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Effects of soil conservation techniques on water erosion control: A global analysis

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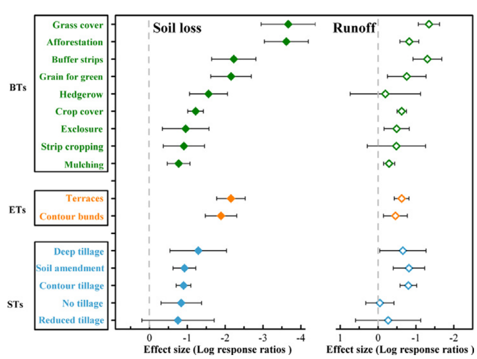
HIGHLIGHTS

- We quantified the efficiency of soil conservation techniques (SCTs).
- The SCTs were more effective at reducing soil loss than reducing runoff.
- Biological techniques were more effective than other techniques.
- The efficiency of SCTs was closely related to terrain slope.
- The SCTs on cultivated lands in temperate CZ were more efficient.

GRAPHICAL ABSTRACT



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ABSTRACT

Water erosion control is one of the most important ecosystem services provided by soil conservation techniques (SCTs), which are being widely used to alter soil and water processes and improve ecosystem services. But few studies have focused on providing this service using various techniques across the world. Here, a comprehensive review was conducted to compare the effects of SCTs on water erosion control. We conducted a meta-analysis consisting of 1589 sample plots in 22 countries to identify SCTs, which we classified into three groups: biological techniques (BTs, such as afforestation and grain for green), soil management techniques (STs, such as no tillage and soil amendment), and engineering techniques (ETs, such as terraces and contour bunds). Our results were as follows: (1) The SCTs had significant positive effects on water erosion control, and they were generally more effective at reducing annual soil loss (84%) than at reducing annual runoff (53%). (2) The BTs (e.g., 88% for soil and 55% for runoff) were generally more effective at reducing soil and water loss than ETs (e.g., 86% for soil and 44% for runoff) and STs (e.g., 59% for soil and 48% for runoff). (3) On bare lands, the efficiency of water erosion control decreased as the terrain slope increased, but this value increased as the slope increased on croplands and orchards. Furthermore, the effects of SCTs on runoff and soil loss reduction were most efficient on 25°–40° slopes in croplands and on 20°–25° slopes in orchards. (4) The SCTs were more efficient on croplands and orchards in temperate climate zone (CZ), while those on bare lands were more effective in tropical CZ. (5) The SCTs in Brazil and Tanzania were more effective at reducing runoff and soil loss than those in the USA, China and Europe.

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1. Introduction

Soil erosion by water is the most widespread form of soil degradation worldwide (Garcia-Ruiz et al., 2017; Maetens et al., 2012a), and it is considered one of the major threats to soil ecosystem services (Borrelli et al., 2017; Li and Fang, 2016; Prosdocimi et al., 2016a), especially in the semi-arid and semi-humid areas of the world (Borrelli et al., 2017), such as the Mediterranean (Cerdan et al., 2010), central Asia (Sadeghi et al., 2015), the USA (Morgan, 2005), and China (Guo et al., 2015). Although soil erosion cannot be totally prevented, it can be reduced to a maximum acceptable level, or soil loss tolerance can be developed (Montgomery, 2007; Morgan, 2005). Many soil conservation techniques (SCTs) have been widely used around the world to alter soil and water processes.

SCTs perform multiple functions that improve environmental quality, including provision of the following ecological services: (1) reducing runoff and conserving soil (Buendia et al., 2016; Jiang et al., 2016; Jiang and Zhang, 2016; Maetens et al., 2012a; Peng et al., 2017a; Peng et al., 2017b; Wang et al., 2017), (2) improving soil fertility and land productivity (Kagabo et al., 2013), (3) increasing crop yield and ensuring food security (Borrelli et al., 2017), (4) enhance biodiversity (Buscardo et al., 2008), (5) filtering water (Ausseil and Dymond, 2010; Layman et al., 2014) and (6) creating esthetic landscapes (Wei et al., 2016; UNESCO, 2008). As one of the most important ecosystem services provided by SCTs, water erosion control has been well studied, and recent research has focused on the efficiencies of some SCTs, such as afforestation (Buendia et al., 2016), terraces (Chen et al., 2017; Kagabo et al., 2013; Wei et al., 2016; Wickama et al., 2014), mulching (Fernández and Vega, 2014; Liu et al., 2012; Prats et al., 2016; Prosdocimi et al., 2016a; Prosdocimi et al., 2016b), and soil management techniques (Carpenter-Boggs et al., 2016; Keesstra et al., 2016) on water erosion control.

The benefits of SCTs vary according to correlations between the natural environment and anthropogenic activities, and their effects on water erosion control at the plot scale have been extensively tested in field runoff plots. However, only a few previous studies have focused on quantifying the effects of various SCTs at the regional scale (Maetens et al., 2012a), and only one type of SCT has been studied at the national (Chen et al., 2017), regional (Prosdocimi et al., 2016a) and global scales (Prosdocimi et al., 2016b; Wei et al., 2016). Therefore, a comprehensive overview and quantification of various SCTs at the global scale is lacking.

A global overview of the effects of various SCTs on water erosion control can provide evidence-based means for implementing more sustainable soil management practices. In addition, the results can provide information for the cover management (C-factor) and support practices (P-factor) parameters of the Universal Soil Loss Equation (USLE) (Maetens et al., 2012a; Renard, 1997) to assess soil loss risk on a large scale. Therefore, an extensive literature review is needed to compile the results of earlier studies and analyze the effects of various SCTs on water erosion control at the global scale.

The objectives of this paper are (i) to develop a documented global database of field plot data on the use of SCTs; (ii) to quantify the effects of different SCT types on water erosion control at the global scale; and (iii) to compare the effects of SCTs on water erosion control for different slopes, land uses, continents and climate zones (CZs).

2. Materials and methods

2.1. Data collection

A database of runoff, soil loss and runoff plot measurements acquired from areas where SCTs were applied was mainly compiled from scientific journal articles, books and Ph.D. dissertations. We reviewed the ISI Web of Science, China National Knowledge Infrastructure, and Google Scholar databases to identify articles matching the keywords, soil loss and sediment yield, and we selected the sources based on the following criteria: (1) the article contained at least one runoff or soil loss response variable; (2) each data point was collected during at least a full year, or the reported data could be extrapolated to represent a full year with a sufficient degree of reliability; (3) the same response variables were compared between lands treated with SCTs (hereafter called treated) and those not treated with SCTs (hereafter called control); (4) the treated lands and control lands were exposed to the same environmental conditions; (5) the number of replications was reported; and (6) the groups of categories contained more than two data pairs. Only runoff and soil loss measurements from bound runoff plots equipped with tanks for collecting runoff and soil loss were used to reduce the influence of measurement uncertainties, and only plots with a minimum length of 5 m were retained because they were considered to be representative (Maetens et al., 2012a). For each data point, the corresponding number of plot-years was determined; one plot-year corresponded to a measurement period of one year on a single runoff plot.

The final database was comprised of 1589 sample plots (corresponding to 7157 plot-years) for annual soil loss and 1098 sample plots (corresponding to 4936 plot-years) for annual runoff from 121 studies conducted in 22 countries (Fig. 1). The earliest record in this database is from 1931 (U.S. Department of Agriculture), and the number of plot-years has increased significantly since 1980. Furthermore, the data acquisition trend has decreased since 2005, possibly because some ongoing research has not yet been reported (Fig. 2). For each grouping category, the originally documented information included the annual runoff, annual soil loss and number of replicates of both the treated lands and control lands, and the plot length, plot gradient, annual precipitation and measurement period were also included if available. SCTs were classified into three groups according to Morgan (2005) and Maetens et al. (2012a) (Supplementary Tables 1 and 2): biological techniques (BTs), which utilize the protective effects of plant covers to reduce erosion, thus conserving soil and water; soil management techniques (STs), which are used to maintain the fertility and structure of the soil, as highly fertile soils result in high crop yields, good plant cover and, therefore, conditions that minimize the erosive effects of raindrops and runoff; and engineering techniques (ETs), which control the movement of water over the soil surface (Morgan, 2005).

2.2. Data analysis

We conducted a meta-analysis, an approach that has been increasingly used in ecological studies (Gurevitch et al., 2018), to quantitatively analyze and synthesize the results of compiled studies. We calculated log response ratio (*LRR*, hereafter termed response ratios, Eq. 1) to measure the effect size (Benitez-Lopez et al., 2017; Hooper et al., 2012) using a categorical random effects model as follows:

$$\mathrm{LRR} = \ln\left(\overline{X}_t/\overline{X}_c\right) \quad (1)$$

where $\overline{X}_t$ and $\overline{X}_c$ denote the mean annual runoff or soil loss of treated lands and control lands, respectively.

In all meta-analyses and meta-regressions, the observed effect sizes (LRRs) were weighed by the inverse of the sampling variances, which were calculated as follows:

$$\sigma^2(LRR) = \frac{{SD_t}^2}{N_t{\overline{X}_t}^2} + \frac{{SD_c}^2}{N_c{\overline{X}_c}^2} \quad (2)$$

where *LRR* represents the log response ratio, SD_t and SD_c represent the standard deviations of $\overline{X}_t$ and $\overline{X}_c$, respectively, and N_t and N_c represent the number of treated and control land replicates, respectively. Not all studies reported estimates of the standard deviation (SD), variances or

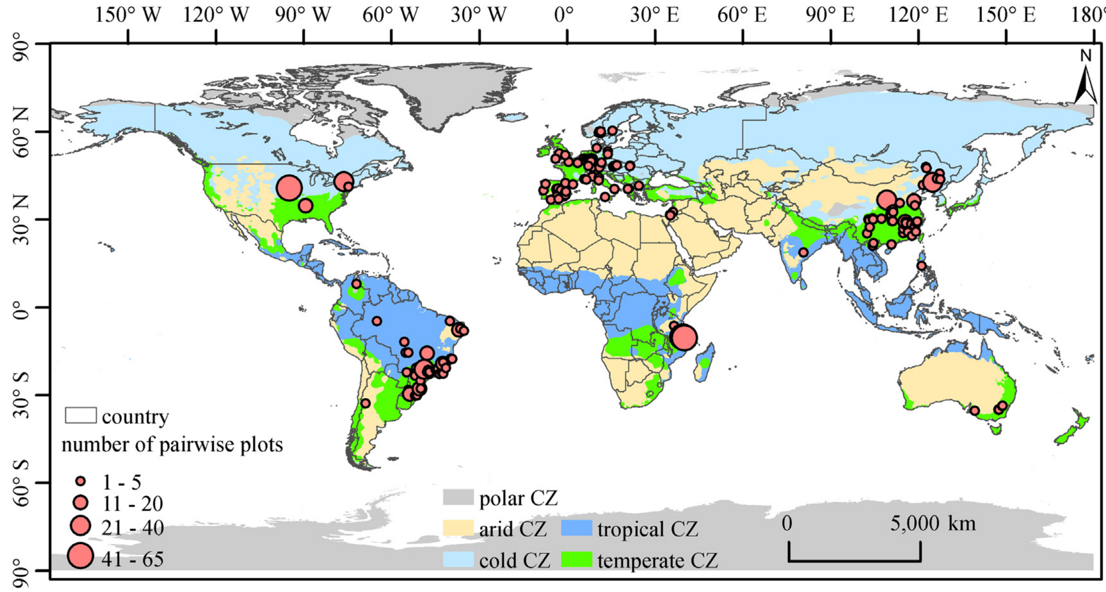

Fig. 1. Worldwide distribution of the soil conservation techniques.

standard error (SE); in such cases, SD_t and SD_c could be estimated by assuming that the data followed a Poisson distribution.

To further analyze the efficiencies of SCTs among different subgroup categories, the heterogeneity of effect sizes was assessed with p-values that describe the variations in effect sizes that can be attributed to differences among the categories of each predictor variable. The overall effect sizes and 95% confidential intervals (CIs) were computed and compared using the program Metafor 2.0. A negative effect size ($LRR < 0$) indicated a decline in runoff or soil loss as a result of SCT application, and effect sizes close to zero ($LRR \approx 0$) indicated little or no effect of the SCTs. When the CI crossed the invalid line (including 0), the efficiency was deemed not significant. The results are reported as LRRs and as the percentage decline in abundance by back-transforming the LRR values to unlogged ratios and multiplying by 100 (percentage decline $= (1 - \exp(LRR)) \times 100$ (Benitez-Lopez et al., 2017).

3. Results

3.1. Effects of SCTs on water erosion

The overall effects of SCTs on runoff and soil loss were negative and highly heterogeneous (runoff: $LRR = -0.75$, $p < 0.001$; soil loss: $LRR = -1.86$, $p < 0.001$) (Fig. 3). Soil loss and runoff were reduced by 84% (95% CI: 82, 86%) and 53% (95% CI: 48, 57%), respectively. SCTs had a larger effect on soil loss than on runoff. We classified SCTs into three groups (Supplementary Table 1), and across the database, more than half of the analyzed cases consisted of BTs (e.g., 70% for runoff and 67% for soil loss) with only a few consisting of STs (e.g.,16% for runoff and 20% for soil loss) and ETs (e.g., 10% for runoff and 9% for soil loss). Each of the three groups exerted significant effects on runoff and soil loss reduction, and all three of the corresponding tests for overall effect size were significant ($p \le 0.001$). Both soil loss and runoff reduction were greater in response to BTs (Fig. 3). The effects of BTs and ETs were 88% (CI: 85, 90%) and 86% (CI: 82, 90%), respectively, which were larger than the 59% (CI: 53, 65%) of STs in relation to soil conservation, and the efficiency of BTs (55%, CI: 49, 60%) was greater than those of ETs (44%, CI: 34, 52%) and STs (48%, CI: 38, 57%) in relation to runoff reduction. These differences demonstrate that BTs are both the most popular techniques globally and some of the most effective SCTs at reducing runoff and soil loss (Fig. 3). This high heterogeneity of overall SCT effect size was related to the SCT type.

Regarding BTs, each SCT had a significant effect on soil loss reduction, of which grass cover, afforestation, buffer strips and grain for green were generally more effective at reducing soil loss than the other SCTs, and runoff reduction was greater in response to buffer strips and grass cover (Fig. 4). With respect to STs, deep tillage and no tillage

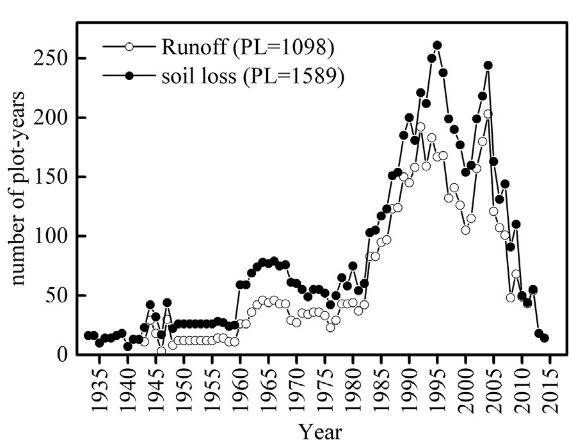

Fig. 2. Distribution of the number of plot-years over time (PL: number of plots).

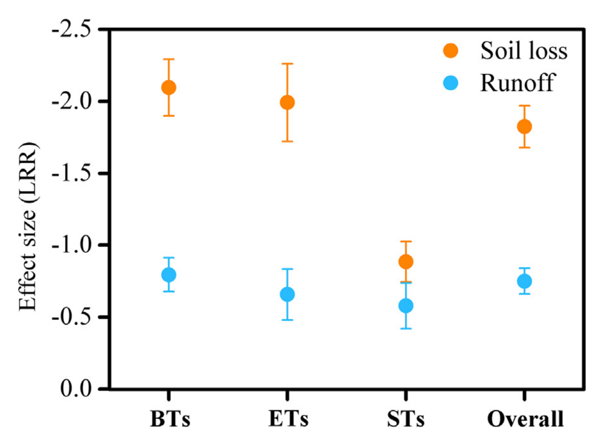

Fig. 3. Reductions in soil loss and runoff resulting from BTs, ETs and STs. LRR, log response ratio (effect size), are represented as dots with 95% confidence intervals (CIs) as error bars. Overall weighted mean effect sizes were estimated for BTs, ETs, STs and SCTs.

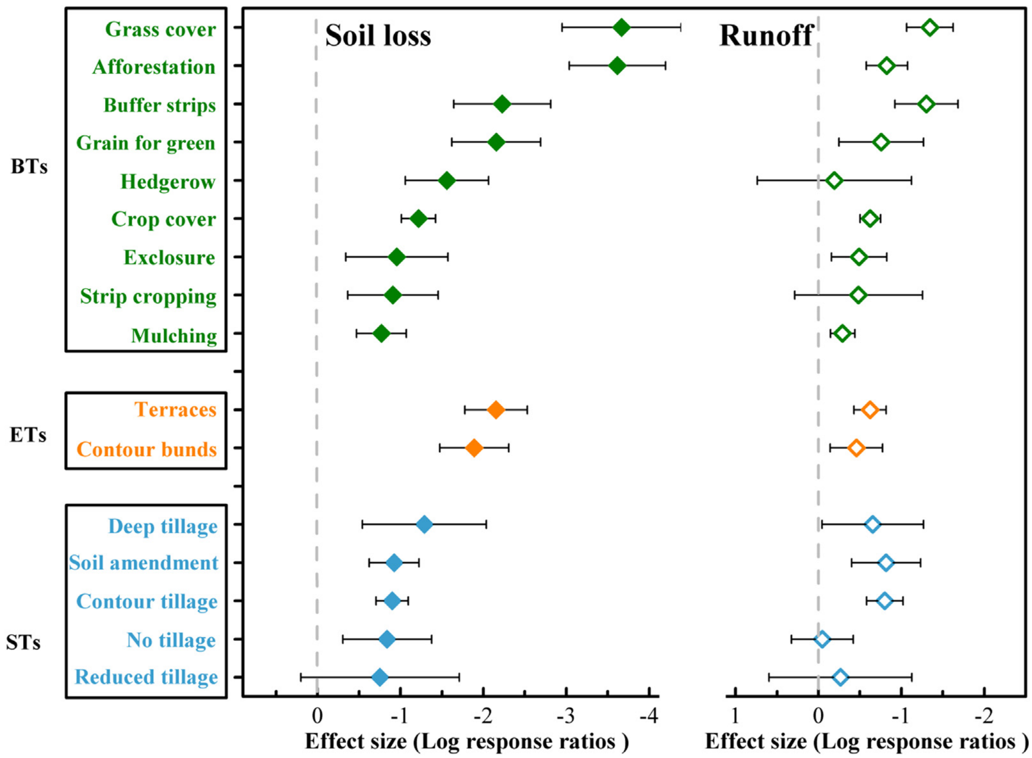

Fig. 4. Reductions in soil loss and runoff resulting from different SCTs. LRR, log response ratio (effect size), are represented as dots with 95% confidence intervals (CIs) as error bars. The effect is significant if the 95% confidence interval does not include zero. LRR = 0, dashed black line.

appeared more effective at reducing soil loss than soil amendment and contour tillage but less effective at reducing runoff (Fig. 4). Hedgerows, strip cropping, no tillage and reduced tillage were not recognized as powerful tools for reducing runoff because their 95% CIs were approximately 0. For some sample plots to which hedgerows, strip cropping, no tillage or reduced tillage were applied, a reduction in soil loss but an increase in runoff was observed, and this difference was probably attributed to increased soil sealing, which reduced soil loss but limits infiltration and increases runoff (Maetens et al., 2012a, 2012b). The overall effect of each SCT on soil loss reduction was highly heterogeneous ($p \leq 0.001$), except for that of reduced tillage ($p = 0.122$). In terms of runoff reduction, each SCT was highly heterogeneous ($p \leq 0.001$), except for hedgerows ($p = 0.687$), strip cropping ($p = 0.22$), reduced tillage ($p = 0.546$), no tillage ($p = 0.805$) and deep tillage ($p = 0.035$).

3.2. Variations in the effects of SCTs on water erosion with different slopes

In the database, SCTs were applied to five land-use types: cropland, bare land, forest land, shrubland and orchard. A large proportion of the case studies were associated with croplands (46.3% for soil loss and 32.6% for runoff), followed by bare land (42.5% for soil loss and 47.1% for runoff) and orchard (8.2% for soil loss and 12.2% for runoff), and only a few of the analyzed cases focused on forest and shrub land (3.0% for soil loss and 8.1% for runoff). The SCTs were considered effective for water erosion control when the effect size was less than zero.

We analyzed the effects of SCTs on bare lands, croplands and orchards (Fig. 5) due to the few studies on forest and shrub land, which implies that our results are less generalizable for these land uses. SCTs applied to orchards were the most efficient at reducing soil loss and runoff (soil loss: LRR = −2.95, runoff: LRR = −1.14) followed by those applied to bare lands (soil loss: LRR = −2.03, runoff: LRR = −0.78) and croplands (soil loss: LRR = −1.37, runoff: LRR = −0.58), indicating that applying SCTs to orchards, croplands and bare lands significantly reduced soil loss and runoff (Fig. 5). Effect sizes varied with slopes in different land uses (Fig. 5). Slope angles were classified into seven groups based on the dataset and the standards for soil erosion classification (Chen et al., 2017): (1) 0–3°, (2) 3–5°, (3) 5–10°, (4) 10–15°, (5) 15–20°, (6) 20–25°, and (7) >25°. In general, the SCTs reduced both runoff and soil loss as the slope angle varied.

For bare land, the effect sizes of SCTs on soil loss and runoff increased as the angle of the slope increased, demonstrating that the efficiency of water erosion control decreased as the slope increased, and the effects on runoff were weaker than those on soil loss (Fig. 5). However, the efficiency of SCTs on soil conservation generally increased as the slope gradient increased on croplands and orchards, but this trend was not observed in runoff reduction (Fig. 5). This may indicate that the effects of SCTs on runoff may be influenced more by other environmental characteristics than the terrain slope. The two greatest reductions in soil loss were noted for SCTs encompassing two slope categories (5–10° and >25°) on croplands, and these two slope categories also produced the greatest reductions in runoff. The slopes of the investigated orchards were between 5°–15° and 20°–25°, and the SCT-induced reductions in soil loss increased as the angle of the slope increased. For any slope in the database, the 95% CIs indicated that SCTs positively reduced soil loss on bare lands, croplands and orchards. However, the below-zero 95% CIs for 10°–25° group for croplands showed that the effects on runoff were not significant.

3.3. Variations in the effects of SCTs on water erosion in different climate zones

The division of all data into 17 different CZs, some of which were associated with minimal data, according to the updated world Köppen-Geiger climate classification (Peel et al., 2007) was found to be too detailed, so we combined the CZs into four groups (Fig. 1): tropical, arid, temperate and cold. A large proportion of the analyzed cases were associated with the temperate CZ (38.7% for soil loss and 58.3% for runoff), followed by cold (31.7% for soil loss and 21.1% for runoff) and tropical

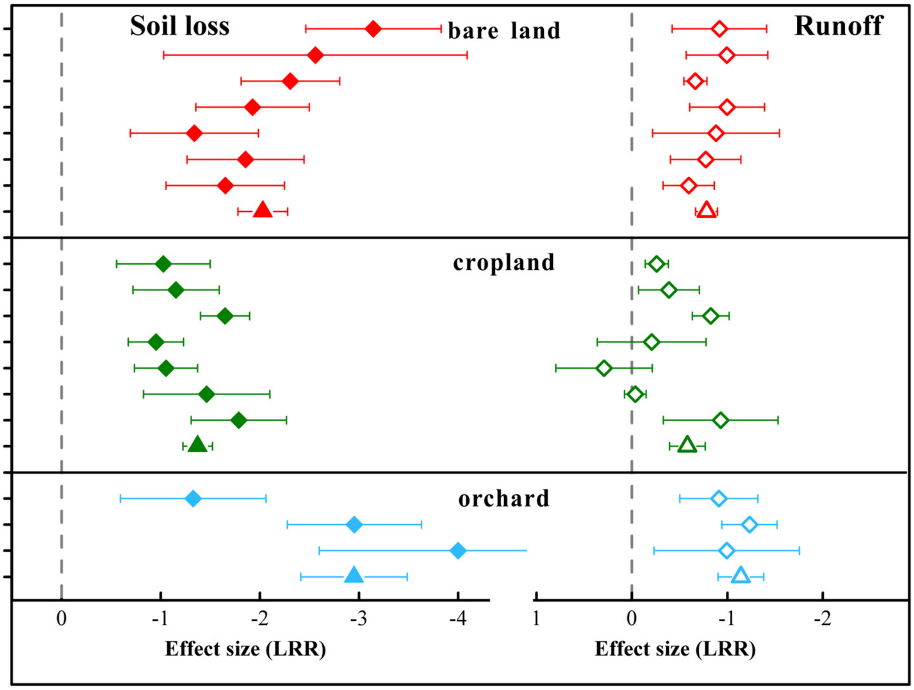

Fig. 5. Reductions in runoff and soil loss resulting from SCTs used on land with various slopes under different land uses. LRR, log response ratio (effect size), represented as diamonds with 95% confidence intervals (CIs) as error bars. Overall estimated weighted mean effect sizes of bare land, cropland and orchard, triangles with CIs as error bars. LRR = 0, dashed black line.

(21.8% for soil loss and 9.43% for runoff) CZs. Only a few of the analyzed cases focused on the arid CZ (7.62% for soil loss and 11.1% for runoff).

In general, SCTs had a larger effect on soil loss than on runoff for each category (Fig. 6). The benefits pertaining to soil loss and runoff reduction were approximately equivalent for all categories, but the benefit was not significant for SCTs on croplands in the arid CZ. For croplands, the SCTs had larger effects on soil loss in the temperate (e.g., 83.7% for soil loss reduction and 43.9% for runoff reduction) and tropical (e.g., 75% for soil loss reduction and 49% for runoff reduction) CZs than in the cold CZ (e.g., 64.5% for soil loss reduction and 50.1% for runoff reduction); but the latter had a larger effect on runoff. Soil loss in the arid CZ was not significantly different from that in the control but was numerically slightly smaller with SCTs. For bare lands, SCTs had significant effects on soil conservation across the CZs; the greatest reduction in soil loss was noted for SCTs encompassing the tropical CZ (e.g., 96.7% for soil loss reduction), and the effect sizes were similar for runoff across CZs. The investigated orchards were in the temperate CZ, in which SCTs had significant effects on soil loss and runoff decline (e.g., 95% for soil loss reduction and 68% for runoff reduction).

3.4. Variations in the effects of SCTs on water erosion in different continents

In the database, SCTs were applied in 22 countries, and based on the variation in geographical locations, the database was divided into five subgroups: North America, South America, Asia, Europe and Africa. While the data were widely distributed in Europe, most originated from the USA (North America), Brazil (South America), China (Asia), and Tanzania (Africa), and the effect sizes differed across continents (nations) for both soil loss and runoff (Fig. 7). The SCTs applied in Brazil (e.g., 95% for soil loss reduction and 60.7% for runoff reduction) and Tanzania (e.g., 89.8% for soil loss reduction and 67.1% for runoff reduction) were more effective at reducing soil loss and runoff than that those in the USA (e.g., 82.3% for soil loss reduction and 53.3% for runoff reduction), China (e.g., 78.3% for soil loss reduction and 53.4% for runoff

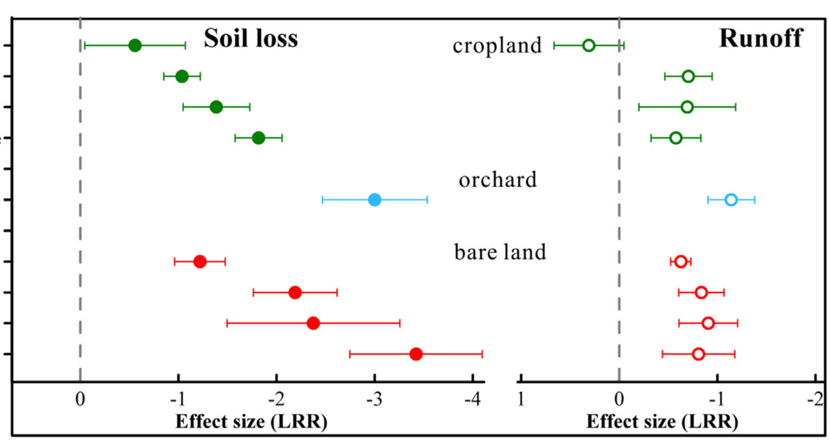

Fig. 6. Reduction in runoff and soil loss resulting from ECTs with different land uses and climate zones. LRR, log response ratios (effect size), points with 95% confidence intervals as error bars. LRR = 0, dashed black line.

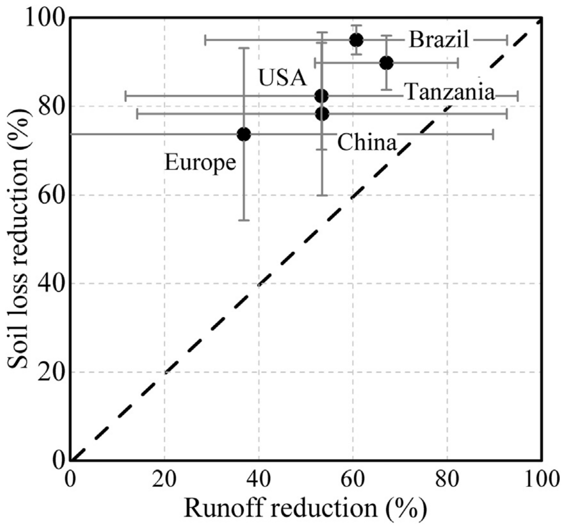

Fig. 7. Relation between runoff reduction and soil loss reduction for SCTs in different continents. The SCTs plotted along the 1:1 line indicate that soil loss reduction is stronger than runoff reduction.

reduction) and Europe (e.g., 73.7% for soil loss reduction and 36.9% for runoff reduction). The SCTs used in Brazil were generally more effective at reducing soil loss than the SCTs used in Tanzania, but the latter were slightly more effective at reducing runoff.

Regarding the types of SCTs, afforestation, grass cover, grain for green, crop cover, buffer strips and mulching were widely used BTs; terraces and contour bunds were popular ETs; and contour tillage and soil amendment were applied across different continents or nations. However, the effect sizes of these SCTs were different in different continents (nations) (Fig. 8). Afforestation and grass cover were the most efficient at reducing soil loss across continents (nations), but afforestation was less effective in China, where mulching was more effective than in other continents (nations).

4. Discussion

4.1. Effects of land use and the original grounds slope

Based on this study, the efficiency of water erosion control generally decreased as the original ground slope increased on bare lands. BTs (afforestation, crop cover and grass cover were the main SCTs) accounted for 95%, and they contributed to revegetation, in which the vegetation

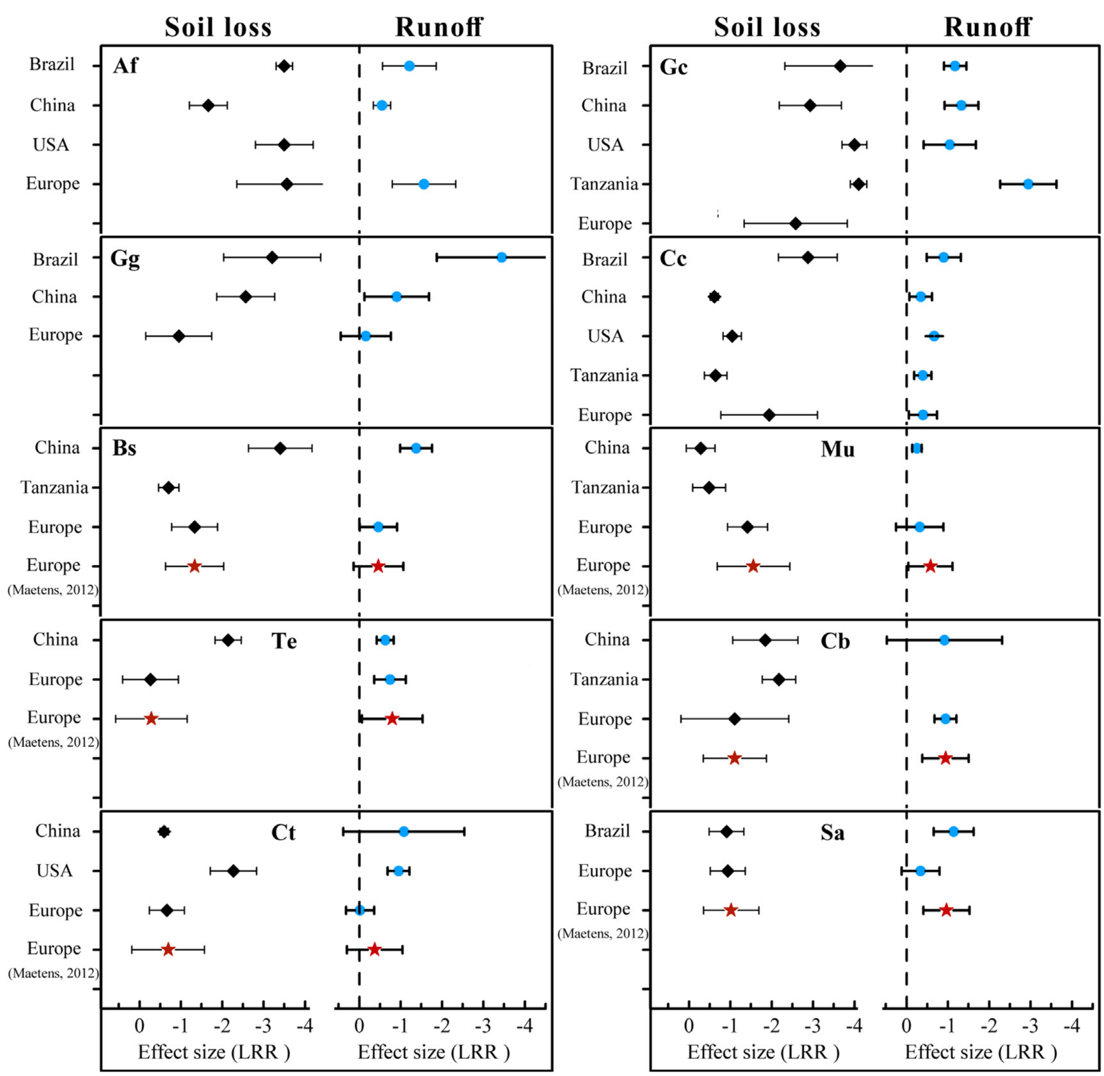

Fig. 8. Reduction in runoff and soil loss resulting from ECTs in different continents (nations). LRR, log response ratios (effect size), black diamonds with 95% confidence intervals (CIs) as error bars for soil loss, blue dots with 95% CIs as error bars for runoff. Red stars with CIs as error bars were results from Maetens et al. (2012a). LRR = 0, dashed black line. Af: afforestation, Gc: grass cover, Gg: grain for green, Cc: crop cover, Bs: buffer strips, Mu: mulching, Te: terraces, Cb: contour bunds, Ct: contour tillage, Sa: soil amendment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

planted on bare lands included trees, crops and grasses and resulted in changes in vegetation cover (Morgan, 2005). Increased vegetation cover can result in significantly decreased soil loss and runoff (Maetens et al., 2012b). However, since runoff velocity increases with increased slope angle (Chen et al., 2017; Jiang et al., 2014), the larger potential velocity of runoff on deep slopes may mask the effects of BTs in reducing runoff and soil loss (Chen et al., 2017).

For croplands, STs and BTs were the main SCTs used on cropland; based on the literature, the STs like contour tillage were mainly applied to croplands with gentler slopes while BTs were generally applied to lands with steeper slopes. BTs were generally more effective than STs at reducing soil loss and runoff, which may explain why the effects of SCTs on soil loss reduction were generally larger on steeper slopes. For orchards, the benefits of SCTs in term of soil loss reduction increased as the slope increased, and buffer strips (38%) and terraces (26%) were the main SCTs. Previous studies found that the benefits of runoff and soil loss control increased as the topographic gradient increased (Chen et al., 2017; Xu et al., 2011). Buffer strips can increase the vegetation cover of orchards resulting in significantly reduced soil loss and runoff (Prosdocimi et al., 2016a; Prosdocimi et al., 2016b). The overall effectiveness of terraces and buffer strips was larger in steeper orchards.

4.2. Effects of land use and climate zones

The high rainfall erosivity in tropical and temperate CZs (Panagos et al., 2017) greatly contributes to soil loss and runoff, and the combination of snowmelt and frozen soil in spring and the generally lower evapotranspiration rate at high latitudes may result in high soil loss and runoff in cold zone (Maetens et al., 2012b); soil loss and runoff are much lower in the arid CZ. Only a few of the analyzed cases located in the arid CZ, and applying SCTs in plots where the runoff and soil loss rates are low can produce uncertainty over the degree of effectiveness (Maetens et al., 2012a). Therefore, the effectiveness of SCTs in tropical, temperate and cold CZs were more generalizable.

Rich rainfall and high temperatures in tropical and temperate CZs are beneficial to vegetation growth (Seddon et al., 2016; Zhang et al., 2017). For bare land, the greater effectiveness of SCTs in tropical and temperate zones may be attributed to the rapid growth of vegetation on lands with BTs. Even though the annual rainfall is much higher in tropical zone, the canopies could intercept precipitation and decrease rainfall velocity, thus reducing rainfall erosivity (Wang et al., 2017). BTs were the main SCTs on bare lands and their effectiveness was greatest in the tropical zone, which may be because the effects of BTs on vegetation cover were much stronger than other factors, such as precipitation. However, for cropland, STs and BTs were the main SCTs, and their effectiveness was greatest in the temperate zone, which may be attributed to that the effectiveness of STs was more sensitive to the negative effects of the larger potential runoff velocity in the tropical zone (Chen et al., 2017).

4.3. Effects of SCTs in different continents

The types of SCTs used in a country depends on factors such as its topography (Wei et al., 2016), economy (Borrelli et al., 2017) and government policies (Wang et al., 2017). The SCTs applied in Brazil and Tanzania were more effective at reducing soil loss and runoff than those in the USA, China and Europe (Fig. 7), possibly because the types and effectiveness of SCTs differed across countries (Fig. 8).

The main SCTs used in Brazil were afforestation, grass cover, grain for green, crop cover and soil amendment, all of which were more effective at reducing soil loss than in the other continents (nations), resulting in the greatest SCT effectiveness in Brazil. The greater effectiveness of BTs may be attributed to the tropical climate (Fig. 1) and the gentler slopes. The effectiveness of SCTs was the lowest in Europe, and the results were similar to those of the study by Maetens et al. (2012a) (Fig. 8), which implies that our findings are generalizable.

The effectiveness of the same type of SCTs varied in different continents (nations) (Fig. 8). Afforestation in China was less effective, potentially because the slopes of the investigated afforestation regions were 20°-30°. Mulching was more effective at reducing soil loss in China than in other continents (nations), potentially because the slopes to which mulching was applied were less steep.

4.4. Limitations and future research directions

Previous studies showed that slope gradient and length (Buscardo et al., 2008; Maetens et al., 2012b), soil characteristics (Carpenter-Boggs et al., 2016; Maetens et al., 2012a) and rainfall intensity (Nearing et al., 2005; Panagos et al., 2017) can strongly affect runoff and soil loss, so they may also affect SCT efficiency (Maetens et al., 2012a); the years of application (Maetens et al., 2012a) can also affect SCT efficiency. In addition, land use and vegetation cover (Gessesse et al., 2015; Prosdocimi et al., 2016a) can affect SCT efficiency. Furthermore, ET structures (Chen et al., 2017) can affect SCT efficiency. Due to a lack of detailed information about some of the abovementioned factors and the types of SCTs in this study (Supplementary Tables 1 and 2), as well as the substantial variation in study conditions, the environmental and experimental factors controlling the variability in the efficiency of each SCT could not be clearly identified in this study.

The effectiveness of some techniques such as no-tillage and terraces changes over time after consecutive years of application (Chen et al., 2017; Maetens et al., 2012a). Longer-term trends and inter-annual variability of SCT effectiveness can contribute to an improvement in the selection of SCTs to control water erosion (Maetens et al., 2012a). However, there were many short-term studies (one year) in this meta-analysis, which may have introduced uncertainties of the effectiveness of SCTs. In addition, the factors resulting in differences between the effectiveness of reducing soil loss and reducing runoff were not clearly identified, but Maetens et al. (2012a) suggested that runoff reduction and infiltration promotion may be a much larger concern than reducing soil loss. In the future, studies should focus more on identifying the factors controlling the efficiency of each SCT and provide details for key factors, such as soil type and properties, vegetation cover and rainfall intensity; the effectiveness of SCTs over longer time periods should be assessed; and the differences between the effectiveness of reducing runoff and reducing soil loss and the influencing factors should be considered.

5. Conclusions

We compared the efficiency of SCTs and analyzed the influencing factors and found that SCTs were generally more effective at reducing soil loss (84%) than at reducing annual runoff (53%). The BTs and ETs were more effective than STs at conserving soil, while the ETs were less efficient than BTs and STs at reducing runoff. The efficiency of water erosion control decreased as the terrain slope increased on croplands. However, the efficiency of water erosion control generally increased as the terrain slope increased on croplands and orchards, and the effectiveness was highest for the slope categories of 25°–40°and 5°–10° on croplands and 20°–25° on orchards. The SCTs were more efficient on croplands and orchards from temperate CZ, while those on bare lands were more effective in tropical CZ. The SCTs were more effective at water erosion control in Brazil and Tanzania than in the USA, China and Europe. This study provides useful methods for quantifying the effectiveness of SCTs on water erosion control. Specifically, the effectiveness of soil loss reduction can provide references for the C-value and P-value in USLE-based modeling at large scales. The results presented here can serve as a scientific basis to enable land managers and decision makers to reduce ecosystem degradation and improve ecosystem services.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.07.124.

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