SOIL AND WATER CONSERVATION MEASURES ON WATERSHED DYNAMICS: A REVIEW

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Abstract

Abstract Land degradation due to poor land management is the main constraint for agricultural productivity globally. Many developing countries have developed national soil and water conservation (SWC) program however, sustainable land management is not yet attained. To understand the effect of SWC measures, a bibliographical review was carried out from the Scopus Elsevier citation database from 1990 to 2017 using the keywords "Effect of SWC" in the title, abstract or keywords. Total amounts of 869 documents were found, and synthesis was made from these scientific journal articles to assess the main biophysical dynamics of watersheds due to SWC measures and to highlight the research gaps. The synthesis revealed that SWC measures in agricultural landscapes have a significant impact on water and sediment connectivity and therefore on the erosion process. It potentially slows the runoff generation, reduces the soil particle detachment and sediment transport; and subsequently, enhances soil moisture and nutrient availability. However, many research article outputs and recommendations focus on plot and small-scale watersheds and are based on short-term or intermediate time frame results. Since there is a lack of sufficient recommendations and scientific evidence founded on long-term observations strong scientifically based feedback on the dynamics of soil properties, surface runoff and erosion processes at watershed and parcel scale should be drawn based on both short- and long-term evidence and considering connectivity and natural-based solutions. This will help to develop and promote ecologically sound, economically viable and socially acceptable conservation measures in agricultural watersheds.

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Land degradation due to poor land management is the main constraint for agricultural productivity globally. Many developing countries have developed national soil and water conservation (SWC) program however, sustainable land management is not yet attained. To understand the effect of SWC measures, a bibliographical review was carried out from the Scopus Elsevier citation database from 1990 to 2017 using the keywords "Effect of SWC" in the title, abstract or keywords. Total amounts of 869 documents were found, and synthesis was made from these scientific journal articles to assess the main biophysical dynamics of watersheds due to SWC measures and to highlight the research gaps. The synthesis revealed that SWC measures in agricultural landscapes have a significant impact on water and sediment connectivity and therefore on the erosion process. It potentially slows the runoff generation, reduces the soil particle detachment and sediment transport; and subsequently, enhances soil moisture and nutrient availability. However, many research article outputs and recommendations focus on plot and small-scale watersheds and are based on short-term or intermediate time frame results. Since there is a lack of sufficient recommendations and scientific evidence founded on long-term observations strong scientifically based feedback on the dynamics of soil properties, surface runoff and erosion processes at watershed and parcel scale should be drawn based on both short- and long-term evidence and considering connectivity and natural-based solutions. This will help to develop and

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KEYWORDS: biophysical dynamics, short and long-term effect, soil property, surface runoff, soil erosion, research gaps

Introduction

Land degradation is one of the main constraints for agricultural productivity (Pender, Nkonya, Jagger, Sserunkuuma, & Ssali, 2004; Taddese, 2001) in areas that have undulating topography, erratic and intense rainfall and, unsustainable land management practices (Liu et al., 2013). The extent of land degradation in terms of agricultural productivity has become the critical challenge for those countries, which mainly depends their economy on agriculture (Hurni & Pimentel, 1993). The concern of land degradation is a critical among other global issues because of its impact on world food security and quality of the environment (Alam, 2014; Eswaran, Lal, & Reich, 2001).

The global importance of soil conservation and the control and mitigation of land degradation are more highly recognized now than at any time in the past. To mitigate land degradation, many developing countries have developed national SWC programs and it has brought relative improvement in land productivity. However, sustainable land management is not yet attained (Desta, Carucci, Wendem, & Abebe, 2005). This is mainly because of the lack of sufficient scientifically based evidence and recommendations about the requirements, improvement and impacts of SWC measures (Hurni, 1999; Nyssen et al., 2010). Since watersheds characterisitics change structurally and functionally after intervention, understanding the biophysical dynamics of watersheds are a very crucial issue for sustainable utilization of agricultural watersheds (Amsalu, Stroosnijder, & Graaff, 2007; Nyssen et al., 2004). Therefore, considering the change in biophysical characteristics of watersheds is of primary importance in strengthen knowledge about the impact of different SWC measures for further scaling up of SWC technologies (Negussie, Urbaniak, & Zalewski, 2011).

This review paper explores the effect of SWC measure on watershed biophysical (soil properties, surface runoff, erosion and soil loss) dynamics at different spatial and temporal scale for better understanding of landscape biophysical parameters, which are of great interest for land managers and policy makers. Therefore information and knowledge is needed on adequate scale. Spatially on the farm or watershed scale; temporally annualy or decadal scale. Therefore, this review aims: i) to assess the available scientific documents and recommendations in the field of SWC on different spatial and temporal scales; ii) to identify the research gaps and to propose feature research objectives; iii) to understand the key biophysical dynamics (soil properties, surface runoff and soil erosion) of watershed due to SWC measures at different temporal and spatial scale.

Material and Methods

SWC measures such as soil bunds, terraces, tillage types, cover management, grass strips, watershed management (before and after intervention) and other agronomic measures were evaluated on their effect on catchment erosion, runoff and soil properties dynamics. The Scopus Elsevier database was used to search for research papers using the key words “Effect of SWC” on soil properties, runoff and soil loss in the title, abstract or keywords from 1990 to 2017. The resulting 869 documents (Table 1) comprised of 79% were journal articles, 12 % conference papers and, the remaining (9 %) are reviewed book chapters, conference reviews and articles in press. The bibliographical search was further expanded using the words “effect of SWC on erosion and soil loss”, “effect of SWC on runoff” and, “effect of SWC on soil properties” to address the specific biophysical parameters (soil properties, surface runoff and, erosion and soil loss) of agricultural watersheds worldwide (Table 2). From the second search, we found 158 documents with the word ‘erosion and soil loss’, 96 documents with the word ‘runoff’ and 138 documents with the word ‘soil properties’. After this review, a critical selection synthesis based on the watershed approach was carried out to evaluate the effect of SWC on the biophysical parameters found in the different scientific journal articles, conference papers and book chapters. This have been summarized into three main watershed characteristics, (i) soil properties (physical and chemical), (ii) surface runoff, and (iii) erosion and soil loss.. Data on the effect of SWC on soil properties, run-off, erosion and soil loss were organized in a database using Microsoft Excel.

Once the data were organized and structured, different descriptive statistics were conducted to synthesize the data.

Results

Physical, biological and agronomic SWC measures are a major component of agricultural watershed management, which affects surface roughness and cover of the soil, whereby it potentially has a positive impact on soil retention against raindrops and running water and soil chemical, physical and biological improvement. Table 3 provides a summary of previous studies describing the effect of SWC measures on soil physical and chemical properties. The evaluation was addressed the major soil properties such as organic matter (OM), organic carbon (OC), bulk density, soil moisture content, total nitrogen (TN), available Phosphorus (Ava.P) and, pH. As shown in table 3, the effect of SWC practices on soil properties could be positive (+), negative (-) or neutral (0). Regarding soil properties, from the total reviewed papers, 71 % of the research articles were carried out at plot level while the remaining 29% was at catchment scale. The synthesis revealed that from the total observation 75% showed that physical, biological and agronomic SWC measures has a positive effect on most soil properties while the remaining 25 % indicate SWC measures has negative or neutral effects on the selected soil properties. In all cases it is observed that, physical, biological and integrated SWC measures such as soil bunds, stone bunds, mulching, and agronomic measures has an impact on the improvement in soil properties as compared to the untreated conditions. It is also observed that individual SWC measures has less effect on the improvement of soil physical and chemical properties as compare to the integrated SWC measures.

The results in Table 4 present the condition of surface runoff with and without of SWC measures. The review indicated that, most of the research reports (70%) carried out on the bases of plot level observations whereas catchment level researches accounts only 30 %. As indicated in the table below, the synthesis shows that, SWC measures, such as physical structures, biological measures and agronomic measures have a significant impact on the improvement of hydrological process through infiltration enhancement and surface runoff reduction. From the total reviewed papers, 87% articles indicated that, surface runoff has reduced significantly due to SWC measures as compared to the untreated once; while 13% articles that shows there is an increment of runoff by 9% as a result of graded SWC measures. The reduction in surface runoff ranged from 24% to more than 100%. The increment in runoff due to graded SWC structures are mainly because of its structural designed to expose direct runoff safely from the farm without scoring effect. The review showed that physical SWC structures as terrace reduces the surface runoff by three times.

As presented in Table 5, the review also addressed the effect of different SWC measures on erosion and soil loss. The synthesis showed that among the reviewed papers 53 % of research articles were carried out based on plot level experiments and the remaining 47 % belongs to catchment scale researches, which has been discussed in section 4.3. All the reviewed articles indicated that SWC measure has a positive effect on soil loss reduction at plot and catchment scale. The reduction in of soil loss ranges from 15% to more than 100% as compared to untreated (control). The review showed that in some cases physical SWC structures such as terrace reduces soil loss by three times, than the untreated plots.

1. **Discussion**
2. **Effect of SWC on soil properties**

Soil properties are one of the major governing factors in erosion processes in the landscape particularly for detachment phase (Wei et al., 2012) which mainly is affected by soil and water management interventions(Abegaz et al.„ 2016; Su et al., 2010). The dynamics of soil properties are always depending on both land management practices and the inherent properties of the soil (Jenny, 1941; RE, 2013). Depending on how it is managed, soil is a sink of plant nutrients like carbon and nitrogen, microorganisms, water, and other toxic substrates (Lal & Pierce, 1991) and it determines what an ecosystem will look like in terms of production (Hati et al., 2013). SWC measures are the major component of soil and water management practices in the catchment, which potentially affects soil chemical, physical and biological improvement (Castellini & Ventrella, 2012; Green & Erskine, 2011). In many cases, agronomic and vegetative SWC measures such as mulching, compost, conservation tillage, residue management and other tillage practices have a significant contribution on the improvement of soil physical and chemical properties (Mekuria et al., 2007; Zhang et al., 2009) when it implements integrated with physical SWC measures (Bienes et al.,2016; Hailu, 2017). As shown in table 3, physical SWC measures such as stone terraces, soil bunds, Fnya juu and contour ridges mainly governs the movement of soil nutrients in the landscape through sediment trapping (Guzman & Al-Kaisi, 2011; Hailu, 2017; Mekonnen et al.„ 2015; Xu et al., 2012). According to G/mariam (2015), the treated cultivate land with integrated SWC measures had significantly higher mean percentage of SOM and TN compared to untreated cultivated lands. The finding in the Chinese catchment indicated that, from the total transported soil and nutrients 94.8 % had been locally retained in the catchment due to SWC measures (Xu et al., 2012). Similarly, Demelash & Stahr (2010) and Hailu (2017) also reported that farmland with physical SWC measures had higher total nitrogen and organic matter and lower bulk density compared toland without SWC measures.

Al-Seekh and Mohammad (2009) and Fu et al. (2003) reported that conservation practices were found to be more effective in increasing soil moisture storage in dryland areas. The research conducted by Zougmoré et al. (2004) indicated that, the stone rows and grass strips combined with compost reduced runoff and increased soil water storage. These combined practices could create sound soil water conditions and were able to satisfy the crop's water demand (Mengistu et al., 2016). In general, this review and synthesis showed that the implementation of physical, biological and integrated soil and water conservation practices such as soil bunds, stone bunds, mulching, and agronomic measures reduces soil erosion by water and thereby decreases fertile soil loss and enhance soil physical and chemical properties. However, when we consider the dynamics of soil properties, it is better to have long term time series to have have a good chance to have captured all temporal dynamics of soil fertility and land productivity.

Surface Runoff

Surface runoff might occur when rainfall or run-on form adjacent areas exceeds the infiltration rate of the soil. Since surface runoff is the primary agent for soil erosion, studying the extent and its process is important to understand the hydrologic impact of SWC measures in a watershed. Runoff is influenced by catchment factors such as topography (Cerdà & García-Fayos, 1997; Nyssen et al., 2008), vegetation (Cerdà & Doerr, 2005; Keesstra, 2007), infiltration rates and soil storage capacity (Bouchnak et al., 2009; Desta et al., 2005). SWC measures affects surface roughness and cover of the soil, whereby it potentially has an impact on hydrological process particularly surface runoff (Castellini & Ventrella, 2012; Green & Erskine, 2011). Al-Seekh & Mohammad (2009) also indicated tha the amount of runoff varied under different management conditions and it is affected by soil surface roughness and vegetation cover. Similarly, a study carried out on four differentially treated catchments in the northwest part of Punjab in India by Kukal & Bawa (2013) who stated that the runoff was 71% higher in untreated catchment than in treated catchments. This is because SWC measures divide the slopes in a landscape and reducing with this the quantity and speed of surface runoff by increasing the time of concentration.

Similarly, Mengistu et al. (2016) and Amare et al. (2014) reported that, surface runoff generated from soil bund and Fanya juu was significantly lower than in the control plots. The study conducted in West Bank showed that, runoff reduced by 65–85% in stone terraces and semicircle bunds compared to the control at the semi-humid site (Al-Seekh & Mohammad, 2009). SWC practices also have an impact on catchment landscape terrace development and this plays a crucial role in reducing water erosion and surface runoff (Carla McCullough et al.„ 2008; Nyssen et al., 2010). This is due to the fact that terrace development could decrease the parcel slope angle and slope length, which finally leads to minimizing the runoff extent and speed. Wang et al. (2011) indicated that, from a natural rainfall experiment plot with reverse-slope terraces could cut down runoff by 65.3%. Surface runoff amount and runoff coefficient of control slope fields increased by 21.5 - 41.0 % and 27.5 - 69.7 % respectively as compared to those of sloping terraces (Zhang et al.„ 2008).

Vegetative and agronomic SWC measures plays an important role in runoff reduction due to the enhancement of infiltration rate and minimize runoff velocity (Adimassu et al., , 2012; Mitiku et al., 2006). According to Liu et al., (2017), grass hedges decreased runoff by 50.1%–60.7% compared with the control plots without grass hedges. This is because grass strips decrease the flow velocity and filter sediment from the flow (Cao et al., 2015). A similar study, which was conducted in Spain, indicated that, the application of straw mulching at different mulching rates significantly delayed the runoff time compared with uncovered treatments (Keesstra et al., 2016; Zhang et al., 2015). Zhang et al. (2015) also reported that compared with no straw mulching treatment, 30% straw mulching treatment significantly reduced total runoff by 17.9%-38.7%.

Soil Erosion and Sediment Loss

SWC measures in the watershed management is a key factor influencing soil erosion and hydrological processes and sediment connectivity on agricultural land. These management practices, such as physical SWC structures, vegetative and mulch covers have a significant effect on preventing raindrops from hitting the soil and causing detachment and transportation of the soil particles along the slope. Landscape topographical variations due to SWC measures change local flow velocities, and the process of soil delivery and sedimentation, thereby affecting the intensity of soil erosion and water and sediment connectivity (Keesstra et al., 2009; Liu et al., 2013). The impact of SWC in the watershed management could be explained in terms of minimizing soil erosion rates and increase soil moisture availability by diverting the channels and water movement and thereby reduce sedimentation (Liu et al., 2013). Mekonnen et al. (2017) also reported that, SWC barriers have a significant role to trap sediment within the catchment by decreasing soil erosion and enhancing the rate of sedimentation within a catchment through channel dis-connectivity. Setegn et al., (2010a) reported that, a single slope discretization, gave a lower average monthly sediment yield than other scenarios in comparison with the measured sediment yield at the outlet of the watershed.

Physical SWC measures, like terracing, bunds and other barriers are also the main components in soil loss reduction. The study in China under different simulated rainfall indicated that sediment yields decreased by terrace construction by more than 20% (Liu et al., 2013). Similarly, in India, the temporal variation of soil loss on differently treated catchments was tested. The result indicated that, soil loss during the initial years after SWC measure implementation in the catchment, the fully terraced catchment had the lowest soil loss (25.2 Mg ha^{-1} y^{-1}) and the highest (43.3 Mg ha^{-1} y^{-1}) was recorded in the untreated catchment. However, during the later period the trends reversed (Kukal & Bawa, 2013). This could be simply due to the fact that during initial stage SWC structures retained the sediments on the upstream side of the structure whereas in the final stage, the deposition of sediments resulted in complete siltation may increases soil erosion (Fiener & Auerswald, 2006; Kukal & Bawa, 2013). Therefore, understanding on the effect of different SWC measures on biophysical dynamics of watersheds at different temporal scale is very important for sustainable land management.

The study that was conducted in West Bank showed that, sediment is reduced by 58–69% in stone terraces and semi-circle bunds compared to the control plot which doesn't receive any SWC structures (Al-Seekh & Mohammad, 2009). Zhang et al. (2008) reported that the sediment yields on the slope fields without any SWC measures were higher (34.41 - 331.67 %) than those on sloping terraces; due to the fact that terracing plays a significant role on soil erosion reduction in cultivated sloppy areas. Like previous studies, Shen et al., (2010) and (Li et al., 2011) found that planting vegetation on dike terrace was beneficial in controlling soil erosion compared to farming of sloped land. Plant roots have been found to hold soil in place and prevent soil from collapsing during rainstorm events (Baets et al., 2006; Dong et al., 2015). Therefore, it is recommended that optimum coverage of sloppy areas is very important to stabilize and protect the bottom of sloped land against erosion (Liu et al., 2013).

Main research gaps

Understanding erosion processes on a larger scale: downstream effects

Nowadays there are many research articles, publications and recommendations on the implication and effectiveness of SWM measures for sustainable land resource management. Several research articles in this review explain the effectiveness and impact of SWC measures mainly at plot and small-scale watersheds however; the evaluation should have addressed both long-term and short-term impacts at medium or large-scale watersheds for better understanding of landscape biophysical parameters. Beside the insufficiency of the studies and recommendations, many policy briefs, decisions, and planning and implementation of SWC measures have been decided on, based on plot level and small-scale watershed observations. A more profound understanding of the changes that involve situation specific interactions among various factors at different spatial and temporal scales is therefore needed (Lambin et al., 2003; Veldkamp & Verburg, 2004). Larger scale studies can consider the management effects in the whole landscape and it finally leads to understand the connectivity of sediment and waters.

Long-term effects: changing soil properties and hydrology

When we consider sustainable land resource management through SWC measures, the focus should be at larger scale based on long-term evidences, because the phenomenon generally takes place over a long period of time. Especially the improvement of soil quality and ecosystem services in the landscape is a long-term process (Abegaz et al., 2016; Amsalu et al., 2007). In this review, we observed that, many research outputs on the effect of SWC measures are at plot scale manly based on short-term based evidence. Therefore, due to insufficient long-term based studies, SWC strategies are tested and adopted at the small scale and usually originate from simple blanket decisions. Therefore, there is a strong demand to address the impact of SWC measures based on time series observations and evidences for better understanding of biophysical dynamics in the landscape.

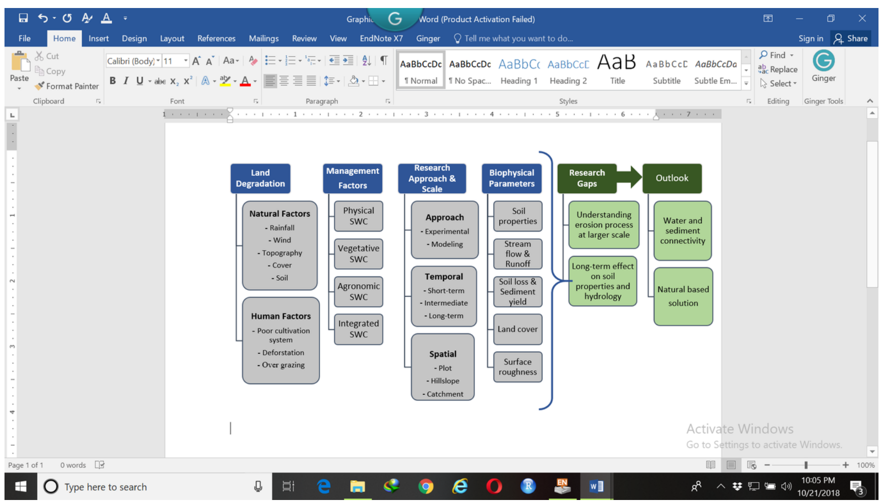

Figure 1. Scheme explaining the effect of SWC on soil properties, runoff and soil loss dynamics

Two recommended research approaches

When designing new research for sustainable land and water management it is important to take the whole erosion process into account, not only to focus on the detachment, but also to incorporated research on the transfer paths and the deposition phase of the erosion process (Bryan, 2000; Cebecauer & Hofierka, 2008; Rodrigo-Comino et al., 2018). Eroded sediment many times ends up on unwanted places, like reservoirs, and damage the natural resources and human investments (Clark, 1985; Rodrigo-Comino et al., 2018; Terranova et al., 2009). Successful approaches that are needed to come to sustainability from the point of view of erosion, all three elements of the process need to be tackled. Prevent detachment, prohibit transport, create deposition potential in places that are not harmful, or even beneficial. Two approaches lie at the basis of this approach: Nature-based solutions and connectivity based approaches.

Connectivity

The concept of sediment connectivity can be used to understand and analyze the continuity of sediment transfer from a source to a sink in a catchment, and movement of sediment between different zones within a catchment. The effect of different SWC measures should evaluated based the connectivity concept (Bracken et al.,2015; Keesstra et al., 2018) at larger scale through watershed approach which can be addressed using field investigation and modelling tools which finally leads to better adoption rate and upscaling of sustainable land management practices. In the catchment system, buffers and physical barriers as agricultural land management are acting as blocking agents in water and sediment connectivity systems (Mekonnen, et al., 2015). The possibility for sediment to be trapped within the catchment is enhanced by the appropriate placement of barriers and buffers, which can reduce sediment connectivity (Fryirs, 2013; Mekonnen et al., 2017).

Nature based solutions

Natural base solutions are a phenomenal approach for sustainable land management by considering the whole processes like erosion processes (detachment, transportation and deposition) and predict its long-term effect on landscape dynamics that determine sediment and water connectivity and its infraction within landscape. It has two types of measures: landscape and soil solutions. Landscape solutions mainly focus on hillslope morphology, runoff pathways, topographic wetness and water and sediment sinks (Ballard et al., 2013; Keesstra et al., 2018). The soil-based solution is mainly based on soil health, which can be explained by soil stability and soil roughness reduce overland flow and associated sediment transport. Vegetative and integrated SWC measures like grass strips trappings of sediment with vegetation and transform over time into a terrace can be seen as nature-based solutions which determines the potential for water and sediment to be transported and trapped through the system (Cerdà & Doerr, 2005; Masselink et al., 2016; Mekonnen et al., 2016). Within the nature-based solutions organic farming is a key management as allow the growth of vegetation and then reduce the raindrop detachment, overland flow velocity and enhance infiltration (Cerdà et al., 2018; Cerdà et al., 2018; Kirchhoff et al., 2017).

Conclusion

To overcome land degradation through sustainable land management, many efforts have been made globally. On the basis of these efforts many research articles have been published to understand the implication of different SWC measures on the biophysical dynamics of the watershed. A critical review was carried out from scientific journal articles to the effect of physical, agronomic, vegetative and integrated SWC measures on soil properties, surface runoff and soil loss. The synthesis reveals that, vegetative and agronomic measures play an important role for soil fertility enhancement and thereby improving soil quality for better production. Whereas structural measures such as terraces, bunds, fanya juu, and conservation tillage have a significant impact on runoff reduction by increasing the time of concentration and decreasing the velocity of running water. The combined implementation of SWC (physical, vegetative and agronomic) measures have also decreased soil erosion and improves the sediment trapping capacity of the landscape.

From this synthesis, research gaps have been identified. The evaluation of SWC measures on soil properties, runoff and, erosion and soil loss should mainly focus on larger scale on the bases of long-term evidences. In addition, the effect of different SWC measures should consider the connectivity concept to understand erosion and hydrological processes at large-scale, which can be addressed using field investigation and modeling tools. This approach finally leads to developing and promoting ecologically sound, economically viable and socially acceptable conservation measures for sustainable land management in agricultural watersheds.

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