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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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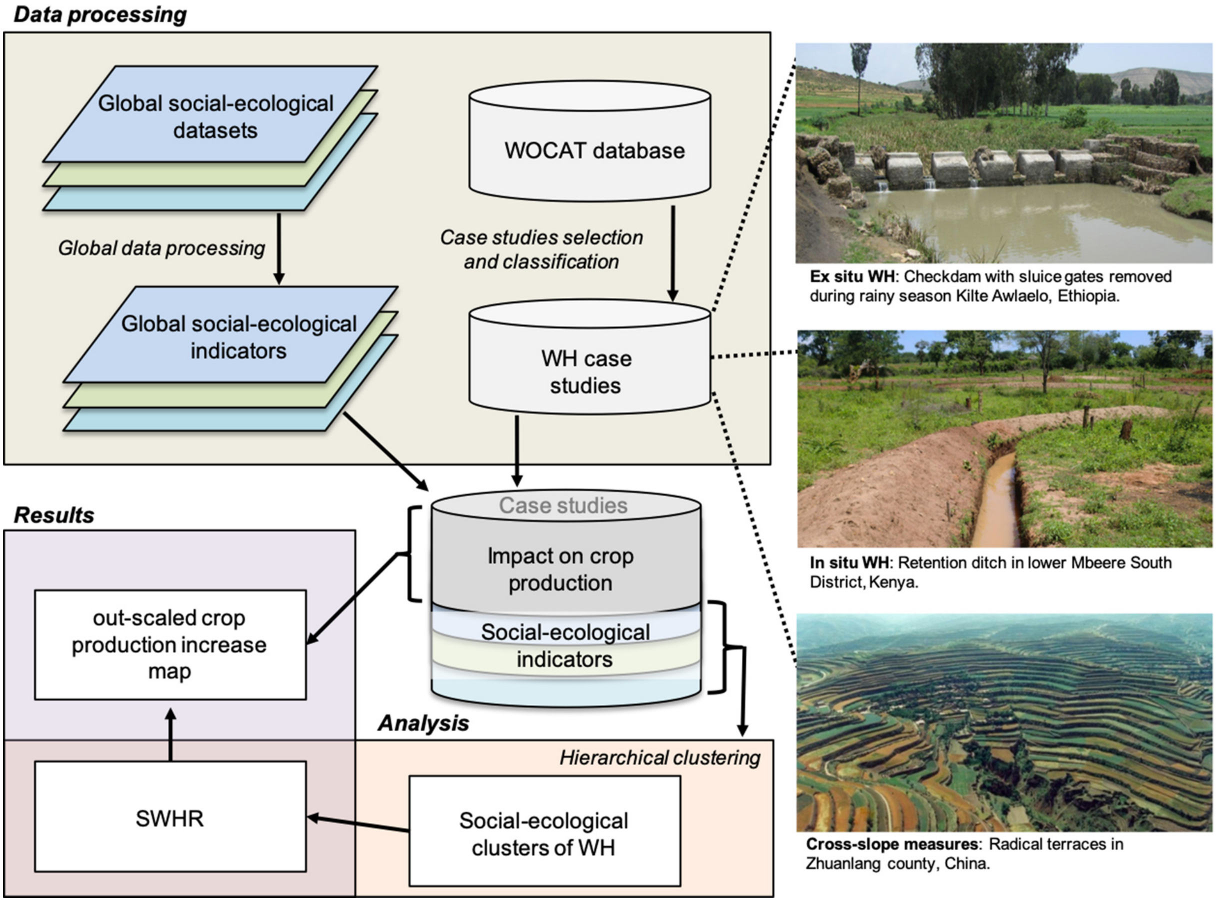

Fig. 1. Analytical framework used to map the out-scaled benefit of water harvesting on crop production. Data processing includes both the WOCAT case study selection and classification (with pictures as example of the three water harvesting groups) and the global dataset processing to create the social-ecological 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

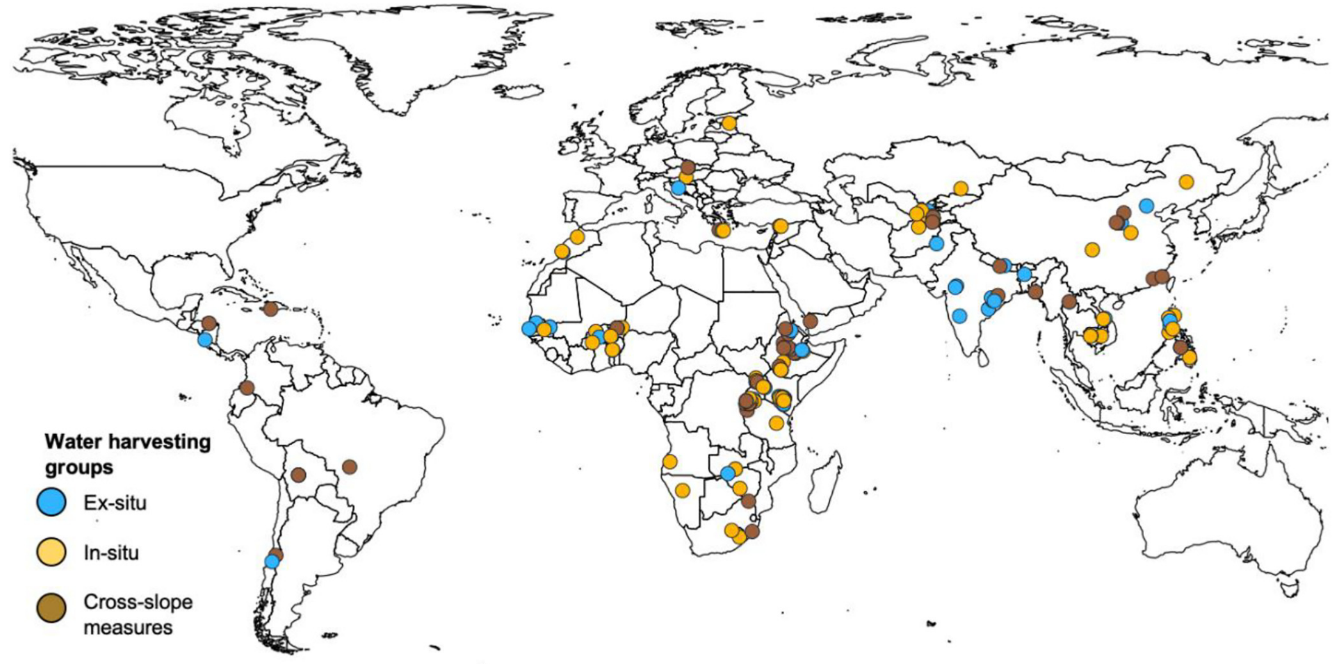

Fig. 2. Location of the final set of case studies (n = 167) selected from the WOCAT database divided in the three water harvesting groups "Ex-situ", "In-situ" and "Cross slope measures".

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:

$$\text{Uncertainty} = \frac{\text{Ar}_R}{\text{N}} \tag{1}$$

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

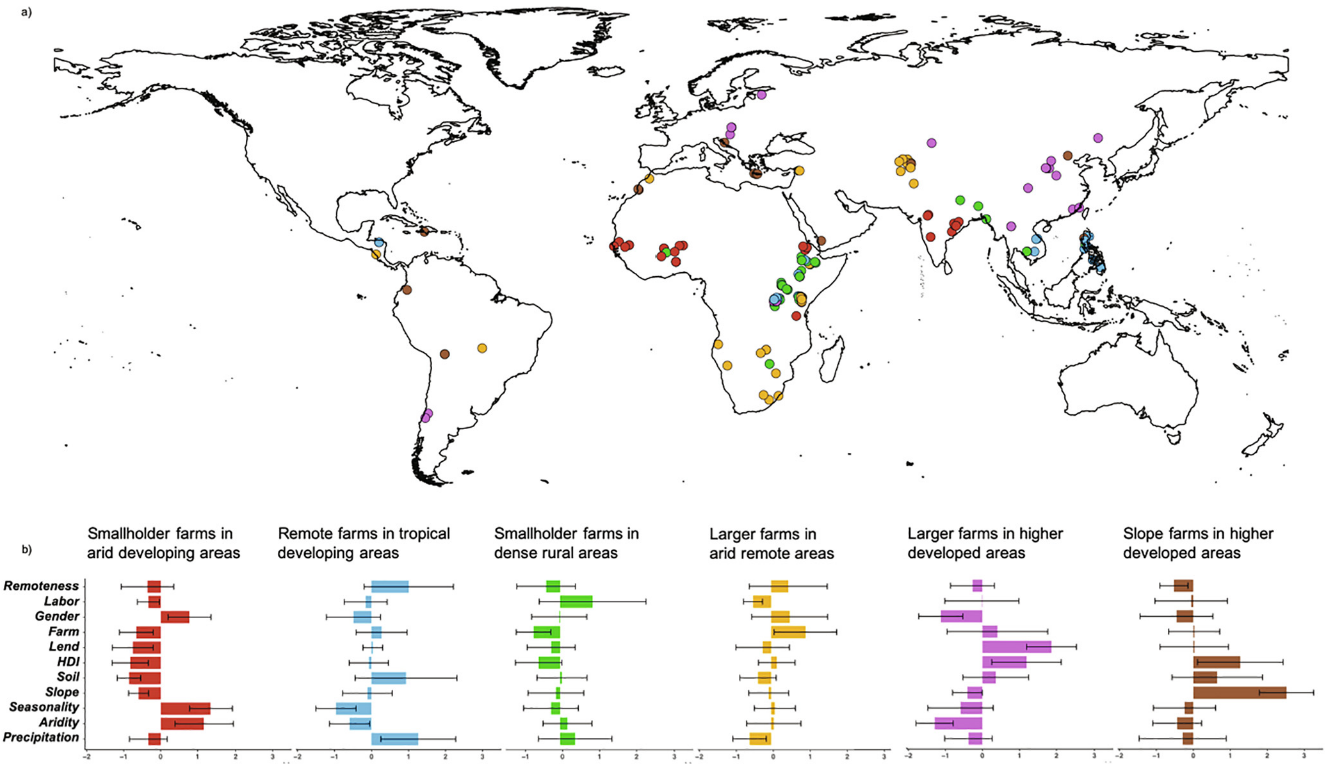

Fig. 3. Location (a) of the water harvesting case studies classified in seven clusters and (b) bar plots of the ranges of social-ecological indicators for each cluster. The names of each cluster represent the most representative characteristics of each cluster.

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

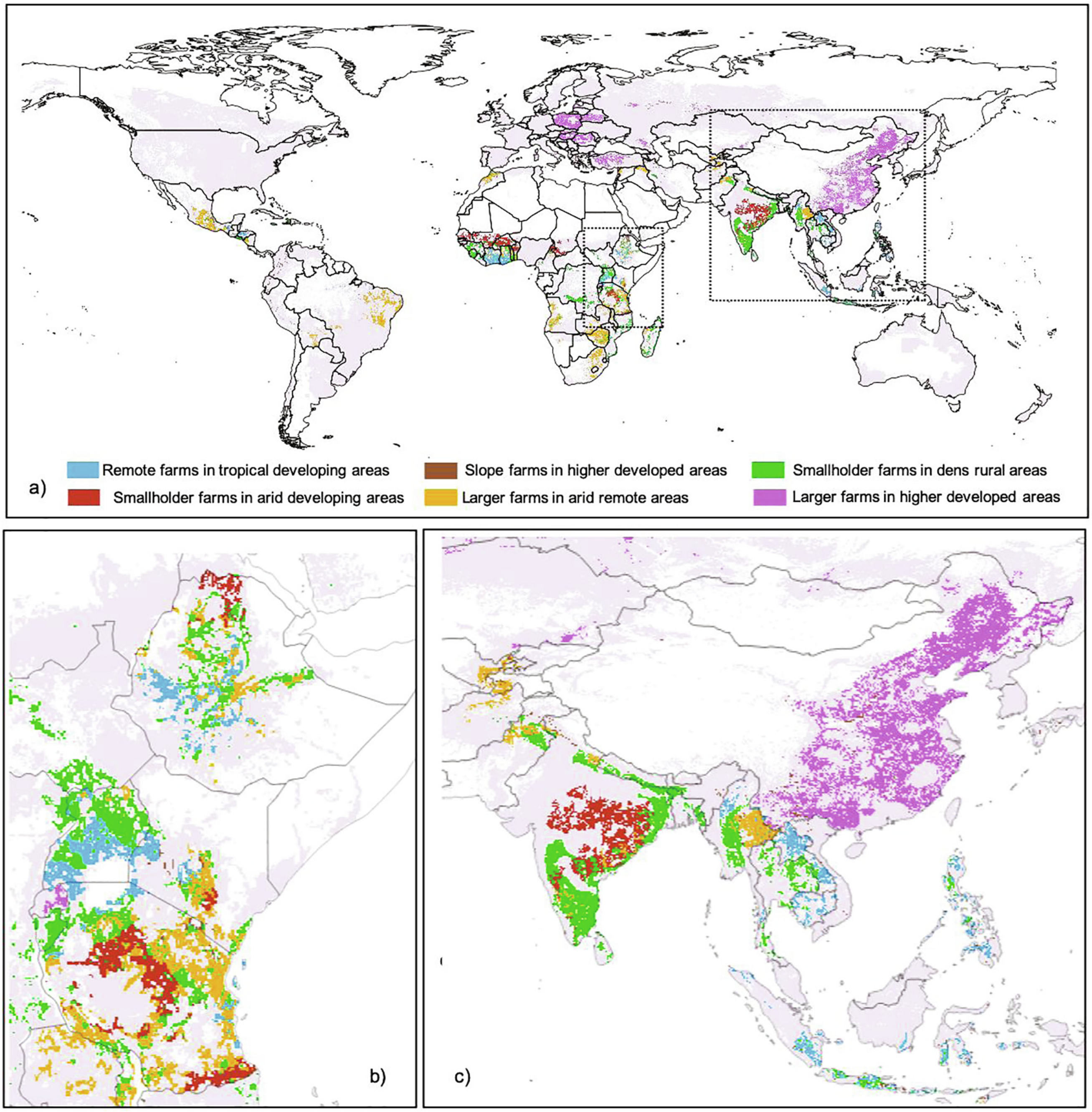

Fig. 4. (a) Global map of archetypes of successful water harvesting, and regional snapshots in (b) East Africa and (c) South-Eastern Asia. When multiple overlapping archetypes, the archetype with the smallest spatial extent is shown.

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*

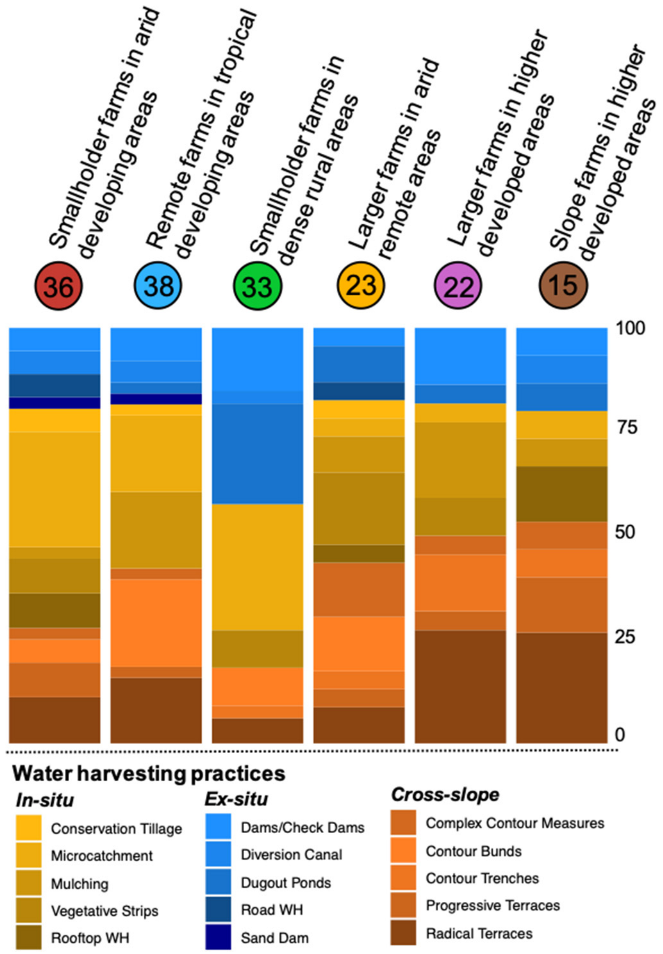

Fig. 5. Distribution of water harvesting practices in the six archetypes. The axis shows the percentage of case studies in each cluster that correspond to a given water harvesting group, in-situ (yellow), ex-situ (blue) and cross-slope (orange). The number of case studies per archetype is in the circles 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-

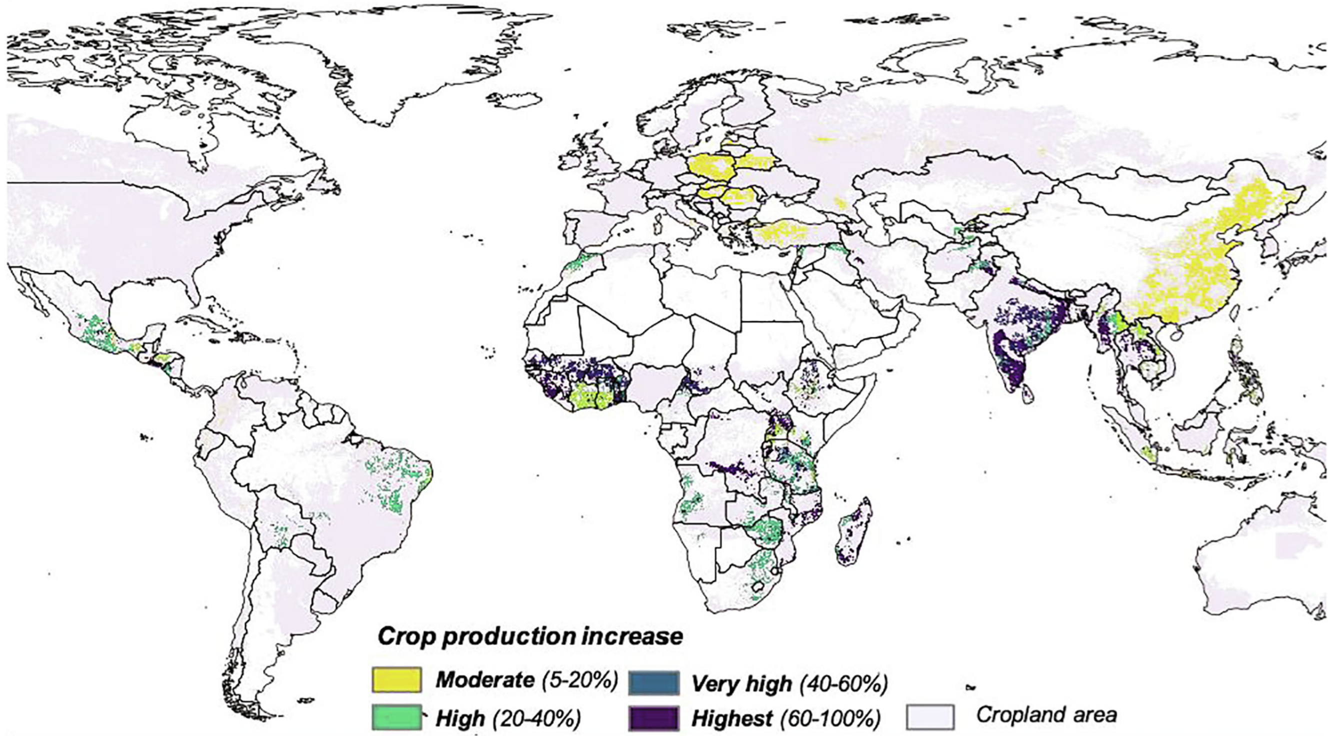

Fig. 6. Potential increase in crop production by implementation of water harvesting practices based on WOCAT studies. The potential crop production increase is quantified in four classes from moderate (5–20%) to highest (60–+100%) – from yellow to dark blue. The background area (light grey) represents 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

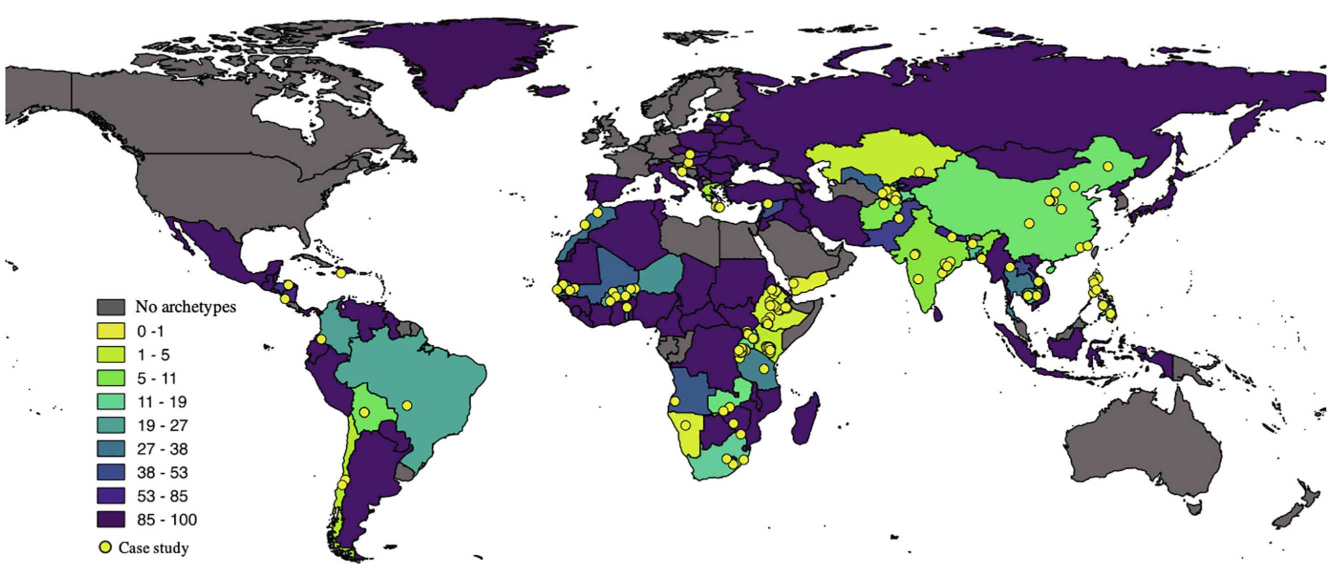

Fig. 7. Indicator of uncertainty in the estimate of archetype, considering the extent of archetype compared to the number of case studies at national level. Light colours with low uncertainty (Eq. (2)) evidence the reliability of the archetype application. The dark grey countries have no projected archetypes, 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.)

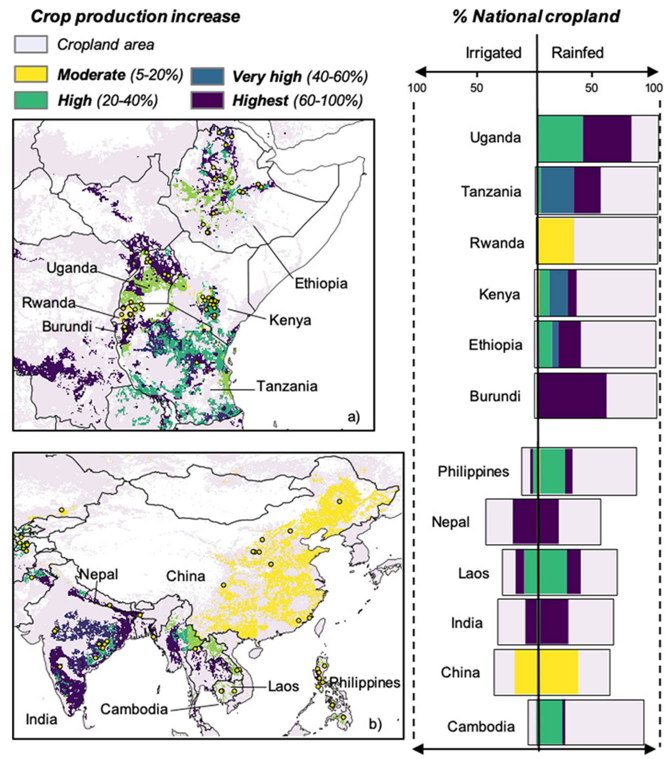

Fig. 8. Potential crop production increase with water harvesting for the two regional hotspots of East Africa (a) and South-Eastern Asia (b). The maps are snapshot of the global map (Fig. 6). Bar plots show the percentage of national rainfed and irrigated cropland under potential crop production increase 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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