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Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: A review

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ABSTRACT

Soil erosion by water is one of the main causes of land degradation and reduced agricultural productivity in Africa leading to an estimated annual loss in crop yield of 280 million tons. To reverse this problem, various indigenous and recently introduced cross slope barrier soil and water conservation (CSB-SWC) techniques have been implemented. These include *Fanya juu*[1], soil bunds, stone bunds, bench terraces, vegetative barriers, and tied-ridges. In this review, we analyze and synthesize the results of various studies that focused on the effects of CSB-SWC techniques on runoff, soil loss, soil properties, crop yield, and biomass in Sub-Saharan Africa (SSA). Introduction of various CSB-SWC techniques was found to reduce runoff and soil loss by 13–71% and 39–83%, respectively. More than 80% of the reviewed scientific studies showed a positive effect on crop yield mainly due to retention of nutrients and moisture. The effect of CSB-SWC techniques on crop yield varies with rainfall and slope, with most of the CSB-SWC techniques improving crop yields in low rainfall areas. *Fanya juu* and soil bunds were effective on relatively gentle slopes while hedgerows and stone bunds were effective even on moderately steep slopes. However, studies across SSA indicate that some CSB-SWC techniques could have negative side effects such as waterlogging. Also, these techniques are associated with the occupation of significant areas of cultivable land. Thus, they require proper design and implementation. In most cases, CSB-SWC techniques are economically feasible, due to improved crop yield and low labor opportunity costs. However, implementation may be hampered by high construction costs, small landholding size, land tenure insecurity, and low short-term benefits. Effectiveness and benefits of CSB-SWC can be improved by their integration with other land management techniques such as soil fertility amendments and conservation tillage.

1. Introduction

Soil quality and water availability are major factors determining global food production, obtained from only 12% of the earth's land surface (FAOSTAT, 2015). Soil erosion, one of the main causes of soil degradation, is common in many regions (Troeh et al., 1991), removing 75 billion tons of soil annually (Pimentel et al., 1995). Agricultural activities are responsible for 75% of global soil erosion, affecting 80% of the world's cultivated soils (Pimentel, 2006) and adversely impacting food production on 40% of the agricultural land (Bossio et al., 2010). Retaining soil quality and increasing soil water availability is a challenge of paramount importance for the production of food for the increasing global population.

Agricultural productivity and food security have been particularly challenging in most countries in sub-Saharan Africa (SSA), where soil quality and soil water availability are major limiting factors. Agriculture in SSA is also important as it provides employment for about 70% of its more than 1 billion inhabitants (Rockström et al., 2010; Serdeczny et al., 2016; World Bank, 2016). Africa is among the continents that suffer much from soil erosion and land degradation (Pimentel et al., 1995; Nyssen et al., 2009). The problem of soil erosion is most severe in the densely populated highlands of East Africa (Place et al., 2006). As a result, Africa loses 280 million tons annually of crop yield with an estimated economic value of 127 billion USD year^{-1} (UNEP, 2015). The severity of soil erosion and its consequences in some SSA countries was already recognized in the 1930 s and 1940 s (Young, 1990), but the implementation of effective countermeasures remains a challenge throughout the region.

The severity and spread of soil erosion depend mainly on the management of agricultural land. Cultivation of marginal lands by the

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[1] A Kiswahili word referring to 'throw uphill', corresponding to the CSB-SWC structure built by throwing soil upslope from a ditch

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increasing population (decreasing area per capita landholding) has aggravated soil erosion in Africa (Willcocks and Twomlow, 1993). Furthermore, the nature of soils such as susceptibility to crusting (Spaan et al., 2005), the erosive and torrential nature of the rainfall (Angima et al., 2002; Babalola et al., 2007), and the steepness of slopes make soil erosion severe in the SSA. In addition, about 50% of the soil in Africa is categorized as Arenosols, Leptosols and Ferrasols, all having low inherent fertility due to limited nutrient reserves and water retention capacity (Jones et al., 2013; Tully et al., 2015).

Erosion further degrades hydrological properties of the soil through the decrease of soil organic matter content and consequently declining aggregate stability and water holding capacity, while increasing soil crusting. Accordingly, erosion reduces water use efficiency and increases drought stress (Tsubo and Walker, 2007; Stroosnijder, 2009). The excessive removal of essential plant nutrients and soil organic matter by erosion can impede the physical, biological, and chemical functioning of soil. Ultimately, soil erosion and degradation imperil crop production and food security. For instance, annual agricultural production declines of 0.5–1% in Burkina Faso (Niemeijer and Mazzucato, 2002) and 1–2% in Ethiopia (Adgo et al., 2013) have been observed.

Ninety-five percent of the African agricultural land is rain-fed (Rockström, 2004) and 41% of the land area in SSA is estimated to receive less than 600 mm rainfall annually (Vohland and Barry, 2009). Considering the rainfall threshold to create sufficient soil moisture for a given crop, e.g. 500 mm to grow maize (Wiyo et al., 2000), there is a significant risk of water shortage for plants in SSA (Rockström et al., 2010; World Bank, 2017). In semi-arid areas of SSA, long dry spells and drought occur once or twice in every ten years and the affected areas are characterized by a potential evapotranspiration being greater than rainfall, during half of the year (Mupangwa et al., 2006). Examples of severe droughts have been reported for Burkina Faso in 1970 s (Reij et al., 2005), Malawi in 1980s and 1990s (Wiyo and Feyen, 1999), Ethiopia in 1970s, 1980s, 1990s, 2000s (Bekele and Drake, 2003; Biazin and Sterk, 2013) and South Africa (Tsubo and Walker, 2007).

To solve soil degradation and soil water scarcity problems, farmers in the Nile basin have developed and implemented cross slope barrier soil and water conservation (CSB-SWC) techniques that fit their specific agricultural activities during the last 7000 years (Lowdermilk, 1948; Roose, 2008). Applied CSB-SWC techniques involve features that are meant to obstruct surface runoff and soil loss. Examples of indigenous CSB-SWCs (sometimes called ethno-engineering) include trenches and terraces. In some rain-fed, yet water deficient areas, where stones are available, farmers built stone bunds to limit surface runoff and soil erosion, while retaining water (Critchley et al., 1994). For instance, the Konso people in Ethiopia adopted and continuously implemented stone bunds for more than 500 years to improve and sustain crop production in dry areas (Beshah, 2003). Stone bunds also have been used for many years in other parts of SSA, including Ghana, Mali, Cameroon, and Malawi (Reij et al., 1996)), mainly on steep sloping lands (WOCAT, 2011).

Besides stone bunds, other indigenous and introduced CSB-SWC practices have been adopted in different parts of the SSA. Small pits, bunds, *Fanya juu*[2], ridges and grass strips have long been used to conserve water for crop production in dry areas of some countries such as Tanzania, Mali, Burkina Faso, Niger, Sudan, and Kenya (Critchley et al., 1994; Malley et al., 2004). For instance, the Matengo people in Tanzania practice 'ngoro' (planting pits) for more than 200 years to harvest and conserve rainwater (Malley et al., 2004). Planting pits, labeled 'zai'/'tessa'/ 'towalen', are well adopted in West Africa (Lahmar et al., 2012) and common in Mali and Burkina Faso (Reij et al., 1996) and Niger (Baidu-Forson, 1999). In eastern Sudan, 'teras' or small earthen bunds are common and used to conserve water and nutrients (Niemeijer, 1998). *Fanya juu*, a combination of ditch and earth embankment, has been adopted in Kenya (Ellis-Jones and Tengberg, 2000). Ridges, a combination of a small furrow and soil embankment, are practiced in West Cameroon (Tchawa, 1996). In Tanzania, 'Miraba' or scattered grass strips have been traditionally practiced (Mwango et al., 2015a).

Upon increased recognition of the negative impacts of water shortage, soil erosion and land degradation on agricultural production, the governments in several countries of the SSA emphasized the promotion and implementation of CSB-SWC techniques since the 1950 s (Young, 1990). Thus, indigenous practices in combination with novel techniques, developed and tested in other areas, were introduced for wider implementations. Depending on local conditions, several techniques have been tested and adapted on-station and on-farm, prior to promotion and implementation in cultivated lands of SSA (Babalola et al., 2007) (Table 1). Selected CSB-SWC techniques, developed and tested in different parts of SSA, often vary with edaphic, climatic, topographic, and crop characteristics and their interactions. Here we present a comprehensive and updated review and synthesis on effects of CSB-SWC in diverse agro-ecological and socio-economic conditions of SSA. The aim of the review is to examine and synthesize the effects of CSB-SWC on surface runoff, soil and nutrient loss and crop yield in SSA. To this aim various studies from across the SSA were accessed online in Google Scholar and Web of Science, using combinations of keywords (such as soil and water conservation, crop yield and biomass, soil loss, runoff, soil property, *Fanya juu*, soil bund, stone bund, terrace, bench terrace, grass strip, hedgerow, vegetative barrier, ridges/tied-ridge, pits, and names of countries in SSA). In addition to the relative effects of CSB-SWC on runoff, soil loss, soil properties, and crop yield, the importance of rainfall and slope on the efficiency of various CSB-SWC techniques was assessed. The economic feasibility of CSB-SWC's and the associated socio-economic and institutional aspects influencing their implementation and management were also examined.

2. Scope and overview of CSB-SWC techniques in SSA

Small ditches and planting pits can collect surface runoff and store water, ultimately abating soil erosion. In addition, other physical barriers, in general parallel to the contour lines, may limit surface runoff. Such barriers may consist of bunds made of soil or other materials such as stone, crop residue, and wood. Accordingly, various forms of CSB-SWC techniques such as stone bunds/lines, soil bunds, *Fanya juu,* bench terraces, vegetative barriers, trash lines, and ridges/tied-ridges are practiced in different parts of SSA (WOCAT, 2011) (Fig. 1). The choice of techniques depends on biophysical characteristics, availability of construction materials and land management experiences of farmers. Here, we emphasize the commonly practiced CSB-SWC techniques in SSA (Table 1), utilized in annual cropping systems and assess their effect on surface runoff, soil loss, soil moisture distribution, nutrients and soil organic matter content, and crop yields.

3. Effect of CSB-SWC on runoff and soil moisture

CSB-SWC techniques reduce surface runoff on average by 13–71% (Fig. 2). Level *Fanya juu* reduces surface runoff on average by 71%, whereas stone bunds, bench terraces, tied-ridges and trash lines reduce it by 51–57%. Effects of CSB-SWC on runoff varies from place to place based on rainfall, slope, and selected technique. For instance, studies in Ethiopia (Herweg and Ludi, 1999) and Tanzania (Tenge et al., 2011) indicate that level *Fanya juu* reduced surface runoff by 54–95%, whereas level soil bunds in Ethiopia reduced the surface runoff by 17–94% (Herweg and Ludi, 1999; Amare et al., 2014). In both *Fanya juu* and soil bunds, the ditch and soil embankments are designed to obstruct and temporarily store surface runoff and thus reduce cumulative surface flow. Level and graded *Fanya juu* and graded soil bunds limit

[2] A Kiswahili word referring to 'throw uphill', corresponding to the CSB-SWC structure built by throwing soil upslope from a ditch