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Review

Assessing the returns to water harvesting: A meta-analysis

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ABSTRACT

This study presents the results of a meta-analysis of the peer reviewed literature on water harvesting technologies, with a focus on the crop yield impacts of water harvesting in semi-arid Africa and Asia. Main aim of the analysis is to assess whether water harvesting significantly improves crop yields, and whether the type of water harvesting technology and the quality of the rainy season correlate with the change in yield. We find that water harvesting improves crop yields significantly, and that the relative impact of water harvesting on crop yields is largest in low rainfall years. Smallholder farmers may still be reluctant to invest in water harvesting, however, as in regions with low agricultural productivity the returns to investment are limited. Finally, our review of the literature suggests that there is only a limited number of studies that has systematically evaluated the crop yield impacts of water harvesting technologies. More work is needed to strengthen the scientific knowledge base.

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1. Introduction

Traditionally, smallholder farmers in semi-arid regions have invested in water harvesting techniques to cope with droughts and enhance the productivity of their land (Critchley et al., 1994). Rainwater harvesting is defined as a method of inducing, collecting, storing, and conserving local surface runoff for agriculture (Boers and Ben-Asher, 1982; Rockström et al., 2010). In addition, rainwater harvesting may be used for domestic purposes, but in this study we only consider agricultural use. Water harvesting technologies (WHT) include techniques that capture and store water in the soil and techniques that store water in reservoirs (Rockström, 2000). Research has found that these traditional practices can indeed increase agricultural productivity (Rockström et al., 2010; Oweis, 1997; Barron and Okwach, 2005), but attempts to spread or intensify the practice of rainwater harvesting generally have had limited success (see for example Awulachew et al., 2005; Drechsel et al., 2010). Given the renewed interest in water harvesting as an adaptation measure to climate change (Howden et al., 2007; Lasage et al.,

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2015) it is important to understand WHT potential and why it has been difficult to scale up success.

To the authors' knowledge no systematic review of the literature has yet been conducted to assess the crop yield impacts of WHT. Hence, this study presents a meta-analysis of the literature, combining data from the peer reviewed, academic literature on WHT investments with information about the rainfall characteristics of the study sites. The main aim of the analysis is to assess whether WHT significantly improves crop yields, and whether the type of WHT system and the quality of the rainy season correlate with the change in yield. In addition, we explore the returns to WHT investment, comparing the average returns to investment for an Asian maize producer with those of an African producer, were productivity is, on average, lower. Clearly, this gives only a rough indication, but it still illustrates why farmers may be reluctant to invest.

We consider two types of WHT, reservoir storage and in soil storage techniques, which have different biophysical and hydrological requirements. Reservoir storage techniques require overland flow to recharge the reservoir (e.g. cisterns, ponds) and are thus dependent on intense rainfall events (Boers et al., 1986; Ngigi et al., 2005), whereas in soil storage techniques (e.g. planting pits, trenches, ridge and furrow) can capture rainfall of lower intensities and amounts (Li et al., 2000a). Also soil characteristics influence the choice of WHT: soil storage, for example, is most effective in loamy soils with medium texture (Critchley and Siegert, 1991), whereas techniques which depend on overland flow are more suitable in areas with a hard top layer. Given the generic character of our analysis, e.g. a meta-analysis, we cannot assess the optimality of technology choice (as this is highly context specific) in our analysis, but instead assume optimal technology choice and under this assumption assess the crop yield impacts of WHT.

We assess the crop yields impacts of WHT by considering studies reporting crop yields with and without WHT investment, attributing the difference in crop yield to WHT. In some regions, water harvesting is also used to recharge groundwater aquifers (Sharda et al., 2006; Glendenning et al., 2012), but given that studies that report groundwater recharge impacts of water harvesting generally do not report crop yields with and without WHT we could not include these studies in our analysis. Also, we could not address the potential downstream impacts of WHT. Several studies indicate that downstream impacts may occur when WHT is widely implemented in a catchment (e.g. Schreider et al., 2002; Garg et al., 2012; Lasage et al., 2015; Bouma et al., 2011), but none of the studies reporting WHT impacts discussed the potential downstream impacts of the investments made. As a result, we focus on the local impacts of individual WHT, which may include collective investments like ponds and small dams.

The remaining part of this paper is organized as follows: In the next section we discuss approach and methodology. In section three we present the results of the meta-analysis, in three parts: (i) the results of the literature search and assessment, (ii) the analysis of WHT crop yield impacts, and (iii) the assessment of WHT investment returns. In the last section we discuss the findings and conclude. Appendix A provides an overview of the studies included in the meta-analysis. Appendix B describes the different water harvesting technologies.

2. Approach and methodology

2.1. Literature search

To collect the relevant studies in the field we used search engines like *Google Scholar* and *ISI web of Science* (see also Cooper et al., 2009) applying search terms like 'water harvesting', 'soil and water conservation', 'watershed development' to mention a few. In line with Boers and Ben-Asher (1982) we selected studies reporting the impacts of technologies that induce, collect, store or conserve water, thus not including studies that report impacts of interventions that increase the capacity of the soil to retain water (viz. soil fertility improvement, conservation agriculture). Still, some of the studies included in our database report crop yield impacts of soil fertility treatment as part of WHT investment, which we control for in our analysis.

We included studies reporting findings from experiments conducted in semi-arid Africa and Asia, excluding a few studies that report impacts from water harvesting in arid or non-arid regions, or that report impacts from experiments conducted in Europe, the USA and Australia. The range of experiments reported includes farmer field experiments and controlled research station experiments, a difference we control for in our analysis. We also control for study location, although due to limited sample size we can only control for continent.

2.2. Database compilation

In line with the study's objective, for each selected study we included in the database, information about crop yields with and without water harvesting intervention, type of crop, type of WHT, rainfall data for the year of the experiment, average yearly rainfall in the study site, continent, type of experiment (field experiment or research station) and additional investments (if any) in soil fertility improvement. We only report crop yields on cultivated land, and do not account for the area that is used as catchment area, or the area that is not available for growing crops due to the water harvesting technique used (e.g. area occupied by stone bunds). This is because most studies only reported crop yield impacts on cultivated land.

With regard to the type of WHT considered we distinguish between in soil storage technologies (including planting pits, earthen bunds, (plastic covered) ridge-and-furrow, stone bunds, terraces, etc.) and reservoir storage technologies (including household ponds, small check dams, underground water tanks, etc.). There are two reasons why we make this distinction. First, reservoir storage makes it possible to apply supplementary irrigation whereas in soil storage does not (Röckstrom et al., 2010; Molden et al., 2010 Molden et al., 2010). Since, systems that allow for supplementary irrigation are better geared towards ameliorating the impacts of intra-seasonal dry spells (Ngigi et al., 2005; Nyakudya and Stroosnijder, 2011) we expect reservoir storage techniques to have a larger impact on crop yields in low rainfall years. Second, in soil storage and reservoir storage technologies differ in terms of investment and maintenance costs (Lasage and Verburg, 2015). Most in soil storage structures require limited investments but substantial (labor) costs: heavy rains may damage the structures, and investments like planting pits need to be re-done annually. Reservoir storage structures, on the other hand, require substantial initial investments, but once they have been constructed maintenance costs are relatively low (Lasage and Verburg, 2015).

Within these two categories the range of techniques included is wide. In soil storage structures include traditional planting pit technologies (zaï) in Burkina Faso but also plastic covered ridge and furrow on China's Loess plateau. Similarly, reservoir storage includes small household ponds in Ethiopia and earthen dams in India. Appendix B gives an overview of the water harvesting techniques included in the analysis.

It is important to note that the choice of WHT depends on local conditions, like rainfall, soil quality and slope, factors which influence the reported crop yield impacts of WHT too. Since, we have only limited information about local conditions, we cannot address the question whether the choice of WHT technology was optimal. Also, we cannot separate out whether crop yield improvements are caused by WHT *as such* or in combination with other factors (Barrett