread uptake of SLWM is yet to be achieved (Pretty et al., 2003). There are currently no assessments on the global extent of adoption of SLWM, although some studies suggest implementation of SLWM practices on 15-20% of global agricultural land (Prestele Reinhard et al., 2018; Pretty et al., 2003). While the biotechnological approach that focuses on standard efficiency improvement in large-sized farms is well suited for large-scale assessments (global and national), the more holistic and bottom-up agroecological approach made of a wide range of different practices is difficult to assess at large scales (Loos et al., 2014).

Out-scaling local SLWM

The present and future challenge of agroecological intensification is on promoting, supporting and replicating the successful solutions of SLWM to a massive number of small farmers. This process of spreading innovations is generally referred to as "scaling" (Dalgaard et al., 2003), and specifically as out-scaling and up-scaling. Out-scaling refers to the spreading of SLWM within the same social-ecological context through horizontal exchange of information, for example within a village or a contiguous geographic area. Up-scaling refers to the integration of SLWM into higher political or institutional levels, so that "up-scaling can create an enabling environment for further out-scaling beyond the community in which the new practice was developed" (Hermans et al., 2013; Schut et al., 2020).

The main scepticism around agroecological intensification is its potential to scale out local SLWM practices sufficiently to feed a growing population (Bernard and Lux, 2017). The valuable contribution of case-based research in understanding and describing successful SLWM at the local scale provides context-specific and fragmented insights, which needs to be upscaled to effectively guide higher-level decision-making. To avoid the dispersion of valuable local knowledge, the World Overview of Conservation Approaches and Technologies (WOCAT, 2019) has been collecting successful local cases of SLWM since 1992. The aim of WOCAT's database is to promote replicability across social-ecological contexts (Cherlet et al., 2018). Evidence-based decision-making from WOCAT has been used in the World Atlas of Desertification (Cherlet et al., 2018) and in other FAO reports to up-scale local solutions to land degradation (FAO, 2016, 2009), demonstrating its relevance as an information source. However, no systemic approach has been used to synthesize and out-scale information from cases across social-ecological regions. The lack of large-scale insights might hinder the coherent design of national policies and large-scale investments required to boost widespread adoption of SLWM (Liniger et al., 2019; Rockström and Falkenmark, 2015).

The aim of this thesis is to provide large-scale evidence on the barriers and opportunities offered by SLWM to achieve sustainable intensification of agriculture from an agroecological perspective.

In the next section, I give an overview of the social-ecological thinking that frames this thesis and the methodological approach built on archetype analysis, which was used to out-scale insights from local cases.

Theoretical framing and approach

Social-Ecological Systems thinking

In approaching sustainable agricultural intensification from an agroecological perspective, this thesis embraces the position that human wellbeing and the long term sustainability of human development cannot be separated from the state of the biosphere, which represents the foundations of life on this planet (Folke et al., 2016). In sustainability science, social-ecological system (SES) thinking is a way of framing the connectedness of human and nature dimensions as a coherent system of biophysical and socio-economic factors interacting at different scales, which adapts and transforms to internal and external stressors through complex dynamics (Folke, 2016).

The reason for using the SES lens to analyse the large-scale potential of SLWM lies in the complex nature of agro-ecosystems managed with agroecological principles. Agro-ecosystems can be seen as SES, determined by the interplay between climatic conditions, environmental features, human values, socio-economic conditions, market development and policy decisions (Moraine et al., 2017; Robertson and Swinton, 2005). At the same time, farmers constantly shape the agricultural landscape with their farming practices to fulfil their needs (Rivera-Ferre et al., 2013). The varieties of SLWM practices used worldwide is countless. Although SLWM practices are all designed to retain water and nutrients within the farm, the most suitable type of practice, their costs and effectiveness on crop production vary depending on the social-ecological conditions of the farm and the larger landscape/regional context (Barron et al., 2015; Magombeyi et al., 2018).

Overlooking the complexity of agro-ecosystems, large-scale biophysical assessments on sustainable intensification often represent agricultural land as a land cover feature, characterized by biophysical parameters that need to be optimized/maximized to increase the crop yield. For example, the large-scale potential of increasing crop production by expanding irrigation is calculated as the gap between the water input (precipitation) and the plant water requirement (Neumann et al., 2010; Pradhan et al., 2015).

Using a SES lens, this work attempts to add a layer of complexity to the conventional large-scale assessments on sustainable intensification. This allows us to explicitly consider both the biophysical and the socio-economic components of agriculture at the large scale, where social-ecological complexity is often masked (Fischer et al., 2017).

Archetypes analysis in Sustainability Science

The tension between the need to capture the local complexity of the SES and to find solutions to sustainable intensification at larger scales is the essential driver of the archetype approach used in this thesis to transfer insights across scales. Archetype analysis is an approach that aims at finding patterns of social-ecological factors and processes that commonly shape the (un)sustainability of problems and solutions across cases and contexts (Kok et al., 2016; Sietz et al., 2019).

By identifying similarities across cases or places, archetype analysis allows to generalize insights from case studies in a context-sensitive manner (Eisenack et al., 2019; Oberlack et al., 2019). For example, in SES research, archetype analysis has been used to identify areas sharing similar social-ecological drivers of vulnerability (i.e. archetypes of vulnerability) in farming systems (Kok et al., 2016; Manuel-Navarrete et al., 2007; Sietz, 2014; Sietz et al., 2017; Sietz and Van Dijk, 2015). These studies suggest that archetypes of vulnerability can help develop context-specific policy responses to increase local resilience to climate change in agroecosystems. The fundamental assumption building on the SES perspective adopted by archetype analysis studies and that permeates this work is that *"insights from local cases can be out-scaled in areas with similar social-ecological conditions"*.

The archetype analysis approach in sustainability science can help address a concrete problem. In order to plan for the most suitable solutions to sustainable agricultural intensification, policy makers and development partners need empirical evidence at a scale that can be directly useful to decision makers, which is not too specific as local case studies nor too generic as the one provided by global biophysical models. Evidence-based decision making has been used in the World Atlas of Desertification (Cherlet et al., 2018) and in other FAO reports to scale-up local solutions to land degradation (FAO, 2016, 2009), demonstrating to be a relevant source of information.

However, no systemic approach has been used to select and synthesize information from cases across social-ecological contexts. Results of large-scale assessments neglecting local social-ecological contexts might be unsuitable, or misinterpreted, leading to failure in local implementations of SLWM, which could discourage further adoption. Some archetype papers have raised the necessity and usefulness of approaching this gap by mapping spatially explicit social-ecological archetypes (Oberlack et al., 2016; Sietz, 2014; Sietz et al., 2017; Tittonell et al., 2020), suggesting a potential use of spatial archetypes for transferability of local solutions (Kok et al., 2016; Rocha et al., 2020; Václavík et al., 2016, 2013). Nevertheless, this approach has yet to be fully exploited.

Scope and research questions

This thesis uses archetype analysis guided by a SES lens to explore the potential benefits of and the barriers to large-scale adoption of SLWM in a quantitative, context-sensitive and spatially-explicit way.

The four papers within this thesis present three major components related to scales: (a) scale of assessment (b) archetype scale and (c) local case studies (Figure 3). The assessment scales span from the global (**Paper I**) to the national scale (**Paper III** and **IV**), with Uganda being the national case study. The insights considered in the local cases are crop production increase (**Paper II** and **IV**), perceived barriers to adoption of SLWM (**Paper III**) and types and costs of SLWM practices (**Paper IV**). The individual research questions (RQ) of the papers are:

RQ1: What are the future hydroclimatic impacts on African agriculture?

RQ2: What is the global potential of SLWM to increase crop production?

RQ3: What are the barriers to out-scale SLWM in Uganda?

RQ4: What is the investment required to out-scale SLWM in Uganda and what are the benefits?

Paper I is an Africa-wide hydroclimatic assessment based on a hydrological basin-scale analysis on the 50 largest basins across the continent. The aim of this paper is to characterize the future impacts of climate change on the main hydrological parameters affecting agriculture (i.e. precipitation, evaporation, runoff and soil moisture), and composite indicators such as the evaporative ratio and aridity index, by identifying basins with similar projected hydroclimatic change (i.e. hydroclimatic-change regions). The paper further suggests potential evidence-based adaptation strategies by showcasing the use of different types of SLWM practices to cope with the expected hydroclimatic changes.

Paper II presents a global assessment on the potential that a wide adoption of water harvesting (broadly defined to embrace a wide range of SLWM practices) could have on global crop production. The paper uses archetype analysis to out-scale local successful SLWM case studies (i.e. which led to an increase in crop production after adoption).

Paper III examines the barriers hindering the widespread adoption of SLWM in Uganda, describing the main typologies (or bundles) of barriers to adoption of SLWM and their spatial distribution at the district level.

Paper IV provides an evidence-based description of the types of SLWM practices commonly adopted in Uganda drawing from local case studies and estimates the total investment required to cover the costs for smallholders to implement these bundles of SLWM practices at the national scale, and the resulting crop production and income increase.

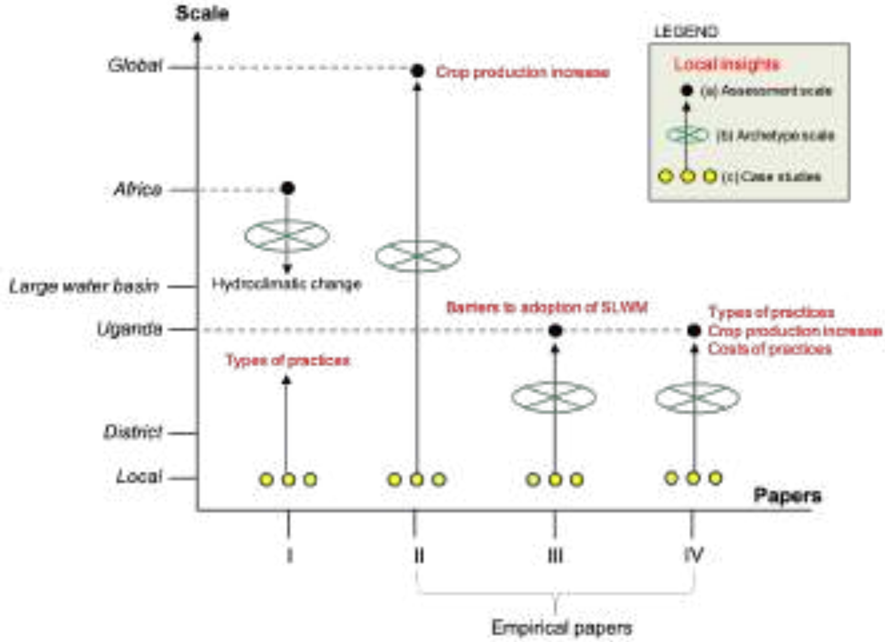

Figure 3. Overview of the four papers of this thesis, showing the interplay between the scale of assessment (a), archetype scale (b) and out-scaling of local insights (c).

Uganda

Uganda was selected as a national case study because of its high diversity in agroecological, as well as socio-economic conditions. The North-South gradient of social-ecological conditions spans from the humid and densely populated southern highlands to the semi-arid Karamoja region in the North-East. The Central Region passes from the equatorial climate of the Lake Victoria crescent, where most of the largest cities are located to the cattle corridor, increasingly direr and inhabited mostly by nomadic tribes (Bernard, 2018; Wortmann and Eledu, 1999). Using archetypes analysis is particularly relevant in such a diverse social-ecological context when targeting context-specific SLWM practices. Moreover, the problem of sustainable intensification is urgent in Uganda, which has a very high potential to increase crop production due to its fertile soils, but lacks proper land and water management despite the long effort from governments to combat soil erosion during the last decades (AFTAR, 2008; Ministry of Foreign Affairs, 2006). Finally, the available scientific literature on local SLWM practices (reviewed in **Paper III**) and the long list of case studies collected by the WOCAT database for Uganda provided a good data and knowledge base to build archetypes for out-scaling local insights at the national scale.

Methodology and Methods

Sustainability science is an interdisciplinary field, drawing from natural science, social science and humanities, to pursue problem-driven and solution-oriented research (Miller, 2013; Miller et al., 2014). Within sustainability science, archetype analysis is used as a methodological approach to understand recurrent patterns of variables within SES, allowing and encouraging the adoption of combination of methods from different disciplines (Oberlack et al., 2019; Sietz et al., 2019). Archetypes can be created using different methods of reasoning such as building from theories in a deductive manner or drawing from empirical case studies in a inductive manner. The four papers within this thesis all use archetype analysis to bridge insights across scales, while building on a variety of data, analytical tools and methods of reasoning. Together, this analysis provides a plurality of perspectives around the large-scale challenges and opportunities of SLWM.

Paper I uses the Budyko hydroclimatic framework (Budyko, 1971, 1963) to deductively identify hydroclimate-change regions in Africa. The Budyko framework indicates the changes in water resources induced by changes in climatic conditions. The main data used to quantify these changes were climate forecasts taken from an ensemble of nine models of the Coupled Model Intercomparison Project (CMIP5). Hierarchical clustering was then used to group the basins showing a similar overall trend in hydroclimatic change (i.e. hydroclimate-change regions of Africa). Finally, local case studies of SLWM from literature were used to showcase the potential use of SLWM practices to cope with the assessed hydroclimatic changes.

Paper II, III and IV were developed using abductive approaches, guided by the social-ecological lens, but drawing from empirical local case studies. The abductive approach reflects the pragmatic paradigm and the empirical vocation of this work, which harvests insights from case studies to inform planning and implementation in similar social-ecological contexts. Providing a bottom-up perspective building on real cases, enables to plan for solutions that have "demonstrated" successful in the same social-ecological context when compared to generic top-down approaches that are "assumed" to be working regardless the local context.

Paper II is a quantitative data-driven paper, which introduces the application of archetype analysis to provide large-scale assessment building from local case studies. The case studies are taken from the WOCAT database (see Paper II for a detailed description of the database). The archetypes were generated using cluster analysis to identify groups of case studies with similar social-ecological conditions and then mapping the global extent where similar conditions are found. The parameters defining the social-ecological conditions were identified through literature review and the data used as proxy for these parameters were taken from available global spatial data.

Paper III presents a mix of quantitative and qualitative methods in the attempt to capture local perceptions, while still keeping a quantitative, large-scale approach. Qualitative fieldwork methods such as participant observation, in-depth interviews and focused group discussions were used to gain a general understanding on the complexity and diversity of local perception on the barriers to adoption of SLWM in Uganda. A list of barriers was first compiled in a participative workshop with a representation of different stakeholder groups and genders. Based on this list, a series of individual semi-structured interviews provided the ranking of relevance for each barrier that was later used in the quantitative analysis (clustering) to generate archetypal barriers (here called bundles, to differentiate them from the spatial archetypes). The spatial archetypes were produced using the same methodological steps developed in **paper II**, the parameters used in the clustering were identified through a meta-analysis on barriers that are specific to Uganda. Finally, the barriers bundles were compared with existing theories in the realm of rural anthropology, rural sociology and peasant economics to further explore the potential implications of the emergent archetypes.

Paper IV is a practical application of the archetype methodology developed and refined in **paper II** and **III**, with a quantitative vocation. The methodological steps are similar to the ones described for **paper III** and the case studies data come from both WOCAT cases and fieldwork data. The out-scaled insights are: types of practices, cost of practices and crop production increase. The crop production increase was then translated into monetary value assuming that the resulting crop production increase would come from the same types of crops currently produced in Uganda at the district level and the farm gate price of crops (price that farmers charge when selling to local market) are the current average national prices.

In the pursuit of a large-scale perspective on such a context-dependent topic, this work bounced between a quantitative large-scale data analysis where cultural and traditional elements of agriculture are masked by cumulative socio-economic statistics, and an in-depth immersion in the Ugandan rural context where cultural and personal perspectives are essential to understand the actual nature of sustainability problems and solutions to sustainable intensification. Hereinafter, I share some reflections on the fieldwork experience that helped my thinking in the complicated job of navigating between scales and contexts.

Reflections on the research process

I approached my fieldwork as a learning experience, which contributed to both my research framing and my personal development. I took part in the Uganda Landcare Conference (Kabale, December 2019) during my fieldwork, with the aim of bringing real-life context into my research rather than bringing my own scientific knowledge to the conference. Gaining first-hand experience of the local context of SLWM in different Ugandan regions contributed to the interpretation of the large-scale social-ecological patterns resulting from the archetype analysis.

I went to Uganda with a *Tabula rasa* – with no previous academic knowledge on the Ugandan agricultural context – distancing myself as much as possible from existing concepts and theories to maintain an explorative approach. Local partners and collaborators from the Uganda Landcare Network helped me develop a broad understanding of the problems around SLWM and provided practical guidance during the fieldwork. The contacts and previous engagement of my collaborators with farmers allowed me to move within a trust network, where farmers were open to share their experience. My fieldwork assistant, Rick Kamugisha, is a local PhD student with a long experience working with local communities on SLWM in Uganda. Having Rick as my gatekeeper was instrumental to perform a large number of interviews in a short time span, identifying the most suitable, interesting and available locations, getting in touch with local focus persons and supporting me in the logistics. Also, since the one month stay in Uganda was not sufficient to gain a deep understanding of the local context, I strongly relied on my Rick and the other Ugandan academic collaborator to make sure that my perspectives well captured and respected the local view of the problems and the validity of the proposed outcomes.

Finally, I often reflected on the implications of being in the field as a foreign, western researcher. I am aware that conducting contextual research in a context that is unfamiliar to me (given my Italian origins and socio-cultural background) represents a living contradiction that might seem hard to defend. Nevertheless, I believe that my understanding of the problems addressed in this thesis and the consequential results would have been much less insightful without the fieldwork.

Figure 3. Focus group discussion used in **Paper III** – Gulu, Uganda, December 2019.

Summary of the results

RQ1. What is the future hydroclimatic impact on African agriculture?

Paper I found that regardless of the socio-economic scenario, the 50 largest water basins in Africa will experience a change in hydroclimatic condition that will mostly have a damaging effect on agricultural production if no actions are taken to manage water and soil at the farm scale. The main insights are:

- The change in hydroclimatic conditions in African hydrological basins can be summarized in four different patterns of change, which corresponds to four geographic areas (hydroclimatic-change regions).
- The hydroclimatic-change regions are consistent across the business-as-usual and the Paris agreement mitigation scenarios, suggesting that regardless of the mitigation scenario, African hydroclimatic recourses will experience a change.
- Precipitation and runoff are projected to increase in tropic basins and decrease in dry basins (apart from the Sahel).
- At the same time, soil moisture is projected to have an ubiquitous decrease.
- The paper concludes by suggesting that hydroclimatic resources are expected to have a partially detrimental change regardless of the emission mitigation scenarios. A more effective mitigation strategy for agriculture might come from in-farm SLWM.

RQ2. What is the global potential of SLWM to increase crop production?

Paper II characterizes the social-ecological suitability of global agricultural land to SLWM by identifying six archetypal regions drawing from 162 case studies. The results show:

- The six spatial archetypes cover 19% of global agricultural land.
- The highest potential of crop production increase is found in East and West Africa and South-East Asia (Increase between 60 to 100% compared to current productivity).
- Burundi shows extensive areas, 60% of national agricultural land, with the highest potential of crop production increase (60-100%).
- Uganda is the country with the highest share of national agricultural land (78%) showing high potential of crop production increase (between 40% to 100% increase). Uganda also presents the lowest uncertainty in the estimate of crop production increase potential.

RQ3: What are the barriers to out-scale SLWM in Uganda?

Paper III delineates six archetypal social-ecological barriers in Uganda and their geographical distribution, explaining how:

- Ineffective extension services and poverty are cross-cutting barriers to adoption of SLWM in Uganda.
- Other barriers are context-specific. For example, the post-conflict situation in the North of the country keeps farmers in extreme poverty, thus hindering the adoption of SLWM.
- The spatial archetype of small farms on steep land, mostly covering hilly districts in the South-West and East of Uganda, shows the highest number of co-occurrent barriers, related to "overpopulation", "poverty trap" and "rural isolation".
- Small semi-commercial farms, located along Lake Victoria's shores and better socio-economic conditions, presents barriers related to *farmers' resistance to change.*
- Policy-makers need to consider the geographical diversity of barriers to target more effective interventions to spread implementation of SLWM.

RQ4: What is the investment required to out-scale SLWM in Uganda and what are the benefits?

Paper IV identifies six main group of practices that are more commonly adopted across the country: Trenches, Mulching, Intercropping, Rainwater harvesting, Integrated crop-animal production and Agroforestry-trenches. Out-scaling these groups of practices on 75% of Ugandan agricultural land would imply:

- An overall investment of 4.4 billion USD from smallholders.
- A production increase that could be worth 4.7 billion USD per year, once the practices are fully productive.
- The Northern region shows higher costs and a relatively lower production increase, while the Highland districts would have lower costs and a higher impact.
- Overall, the paper can help target specific group of practices that have already been successfully adopted in different Ugandan regions.
- Finally, the paper can guide planning of investment funds to support smallholders in adopting SLWM, by prioritizing areas and types of SLWM interventions.

Contributions and reflections

This thesis contributes to the current scientific debate on sustainable intensification of agriculture and archetype analysis by: (1) providing large-scale evidence on the necessity and profitability of SLWM to increase food security, (2) advancing the methodological portfolio in archetype analysis, and (3) supporting the production of policy-relevant work, reaching non-scientific communities working towards mainstreaming SLWM.

1. New, large-scale evidence of the need of SLWM

Until now, large-scale assessments of *SLWM* and agricultural intensification have focused on the biophysical limits to crop production increase at large scales (from water catchment hydrology to global vegetation dynamic models) (Müller et al., 2018; Neumann et al., 2010; Pradhan et al., 2015).

The difference between these assessments and the social-ecological approach proposed in this thesis boils down to the difference between modelling the ideal potential (i.e., what can be theoretically achieved in the best-case scenario) and the realistic potential (i.e., what can be *actually achieved with context-specific technology and considering the experiential socio-economic boundary conditions)*. Examining this difference is relevant not just in sustainability science, which is devoted to provide solution-oriented insights and practical guidance to address the most pressing environmental problems, but also in policy-making. Policy makers would benefit from holistic information to target interventions that not only addresses the potential crop production gap, but also accounts for a socio-economic context where solutions can be feasible, convenient and realistically implementable.

A good case showing the difference between the two approaches is provided in **paper IV** by comparing the social-ecological approach with a biophysically-based study on soil erosion in Uganda (Karamage et al., 2017). After estimating the soil erosion risk in Uganda, terraces were proposed by the latter study as the practice with the highest soil erosion reduction potential, therefore recommending adoption. However, terraces appear to be marginally adopted in most parts of Uganda because they are labour intensive, expensive and require frequent maintenance (Amsalu and de Graaff, 2007).

On the other hand, estimates using the social-ecological perspective from **paper IV** reveal that trenches and vegetation strips may be more feasible solutions to out-scale since they better fit local farming styles and provide a cost-effective strategy to ease farmers into SLWM. This means that promoting practices that farmers are already acquainted with is more likely to result in higher adoption rates, since they suit the social-ecological context. The development initiated in this thesis shows the potential to improve current estimate by complementing the conventional biophysical modelling approach with contextual social-ecological analysis. A further harmonization of social-ecological assessment with biophysical assessments represent a necessary improvement in sustainability research.

2. New methodological insights for the archetype community

Besides the contribution to the scientific discourse on the sustainable intensification of agriculture, every paper has its own small (or large) methodological contribution to the development of archetype analysis research in sustainability science. **Paper I** represents a first attempt to identify archetypes of change in hydroclimatic condition *to bridge hydroclimatic science with sustainability science*. **Paper II** introduces spatial archetypes identified from successful cases, which is a different approach compared to the spatial archetypes usually delineated from regional social-ecological conditions (Rocha et al., 2020; Sietz et al., 2017; Václavík et al., 2013). **Paper III** and **Paper IV** combines different archetype approaches by linking case typologies with spatial archetypes and provides concrete applications of previous methodologies proposed for transferability of sustainable solutions.

These papers showcase the operational use of archetypes for policy-relevant research, which is one of the methodological challenges identified during the third workshop on archetype analysis in sustainability research, held in Olomouc (Czech Republic) in October 2019. During the development of this thesis, I have been actively engaged within the archetype community in advancing the frontier of archetype analysis, which led me to organize and host the upcoming fourth workshop in Stockholm, planned for February 2021.

3. Beyond-research impact

The contribution of this work extends beyond the scientific community, involving and reaching out to international organizations and local SLWM stewards to contribute to sustainability change from science to practice. In different steps of this work, I have involved co-authors and collaborators from development organizations, from SIWI (The Swedish International Water Institute) to WOCAT and the National Uganda Landcare network, to develop and frame my research question in a way that embraces concrete problems and gaps directly useful to practitioners. For example, the TIARA project from SIWI, is working to “scale up SLWM by enhancing knowledge of how to implement rainfed agriculture in Africa and the related challenges and opportunities” (SIWI, 2019). **Paper II** was well received by the WOCAT network and it has been requested as contribution to FAO reports, which emphasizes the importance of agriculture and food security in the climate change agenda within the UNFCCC.

Moreover, the collaboration with WOCAT supports the visibility of the WOCAT database by promoting its use. This could potentially attract more cases to the database, more evidence supporting SLWM, more awareness from policy makers and eventually more funding towards the adoption of SLWM at the local scale.

Last but not least, during my fieldwork I was explicitly told that seeing a researcher from Sweden in their context generated enthusiasm and increased the confidence of local actors in pursuing SLWM. That was an important opportunity for me to realize the (often unintentional) impact that researchers can have when they engage in a problem/solution-oriented science. It is an open debate in sustainability science on the changing role of researchers from generators of knowledge to initiators of change with "action research" (Wittmayer and Schäpke, 2014). Especially in sustainability science, researchers are often driven by the goal of promoting change, and not just providing more knowledge, but also communicating, co-generating and co-designing knowledge to better embrace the interdisciplinary nature of the sustainability challenge. Even though this work has not explicitly carried out action-oriented research, I think it is important to be aware and reflect on the different ways in which a research project can generate impact beyond paper publications.

Limitations and next steps

Current extent of SLWM

There are different aspects of this work that presents certain limitations, which need to be acknowledged and further explored to advance the reliability, potential usability and application of the large-scale social-ecological approach to SLWM introduced by this thesis.

One major limitation in the solution-oriented papers (**Paper II** and **Paper IV**) is that there is no assessment of the current extent of SLWM, which could make the potential crop production increase resulting from these papers overestimated. However, we do not currently know how much of the global agricultural land is under SLWM. This is because farming practices are constantly changing and the available methods to assess and monitor them are based on time-consuming and demanding tasks (e.g., field survey, national census). For example, in the southern highlands of Uganda, the landscape is dominated by old progressive terraces and other visible SLWM practice, which were first introduced by the English colonizers in the first half of the 1900 (Kassie et al., 2011). Later on, these practices have been abandoned in large parts of the area and it is impossible to quantify the actual extent of active SLWM.

On the other hand, the lack of spatial information on sustainable farming practices is the main factor inspiring the archetype approach used in **Paper II** and **IV**. The WOCAT database was developed explicitly to collect evidence on the types of practices implemented locally with the final aim of informing potential transferability of local solutions in the lack of better assessments. To narrow the space of uncertainty in current estimates, a necessary step forward is to assess the current spatial extent of these solutions. This could be promoted at the national scale by integrating or extending the assessment of SLWM in agricultural surveys, currently used in many Sub-Saharan countries (including Uganda) to keep track of development progresses.

Moreover, it is important to refine and further develop mixed-method approaches that bridge local evidence with larger scales such as remote sensing and spatial modelling. In this direction, a spatially explicit global assessment on the extent of conservation tillage from Prestele Reinhard et al. (2018) presented a first combination of national census with spatial modelling, showing the use for global environmental modelling purposes. Archetype analysis could provide inspiring entry points to further develop these types of approaches and bridge local evidence to global patterns.

Archetypes validation

Another major gap is related to the archetype approach and specifically to the lack of a systemic and rigorous validation procedure. This lack of a fundamental component of the scientific analysis process might limit the use and reliability of proposed archetypes. Although this is a genal limitation of all the research on "typologies", "styles" and other "ideal types" of approaches used across sciences to generalize concepts (Eisenack et al., 2019; Oberlack et al., 2019), it is important to acknowledge this as a crucial gap that needs to be addressed. Previous work has used existing literature to support the validity of their spatial archetypes (Kok et al., 2016; Sietz et al., 2017), but this approach is not systemic and it is only used to "confirm" the pattern identified in the archetypes, not to disprove it.

Paper III provides some hints to approach validation by cross-checking the qualitative perception of local cases with quantitative data at higher scales (district level in this case), providing a sense of robustness of the resulting archetypes. Other works have used statistical approaches to evaluate the robustness of the proposed archetypes within the statistical clustering step (Rocha et al., 2020; Walther and Lüdeke, 2012).

However, to provide a more concrete contribution to sustainability, validation of archetypes should move beyond the internal statistical consistency and approach also the "empirical validity" (Oberlack et al., 2019). Empirical validity relates to how stakeholders find archetypes useful and "valid" for the purpose they were developed. This approach could potentially involve stakeholders in the definition and identification of archetypes themselves, moving towards trans-disciplinary archetypes. Some open questions that need to be addressed to enrich the validation portfolio are:

i) How can we assess if the modelled spatial area of transferability is realistic?
ii) How can archetypes be used by stakeholders outside academia to address sustainability-related problems?
iii) How can trans-disciplinary archetypes be approached?

I look forward to continuing to explore these questions during the coming archetype workshop and beyond.

Conclusions

Achieving agroecological intensification calls for commitment at the national to global scale, which is where long-term political strategies are formulated and large funding are managed. This work has provided a large-scale perspective (national to global) on the role of SLWM to contribute to agroecological intensification, using archetype analysis to bridge local case studies with large-scale assessments.

Overall, the findings suggest that SLWM can be a feasible solution to sustainably face the problems of climate change and land degradation. As shown in the Uganda case, SLWM can also be a profitable and convenient way to increase agricultural productivity from a socio-economic point of view. The large-scale evidence produced in this thesis complements the detailed case-based research that supplies evidence at the local scale, as well as the conventional large-scale biophysical assessments by providing contextual social-ecological archetypes.

Recommendations for future research would be to:

a) further refine the approach presented in this work with a rigorous validation procedure, and

b) harmonize it with the biophysical assessments to increase the breath of complexity and reliability of large-scale assessments on sustainable intensification.

Beyond the contributions to the research community, I hope to generate interest in practitioners and policy makers to use the outcomes of this thesis for planning the actual out-scaling of SLWM. The maps, barriers and practices bundles developed in **Paper III** and **IV** for Uganda can guide effective mainstreaming of SLWM if adequately supported by governments, international NGO and investors with enabling policies and financial support to smallholders.

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I

Earth's Future

RESEARCH ARTICLE
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Key Points:
- Hydroclimatic parameters show a consistent pattern of change delineating four hydroclimate change regions
- Future African hydroclimate is likely to change with similar regional patterns regardless of the emission mitigation scenarios
- The Paris Agreement could limit the intensity of the hydroclimatic change but not the direction of the change

Supporting Information:
- Supporting Information S1

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Future Hydroclimatic Impacts on Africa: Beyond the Paris Agreement

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Abstract Projections of global warming in Africa are generally associated with increasing aridity and decreasing water availability. However, most freshwater assessments focus on single hydroclimatic indicators (e.g., runoff, precipitation, or aridity), lacking analysis on combined changes in evaporative demand, and water availability on land. There remains a high degree of uncertainty over water implications at the basin scale, in particular for the most water-consuming sector—food production. Using the Budyko framework, we perform an assessment of future hydroclimatic change for the 50 largest African basins, finding a consistent pattern of change in four distinct regions across the two main emission scenarios corresponding to the Paris Agreement, and the business as usual. Although the Paris Agreement is likely to lead to less intense changes when compared to the business as usual, both scenarios show the same pattern of hydroclimatic shifts, suggesting a potential roadmap for hydroclimatic adaptation. We discuss the social-ecological implications of the projected hydroclimatic shifts in the four regions and argue that climate policies need to be complemented by soil and water conservation practices to make the best use of future water resources.

1. Introduction

Attaining the Sustainable Development Goal No. 2 of hunger eradication in Africa, the continent with the world's highest malnutrition (Bain et al., 2013), highest estimated population growth (Asongu, 2013) and severe water scarcity (Porkka et al., 2016) is a major challenge. Additionally, anthropogenic climate change is expected to further compromise water availability and food security in the next decades (Arnell, 2004; Rockström et al., 2017), considering that Africa is highly dependent on hydroclimatic resources (Collier et al., 2008) and has low adaptive capacity to these changes (Downing et al., 1997).

To prevent the negative consequences of climate change, the international community recently committed to constrain anthropogenic global warming within the Paris Agreement (UNFCCC, 2015), but the effectiveness of complying with the 2° target for African water resources is still debated (Easterly, 2009; Raftery et al., 2017). The reason is that, to date, there is no comprehensive assessment of the impact of different climate change scenarios on African water resources. In fact, model-based assessments usually rely on separate analysis on hydroclimatic parameters such as precipitation (P; Giorgi et al., 2014) or runoff (R; Boko et al., 2007; Goulden et al., 2009; Nohara et al., 2006), commonly used to measure water availability (Faramarzi et al., 2013; Mekonnen & Hoekstra, 2016). For P, climate projections foresee a general decrease over Northern and Southern Africa and increase in the equatorial region and the Sahel (Huntington, 2006; Karl & Knight, 1998). In relation to R, some studies predict a decrease over Southern Africa (Hagemann et al., 2013; Vörösmarty et al., 2000), increase over eastern equatorial Africa (Schewe et al., 2014; Vörösmarty et al., 2000) and potential severe water stress—defined as total water demand over runoff—in North Africa, Sahel, Horn of Africa, and South West Africa during the first half of the current century (Milly et al., 2005). In addition, climate models also show a ubiquitous decreasing trend in soil moisture (Sm) in the coming decades (Sheffield & Wood, 2008). These hydroclimatic changes may affect crop production, putting an extra burden on countries where migration of famine refugees has caused conflicts and social tensions (Nnoli, 1990). However, the high uncertainty related to the projections of P, R, and Sm (Scheff & Frierson, 2015; Teng et al., 2012) calls for an increased effort in hydrological assessment to provide more consistent estimates of future hydroclimatic trajectories. In fact, hydroclimatic impacts based on only one parameter (e.g., P or R) are highly conditioned by the resolution and reliability of the models to capture the specific physical processes related to that parameter (Sylla et al., 2013), while the assessment based on multiple hydroclimatic parameters can reduce this uncertainty (Trenberth et al., 2003). Another major limitation with assessments based on single hydroclimatic parameters is that they do not consider cumulative effects (e.g., what happens if R increases and Sm decreases simultaneously?) providing partial information that can cause misleading interpretation and uninformed planning (Dai, 2011a, Hirabayashi et al., 2008).

What determines water availability for food production and ecosystems, particularly on the African continent where >95% of agriculture is rainfed (Schuol et al., 2008), is the net amount of water in soils after subtracting loss of water due to evaporation. In this context, hydroclimatic assessments, looking at the combined effect of changes in P, potential evapotranspiration (PET), and actual evapotranspiration (E; Weiskel et al., 2014; Scheff & Frierson, 2015), can better describe the overall effect of climate warming on the hydroclimate (Bring et al., 2015; Gudmundsson et al., 2017; Huntington, 2006). In fact, over long time scales, the partitioning of water between R and E is controlled by water and energy availability in terms of P and PET (Budyko, 1971). PET depends on energy among other factors, and it is expected to increase with global warming as temperatures rise (Morsy et al., 2016), modifying the patterns, magnitude, and seasonality of P (Dore, 2005), with unclear effects on aridity and water partitioning. For instance, in regions where the increase in P is less relevant than the increase in PET, the net water balance would lead to an increase in aridity conditions (aridification; see Sherwood & Fu, 2014); however, the assessment based on changes in P only would predict increasing water availability leading to potential misinterpretations.

In this work, we use the Budyko framework (Budyko, 1963) to provide a comprehensive hydroclimatic assessment of the impact of the two main Representative Greenhouse Gas Concentration Pathways (RCPs)—the Paris Agreement (RCP4.5) and the business as usual (RCP8.5). The RCPs are climate projections forced with distinct greenhouse gas concentrations, generally covering the period 2006–2099. The RCP4.5 corresponds to the midrange mitigation emission scenario adopted by the Paris Agreement, while the RCP8.5 represents the highest emission rate from a business as usual scenario—a scenario without any emission mitigation strategy.

The Budyko framework provides a relationship between the aridity index (PET/P) and the evaporative ratio (E/P). As such, we refer to the mathematical space generated by PET in the *x* axis and E/P on the *y* axis as the Budyko space. Looking at the ratios between the key water and energy balance parameters can give a general insight on the main wetting and drying trends (Greve et al., 2014), linking changes in energy demand driven by climate warming to resulting effects on water partitioning and water availability on land. We first use the multimodel ensemble data from nine Earth system models (ESM) within the CMIP5 project (Taylor et al., 2011) that have simultaneous fine-scale data on temperature (*T*), P, R, E, and Sm to characterize in the Budyko space the aridity and water partitioning conditions in the 50 largest African basins. Second, we compare the hydroclimatic changes expected for both scenarios, here referred to the changes in the main hydroclimatic parameters (P, R, E, Sm, PET/P, and E/P). Finally, we cluster African basins into four hydroclimate change groups, highlighting potential implications for human and agricultural activities. This classification may be used by water-related stakeholders to understand the main trade-offs and synergies of forthcoming hydroclimatic change and water management and to plan sustainable strategies for eradicating hunger in Africa.

2. Data and Methods

To investigate the impacts of the two RCPs—RCP4.5 and RCP8.5—on African hydroclimate, we calculate hydroclimatic changes between the periods 1960–1989 and 2070–2099 for the RCPs and the historical experiment. The historical experiment consists of a set of simulations forced by observed atmospheric conditions from both natural and anthropogenic sources—including land cover modifications—covering the whole twentieth century.

We used simulations from nine ESM (models' characteristics in supporting information Table S1) within the Coupled Model Intercomparison Project (CMIP5). The CMIP5 simulations have been used in previous studies for direct calculation of hydrological fluxes in basins greater than 10,000 km^2 without necessary downscaling (Asokan et al., 2016; Bring et al., 2015; Flint & Flint, 2012). In the model selection process, we excluded the lower-resolution models (>2.5° resolution) because of their poor performance when reproducing T, P, and E for Africa (Bhattacharjee & Zaitchik, 2015; Kharin et al., 2007; Siam et al., 2013). Nine is the maximum number of CMIP5 models providing all the variables used in this study. The variables taken from the CMIP5, (with their original database names in brackets) are total soil moisture content (mrso), runoff (mrro), specific humidity (hus), surface downwelling shortwave radiation (rsds), air temperature (ta), precipitation (pr), evapotranspiration (evpbs), and surface air pressure (ps)—for the three experiments analyzed ("historical," "RCP4.5," and "RCP8.5"). The reason of the (relatively) limited number of models used in this study is because usually multimodel ensemble studies focus on the atmospheric component of ESM. The atmospheric component is the most common and well studied within the CMIP5 project, so a large number of models provide simulations for atmospheric variables (e.g., precipitation and radiation). Unfortunately, not all ESM have a complex land system component, which is the one computing soil moisture and (in most cases) runoff. Since our study aims at providing a comprehensive analysis on the main component of the water cycle interacting with climate, only nine models could provide the necessary atmospheric and land system variables for the three experiment used in our analysis.

Since climate simulations are dependent on their initial state (i.e., the values of some physical parameters set to represent the climate variability), the CMIP5 models produce ensembles of simulations with different initializations to capture the natural climate variability, called realizations. In our analysis, the realization r1i1p1 (r: realization, i: initialization, and p: perturbation) was used, in analogy with other studies (Bring et al., 2015), because it provides the largest number of simulations.

Geospatial data of African basins were derived from the Global Runoff Data Centre (2017). We first selected the basins with surface areas larger than 10,000 km^2 (53 in total) to deal with the coarse resolution of some models' outputs. We later excluded some river basins such as the Doring in South Africa, Sebou in Morocco, and Lake Turkana in East Africa, because not all the models could cover their extent given their coarse resolution. Hence, the final number of basins analyzed in this study became 50, covering the 62.2% of the total African surface. The 50 basins are located mostly in sub-Saharan Africa, leaving only small coastal basins and desert areas (e.g., Namibia and the horn of Africa) out of the basin coverage.

2.1. Estimation of PET

Because estimation of aridity may be very sensitive to the methods behind the calculation of PET (Milly & Dunne, 2016; Seneviratne, 2012), we computed PET in two different ways: the open water Penman-Monteith PET, here referred to as PET_{OW} (Dai, 2013; Donohue et al., 2010; Sheffield et al., 2012), and the energy-only PET suggested by Milly and Dunne (2016) and used specifically for CMIP5 model outputs, here referred to as PET_{EO} (Milly & Dunne, 2016). We calculated the average of the two different methods to estimate mean PET at the basin scale. The two PET equations are the following:

$$\mathrm{PET_{OW}} = \frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma}\frac{6.34(1+0.536u)(e_s - e)}{L_v}, \tag{1}$$

$$\mathrm{PET_{EO}} = 0.8(R_n - G), \tag{2}$$

where R_n (mm/day) is the net radiation; u (m/s) and G (mm/day) are the wind speed at 2-m height and the heat flux into the subsurface, respectively. The values of u and G were set to 1 and 0, respectively, as PET has been previously tested on these parameters and found to be largely insensitive to their variations (Cook et al., 2014). The term 0.8 of the PET_{EO} equation represents the fraction of available energy that goes into latent heat flux (Milly et al., 2016), estimated by Koster and Mahanama (2012) to be about 80% based on observation-model analysis.

The L_v is the latent heat of vaporization of water (MJ/kg), given by

$$L_v = 2.501 - 0.002361T, \tag{3}$$

where T (°C) is air temperature at 2-m height; e (kPa), e_s (kPa), and Δ (kPa/K) are the vapor pressure at 2 m (equation (4)), the saturation vapor-pressure function (equation (5)), and its derivative with respect to T (equation (6)), respectively, while γ (kPa/K) is the psychrometric constant (equation (7)).

$$e = \frac{Pq}{0.622 + 0.378q} \tag{4}$$

$$e_s = 0.6108 \exp\left[\frac{17.27T}{T + 273.3}\right] \tag{5}$$

$$\Delta = \frac{4098 e_s}{(T + 273.3)^2} \tag{6}$$

$$\gamma = 0.000665P \tag{7}$$

2.2. Analysis of Hydroclimatic Change in the Budyko Space

We analyzed changes in PET/P and E/P within the Budyko hydroclimatic framework to describe the future trends in aridity and water partitioning. The Budyko framework describes the relationship of the partitioning of water and energy on land, considering that evapotranspiration is limited by the availability of water (i.e., P) and energy (i.e., PET). The relationship between PET/P and E/P has been analytically described by a set of Budyko-type equations (e.g., Choudhury, 1999; Yang et al., 2008) expressing E/P as a function of PET/P. For example, the "Budyko-type" formulation of Yang et al. (2008) is a climatic model of E/P in terms of PET/P and other parameters representing the effect of basin characteristics, such as vegetation, soils, and topography. A basin that changes its hydroclimatic conditions from a period 1 (p_1) to a period 2 (p_2) can be represented in Budyko space by a point moving from the initial conditions p_1 to the final conditions p_2 (Figure S1). These conditions should be constrained to the limits E/P < 1, E/P > 0, and E/P < PET/P. Under the hypothetical condition that the changes in PET/P are the only drivers of change in E/P, the basin will move to a new location along the Budyko-type curve representing the characteristic initial climatic and catchment conditions. However, in a more realistic scenario where E/P depends not only on changes in PET/P but also on other drivers in the landscape, the basin can move anywhere in Budyko space (van der Velde et al., 2014).

We then define the total hydroclimatic change experienced by any basin over time as the movement vector ($\vec{h}_s$) in the Budyko space between the two points representing the initial and final hydroclimatic conditions of the basin. As such, the horizontal component of the movement vector is the difference between the 30-year annual means of PET/P of the periods 1960–1989 and 2070–2099, Δ (PET/P), and the vertical component the difference between the 30-year annual means of E/P of the periods 1960–1989 and 2070–2099, Δ(E/P). These periods have been often selected to study the future hydroclimatic conditions of a given basin and its corresponding change (Bring et al., 2015; Feng & Fu, 2013).

The intensity of the total movement (I_s) is the magnitude of the vector, and the direction (θ_s) is the clockwise angle between $\vec{h}_s$ and the positive y axes, as follows:

$$I_s = \left|\vec{h}_s\right| = \sqrt{\Delta\left(\frac{PET}{P}\right)^2 + \Delta\left(\frac{E}{P}\right)^2}, \tag{8}$$

$$\theta_s = b - \left(\text{atan2}\frac{\left(\Delta\left(\frac{E}{P}\right)^2, \Delta\left(\frac{E}{P}\right)^2\right)*180}{\pi}\right), \tag{9}$$

where $b = 450°$ when Δ(E/P) > 0 and Δ (PET/P) < 0, and $b = 90°$.

We used this vector representation to depict the movements of the 50 largest African basins in the Budyko space, visualized by a wind rose diagram. Wind rose plots aggregate information on intensity, direction, and frequency of the movement. This type of diagrams has been used in global (Jaramillo & Destouni, 2014, 2015) hydroclimatic change assessments. We used this approach to depict simultaneously the hydroclimatic movement in the Budyko space for the 50 largest African basins for both the RCP4.5 and RCP8.5, following Jaramillo and Destouni (2014). All the basins with movements in Budyko space in a particular range of direction are grouped in a petal.

2.3. Identification of Future Hydroclimate Change Regions

To infer possible regional patterns of future hydroclimatic change, we clustered the basins in four main groups according to their current aridity conditions and their forecasted change in PET/P, E/P, P, and Sm. We first classified the basins in two main aridity classes using the average value of the PET/P in the period 1960–1989 as measure of aridity. Because of the diverse—and inconsistent—approaches used to delineate the boundaries between aridity classes (Gamo et al., 2013; Maliva & Missimer, 2012; Thornthwaite, 1948), we here used a simple method to split our group of basins in two major aridity groups, those tending to arid conditions and those to humid ones. As a threshold, we used the median PET/P value of the 50 African basins (PET/P = 2.4) to have a comparable number of basins in both aridity classes, so that the basins with condition PET/P > 2.4 were classified as arid and the remaining (i.e., PET/P < 2.4) as humid. The value 2.4 is a suitable threshold because it falls in the transitional semiarid group ($2 \leq PET/P < 5$) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) classification of climate zones based on aridity index (Barrow, 1992).

For each aridity group we then performed a hierarchical cluster analysis to identify the possible future hydroclimate change groups. Since we were interested in grouping basins with the same overall profiles regardless of their magnitudes, we used the Pearson correlation-based distance as a dissimilarity measure. The correlation-based distance considers two objects similar if their features are highly correlated, even though the observed values may be far apart in terms of Euclidean distance. This is the case of our hydroclimate change assessment, where we want to consider basins as “similar” if their hydroclimatic parameters (e.g., P or R) increase or decrease all together. Each resulting group represents a region with a coherent change in the hydroclimatic parameters relevant for African water availability (i.e., PET/P, E/P, P, and Sm), with distinctive implications for water resources management and specific social-ecological issues.

3. Results

3.1. Future Hydroclimatic Change Scenarios

The initial hydroclimatic conditions of the 50 African basins show a close resemblance between the spatial distributions of the aridity (i.e., PET/P) and water partitioning on land (i.e., E/P) throughout the continent (Figure 1). The initial aridity conditions in Africa from our analysis well reflect the pattern of previous estimates, showing a generally wetter condition in Congo and the western tropical coast (Zomer et al., 2008). Basins located in the Northwestern Africa and on the Sahel are arid, and precipitation is mostly partitioned into evapotranspiration (i.e., PET/P > 4 and E/P > 0.9), especially in the Chelif, Senegal, Gambia, and Lake Chad River Basins. In Southern Africa, especially the basins in the countries of Namibia and South Africa show equally high evaporative ratios as those of Northern Africa (i.e., 0.9 < E/P < 1.2) although not as high aridity values (2 < PET/P < 3). On the other hand, the tropical strip is the most humid region, with precipitation partitioned mostly into runoff, most notably in the west coast of Central Africa, where basins like Cross and Sanaga have low evaporative ratios (i.e., 0.6 < E/P < 0.7)

Our analysis shows differences in expected hydroclimatic change between the two development pathways (Figure 2, summarizing the changes in E/P and PET/P from the period 1960–1989 to the period 2070–2099). In the RCP4.5 scenario, PET/P increases in 90% of the analyzed basins, while E/P shows much smaller changes when compared to those in PET/P. The RCP8.5 scenario shows more varied hydroclimatic changes among basins, with about 40% of the basins increasing PET/P (20% with intensity of the shift >0.3) and a range of basins with simultaneous decreasing PET/P and E/P. This trend agrees with the generic behavior described by the relation between E/P and PET/P in the Budyko Framework, where basin movements are more likely to occur in the directions represented by the upper-right or lower-left quadrants of the rose diagram (Gudmundsson et al., 2016; Yang et al., 2008).

On the contrary, movements in the direction of the lower-right quadrant, corresponding to increasing PET/P and decreasing E/P, and in the upper-left quadrant (decreasing PET/P and increasing E/P) account for almost 40% of the basins under the RCP4.5 scenario but less than 5% under RCP8.5. As such, changes in the partitioning of water into E and R for the RCP8.5 agree more with the expectations from the Budyko-type empirical models than for the RCP4.5, highlighting the driving role of the atmospheric water supply and energy availability on future water partitioning.

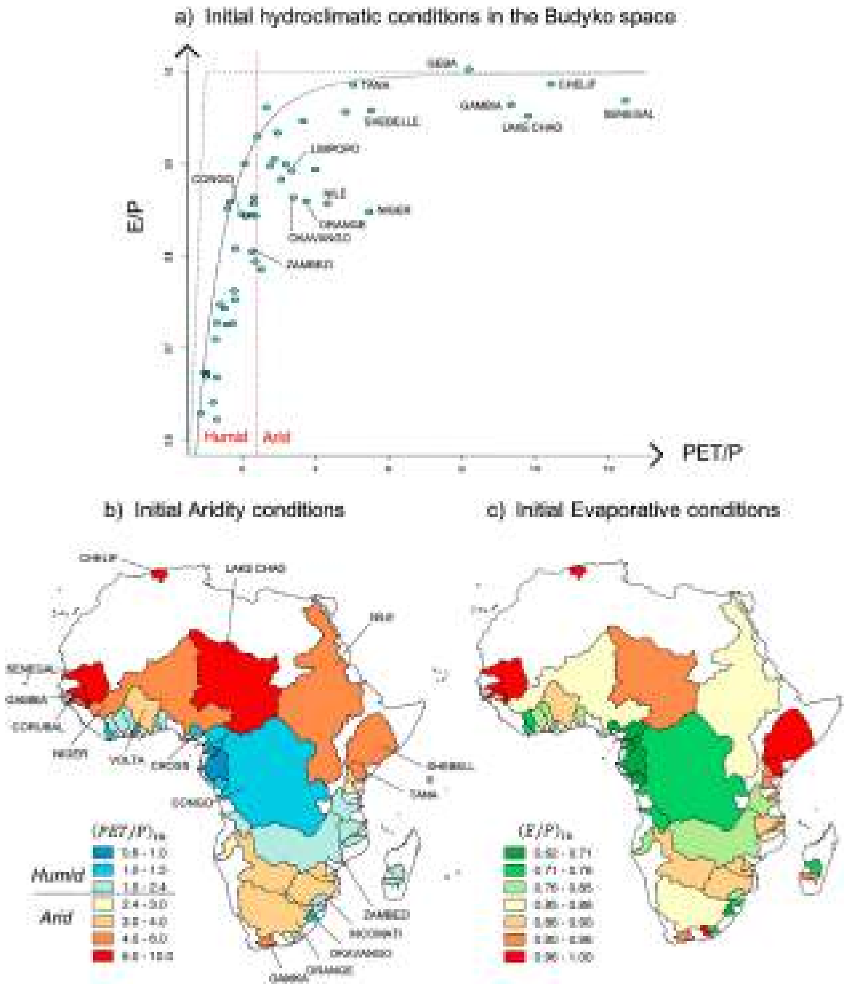

Figure 1. (a) Initial hydroclimatic conditions of the 50 largest African basins represented in Budyko space and given by the mean 30-year values of the aridity index (PET/P) and evaporative ratio (E/P) for the period 1960–1989. Maps of (b) the mean aridity index (PET/P) and (c) evaporative index (E/P).

3.2. Regional Patterns of Future Hydroclimatic Change in Africa

To understand the implications of hydroclimatic changes depicted in the roses (Figure 2), we performed a hierarchical cluster analysis on the average changes in E/P, PET/P, P, and Sm separately for arid (PET/P > 2.4) and humid (PET/P < 2.4) basins (see Figures S2 and S3 for detailed dendograms). The results suggest that four different groups of basins can represent the patterns of hydroclimatic change for both the RCP4.5 and RCP8.5 scenarios in Africa (Figures 3 and S4). The error bars indicate the standard deviation—the spread between the average value and the nine ESM—which gives an indication of the agreement between the nine models. Overall, the agreement is lower for R and particularly low for Sm simulations, which are the most uncertain with only 10% of the basins showing a statistically significant change ($p < 0.05$). The hydroclimate change group 1 shows the most reliable predictions given the highest number of significant

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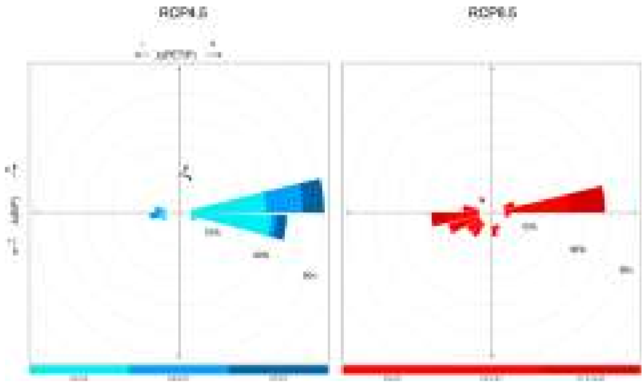

Figure 2. Roses of movement in Budyko space for the 50 basins represented as the combined changes in PET/P (horizontal axis) and E/P (vertical axis), between the 30-year means of the periods 1960–1989 and 2070–2099 for the RCP4.5 (blue) and RCP8.5 (red) scenarios. Each petal includes the basins moving within a range of directions of 15°, with directions θ starting from the vertical axes and counterclockwise. The size of the paddle indicates the percentage of basins moving in that direction θ. The intensity of the color indicates the intensity of the movement in the Budyko space in a given direction θ.

changes across all the hydroclimatic parameters. Moreover, the pattern of change is fairly consistent across the two emission scenarios, with all the basins falling into the same groups in both scenarios, with the exception of the three arid basins in East Africa, Ruvu, Pangani, and Messalo, which cluster into group 1 in the RCP4.5 (Figure S4) and in group 2 in RCP8.5 (Figure 3).

The basins for each group are spatially distributed in a way that enables a clear delineation of the four regions depicted in Figure 4, regardless of the scenario. More specifically, group 1 (dark red group in the

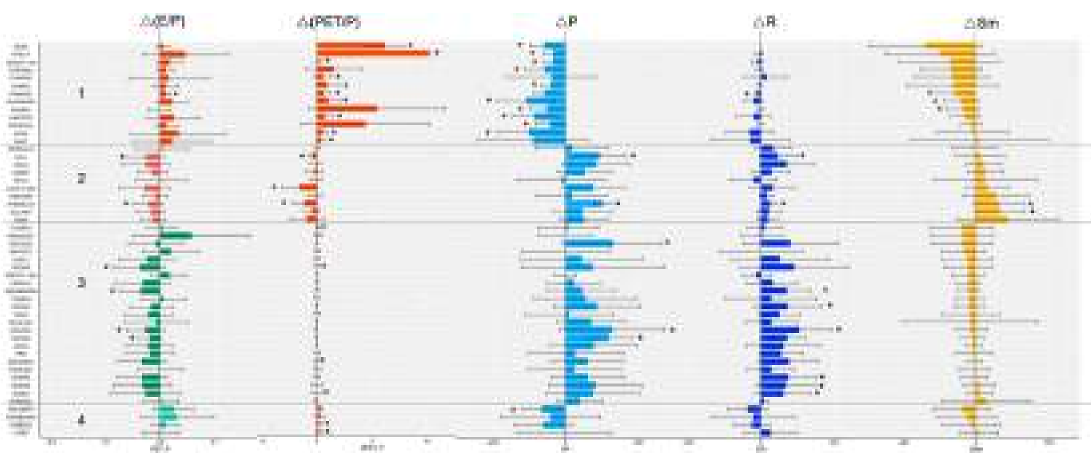

Figure 3. Bar plot showing the pattern of change in the main hydroclimatic parameters of evaporative ratio, E/P; aridity index, PET/P; precipitation, P; runoff, R; and soil moisture, Sm, from 1960–1989 to 2070–2099 for the RCP8.5 scenario. P, E, R, and Sm were derived from climate models' outputs, and PET is the average of two different methods (see section 2). Error bars represent the spread between the nine ESM and statistically relevant changes (Pearson; $p < 0.05$) are marked with asterisks. The colors of the different parameters are chosen for visual purpose and are consistent throughout the paper. The colors of Δ(E/P) represent the four clusters of hydroclimatic change used from now on—dark red for group 1 (for arid basins becoming more arid), light red for group 2 (for arid basins becoming wetter), dark green for group 3 (for humid basins becoming wetter), and light green for group 4 (for humid basins becoming drier).

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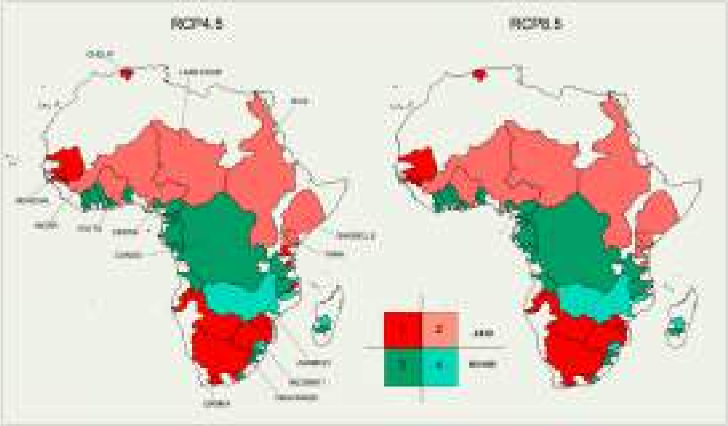

Figure 4. Map of African basins clustered according to the four future hydroclimate change regions for RCP4.5 (a) and RCP8.5 (b). The four groups emerge from the hierarchical cluster analysis accounting for changes in E/P, PET/P, P, and Sm in humid (PET/P < 2.4) and arid (PET/P > 2.4) basins separately.

following figures) includes five of the most arid basins in Northwestern Africa and the arid basins in Southern Africa, likely to experience a marked increase in aridity and a decrease in P, R, and Sm. Group 2 (light red) includes the Sahel strip and three of the largest African basins—Niger, Chad, and Nile—and it is characterized by decreasing aridity, resulting in a shift toward increasing P, R, and Sm. Group 3 (dark green), including mainly humid basins in tropical Africa, will experience increasing P and R without significant change in aridity conditions, leading to a slight decrease in Sm. Finally, group 4 (light green) is located in Southeastern Africa and embraces four humid basins, including the Zambezi River. These basins will experience a slight increase in aridity and a decrease in P, R, and Sm.

4. Discussion

Regardless of the future emission trajectory, the 50 largest African basins are likely to experience a similar hydroclimatic direction of change in Budyko space as outlined in the four hydroclimate change groups. The difference in the two scenarios resides mainly in the intensity of the change (although disagreement between models is large) and the dominance of change in P and PET as drivers of changes in water partitioning, both stronger in the business as usual scenario (RCP8.5) when compared to the Paris Agreement one (RCP4.5).

In our basin-scale assessment, precipitation and runoff show a decreasing trend in the northern and southern regions of the continent (groups 1 and 4) and an increasing trend in tropical Africa and the Sahel (groups 2 and 3), which corroborates the results of previous studies (Dai, 2011a, 2011ab; Milly et al., 2005). With the exception of group 2, soil moisture shows mostly a downward trend in RCP8.5. The change in PET/P is a critical factor to interpret these changes. The PET/P trends in our results are in line with the widespread scientific opinion of the aridification of Southern and Northern Africa for both RCPs (Dai, 2011a, 2011ab; Feng & Fu, 2013; Fu & Feng, 2014; Scheff & Frierson, 2015). However, our results highlight a decrease in PET/P over the Sahel region (group 2), which can be the main driver of increasing soil moisture. Similarly, the moderate increase of PET/P in group 3 could explain the decrease of soil moisture despite the increase in precipitation and runoff, discussed further in detail.

The expected hydroclimatic changes for Africa can produce mixed effects on water resource management, potentially exacerbating water scarcity in the most critical regions of dry North and Southern Africa, whereas bringing potential benefits to food production and natural vegetation in the Sahel, currently experiencing a greening phase (Herrmann et al., 2005). The hydroclimate change regions are presented in combination with some relevant agriculture-related socioeconomic indicators in Figure S5 to provide further guidance for understanding the social-ecological implications in the key African countries.

Group 1 (dark red basins in Figures 3–5) covers the arid regions of Northwestern and most of Southern Africa, dominated by pastoral lands and extensive cropping systems. These regions are likely to experience a marked increase in aridity and a decrease in long-term P, R, and Sm. This group includes Algeria and South Africa, which are the countries with the most intensive use of irrigation (You et al., 2011) and currently the most affected by water scarcity in the continent (Hoekstra et al., 2012). The projected hydroclimatic changes will increase the need of irrigation on one hand and decrease the availability of water for agriculture on the other hand, thus increasing the pressure on groundwater resources and potentially damaging agricultural productivity in both rainfed and irrigated fields. Another hotspot country is Mali, where extensive agriculture, supporting over 30% of the national gross domestic product (GDP), is concentrated in the Senegal basin, which will experience a decrease in precipitation and a marked increase in aridity. This long-term scenario appears heavily unsustainable for natural vegetation and human life, especially considering that the African population is expected to double by 2050 (Gerland et al., 2014). The widespread aridification underlines the need to implement agricultural practices able to cope with high PET in a context of reduced water availability. Basins in this group would benefit from practices such as (i) mulching and intercropping to avoid rapid soil evaporation, (ii) terracing to increase infiltration and increasing soil moisture, and (iii) rainwater harvesting techniques to make the best use of the scarce and seasonal precipitation. These practices are particularly effective in contrasting desertification in the arid and semiarid fringes of Senegal and Namibia, where combined intercropping and mulching increased crops yield considerably (Oweis & Hachum, 2006; Trail et al., 2016). Nevertheless, the rate of adoption of these practices among farmers is still low (Kahinda et al., 2008).

The second group (light red) embraces pastoral land and extensive cropping systems in the Sahel strip, characterized by arid basins with a projected increase in P resulting in increasing R and Sm. The Sahel is a region suffering from drought and famine, with large amount of undernourished population (58% in Central African Republic and 39% in Uganda with 39% and between 32.5% in Chad, 26% in Sudan, and 29% in Ethiopia). The economy of these countries is strongly dependent on agriculture (up to 51% of total GDP in Chand and Central African Republic) despite the current low crop yield. Crop production in the Sahel has a great potential for improving yields through irrigation (Jägermeyr et al., 2016), and it could benefit from increasing P and R. However, the presence of some of the largest African transboundary basins (Niger, Chad, and Nile) could rise upstream-downstream conflicts in water resources management, as has already happened between Ethiopia, Sudan, and Egypt over the Nile River (Swain, 2011). In fact, in these countries, barren lands and pastoral systems dominate the landscape and agriculture is heavily dependent on freshwater resources near rivers. Moreover, other trade-offs in water use might emerge between irrigation, urban water supply, and energy production—for example, hydropower, which is gaining popularity in Ethiopia (Bartle, 2002). In this context, the increase in P could represent a good opportunity to improve food production if properly harvested. For instance, water harvesting practices can be effectively used to increase water productivity in rainfed agriculture, increasing the yield without affecting downstream regions (Dile et al., 2016; e.g., Egypt), thus saving freshwater resources for other activities.

Group 3 (dark green) comprises the tropical forests of Central Africa, including the Congo and some coastal areas of Central and Western Africa. This group will experience an increase in precipitation and a slight increase in PET/P that will result in higher R in tropical humid/subhumid basins. The increasing P could benefit rainfed crop production in countries as Ivory Coast, Benin, and Togo where agriculture covers more than 70% of the land and has a strong influence on the economy (around 30% of GDP). However, the additional precipitation could likely come from stronger tropical cyclones (Knutson et al., 2010), thus increasing the R to P ratio and explaining the expected decrease in Sm. In fact, steady moderate P infiltrates more easily into the soil, increasing Sm, while the same amount of P concentrated in shorter periods causes higher R (possibly flooding) leaving soils eventually much drier (Trenberth et al., 2003). The same mechanism is also likely to promote nutrient loss because of the washout of the topsoil layer during extreme events, with negative consequences for agricultural productivity as already observed in the Congo basin (Few et al., 2014). National authorities should consider strengthening flood risk prevention plans, particularly in view of the expanding urban settlements. On the agricultural side, terracing and other slope control measures can prevent soil erosion and increase infiltration. Positive examples of these practices can be found across different

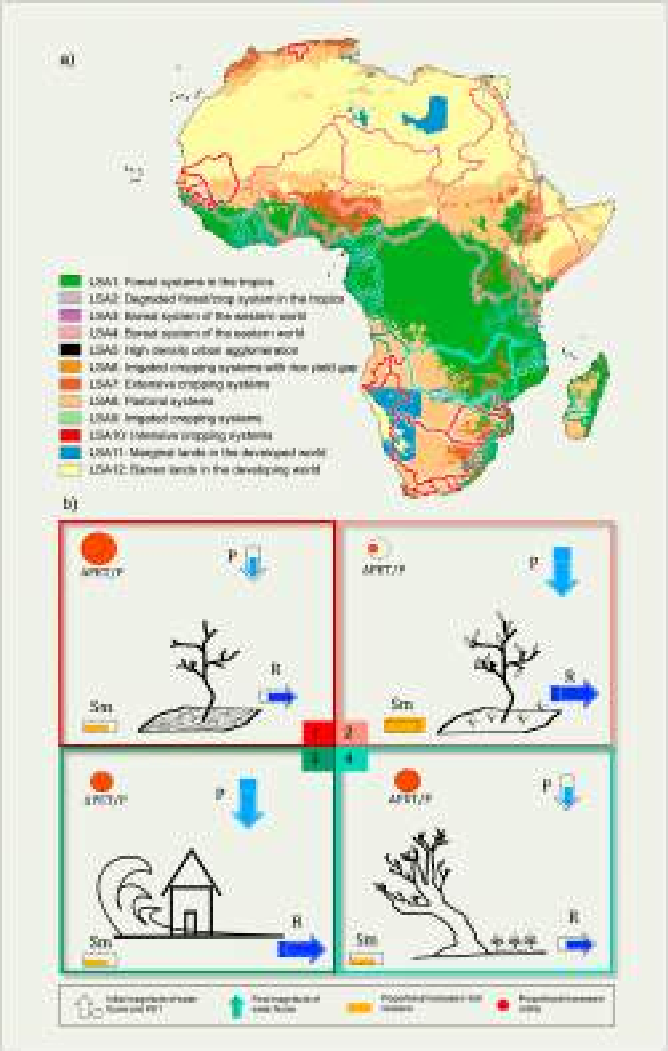

Figure 5. Implications of hydroclimatic changes for future water resources in Africa. The map (a) shows the 50 African basins divided in the four hydroclimate change groups in the RCP8.5 (as in Figure 4) overlaid to the land system archetypes (LSAs) map developed by Václavík et al. (2013). The LSA synthetizes the main social-ecological systems in Africa. The panel (b) is a graphic synthesis of the future hydroclimatic changes in Africa. The relative magnitude of water fluxes is depicted for precipitation (P), runoff (R), soil moisture (Sm), and aridity (PET/P) between the periods 1960–1989 (dashed) and 2070–2099 (colored). The four groups are the outcome of the cluster analysis, combining initial aridity conditions (PET/P < 2.4 and PET/P > 2.4) with the two sets of changes in PET/P, E/P, P, and Sm foreseen in Africa. The icons in the four groups serve to illustrate the potential implications of changes in hydroclimatic parameters on African social-ecological systems.

social-ecological context of Uganda, Rwanda, and Burundi (Liniger et al., 2002; WOCAT, 2017), where slope control measures helped contrasting excessive R and increasing Sm, leading to increased crop production and food security.

The last group (light green) includes six humid Southern African basins (e.g., the Zambezi River basin) with a projected increase in PET/P and decrease in P, R, and Sm. These hydroclimatic changes will result in less water available for both natural vegetation and rainfed agriculture in inland areas, with a particularly negative impact on the vast semiarid grasslands. These grasslands are most dependent on precipitation resources for vegetation growth and ecosystem's health (Weltzin et al., 2003). Grazing activities could put further pressure on rangelands increasing the risk of desertification triggered by increasing aridity. The Zambezi, for instance, is one of the largest rivers flowing on semiarid lands, making social-ecological systems notably dependent on its seasonal flooding cycles. The projected decrease in R could thus reduce or change flooding patterns, threatening the rich biodiversity of its delta, closely dependent on river discharge. Zambia represent a particularly sensitive situation, with 46% of undernourished population, but with an increasing crop production that may be at severe risk from hydroclimatic change. It is important to notice that in this group, the intensity of the hydroclimatic changes is essentially identical in both RCPs, suggesting that CO_2 emission reduction policies alone might not be enough to prevent the negative effects of climate change on water resources (decrease in P, R, and Sm). Decision makers could subsidize agricultural management practices that optimize the use of precipitation resources to compensate the possible loss of rainfed crop production and help cope with increasing risk of aridification. For instance, in Zambia (WOCAT, 2017) small Earth dams are being successfully used to collect runoff and provide irrigation and water for livestock.

Given the high uncertainty of model's projections and the weak agreement between models (especially regarding soil moisture simulations), this study does not aim to predict the impacts of hydroclimatic change on the socioeconomic activities of Africa. Rather, the aim of this study is to provide a general overview of the implications of future hydroclimatic change on water resources at the continental scale so as to provide guidance for large-scale policy decision making to support freshwater resources and agricultural development. Even if the Paris Agreement represent a potential desirable scenario to limit depletion of African water resources in key regions such as Northern and Southern Africa, its effectiveness is largely conditioned by the most developed countries outside of the continent. African countries can instead have more jurisdiction on local land management plans and thus directly contribute to preserve freshwater resources using sustainable agricultural practices. There are barriers to the implementation and spreading of the recommended agricultural management practices (e.g., mulching and rainwater harvesting), especially the financial costs in the implementation phase, higher labor required for some practices, and the high level of knowledge needed to properly implement and maintain these practices (Liniger et al., 2019). This paper delineates the potential use and the purpose of some of these practices to cope with hydroclimatic changes in the four key hydroclimate change regions of the African continent to inform policy and funding plans that could overcome these socioeconomic barriers and facilitate the implementation of such practices.

5. Conclusions

Hydroclimatic conditions following the Paris Agreement are likely to affect water resources in Africa less than the business as usual scenario, but in either case, African basins will consistently experience hydroclimatic change as outlined across the four groups here presented. This result highlights the potential of our hydroclimatic assessment to provide a roadmap to understand the major implications of hydroclimatic change on water resources and plan for effective and sustainable adaptation strategies at the regional level.

Climate change can induce unequal water availability in terms of precipitation and runoff, leading to reductions in irrigation potential, agricultural production, and possibly exacerbating conflicts over water resources in Northern and Southern Africa. On the other hand, some hydroclimatic changes can potentially provide more water to the key region of the Sahel, where water and land conservation practices such as water harvesting can promote agricultural production for the growing population. Sustainable land management can be extremely important to preserve and improve soil moisture and limit soil evaporation in regions with projected increase in PET/P, supporting food production under drier conditions (Southern and Northern Africa) and preventing soil loss and floods damage in wet regions (basins in tropical Africa).

However, more policies and funding are needed to make the spreading of these practices feasible and effective at larger scales.

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AGU PUBLICATIONS

Earth's Future

Supporting Information for

Future hydroclimatic impacts on Africa: Beyond the Paris Agreement

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This document contains supplementary figures and tables providing additional information on the methodology used to calculate hydroclimatic changes (Figure S1), additional results of the hierarchical clustering trees (Figures S2 and S3), bar plots of hydroclimatic change in the RCP4.5 (Figure S4), hydroclimatic-change regions with four socio-economic indicators at country level (Figure S4) and the table with the 9 CMIP5 models used in this paper with the main specifications (Table S1).

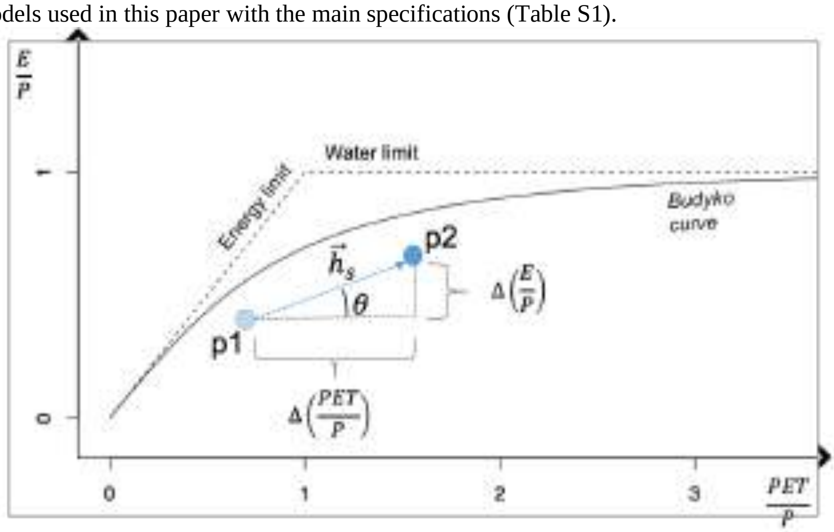

Figure S1. Movement in the Budyko space. The Budyko space is represented by the two axis PET/P and E/P in which the hydroclimatic condition of a basin can be described by the Budyko curve, which is constrained by the water and energy limits (dotted lines). The vector of hydroclimatic change of a basin between two periods in time p1 and p2 is denotes as ($\vec{h}_s$) with corresponding initial and final conditions of the aridity index (PET/P) and evaporative ratio (E/P).

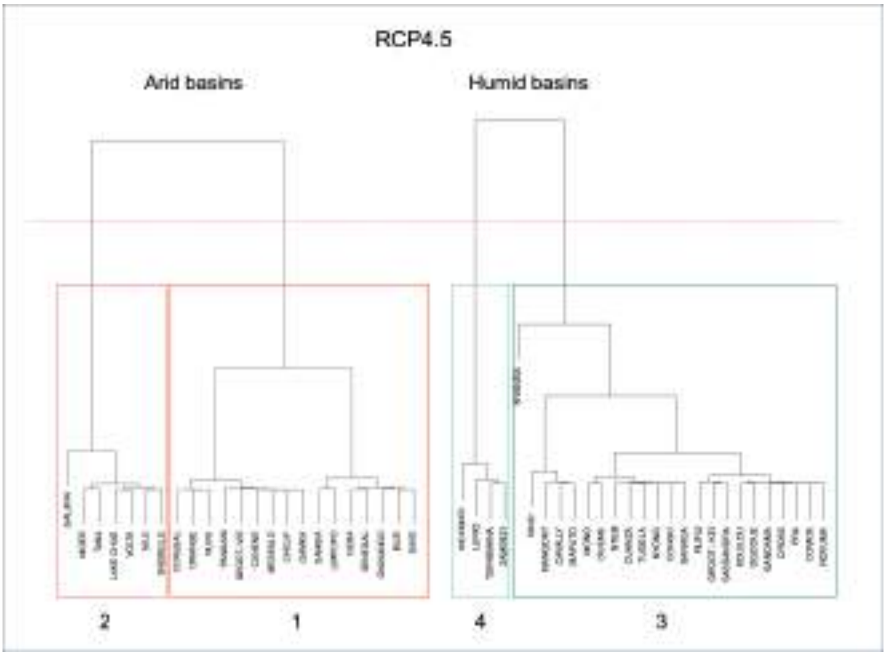

Figure S2. Hierarchical cluster analysis of hydroclimatic change parameters of the 50 largest African basins for RCP4.5. Four hydroclimate-change groups were identified, two for arid basins (red shaded rectangles) and two for humid basins (green shaded rectangles).

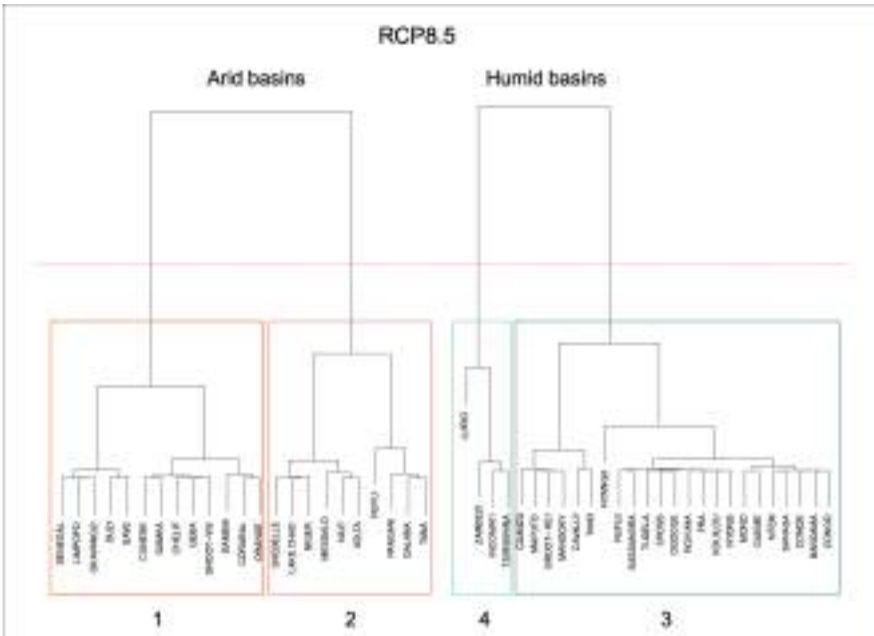

Figure S3. Hierarchical cluster analysis of hydroclimatic change parameters of the 50 largest African basins for RCP8.5. Four hydroclimate-change groups were identified, two for arid basins (red shaded rectangles) and two for humid basins (green shaded rectangles).

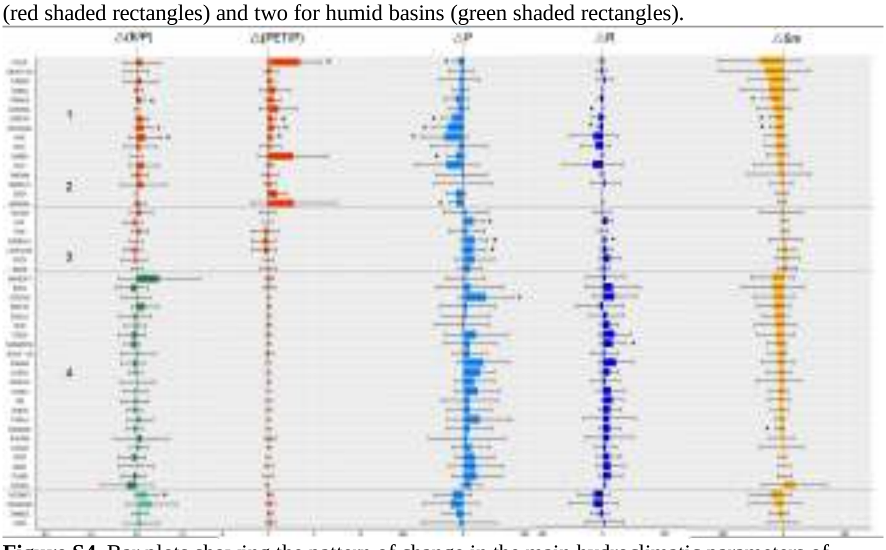

Figure S4. Bar plots showing the pattern of change in the main hydroclimatic parameters of evaporative ratio – E/P, aridity index – PET/P, precipitation – P, runoff – R and soil moisture – Sm, from 1960-1989 to 2070-2099 for the RCP4.5 scenario. P, E, R and Sm were derived from climate models' outputs and PET is the average of two different methods (see methods section). Error bars represent the spread between the 9 ESM and statistically relevant changes (Pearson; $p<0.05$) are marked with asterisks. The colors of the different parameters are chosen for visual purpose and are consistent throughout the paper. The colors of $\Delta(E/P)$ represent the four clusters of hydroclimatic change – dark red for group 1 (because describe arid basins becoming more arid), light red for group 2 (for arid basins becoming wetter), dark green for group 3 (for humid basins becoming wetter) and light green for group 4 (for humid basins becoming drier).

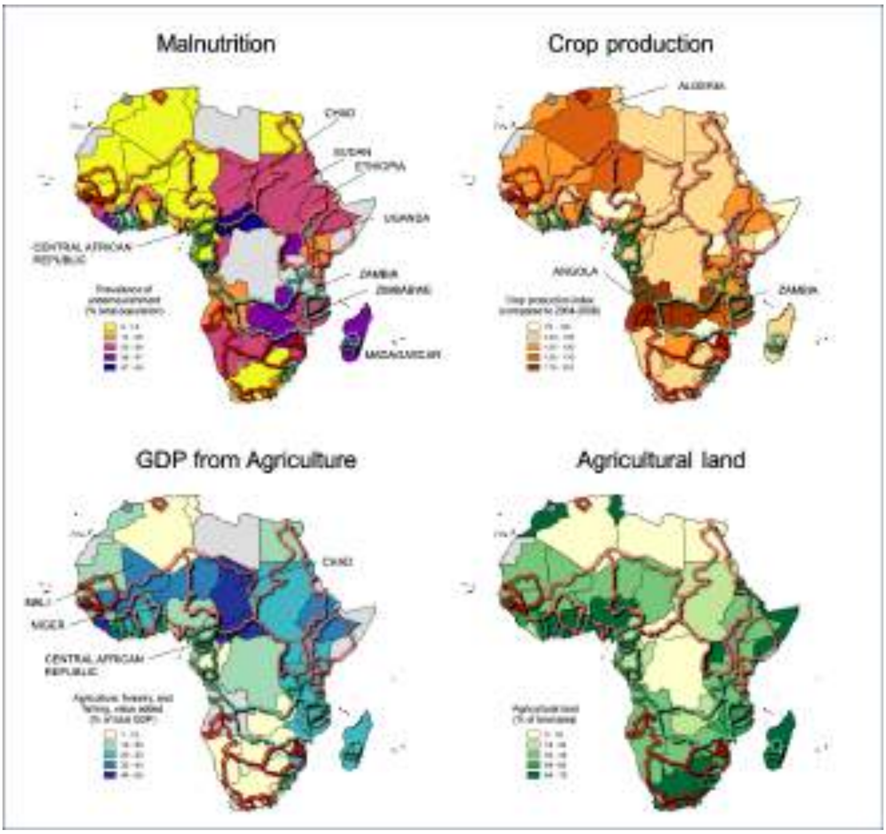

Figure S5. Maps showing the basins classified in the four hydroclimatic-change regions for the RCP8.5 scenario overlaid with the four agriculture-related socio-economic indicators of "Malnutrition", Crop production", "GDP from agriculture" and "Agricultural land" estimated from FAO (FAO, 2005) at national scale. Hotspot countries are indicated in the figure. The four indicators are described in detail hereafter.

Malnutrition

We estimate malnutrition by using the indicator "prevalence of undernourishment", which represent "the proportion of the population whose habitual food consumption is insufficient to provide the dietary energy levels that are required to maintain a normal active and healthy life" .

This indicator is being used to measure progress towards the Sustainable Development Goal 1 (SDG1, “No hunger”), target 2.1 of the SDG framework.

Crop production

Crop production index shows agricultural production for each year relative to the base period 2004-2006, including all crops except fodder crops. Values are expressed in international dollars, normalized to the base period 2004-2006.

GDP from agriculture

Proxy of the contribution of agriculture to the national GDP. Percentage of the GDP at country level from agriculture, forestry, and fishing.

Agricultural land

Percentage of country area dedicated to agriculture.

Model	**Atmospheric resolution**	**Specifications**
NorESM1-ME	2.5° X 1.9°	Norwegian Earth System Model with interactive carbon cycle, version 1 (medium resolution)
NorESM1-M	2.5° X 1.9°	Norwegian Earth System Model, version 1 (medium resolution)
MRI-CGCM3	1.12° X 1.12°	Metereological Research Institute – Coupled Atmosphere-Ocean General Circulation Model, version 3
MIROC5	1.4° X 1.4°	Model for Interdisciplinary Research on Climate
CNRM-CM5	1.4° X 1.4°	Centre National de Recherches Meteorologiques – Coupled Global Climate Model, version 5
CMCC-CM	0.75° X 0.75°	Centro Euro-Mediterraneo per i Cambiamenti Climatici – General Ocen-Atmosphere Circulation Model
inmcm4	2° X 1.5°	Institute of Numerical Mathematics – Coupled Model, version 4.0
IPSL-CM5A-MR	2.5° X 1.26°	L’Institut Pierre-Simon Laplace – Coupled Model, version 5, coupled with NEMO, mid resolution
MPI-ESM-MR	1.865° X 1.875°	The Max Planck Institute for Meteorology Earth System Model, mid resolution

Table S1. List of CMIP5 climate models analyzed in the study, with details on their horizontal and vertical atmospheric resolutions and the main model components.

II

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Estimating the global potential of water harvesting from successful case studies

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ABSTRACT

Water harvesting has been widely applied in different social-ecological contexts, proving to be a valuable approach to sustainable intensification of agriculture. Global estimates of the potential of water harvesting are generally based on purely biophysical assessments and mostly neglect the socioeconomic dimension of agriculture. This neglect becomes a critical factor for the feasibility and effectiveness of policy and funding efforts to mainstream this practice. This study uses archetype analysis to systematically identify social-ecological regions worldwide based on > 160 successful cases of local water harvesting implementation. We delineate six archetypal regions which capture the specific social-ecological conditions of the case studies. The archetypes cover 19% of current global croplands with hotspots in large portions of East Africa and Southeast Asia. We estimate that the adoption of water harvesting in these cropland areas can increase crop production up to 60–100% in Uganda, Burundi, Tanzania and India. The results of this study can complement conventional biophysical analysis on the potential of these practices and guide policy development at global and regional scales. The methodological approach can be also replicated at finer scales to guide the improvement of rainfed agricultural.

1. Introduction

Improving rainwater use in agriculture is necessary to ensure sustainable food production for the growing global population (Rockström et al., 2009; Springmann et al., 2018). Since the use of water from river and groundwater resources is reaching unsustainable rates (Aeschbach-Hertig and Gleeson, 2012; Hoekstra and Wiedmann, 2014; Jaramillo and Destouni, 2015), increasing water withdrawals and consumption by intensive irrigation is not a suitable option in many regions of the world. Moreover, a better management of freshwater resources alone will not be sufficient to ensure sustainable food production, because land degradation caused by climate and land use change drivers is a major constrain to agro-ecosystems' functions (IPBES, 2015). On the other hand, rainfed agriculture still has a large untapped potential, particularly in dry and tropical developing areas (Rockström et al., 2010). To tackle this urgent issue, the UN General Assembly recently declared the 2021–2030 as the "Decade on Ecosystem Restoration", which acknowledges and enforces the restoration of degraded ecosystems as a necessary measure to fight climate change and enhance food security, water supply and biodiversity (P. Besseau et al., 2018; UN Environment, 2019).

To address the sustainability of future agriculture in this context, a more holistic approach aiming at agro-ecological restoration through sustainable land and water management is a fundamental milestone (Rockström et al., 2014, 2009). Rainwater harvesting can represent an important strategy to improve rainfed agriculture and increase crop yield sustainably, especially in marginal areas and improve human wellbeing (Mugagga and Nabaasa, 2016; UNEP, 2009). Broadly, water harvesting can be defined as the set of practices intended to increase water availability for plants, including water infiltration and retention in the soil, through the collection and storage of rainwater or runoff. Retaining and conserving more rainwater for productive purposes can help coping with prolonged dry spells, the major challenge faced by rainfed agriculture, especially in the most arid and semi-arid areas of the world (Rockström et al., 2002). Typical examples of rainwater harvesting practices are dugout ponds, used to collect and store

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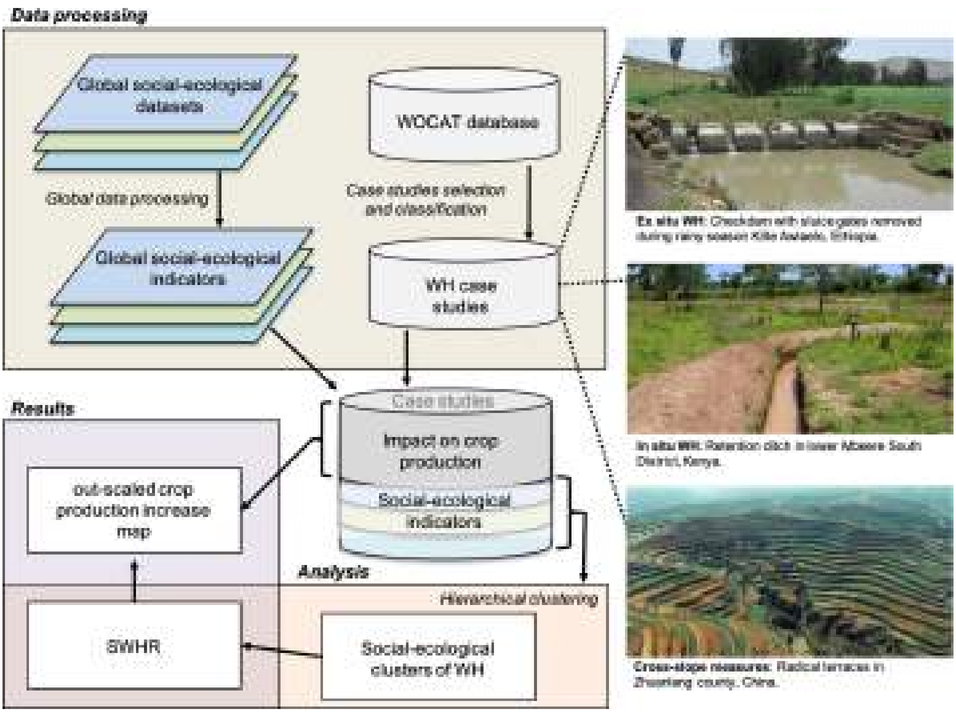

Fig. 1. Analytical framework used to map the out-scaled benefit of water harvesting on crop production. Data processing includes both the WOCAT case study selection and classification (with pictures as example of the three water harvesting groups) and the global dataset processing to create the social-ecological indicators. Cluster analysis on the selected case studies was used to extract the ranges of social-ecological indicators to create the archetypes, mapped at global scale and used to produce the out-scaled potential on crop production. The photos are taken from the case studies "1244" for in-situ, "1547" for ex-situ and "1419" for cross slope measures.

rainwater within the farmland for supplementary irrigation during dry periods (Liniger and Mekdaschi Studer, 2019). Other widespread practices are terraces, built on steep terrains to slow down runoff and increase infiltration and traditionally used in the Latin American, African and Asian highlands (Denevan, 2003; Mekdaschi Studer and Liniger, 2018; Saiz et al., 2016; Stroosnijder, 2009).

Rainwater harvesting (from now on termed water harvesting) has been for long considered a sustainable way of increasing water productivity in rainfed agriculture (Rockström et al., 2010) with positive examples ranging from local (Barron and Okwach, 2005; Rockström et al., 2002) to catchment-scale implementations (de Bruin et al., 2015; Dile et al., 2016; Uhlenbrook et al., 2004). Nevertheless, the large-scale uptake of water harvesting is hindered by limited knowledge on eco-hydrological limits at the catchment scale (Ngigi, 2003), the lack of large scale investments (Rockström and Falkenmark, 2015) and the poor understanding of farmers' socioeconomic and agro-ecological circumstances and needs by governments (Anderson, 2004). On the other hand, global assessments of water harvesting and its potential impact on reducing the yield gap are generally based on ecohydrological analysis (e.g. Jägermeyr et al., 2016; Mueller et al., 2012; Rosa et al., 2018; Wisser et al., 2010). These assessments highlight the good potential of water management (including non-intensive irrigation) to close the yield gap in most of Eastern Africa, Western Sahel, India and Eastern China. However, they do not account for the social-ecological complexity of land degradation and water management, which is context-specific and difficult to capture at a global scale (Cherlet et al., 2018), with the risk of providing generic estimates of ideal potential or best-case scenarios (Tittonell and Giller, 2013).

Archetype analysis is an approach used in sustainability research to bridge the complexity of global problems with the low generalizability of local solutions by revealing recurrent social-ecological patterns (Oberlack et al., 2019; Sietz et al., 2019). Previous research (Seppelt et al., 2018; Václavík et al., 2016, 2013) has shown the use of spatially-explicit archetypes to inform the out-scaling of local projects based on the assumption that similarity in social-ecological characteristics is a requisite for transferability of outcomes to different regions.

Building on the archetype approach, we present global spatially-explicit archetypes derived from successful water harvesting case studies. We analyse 167 cases of successful water harvesting implementation collected by the World Overview of Conservation Approaches and Technologies (WOCAT, 2019), with the intention of learning from local projects that are already in place to inform on the potential spatial out-scaling of water harvesting. Our approach offers a systematic methodological contribution to outline transferability areas from case studies. By identifying similar social-ecological regions (archetypes), we provide an intermediate level of generalization – not too context-specific, which would make replicability impossible, neither too generic, to avoid one-fits-all solutions.

The objective of this paper is twofold; i) to map social-ecological archetypes for transferability of water harvesting implementations, and ii) to estimate the potential increase in crop production within the archetypes derived from the case studies. The results presented in this paper can serve to complement purely eco-hydrological estimates based on a-priori environmental and climatic conditions. The methodological approach can be replicated at different scales and used as a planning tool to support global to regional decision making in the development of large-scale policies, funding and implementation of sustainable land and water management projects to support the coming UN decade of ecosystem restoration.

2. Data and methods

We first provide an overview of the methodological steps used to develop the archetypes and how we used them to quantify the crop production increase resulting from the global extrapolation of water harvesting based on case studies (section 2.1). We then explain in detail the selection and processing of the data – social-ecological indicators and the classification of case studies (section 2.2). Finally, we describe the clustering analysis performed to define the archetypes (section 2.3).

2.1. Analytical framework

To out-scale the impact of the water harvesting case studies on crop production to the global scale, we use a mixed methodology building on hierarchical clustering and spatial analysis (Fig. 1). Our main assumption, building on the use of archetypes for transferability of local case studies (Václavík et al., 2016), is that the crop production increase observed in the WOCAT case studies can be replicated in the areas with similar social-ecological conditions. The conditions related to replicability of water harvesting are defined by the relevant social-ecological indicators described in section 2.2.1.

In a first step of our methodology (data processing in Fig. 1), we selected and processed the social-ecological datasets (Table 1) to obtain spatially-explicit social-ecological indicators with a global coverage. We then masked the eleven social-ecological indicators for each WOCAT case study based on their latitude and longitude location. In a second step, we clustered the case studies on the basis of the eleven social-ecological indicators that were selected according to the criteria explained in Section 2.1. These clusters represent groups of case studies with similar social-ecological conditions. We extracted minimum and maximum values of each indicator and for each cluster, defining the range of social-ecological conditions of each cluster. The out-scaling procedure used the ranges of social-ecological indicators to define spatial areas (archetypes) with similar social-ecological conditions as in the successful water harvesting case studies. From a computational point of view, every pixel (of a global raster dataset) with all the social-ecological indicators within the ranges defined by the same cluster was attributed to the same archetype.

Finally, we used the impact assessment information of the WOCAT case studies (specifically the *crop production* change) to out-scale crop production increase within every archetype, as described in section 2.3.

2.2. Data selection and processing

To identify the social-ecological similarity between water harvesting case studies with a cluster analysis, we used eleven global raster datasets of different social-ecological factors that are relevant to water harvesting implementation and success (Table 1) and the WOCAT database of successful water harvesting case studies across the world (WOCAT, 2019). Hereinafter, the detailed description of the selection and processing of these data is presented.

2.2.1. Selection of social-ecological indicators

We conducted a qualitative literature review to identify the social-ecological factors most relevant for the implementation of water harvesting techniques. We used these indicators to define the out-scaling conditions of water harvesting, in line with other global agricultural out-scale assessments and archetype analysis (Prestele Reinhard et al., 2018; Sietz et al., 2017, 2011). The factors relevant for the adoption of agricultural practices usually span over several social-ecological domains. Following Woittiez et al. (2015), we identify factors across physical, socioeconomic, institutional and cultural domains. In these domains, we only considered those factors that are not too context-specific and allow for an intermediate level of abstraction for the sake of generalizability, which is key in building archetypes (Oberlack et al., 2019). For this reason, although cultural and traditional factors such as trust, cooperation, norms and values are extremely important for the implementation of water harvesting at field level (Descheemaeker et al., 2019; Sterling et al., 2017; Woittiez et al., 2015) we did not explore the relevance of these factors because of their highly contextual nature, which needs to be taken into account at a local level.

Using the definition given by Ouessar et al. (2012) and (UNEP, 2009), we considered water harvesting as "The collective term for a wide variety of interventions which are primarily or secondarily intended to collect natural water resources which otherwise would have escaped from human reach, and buffer them through storage and/or recharge on or below the soil surface". The large set of practices embraced by this definition can be generally classified in the three main groups of "ex-situ", "in-situ" and "cross slope measures". Ex-situ water harvesting includes practices that collect runoff water from an area external to the storage point (the farmland), generally used for irrigation (e.g., small dams and check dams, road water harvesting, dugout

Table 1
Global datasets covering physical, socioeconomic, institutional and cultural dimensions, used to delineate the social-ecological archetypes.

Indicator	Processing	Source
Physical		
Potential evaporation	Mean annual value (mm yr^{-1}) for the period 1986–2016, aggregated from monthly data.	Harris et al. (2014)
Precipitation	Mean annual value (mm yr^{-1}) for the period 1986–2016, aggregated from monthly data.	Harris et al. (2014)
Seasonality	Dimensionless index averaged for the period 1986–2016.	Walsh and Lawler (1981)
Slope	In degrees. Calculated from terrain elevation data of the harmonized world soil database v12.	Fischer et al. (2001)
Soil quality	Soil organic carbon content (Mg C. ha^{-1})	FAO (2017)
Socioeconomic		
Human Development Index (HDI)	Aggregate dimensionless indicator.	Kummu et al. (2018)
Farm size	Dimensionless field size indicator according to source from 10 (smaller) to 40 (larger), rescaled at 10 km resolution.	Fritz et al. (2015)
Agricultural labour	Ad-hoc indicator of working age population density (16 to 65 years old) at grid level adjusted with percentage of national employment in agriculture at country scale.	Doxsey-Whitfield et al. (2015, p. 4). http://www.fao.org/faostat/en/#data.
Remoteness	Minutes to reach the closest market (city with > 50.000 people).	Weiss et al. (2018)
Institutional		
Land tenure	Average of 10 dimensionless indicators for registering properties at national level.	*Doing* Business 2020 (2020)
Socio-cultural		
Gender inequality	Subnational indicator of patrilocality adjusted with national patrilocality index to fill the gaps.	Szołtysek et al. (2017)

ponds). In-situ water harvesting refers to in-field soil and vegetation management practices applied to increase infiltration and reduce runoff and evaporation (e.g., micro-catchment, mulching, conservation tillage, vegetative strips). Finally, cross-slope measures are practices that increase retention of runoff and infiltration within the farm through slope stabilization and contour measures in steep terrains (e.g., progressive and radical terraces, contour trenches and bunds).

The three groups of water harvesting practices range across various application purposes and implementation efforts, which require specific socioeconomic and institutional conditions to support them. For instance, cross slope measures and most of the ex-situ techniques (e.g., Sudanese Teras systems reported by Niemeijer, 1998) require a long-term commitment due to their high costs and labour intensity. Also, farmers need skills and information to properly implement and maintain these practices, and generally higher educated farmers have higher chances to succeed (Woittiez et al., 2015). The material costs for expensive measures are often covered by loans or credit and are particularly decisive in the initial part of the implementation of the water harvesting practices (Mekdaschi Studer and Liniger, 2018). In absence of the latter, price subsidies and tax relief are some financial measures used by governments to foster access to water for agriculture (Lado, 1997; Mankad and Tapsuwan, 2011). The profitability of water harvesting is also conditioned by accessibility to roads and market, which is crucial to buy inputs and most importantly for selling the produce (Barron et al., 2015; Hatibu et al., 2006; He et al., 2007). Moreover, government decisions and enforcement are more effective and the quality of public services is generally higher as the regions are more accessible and connected to larger cities (Sietz et al., 2017).

Depending on the cost and labour availability, the farm size is also relevant, because the implementation of practices in larger plots with low labour availability is very difficult and their maintenance cannot be sustained (Petanidou et al., 2008). Moreover, in these adverse conditions, farmers are more willing to invest in water harvesting when they have a certain degree of land security, with long term contracts or well-established ownership (Gebremedhin and Swinton, 2003; Kyomugisha, 2008; Woittiez et al., 2015). Similarly, life expectancy is important in determining the feasibility of a long-time commitment in land management (Amsalu and de Graaff, 2007), since young farmers have a longer time to return their initial investment when compared to older farmers. However, more experienced farmers might have a better knowledge and ability to perceive the risk of soil erosion, thus increasing the chances of a successful implementation (Sheikh et al., 2003; Tiwari et al., 2008).

Amongst relevant socio-cultural factors related to the successful adoption of water harvesting, gender discrimination plays an important role. When gender inequality is high, extension officers target mostly male farmers, hindering the potential adoption by women farmers, who are often lacking access to irrigation (Baguma et al., 2013; Ragasa et al., 2013; Zwarteveen, 1997). Moreover, in highly patriarchal societies, women do not own the land, thus they lack the decision power to implement practices.

For what concerns the physical (hydroclimatic and environmental) factors driving the adoption of water harvesting, the literature has extensively referred to the precipitation availability and its distribution within seasons, aridity conditions and soil quality as common factors driving the adoption of water harvesting across socioeconomic regions (Ammar et al., 2016; Bulcock and Jewitt, 2013; Hoff et al., 2010). The purpose of water harvesting is to make the most productive use of precipitation that is either scarce because of low amount or high potential evaporation, or unavailable due to high seasonality. These factors affect the soil quality, even when precipitation is very intense, inducing soil erosion, which can be effectively addressed by cross-slope measures in steeper terrains. In fact, the slope of the terrain is another relevant factor determining the potential and type of water harvesting techniques (Bulcock and Jewitt, 2013). For instance, radical terraces are better suited for very steep terrains when compared to progressive terraces, which are rather used on gentle slopes.

To account for the relevant factors described above, we preliminarily selected the 14 indicators of “precipitation amount”, “seasonality”, “aridity”, “slope”, “water yield-gap”, “soil organic carbon”, “farm size”, “agricultural labour”, “land tenure”, “governance”, “remoteness”, “Human Development Index” (HDI), “access to credit” and “gender inequality”. We used the HDI as an aggregate indicator which embraces the key aspects of “education”, “income” and “life expectancy” (Kummu et al., 2018).

Since many of the selected social-ecological factors are unavailable at the global scale and/or lack the sufficient spatial resolution, we created spatial indicators to extend the factors with a global coverage (see Supplementary information section). To avoid redundancy, we checked for spatial correlation among indicators using the Pearson method. From the original set of indicators, we excluded “access to credit” and “governance” due to their high correlation to “HDI” ($|r| > 0.7$). We also excluded the “water yield gap” due to its correlation with “precipitation” ($|r| > 0.6$) – see correlation matrix in Table S3 (supplementary information). The final set of eleven indicators is summarized in Table 1. Because of the different units of measurement and magnitudes across datasets, we scaled all the indicators to a spatial resolution of 5 arc-min (0.083 degree) and normalized them (i.e., zero mean and unit variance) before performing the clustering analysis.

2.2.2. WOCAT case studies

All the case studies used for the out-scaling process were taken from the WOCAT database (Liniger et al., 2019), which gathers 1046 case studies as of March 2019, covering a wide range of sustainable land management practices across 130 countries, including those related to agroecology, agroforestry, mixed agricultural-pastoral systems and water harvesting. The WOCAT has been established since 1992 and it has been officially recognized by the UNCCD as the primary recommended Global SLM Database for best practices. It has been referenced/used in the UNCCD Science-Policy Interface report on Sustainable Land Management, the IPBES assessment report on land degradation and restoration and in the EC JRC World Atlas of Desertification (Cherlet et al., 2018; Liniger et al., 2019). All the case studies include a standardized assessment of the impact of the practices after their implementation (Liniger et al., 2019). Although the WOCAT database is a self-reported database, its quality and reliability are guaranteed by a reviewing process involving national and international land management specialists.

We screened the 1046 cases of sustainable land management practices available in the latest web-based version of the database and selected only the case studies related to water harvesting, that is, all the practices that directly or indirectly aim at increasing the retention of water in the landscape for agricultural purposes. After excluding the cases with missing spatial information (geographic coordinates), we obtained a subset of 173 case studies that we further screened to exclude multiple cases falling within the same gridded pixel, which would be redundant given our methodological approach described in detail in sections 2.3 and 2.4. We obtained a final number of 167 cases, which we then classified into the three main water harvesting groups described in section 2.2.1 (i.e., ex-situ, in-situ and cross-slope measure) and further split them into subgroups to capture the diversity of the range of practices present in the database (Table S1, supplementary material). The resulting final set of case studies is spread across all continents and different social-ecological contexts and has a higher representation in African and South Eastern Asian countries (Fig. 2 and Table S2).

One core component of the WOCAT case studies used in this work is the “impact assessment information”. The section is structured as a questionnaire compiled by a field expert (i.e. extension officers, agronomist and social scientists) together with local farmers some years after the implementation (typically 5–10 years). The questionnaire contains the impacts of the practice related to the change of a set of

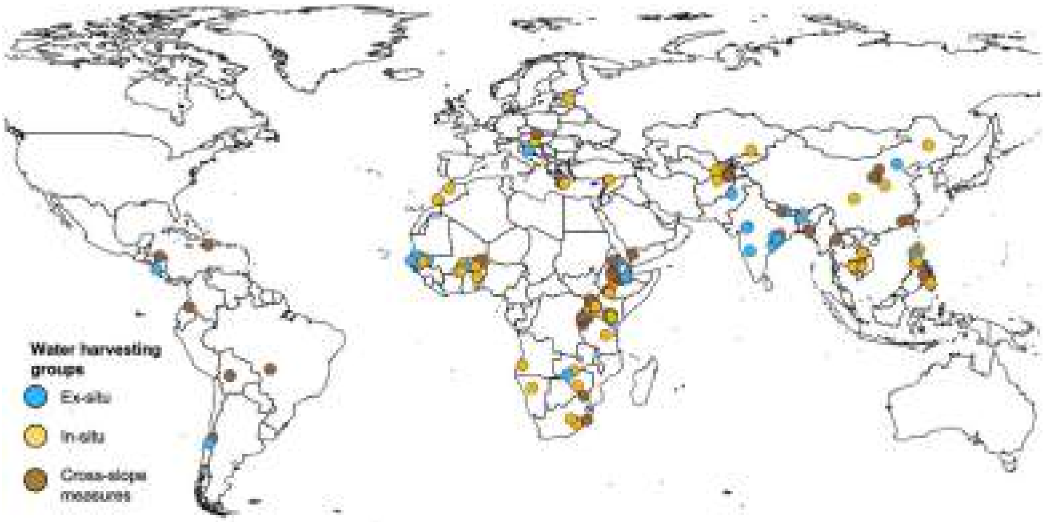

Fig. 2. Location of the final set of case studies (n = 167) selected from the WOCAT database divided in the three water harvesting groups "Ex-situ", "In-situ" and "Cross slope measures".

social-ecological indicators, including crop production. The impact is presented as a seven-item scale of crop production change ranging from very negative (−50–100%) to very positive (+50–100%), with the 3 positive scores corresponding to slightly positive (+5–20), positive (+20–50) and very positive (+50–100%) increases in crop production. When the impact data could not be assessed based on measurements, compilers gave their best estimate following a detailed guideline provided by WOCAT. A snapshot of the impact assessment sheet is presented in Fig. S1 of Supplementary material. This information was used in the out-scaling phase of the study, where regions with similar social-ecological characteristics were assigned the same impact outcome (percentage increase in crop production) as in the case studies, as described in the next section.

2.3. Cluster analysis and archetypes

The clustering analysis is a statistical procedure that assigns objects (case studies in this case) to exclusive groups based on the overall similarity of the clustering factors (e.g. the eleven social-ecological indicators). Other global land system studies have used a different clustering approach that involves the classification of every grid cell in a map using either a-priori criteria for threshold selection (supervised classification) or unsupervised criteria that might result in a generic and less contextual classification (unsupervised classification). We performed K-means clustering (Master and Professor, 2011) on the ensemble of the 167 successful case studies. To determine the optimal number of clusters, we used the NbClust function (NbClust package in R, (Charrad et al., 2014)) with the "ward.D" hierarchical method (Ward, 1963) and "Squared Euclidian" distance matrix. The function calculates 30 different indices to find the best number of clusters based on the majority rule. The highest number of indices (seven) proposed six as the optimal number of clusters. Guided by the NbClust analysis, we inspected different number of clusters (between 6 and 10), noticing that six was indeed the optimal one needed to ensure enough number of case studies in each cluster and cover the highest ranges of clusters. Each cluster is characterized by a set of ranges of social-ecological indicators representing the specific social-ecological conditions that are common between multiple successful water harvesting case studies.

To generate the successful water management archetypes, we extracted the range of values (min–max) for each indicator in every cluster. If all the values of a pixel were within the ranges of a cluster, then the pixel was assigned to that specific archetype. Hence, archetypes may overlap in space, representing transition areas with similar social-ecological characteristics. When overlapping, we chose the archetype with the smallest extent since it provides a more accurate description of the local situation, representing more niche social-ecological conditions.

We assigned the crop production increase to each archetype by using the average value of impact for all case studies in each cluster, as stated in the impact assessment section of the case studies (Supplementary Fig. 1). In case of overlapping archetypes, we picked the lowest value of crop production increase as a conservative estimate.

Finally, we calculated a national level index in order to include a measure of uncertainty in our analysis. This index considers higher uncertainty levels in countries with lower number of case studies and higher estimated archetype extent, by using the following equation:

$$\text{Uncertainty} = \frac{Ar_R}{N} \tag{1}$$

where Ar_R is the ratio of archetype extent to total cropland area at national level and N is the number of WOCAT case studies in each country. We performed all data processing and analysis in R Studio (R Core Team, 2016).

3. Results

The clustering analysis produced six clusters of WOCAT case studies, which synthetize the social ecological conditions of the 167 successful water harvesting case studies (Fig. 3).

The archetypes mapped from the clusters of water harvesting case studies have different, but sometimes overlapping, geographical extents that cover large portions of Africa, Central America and Asia, and minor representations in South America and Eastern Europe (Fig. 4). Altogether, all archetypes cover 19% of the global cropland area. In other words, the 167 water harvesting case studies exhibit the set of social-ecological conditions that can be found in the 19% of the global

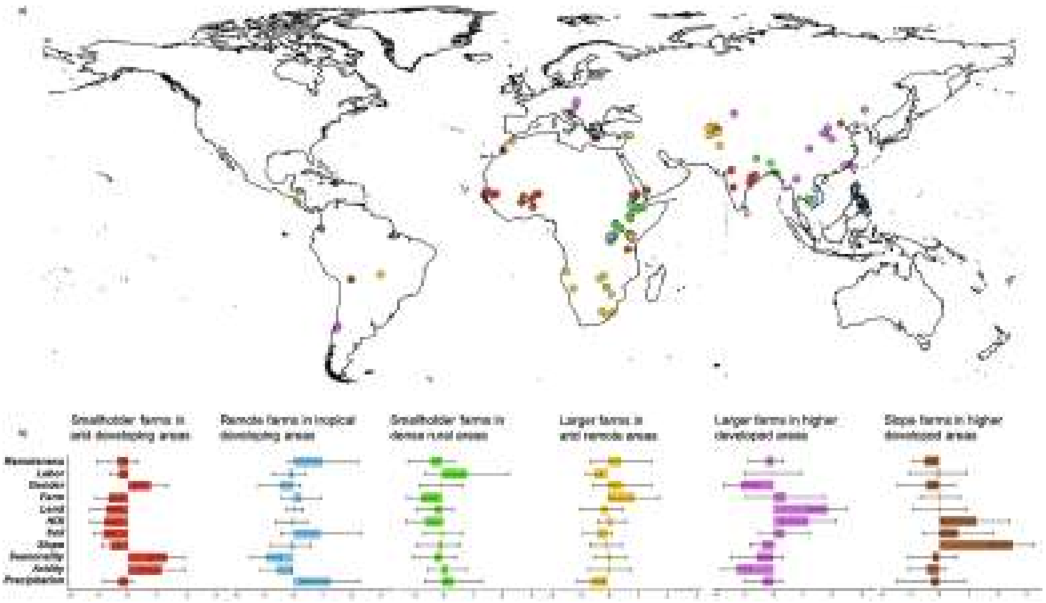

Fig. 3. Location (a) of the water harvesting case studies classified in seven clusters and (b) bar plots of the ranges of social-ecological indicators for each cluster. The names of each cluster represent the most representative characteristics of each cluster.

cropland surface area. In detail for each archetype:

"Smallholder farms in dense rural areas" is characterized by wet and seasonal climate (SI > 0.6), smallest average farm size and highest density of labour availability in the context of countries with high agricultural employment (e.g., Uganda and India). These conditions favour the implementation of water harvesting, because there is enough precipitation to provide a buffer for the dry season and enough labour force to implement larger ex-situ practices (Fig. 5; dugout ponds and dams being the most common water harvesting practices).

"Remote farms in tropical developing areas" is spread over South-East Asia (Laos, Philippines, Cambodia) and tropical Africa (mostly Uganda, Ghana and Ivory Coast). These areas do not stand out for specific socioeconomic characteristics apart from remoteness (over 300 min to the closest city), however, they are characterized by annual precipitation above 1800 mm y^{-1} and relatively high soil organ content (SOC). In this context, the most implemented practices are micro-catchment, mulching and contour bunds, which are primarily used to avoid excessive runoff that can cause soil erosion and preserve soil moisture for plant availability.

"Smallholder farms in arid developing areas" covers the Sudano-Sahel region (specifically Senegal, Burkina Faso, Niger and very small areas of Benin), some arid cropland regions in north Ethiopia and Tanzania and the central plateau of India. The very low precipitation (~900 mm y^{-1}) is concentrated in less than 3 months and the very high potential evaporation makes this archetype as the most arid of the group. The adverse hydroclimatic conditions are worsened by the low human development and the highest gender inequality, contributing to the poorest soil conditions. The most implemented water harvesting practices are in-situ, specifically micro-catchment and conservation tillage, to increase infiltration and make the best use of sporadic rainfall.

"Larger farms in remote arid areas" is characterized by semi-arid conditions, with average annual precipitation below 800 mm, and clear seasonality (seasonality index > 0.7). This archetype stands out for the very high remoteness (over 240 min to the closest city), low development (HDI of 0.58), the lowest labour availability (17 workers per km^2) and one of the highest gender gaps (0.6). These conditions exemplify rural areas with low access to irrigation and other water infrastructure where water harvesting is generally used to ensure a constant water provisioning. These conditions apply to large farmlands in Sub-Saharan Africa (Tanzania and Kenya, Zimbabwe and South Africa), the Middle East (Syria, Tajikistan, Afghanistan and Pakistan) and Latin America (Mexico, Bolivia and Brazil).

"Larger farms in high developed areas" spans from Eastern Europe (Greece Hungary, Slovakia and Estonia) to China. This archetype is determined by socioeconomic factors more than environmental ones, thus covering a broad agro-climatic spectrum – with higher representation of low precipitation areas. Here we find the largest farms in areas with the highest score in all the socioeconomic indicators – the second highest HDI, the highest lend tenure indicator and the lowest gender inequality. In this context, water harvesting serves to improve agricultural land management. Most of the cases are implementation of cross slope measure and in-situ water harvesting technologies that aim at increasing soil moisture retention (e.g., mulching and vegetative strips).

"Slope farms in higher developed areas" is the most specific archetype, characterized by high slopes (around 3 degrees) in areas with high human development (HDI of 0.72). The extent of this archetype is restricted to the limited areas with such particular conditions, thus it covers a small but characteristic extent.

The six archetypes present bundles of water harvesting practices that are generally comprehensive of all the water harvesting groups and high diversity of subgroups (Fig. 5). This result suggests that the three groups of water harvesting practices can be generally implemented in any social-ecological context represented across the 167 case studies, although with some differences, as highlighted in the description of the archetypes. A clear example is provided by "Slope farms in higher developed areas", where cross-slope measures are the dominant group to cope with the high slopes. It is worth noticing that water harvesting practices of different groups can also be applied simultaneously, for instance some case studies present a combination of structural and

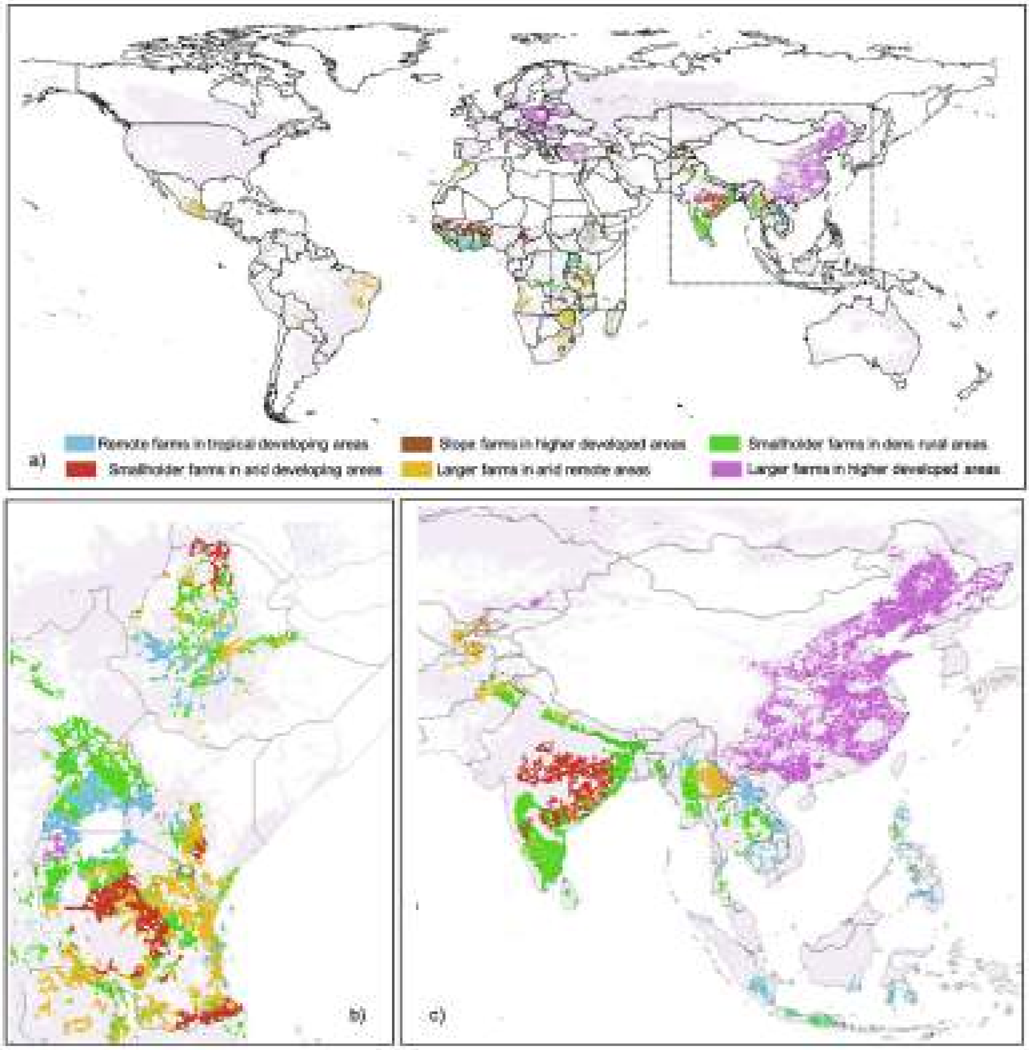

Fig. 4. (a) Global map of archetypes of successful water harvesting, and regional snapshots in (b) East Africa and (c) South-Eastern Asia. When multiple overlapping archetypes, the archetype with the smallest spatial extent is shown.

agronomic measures like pits together with terraces and mulching (e.g. WOCAT case studies Nr. 1106, 1160, 1215 and 2826; www.wocat.net).

3.1. Potential of out-scaling water harvesting on crop production

Of the total 19% of global cropland where water harvesting can be successfully implemented, the out-scaling evaluation attributes potential *moderate* (*5–20*%) increases in crop production on 8% of cropland, *high (+20–40*%) and *very high (+40–60%)* on 1% and 3%, respectively, and the *highest* increase *(+60–100%)* on the remaining 7% of global cropland area (Fig. 6). The lowest increase (+*5–20*%) is projected only in *"Larger farms in higher developed areas*", across Eastern Europe and China, while the highest increase (+*60–100*%) appears in "Smallholder farms in dense rural areas". Despite the modest global extent, the distribution of the archetypes highlights regional potential implementation hotspots located in Western Africa, East Africa, Middle East, India and China (Fig. 6).

Of these areas, East Africa and South-East Asia emerge from the uncertainty evaluation (Fig. 7) as the regions with the most reliable outcome, where our results have the lowest uncertainty because of the highest density of case studies per country. Burundi and Uganda hold the highest percentage of national cropland area under archetype, 78% and 59% respectively (Fig. 8). Among the countries with the highest number of case studies, Rwanda, Tanzania, Kenya and Ethiopia also show a total potential for water harvesting in at least 30% of their cropland area (30%, 53% and 33% and 37%, respectively). The *highest*

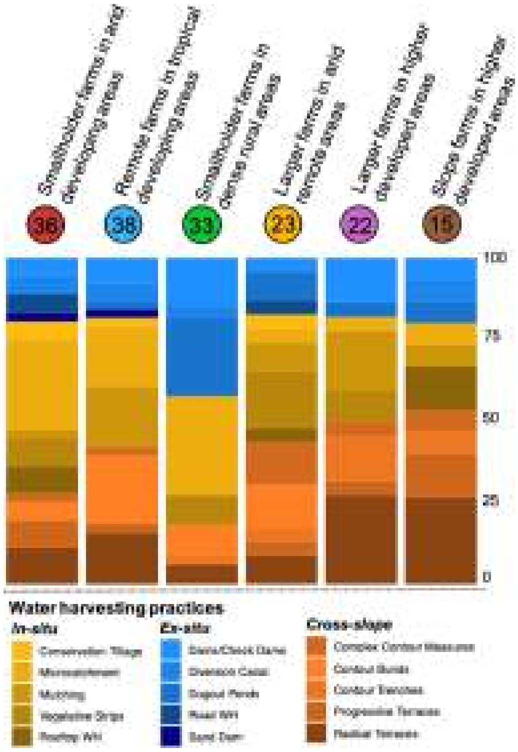

Fig. 5. Distribution of water harvesting practices in the six archetypes. The axis shows the percentage of case studies in each cluster that correspond to a given water harvesting group, in-situ (yellow), ex-situ (blue) and cross-slope (orange). The number of case studies per archetype is in the circles on top of the graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

potential increase in crop production is found in Burundi, in over half of the Ugandan archetype extent and partially in Tanzania and Ethiopia. Asia presents a more diverse pattern of water harvesting impact in both rainfed and irrigated agriculture, generally with higher impact on rainfed systems. The cropland extent under *high* potential, relative to total cropland area, ranges from 25% in Cambodia to 57% in Laos. The full list of impact areas and relative crop production increase is per country in available in supplementary material (Table S4).

While the potential of water harvesting on areas with rainfed agriculture is clear, on areas with current irrigated agriculture the implications of water harvesting are less evident. For instance, Nepal and India have around 40% of croplands under *highest* potential, with nearly a half of these areas already equipped with irrigation. Generally, irrigation can be much more effective when combined with most of the in-situ and cross-slope measures (Singh et al., 1990). Terraces are a clear example of the benefits of combining water harvesting practices and irrigation in rice cultivation (Sutton, 1984); while mulching and conservation tillage are in-situ practices that when coupled with irrigation, can help increase the rate of infiltration and reduce evaporation losses (Chukalla et al., 2015). Moreover, ex-situ practices can be used in areas equipped with irrigation to alleviate potential conflicts on water resources. As such, the expansion of water harvesting is not necessarily against ongoing implemented traditional irrigation, but a compliment to increase water availability and crop production in areas with similar physical and social-ecological conditions as those of the WOCAT dataset.

4. Discussion

Most of the archetypes are spread across the world but some with limited extent because of the particular social-ecological conditions captured by the WOCAT case studies. Generally, when the range of social-ecological indicators of an archetype is centred around the normalized mean (see Fig. 3), the archetype covers a broader spatial extent when compared to archetypes with ranges that are skewed. For instance, *Slope farms in higher developed areas* stands out for its particularly high range of terrain slopes (above 3 degrees) and a spatial coverage in the vicinity of the case studies. On the other hand, *Larger farms in remote arid areas* is characterized by a range of social-ecological conditions mostly centred around the normalized mean, leading to a broader geographical coverage that extends from Latin America to East Asia. The relationship between skewness of the range of indicator values and spatial extent of the archetype is related to the clustering methods applied and it is a common feature in archetype analysis (Sietz et al., 2017; Václavík et al., 2013). The fact that the overall coverage of the archetypes embraces only the 19% of the total global cropland does not necessarily mean that the remaining 81% of global cropland is unsuitable for water harvesting. Rather, it means that the social-ecological conditions in these areas are not captured by the social-ecological spectrum in the water harvesting cases analysed. A such, we cannot out-scale information on water harvesting to those areas.

Since the WOCAT database was originally developed to inform the design of development projects funded by international financial mechanisms of the Multilateral Environmental Agreements (e.g. the GEF, GCF and the Adaptation Fund), it does not include water harvesting cases in Northern America, Western Europe and Australia. Although water harvesting is currently implemented in these regions, the archetypes here developed are underrepresented in the most developed economy since their social-ecological conditions are not captured in the WOCAT case studies. A more comprehensive list of case studies (for example complemented by databases covering western economies) could enrich the spatial coverage and accuracy of the archetypes, thus improving the understanding of global implication of water harvesting, necessary to guide the development of agriculture in a context of complex climatic, environmental and social change.

4.1. Potential crop production increase and hotspot regions

Although no previous work has attempted to estimate the social-ecological suitability of water harvesting at a global scale, our results can be compared to other global scale assessment of agricultural land and water management improvements. Interestingly, the potential increase in global production (in kilocalories) with integrated crop water management (including ex-situ and in-situ water harvesting) from the study of Jägermeyr et al. (2016), which is based on biophysical indicators, shows the highest potential in the Middle East, parts of India and China, West Sahel, East Africa and South America, in line with our results. The simulated global potential of conservation agriculture from Prestele Reinhard et al. (2018) – which includes some water harvesting practices like no-till and mulching –only overlap with our analysis in South America (Argentina, Paraguay and Brazil) and partially Northern China and the Middle east (Fig. 6). it is worth noting that their study includes the most developed economies with higher access to agricultural machinery and inputs. As an additional comparison, our estimates well resemble the global potential of ex-situ water harvesting calculated by Wisser et al. (2010) which finds a hotspot for increase in crop production in West Sahel and the Lake Victoria region in Africa and a moderate impact in Eastern Europe, in line with our results.

Importantly, our estimated area for successful implementation of water harvesting is smaller than that found in these studies using a-

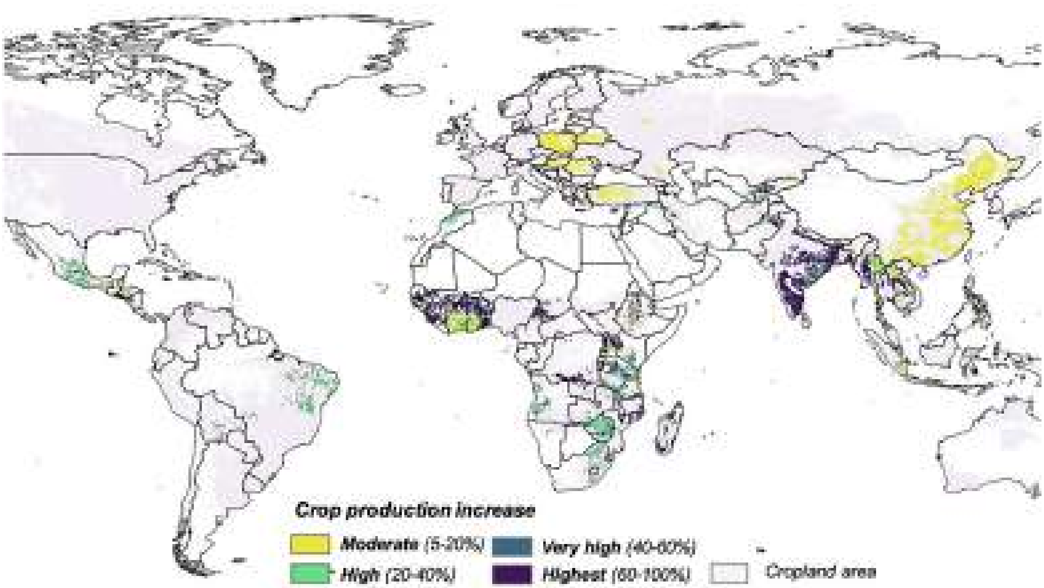

Fig. 6. Potential increase in crop production by implementation of water harvesting practices based on WOCAT studies. The potential crop production increase is quantified in four classes from moderate (5–20%) to highest (60–+100%) – from yellow to dark blue. The background area (light grey) represents the total global cropland area estimated by FAO (2005). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

priori modelling criteria, because we constrained our analysis to observed successful outputs. In this sense, our estimate might neglect some potentially suitable areas, but it provides a more reliable representation of the overall social-ecological potential for successful implementation of water harvesting, particularly in hotspot regions such as East-Africa and South-East Asia.

In East Africa, water harvesting has been used for decades to contrast soil erosion and its consequences on low crop yields (e.g. Ellis-Jones and Tengberg, 2000) and it represents a sustainable strategy to adapt water management to future climate change (Castelli et al., 2019; Piemontese et al., 2019). Our estimated crop production increase of +20–40% in this region is in line with previous in-field and modelled results. For example, in the district of Kabale, Uganda, trash lines, mulching and ditches are observed to avoid yield decline (Ellis-Jones and Tengberg, 2000) and in the semi-arid Machakos district, Kenya, a combined modelled and infield experiment study by Barron and

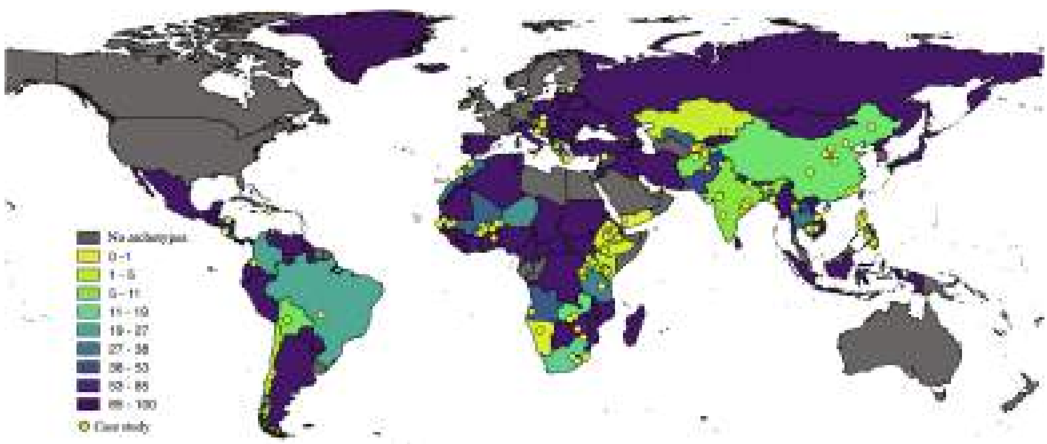

Fig. 7. Indicator of uncertainty in the estimate of archetype, considering the extent of archetype compared to the number of case studies at national level. Light colours with low uncertainty (Eq. (2)) evidence the reliability of the archetype application. The dark grey countries have no projected archetypes, while the more uncertain ones (dark purple, 85–100) have no case studies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

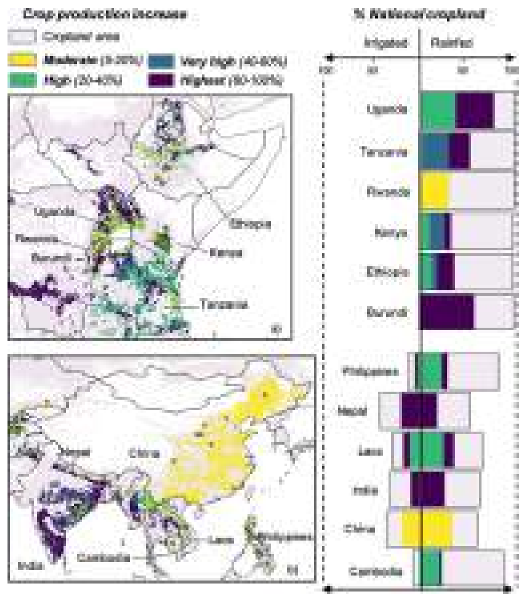

Fig. 8. Potential crop production increase with water harvesting for the two regional hotspots of East Africa (a) and South-Eastern Asia (b). The maps are snapshot of the global map (Fig. 6). Bar plots show the percentage of national rainfed and irrigated cropland under potential crop production increase for some key countries. The yellow dots indicate the location of the case studies. The colour palette is the same as Fig. 6. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Okwach (2005) reports similar crop production increase with ex-situ practices used for supplemental irrigation.

In India, the archetypes cover large portions of Odisha, Chhattisgarh, Telangana and Madhya Pradesh provinces. The main use of water harvesting in these areas is to collect and store runoff to increase in-situ moisture conditions and increase groundwater recharge (explicitly stated in several case studies 1474, 1475, 1479, 1480, 1481, www.wocat.net). For example, in Odisha, where most of the Indian case studies are located, in-situ practices such as V-shaped structures on contour lines and sunken gully pits led to an increase in farm income of around 7$ per hectare (i.e., in case studies 1478 and 1479). These outcomes match previous research of a combined modelling-observation approach, which reported higher groundwater recharge during all seasons with ex-situ practices and a doubled net income with a combination of in-situ and ex-situ practices in the Osman Sagar catchment (Garg et al., 2013).

According to our results, 50% of the extent of China's cropland can benefit from *moderate* crop production increases due to water harvesting implementation. In several regions of the country, groundwater depletion and soil erosion are the main constrains for agriculture (Aeschbach-Hertig and Gleeson, 2012) and many water harvesting practices are already in place. For instance, in up to 85% of agriculture area in the Loess Plateau cross-slope measures are widely implemented to combat soil erosion of cropland area (Guobin, 1999). Hence, our analysis might overestimate the extent of cropland where water harvesting can be implemented and consequently the increase in crop production (Fig. 8). However, a high potential still lies in the combination of terraces and other in-situ and ex-situ practices, needed to achieve higher yields (Li et al., 2000; Wang et al., 2009).

4.2. Limitations and uncertainty

Our results highlight the potential of water harvesting to sustainably increase food production in some of the global hotspots concerning food security, such as East Africa. However, this consideration has to be balanced with in depth hydrological modelling at basin scale to capture the potential trade-offs of water use between upstream and downstream locations. In fact, some water harvesting technologies, especially ex-situ practices can reduce runoff downstream of the site of implementation (Dile et al., 2016; Glendenning and Vervoort, 2011). For instance, although ex-situ water harvesting can be used in arid and semi-arid regions to collect and concentrate runoff from an area up to 100 times larger than the farmland to increase water availability at the farm level, it may be at the cost of downstream farmlands. Thus, this approach could only be applied sustainably to a limited portion of the arable land of a region – 30% at most (Garg et al., 2013) – limiting the out-scalable area of water harvesting.

Nevertheless, most of the cross-slope measures and in-situ technologies do not appear to affect water availability downstream (Andersson et al., 2011; De Winnaar and Jewitt, 2010; Rockström et al., 2004). They can rather improve water quality and soil stability for downstream locations. Moreover, water harvesting practices are used to increase the poor soil quality of marginal and abandoned land and can thus help to sustainably extend agriculture to areas with low impact on natural ecosystems (Grum et al., 2017; Niemeijer, 1998). These complex eco-hydrological dynamics are specific to the catchment scale and very difficult to capture at a global scale.

Furthermore, although water harvesting is a well-studied and implemented component of national strategies to improve rainfed agriculture, especially in Africa (Adimassu et al., 2017; Douxchamps et al., 2014), there is up to date no comprehensive assessment of the extent of implementation of water harvesting (UNEP, 2009). For thise reason, water harvesting might be already implemented in the area covered by our archetypes. Nevertheless, our assessment can serve as guidance to policy development at global and regional scales and as a methodological blueprint for identifying the transferability potential of existing water harvesting implementations. At a local scale, we suggest to downscale the impact assessment of water harvesting practices at the watershed level, where it should be complemented by more in-depth social-ecological analysis and local knowledge to avoid potentially negative top-down interventions. In fact, our methodology is scalable at different spatial resolutions depending on the availability of information on successful case studies, on the resolution of social-ecological datasets and on the purpose of the analysis. For example, regional assessments with high-resolution social-ecological data and higher density of case studies can better capture the spatial representation of the local diversity, therefore providing more precise estimates of water harvesting scalability and impact.

5. Conclusions

This study is a first global estimate of the potential of water harvesting based on local successful implementations. We provide a scalable methodological approach accounting for both environmental and socioeconomic dimensions in order to out-scale the outcomes of local water harvesting projects. Our results show that about 19% of global cropland can replicate the crop production increase achieved by the successful water harvesting case studies (i.e., showing an increase in crop production after implementation). The hotspots of the potential effective implementation of water harvesting are located in East and West Africa and South-East Asia, where water harvesting can be implemented in 40% to 70% of the agricultural land, with the highest crop production increase (60–100%) in Uganda, Burundi and India. Even though our results are subject to limitations related to: i) limited number of case studies (167) and ii) skewed distribution of case studies (e.g., underrepresentation of Latin America and Europe, and the absence of North America and Australia), the results of this study can serve as a complement to global biophysical modelling estimates of water management potential. These results are a first evidence-based assessment of the global contribution of water harvesting, providing a scalable methodological approach that can be replicated at regional-national level to provide guidance for policy and planning of rainfed agriculture improvements with water harvesting.

Credit authorship contribution statement

Luigi Piemontese: Conceptualization, Methodology, Data curation, Software, Formal analysis, Visualization, Writing - original draft. **Giulio Castelli:** Conceptualization, Methodology, Data curation, Resources, Writing - review & editing. **Ingo Fetzer:** Methodology, Writing - review & editing. **Jennie Barron:** Resources, Writing - review & editing, Validation. **Hanspeter Liniger:** Conceptualization, Data curation, Writing - review & editing. **Nicole Harari:** Conceptualization, Data curation. **Elena Bresci:** Writing - review & editing. **Fernando Jaramillo:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2020.102121.

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Supplementary Information for

Estimating the global potential of water harvesting from successful case studies

This document contains supplementary information on the data and methods (Figure S1, Tables S1, S2 and S3) and results (Tables S4).

Figure S1. Snapshot of a WOCAT case study questionnaire sheet. The section 6.1 collect farmers' assessment on the consequences of the implemented practice on a range of social-ecological indicators including crop production, the indicator used in our out-scaling analysis. The impact assessment section contains a ranked evaluation of the change in social-ecological indicators after the implementation of the WH practice and comments that further clarify the quality of the change.

Water harvesting Group	*Subgroup*	*Definition*
Ex-Situ (Collection of runoff from an area > 10 larger than the farm size)	Dams/Check Dams	Water ponds realized by a damming wall in impluvium and gullies
	Diversion Canal	Floodwater diversion by canal
	Diversion Weir	Floodwater diversion by weir
	Dugout Ponds	Excavated in-situ water ponds
	Road Water Harvesting	Water harvested from roads
	Sand dams	Damming of dry riverbed to store sand in artificial aquifers

In-Situ (Retention of runoff from an area < 10 larger than the farm size)	Micro-catchment	in-situ techniques to increase infiltration and prevent evaporation (pits, semi-circular bunds)
	Conservation Tillage	Conservation Tillage
	Mulching	Soil cover for reducing evaporation
	Rooftop	Water harvested from rooftops
	Vegetative strips	Strips of vegetation on contour lines and/or in gullies
Cross-Slope Measure (Retention of runoff within the farm through slope stabilization and contour measures)	Progressive terraces	Contour bunds built aiming the slow formation of flat terraces by sedimentation of eroded material
	Radical terraces	Terraces built with earth movement
	Complex Contour Measures	Mix of bunds, trenches and vegetative measure on contour lines to block sheet runoff in slope areas
	Contour bunds	Bunds (stones or earth) built on contour lines to block sheet runoff in slope areas
	Contour Trenches	Trenches built on contour lines for trapping sheet runoff in slope areas

Table S1. Classification of water harvesting case studies from the WOCAT database in water harvesting groups and subgroups.

Country	**Code**	**Group**	**Subgroup**
India	1088	1	Dugout Ponds
Kenya	1094	1	Road Water Harvesting
Philippines	1102	1	Dams/Check Dams
Burkina Faso	1142	1	Diversion Canal
Burkina Faso	1144	1	Dugout Ponds
Tanzania, United Republic of	1157	1	Dugout Ponds
Zambia	1331	1	Dams/Check Dams
Bangladesh	1344	1	Dams/Check Dams
China	1364	1	Dams/Check Dams
China	1365	1	Dams/Check Dams
Uganda	1390	1	Diversion Canal
Senegal	1425	1	Dams/Check Dams

Senegal	1426	1	Dams/Check Dams
Senegal	1433	1	Dugout Ponds
Tajikistan	1454	1	Diversion Canal
India	1471	1	Dugout Ponds
India	1472	1	Dugout Ponds
India	1474	1	Dugout Ponds
India	1475	1	Dugout Ponds
India	1479	1	Dugout Ponds
India	1481	1	Dams/Check Dams
Kenya	1483	1	Road Water Harvesting
Kenya	1486	1	Sand Dam
Kenya	1487	1	Road Water Harvesting
Philippines	1507	1	Dams/Check Dams
Kenya	1537	1	Sand Dam
Ethiopia	1547	1	Dams/Check Dams
Rwanda	1551	1	Dugout Ponds
Croatia	1562	1	Diversion Canal
Burkina Faso	1617	1	Dams/Check Dams
Nepal	1655	1	Dugout Ponds
Slovakia	1664	1	Dams/Check Dams
Chile	1689	1	Dams/Check Dams
Nicaragua	1719	1	Dams/Check Dams
Senegal	1748	1	Dams/Check Dams
Laos	2920	1	Dugout Ponds
Morocco	3204	1	Dugout Ponds
Pakistan	540	1	Diversion Canal
Bangladesh	779	1	Dugout Ponds
Ethiopia	943	1	Diversion Canal
Philippines	1021	2	Conservation Tillage
Tajikistan	1033	2	Vegetative Strips
Ethiopia	1066	2	Microcatchment
Ethiopia	1075	2	Microcatchment
Hungary	1081	2	Microcatchment
India	1086	2	Microcatchment
Kazakhstan	1090	2	Vegetative Strips
Kenya	1097	2	Microcatchment
Philippines	1105	2	Vegetative Strips
Morocco	1110	2	Vegetative Strips
Zambia	1139	2	Conservation Tillage
Rwanda	1160	2	Mulching
Burkina Faso	1176	2	Microcatchment
Tanzania, United Republic of	1184	2	Mulching
Zambia	1187	2	Conservation Tillage
Ethiopia	1197	2	Microcatchment
Tanzania, United Republic of	1215	2	Microcatchment

Niger	1222	2	Mulching
Kenya	1244	2	Microcatchment
Philippines	1303	2	Mulching
Philippines	1308	2	Vegetative Strips
Kenya	1318	2	Mulching
Kenya	1325	2	Mulching
Zimbabwe	1327	2	Conservation Tillage
Ethiopia	1387	2	Mulching
Uganda	1391	2	Microcatchment
Tanzania, United Republic of	1392	2	Vegetative Strips
Togo	1403	2	Vegetative Strips
Senegal	1436	2	Microcatchment
Tajikistan	1446	2	Rooftop
Tajikistan	1460	2	Rooftop
India	1478	2	Microcatchment
Kenya	1484	2	Microcatchment
Kenya	1485	2	Microcatchment
Tajikistan	1508	2	Microcatchment
China	1544	2	Vegetative Strips
Ethiopia	1546	2	Microcatchment
Syria	1549	2	Microcatchment
Uganda	1595	2	Rooftop
Niger	1613	2	Microcatchment
Niger	1614	2	Microcatchment
Niger	1621	2	Vegetative Strips
Greece	1658	2	Rooftop
Kenya	1676	2	Microcatchment
Afghanistan	1728	2	Rooftop
Philippines	1930	2	Vegetative Strips
Uganda	2254	2	Microcatchment
Cambodia	2255	2	Mulching
Uganda	2274	2	Microcatchment
Uganda	2757	2	Mulching
Uganda	2818	2	Mulching
Kenya	2895	2	Microcatchment
Greece	2922	2	Microcatchment
Laos	2930	2	Vegetative Strips
Namibia	2989	2	Microcatchment
Estonia	3113	2	Mulching
Angola	3141	2	Microcatchment
Cambodia	3142	2	Mulching
Cambodia	3152	2	Mulching
Morocco	3205	2	Rooftop
China	3239	2	Mulching
South Africa	3377	2	Microcatchment
Uzbekistan	3654	2	Vegetative Strips
Burkina Faso	613	2	Microcatchment
Burkina Faso	959	2	Microcatchment

South Africa	968	2	Microcatchment
China	972	2	Mulching
Ethiopia	979	2	Microcatchment
Uganda	989	2	Mulching
Togo	996	2	Vegetative Strips
Ethiopia	1045	3	Contour Bunds
Ethiopia	1046	3	Contour Bunds
Ethiopia	1059	3	Contour Bunds
Ethiopia	1060	3	Contour Bunds
Ethiopia	1062	3	Contour Bunds
Ethiopia	1067	3	Radical Terraces
Ethiopia	1076	3	Contour Bunds
China	1106	3	Radical Terraces
Philippines	1133	3	Progressive Terraces
Burundi	1148	3	Contour Bunds
Yemen	1174	3	Radical Terraces
Uganda	1178	3	Complex Contour Measures
Burundi	1181	3	Radical Terraces
Kenya	1243	3	Radical Terraces
Chile	1258	3	Contour Trenches
Brazil	1275	3	Radical Terraces
Philippines	1287	3	Complex Contour Measures
Kenya	1336	3	Radical Terraces
Bangladesh	1346	3	Progressive Terraces
Bolivia	1347	3	Progressive Terraces
Bolivia	1349	3	Progressive Terraces
Bolivia	1350	3	Complex Contour Measures
South Africa	1369	3	Radical Terraces
Ethiopia	1388	3	Radical Terraces
Ethiopia	1389	3	Contour Bunds
Ethiopia	1396	3	Contour Trenches
Ethiopia	1397	3	Contour Bunds
Togo	1401	3	Radical Terraces
Togo	1402	3	Radical Terraces
Thailand	1404	3	Radical Terraces
Thailand	1405	3	Contour Trenches
Syria	1411	3	Radical Terraces
Ethiopia	1415	3	Contour Bunds
China	1419	3	Radical Terraces
China	1445	3	Radical Terraces
Tajikistan	1450	3	Progressive Terraces
Tajikistan	1457	3	Complex Contour Measures
India	1480	3	Contour Bunds
Kenya	1488	3	Progressive Terraces
Colombia	1510	3	Contour Trenches

Greece	1512	3	Radical Terraces
China	1522	3	Progressive Terraces
Rwanda	1550	3	Contour Trenches
Rwanda	1553	3	Radical Terraces
Kenya	1581	3	Contour Bunds
Niger	1616	3	Contour Bunds
Niger	1625	3	Contour Trenches
Niger	1652	3	Complex Contour Measures
Slovakia	1666	3	Complex Contour Measures
Nepal	1683	3	Contour Bunds
Philippines	1700	3	Radical Terraces
Haiti	1832	3	Radical Terraces
Uganda	2826	3	Complex Contour Measures
Tajikistan	3695	3	Radical Terraces
Afghanistan	607	3	Radical Terraces
Uganda	616	3	Radical Terraces
Uganda	711	3	Contour Trenches
Honduras	735	3	Contour Bunds
Honduras	736	3	Complex Contour Measures
South Africa	938	3	Progressive Terraces
Ethiopia	949	3	Radical Terraces
China	981	3	Radical Terraces
Ethiopia	991	3	Contour Bunds

Table S2. List of the 173 case studies selected for the analysis, including codes, country, WH group and subgroups. The three WH groups are Ex-Situ (1), In-Situ (2) and Cross-Slope Measures (3). The codes can be used to access the online sheet for individual case studies at the address: https://qcat.wocat.net/en/wocat/technologies/view/technologies_code/. For example to explore the case study 1303 the address is: https://qcat.wocat.net/en/wocat/technologies/view/technologies_1303/.

	Farm	credit	Gender	Govern	HDI	Labor	Land	Remote	Arid	Prec	Season	Slope	Soil	Water gap
Farm	1,0													
Fina	0,4	1,0												
Gender	-0,4	-0,4	1,0											
Govern	0,3	0,8	-0,4	1,0										
HDI	0,6	0,7	-0,5	0,7	1,0									
Labor	-0,4	-0,1	0,2	-0,1	-0,2	1,0								
Land	0,4	0,5	-0,4	0,3	0,6	-0,2	1,0							

Remote	0,0	0,1	-0,1	0,3	0,1	-0,1	0,1	1,0						
Arid	-0,2	-0,4	0,4	-0,3	-0,4	0,1	-0,6	-0,4	1,0					
Prec	-0,2	-0,1	-0,1	0,0	-0,2	0,1	-0,3	-0,1	0,1	1,0				
Season	-0,4	-0,4	0,3	-0,3	-0,5	0,1	-0,4	-0,1	0,5	-0,3	1,0			
Slope	-0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-0,1	0,0	0,0	1,0		
Soil	0,1	0,3	-0,3	0,2	0,3	-0,1	0,4	0,1	-0,6	0,1	-0,4	0,1	1,0	
Water gap	0,2	0,1	0,2	0,0	0,1	-0,1	0,1	0,0	0,2	-0,6	0,1	0,0	-0,2	1,0

Table S3. Pearson correlation between the first-round selected social-ecological indicators. In red the highly correlated indicators that we excluded from the final pool of indicators used in the cluster analysis to avoid redundancy.

Calculation of indicators

Seasonality

To account for rainfall seasonality, we calculated the seasonality index (Eq.1) developed by (Walsh and Lawler, 1981, referenced in the main text), which takes into account the inter-annual temporal variability of precipitation (from the same CRU dataset) and averaged it in the same 30-year period 1986-2016 as for the precipitation and aridity indicators.

$$SI = \text{mean}\left(\frac{1}{R_y}\sum_{m=1}^{12}\left|X_m - \frac{R_y}{12}\right|\right) \qquad (eq.1)$$

R_y is the cumulative annual precipitation within the year *y* and X_m is the monthly precipitation in the month *m*. For *SI*<0.19, precipitation is considered spread throughout the year, for 0.4<*SI*<1 the precipitation distribution is considered seasonal and for *SI*>1 very seasonal, with precipitation concentrated within at most three-months.

Land tenure

We used "registering property" as a proxy of land tenure. This indicator accounts for the steps, time, and cost involved in registering a property, assuming a standardized case of "an entrepreneur who wants to purchase land and a building that is already registered and free of title dispute" (https://www.doingbusiness.org/en/methodology/registering-property). In addition, the indicator measures the quality of the land administration system in each country, accounting for the five dimensions of reliability of infrastructure, transparency of information, geographic coverage, land dispute resolution, and equal access to property rights (between genders). The indicator is the equally weighted average of the scores for each of the component indicators.

Country	Mod_IRR	High_IRR	Very high_IRR	Highest_IRR	Mod_RFE	high_RFE	Very high_RFE	Highest_RFE	Total	n. cases	Uncerty
El Salvador	0	0	0	5	6	0	81	0	91	0	100
Ghana	0	0	0	0	0	56	20	8	84	0	100
Togo	0	0	0	0	0	1	58	21	80	4	20
Panama	0	0	0	0	0	0	8	0	9	0	100
Moldova	2	0	0	0	7	0	0	0	9	0	100
Afghanistan	0	0	3	1	0	0	0	6	9	2	4
Colombia	1	0	0	0	7	0	0	0	9	1	9
Brazil	0	0	0	0	0	1	0	7	9	1	9
Greece	3	0	0	0	5	0	0	0	8	3	3
Uganda	0	0	0	0	0	37	41	1	78	12	7
C√¥te d'Ivoire	0	0	0	0	0	70	4	2	76	0	100
Sierra Leone	0	0	0	1	0	0	73	0	74	0	100
Zimbabwe	0	0	3	0	0	0	5	64	72	1	72
Slovakia	10	0	0	0	62	0	0	0	72	2	36
Poland	1	0	0	0	71	0	0	0	71	0	100
Czechia	0	0	0	0	8	0	0	0	8	0	100
Serbia	0	0	0	0	8	0	0	0	8	0	100
Albania	2	0	0	0	5	0	0	0	7	0	100
Jamaica	0	0	0	6	2	0	60	0	68	0	100
Hungary	3	0	0	0	62	0	0	0	65	1	65
Benin	0	0	0	0	0	0	45	19	64	0	100
Burkina Faso	0	0	0	0	0	0	64	0	64	6	11
Haiti	0	0	0	5	6	0	41	8	61	1	61
Honduras	0	1	0	0	3	44	11	0	60	2	30
Burundi	0	0	0	1	0	0	57	0	59	2	29
Morocco	0	0	5	2	3	0	5	43	58	3	19
Myanmar	0	1	1	6	0	5	35	7	57	0	100
Laos	0	12	0	7	0	25	12	0	57	2	28
China	20	5	0	0	36	0	0	0	55	10	6

Tajikistan	1	0	36	0	2	0	0	15	54	8	7
Tanzania	0	0	1	1	0	2	23	28	54	4	13
Belarus	1	0	0	0	51	0	0	0	51	0	100
Syria	1	0	13	1	2	0	1	32	50	2	25
Iran	1	0	0	1	2	0	2	0	6	0	100
Italy	1	0	0	0	5	0	0	0	5	0	100
Cyprus	3	0	0	0	3	0	0	0	5	0	100
Nicaragua	0	0	1	0	1	0	12	34	47	1	47
Mali	0	0	0	1	0	0	44	0	45	2	22
Romania	2	0	0	0	40	0	0	0	43	0	100
Guinea	0	0	0	1	0	0	41	0	43	0	100
Malawi	0	0	1	0	0	0	15	25	40	0	100
Senegal	0	0	0	0	0	0	40	0	40	3	13
Nepal	0	0	0	21	0	0	18	0	40	1	40
Chile	5	0	0	0	0	0	0	0	5	2	2
Palestine	0	0	1	0	0	0	0	3	5	0	100
Peru	2	0	0	0	2	0	0	0	4	0	100
Cameroon	0	0	0	0	0	0	33	5	39	0	100
Belize	0	2	0	0	0	36	0	0	38	0	100
India	0	0	0	10	0	0	25	2	38	10	4
Madagascar	0	0	1	9	0	0	24	4	37	0	100
Ethiopia	0	0	0	1	0	12	19	5	37	22	2
Philippines	0	4	0	2	2	22	7	0	37	10	4
Kenya	0	1	0	0	1	8	8	16	33	17	2
Turkey	3	0	0	0	28	0	0	0	31	0	100
Dominican Rep.	1	0	0	4	4	0	22	0	31	0	100
Thailand	0	0	0	6	0	0	24	0	31	2	15
Rwanda	0	0	0	0	29	0	0	0	30	4	8
Eritrea	0	0	0	0	0	0	3	0	3	0	100
South Africa	0	0	2	0	0	1	0	26	29	4	7
Pakistan	0	0	1	13	1	0	6	8	28	1	28
Mexico	0	0	4	1	2	3	3	14	28	0	100
Liberia	0	0	0	0	0	0	28	0	28	0	100
Latvia	0	0	0	0	27	0	0	0	27	0	100
Guatemala	0	0	0	1	7	0	18	0	27	0	100

Jordan	0	0	4	0	0	0	1	21	27	0	100
Niger	0	0	0	0	0	0	26	0	26	2	13
Cambodia	0	1	0	0	0	22	3	0	26	3	9
Angola	0	0	0	0	0	0	2	22	25	1	25
Indonesia	0	2	0	4	1	14	3	0	25	0	100
Bangladesh	0	0	0	11	0	0	13	0	24	3	8
Sri Lanka	0	0	0	8	0	0	16	0	24	0	100
Iraq	0	0	1	0	1	0	0	22	24	0	100
Uzbekistan	0	0	16	0	0	0	0	5	22	1	22
Russia	0	0	0	0	3	0	0	0	3	0	100
Estonia	0	0	0	0	3	0	0	0	3	1	3
S. Sudan	0	0	0	0	0	0	2	0	2	0	100
Zambia	0	0	1	0	0	0	1	17	19	3	6
Mozambique	0	0	0	1	0	0	17	0	18	0	100
Chad	0	0	0	0	0	0	18	0	18	0	100
Dem. Rep. Congo	0	0	0	0	0	0	17	0	17	0	100
Bolivia	0	2	1	0	0	0	0	13	15	3	5
Lebanon	5	0	0	0	7	0	0	0	12	0	100
eSwatini	0	0	1	0	0	6	2	2	10	0	100
Ecuador	2	0	0	1	4	0	2	0	10	0	100
Kazakhstan	1	0	0	0	1	0	0	0	2	1	2
Mongolia	0	0	0	0	2	0	0	0	2	0	100
Algeria	0	0	0	0	0	0	1	0	2	0	100
Spain	0	0	0	0	1	0	0	0	1	0	100
Tunisia	0	0	0	0	0	0	0	0	1	0	100
Guyana	0	0	0	0	0	1	0	0	1	0	100
Bulgaria	0	0	0	0	1	0	0	0	1	0	100
Vietnam	0	0	0	0	1	0	0	0	1	0	100
Gambia	0	0	0	0	0	0	1	0	1	0	100
Namibia	0	0	0	0	0	0	0	1	1	1	1
Montenegro	0	0	0	0	1	0	0	0	1	0	100
Lithuania	0	0	0	0	0	0	0	0	0	0	100
Lesotho	0	0	0	0	0	0	0	0	0	0	100
Mauritania	0	0	0	0	0	0	0	0	0	0	100
Botswana	0	0	0	0	0	0	0	0	0	0	100

Guinea-Bissau	0	0	0	0	0	0	0	0	0	0	100
Azerbaijan	0	0	0	0	0	0	0	0	0	0	100
Kyrgyzstan	0	0	0	0	0	0	0	0	0	0	100
Central African Rep.	0	0	0	0	0	0	0	0	0	0	100
Japan	0	0	0	0	0	0	0	0	0	0	100
North Korea	0	0	0	0	0	0	0	0	0	0	100
Yemen	0	0	0	0	0	0	0	0	0	1	0
Croatia	0	0	0	0	0	0	0	0	0	1	0
Nigeria	0	0	0	0	0	0	0	0	0	0	100
Paraguay	0	0	0	0	0	0	0	0	0	0	100
Sudan	0	0	0	0	0	0	0	0	0	0	100
Portugal	0	0	0	0	0	0	0	0	0	0	100
Ukraine	0	0	0	0	0	0	0	0	0	0	100
Argentina	0	0	0	0	0	0	0	0	0	0	100
Venezuela	0	0	0	0	0	0	0	0	0	0	100

Table S4. Out-scaled impact of water harvesting on national cropland area, expressed as % of impact per total cropland area, for irrigate (IRR) and rainfed (RFE) fields separately, as in Figure 6. Impact levels corresponds to *moderate (+5-20%), high (+20-40%), very high (+40-60% and highest (60-100%)*. The table also contains the number of case studies per country and the uncertainty index.

III

Unpacking the barriers to adoption of sustainable land and water management in Uganda

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Abstract

Sustainable Land and Water Management (SLWM) is key to improve agricultural production and food security while coping with climate change. However, the rate of SLWM adoption remains low particularly in developing countries, suggesting a gap between generalized SLWM advantages for rural development across the literature and the existence of context-dependent barriers to its effective implementation. Uganda is an example of this paradox: SLWM adoption rate is low despite its favorable ecological conditions for agriculture development and a large rural population. A systemic understanding of the barriers hindering the adoption of SLWM is therefore crucial to develop coherent policy frameworks and enable effective funding strategies. In this study, we use archetype analysis to identify and link barriers to SLWM adoption in Uganda. We performed 80 interviews across the country to build cognitive archetypes, harvesting stakeholders' perception on different types of barriers. We complemented this bottom-up perspective with a spatial archetype analysis to contextualize these results across different social-ecological regions. We find poverty trap, overpopulation, farmers resistance, rural isolation and post-conflict patriarchal systems as effective cognitive archetypes that synthetize the different dynamics of barriers to SLWM adoption in Uganda. In addition to resonating with existing socio-economic theories of rural development, our results reveal both specific and cross-cutting barriers. Surprisingly, ineffective extension services emerges as a ubiquitous barrier, even in the districts with the highest coverage of extension workers, while gender inequality is a priority barrier in *large supported farms* and *farms in drier lowlands* in Northern Uganda. The cognitive and spatial archetypes here defined can help overcome ineffective one-fix-all solutions and support context-specific policy plans to up-scale SLWM, rationing resources to support a sustainable intensification of agriculture.

Introduction

Inadequate food production affects the livelihoods of millions of people globally and is the top national and international challenge for achieving the sustainable development goals (Conceição et al., 2016; Pérez-Escamilla, 2017). In the subsistence farming systems of sub-Saharan Africa, low land productivity is driven by land degradation, low access to irrigation infrastructure and limited access to farm inputs, markets and technologies (Sietz and Van Dijk, 2015; Pimentel, 2006). Land degradation is further exacerbated by climate change, which is shifting seasonal precipitation patterns, increasing frequency of droughts and extreme precipitation events (Zika and Erb, 2009). Sustainable land and water management practices (SLWM) can play a key role in coping with hydroclimatic changes, by determining the amount and frequency of precipitation reaching the crops, maintaining and sustaining soil health (Piemontese et al., 2019). In most of the rainfed agriculture of sub-Saharan Africa, 50 to 70 % of precipitation is lost as soil evaporation or surface run-off (i.e. not contributing to plant growth), undermining crop production and triggering soil erosion (Wani et al., 2009).

Generally, SLWM has the primary aim of enhancing soil water productivity, limiting surface runoff and maximizing water storage in the soil while preserving its long-term environmental functions. Typical examples of SLWM practices are trenches and terraces, usually implemented along contour lines in steep terrains to slow down precipitation runoff and increase infiltration and mulching – soil cover, often with organic matter – used to limit water loss from evaporation and build soil structure. These kinds of practices are often combined to increase water productivity at the farm scale , with long-term positive effects on food security and income (Bouma et al., 2016; Howie, 2008). To achieve the potential to meet the sustainable development goals, SLWM practices need to be adopted by a critical mass of farmers and widely replicated and extended across geographic space with the support of national, regional and international policies (Thomas et al., 2018) with a process that is commonly known as upscaling (Howie, 2008). A critical step in the scaling process is the identification and thorough understanding of the barriers to the adoption of SLWM (Wigboldus et al., 2016).

Upscaling SLWM is particularly relevant for Uganda, where 80% of the population are subsistence smallholder farmers and the agro-climatic conditions in the country are generally favorable for agriculture (Banadda, 2011; Fowler and Rockstrom, 2001). For instance, in the Kabale district, conservation agriculture has improved cereal yields by 50–100% (Ellis-Jones and Tengberg, 2000; Pretty, 1999), while trenches and terraces, implemented on the steep landscape, have increased crop quality and production by at least 20-50% (WOCAT, 2019). In the Northern regions of the country, agroforestry and mulching have been commonly implemented to limit evaporation, leading to an increase in banana production up to 10 times (WOCAT, 2019).

Nevertheless, despite the documented successes of SLWM, adoption rates remain low in Uganda (Hart and Mouton, 2005). Local studies have identified barriers related to farm characteristics (e.g., farm size, location and slope; Kassie et al., 2011; Mugisha and Alobo, 2012), household conditions (e.g., household size, education and occupation; Ebanyat et al., 2010; Nkonya, 2002) and the socio-economic context (e.g., access to market, gender inequality and agricultural extension services coverage; Aduwo et al., 2019; Mwangi and Kariuki, 2015). However, even though the barriers to adoption of SLWM are studied and reported for individual cases, the relation to the broader geographical context and the lack of focus on the causes and effects of the existing barriers provide a partial and fragmented understanding of the problem, bringing uncertainty on the interventions needed to facilitate the adoption and scaling up of SLWM (Sietz and Van Dijk, 2015; Wigboldus et al., 2016). In fact, policy instruments and large-scale funding are guided by national understanding of both the problems and the solutions to land degradation (Sietz and Van Dijk, 2015) and lack of clear policy and legal frameworks can lead to failing government efforts (Ntale et al., 2005). If the manifold problems arise at the local scale, but the solutions are provided top-down from standardized national plans, the lack of system perspective impedes the development of an enabling environment for the successful implementation of SLWM (Ampaire et al., 2015; Anderson, 2004; Tengberg and Valencia, 2018). However, finding the best level of generalization that allows the capture of local differences while generating insights applicable to broader areas is a major challenge.

We here use archetype analysis to identify recurrent barriers to SLWM adoption across different social-ecological contexts of Uganda. Archetype analysis is a methodological approach used in sustainability science to support the identification of patterns of similar conditions with the aim of supporting the scaling-up of sustainability solutions (Sietz et al., 2019, Eisenack et al. 2019). This approach builds on the assumption that similar solutions can be implemented under similar social-ecological conditions (Kok et al., 2016; Sietz et al., 2019). We propose a multimethod approach combining cognitive archetypes, based on interviews with local stakeholder, with spatial archetypes from district-level data in Uganda. Spatial archetypes are used to identify places for transferability of solutions (Václavík et al., 2016) and cognitive archetypes (Karrasch et al., 2019) use stakeholder opinions to identify patterns of perceptions. The identification of these patterns lets us understand the deep motivations and conditions enabling the adoption of sustainable practices (Lim-Camacho et al., 2017). We use cognitive archetypes to provide insights on social-ecological dynamics hindering the adoption of SWLM, and spatial archetypes to delineate potential areas of generalizability of such dynamics. The results can be used by local and national policy makers to develop context-specific plans to up-scale SLWM, thus rationing resources to support wide adoption and speeding the transition to sustainable agriculture.

Data and Methods

Methodological approach: Archetype analysis

We use archetype analysis as a methodological approach to break down the complexity of the barriers to adoption of SLWM across the diverse social-ecological contexts of Uganda. Following Eisenack et al. (2019), we define the similarities in socioecological conditions according to a set of attributes, which we selected inductively (i.e. from stakeholder consultation and meta-analysis). We use existing theories in the realm of land system change, rural anthropology and economy to interpret these archetypes by explaining the configuration of attributes resulting from the archetype analysis (Cullum et al., 2015). In general, archetype literature defines two major types of archetypes based on their meaning and use: "building blocks" and "typology of cases" (Oberlack et al., 2019). Archetypes as building blocks can be used to identify and describe specific processes and mechanisms, which can be combined (as building blocks) to explain the complexity of a single case (Oberlack et al., 2019). On the other hand, typology of cases aim at identifying common patterns across a number of cases, generally suited to delineate spatial archetypes, such as individual districts with similar social-ecological patterns) (Rocha et al., 2020; Sietz et al., 2017; Václavík et al., 2013).

We use purely inductive reasoning to build archetypes as typology of cases from both spatial data (every district is a case for the spatial archetype) and stakeholders' interviews (every interview is a case for the cognitive archetype). In this way, every district belongs to only one spatial archetype and, similarly, every interview is assigned to only one cognitive archetype. We performed 80 interviews in the four macro-regions of Uganda to gain a comprehensive picture at the country scale. We then use the cognitive archetype as building blocks to explain the configuration of different types of barriers in different regions of Uganda, represented by the spatial archetypes.

Analytical framework

In this section, we provide a detailed description of the methodology. The two different archetypes present common methodological steps such as the attribute selection, the data collection and the analysis, which are synthesized in Figure 1 and described in the next paragraphs. The final analytical step involves the comparison of the two archetypes to evaluate the ranges of validity and interpretability of the results, which provides a measure of uncertainty.

Attributes selection

A key component in the delineation of archetypes is the set of attributes that are used to compare cases and assess their degree of similarity. In this study, we used two sets of cases, interviews and districts, and their two corresponding sets of attributes, cognitive and spatial attributes respectively. In general, attributes selection can be guided by qualitative literature review (Sietz et al., 2017; Václavík et al., 2013), grounded in existing theories (Oberlack et al., 2019; Rocha et al., 2020), or derived by inductive bottom-up knowledge (Karrasch et al., 2019).

We use the last approach to limit the biases of pre-existing theories and we build on purely empirical knowledge. For the spatial attributes, we use a meta-analysis of case-based research in Uganda, while for the cognitive attributes we use a stakeholder workshop, described in detail in the next paragraphs.

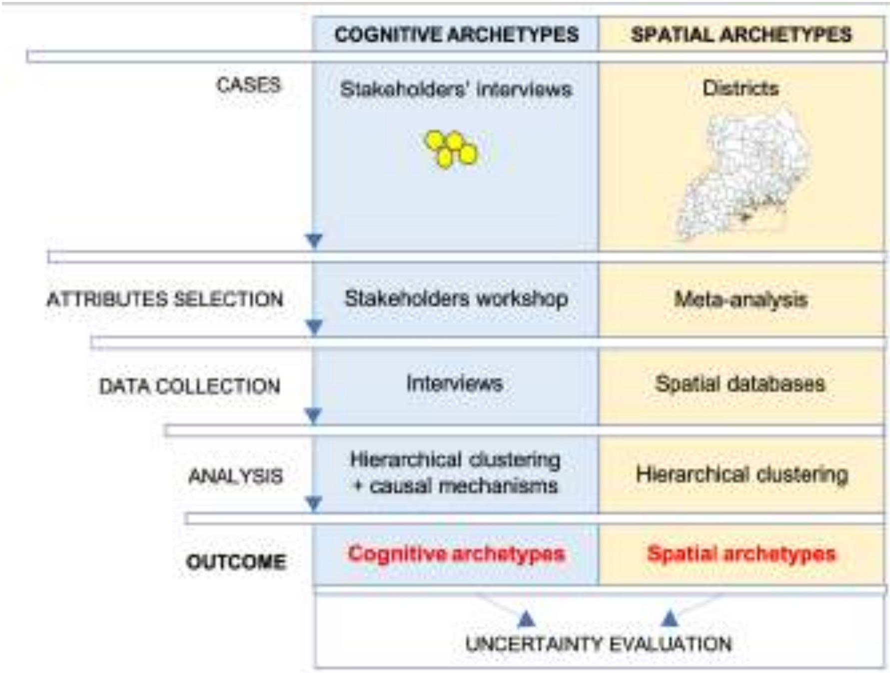

Figure 1. Analytical framework. Analytical steps used to delineate archetypes and the sections where we describe them. The steps are common to the two archetypes; "cognitive archetypes" (left) and "spatial archetypes" (right).

Cognitive attributes: Stakeholders workshop

The set of attributes used to generate the cognitive archetypes of barriers builds on the workshop run during the conference "Uganda Land Care Conference and Awards", held in Kabale (South-west Uganda) on November 28th, 2019. The workshop was a one-hour break-up group discussion with forty attendees from different backgrounds (i.e., farmers, private sector, policy makers, researchers and agricultural officers). We guided the discussion around the topic "Barriers to up-scaling SLWM in Uganda". The discussion started by listing the barriers to SLWM adoption in Uganda, followed by a debate on the relative importance of different barriers depending on the geographical context. The workshop served to gain a system understanding of the type and geographical diversity of barriers, as perceived by the different groups of stakeholders, and to identify a set of barriers to be used in the interviews following the workshop (described in section "Data collection"). This final set of cognitive attributes is listed in Table 1.

Spatial attributes: Meta-analysis in scientific literature

We performed a meta-analysis of scientific papers focusing on the adoption of SLWM in Uganda to select the relevant spatial indicators to build the spatial attributes. We screened 24 papers by searching in Google Scholar for "adoption barriers in agricultural intensification in Uganda" and identified 45 potential attributes. The list of papers is available in supplementary material together with the full list of potential attributes emerging from the meta-analysis (Table S1). We only selected attributes mentioned in at least three of the 24 papers, as a conservative measure. Excluded attributes include "age" because it is too generic for spatial district-level analysis and "land tenure/ownership" and "distance farm-house" due to the unavailability of information at the district level in Uganda. For the specific case of "farm income" we used the proxy of "rural poverty" as it is more inclusive by embracing "capital" and "cash" and for "slope/location" we used "elevation" from above sea level instead. We replaced "agro-climatic conditions" with the proxies of "precipitation" and "temperature" to represent climatic and environmental conditions otherwise underrepresented. After these changes, we resulted with a set of thirteen spatial attributes, listed in Table 1.

Table 1. List of cognitive and spatial attributes. The first five attributes (with green background) were used in the uncertainty analysis, described in section 2.2.4.

Cognitive attributes	**Spatial attributes**
Land fragmentation	Farm size
Women empowerment	Gender gap
Ineffective agricultural extension services	Access to agricultural extension services
Lack of input/credit	Access to credit
Poverty	Rural poverty
Lack of awareness on SLWM practices	Precipitation
Limited farming skills	Temperature
Resistance to change	Slope
Lack of interest	Elevation
Unpredictable weather	Household size
Storms	Farmers organizations
Drought	Livestock
Pests and diseases	Remoteness
Weak law enforcement	Education
Uncontrolled bush fire	

Population growth	
Land tenure	
Conflicts	

Data collection

Interviews: Ranking of cognitive attributes

The aim of the interviews was to build the cognitive attributes through a stakeholder-driven representation of different configurations of barriers for adoption of SLWM. We conducted a series of interviews (n = 80) during a fieldwork between November 21st and December 20th of 2019. The data collection was designed in collaboration with the Uganda Landcare Network (ULN), which is a national landcare platform that fosters sustainable land and water management in Uganda, with an extensive network of over 600 members**.** Interviewees include farmers, local and national government officers and policy makers, involved in the adoption of SLWM practices and identified within the network of the ULN. We also included perspectives from both genders when possible. During the interviews, respondents were asked to rank the five most relevant barriers to SLWM according to their experience, amongst the eighteen cognitive attributes that emerged from the workshop.

To obtain reliable answers, we approached the interviewees with the assistance of a person with a deep understanding of the local conditions and connections with farmers (e.g. local extension workers). Upon agreement, respondents were interviewed only in case they had adopted any type of SLWM practice within the most recent two-year period. Figure 2 synthesizes the location and stakeholder compositions of the interviews. Finally, we readjusted the cognitive archetypes based on feedback from the interviews (names and meanings) by using the qualitative information obtained in selected interviews, allowing to build qualitative descriptions of the barriers as perceived by the stakeholders.

Spatial attributes: datasets

We gathered spatial data on the thirteen spatial attributes to represent the distribution of social-ecological characteristics and barriers to SLWM in the different districts in Uganda (Figure3). We used the Ugandan administrative boundaries of level two from GADM (2012) as units of analysis. All the spatial data were averaged at the district level. Only districts labeled as "county" were selected, discarding municipalities since the analysis focused on rural areas. The data vary across different attributes from global raster databases (e.g., education attainment and total tropical livestock unit) to tables compiled by national statistical reports (e.g., farmers' organization and extension services). The complete list of spatial attributes, with description and data sources, is presented in Table S2.

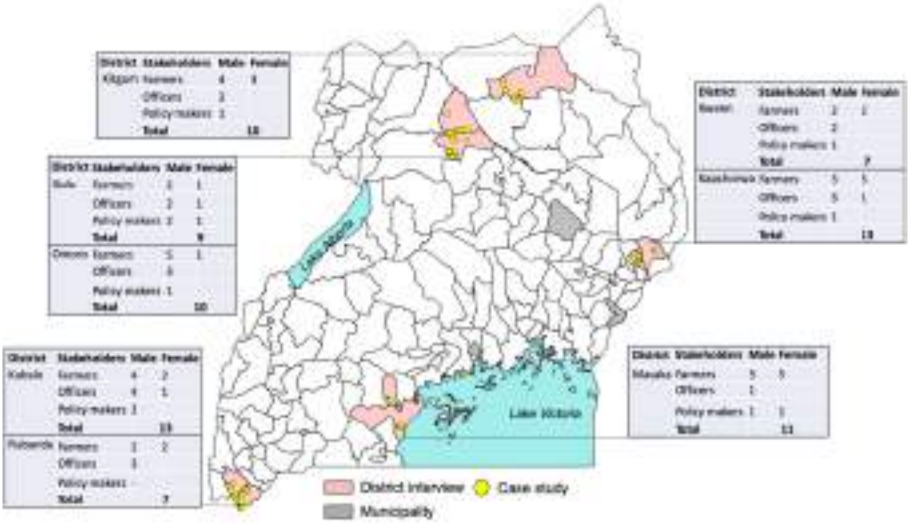

Figure 2. Distribution of the interviews in Uganda. Interviews and details on the districts, gender and type of stakeholders. The pink districts are the interview locations. The municipalities (in grey) were excluded from further analysis because representing non-rural contexts.

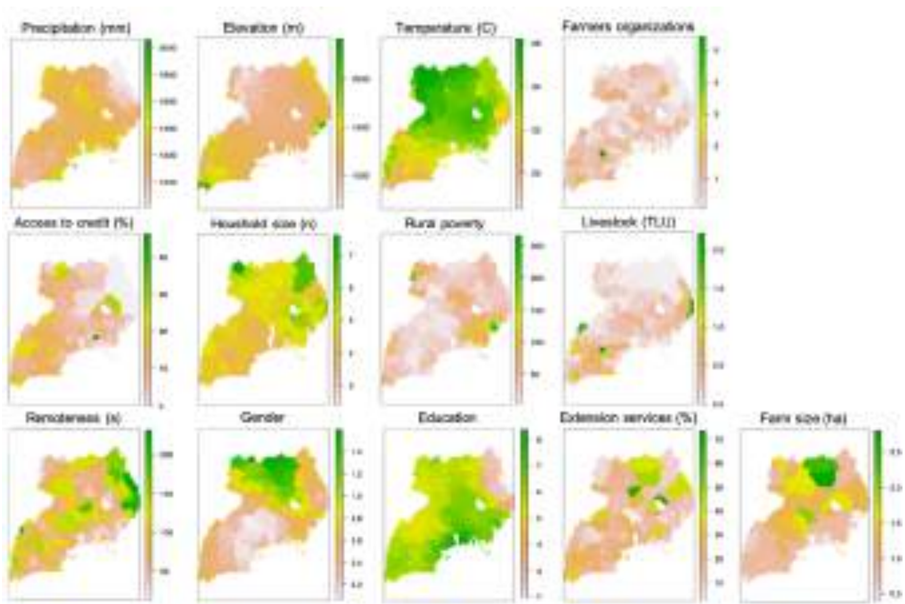

Figure 3. Spatial attributes of the barriers for SLWM adoption in Uganda at the district level. Dimensionless attribute are not reported in this Figure are listed in the supplementary material (Table S2)

Analysis

Hierarchical clustering and causal mechanisms

We used cluster analysis, which is a statistical tool that group objects with similar attributes into exclusive clusters (Walther and Lüdeke, 2012), to identify the patterns of barriers for the implementation of SLWM in both types of archetypes. The resulting clusters are interpreted qualitatively to form the final archetypes.

Clustering is a common approach in archetype analysis and in general a tool used to dissect the complexity of social-ecological systems (Sietz et al., 2019). Within the varieties of clustering algorithms, we used hierarchical clustering (ward.D method; Ward, 1963), commonly used in studies of social-ecological archetypes (Rocha et al., 2020). For the spatial archetype we also normalized the attributes by scaling them to zero mean and unit variance, to make the different magnitudes comparable and remove the effect of outliers (Václavík et al., 2013). For the sake of building representative archetypes, we selected the appropriate number of clusters by using an iterative approach. We inspected different cut-off numbers (from 4 to 10) aiming at minimizing the number of clusters while explaining the highest diversity, keeping a balanced number of objects per cluster. Less than four clusters may render the analysis purposeless, while more than ten clusters can excessively increase the complexity and compromise the interpretability of the results (Neudert et al., 2019; Sietz et al., 2019).

The quantitative clusters are interpreted qualitatively through techniques such as participant observation, field notes and interviews extracts (Hirschman, 1986; Schatzman and Strauss, 1972; Spradley, 2016). This interpretation enriches systemic linkages across the quantitative clusters and essential qualitative data obtained in the previous attribute selection and data collection steps that could not be included in the formal analysis. In the qualitative analysis, we use field notes to identify the interviews with the richest explanation of the key causal dynamics and personal insights on how different barriers collectively characterize the overall gap in adoption of SLWM.

Further qualitative analysis entails the combined analysis of cognitive and spatial archetypes. The combination merges complementary sources of knowledge from stakeholders and databases that can be interpreted jointly. As part of this methodology we map the locations of the interviews (conducted to determine the cognitive archetypes) throughout the spatial archetypes.

Uncertainty analysis

We compared the stakeholders' ranking of barriers with the corresponding spatial data (described in the data collection section "Data collection") to understand the level of comparability when extending the implications of the cognitive archetypes within the spatial archetypes. Five attributes within the two sets of cognitive and spatial archetypes are comparable as they relate to the same concepts. These pairs of attributes, listed in Table 1, are: i) "farm size and land fragmentation, ii) "gender gap" and "women empowerment", iii) "Access to credit" and "lack of inputs/credit", iv) "agricultural extension services coverage" and “ineffective agricultural extension services” and v) “rural poverty” and “poverty”. For instance, understanding whether the perception of land fragmentation (cognitive attribute) agrees with regional average farm size (spatial attribute), can indicate how much of the stakeholders´ perception is well captured by the district level data. The perception data underlying the cognitive attribute is a ranking (i.e. priority level from 1 to 5), while the spatial data are quantitative measure of different units (e.g. farm size is in hectares). In order to make the two sets of data comparable, we first calculated a dimensionless score for the cognitive attributes (Priority Score), then we joined the Priority Score and the spatial attributes, and we normalized and centered them on the national average, similarly to the preprocessing performed for the clustering described in the previous section.

To obtain the Priority Score, we first gave each priority level (Pi) a score: the highest priority (1) was given 5 points, while the least important attribute was given 1 point. Secondly, we calculated the frequency at which each cognitive attribute was given priority 1, 2, 3, 4 or 5 (i.e. how many interviews per spatial archetypes) using Eq. 1:

$$\text{Priority Score} = \frac{\sum P_i}{n} \qquad \text{Eq.1}$$

The Priority Score, after normalization and scaling to zero mean and unit variance, is a dimensionless score ranging from -1 to +1, which indicates the priority level of each attribute compared to the national average. Negative values of the Priority Score for an attribute imply that this cognitive attribute is perceived less of a priority than in other spatial archetypes of Uganda. For example, if the Priority Score for the attribute “land fragmentation” in a spatial archetype is positive, it means that stakeholder perceive land fragmentation as more urgent than in other areas of the country. This Priority Score is then compared with the spatial data of farm size of that spatial archetype to check whether it is larger or smaller than in other spatial archetypes. If the normalized farm size is higher than the national average, there is an agreement between cognitive and spatial attributes, which means that stakeholders perceive land fragmentation as a priority in a spatial archetype where farm size is indeed smaller than in other parts of Uganda.

Results

Cognitive archetypes of barriers for SLWM implementation

The cluster analysis on the ranking of cognitive attributes reveals the emergence of five cognitive archetypes of barriers to the adoption of SLWM in Uganda (Figure 4). We define these archetypes as:

“Poverty trap”: Combined land fragmentation and inadequate farming skills yield low crop production, keeping farmers in poverty conditions. Although farmers would benefit from the implementation of SLWM, they lack resources and awareness on SLWM often driven by insufficient extension services.

“Overpopulation”: Rapid population growth has caused deforestation, triggering land degradation and fragmentation due to the traditional land inheritance system.

Usually local legislation prescribes the implementation of SLWM to prevent soil erosion and land degradation; however, the implementation and scaling-up is hindered by lack of awareness, weak enforcement and ineffective support from extension services.

"Farmers resistance": SLWM implementation is primarily limited by resistance to change and lack of awareness on SLWM. External factors, such as lack of inputs (e.g. tools, seedlings, manure etc.) and droughts, further demotivate farmers, increasing their resistance to adoption.

"Rural isolation": Unfavorable conditions of small and isolated agricultural plots, often located on slopes, where suitable SLWM measures may require large space, long time of implementation and large amount of resources (e.g. trenches cover up to 40% of the farmland). These conditions render their adoption unfeasible.

"Post-conflict": After a prolonged armed conflict and farming inactivity, a rigid patriarchal society and customary land tenure system prevent individual initiative to adopt innovative SLWM practices, keeping farmers in poverty conditions.

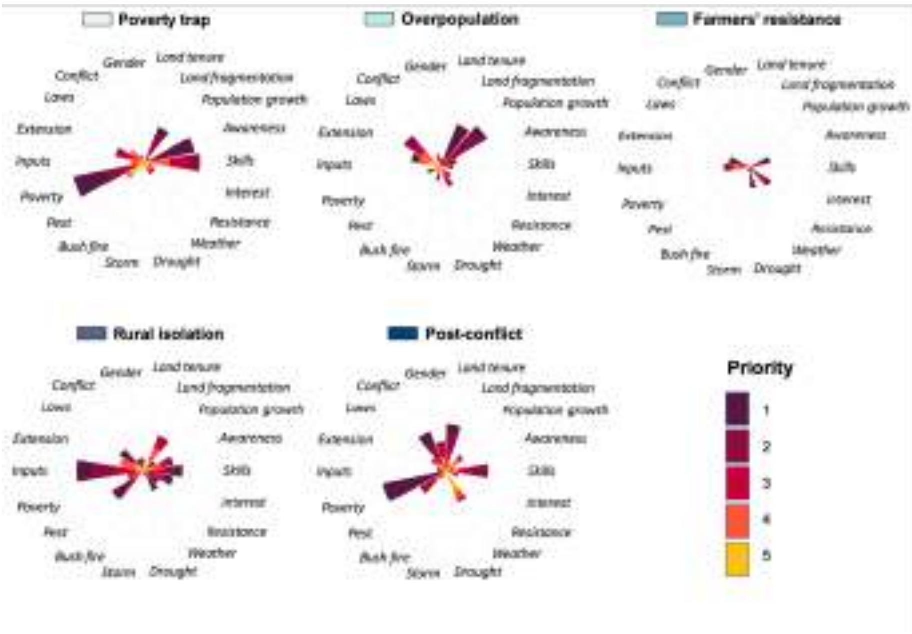

Figure 4. Cognitive archetypes of barriers for SLWM adoption. The red shades indicate the level of priority (highest in dark red and lowest in yellow) as expressed by interviewees.

Spatial archetypes of barriers for SLWM implementation

Seven spatial archetypes emerge from the clustering of districts' spatial attributes that represent geographical distribution of similar social-ecological characteristics and barriers to SLWM implementation within Uganda (Figure 5).. These spatial archetypes are described below.

Small farms on steep lands: Comprises highland systems with mean temperature below country average, very small average farm size, lower rural poverty conditions and higher access to credit relative to national average. This archetype covers most of South-Western Uganda, and three mountainous districts in the East around the Mount Egon and the Nebbi district in the North-West.

Small semi-commercial farms: Comprises the districts of Central Uganda in the proximity of Lake Victoria. In relation to national averages, the archetype presents a more humid climate and wealthier socio-economic conditions, including higher connectivity to cities, lower rural poverty, lower gender imbalance, higher education and higher degree of market integration.

Farms in drier lowlands: It is the largest spatial archetype, characterized by a drier climate, lower education, larger gender gap and poorer farmer support (i.e., low extension service coverage and few farmers' organizations), when compared to the national averages.

Large supported farms: This spatial archetype is in the North and, apart from presenting characteristics of farms in drier lowlands, it is characterized by larger farms, the highest extension service coverage and gender gap of all archetypes.

Poorest small farms: Characterized by similar social-ecological conditions as *Small semi-commercial farms*, but with the highest poverty in Uganda and slightly lower scores of socio-cultural attributes (e.g. education and gender gap).

Organized farms: Spatially surrounded by the archetype *small farms on steep lands*, *organized farms* shares similar scores with *small farms on steep lands* on most attributes, apart from having the highest number of farmers organizations and livestock availability.

Farms in remote drylands: It covers the North-Eastern part of Uganda, characterized by remote areas with the driest climate in the country, lower education and access to credit and poorer agricultural services (i.e., poor extension services and few farmers organizations), when compared to the national averages.

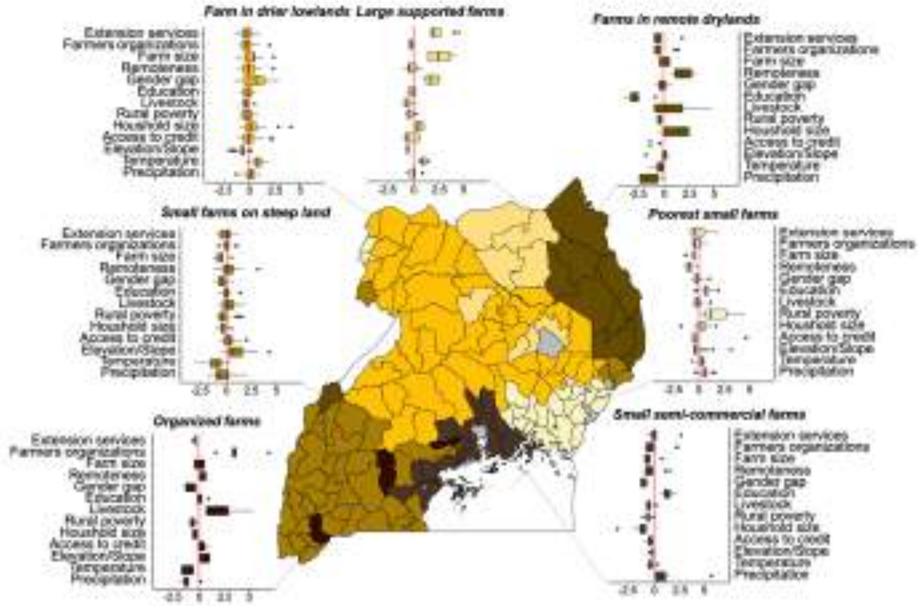

Figure 5. Spatial archetypes of barriers to SLWM adoption. The map shows the geographical location of the spatial archetypes, while the box plots present the dimensionless (normalized and scaled at the national level) ranges of the 13 spatial attributes characterizing the social-ecological barriers. A value of zero for an attribute (vertical red lines) equals the attribute's average values for Uganda, while positive and negative values reflect values larger and smaller than the attribute's national average, respectively. The districts in grey are excluded from the analysis.

Combined cognitive and spatial archetypes of barriers to SLWM adoption

The locations of the interviews conducted to determine the cognitive archetypes are found in only four out of seven spatial archetypes – *small farms on steep lands*, *small semi-commercial farms*, *farms in drier lowlands* and *large supported farms*. By combining the cognitive archetypes with these four archetypes we can determine the relative importance of the cognitive archetypes in different contexts of Uganda. Every spatial presents at least one dominant cognitive archetype (Figure 6).

Small farms on steep lands is the most complex spatial archetype, also considering that it includes all five cognitive archetypes. Nevertheless, over 85% barriers as perceived by stakeholders reflect rural isolation, overpopulation and poverty trap. The pressure posed by population growth on natural resources and abundant precipitation have vastly increased soil erosion. Typical measures identified by interviews in this spatial archetype present soil erosion mitigation practices (e.g. trenches, terraces and soil and water conservation; Figure S1 in supplementary material).

Similar SLWM practices are adopted in the archetype *small semi-commercial farms* with the same soil erosion reduction purpose. Additionally, given the higher market integration, intercropping is used to grow cash crops together with staple crops to optimize the use of space in small farm plots (for example banana trees offer shade to coffee plants) and water harvesting to provide additional irrigation and boost production. In this spatial archetype, six out of ten interviews fall within the dynamics of farmer's resistance. In a context of higher market integration and lower poverty rates, farmers have generally higher access to inputs and credit, thus the remaining barriers are the low awareness of isolated farmers (e.g. the ones not part of farmers organizations) and the limited resources (capacity and knowledge) of extension workers.

In the North of the country, harboring *farms in drier lowlands* and *large supported farms*, the dominant SLWM practices are mulching, intercropping, zero grazing and agroforestry, which are generally used to decrease soil evaporation and increasing soil fertility to build a productive agricultural system and improve the poverty conditions that are particularly severe in these areas. This set of practices is mirrored by the distribution of practices shown by the cognitive archetype *post-conflict*, which is the dominant one (covering 60% of the interviews) in the spatial archetype *farms in drier lowlands*. No single cognitive archetype can fully explain the barriers for SLWM implementation in large supported farms, though *poverty trap* has the highest representation with four out of ten interviews.

Uncertainty analysis results

In order to assess the level of generalization between the two types of archetypes, we compared the perceived barriers from stakeholders' interviews which form the cognitive archetypes (quantified with the Priority Score) and the spatial social-ecological data used for the spatial archetypes (Figure 7) – see Figure S2 in supplementary material for the complete comparison between the Priority Scores and spatial data.

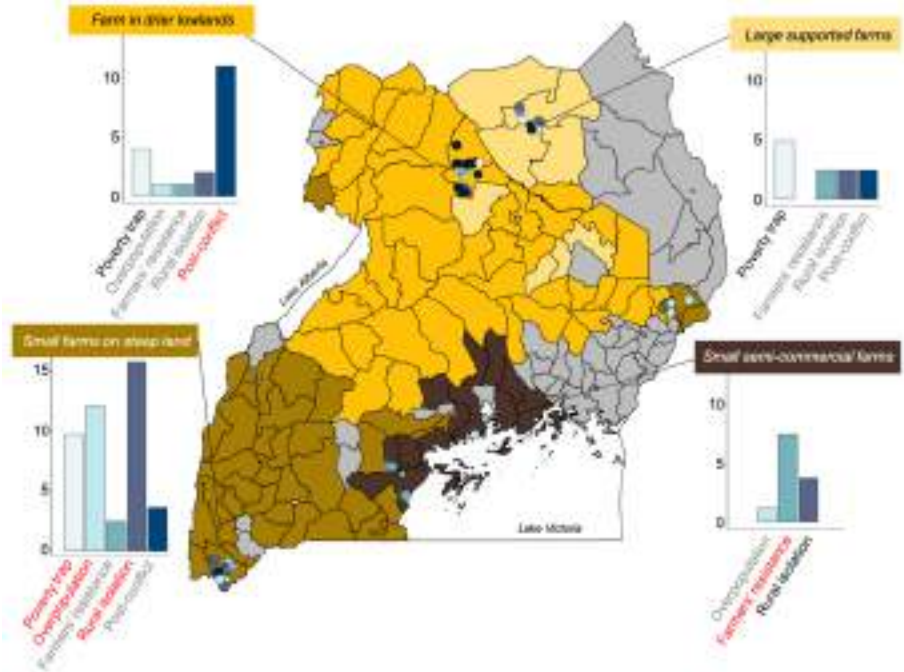

Figure 6. Combined cognitive and spatial archetypes. The bar plots show the distribution of the five cognitive archetypes (number of interviews on the vertical axes) on the four spatial archetypes hosting interviews. Interviews locations are shown as colored dots on the map. The three spatial archetypes without interviews within borders are masked in grey. The name of the most relevant cognitive archetypes per region (in the bar plots) are highlighted in red, the second-best ones are in black and the least relevant ones are in gray.

We found that *gender gap* is the attribute with the highest agreement between the two sets of data, meaning that in spatial archetypes with higher gender inequality (compared to national average) gender inequality is perceived as a higher priority barrier, while it is considered a less urgent barrier in spatial archetypes with lower gender inequality. Land fragmentation. Land fragmentation is the attribute with the second-best agreement between stakeholders' perception and spatial data. Land fragmentation is perceived as a barrier in *small farms on steep land*, which is the spatial archetypes with the smaller average farm size, and it is not perceived as a barrier in *large supported farms,* which has the largest average farm size. *Access to credit* and *poverty* show agreement between perception and spatial data in two of the four spatial archetypes, while extension services shows a complete disagreement between stakeholders' perception and spatial data.

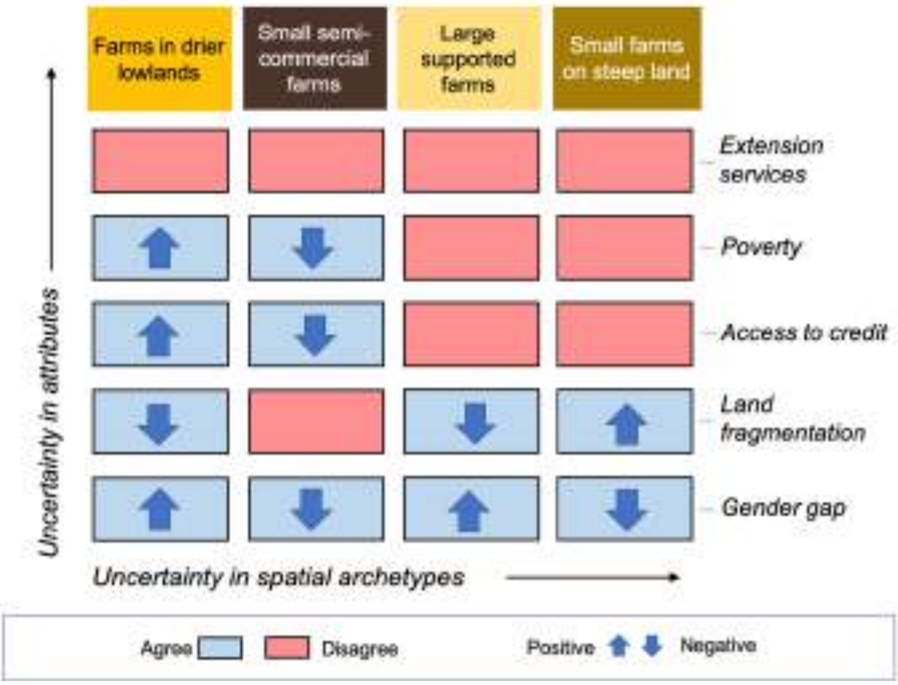

Figure 7. Match between spatial data and stakeholders' perceptions. The rectangles show agreement (blue) and disagreement (red) between district data (averaged at spatial cluster level) and the Priority Score (from stakeholders' perception) within the four spatial archetypes. The two sets of data agree when both exhibit conditions higher (upwards arrow) or lower (downwards arrow) than the national average, otherwise they disagree. The five spatial attributes are the common ones between the spatial archetype and the cognitive archetypes. The detailed comparison between the Priority Score and spatial data is available in Figure S2 in supplementary material.

Discussions and Conclusions

A system perspective on the barriers to adoption of SLWM

The multimethod approach combining cognitive and spatial archetypes presents a comprehensive picture of the barriers to the implementation of SLWM practices in Uganda, by bringing together social-ecological case-based (interviews) and spatial (district) data. While the cognitive archetypes reveal the barriers for implementation from the stakeholders' perspective, the spatial archetypes identify the spatial domain of transferability for these cognitive archetypes. These two approaches have traditionally been implemented and used separately. The main insight from the cognitive archetypes is that there is no single set of cognitive attributes that can explain the barriers for implementation of SLWM across all interviews. Rather, five cognitive archetypes can collectively explain the dynamics of implementation of SLWM in Uganda.

In order to allow spatial transferability of archetype findings, social-ecological systems in other studies have been mapped at different scales, from the national (Rocha et al., 2020) to the global scales (Václavík et al., 2013). Our approach assumes that similar outcomes (e.g., removal of barriers) can be applied to similar social-ecological contexts (Václavík et al., 2016). Building on this assumption, we identify seven spatial archetypes of barriers for SLWM implementation to spatially extrapolate to the country scale the cognitive archetypes defined from the interviews. We used for such extrapolation the four spatial archetypes that had interview cases within their spatial domains (Figure 6). However, this assumption, although largely utilized in other studies (Rocha et al., 2020; Sietz et al., 2017; Václavík et al., 2016) , has never been tested, and validation still remains a challenge with this approach (Sietz et al., 2019).

To go beyond this untested assumption, we inspected the agreement between spatial barriers to SLWM and stakeholders' perception. Our results show that spatial district-data on gender gap and land fragmentation adequately reflect and support the stakeholders' concerns. Access to credit and poverty show a partial mismatch in the archetypes *large supported farms* and *small farms on steep land*, while extension services shows a complete disagreement between spatial data and perception data. The mismatch does not necessary imply unfit or flawed data, rather reinforces our finding that district-level data and spatial archetypes need to be interpreted jointly with stakeholders' perception. Following the example of extension services, the spatial archetype *large supported farms* is characterized by the highest coverage of extension services with around 50% of the families declaring to have received assistance from extension workers. Nevertheless, the stakeholders claim that ineffective extension services are one of the barriers for SLWM implementation in their region. The mismatch shows that the spatial analysis alone is insufficient. In fact, when compared to other African regions, the highest extension service coverage in the spatial archetype *large supported farms* is low. To explain the lack of awareness of the benefits of SLWM in rural Nigeria, Chianu and Tsujii (2004) reported that "only 63% of the farmers had had contact with agricultural extension service staff in the previous 5 years", highlighting the necessity to increase the extension services coverage in the country. Therefore, it is not surprising that stakeholders claim that extension services are still scarce, despite the spatial archetype having the highest extension service coverage in Uganda.

In the remaining spatial archetypes, the average extension service coverage ranges between 15 to 20%; extremely low when compared to other sub-Saharan Africa countries. This evidence suggests that while the improvement of extension services is an acknowledged priority in Uganda as a country, (AfranaaKwapong and Nkonya, 2015; Benin et al., 2011; Fan and Zhang, 2008; Hasan et al., 2013), it needs to be understood and addressed within context-specific barriers identified through the spatial archetypes.

Bridging rural development theories with policy strategies

Policies for up-scaling SLWM need to consider context-dependent adoption barriers. While rural development (including land intensification, rural anthropology and economic theories) provide general frameworks to understand SLWM adoption mechanisms (Meyfroidt et al., 2018), they are too generic and need to be contextualized to capture the social-ecological complexity and diversity. On the other hand, local socio-economic analysis on adoption can be too case specific and thus provide a fragmented understanding of the problem. The cognitive and spatial archetypes developed here can be used to guide both contextualization and framing for rural development policies.

In *small farms on steep lands*, the barriers to SLWM implementation are related to the dynamics of rural isolation and the nature of the practices. Remoteness to cities and markets puts farmers in a position of disadvantage when buying inputs and selling their produce (Magingxa et al., 2009), and impedes the contact with extension workers who often lack resources to cover remote areas (Abesiga and Musali, 2002). Digging trenches and building terraces are very tiresome jobs and require high investments in terms of labor and inputs, which discourage farmers. The costs of implementation and inputs (e.g. seed, manure, hired labor, transportation) are to be faced by poor farmers, in absence of appropriate credit mechanisms (Katwijukye and Doppler, 2004; Vanclay and Lawrence, 1994). Moreover, land fragmentation exacerbates the difficulty of investing in a small plot (Turinawe et al., 2015). In this context, the institutional approach currently focuses on forcing the implementation of trenches and terraces with by-laws (i.e. local laws and regulations), but their implementation is ineffective (Kassie et al., 2011). These SLWM practices are embedded in local knowledge since they were first introduced around 1930 by the colonial government and were enforced using by-laws. These by-laws still exist, but the rigid top-down approach and the weak enforcement of policies seems to be a limit to the widespread adoption in current regulations (Kassie et al., 2011). In this stagnant situation, Institutional change is necessary to promote adoption. The district authorities should involve the community and their leaders in the by-law formulation through a flexible and participated process (Sanginga et al., 2010; Wagoire et al., 2013). Furthermore, the national and district governments could for example encourage and facilitate establishment of rural financial services to improve access to credit, support land reform to tackle land fragmentation and gender biases and, reform rural extension services and advisory services by also inviting private service providers.

In *farms in drier lowlands*, citizens were displaced in camps during a long conflict, with no opportunity to continue farming (Bozzoli et al., 2011). This situation affected agricultural and societal development, the latter reflected in the low education and high gender gap of the archetype. In this region, poverty is the dominant barrier and the population still relies on subsidies (Tusiime et al., 2013). Women, as in the rest of Uganda, are the ones working in the fields, but land ownership and use in this region are controlled by men. This rigid patriarchal customary land system, where decisions are taken by the older man of the clan, often repress the initiative to implement of SLWM taken by women in favor of traditional practices. Moreover, the extremely depraved conditions of poverty and the lack of experience and skills caused by the prolonged confinement in internal displacement camps, creates a situation of discouragement and resignation which make farmers less inclined to improve their farming practices and skills. The extension service support needed to bridge the lack of knowledge and skills is still weak and there are few farmer organizations, which together hinder the adoption of SLWM. Extension workers should be given resources (i.e. fuel, tools and seedlings) to raise awareness on SLWM and support farmers in the implementation phase.

Although also located in the region affected by the armed conflict, in *large supported farms* the cognitive archetype *post-conflict* is marginally represented. In these districts, the social-ecological conditions are similar to those of the archetype *farms in drier lowlands* (Figure 5), but with larger farms, higher extension service coverage and higher gender gap. In fact, this spatial archetype presents similar socially-embedded norms (such as customary land tenure system and patriarchy) already discussed for the farms in drier lowlands (Adelman and Peterman, 2014). Ironically, despite it exhibiting the highest extension service coverage in the whole country, ineffective extension services emerge as a concern for stakeholders (Figure 8). This apparent contradiction may be explained by the socio-economic post-conflict conditions, which have hindered agricultural development to the point that the current farming practices are still lagging behind other regions, thus the extension services need to be further improved to provide a prompt recovery of the local agricultural sector.

A completely different situation governs the barriers in *small semi-commercial farms*, which is the archetype with the best access to markets and best score in socio-economic indicators. This situation is the most favorable to the implementation of SLWM practices, especially for the semi-commercial farmers planting a range of cash crops (especially coffee and banana), allowing for better income. Land fragmentation is lower than in other spatial archetypes but is still an important process. However, in this archetype, land fragmentation weighs less than in small farms on steep land because of the proximity to markets, which provides more opportunities for cash crop production and liquidity. Nonetheless, our results suggest that even when socio-economic barriers are removed, the adoption can be hindered by the norms and beliefs of farmers, which are not generally captured by socio-economic analysis. A potential explanation is provided by the "full belly" theory (Kaimowitz and Angelsen, 1998), which describes how farmers refrain from adopting new technologies because they tend to minimize the work effort as soon as they reach the subsistence level of production. Other interpretations suggest that, even when aware of SLWM technologies, farmers might intentionally decide to not adopt certain practices because they do not seem to fit their farming paradigm, which is influenced by local cultural and social norms (Vanclay and Lawrence, 1994), and they rather adopt diversified household strategies more in line with their way of living, for example compensating the loss in agricultural production with off-farm income (Ellis, 1998; Ellis and Freeman, 2004). These dynamics, here capture by the "Farmer's resistance" cognitive archetype, represent an underlying factor across all spatial archetypes in Uganda, also found in other African contexts (Sietz and Van Dijk, 2015). To deal with this case, the extension service approach needs to penetrate the local context, understanding the deep motivations driving farmer's resistance. Extension service workers should also consider more inclusive strategies to involve marginalized farmers' groups such as women, less educated and poorer farmers (i.e. subsistence farmers) and farmers outside local formal organizations, which are usually left behind (Lubwama, n.d.; Ragasa et al., 2013). Also strengthening local institutions, such as local farmers' organization, can prove an effective strategy (Feder et al., 2010).

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Supplementary material for "Unpacking the barriers to adoption of sustainable land and water management in Uganda"

Table S1. List of factors associated to adoption of agricultural innovations in Uganda from meta-analysis. In green are the factors selected as attributes for the analysis and in orange the factors that are included as proxies in some of the selected attributes (e.g. the factor "land size" was selected as spatial attribute, but it also represents a proxy of farm size (Prestele Reinhard et al., 2018)).

FACTOR	PAPERS (n=24)
Education	8
Labour	7
Access to credit	6
Age	6
Off-farm income	5
Extension services	5
Gender	5
Farm size	4
Houshold size	4
Land size	4
Livestock units	4
Land tenure	4
Farmer associations	3
Distance to Market	3
Distance farm-house	3
Land ownership	3
Slope/location	3
Clear policy and legal framework	2
Subsidy provision	2
Security of land tenure	2
Agro-climatic conditions	2
Transport	2
Training	2
Lack of government support	1
Drastic seasonal variability	1
High investment costs	1

On-farm income	1
Information	1
Capital	1
Decision making power	1
Norms and beliefs	1
Value of output	1
Fragmented land	1
Drought/rainfall	1
Marketing facilities	1
Cash	1
Naighbouring SWC	1
Soil fertitily	1
Radio/communication	1
Crop type	1
Crop diversity	1
Crop production	1
Agricultural and environmental related programs	1
Land degradation	1
Roads	1

Table S2. Spatial attributes and corresponding datasets used for the classification of spatial archetypes of social-ecological barriers in Uganda.

Attribute	***Description***	***Source***
Precipitation	Total precipitation (mm y^{-1}) averaged for the period 1986-2016 from monthly time series data.	(Goodman et al., 2019)
Elevation	Elevation from sea level (m)	(Goodman et al., 2019)
Temperature	Air temperature (C), yearly average	(Goodman et al., 2019)
Education	Average education attainment	(Graetz et al., 2018)

Gender gap	Gap in education attainment between genders	Derived from Graetz et al. (2018)
Remoteness	Accessibility to cities (with more than 50.000 people) in minutes.	(Weiss et al., 2018)
Household size	Average household size (number of people).	(Uganda Bureau of Statistics (UBOS), 2010)
Rural poverty	Percentage of the rural population living below the national rural poverty line.	(*Poverty GIS Database*, 2008)
Livestock	Total Tropical Livestock Unit (TLU)	(*Africa Ruminants Tropical Livestock Units (TLU)*, 2015)
Farmers organisations	Number of farmers organizations	(*Farmers' organization of Uganda*, 2017)
Farm size	Median Landholdings of households	(*The National Livestock Census Report*, 2008)
Access to credit	Percent of agricultural households reporting having access to credit	(Uganda Bureau of Statistics (UBOS), 2010)
Extension services	Percent of agricultural households that reported receiving extension services on farm management	(Uganda Bureau of Statistics (UBOS), 2010)

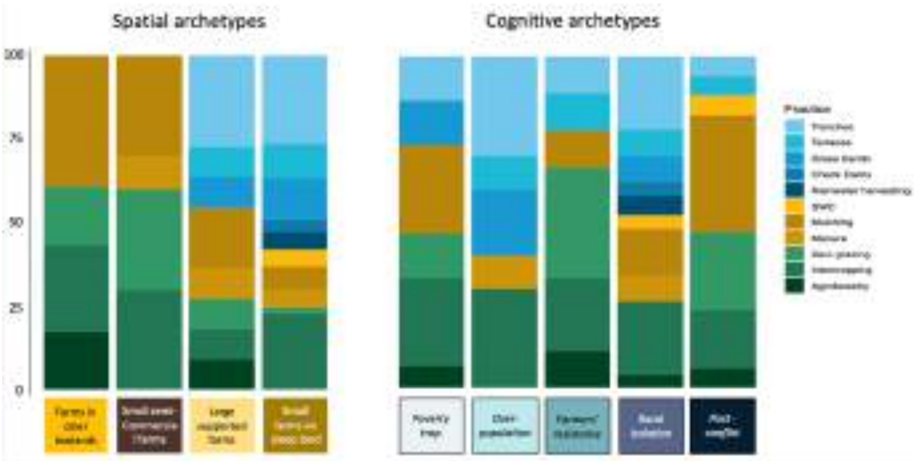

Figure S1. Distribution of sustainable land and water management (SLWM) practices across four spatial and five cognitive archetypes in Uganda. The practices are color-coded according to their purposes: soil erosion reduction (blue shades), soil rehabilitation (yellow shades) and increased productivity (green shades).

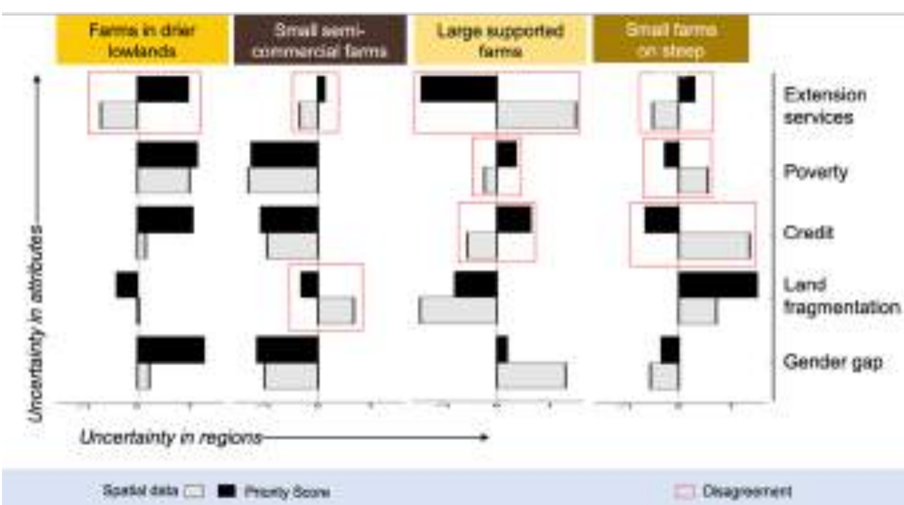

Figure S2. Complete comparison between the Priority Scores and spatial data in the four spatial archetypes hosting interviews. The bars show the relative agreement/disagreement between the two sets of data used to generate cognitive (Priority Score) and spatial (spatial data) archetypes.

Source of data used for the spatial attributes

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IV

Sustainable intensification of agriculture in Uganda: quantifying large-scale investments for small-scale farmers

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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 analyzing 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 successful practices to 75% of agricultural land would require a one-time investment of US$ 4.4 billion from smallholders. The resulting crop production increase could generate US$ 4.7 billion every year, once the practices are fully operational. These results highlight the necessity, and profitability, of investing in smallholder farmers to achieve the SDGs in Uganda, as opposed to large-scale agricultural interventions that might not profit local communities. This study can guide the development of nation-wide programs to mainstream SLWM by targeting the most suitable practices and plan for adequate financial support from government, investors and international development aids to smallholder farmers.

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 the socio-economic backbone of the country, accounting for 40% of GDP and providing the livelihood of about 80% of the population, which comprises smallholder farmers[4]. The modernization plan of agriculture of the Ugandan government 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 (around US$ 600 million per year)[7]. Locally, land degradation affects up to 90% of arable land in the most affected districts of Kabale and Kisoro in the highland areas[7].

To reverse the unsustainable rates of land degradation and achieve the SDGs, agriculture has to transform from the source of the problem to its solution[8,9]. Sustainable agricultural intensification through SLWM has the potential to mitigate climate change, reverse land degradation and increase food production if widely adopted[8,10]. Practices such as agroforestry, intercropping and conservation tillage can contribute to CO2 sequestration, conserving water in the soil and increasing soil fertility and eventually increasing yields[11,12].

Many local applications and case studies have demonstrated that investing in SLWM is economically sound[13,14]. Up to March, 2020, the World Overview of Conservation Approaches and Technologies (WOCAT) had documented more than 50 cases of implementation of SLWM across Uganda, with the aim of spreading the adoption of suitable practices by learning from existing successful experiences[15,16]. At the global scale, the large majority (93%) of WOCAT case studies reported a positive or very positive cost/benefit ratio in the long term[17].

However, despite the documented local benefits and the need for such implementation, the large-scale uptake required to reverse the current scale of land degradation is far from being achieved[18].

The successful adoption of SLWM depends on many factors, including the agro-climatic suitability of the practice (e.g. terraces only make sense on steep terrains), the social and cultural acquaintance of the practice (i.e. traditional practices are easier to adopt), the knowledge and skills required to implement the innovation, the economic resources to establish and maintain the practices and the intrinsic motivation of the farmer[19,20]. In such a contextual situation, it is hard to predict what practices might be more suitable in different contexts and at larger spatial scale such as the national scale. As a result, many top-down funding and policy initiatives have failed in achieving a widespread adoption of SLWM as the promoted technologies are not adequate for the specific social-ecological contexts[21–24].

Even when the practices are properly targeted, the establishment costs represent an unbearable burden for most farmers[25]. To support smallholders in the adoption of SLWM, a large-scale investment plan for US$10 billion to $20 billion per year for 10–15 years is needed for all Africa[26]. However, funding from both donors and public agencies in Uganda has decreased from US$34 million in 2002 to US$14 million[27]. Even though most of this funding is intended to improve access to market and infrastructure, which would eventually decrease the establishment and maintenance costs of SLWM for farmers, it does not directly contribute to provide the necessary labor and material required for *in-situ* SLWM implementation.

In this paper, we address two research questions: i) What are the most suitable SLWM that should be replicated across Uganda? and ii) what is the investment needed to establish and maintain these SLWM practices at the national scale? 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[28]. However, this information is crucial to unlock the necessary investments to smallholders as donors and investors need to know the costs and benefits before considering investing[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 why large-scale funding should target smallholders to support the widespread adoption of SLWM in Uganda.

Data and Methods

To quantify the cost-benefit of SLWM implementation at the national scale from successful case studies, we use archetype analysis, which is a methodological approach that allows to synthesize knowledge among cases and delineate areas for transferability of outcomes[30,31]. Archetype analysis has been used to find recurrent solutions between multiple cases[32,33] and, when applied to spatial data, to identify patterns of social-ecological conditions that allow for context-sensitive transferability of outcomes[21,34,35].

The case-based data for the analysis are 51 case studies from the WOCAT database, containing information on the types of SLWM practices implemented along with their establishment and maintenance costs, and the crop production resulting from the adoption of these practices (see detailed WOCAT case studies description in supplementary material). We complemented these data by in-situ interviews in November/December 2019 (31 cases), collecting further information on the types of practices and resulting crop production increase, following WOCAT standards, in the four main Ugandan regions to increase data coverage and resolution (see case studies location in Figure 2). From these data, we further estimate the potential income increase resulting from the crop production increase, using average crop production data at the district level and 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 S2 in supplementary material).

To out-scale the outcomes of local case studies, we first identify the most suitable set of SLWM practices (bundles). We use hierarchical clustering[20,36] to delineate the bundles of SLWM practices, using the Gower dissimilarity matrix[37] because this information is available as categorical data. Once the bundles of SLWM are defined, we delineate the spatial social-ecological archetypes using hierarchical clustering by following the methodology of Rocha et al, 2020[36]. The spatial social-ecological archetypes encompass districts with similar social-ecological conditions based on 15 social-ecological indicators, with every district belonging to only one spatial archetype. We selected the same indicators used by Piemontese et al, 2020[19], as they represent context-specific conditions of agriculture at large scale, with additional indicators available at national scale, such number of farmers organizations, coverage of agricultural extension services. We also replaced the indicator of Human Development Index with the more specific indicators of GDP per capita, rural poverty and education, which were available at the district level (see table S3 in supplementary material). The final list of indicators comprises annual cumulated precipitation, precipitation seasonality, aridity, soil quality, slope, elevation, agricultural labor, remoteness, farm size, extension services, number of farmers organizations, gender gap, GDP per capita, rural poverty and education.

After identifying both bundles and spatial archetypes, we characterize the distribution of bundles in every spatial archetype and we use the relative distribution of bundles (% of bundles within spatial archetypes) to out-scale the average costs and crop production increase of the case studies. For example, if the spatial archetypes “A” contains 10 case studies, 2 of which belong to the bundle “X”, we calculate the average implementation costs and crop production increase obtained from these 2 case studies and then we attribute these average costs and production increase to 20% (i.e., 2/10) of the agricultural area of all the districts belonging to the spatial archetype “A”. This allow us to identify the percentage of agricultural land within each district that is suitable for the implementation of each SLWM bundle. We multiply the average crop production increase expected from the implementation of each bundle, with the current agricultural production of the nine main food crops cultivated in the domain of each spatial archetype to obtain the potential production increase and the resulting income increase. In similar way, we calculate the total costs of implementation and maintenance. Finally, we calculate cumulative values of costs and income increase at the spatial archetype scale by summing up the costs and income increase of the individual districts within each spatial archetype.

Results

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 to provide 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.

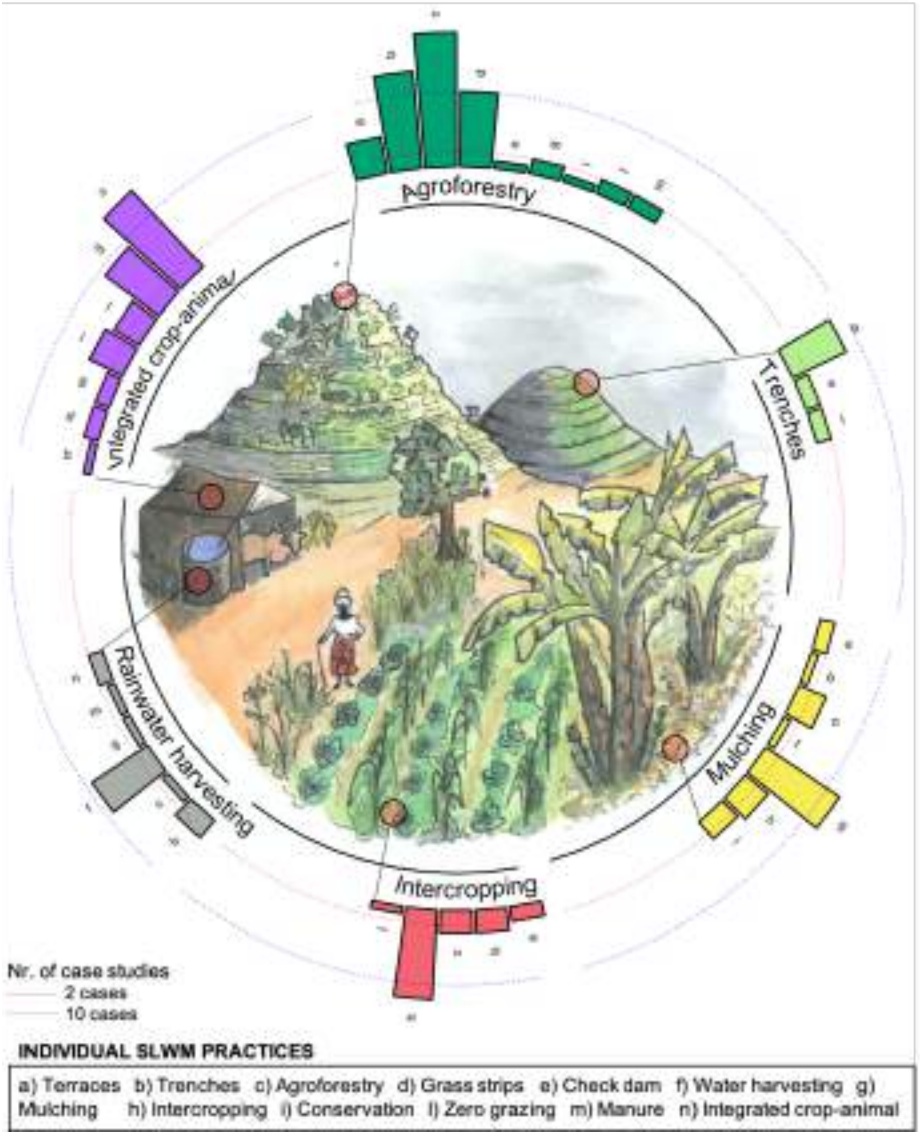

Figure 1: Bundles of SLWM in Uganda constructed from case studies (n=82). The outer bar plot shows the distribution of practices in each bundle (number of case studies on the y axes). The painting in the inner circle is an artistic representation of the bundle of practices in a farming landscape and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

Regarding the spatial archetypes of socio-ecological conditions, the clustering of districts is based on five main spatial archetypes (see supplementary figure S4 for detailed representation of spatial 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), whereas the remaining two archetypes do not contain any case study in their spatial domain. 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 best soil quality which includes the districts with highest average slopes and altitude; it is better connected to markets then the Northern region, high labor availability, but low access to extension services. The Central archetype covers all districts in the Central Uganda region and expands into the lowland districts of western Uganda, which present relatively humid hydroclimatic conditions and below-average labor availability and education.

With the exception of the bundle "Trenches" in the Central archetype, all SLWM bundles are adopted within the spatial domain of the three spatial archetypes with case studies (Figure 2a). Trenches are mostly implemented in the Highlands archetype (blue region) 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.

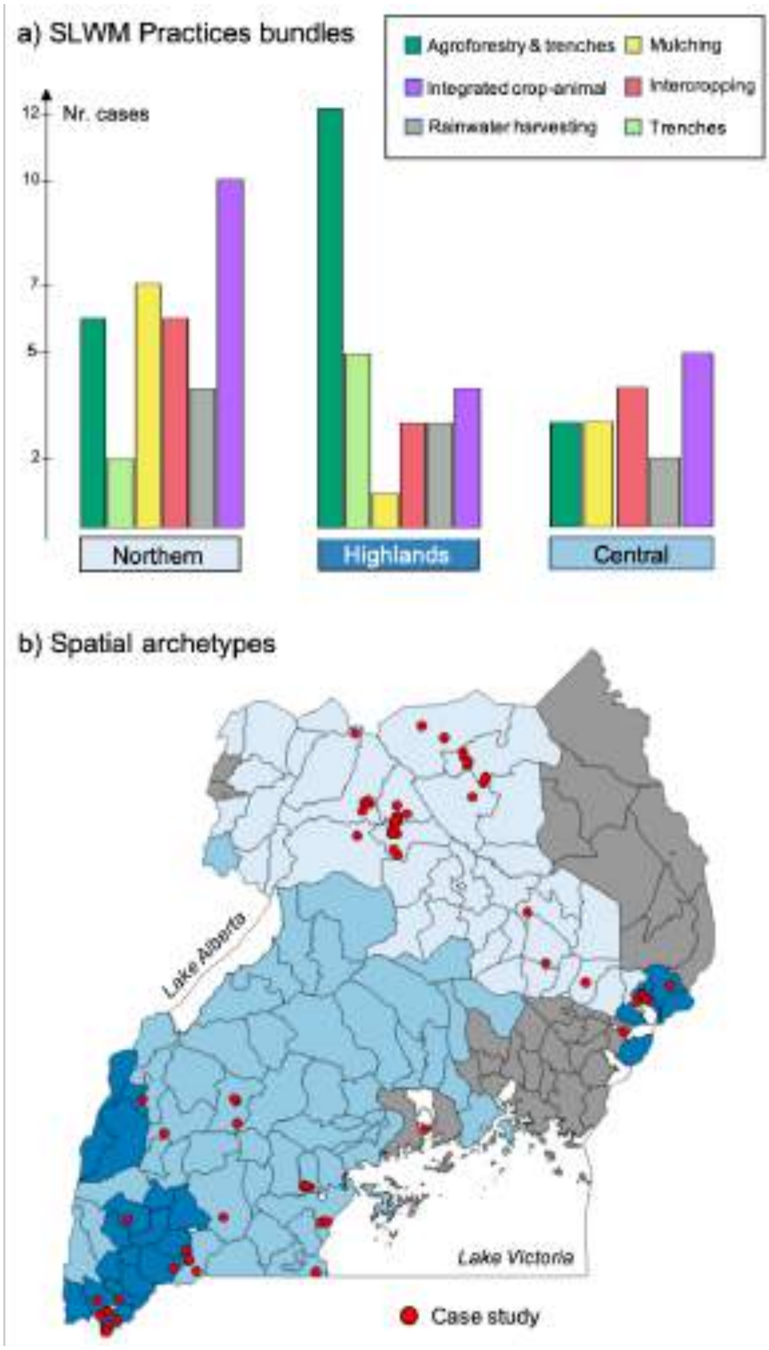

Figure 2: Distribution of (a) SLWM bundles in the three spatial archetypes hosting case studies and (b) districts grouped within the spatial archetypes, including case studies location (red dots). The grey-colored spatial archetypes do not contain case studies.

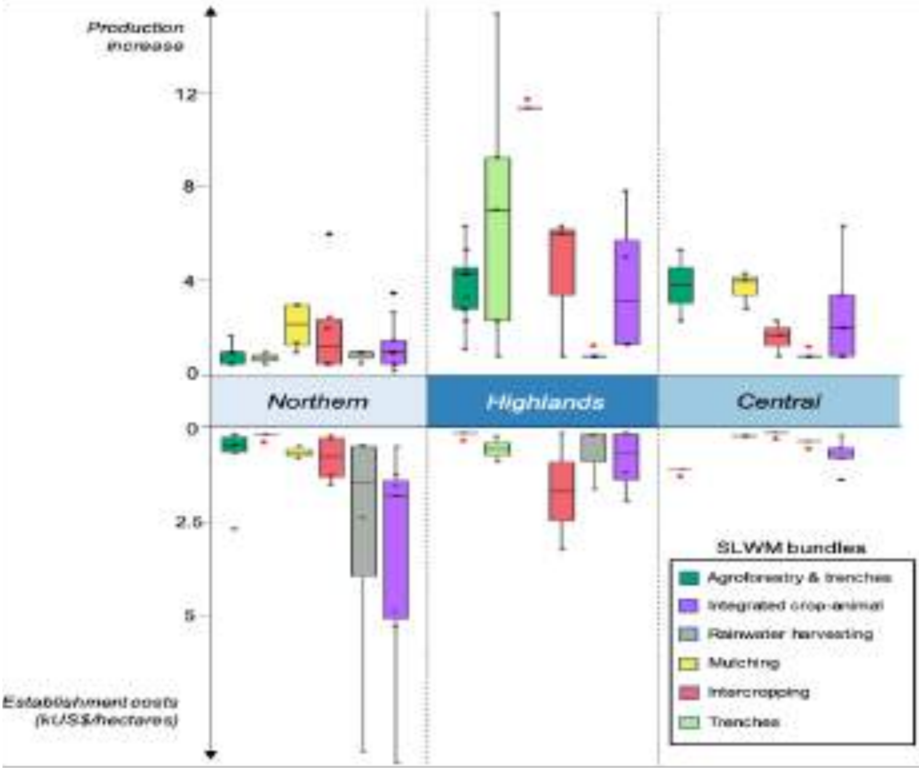

Figure 3: Crop production increase (compared to current production) and establishment costs (in kUS$ per hectare) for the six SLWM bundles in the three spatial archetypes hosting case studies. Red asterisks indicate bundles with only one case or no cases (in which case the average cost among bundle was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

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 region, with average crop production increase of three times the production before SLWM implementation.

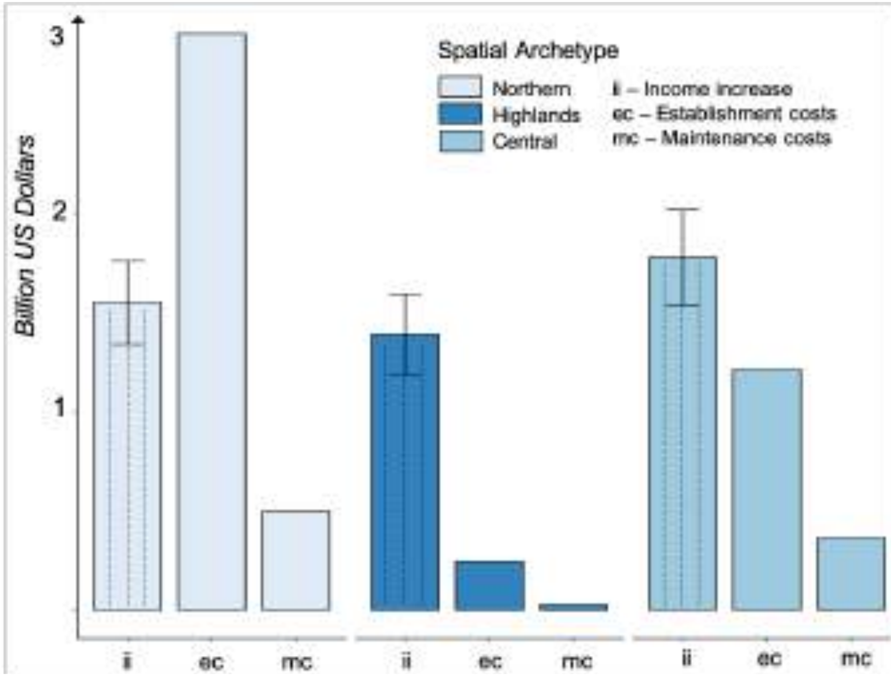

Figure 4: Cost-benefit analysis of out-scaling SLWM in Uganda. Establishment, maintenance costs and income increase (dotted bars) of implementation of SLWM in the three spatial archetypes hosting case studies. The income increase is calculated for both low-range and high-range farm-gate price.

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 increased yearly income 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 yearly 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 region.

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. 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[38,39]. 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[40]. 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 labor intensive, expensive and require frequent maintenance[41]. Instead, farmers might opt for less effective practices that better fit their farming style and needs[42]. This is the case of trenches, which are frequent in the highlands archetypes because easier to implement and imbedded in the historical landscape[43]. Hence, trenches and vegetation strips provide a first cost-effective step for farmers to engage with SLWM, and they might eventually encourage further adoption of terraces[44]. On the other hand, one of the surprising findings 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 Ugnada[45], assuming a flat investment cost of 1,000 US$ per hectare across SSA countries. Another study[46] 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 per hectare in every SSA country. The World Bank[47] 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 $12,000 respectively, and average crop increase estimate. With this premises, they estimated a total required investment of 1.2 billion US$ only in the Ugandan drylands (which is a marginal part of Ugandan agriculture). They also highlight that large-scale irrigation might provide higher yields at higher costs, but lower potential to scale compared to small scale SLWM[48]. On the other hand, other studies argue that raising productivity might be harder for smallholders than for large farms, giver their higher access to technology and credit[49].

In fact, large-scale land acquisition by international investors is currently the main driver of modernization of African agriculture[50,51]. Large-scale acquisitions are often seen as a way to improve yields by bringing technological advances to low productivity farmland in developing countries[52,53], implying a conversion from smallholder production to commercial use of land and water resources. However, major international development agencies have raised the necessity to invest in smallholder agriculture[47,48,54] considering not only the cost-benefit of agricultural production, but a broader social-ecological long-term sustainability. In fact, the impact of large-scale projects has been broadly debated as they drain water resources through intensive-irrigation schemes and potentially harm the accessibility to food by poor local communities[52,55]. Furthermore, large scale CO_2 compensation projects, despite the more sustainable claims of carbon sequestration and afforestation, might negatively affect local communities by interfering with their access to natural resources[18,56].

The major insight here presented, highlights that potential investment in smallholders compared to large-scale land acquisition in Uganda be not only environmentally and socially preferable, but also profitable. Although the required investment is higher than any other previous financial effort documented in Uganda, it is of similar magnitude of investment in SLWM in other East-African countries; for example Ethiopia invested USD 1.2 billion per year over the past 10 years[57]. 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[58], and although original smallholders funding schemes are being tested in East Africa[48,59], 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[60], thus removing power asymmetries and favor smallholder-inclusive investments.

Conclusions

We analyzed the cost-effectiveness of different SLWM documented in 82 case studies in Uganda and used archetype analysis to out-scale context-specific practices in 3 macro regions covering 75% of Uganda's agricultural land. The potential costs that smallholders need to face to implement SLWM largely exceeded the costs in the long term. 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 region 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. These results should enhance awareness of decision makers and investors on the urgency and profitability of investing in smallholders SLWM interventions.

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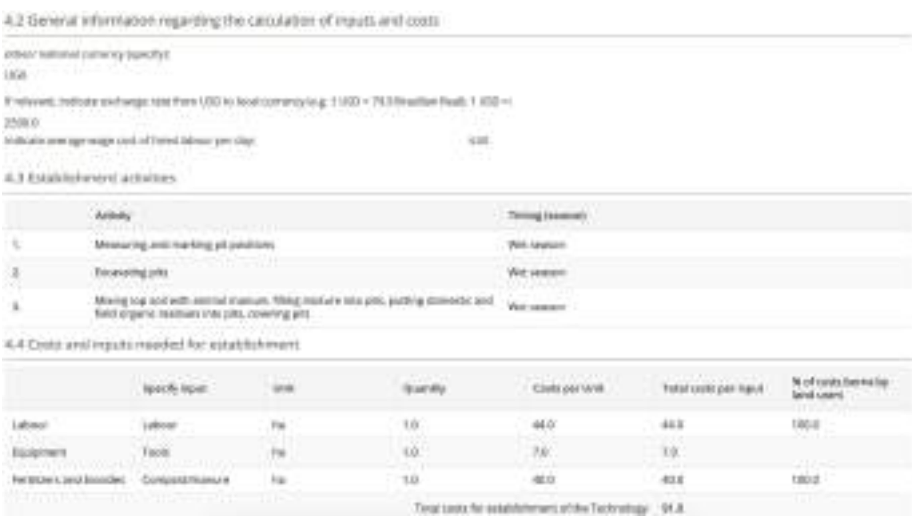
Supplementary material for "Sustainable intensification of agriculture in Uganda: quantifying large-scale investments for small-scale farmers"

WOCAT data

Hereinafter, we report snapshot of a WOCAT case study (technologies_1587) taken from the online database as an example of the type of information related to establishment costs (Figure S1), maintenance costs (Figure S2) and crop production increase (Figure S3) available from the database used in the analysis. All the case studies from the WOCAT database are listed in table S1 below (plus the information from the 31 additional case studies collected in the fieldwork). Every WOCAT case study can be accessed online by their case study code at the website:

https://qcat.wocat.net/en/wocat/technologies/view/technology_**code**/

For example to access the information of the case in Figures S1-S3 the case study **code** is technologies_1587.



4.2 General information regarding the calculation of inputs and costs

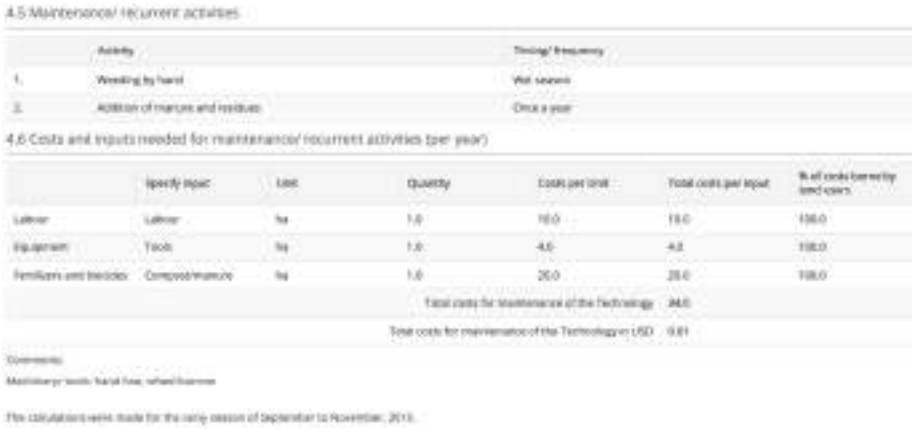
4.3 Establishment activities

	Activity	Timing (season)
1.	Measuring and marking pit positions	Wet season
2.	Excavating pits	Wet season
3.	[illegible]	Wet season

4.4 Costs and inputs needed for establishment

	Specify input	Unit	Quantity	Costs per Unit	Total costs per input	% of costs borne by land users
Labour	Labour	[illegible]	1.0	44.0	44.0	100.0
Equipment	Tools	[illegible]	1.0	7.0	7.0	
Fertilizers and biocides	Compost/manure	[illegible]	1.0	[illegible]	[illegible]	100.0

Figure S1. Snapshot of establishment cost information contained in a WOCAT case study (code: technologies_1587).


4.5 Maintenance/ recurrent activities

	Activity	Timing/ frequency
1.	Weeding by hand	Wet season
2.	Addition of manure and residues	Once a year

4.6 Costs and inputs needed for maintenance/ recurrent activities (per year)

	Specify input	Unit	Quantity	Costs per Unit	Total costs per input	% of costs borne by land users
Labour	Labour	ha	1.0	10.0	10.0	100.0
Equipment	Tools	ha	1.0	4.0	4.0	100.0
Fertilizers and biocides	Compost/manure	ha	1.0	20.0	20.0	100.0
				Total costs for maintenance of the Technology	34.0	
				Total costs for maintenance of the Technology in USD	0.01	

Comments:

Machinery/ tools: hand hoe, wheelbarrow

The calculations were made for the rainy season of September to November, 2015.

Figure S2. Snapshot of maintenance cost information contained in a WOCAT case study (technologies_1587).

Figure S3. Snapshot of crop production increase contained in a WOCAT case study (technologies_1587).

Table S1. Complete list of case studies used for the analysis, containing information on the source (F=Fieldwork, while the number is the WOCAT case study code) SLWM practices (in green) and the cases information used in the out-scaling analysis (in blue).

Source	Mulching	Trenches	Terraces	Agroforestry	Vegetation bands	SWC	Zero grazing	Manure	Intercropping	Check dam	Water harvesting	Integrated crop-livestock	Production increase	Implementation cost (US$)	Maintenance costs (US$)	Land unit (hectares)
3302				X										391	145	0.4
2872									X				0.5	562	371	0.4
2814									X				0.5	70	7	0.4
711		X											0.5	317	0.3	0.4
616			X										0.5	1255.4	25.2	0.4
1561		X											2	102	15.3	1
2817				X									0.5	1146.47	77	2
1749				X							X		0.5	345	726	1
1170									X				5.7	16.5	31	1
3301											X		0.5	243	41	1
2815									X				6	241	14.7	2.8
1587						X		X					3.1	91	34	1
1588							X					X	0.5	413	263	1
619											X		0.5	10	2.2	0.2
1153	X			X		X							4	122	38	1
2321						X						X	1			
2147								X				X				

2818	X												1.4	569	132	0.8
2254								X					2.7	148	13.7	0.4
1390	X	X									X		1	370		1
2836		X											1	454	29	10
3363								X				X	1	542	270	0.5
3328				X									1.7	15		0.4
2784							X	X				X	0.5	340	4	0.2
719	X					X		X					1	740	2	0.4
1589						X							0.5	1260	120	1
1178					X	X						X	4.7	100	38	3
2761												X	0.5	1770	148	0.2
1169		X			X								4	18	13	1
2778				X									1	170	62	2.8
2880				X										414	48	0.16
3376									X				1.4	12	11	1
3461	X												1	280	130	0.6
3362												X	1.7	550	84	0.8
2787				X					X				0.5	283	154	0.25
2821		X		X				X				X	0.2	1038	176	0.2
2812												X	1	480	247	0.5
2819				X									1	72	15	0.2
1391		X						X			X		1	2288	60	1
1188							X					X	6	692	72	1
2796											X	X		1708	60	0.2
1595											X		0.5	1526	216	1
1161	X												2.5	81	125	1
3455		X				X							0.5	85	38	2
3371								X				X	1.5	451	5	0.4

3391											X	X	0.5	164	280	0.8
2839				X									0.5	257	257	0.8
1151	X				X							X	7.5	10	6	1
2757	X												1	289	187	0.8
2143							X	X				X	1	11497	2205	8
2274		X											0.5	23	12	0.4
F		X		X	X	X	X						0.8			
F				X	X		X	X					3			
F		X	X	X									2.5			
F		X	X	X						X			2.5			
F		X								X			15			
F		X								X			8.9			
F	X		X			X							11			
F	X	X	X	X		X							3.7			
F		X							X				0.5			
F			X						X							
F		X									X		0.5			
F	X	X		X									5			
F	X	X			X			X					2			
F		X		X					X				2			
F		X	X	X	X								4			
F		X	X	X	X								4			
F		X	X	X	X								4			
F		X					X		X				6			
F		X		X									20			
F		X		X	X								6			
F		X		X	X								5			
F		X			X								2			
F		X				X							6.7			
F	X												3			
F				X					X				2.5			

F									X				2			
F								X					3.5			
F	X								X							
F	X								X							
F	X			X					X							
F	X			X					X		X		3			

Table S2. Farm-gate price for the main crops grown in Uganda. The prices per ton were estimated from prices per bag, considering that produce is usually sold to local market in 100kg bags (apart from bananas and plantain that are sold in bunches). This information was obtained from expert consultation during fieldwork held in Uganda in November 2019.

Farm-gate price	**UGX/ton**	**UGX/ton**	**US$/ton**	**US$/ton**
Beans	1814000	2721000	490	735
Banana	544200	707460	147	191
Maize	544200	907000	147	245
Sweet Potato	544200	634900	147	172
Sorghum	907000	1360500	245	368
Irish potatoes	907000	1360500	245	368
Cassava	907000	1360500	245	368
Millet	2267500	2721000	613	735
Plantain	544200	707460	147	191

Table S3. List of the spatial social-ecological indicators used in the spatial archetype analysis and their source. All indicators were calculated as average values at the district level.

Indicator	**Description**	**Source**
Precipitation	Total precipitation (mm y^{-1}) averaged for the period 1986-2016 from monthly time series data.	(Harris et al., 2014)
Potential evaporation	Mean annual value (mm yr-1) for the period 1986-2016, aggregated from monthly data.	(Harris et al., 2014)
Seasonality	Dimensionless index averaged for the period 1986-2016.	(Walsh and Lawler, 1981)

Elevation	Elevation from sea level (m).	(Goodman et al., 2019)
Slope	Slope derived from elevation in degrees.	(Goodman et al., 2019)
Soil quality	Soil organic carbon content (Mg C. ha-1).	(FAO, 2017)
Education	Average education attainment.	(Graetz et al., 2018)
Gender gap	Gap in education attainment between genders.	Derived from Graetz et al. (2018)
Remoteness	Accessibility to cities (with more than 50.000 people) in minutes.	(Weiss et al., 2018)
Labor	working age population density (16 to 65 years old).	(Doxsey-Whitfield et al., 2015, p. 4)
Rural poverty	Percentage of the rural population living below the national rural poverty line.	(Poverty GIS Database, 2008)
Farmers organizations	Number of farmers organizations.	(Farmers' organization of Uganda, 2017)
Farm size	Median Landholdings of households.	(The National Livestock Census Report, 2008)
GDPp	Per capita GDP.	(Goodman et al., 2019)
Extension services	Percent of agricultural households that reported receiving extension services on farm management.	(Uganda Bureau of Statistics (UBOS), 2010)

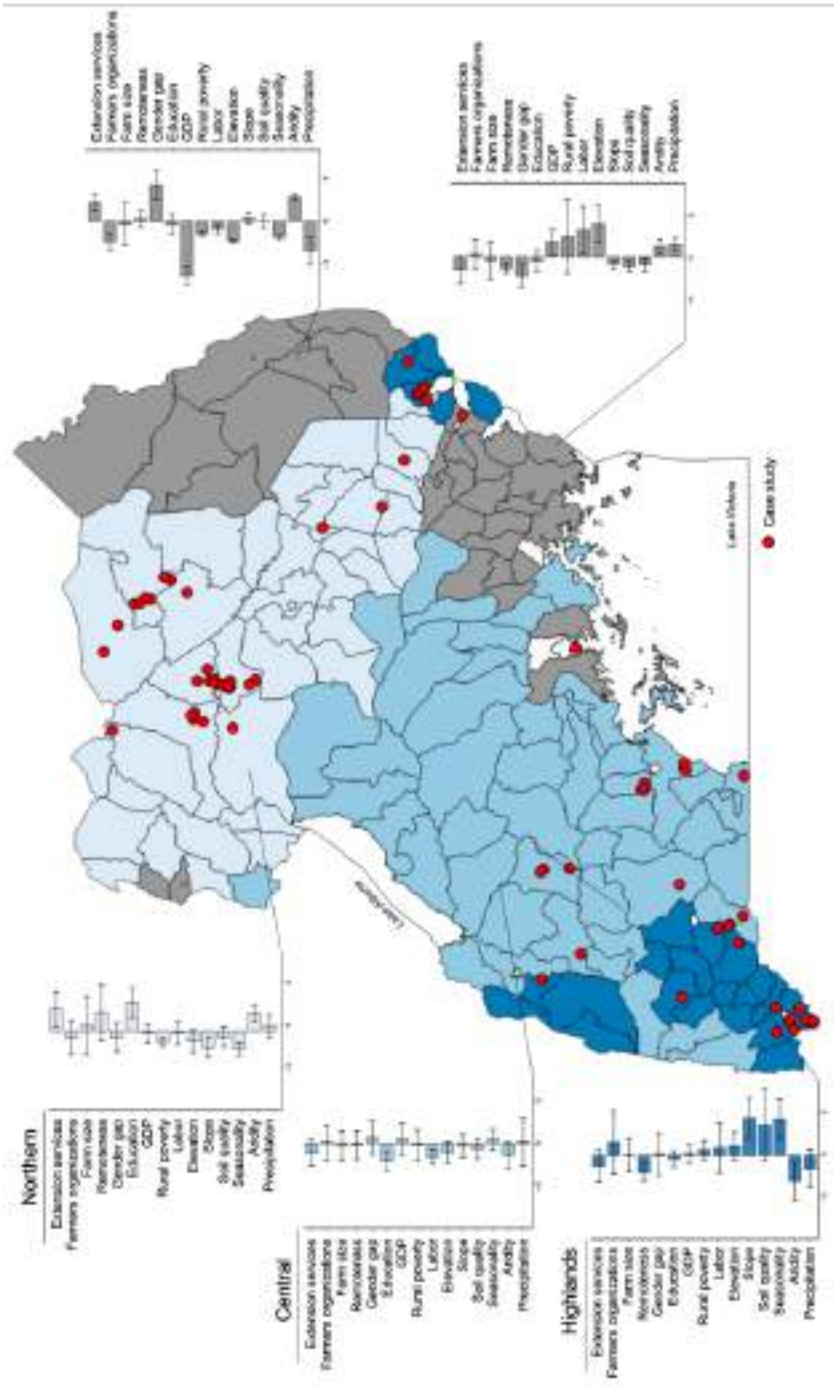


Figure S4. Spatial social-ecological archetypes. The three blue-shaded archetypes are the ones hosting case studies. Case studies' location is represented by the red dots. The bars show the ranges of the 13 attributes defining archetypes' social-ecological conditions.

Source of spatial data for the social-ecological indicators

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