Characterizing and evaluating the impacts of national land restoration initiatives on ecosystem services in Ethiopia

Publisher's DOI:
https://doi.org/10.1002/ldr.3424

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Characterizing and evaluating the impacts of national land restoration initiatives on ecosystem services in Ethiopia

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/ldr.3424

Abstract

Land restoration is considered to be the remedy for 21st century global challenges of land degradation. As a result, various land restoration and conservation efforts are underway at different scales. Ethiopia is one of the countries with huge investments in land restoration. Tremendous land management practices have been implemented across the country since the 1970s. However, the spatial distribution of the interventions has not been documented, and there is no systematic, quantitative evidence on whether land restoration efforts have achieved the restoration of desired ecosystem services. Therefore, we carried out a meta-analysis of peer-reviewed scientific literature related to land restoration efforts and their impacts in Ethiopia. Results show that most of the large-scale projects have been implemented in the highlands, specifically in Tigray and Amhara regions covering about 24 agro-ecological zones, and land restoration impact studies are mostly focused in the highlands but restricted in about 11 agro-ecological zones. The highest mean effect on agricultural productivity is obtained from the combination of bunds and biological interventions followed by conservation agriculture practices with 170 % and 18% increases, respectively. However, bunds alone, biological intervention alone, and terracing (Fanya Juu) reveal negative effects on productivity. The mean effect of all land restoration interventions on soil organic carbon is positive, the highest effect being from “bunds + biological” (139%) followed by exclosure (90%). Reduced soil erosion and runoff are the dominant impacts of all interventions. The results can be used to improve existing guidelines to better match land restoration options with specific desired ecosystem functions and services. While the focus of this study was on the evaluation of the impacts of land restoration efforts on selected ecosystem services, impacts on livelihood and national socio-economy have not been examined. Thus, strengthening socio-economic studies at national scale to assess the sustainability of land restoration initiatives are an essential next step.

Keywords: land degradation, landscape restoration, ecosystem services, effect size, meta-analysis

1. Introduction

Land degradation is a major global environmental and developmental challenge of the 21st Century (Hartmut, 2005; Gashaw et al., 2014). Nearly 5 billion hectares (about 43% of the Earth's vegetated surface) have been degraded through soil erosion, deforestation and loss of tropical forest (Hartmut, 2005). Global economic losses from land degradation are estimated to lie somewhere in-between \$300 billion (Nkoya et al., 2016) and \$10.6 trillion annually (ELD Initiative, 2015). The Montpelier Panel (2014) estimated that 180 million people are affected by land degradation with an estimated annual economic loss of \$68 billion in Sub-Saharan Africa (SSA). Among the SSA countries, Ethiopia experiences the most severe land degradation with an annual cost of \$4.3 billion (Gebreselassie et al., 2016). A recent report shows that about 14.3 million ha of land in Ethiopia (about 50% of the highlands) is severely degraded (FDRE, 2015; Gashaw, 2015).

Soil erosion by water is the most widespread form of land degradation in Ethiopia under different land uses. Estimates of average soil losses range between 3.4 and 84.5 tons ha^{-1} yr^{-1} with maximum rates reaching 300 tons ha^{-1} yr^{-1} (GIZ, 2015; Haile et al., 2006; Hurni et al, 2015; Gashaw, 2015). Relative to other land uses, the highest rate of soil loss occurs on cultivated lands, ranging from 50 tons ha^{-1} yr^{-1} (Adimassu et al., 2012) to 179 tons ha^{-1} yr^{-1} (Shiferaw and Holden, 1999). Due to the negative on-site impacts of soil erosion, the potential of agricultural intensification to enhance land productivity is limited (Adimassu et al., 2012; Gebrehiwot et al., 2013). National level nutrient depletion rates were estimated to be 122, 13 and 82 kg ha^{-1} yr^{-1} for N, P, and K, respectively (Haileslassie et al., 2005, 2006). This nutrient depletion results in decline in agricultural productivity that continues to significantly affect the performance of the national economy. Soil erosion also has tremendous off-site effects. Specifically, siltation of lakes, reservoirs, irrigation canals, flooding, and deterioration of ecosystem services, are issues of great concern. Due to rapid siltation caused by high erosion, the potential contributions of the various water harvesting schemes developed for supplemental irrigation have been compromised (Tamene and Vlek, 2007). High erosion in the upper Blue Nile basin at annual rate of 380 million tons (Hurni et al., 2015) also poses a serious challenge to the Great Ethiopian Renaissance Dam and it may reduce the capacity to generate electricity in the short- to medium-term.

Considering the severity of land degradation and its impact on food security and economic development, Ethiopia has ventured into one of the largest land restoration efforts, with several soil and water conservation (SWC) and sustainable land management (SLM) programs that have been implemented across the country. Following the droughts of the 1970s, SWC work expanded in most parts of the Ethiopian highlands (Girma, 2001; Kebrom, 2001; Nedessa et al., 2005). In the 2000s, the government and its key development partners have taken steps to learn from the strengths and weaknesses of the past environmental rehabilitation initiatives and embraced a multi-stakeholder and multi-sectoral programmatic approach addressing land and water degradation. A major programmatic breakthrough came with the formulation of the Ethiopian Strategic Investment Framework for Sustainable Land Management (ESIF) in 2008. ESIF is a holistic and integrated country-specific strategic planning framework that aims at guiding the broad spectrum of government and civil society stakeholders towards promoting SLM upscaling in all agroecological zones and agricultural production systems in the country. Recently, the sustainable land management program (SLMP) has been leading the coordination and implementation of large scale SWC, SLM and water harvesting options. Over the past few years, annual government led mobilization of communities has resulted in undertaking SWC work in large areas and in the plantation of hundreds of millions of tree seedlings in the Ethiopian highlands. According to a recent study, Ethiopia invested more than USD 1.2 billion per year over the past 10 years for land restoration in four regions (Amhara, Oromia, Tigray and SNNP) of the country (Adimassu et al., 2018).

Despite the various land restoration efforts for over 40 years, impacts and achievements have not been comprehensively assessed. Except for some studies related to area enclosures (Angassa and Oba, 2010; Mekuria and Yami, 2013; Seyoum et al, 2015), there is no clear/quantitative evidence about the performance of the restoration efforts and information on their contribution to improvement of livelihoods and enhancement of ecosystem services across scales. The results of the few studies that have been done are less-comprehensive and based on limited spatio-temporal analyses. Comprehensive studies that compare the “drawbacks vs. successes” of interventions to gain lessons and develop sustainable reforestation and landscape restoration programs are lacking. As a result, our knowledge about what works, where, and how, and the risks to scaling up land restoration practices remain limited. It is thus not possible to understand well the return on investment made in restoring degraded landscapes and their sustainable management in the country. This also undermines the negotiating power to facilitate payment for ecosystem services. This study intends to contribute to closing this knowledge gap. The specific objectives of the study include: (1) collate and map the major landscape restoration interventions in Ethiopia; (2) review, synthesize, and map literature related to the impacts of land restoration practices across the country that are published in peer-reviewed journals; and (3) investigate the impacts of landscape restoration efforts on landscape ecosystem services in the country.

2. Methodology

2.1. Mapping and synthesizing land restoration projects in Ethiopia

We consulted literature and experts to document and map the spatio-temporal distribution of the various land restoration efforts in the country. Publications, reports, proceedings, and PhD Theses were screened to identify candidate projects for analysis, and to determine when and where they were implemented, and document their attributes. Visits were also made to various governmental and regional offices, research and academic institutions, and offices of programs and projects that have been engaged in the coordination and/or implementation of land restoration across the country. Major land restoration initiatives, such as the Productive Safety Net Programme (PSNP) (Devereux et al., 2018), the Managing Environmental Resources to Enable Transition (MERET; Nedessa and Wickrema, 2010), the Sustainable Land Management Programs (SLMP I and SLMP II) as well as smaller projects supported by different NGOs were also reviewed.

Pre-processing steps involved scanning hard copy documents, georeferencing, digitizing, and entering project sites into GIS environment. Georeferenced datasets were directly integrated into the GIS system after relevant projections were made. In addition to project intervention sites, other spatial data, such as topography (SRTM data https://cgiarcsi.community/data/srtm-90m-digital-elevation-database-v4-1/), land use/cover (RCMRD, 2018), agroecology (Ministry of Agriculture, 2000), soil carbon (ISRIC, 2015) and population density (CSA, 2007), were collected and used as explanatory co-variants. The land restoration sites were then integrated with different covariates including administrative region, farming system, time (age) of intervention, terrain characteristics such as elevation and slope, and population density. Figure 1 summarizes the procedure followed for data acquisition, processing, and analysis.

Figure 1. approximately here

2.2. Mapping and synthesizing landscape restoration impact assessment studies in Ethiopia

To synthesize the performance of land restoration activities and produce national level evidence, we collected peer-reviewed papers that have investigated the impacts of land restoration in Ethiopia. Five steps were followed to collate publications related to the impacts of land restoration and management practices in Ethiopia. The first step involved collection of case studies related to land restoration activities using a bibliometrics approach (Eva, 2001). We used the Web search function involving keywords “landscape restoration in Ethiopia”, “impacts of landscape restoration in Ethiopia”, “soil and water conservation practices in Ethiopia”, “impacts of soil and water conservation practices in Ethiopia”, “sustainable land management in Ethiopia”, and “impacts of sustainable land management in Ethiopia”. We collated peer-reviewed publications until August 2018. The next step involved developing database related to the collated dataset using predefined template. The database so developed is organized considering different attributes of the studies such as author (s), year of data collection and/or publication, location of study site, intervention type[1], years of intervention (for how long was the practice in place), the ecosystem services assessed for impacts, and the results obtained in terms of those ecosystem services both before and after implementation (see Table A1 for the list of variables included in the database). All biophysical ecosystem services were extracted, but for statistical purposes, four ecosystem services (soil organic carbon stock (SOC), soil loss, runoff, and productivity) were selected based on frequency of occurrence in the database. The third step mapped the spatial distribution of the relevant study sites using place names and/or geographic coordinates. For cases where the location of the study was not provided in latitude and longitude format, we obtained such coordinates using Google Earth based on study site description and corresponding place names. This step helped visualizing the spatial distributions and linking and analyzing data with covariates having defined spatial attributes such as regions and agro-ecological zones. The fourth step synthesized and characterized the dataset in terms of geographic location, administrative region, year of publication, agro-ecological zone, land use/cover types, terrain types, and ecosystem functions/services. Where necessary and for simplicity, similar land management practices/ types such as conservation tillage, reduced tillage, mulch, green manure, and other local soil fertility enhancing techniques/technologies, were grouped under the term conservation agriculture (CA). This step enabled stocktaking studies conducted in the country and helped identify gaps related to the spatial dynamics of evidence generated about the performance of

[1] The Intervention types are any kind of land management, water harvesting, conservation agriculture practices commonly implemented in Ethiopia to improve land ecosystem services.

land restoration efforts. In the final step, we conducted a detailed statistical and meta-analyses to understand the significances of different practices on ecosystem services. To evaluate the effects of land restorations on various soil, biological[2] and productivity parameters, an effect size given by a response ratio (RR) approach proposed by Hadges et al (1999) and Luo et al (2006) was used. A response ratio (RR) is defined as the natural logarithm of the ratio of the value on land restoration treatment (after or treated) to that of without land restoration (before or control or untreated):

$$\mathrm{RR} = ln\frac{after\ intervention\ (treated)\ paramater\ value}{before\ intervention\ (control) paramater\ value}$$

Assuming that the effect size RR follows a normal distribution (Curtis & Wang, 1998; Luo et al., 2006), the variance, v, of RR was approximated using the following formula:

$$v(RR) = \frac{(SD_t)^2}{N_t X_t{}^2} + \frac{(SD_c)^2}{N_C X_C{}^2}$$

Where SD_t and SD_c are the standard deviation of treated site parameter values, and control (untreated) site parameter values, respectively; N_t and N_c are the numbers of case studies for the treated (after) and untreated (before) groups, respectively; and X_t and X_c are the mean value for treated and control parameter, respectively. The variance is useful to quantify the weights for minimizing the influences of studies with low statistical powers through estimating sample variability in RR. For comparing the effect size of land restoration intervention types, we used the nonparametric weighting function (w) of case studies (Hedges et al., 1999) calculated as an inverse of the pooled variance ($1/v(RR)$). Thus, the weighted response ratio (RR') is obtained as:

$$RR' = w * RR$$

The final mean effect size for each intervention and ecosystem service was calculated by:

$$\overline{\mathrm{RR}'} = \frac{\sum_i^n RR'}{\sum_i^n w}$$

The bias corrected 95% confidence intervals (CIs) of the mean was generated by a bootstrapping procedure (Song et al., 2014). The effects of the land restoration intervention on ecosystem services was considered significant at $P < 0.05$ if the 95% CIs did not include 0

[2] Biological refers to options including agroforestry and tree/forage planting as part of restoration, intensification and/or diversification options.

(Guo and Gifford, 2002). For convenience, the effect size was converted from the natural logarithm to percentage using the equation $(e^{RR} - 1) * 100$ (Luo et al, 2006). This provides the actual response of the intervention in percentage.

The established case study map that represents the spatial distribution of sites was used to evaluate the geographical representativeness of case studies. We used intervention response times and duration of interventions of the studies to explore the relationship between age of interventions and ecosystem responses.

To summarize the ecosystem services related to each intervention type, we aggregated them into major ecosystem services i.e. provisioning, regulating, and supporting and cultural services. Accordingly, yield and biomass productivity and water quantity are categorized as provisioning services. Most soil properties (soil pH, soil moisture, SOC, Total Nitrogen, available phosphorus), soil erosion and event runoff are regulating, and biodiversity as supporting services. We reported limited cultural related services in the review papers. Thus, we have not included those in our analysis.

3. Results and Discussion

3.1. Distribution and characterization of land restoration interventions in Ethiopia

Land restoration efforts in Ethiopia generally attempt to respond to severe land degradation problem caused by population pressure and climate change (Taddese, 2001). The 1970s SWC measures were designed around a food for work (FFW) principle focusing on welfare safety nets for poor communities in food insecure areas. Details of the interventions and approaches of FFW implementation in Ethiopia can be found in Holt (1983) and Bezu, and Holden (2008). Considerable natural resource rehabilitation and development work has been conducted between mid-to-late 2000s within the framework of the PSNP and under MERET projects implemented under the auspices of the World Food Programme (WFP). Other small-scale projects have been implemented with support from bi- and multi-lateral and UN agencies and executed by governmental and non-governmental organizations. In 2008, a major programmatic breakthrough came with the formulation of the Ethiopian Strategic Investment Framework (ESIF) for Sustainable Land Management Program (SLMP). ESIF is a holistic and integrated strategic planning framework that aims at guiding the broad spectrum of government and civil society stakeholders towards promoting SLM upscaling in all agro-ecological zones and agricultural production systems.

The first phase of SLMP started in 2008 and lasted until 2013 with various accomplishments including implementation of water-harvesting and agroforestry options as integral parts of the restoration effort. Since the latter part of 2008, different types of water harvesting structures have been promoted to reduce soil erosion, reduce runoff, and enhance small-scale irrigation across the country (Woldearegay et al. 2018). SLMP II started in 2013 and was planned to operate until 2018. Under the various programs, it is claimed that large areas of degraded hillsides and grazing and farm lands have been rehabilitated using area exclosures (AE) to protect sites from grazing animals; degraded communal lands are conserved through the construction of terraces, deep trenches, and percolation ponds, and according to the government reports, billions of seedlings have been planted in the mid and highlands of the country (Meaza et al., 2016). Figure 2 outlines the temporal sequence of major SLM initiatives in Ethiopia.

Figure 2. approximately here

The results of our analysis showed that the spatial distribution of the major land restoration initiatives that have been implemented in Ethiopia in the last four decades were mostly concentrated along the escarpment of the eastern and western mountains of the country (Figure 3).

Figure 3. approximately here

The Administrative zones with large number of projects and intervention sites include South Wollo, Central Tigray, Southern Tigray, Northern Shewa, and East Harerghe (Figure 4a). Scattered intervention sites, mainly belonging to SLM projects, are present in the western parts of the country. The Somali, Afar, and Benishangul lowlands have seen relatively little land restoration interventions. The PNSP intervention sites were focused on the Eastern and Northern part of the country, while SLM interventions targeted the Western part. This may be because PSNP mainly focused on food-insecure low and dryland areas (MoARD, 2014), while SLM engaged more in the highlands with high agricultural potential. In terms of agro-ecologies, land restoration interventions were carried out in about 24 agro-ecological zones. The tepid sub-moist, tepid moist, and tepid sub-humid mid highlands are the most widely covered agro-ecologies by land restoration initiatives (Figure 4a). Most of the land restoration interventions are concentrated in mid-highlands (Figure 4b) with high population densities (Figure 4c). Given the associated increased pressure on natural resources, the highlands have been, and are, experiencing land resource depletion, which could have been the factor that attracted the land restoration projects. It is important to note that there are very few intervention projects in the lowland peripheral parts of the country where the settled population density is low and some of the places are less accessible.

Intrusion of cropping land into forest and grazing areas is one of the main causes of resource depletion and consequently land degradation. As a result, most of the land restoration process have targeted cultivated lands - i.e. to sustain existing cropping areas and avoid further encroachment. This is shown clearly in Figure 4d with notable land restoration interventions occurring on annual croplands. Considering that agriculture supports more than 85% of the population of the country, it is not surprising to see more focused conservation efforts targeting croplands. Grazing areas and hillsides dominated with shrublands and exposed to land degradation risks were targeted for land restoration (Figure 4c). Relating the land restoration intervention sites with a soil health indicator, the majority of interventions have been implemented on soils whose soil organic carbon concentration is between 11 g kg^{-1} and 40 g kg^{-1} as shown in Figure 4e. This is an indication that most of the interventions are concentrated on degraded lands that have lost significant amounts of their original soil organic matter.

The spatial distribution of the land restoration intervention sites and associated brief characterization given above can facilitate planning and informed decision making. Researchers, planners and decision makers can use this information to understand where major projects have been implemented, and undertake further assessments to plan studies and/or prioritize further interventions as well as exploring options for targeting SLM investments. Stakeholders who are and/or will be engaged in land restoration efforts can utilize such information to prioritize and those who are coordinating and/or monitoring such exercise can use the database and maps to update progress.

Figure 4. approximately here

3.2. Distribution and characterization of land restoration interventions impact assessment studies in Ethiopia

This section assesses studies that have been conducted to evaluate the impacts of land restoration efforts in the country. Our literature search identified 103 peer-reviewed papers containing 445 case studies from 142 sites in which evidence on the contribution of land restoration intervention activities in Ethiopia was documented. The dominant land management practices studied and incorporated in our review include soil and stone bunds (60 case studies) followed by various forms of conservation agriculture (CA) (53 case studies), exclosures, and a combination of bunds and biological interventions (Figure 5). The two most common bunds studied were stone bunds and soil bunds. Various form of CA interventions such as fallow, manuring, and tillage practices were implemented for improving traditional agricultural systems in Ethiopia. The most common CA practice documented by the different studies is tie-ridging followed by minimum tillage. Most studies dealing with CA targeted provisioning ecosystem services, mainly crop production (Figure 5).

Figure 5. approximately here [3].

The third largest category of land restoration interventions that has been analyzed is exclosures aimed at reducing grazing pressure. These studies are the most prevalent in the Tigray region and the focus of the case studies related to exclosure were on supporting and regulating ecosystem services. One of the commonly criticisms of with exclosure interventions is that provisioning co-benefits (such as beekeeping) are limited, and this appears to be borne out in the literature on these interventions.

In terms of time coverage, the earliest peer-review papers that evaluated the impacts of land restoration interventions are from 1998 (Figure 6). In the last five years (2014 - 2018), the number of case studies published decreases in comparison to the previous years (2011-2013). It is important to note that detailed analysis of the impacts of restoration interventions mainly focused on provisioning services followed by regulating ecosystem services while studies on supporting services emerged in 2006.

Figure 6. approximately here

Figure 7 shows the spatial distribution of the study sites across the country. The majority of the studies are located in the highlands, corresponding to large land restoration efforts. Most of the impact assessments took place in the Tigray and Amhara regional states, followed by Oromia and SNNP regional states. The highest geographical representation of the studies available in literature appears in Amhara (40 sites), followed by Tigray (35 sites), Oromia (30 sites), SNNP (17 sites), and Somalia (3 sites) regional states. We did not find impact assessment studies

[3] *Conservation agriculture (CA) refers to various land management practices such a conservation tillage, reduced tillage, mulch, green manure, and other local integrated soil fertility management technologies. Enclosure is complete area closure from grazing and cultivation for a specific duration of time. Fanya Juu is a special kind of bund constructed by digging trenches along the contour of the slope and heaping the soil on the up-hill side. Biological is a bundle of practices (trees, grass strips, vegetative bund stablizers, etc).*

published in peer-reviewed journals covering the Gambella and Binshangule Gumez regions, although land restoration projects have been implemented there (Figure 3). When normalized by the area of the regions, Tigray emerged as the region with the highest density of case studies, followed by Amhara, and SNNP.

Figure 7. approximately here

We were able to trace land restoration projects that have been implemented in more than 24 agro-ecological zones, while scientific evidence is available for activities in only 9 agro-ecological zones. Large proportion of the land restoration projects (Figure 3 and 4) and most of the evidence generated about the impacts of intervention practices (Figure 7) has mainly focused in the tepid moist agro-ecological zone (Figure 8). This highlights the need for spatially targeted studies focusing on improving the representation of agro-ecological zones where performance studies are lacking. We can also observe that the type of land restoration intervention practices considered in the case studies in moist highland zones are multiple types, while intervention practices in the lowland zones are few types (Figure 8).

Figure 8. approximately here

In terms of land use/cover type, most studies reviewed cover agricultural land use (80%), followed by forest land (10%). This implies that the majority of the studies focused on cultivated areas that mainly provide provisioning ecosystem services. Also, the majority of the studies focused their analysis on plot-level (92% of the cases) with a few cases of watershed and farm/field scale analysis.

Out of 313 case studies with the duration of the intervention reported in the paper, we found that about half (48%) were conducted over 5 years or less after the implementation had begun (Figure 9). This implies that there is only limited evidence related to impacts of long established land restoration efforts. Interventions where activities have been undertaken 10 years or more are limited. Since land restoration practices generally bring meaningful impacts after longer periods, it will be essential to conduct impact assessment of long-established restoration sites in the future. Based on a meta-analysis of soil erosion at the global level, Garcia-Ruiz et al. (2015) indicated that a period of at least 20 years of measurements is required to obtain reliable estimates of soil erosion rate reductions that take extreme events into account.

Figure 9. approximately here

3.3. Impacts of land restoration interventions on ecosystem services

In this section, we focused on assessing the impacts of major land restoration practices on selected ecosystem services based on the effect size statistics (Figure 10). Here, we present the mean effect size of land restoration on four selected ecosystem services (SOC, soil erosion, productivity and runoff) associated with different interventions. These ecosystem services are presented in detail because the review shows the majority of the studies have considered these components in their analysis. Within the productivity category, the most reported indicator is crop yield. In Figure 10, the vertical lines along the zero (X-axis) show the boundary between negative and positive effects and the distribution of the 95% confidence intervals reflect the variability of the land restoration impacts in relation to the respective ecosystem services. In cases where the error bars cross and/or touch the vertical lines (when mean effect size is zero), the effects of the land restoration technologies on the status of the respective ecosystem services are considered to be not significantly different from 0.

Fanya juu significantly reduced soil erosion and runoff; the impact on productivity was not significant, but there was a significant improvement in SOC. The mean effect size of biological systems on soil erosion and runoff were -77% (range -90 to -68%) and -38% (range -48 to -21%), respectively. In both cases the 95% CI did not cross zero (Figure 10) showing a significant effect of biological interventions on reducing soil erosion and runoff. The effect of biological systems on productivity was slightly negative (mean effect size of -10%), but not significant at 95% CI (Figure 10). The effects of bunds in reducing runoff (effect size of -69%) and soil erosion (effect size -78%) were significant (Figure 10). Bunds reduced productivity slightly (effect size -9.4%), and had a small positive effect on SOC (effect size 4.9%), but the effect was not significant. A similar result of yield reduction due to these physical measures was reported by Balehegn et al. (2019) using a review analysis in Tigray region. In areas where bunds were integrated with suitable biological systems, there are higher possibilities of yield increase due to complementary benefits. We found a significant positive effect of combined bunds and biological interventions on productivity (mean effect size = 170%, with a range of 97-318%). Bunds and biological options also show significant positive effect on SOC (mean effect size = 139% with a range of 89-164%). These combined interventions reduced runoff (mean effect size of -58% (ranging between -77 to -34%)), but there was inadequate assessment of erosion effects in the studies for us to assess this impact (Figure 10). These observations show that physical measures such as fanya juu terraces (Figure 11a) and bunds (Figure 11b) alone have a negligible effect productivity despite the direct benefits to soil conservation that they can offer (Balehegn et al., 2019). This suggests that loss of cultivatable area offsets productivity gains.

Figure 10. Around here …

The biological measures such as agroforestry (Figure 11c) when implemented alone also did not bring positive change to productivity. However, when bunds are integrated with fodder or multipurpose tree species (Figure 11d) the decline in productivity is less. This could be due to the compound effect of integrated options in improving soil moisture, reducing soil loss and enhancing soil fertility that could ultimately benefit crop production. However, it is important to note that the negative impacts of these measures on productivity are not significant.

The implementation of conservation agriculture (CA) practices in Ethiopia showed multifunctional benefits, with a significant decrease of soil erosion and runoff by 45% and 46%, respectively; and a significant increase of SOC and productivity by 24% and 18%, respectively. If the whole package of CA (minimum tillage, soil cover and rotation) is implemented properly, the positive impacts outweigh associated undesirable effects because of the complementarity between the different components (increased food production; enhanced soil carbon sequestration; reducing soil erosion; improved moisture and nutrient storage and improvement in the water and nutrient cycle). Figure 11e shows plots with adequate surface cover that could facilitate provision of multiple benefits such as the above ones.

Exclosures played a significant role in reducing soil erosion and runoff by 53% and 91%, respectively, while enhancing SOC by 90% (Figure 10). Because most of the enclosures found on hillside slopes (communal lands or grazing areas), there are no studies that reported impact on crop yield. Enclosures (Figure 11f) are generally protected from livestock free grazing and crop cultivation that enable them regenerate and overtime provide various ecosystem functions. When complemented with supplementary options such as apiary or planting fruit trees etc., their economic benefits can magnify enhancing their sustainability.

Figure 11. Approximately here.

Response of ecosystem services to land restoration interventions did not necessarily decrease with the duration of the interventions (Figure 12). For example, the impact of duration of land restoration on crop productivity showed a weak, statistically non-significant, negative trend (Figure 12). However, the impacts of interventions on runoff and SOC increased with the duration. The lack of proper maintenance and the decrease of storage efficiency of practices/bunds can be suggested for the tendency for runoff and soil erosion to increase with time (duration of intervention). The correlation between SOC sequestration and duration of interventions is statistically significant at 90% probability (Figure 12). Commonly, the SOC dynamics over time are described using a sigmod model, i.e. SOC increases, attains a maximum some 5-20 years after the intervention and then increases less notably until a new SOC equilibrium is reached (Sommer and Bossio, 2014). Our meta-analysis could not support such trend. This, however, is not surprising, as the rate at which SOC increases depends on soil texture, topography, and climate. Thus, it is unlikely that pooled data from all parts of the country will follow the 'SOC equilibrium' trend.

Figure 12. approximately here

Further disaggregation of the effect size by agroecological zones are presented in figure 13. The statistics of effect size is calculated for agroecology and intervention combinations with 10 or more case studies. Except for CA, which shows positive effect in many agroecological zones, the effect of other interventions on productivity are negative in all agroecological zones. Comparing the impacts of CA, the performance is higher at warm sub-moist lowlands followed by tepid moist mid highlands. Similarly, bunds have positive effect (32%) on productivity only in warm sub-moist lowlands. Runoff reduction is observed in all agroecological zones for all types of interventions; the largest reduction was found in exclosure at warm sub-moist lowlands (-80%). Comparing CA and exclosure, exclosure has larger positive impacts (55%) on SOC in tepid sub-humid mid highlands agroecological zone whereas it has small negative effect (-5%) in tepid moist mid highlands. Though there is a difference in magnitude, all interventions have soil erosion reduction effects irrespective of the agroecology zone. Bunds have the largest effect on reducing erosion in warm sub-humid lowlands (-92%) followed by tepid moist mid highlands (-81%).

Figure 13: approximately here

In all the above results, the variability of effects of land restoration practices on ecosystem services between agroecological zones, the success of land restoration interventions varies and they depend on the local context and human factors. As shown here, agroecology can be considered one broader context that can help to fine tune land restoration interventions for a targeted ecosystem services. However, many factors such as the design of the interventions, the socio-economic system, the specific types of ecosystem for which services are targeted, etc. should be considered for optimized land restoration techniques. The impacts of land restoration practices on ecosystem services have been drawn from meta-analysis of literature from a range of conditions including agro-ecology, land use type, topography and soil types. Regardless of specific conditions, the average effect has demonstrated the substantial benefits of different types of land restoration practices on soil loss (45-80%) and runoff (38-90%) reduction. While the average effect on soil organic carbon and productivity vary on the type of land restoration practices. Practices like CA and integrated physical and biological practices revealed increase in SOC and productivity. This indirectly implies that low effect of physical land restoration practices on SOC and productivity might be attributed by depletion of soil nutrients and marginal topography to serve for crop production. Thus, we have understood from the analysis of average effect size of land restoration practices drawn from the range of studies that multiple ecosystem services can be enhanced through integrated land restoration interventions including structural, biological/vegetative, agronomic and soil management practices. We therefore recommend to design land restoration strategies and practices targeting different contexts (agro-ecology, rainfall regimes, and land use types).

4. Conclusion and suggestions for future research

This study presents national stocktaking of land restoration initiatives in Ethiopia using spatial mapping, synthesizing and characterization; and analyzes their impacts using response ratio effect size statistics from peer-reviewed papers. The major findings are summarized as follows:

- A concentration of land restoration initiatives and sites were observed following the central north-south orientation whereas the most west and east were sparsely addressed. This orientation implies that land restoration in the last decades has mainly been targeted to address areas with severe land degradation and historical drought problems. Moreover, since most of the impact studies focused their analysis on the plot-level (92% of the cases), there was limited evidence to understand the effect of land restoration on the landscape scale ecosystem service benefits. Generally, it can be concluded that the number of studies conducted to assess the performances of the various landscape interventions are small – especially compared to the extent of the interventions – thus, there is lack of adequate information about successes and failures of the efforts, which can undermine evidence-based planning and decision-making.
- A large proportion of land restoration related projects and most scientific evidence generated about their impacts focus on the tepid moist highlands. However, the largest studies were carried out in the warm sub-moist lowland agro-ecological zones. Projects were implemented in more than 24 agro-ecological zones while scientific evidences are

available only for 11 agro-ecological zones, suggesting that further, spatially targeted studies are needed representing different agro-ecological zones where there is shortage of evidences related to the impacts of land restoration projects (e.g., Hot sub-humid and sub-moist zones). Once such data are available upscaling the impact of interventions at national scale using geographically representative case studies would help to evaluate land restoration benefits at national level and guide interventions to be site-specific.

- The dominant land management practices studied were different forms of conservation agriculture, followed by soil and stone bunds, and exclosures.
- For productivity, the highest effect was observed from bunds + biological intervention followed by conservation agriculture practices, with 170% and 18% increase, respectively. The other interventions (bunds, fanya juu, and biological) reveal negligible effect on productivity. This indicates the need for developing integrated land management practices that enhance multiple ecosystem functions and/or identifying appropriate practices and targeting where they can generate maximum benefit.
- For SOC, the effect of all interventions is positive, the highest effect being from "bunds + biological" (139%) followed by exclosure (90%). All interventions indicated decreasing effect on both soil loss and runoff. Fanya juu has the highest effect (-98%), followed by biological (-75%) and bunds (-74%) on soil erosion whereas the highest effect was obtained from exclosure (-91%), followed by "bunds + biological" (-58%) and bunds (-57%) for runoff. The age of intervention was found to be an important determining factor affecting the performances of interventions.
- Generally, it can be concluded that the number of studies conducted to assess the performance of the various landscape interventions are small – especially compared to the extent of the interventions – thus, there is lack of adequate information about successes and failures of the efforts, which can undermine evidence-based planning and decision-making.
- Many of the studies that attempted to assess the contributions of water and land restoration interventions in Ethiopia are sectorial i.e. they are limited to one or few aspects of the contributions. Such lack of systematic, integrated and compressive assessments can blur the 'true' picture of the significant biophysical, socio-economic and other co-benefits of sustainable land management and restoration efforts. In the long-term this can also undermine the negotiation power of communities and country when negotiating payment for ecosystem services. Socio-economic and livelihood

impact studies are needed to understand the social acceptance, direct and indirect benefits such as cultural ecosystem services.

- For a complete understanding of land restoration initiatives, properly designed studies are needed to assess the cost effectiveness, net social benefit, and trade-off analysis among ecosystem services for each intervention types.

ACKNOWLEDGEMENTS

This research was undertaken with support from the Africa RISING, a programme financed by the United States Agency for International Development (USAID) as part of the United States Government's Feed the Future Initiative. The content is solely the responsibility of the author/s and does not necessarily represent the official views of USAID or the US Government or that of the Africa RISING programme. Africa RISING is aligned with research programmes of the "CGIAR". The Water, Land and Ecosystems (WLE) programme of the CGIAR has equally provided financial support to this research.

Reproducibility

The database and R codes used to produce the results in this paper can be obtained from the first author by request.

Appendix

Table A1: variables and templates used to extract data from the literatures

	ID	Authors	year	Latitude	Longitude	scale	Elevation	Land Use	Rainfall	Intervention type	Duration of intervention	Ecosystem services (ES) or parameters	ES value at with/treated	ES value at without/control
Description	Each paper is indexed with ID to separate papers from case studies	Authors are used to index papers	years of publication is extracted to understand the temporal trends of studies	The latitude and longitude are extracted to locate the study areas and to overlay with other spatil data sets.		used to identify if studies are plot or watershed/landscape scale	These data are used to characterize the studies in terms of elevation, land use/cover and rainfall			Refers to which kind of intervention(s) each paper is analyzed	For how long the intervention has been implemented	Which ecosystem services such as soil parameters e.g. soil pH, soil organic carbon, and soil macro- and micro-nutrients; hydrological parameters e.g. runoff, evapotranspiration and soil moisture; and agricultural parameters e,g.. productivity	Values obtained in treated sites	values obtained in control sites

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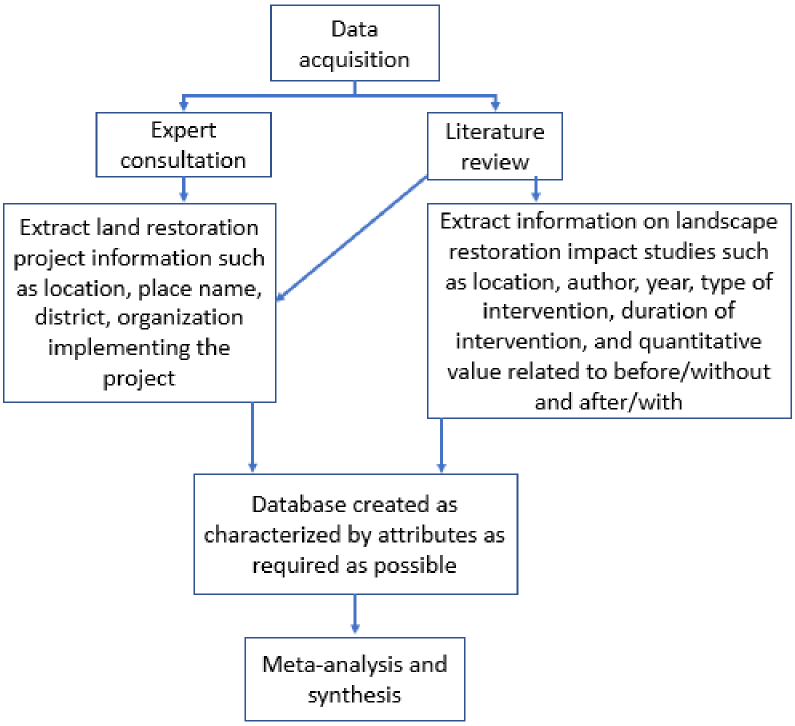

Figure 1. Procedure employed to collate, synthesize and analyze data related to land restoration projects and land restoration impact assessment studies in Ethiopia

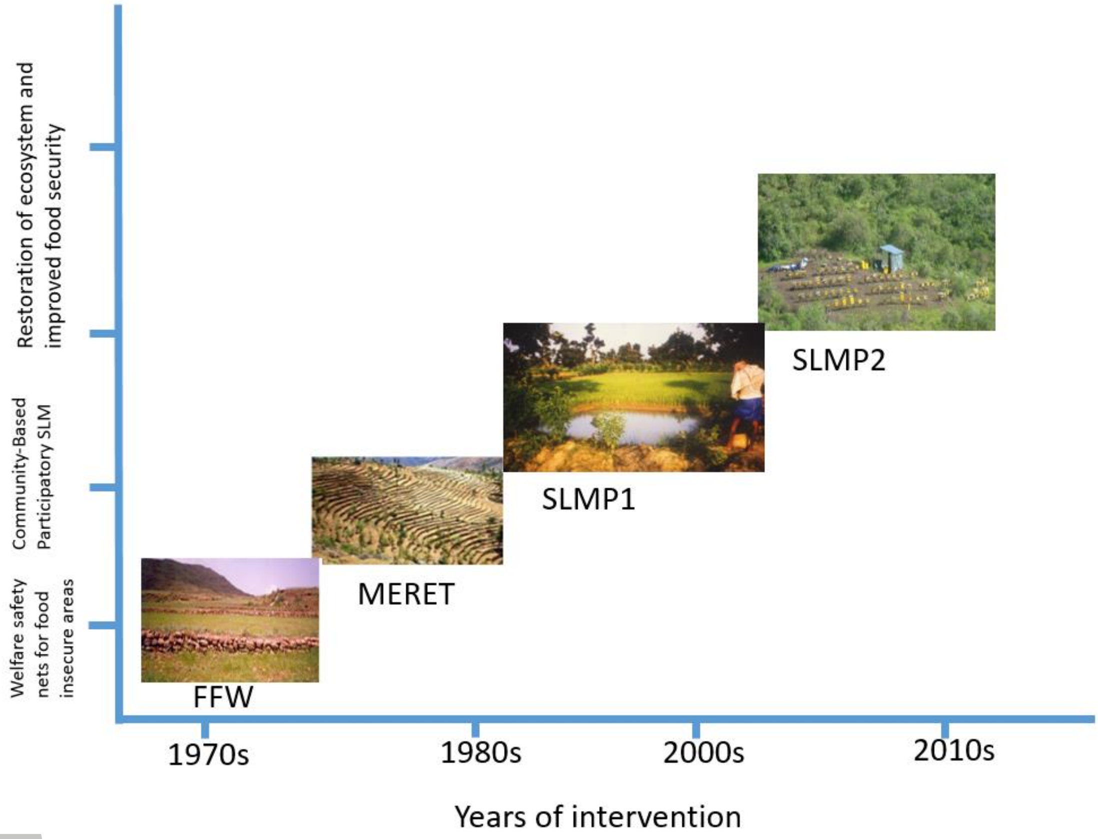

Figure 2. Thematic focus and timeline of major land restoration programs in Ethiopia. Note: FFW - Food For Work; MERET - Managing Environmental Resources to Enable Transitions; SLMP1 - Sustainable land management program Phase I; SLMP2 - Sustainable land management program Phase II. The time-period and project focus (types of interventions) do not have distinct boundary.

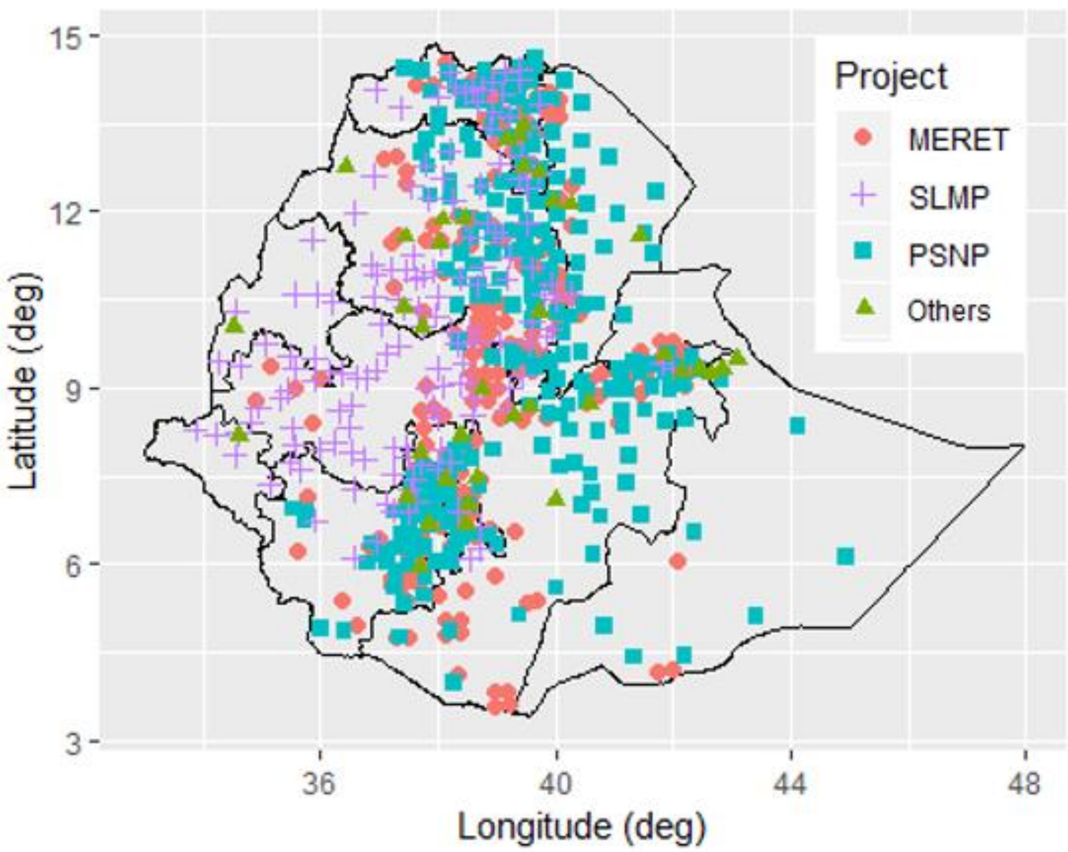

Figure 3. Spatial distribution of project based land restoration intervention sites in Ethiopia. The points represent watershed centroids for SLMP; kebele centroids for MERET and PSNP projects.

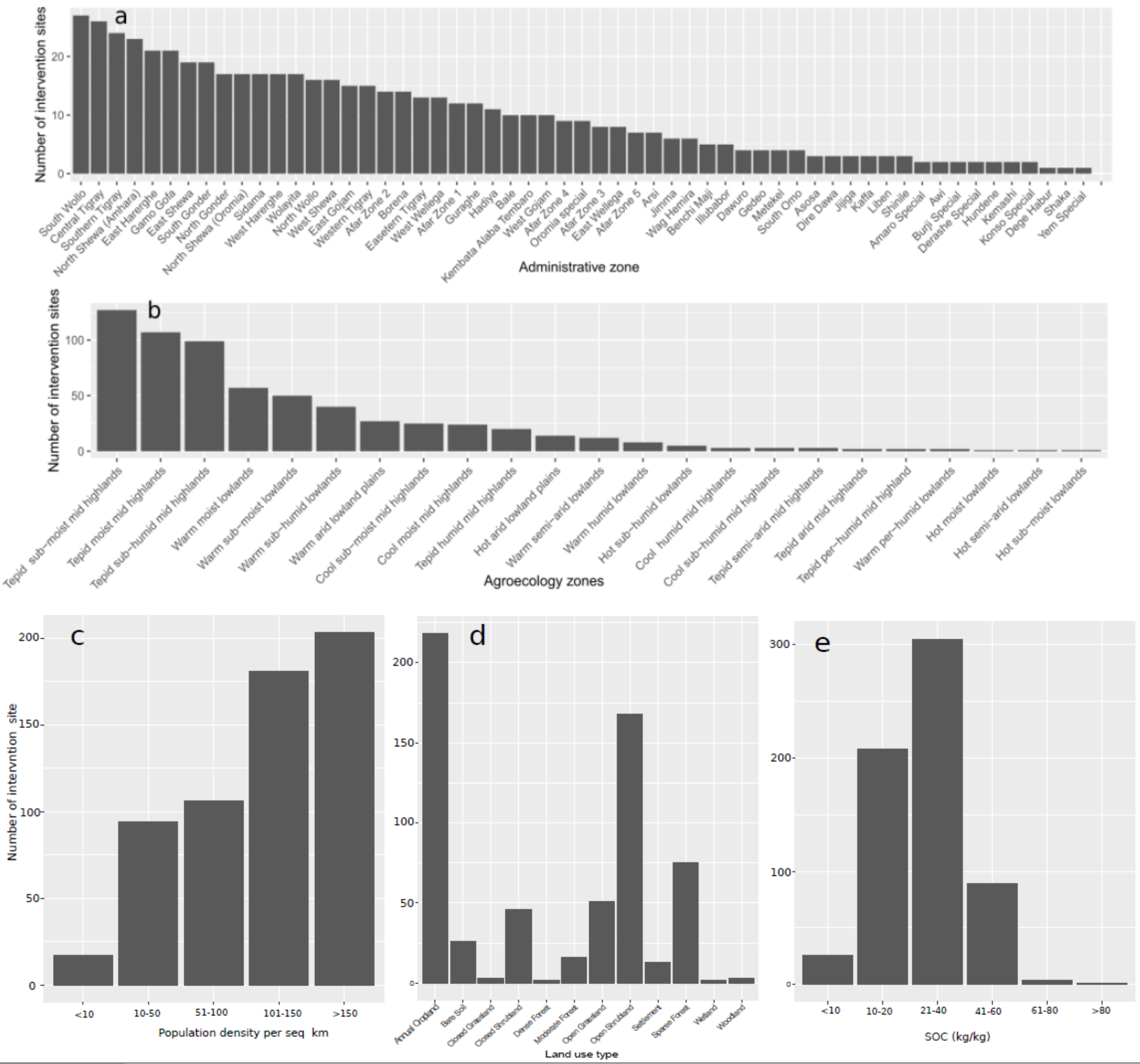

Figure 4. Number of land restoration intervention sites characterized by a) administrative zones, b) agroecology, c) population density, d) land use/cover type, and e) SOC class

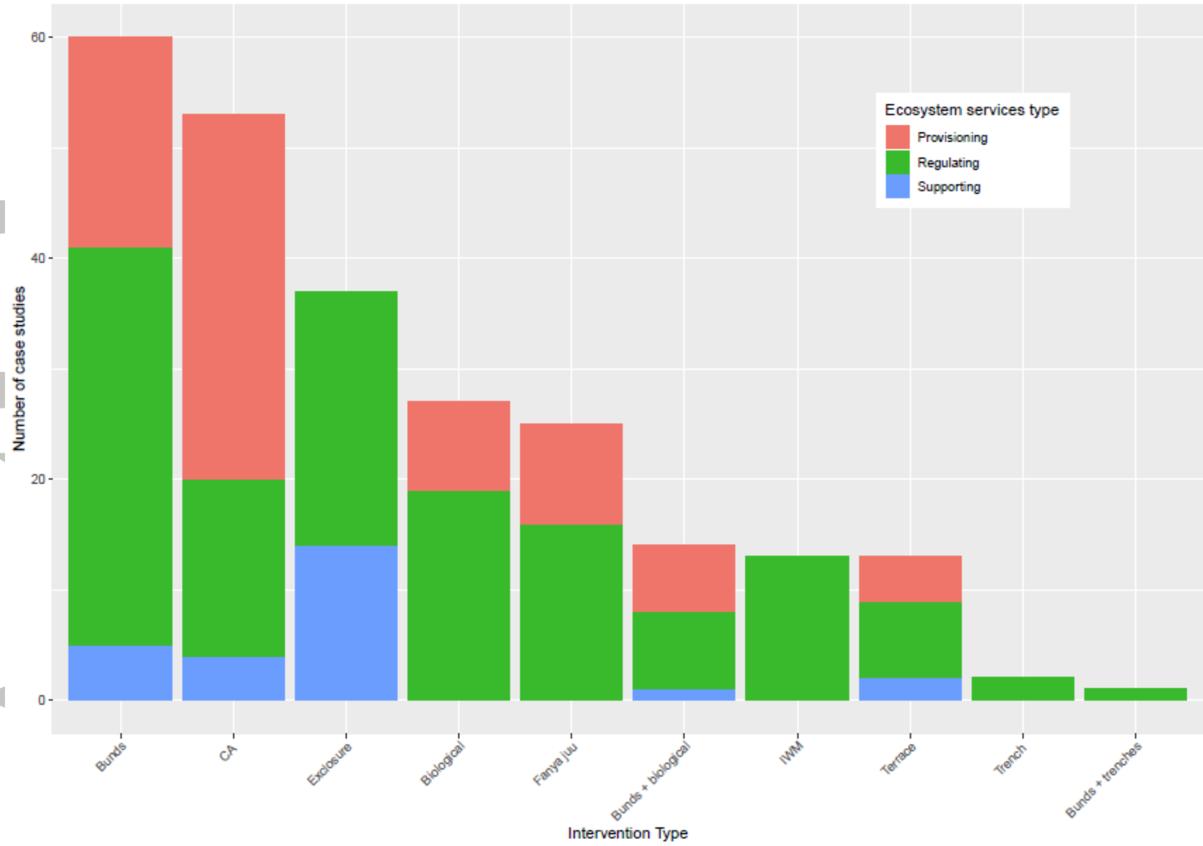

Figure 5. Land restoration intervention practices and the associated supply of ecosystem services against the number of case studies in Ethiopia

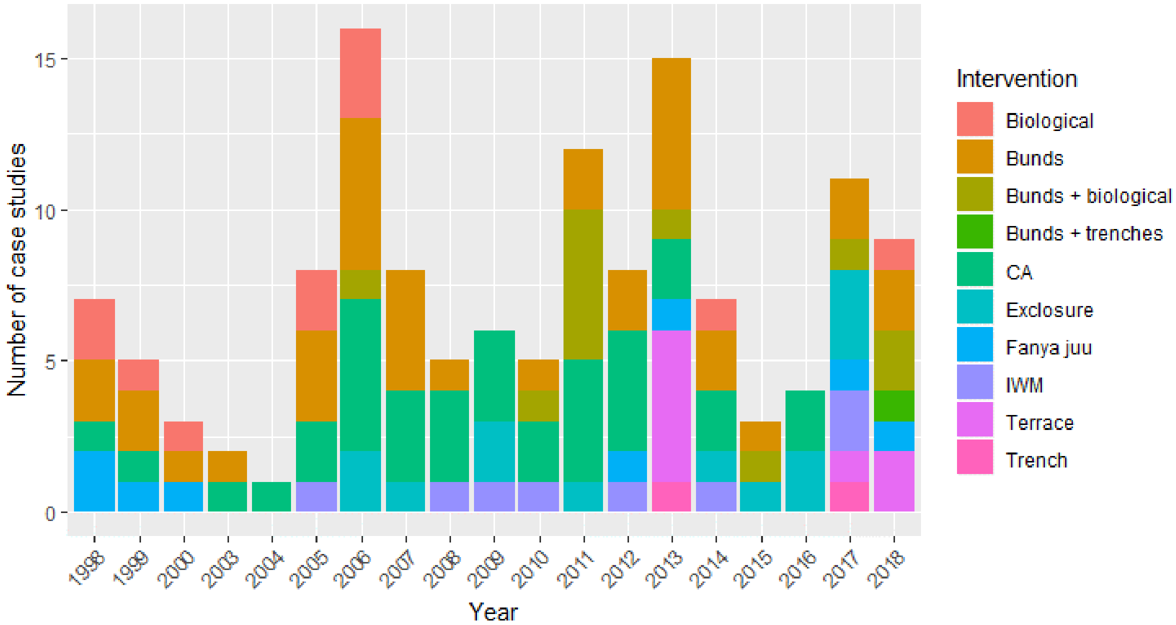

Figure 6. Number of studies over years about the impact of landscape restoration interventions on ecosystem services in Ethiopia (1998-2018).

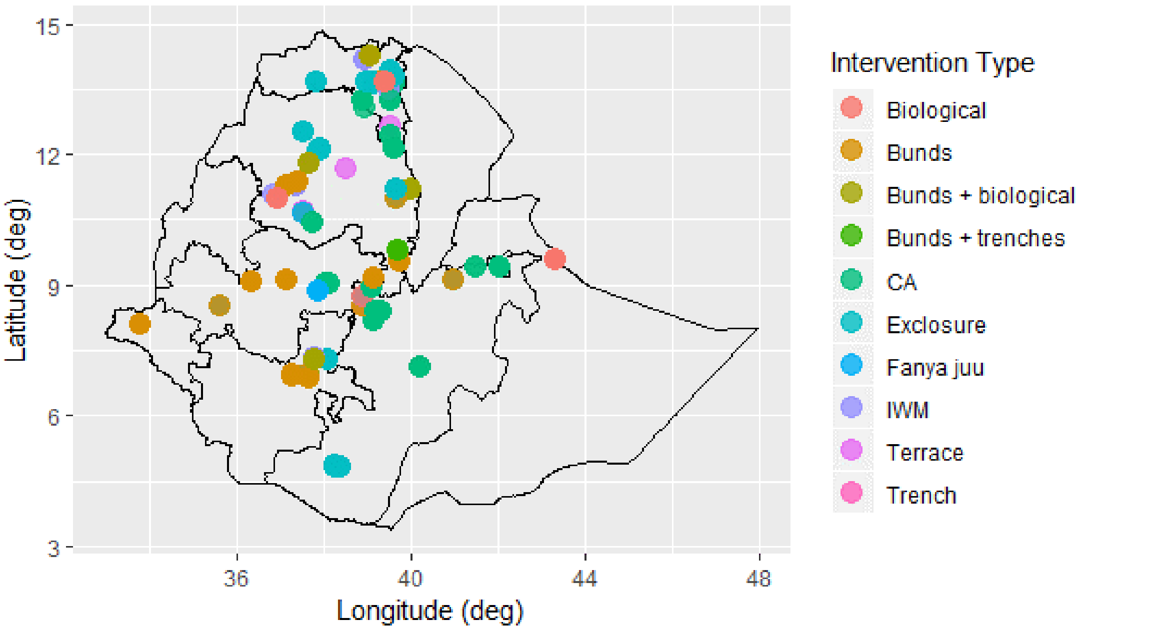

Figure 7. The spatial distribution of land restoration impact assessment case studies in Ethiopia.

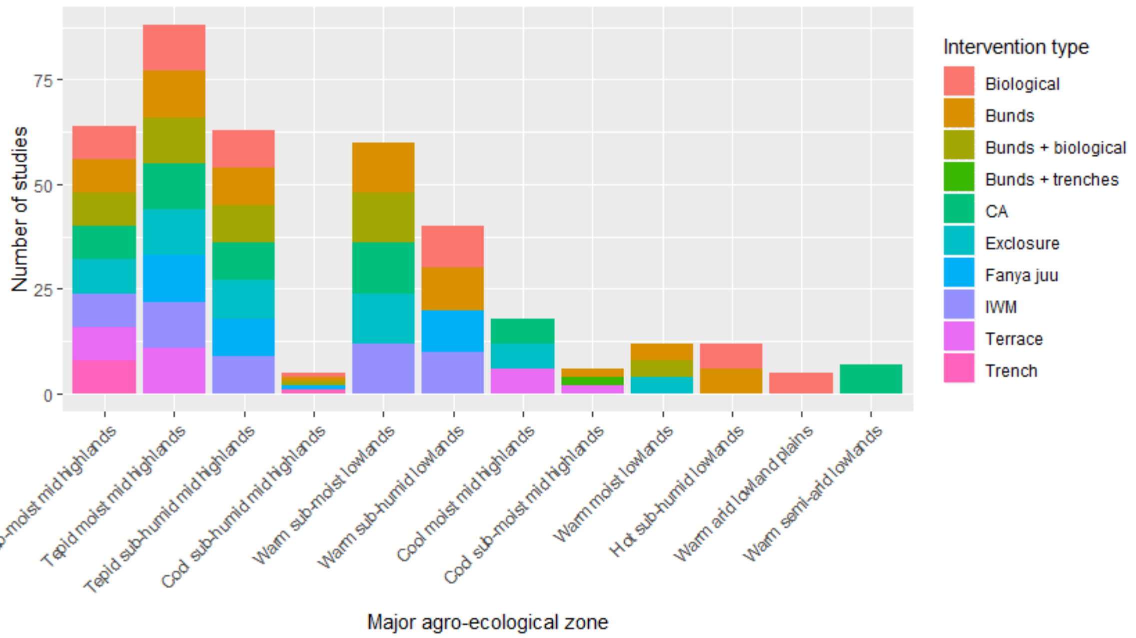

Figure 8. Number of published case studies on the impacts of landscape restoration interventions on ecosystem services by agro-ecological zones in Ethiopia

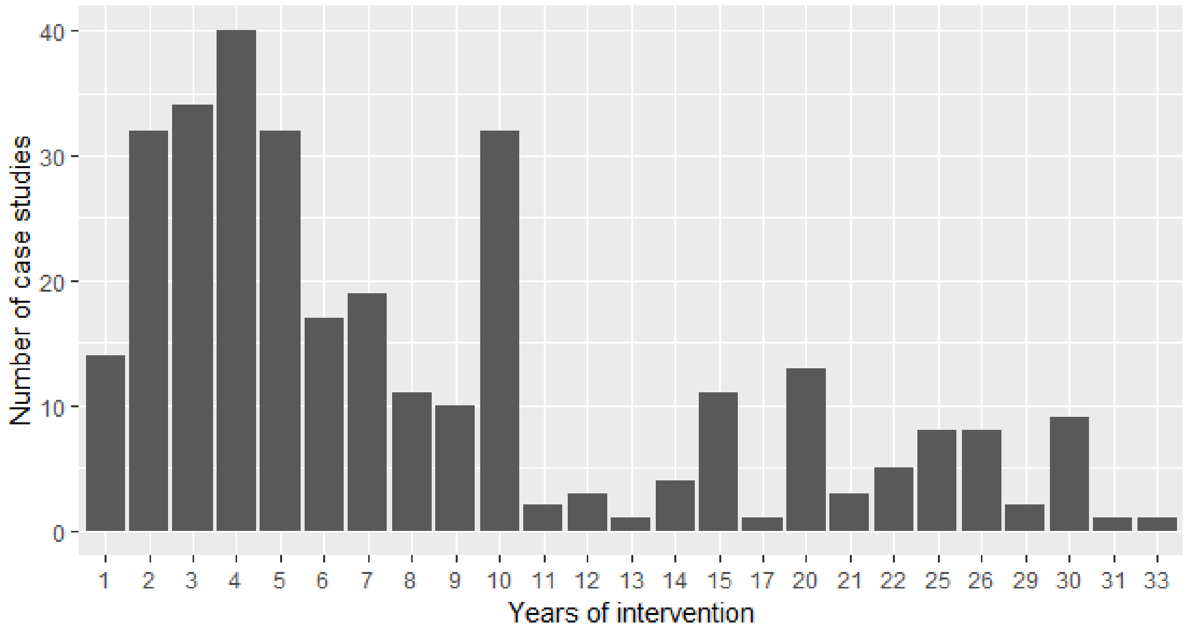

Figure 9. Number of studies published for land restoration interventions with different length of period after implementation in Ethiopia

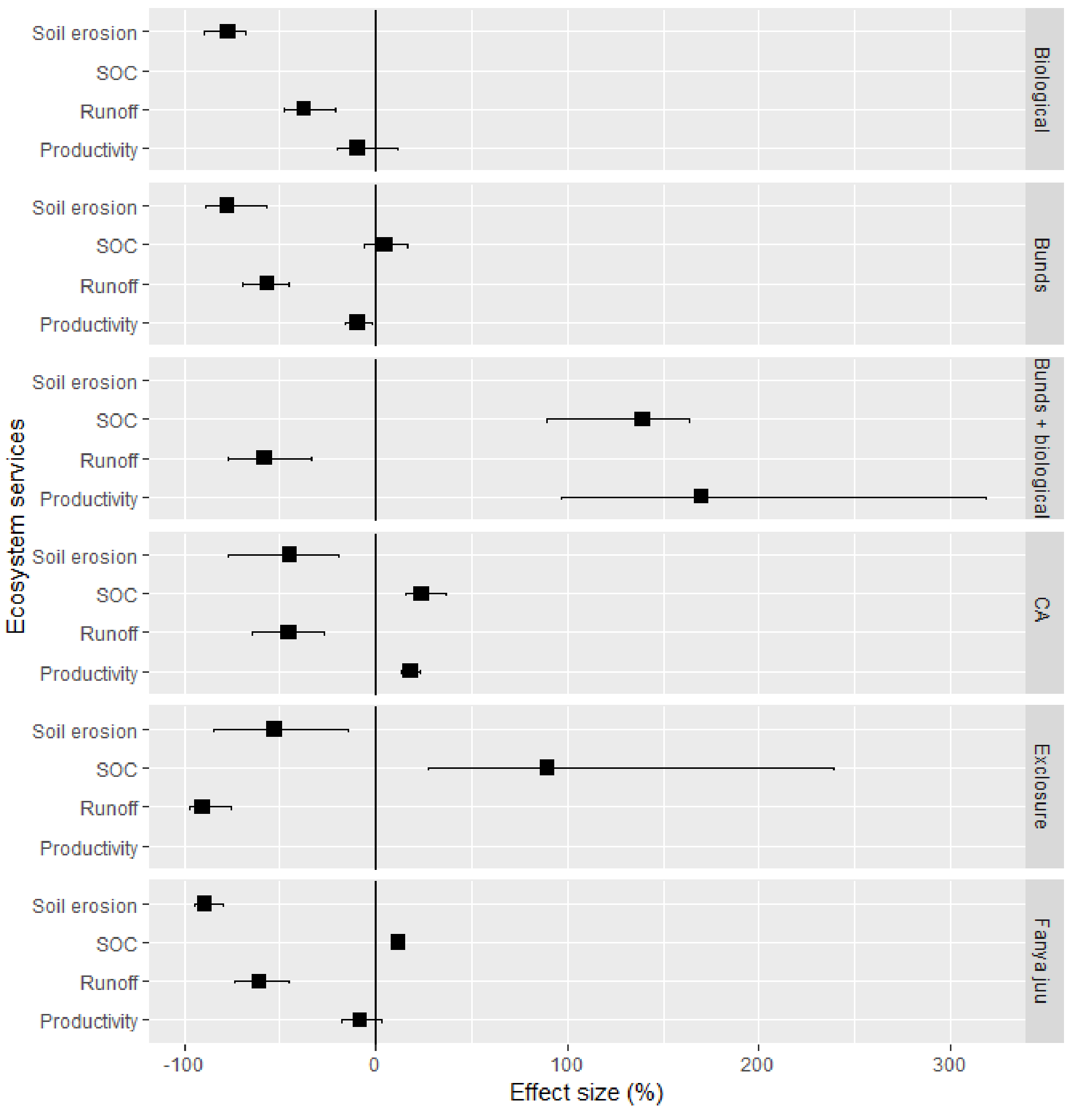

Figure 10. Effect size of SOC, crop productivity, runoff and soil erosion for six land restoration intervention practices implemented in Ethiopia (biological, bunds, bunds + biological, Conservation Agriculture (CA), exclosure, and Fanya juu). Error bars represent 95% confidence interval (CI). The vertical line is drawn at mean effect size of zero. The effect of land restoration intervention was considered significant if the 95% CI of the effect size did not include zero

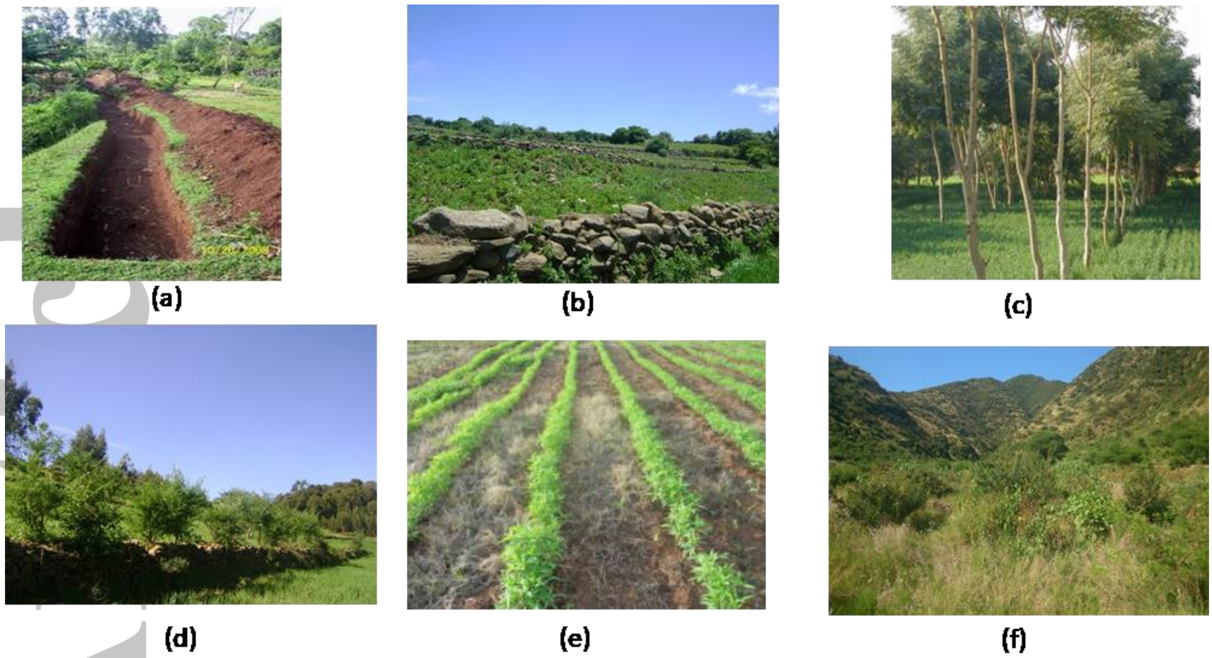

Figure 11. Example of technologies implemented as part of the restoration efforts and for which analysi

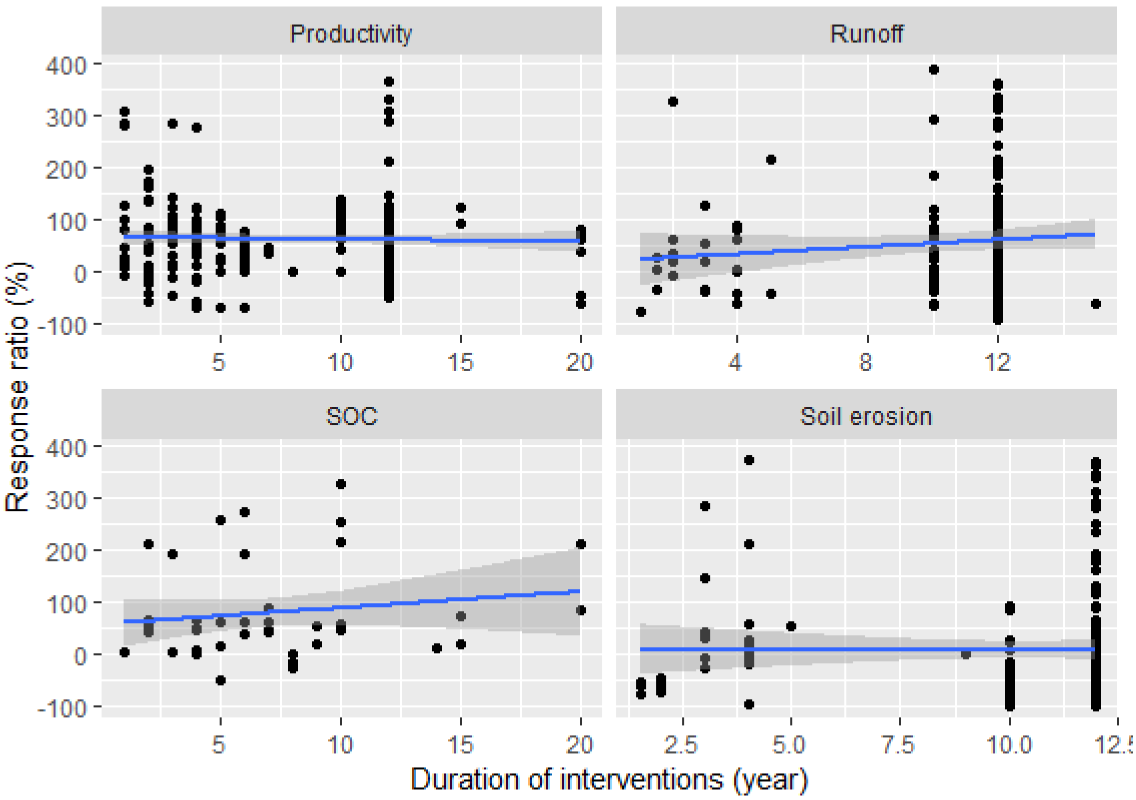

Figure 12. The relationship between response ratio (%) and age of land restoration interventions in Ethiopia

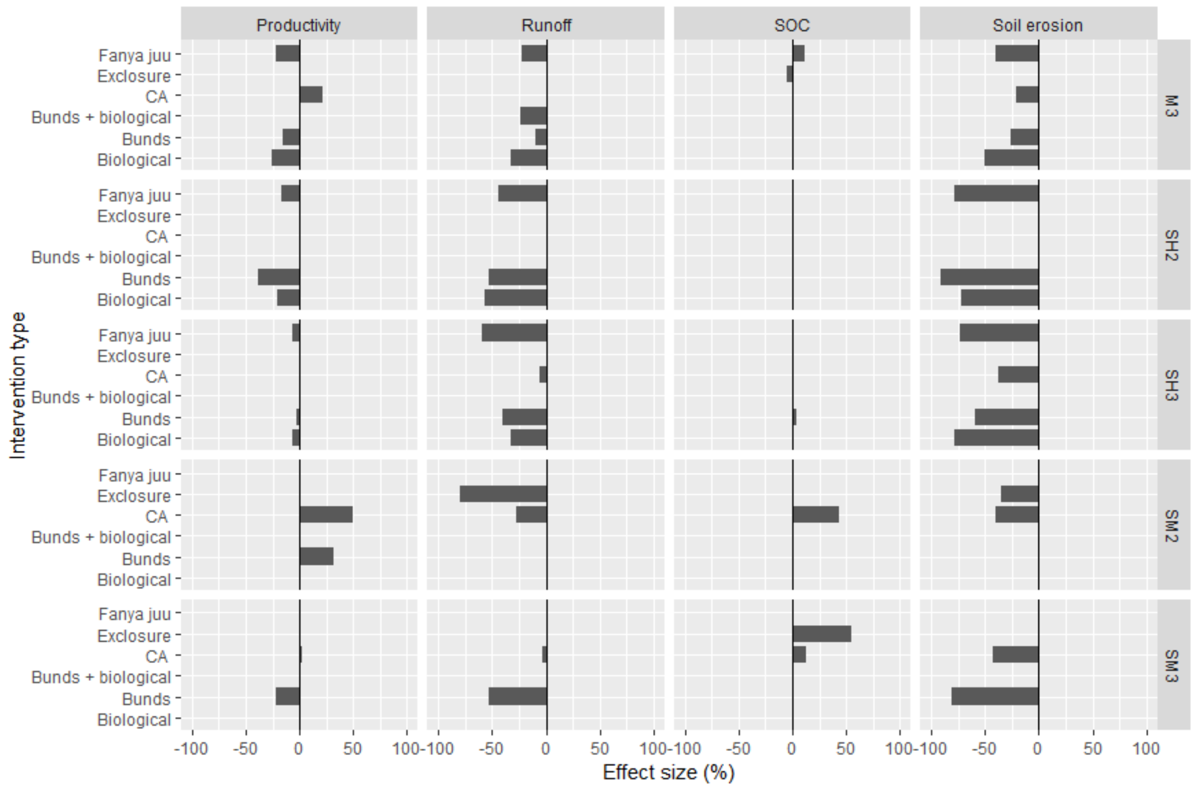

Figure 13. Effect size of SOC, crop productivity, runoff and soil erosion for six land restoration intervention practices implemented in Ethiopia (biological, bunds, bunds + biological, Conservation Agriculture (CA), exclosure, and Fanya juu) by agroecological zone (SM2: Warm sub-moist lowlands; SM3: Tepid sub-moist mid highlands; M3: Tepid moist mid highlands; SH3: Tepid sub-humid mid highlands; SH2: Warm subhumid lowlands)