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Determining RUSLE P- and C-factors for stone bunds and trenches in rangeland and cropland, North Ethiopia

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Abstract

The implementation of soil and water conservation (SWC) measures in the Ethiopian Highlands is a top priority to reduce soil erosion rates. However, the effectiveness of these measures for different hillslope gradients and land use conditions remains poorly understood. This study addresses this knowledge gap by determining support practice (P) and cover-management (C) factors of the Revised Universal Soil Loss Equation for commonly used SWC structures in semi-arid environments. The factor values were calculated on the basis of soil loss data collected with 21 large runoff plots installed in rangeland and cropland sites. The P- and C-factors were calculated following the recommended procedures. Results show P-factors ranging from 0.32 to 0.74 for stone bunds, from 0.07 to 0.65 for trenches, and from 0.03 to 0.22 for stone bunds with trenches. Reduced storage capacities due to sediment deposition resulted in significant declines of the effectiveness of SWC structures over time. For example, the average P-factor value for trenches increased from 0.1 in the first year after installation to 0.51 after 3 years. C-factor values ranged from 0.23 to 0.82 in rangeland and from 0.03 to 0.35 in cropland. For rangeland, this large variability is due to vegetation cover changes caused by grazing. In cropland, C-factors vary with crop types and tillage practices. The results of this study not only aid in modelling and quantifying the short-term impacts of SWC structures on soil erosion rates but also highlight the importance of considering temporal variations of the effectiveness of SWC measures.

KEYWORDS

Ethiopian Highlands, land use, RUSLE, soil and water conservation, soil erosion

1 | INTRODUCTION

The Ethiopian Highlands (>1,500 m asl) are characterized by the highest rates of soil losses in Africa (Vanmaercke, Poesen, Broeckx, & Nyssen, 2014) and even by global standards (Feoli et al., 2002; Haile, Herweg, & Stillhardt, 2006; Zegeye et al., 2010). They are attributed to several factors including not only erosive rainfall and rugged topography (Guzman, Tilahun, Zegeye, & Steenhuis, 2013; Haile et al., 2006; Nyssen et al., 2005) but also poverty and population pressure (Shiferaw & Holden, 1999) and the resulting problems related to overgrazing (Galdino et al., 2016; Mwendera & Saleem, 1997; Nyssen et al., 2009), frequent tillage (Nyssen, Poesen, Haile, Moeyersons, & Deckers, 2000; Tulema, Aune, Johnsen, & Vanlauwe, 2008), deforestation, and subsequent cultivation of steep hillslopes (Haile et al., 2006; Taddese, 2001). These high erosion rates explain the intense land

degradation and constitute a significant threat to sustainable food production in the region (Mwendera & Saleem, 1997; Nyssen et al., 2009; Taye et al., 2013). They are associated with losses of soil nutrients and reductions in crop productivity (Admassu, Mekonnen, Yirga, & Kessler, 2014; Haileslassie, Priess, Veldkamp, Teketay, & Peter, 2005; Haregeweyn et al., 2015) and have important off-site consequences, such as reduced irrigation potential and energy production due to reservoir siltation (Haregeweyn et al., 2015; Vanmaercke et al., 2010), water pollution from sediment-bound agro-chemicals, and reduction of fish production (Moges et al., 2016).

To mitigate these negative impacts, soil and water conservation (SWC) measures (Figure 1) have been implemented at large scale in the Ethiopian Highlands since the 1970s (Desta et al., 2005; Haregeweyn et al., 2015; Herweg & Ludi, 1999; Nyssen et al., 2007; Osman & Sauerborn, 2001; Taddese, 2001). Among the SWC

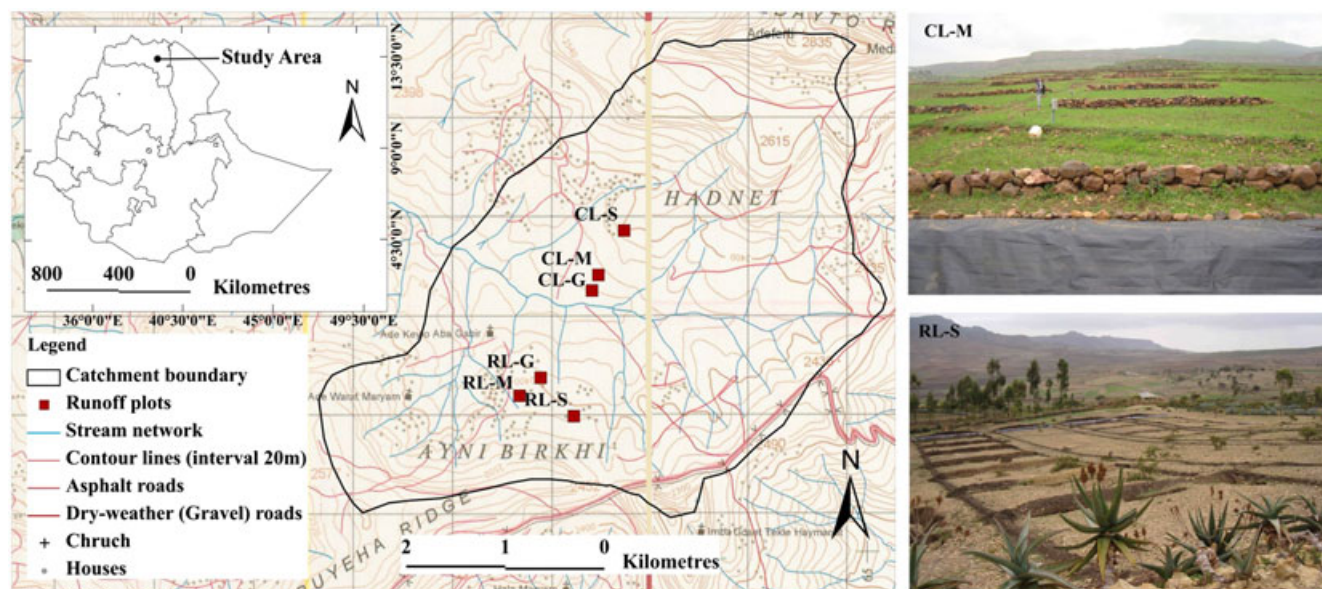


FIGURE 1 Location of the study area in Ethiopia and Mayleba catchment with indication of experimental plot sites in rangeland (RL) and cropland (CL) at different hillslope gradients: G is gentle (5%), M is medium (12%), and S is steep (16%); photos illustrating cropland plots at medium slope (CL-M) site on August 7, 2012, and rangeland plots at steep slope (RL-S) site on July 15, 2010 [Colour figure can be viewed at wileyonlinelibrary.com]

structures, stone bunds are the most extensively installed in both croplands and rangelands (Desta et al., 2005; Nyssen et al., 2007), whereas trenches are mostly installed in both rangelands and exclosures (Nyssen et al., 2008; Taye et al., 2013). Stone bunds with trenches are the most effective SWC measures in reducing runoff and soil loss that are recently introduced in Tigray to increase the effectiveness of stone bunds (Taye et al., 2013).

Various studies have already been conducted to quantify the effectiveness of these measures in terms of soil loss reduction, mostly based on field plot experiments (Desta et al., 2005; Haregeweyn et al., 2015; Nyssen et al., 2007; Taye et al., 2013, 2015). Overall, these studies show a very large variability in erosion reduction, attributable to site characteristics (soil type, rainfall, topography, and land use) and the specificities of the implemented measures (density and dimensions of the implemented measures) and tillage practices (Herweg & Ludi, 1999; Nyssen et al., 2009; Taye et al., 2013). This variability makes it highly difficult to evaluate or predict the effects of SWC measures at regional or at basin scale (de Vente et al., 2013; Haregeweyn et al., 2017). Nonetheless, such evaluations and predictions are much needed (de Vente et al., 2013; Guzman et al., 2017; Haregeweyn et al., 2015; Montgomery, 2007; Munro et al., 2008; Nyssen et al., 2008; Vanmaercke et al., 2014). Hence, there is a need for standardized procedures to estimate the effectiveness of SWC measures over larger areas.

The Revised Universal Soil Loss Equation (RUSLE; Renard, Foster, Weesies, McCool, & Yoder, 1997) is a model that allows for such quantifications. Due to its relative simplicity, low data requirements, potential to be applied in Geographical Information System (GIS) environments, and often well-evaluated predictive power, RUSLE is one of the most commonly applied tools for erosion predictions (de Vente et al., 2013). Especially for data-scarce developing countries, the RUSLE model is commonly used due to its relatively easy applicability (Angima et al., 2003; Karamage et al., 2016; Mati et al., 2000). This

equation includes support practices (P) and cover-management (C) factors that allow to explicitly account for the effect of SWC practices and land use types, respectively (Renard et al., 1997). Both the C- and P-factor values are estimated as soil loss ratio, that is, the ratio of soil loss from a runoff plot with a given cover-management or conservation practice to the corresponding soil loss from a bare runoff plot with the same soil characteristics, slope length, slope steepness, and rainfall conditions (Renard et al., 1997). The cover-management factor (C) incorporates the effects of vegetation cover, crop rotations, the type and timing of tillage operations, and effects of residue cover on rates of soil loss by water erosion (Renard et al., 1997). The conservation practice factor (P) is primarily used to assess the effects of uphill and downhill tillage, contour tillage, and contour strip cropping on soil loss. Likewise, it is used to quantify the effects of other (structural) SWC measures on soil loss, such as terraces and stone bunds (Foster & Highfill, 1983).

Although the simplicity and limited data requirements are clear advantages of the RUSLE, this model has also important limitations and shortcomings. It is a model developed to predict sheet and rill erosion rates at the hillslope scale. As effects of sediment deposition and other erosion processes (e.g., gully and bank erosion and mass movements) are not considered by the model, the RUSLE model cannot be directly used to predict sediment export at the catchment scale (de Vente et al., 2013). As it is a lumped model that predicts average sheet and rill erosion rates at annual timescale, the model is less capable to reproduce detailed spatial and temporal patterns of sheet and rill erosion (Haile et al., 2006; Moges et al., 2016; Zegeye et al., 2010).

Moreover, the RUSLE model is an empirical model that was developed on the basis of standardized soil loss measurements in the United States (Renard et al., 1997). Its application to other regions may therefore induce important uncertainties (de Vente et al., 2013; Maetens, Vanmaercke, Jankauskas, Jankauskiene, & Ionita, 2012; Panagos et al., 2015). This is especially true for the C- and P-factors.

Very few experimentally determined C- and P-factors exist to quantify the effectiveness of SWC measures applied in Ethiopia or even in Africa. As a consequence, researchers are often forced to guess values for these factors without knowing to what extent these values are representative for the implemented measures or the environment. This forms a major bottleneck for soil erosion prediction and understanding impacts of natural resource management in Ethiopia and many other developing countries (Karamage et al., 2016; Mati et al., 2000; Nigussie et al., 2014; Nyssen et al., 2008; Sonneveld, Keyzer, & Albersen, 2001). A further challenge is that, although several studies show that commonly applied SWC measures such as stone bunds and trenches are highly effective (Desta et al., 2005; Nyssen et al., 2007, 2009; Taye et al., 2013), their effectiveness can also strongly decline over time, due to a decline in static storage capacity (SSC; Guzman et al., 2017; Taye et al., 2015). Evaluations of the effectiveness of SWC measures should bring this temporal variability into account. In order to predict the effect of such SWC structures and major land use types at large scale, one needs to have guide values of their erosion-reducing effect such as support practice (P) and cover-management (C) factor values for the common SWC structures and for the major land use types, respectively.

Therefore, the overall objective of this study is to provide reliable support practice (P) and cover-management (C) factor values of the RUSLE for commonly used SWC measures in rangeland and cropland for semi-arid environment. These factors are determined from measured soil erosion rates with runoff plots (Taye et al., 2015). More specifically, the study aims (a) to determine support practice (P) factor values for stone bunds, trenches, and stone bunds with trenches; (b) to determine cover-management (C) factor values for rangeland and cropland; and (c) to evaluate changes of the P- and C-factor values over time in relation to the static sediment storage capacity of these SWC structures.

2 | MATERIALS AND METHODS

2.1 | Study area

The study was conducted at Mayleba catchment (~18 km²) located in the northern Ethiopian Highlands, at ~40 km to the west from Mekelle, the capital of the Tigray region (13°41'N, 39°15'E; Figure 1). The study area is characterized by a cool tropical semi-arid climate. The long-term average annual rainfall (1980 to 2014; measured at Hagere Selam located at ~10 km to the west from Mayleba catchment) is 697 mm. Rainfall is strongly seasonal with ~80% of the annual rainfall concentrated during the main rainy season (June to September; Nyssen et al., 2007). The average monthly air temperature ranges from 12 to 19 °C. The mean annual reference evapotranspiration is estimated at 462 mm and ranges from 276 to 1639 mm year⁻¹ depending on altitude (Gebreyohannes et al., 2013).

Topography is rugged and highly variable over a short distance with average elevation up to 2,500 m asl. The dominant soil types are Leptosol, Vertic Calcisol, Regosol, Cambisol, and Vertisol (Van de Wauw et al., 2008). Dominant land use types are cropland and rangeland, whereas degraded hillslopes are also converted to exclosures to

restore vegetation and soil resources (Munro et al., 2008; Nyssen et al., 2008).

The farming system is characterized as crop- and livestock-based mixed farming. Croplands are tilled by a traditional ard plough (meharesha) pulled by a pair of oxen. Tillage frequency varies from 1 to 4 times in response to available draft power and crop type (Nyssen et al., 2000). Major crop types grown in the catchment are barley (*Hordeum vulgare*), wheat (*Triticum* sp.), teff (*Eragrostis tef*), grass pea (*Lathyrus sativus*), chickpea (*Cicer arietinum*), and lentil (*Lens culinaris*). Croplands are used for growing annual crops during the main rainy season and free stubble grazing during off season (dry season). Due to land use changes, that is, from rangeland to exclosures or to cropland where no free stubble grazing is allowed, rangelands are intensively grazed and highly compacted during the rainy season (Taye et al., 2013).

2.2 | Methods

2.2.1 | Measured soil erosion rates and plot characteristics

Data for rainfall, runoff, and soil erosion rates were collected from 21 large (600 to 1,000 m²) runoff plots installed at three rangeland and three cropland sites of Mayleba catchment (Figure 1; Taye et al., 2013, 2015). For each land use type, a site was located on gentle (5%), medium (12%), and steep (15%) slopes. On each of the three sites in rangeland, four runoff plots were installed: a control plot, a plot treated with stone bunds, a plot treated with trenches, and a plot treated with stone bunds with trenches (Figure 1; Methods S1). Three runoff plots were installed at each of the three sites in cropland: a control plot, a plot treated with stone bunds, and a plot treated with stone bunds with trenches (Taye et al., 2013). Spacing of the SWC measures was determined following local guidelines as a function of the slope steepness. For rangeland, this spacing was 20 m on gently sloping plots, 12 m for medium sloping plots, and 9 m for the steep sloping plots. For cropland, the spacing of SWC structures for gentle, medium, and steep slope plots was respectively 20, 13, and 11 m. More details about the runoff plots, such as site slope gradients, density of the SWC structures and plot soil, and surface characteristics are given in Methods S1 and Taye et al. (2013).

Runoff plots were bounded by soil bunds (45-cm wide and 30-cm high) compacted during installation and carefully inspected and maintained during the measurement seasons (Figure 1). In addition, plots were also protected from upland run-on by diversion ditches. Runoff and sediment collection trenches of ~17 m³ were installed at the bottom of each plot and lined with 0.5-mm-thick geomembrane (Taye et al., 2013). Rainfall–runoff and soil loss were measured on a daily basis during the main rainy seasons in 2010 to 2012 (Figure 1; Taye et al., 2013, 2015). In addition, surface cover by vegetation and/or rock fragments within each plot was measured on a weekly basis during these seasons, using a point-count method (Methods S1).

Six composite topsoil (10-cm depth) samples were collected from each site to determine particle-size distribution. This was done by taking three representative soil samples within each plot avoiding sampling from sediment accumulation zones of the SWC structures. Collected samples were thoroughly mixed and resampled for grain size analysis using dry sieving, wet sieving, and decantation (Taye, 2014).

Similarly, composite topsoil samples were collected for each plot to determine soil organic carbon content, using the wet oxidation (Walkley & Black, 1934). The tillage frequency and crop types grown on the cropland sites were the same during the three rainy seasons. The height of the ridges created by traditional tillage was measured using a ruler after different tillage operations, and average ridge height was calculated.

2.2.2 | The Revised Universal Soil Loss Equation

The Universal Soil Loss Equation and its successor RUSLE is an empirical soil erosion model used to estimate the long-term annual average soil loss rate due to sheet and rill erosion from a certain area with specific slope attributes, land use, and land management combinations (Renard et al., 1997; Renard & Ferreira, 1993; Sonneveld & Nearing, 2003; Wischmeier & Smith, 1978). The governing equation (Equation 1) is based on empirical relationships between soil loss and six factors (Renard et al., 1997; Wischmeier & Smith, 1978):

$$A = R * K * L * S * C * P, \quad (1)$$

where A is the computed long-term average annual soil loss rate (ton ha year^{-1}), R is the rainfall-runoff erosivity ($\text{MJ mm ha}^{-1} \text{hr}^{-1} \text{year}^{-1}$), K is the soil erodibility ($\text{ton hr MJ}^{-1} \text{mm}^{-1}$), L is the slope-length factor (dimensionless), S is the slope-steepness factor (dimensionless), C is the cover-management factor (dimensionless), and P is the supporting practices factor (dimensionless). These factors can be calculated on the basis of measured rainfall, soil and plot surface properties, topographic variables, soil management, and soil loss rates from plots with and without SWC measures.

2.2.3 | Determination of the support practice (P) factor

In the study area, the support practice (P) factor is the result of subfactors due to SWC structures ($P_{\text{struc.}}$) and contouring subfactor ($P_{\text{cont.}}$) that accounts for contour ploughing. The overall support practice (P) factor is calculated as a product of the subfactors (Angima et al., 2003; Nyssen et al., 2009) as:

$$P = P_{\text{struc.}} * P_{\text{cont.}}, \quad (2)$$

where $P_{\text{struc.}}$ is the support practice subfactor value for the SWC structures, that is, stone bunds, trenches, and stone bunds with trenches. $P_{\text{struc.}}$ was calculated as:

$$P_{\text{struc.}} = \text{SL}_{\text{S,SWC}} / \text{SL}_{\text{S,Control}}, \quad (3)$$

where $\text{SL}_{\text{S,SWC}}$ is the measured seasonal soil loss rate ($\text{ton ha}^{-1} \text{season}^{-1}$) on a plot with SWC structures implemented and $\text{SL}_{\text{S,Control}}$ is the measured seasonal soil loss ($\text{ton ha}^{-1} \text{season}^{-1}$) on the corresponding control plot. $P_{\text{cont.}}$ is the support practice subfactor value due to contour ploughing. Its value was set to 1 for bare and intensively grazed control plots in rangelands. Given that contour ploughing is a commonly used practice in the cropland of the study area, it was also applied to the control plots of this study. The corresponding $P_{\text{cont.}}$ value was estimated following the approach proposed by

Renard et al. (1997), based on the slope gradient and the measured average ridge height (Figure 2).

2.2.4 | Determination of cover-management (C) factor

Determination of cover-management (C) factor requires soil loss measurement from plots with crop cover and from bare plots. However, installation of bare plots at the experimental sites was not possible due to the required large plot size. The C -factor was calculated on the basis of measured seasonal soil loss from a control plot divided by the product of calculated factors of the RUSLE at each site as follows:

$$C = \text{SLs} / \text{RKLSP}, \quad (4)$$

where SLs is the measured seasonal soil loss rate ($\text{ton ha}^{-1} \text{season}^{-1}$) for a control plot at each site and RKLSP are the corresponding factors of the RUSLE calculated below (Equations 5–9). R is the rainfall erosivity factor ($\text{MJ mm ha}^{-1} \text{hr}^{-1} \text{season}^{-1}$). Long-term rainfall intensity data are crucial to calculate R -factor values (Angima et al., 2003; Renard & Freimund, 1994). However, such data are very scarce for arid and semi-arid climates where rainfall is highly variable. Empirical relationships between (daily, monthly, seasonal, or annual) rainfall depth and measured R -factor values are therefore often used as an alternative approach (e.g., Hurni, 1985; Mati et al., 2000; Nigussie et al., 2014; Vrieling, Sterk, & de Jong, 2010). In this study, R was estimated as a function of seasonal rainfall depth (P_s) measured at each plot site, using an empirical equation for the Ethiopian Highlands (Hurni, 1985):

$$R = 5.5 * P_s - 47, \quad (5)$$

K is the soil erodibility factor calculated on the basis of soil texture, soil organic matter content, and soil structure code and permeability using (Renard et al., 1997):

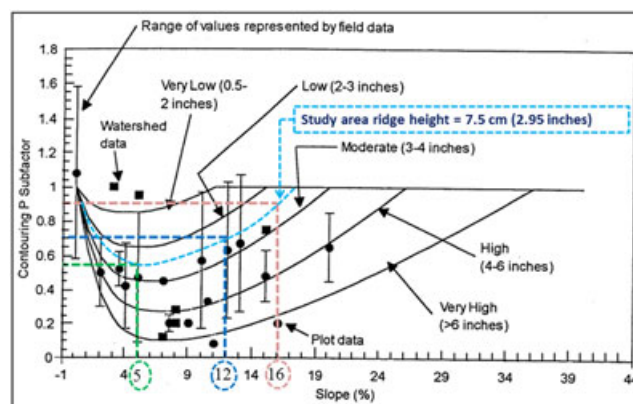


FIGURE 2 Proposed contouring subfactor ($P_{\text{cont.}}$) of the RUSLE for different soil ridge heights and slope gradients, modified after Renard et al. (1997). A curve for the measured mean ridge height of the cropland plots in this study (2.95 in. = 7.5 cm) is added, on the basis of an interpolation of the values for low and medium ridge heights. Also, the estimated $P_{\text{cont.}}$ values for gentle (5%), medium (12%), and steep (16%) slopes are indicated [Colour figure can be viewed at wileyonlinelibrary.com]

$$K^* = \left[2.1 * (10^{-4}) (12 - OM) M^{1.14} + 3.25 (s - 2) + 2.5 (p - 3) \right] * 0.1317 / 100, \quad (6)$$

where K^* is the soil erodibility factor ($\text{ton hr MJ}^{-1} \text{mm}^{-1}$); M is particle-size parameter calculated as $(\% \text{ silt} + \text{very fine sand}) \times (100 - \% \text{ clay})$; OM is percentage soil organic matter content; s is class for soil structure code, ranging between 1 for very fine granular and 4 for blocky, platy, or massive, with default value 2; and p is permeability class, ranging between 1 (*rapid*) and 6 (*very slow*), with default value 3 (Renard et al., 1997). Default values of s and p were used on the basis of soil properties of the study area, that is, blocky structure but with vertic properties and moderate infiltration rate (Taye, 2014). The calculated K^* was corrected for surface rock fragment cover ($R_{fc} \%$; Section 2.2.1) using δ (Poesen et al., 1994), which is adjusted for Ethiopian conditions after Nyssen et al. (2009):

$$\delta = e^{-0.04 * (R_{fc} - 10)}, \quad (7)$$

L is the dimensionless slope length factor calculated using an equation proposed by Renard et al. (1997):

$$L = (\lambda / 22.13)^m, \quad (8)$$

with " λ " being the horizontally projected slope length (in metres) and " m " a dimensionless slope length exponent. Values for the m -exponent were adopted from McCool et al. (1989), assuming a moderate rill-inter-rill ratio and taking into account the slope gradient of each plot. For our gentle (5%), medium (12%), and steep (16%) plot sites, the corresponding m -values used are respectively 0.4, 0.55, and 0.59.

S is the dimensionless slope steepness factor determined using the slope angle of a site (θ) in degrees based on (Nearing, 1997):

$$S = -1.5 + 17 / \left[1 + \exp^{(2.3 - 6.1 \sin \theta)} \right], \quad (9)$$

P is the support practice factor value of the control plot at each site (Section 2.2.3).

2.2.5 | Determination of SSC and length density of SWC measures

In the study area, SWC structures are installed on the contour for a maximum interception of surface runoff and sediment, and therefore, a sediment retention basin is created by these structures. Progressive accumulation of sediment in the trench and in the sediment retention zone of stone bunds causes a declining effectiveness of the SWC structures (Taye et al., 2015). Immediately after plot installation and at the end of each successive rainy season in 2010, 2011, and 2012, the dimensions of trenches and retention zone of stone bunds were measured, and their corresponding SSC was calculated. The SSC equals to the volume of surface water that can still be stored by a given SWC structure divided by the total plot area and is expressed as an equivalent water depth (mm; Taye, 2014). The length density of SWC structures is calculated from the measured length of the structures in a plot divided by plot area (km km^{-2}).

3 | RESULTS AND DISCUSSION

3.1 | The RKLS factors of the RUSLE

Calculated rainfall erosivity (R) factor values for rangeland and cropland sites are presented in Table S1. These R -factor values ranging from 1,638 to 3,903 (Table S1) for the different sites are in line with reported R -factor values for semi-arid environments with measured rainfall intensity (Figure S1; Haile et al., 2006; Angima et al., 2003; Stillhardt et al., 2002; Nigussie et al., 2014). The variability of R -factor values between years and sites is related to variation in rainfall depth (Table S1). Nigussie et al. (2014) also indicated that rainfall erosivity is the highest during July and August accounting for 81.6% of the annual erosivity in Ethiopia. The rainfall outside the rainy season is unreliable and less erosive (Nyssen et al., 2005), whereas rainfall during the main rainy season is erosive due to large drop sizes and the erratic nature of rainfall. Our results of rainfall erosivity (Table S1) are also comparable to those reported from large-scale mean annual rainfall-runoff erosivity mapping for Africa (Diodato, Knight, & Bellocchi, 2013; Vrieling et al., 2010).

Calculated soil erodibility (K) factor values, grain size distribution, and soil textural classes for the different sites are presented in Table S2. On average, K -factor values range from 0.02 to 0.04 for cropland and from 0.01 to 0.04 for rangeland sites. Similarly, Nyssen et al. (2009) reported that soil erodibility values in Tigray range from 0.009 to 0.036 for rangeland and 0.002 to 0.032 for cropland. The K -factor values for Tigray is smaller than those reported by Hurni (1985) for the subhumid central Ethiopia due to the relatively high clay content in the soils and high rock fragment cover at the surfaces (Table S2). Our soil erodibility factor values (0.01 to 0.04) are also comparable to those values reported for a catchment in semi-arid Kenya (Angima et al., 2003). Table S3 shows calculated values of slope steepness (S) and slope length (L) factors. Slope steepness of the sites in rangeland and cropland ranges from 5% to 16%, whereas the plot lengths range from 60 to 63 m for rangeland and from 77 to 100 m for cropland (Table S3). Calculated corresponding horizontal projection of slope length (λ ; Equation 8) ranges from 58.3 to 59.5 m for rangeland and from 73 to 97.1 m for cropland sites (Table S3). Soil and surface characteristics in the study area vary with slope gradient, and soil erodibility is rather low (Table S2; Nyssen et al., 2009). Therefore, the observed high soil erosion rate (Table 1) is related to steep topography and high rainfall erosivity (Nyssen et al., 2005) and also to high pressure from human and livestock population leading to low vegetation cover (Galdino et al., 2016; Haregeweyn et al., 2017; Taye et al., 2013).

3.2 | Support practice factors

Table 1 shows the support practice subfactor values for the common SWC structures ($P_{\text{struc.}}$), subfactor values for contouring ($P_{\text{cont.}}$), and the overall support practice (P) factor values. Support practice subfactor ($P_{\text{struc.}}$) values for the SWC structures are generally lower in rangeland than in cropland plots (Table 1). This is attributed to soil loss differences between rangeland and cropland. Seasonal soil losses measured on cropland plots are overall smaller than those measured

TABLE 1 Calculated support practice subfactor ($P_{\text{struc.}}$) values for SWC structures, subfactor for contouring ($P_{\text{cont.}}$) based on soil ridge height and slope gradient of the sites, and overall support practice (P) factor

Plot code	Season	SLs	$P_{\text{struc.}}$	$P_{\text{cont.}}$	P	Season	SLs	$P_{\text{struc.}}$	$P_{\text{cont.}}$	P	Season	SLs	$P_{\text{struc.}}$	$P_{\text{cont.}}$	P
RL-CO-G	2010	50.0	1.00	1.00	1.00	2011	37.9	1.00	1.00	1.00	2012	42.5	1.00	1.00	1.00
RL-SB-G	2010	16.0	0.32	1.00	0.32	2011	12.1	0.32	1.00	0.32	2012	16.4	0.39	1.00	0.39
RL-TR-G	2010	5.0	0.10	1.00	0.10	2011	9.5	0.25	1.00	0.25	2012	27.5	0.65	1.00	0.65
RL-SBT-G	2010	2.0	0.04	1.00	0.04	2011	2.8	0.07	1.00	0.07	2012	6.7	0.16	1.00	0.16
RL-CO-M	2010	38.0	1.00	1.00	1.00	2011	38.7	1.00	1.00	1.00	2012	40.6	1.00	1.00	1.00
RL-SB-M	2010	16.0	0.42	1.00	0.42	2011	12.2	0.32	1.00	0.32	2012	15.9	0.39	1.00	0.39
RL-TR-M	2010	5.0	0.13	1.00	0.13	2011	5.7	0.15	1.00	0.15	2012	14.9	0.37	1.00	0.37
RL-SBT-M	2010	1.0	0.03	1.00	0.03	2011	2.1	0.05	1.00	0.05	2012	4.0	0.10	1.00	0.10
RL-CO-S	2010	28.6	1.00	1.00	1.00	2011	28.6	1.00	1.00	1.00	2012	37.9	1.00	1.00	1.00
RL-SB-S	2010	10.9	0.38	1.00	0.38	2011	15.4	0.54	1.00	0.54	2012	14.3	0.38	1.00	0.38
RL-TR-S	2010	2.1	0.07	1.00	0.07	2011	7.4	0.26	1.00	0.26	2012	19.8	0.52	1.00	0.52
RL-SBT-S	2010	1.0	0.03	1.00	0.03	2011	2.1	0.07	1.00	0.07	2012	3.3	0.09	1.00	0.09
CL-CO-G	2010	11.4	1.00	0.57	0.57	2011	15.6	1.00	0.57	0.57	2012	13.0	1.00	0.57	0.57
CL-SB-G	2010	6.3	0.55	0.57	0.31	2011	8.4	0.54	0.57	0.31	2012	5.9	0.45	0.57	0.26
CL-SBT-G	2010	1.9	0.16	0.57	0.09	2011	2.0	0.13	0.57	0.07	2012	2.9	0.22	0.57	0.13
CL-CO-M	2010	4.6	1.00	0.71	0.71	2011	9.8	1.00	0.71	0.71	2012	9.3	1.00	0.71	0.71
CL-SB-M	2010	3.4	0.74	0.71	0.52	2011	4.3	0.43	0.71	0.31	2012	6.2	0.67	0.71	0.48
CL-SBT-M	2010	0.6	0.13	0.71	0.09	2011	1.4	0.14	0.71	0.10	2012	1.3	0.14	0.71	0.10
CL-CO-S	2010	4.6	1.00	0.90	0.90	2011	6.2	1.00	0.90	0.90	2012	7.0	1.00	0.90	0.90
CL-SB-S	2010	2.9	0.63	0.90	0.57	2011	3.0	0.47	0.90	0.43	2012	3.1	0.44	0.90	0.40
CL-SBT-S	2010	0.8	0.17	0.90	0.15	2011	0.8	0.13	0.90	0.12	2012	1.0	0.15	0.90	0.13

Note. SLs = measured seasonal soil loss values $\text{ton ha}^{-1} \text{season}^{-1}$. Plot code: RL = rangeland and CL = cropland. Tested soil and water conservation (SWC) structures: CO = control, SB = stone bunds, TR = trenches, and SBT = stone bunds with trenches at slope gradients G = gentle, M = medium, and S = steep.

on rangeland, mainly because smaller rainfall events that generate runoff and erosion in rangeland do not necessarily do so in cropland. In cropland, runoff and erosion due to rainfall events of limited intensity can be prevented by (contour) ridges and overall higher vegetation cover during the rainy seasons. As a result, mainly the larger rainfall events contribute to the measured seasonal soil losses in cropland. It is also during these events that the implemented SWC structures have a limited effectiveness, as the produced runoff volume may exceed the storage capacity of these structures. In rangeland, a larger proportion of the seasonal soil loss is caused by relatively small rainfall events. It is during such events that stone bunds and/or trenches are very effective, resulting in lower $P_{\text{struc.}}$ values for rangeland. This explanation is also consistent with the observation that the overall support practice (P) factor values for SWC structures in rangeland are comparable to those in cropland for the same SWC measures (Table 1; Figure 3). In the case of cropland, erosion during small rainfall events is probably mainly prevented by the ridges (cf. $P_{\text{cont.}}$). In rangeland, the same amount of erosion is prevented by the SWC structures ($P_{\text{struc.}}$, whereas $P_{\text{cont.}}$ is equal to 1, i.e., no ridges).

The average $P_{\text{struc.}}$ values ($n = 3$ years) range from 0.34 to 0.43 for stone bunds, from 0.22 to 0.33 for trenches, and from 0.06 to 0.09 for stone bunds with trenches installed at rangeland sites. In cropland sites, these values range from 0.51 to 0.61 for stone bunds and from 0.14 to 0.17 for stone bunds with trenches. On the basis of measurements of sediment volume trapped by 3- to 21-year-old stone bunds in cropland (Tigay), Desta et al. (2005) reported a long-term average P-factor of 0.32.

In the study area, traditional contour ploughing is an important strategy for seedbed preparation, in situ moisture conservation, and soil erosion control (Taye et al., 2013). The support practice subfactors due to contour ploughing ($P_{\text{cont.}}$) for an average ridge height of 7.5 cm and slope gradients of the sites (Figure 2) are 0.57 for gentle, 0.71 for

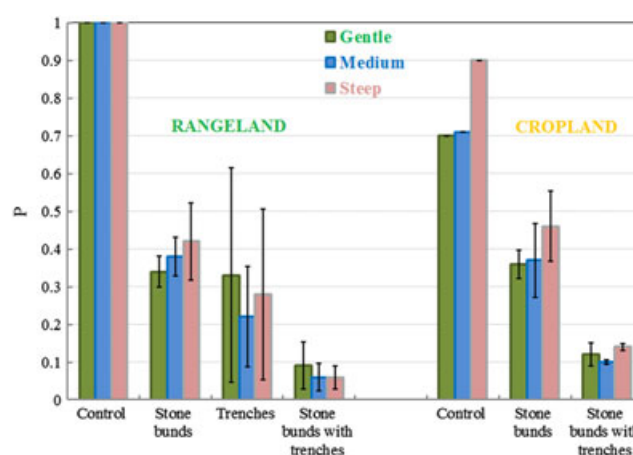


FIGURE 3 Calculated mean ($n = 3$ years) values of the overall support practice factor (P) for the runoff plots with and without soil and water conservation structures for rangeland and cropland and for the three slope gradients. P-factors were calculated, on the basis of Equation 2. Error bars indicate standard deviation of P values measured over 3 years. Note that contour tillage was applied on the cropland control plots, resulting in P values < 1 [Colour figure can be viewed at wileyonlinelibrary.com]

medium, and 0.90 for steep slope sites of the cropland (Table 2), which are similar to those reported by Wischmeier and Smith (1978). Tilahun et al. (2014) also reported that the decline in sediment concentration of the runoff during the rainy season is related to the fraction of newly ploughed land in the monsoon climate of the Ethiopian Highlands indicating the role of contour tillage on runoff and erosion reduction.

The overall support practice (P) factor value for stone bunds range from 0.32 to 0.54 for rangeland and from 0.26 to 0.57 for cropland sites (Table 1). Our P-factor values for stone bunds in cropland (Table 2) are similar to those reported by other authors in the tropics (Desta et al., 2005; Nyssen, 2001; Roose & Bertrand, 1971).

The P-factor values for trenches and stone bunds with trenches installed in rangeland vary over a wide range during the 3-year study period (Table 1, Figure 3). This change is related to a reduced effectiveness of these SWC structures over the measuring seasons (Taye et al., 2015). In contrast to the increasing trends of P-factor values for trenches and stone bunds with trenches in rangeland, Roose and Bertrand (1971) indicated decreasing P-factor values for stone bunds in Niger (Table 2). Our results show that $P_{\text{struc.}}$ values are highly variable, and this variation is related to the change in SSC of the SWC structures explaining 79% of the variation for rangeland and 56% for cropland (Figure 4a). This variation is poorly related to the length density of the SWC structures within the plots (Figure 4b). This

TABLE 2 Calculated support practice subfactors for contouring ($P_{\text{cont.}}$) and overall support practice factor (P) values compared to reported values for (mainly) tropical environments

Land use	SWC structures, practices	Country	Region	Sources	Plot year	Measurements scale	Slope (%)	Values range	Mean (P)
Cropland	Contouring	Ethiopia	Tigray	This study	3	Plot	5	NA	0.57 ($P_{\text{cont.}}$)
Cropland	Contouring	Ethiopia	Tigray	This study	3	Plot	12	NA	0.71 ($P_{\text{cont.}}$)
Cropland	Contouring	Ethiopia	Tigray	This study	3	Plot	16	NA	0.90 ($P_{\text{cont.}}$)
Cropland	Contouring	USA	NA	Wischmeier and Smith (1978)	NA	Plot	1-Feb	NA	0.60 ($P_{\text{cont.}}$)
Cropland	Contouring	USA	NA	Wischmeier and Smith (1978)	NA	Plot	6 to 8	NA	0.50 ($P_{\text{cont.}}$)
Cropland	Contouring	USA	NA	Wischmeier and Smith (1978)	NA	Plot	13 to 16	NA	0.70 ($P_{\text{cont.}}$)
Cropland	Stone bunds	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.31–0.57	0.47 (P)
Cropland	Stone bunds	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.31–0.43	0.35 (P)
Cropland	Stone bunds	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.26–0.46	0.37 (P)
Cropland	Stone bunds	Ethiopia	Tigray	Desta et al. (2005)	1	Plot	NA	NA	0.32 (P)
Cropland	Stone bunds	Ethiopia	Tigray	Nyssen (2001)	NA	Plot	NA	0.36–0.39	0.38 (P)
Cropland	Stone bunds	Niger	Allokote	Roose and Bertrand (1971)	1	Plot	3	NA	0.27 (P)
Cropland	Stone bunds	Niger	Allokote	Roose and Bertrand (1971)	1	Plot	3	NA	0.05 (P)
Cropland	Stone bunds with trenches	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.09–0.15	0.11 (P)
Cropland	Stone bunds with trenches	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.07–0.12	0.10 (P)
Cropland	Stone bunds with trenches	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.10–0.13	0.12 (P)
Cropland	Stone bunds, grassed	Niger	Allokote	Roose and Bertrand (1971)	2	NA	NA	NA	0.05 (P)
Cropland	Earthen bund	Niger	Allokote	Roose and Bertrand (1971)	1	NA	NA	NA	0.0022 (P)
Rangeland	Stone bunds	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.32–0.42	0.37 (P)
Rangeland	Stone bunds	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.32–0.54	0.39 (P)
Rangeland	Stone bunds	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.38–0.40	0.396 (P)
Rangeland	Trenches	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.07–0.13	0.10 (P)
Rangeland	Trenches	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.15–0.26	0.22 (P)
Rangeland	Trenches	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.37–0.65	0.51 (P)
Rangeland	Stone bunds with trenches	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.03–0.04	0.033 (P)
Rangeland	Stone bunds with trenches	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.05–0.07	0.063 (P)
Rangeland	Stone bunds with trenches	Ethiopia	Tigray	This study	3	Plot	5 to 16	0.09–0.16	0.117 (P)

Note. NA = not available; SWC = soil and water conservation.

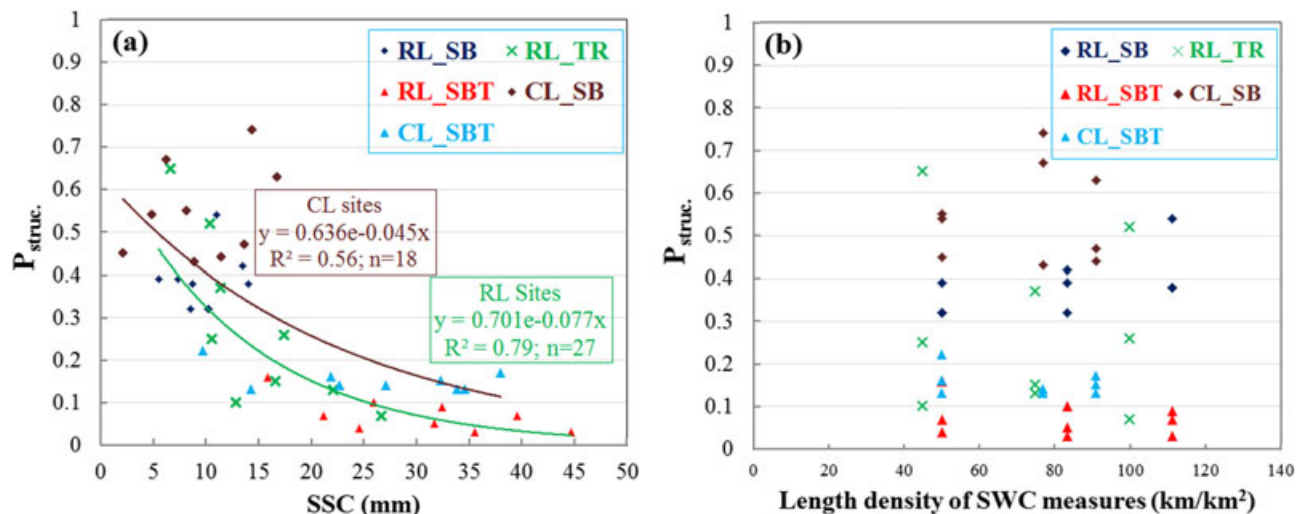


FIGURE 4 Support practice subfactor ($P_{struc.}$) values as a function of (a) the static storage capacity (SSC) of the soil and water conservation (SWC) structures and of (b) the length density of SWC structures installed at the experimental plots for rangeland (RL) and cropland (CL) and for the common SWC structures: stone bunds (SB), trenches (TR), and stone bunds with trenches (SBT) [Colour figure can be viewed at wileyonlinelibrary.com]

poor relation can be attributed to the fact that the length density of the SWC structures increases with slope gradients, whereas soil erosion rates also increases with slope gradients.

Caution has to be taken when applying the P-factor values reported in Table 1. This is because the effectiveness of SWC measures depends on SSC (Taye et al., 2015). Our runoff plots were treated on the basis of the recommended spacing of SWC structures by the Bureau of Agriculture and Natural Resources of Ethiopia that is slightly different compared to the spacing of these structures installed by the farmers (Taye, 2014; Methods S1). Second, there is a large variability of the trench dimensions depending on their purposes. Our trenches are 0.5 m deep, 0.5 m wide, and 3 m long (Figure 5a), which are common dimensions of these SWC structures in the study area, whereas trenches of 1 m deep, 2 m wide, and 4 m long are also installed for recharging groundwater in Tigray (Figure 5b). As indicated (Figure 4 a), $P_{struc.}$ values are strongly related to SSC and hence effectiveness of implemented measures; this needs to be assessed before assigning appropriate P-factor values for predicting their effects at large scale. Consideration of temporal change of the SSC and maintenance aspect

is also crucial for estimating reliable P-factor values. For instance, the effectiveness of SWC measures is high when they are newly installed and maintained but decrease with time (Taye et al., 2015), and hence, the $P_{struc.}$ value increases accordingly (Table 1).

3.3 | Cover-management (C) factor for land use types

Table 3 reports calculated cover-management (C) factor values for all control plots in rangeland and cropland for the three rainy seasons. Some caution is required when using and interpreting these values. Given that no standardized bare plots were available allowing to calculate the C-factors based on a direct comparison of measured soil losses, C-factors were calculated using Equation 4. This implies that potential errors and uncertainties on the calculated R, K, LS, and (for cropland) $P_{cont.}$ subfactors also affect the calculated C-factor values. The exact degree of the resulting uncertainty is, however, difficult to quantify.

Nonetheless, the results clearly show that C-factor values for rangeland plots (0.23 to 0.82) are larger than those for cropland plots

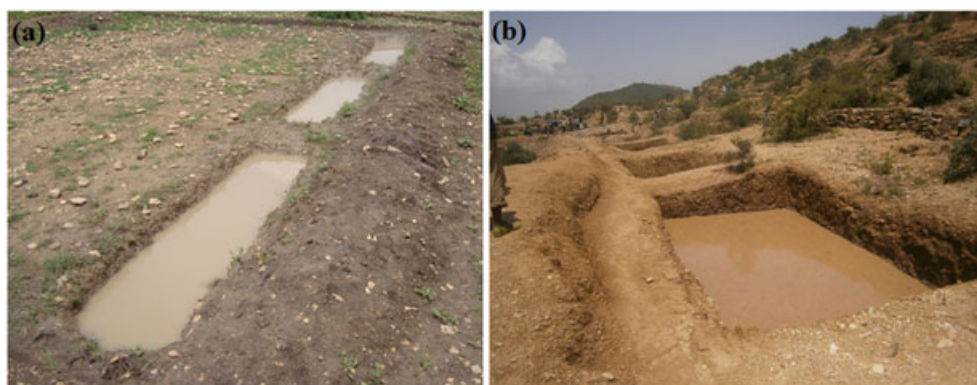


FIGURE 5 Soil trenches: (a) 0.5 m deep, 0.5 m wide, and 3 m long typically used as a soil and water conservation structure Mayleba, September 1, 2010 and (b) 1 m deep, 2 m wide, and 4 m long used as infiltration trenches for recharging groundwater Seharti Samre area, August 16, 2016 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Calculated values of the RUSLE factors (RKLSP; Equation 4) and cover-management (C) factor values for control plots on rangeland (RL) and cropland (CL) sites during the three rainy seasons (2010 to 2012)

Land use (site)	Season	Cover type	SLs (ton ha ⁻¹ season ⁻¹)	R	K	L	S	P	RKLSP (ton ha ⁻¹ season ⁻¹)	C = SLs/RKLSP
RL-gentle	2010	Rangeland	50.0	1,918	0.04	1.47	0.54	1	60.91	0.82
RL-medium	2010	Rangeland	38.0	1,870	0.02	1.71	1.43	1	91.47	0.42
RL-steep	2010	Rangeland	28.6	1,7163	0.01	1.79	2.06	1	63.29	0.45
CL-gentle	2010	Barley	11.4	1,797	0.04	1.81	0.54	0.57	40.05	0.28
CL-medium	2010	Barley	4.6	1,779	0.03	2.15	1.43	0.71	116.47	0.04
CL-steep	2010	Barley	4.6	1,638	0.02	2.02	2.06	0.9	122.70	0.04
RL-gentle	2011	Rangeland	37.9	2,248	0.04	1.47	0.54	1	71.38	0.53
RL-medium	2011	Rangeland	38.7	2,244	0.02	1.71	1.43	1	109.76	0.35
RL-steep	2011	Rangeland	28.6	2,080	0.01	1.79	2.06	1	76.71	0.37
CL-gentle	2011	Wheat	15.6	2,022	0.04	1.81	0.54	0.57	45.06	0.35
CL-medium	2011	Wheat	9.8	2,043	0.03	2.15	1.43	0.71	133.79	0.07
CL-steep	2011	Wheat	6.2	2,129	0.02	2.02	2.06	0.9	159.45	0.04
RL-gentle	2012	Rangeland	42.5	3,903	0.04	1.47	0.54	1	123.93	0.34
RL-medium	2012	Rangeland	40.6	3,663	0.02	1.71	1.43	1	179.13	0.23
RL-steep	2012	Rangeland	37.9	3,558	0.01	1.79	2.06	1	131.21	0.29
CL-gentle	2012	Barley	13.0	2,819	0.04	1.81	0.54	0.57	62.82	0.21
CL-medium	2012	Barley	9.3	2,452	0.03	2.15	1.43	0.71	160.59	0.06
CL-steep	2012	Barley	7.0	2,693	0.02	2.02	2.06	0.9	201.68	0.03

Note. R is seasonal rainfall erosivity (MJ mm ha⁻¹ hr⁻¹ season⁻¹); K is soil erodibility (ton hr MJ⁻¹ mm⁻¹); and L, S, and P are dimensionless slope length, slope steepness, and support practice factors, respectively. RUSLE = Revised Universal Soil Loss Equation; SLs = seasonal soil loss.

(0.03 to 0.35). Among rangeland sites, the C-factor is especially the highest for gentle slope site, where grazing pressure and compaction due to trampling is very high and vegetation recovery during the rainy season is very slow. In addition, the vertic nature of the soil (Vertic Cambisol; Van de Wauw et al., 2008) at the gentle slope and low surface rock fragment cover makes this site more prone to runoff and soil loss (Table 3; Methods S1).

There is a large difference between cropland and rangeland in terms of the C-factor values. On average, the C-factor values in rangeland were 0.56 in 2010, 0.42 in 2011, and 0.29 in 2012,

whereas in cropland, the corresponding values were 0.12 in 2010, 0.15 in 2011, and 0.10 in 2012. The C-factor values for cropland correspond to alternative cropping of barley, wheat, and barley cycle during the three successive rainy seasons. A higher C-factor value in 2011 for cropland (Table 3) is due to the late sowing of wheat. Similarly, large differences in the C-factor values (Table S4) between cropland and rangeland are reported for Ethiopia highlands (Hurni, 1985; Nyssen et al., 2009). At the beginning of the rainy season, vegetation cover for cropland was almost negligible; however, the soils were tilled and dry. Runoff production and soil loss from

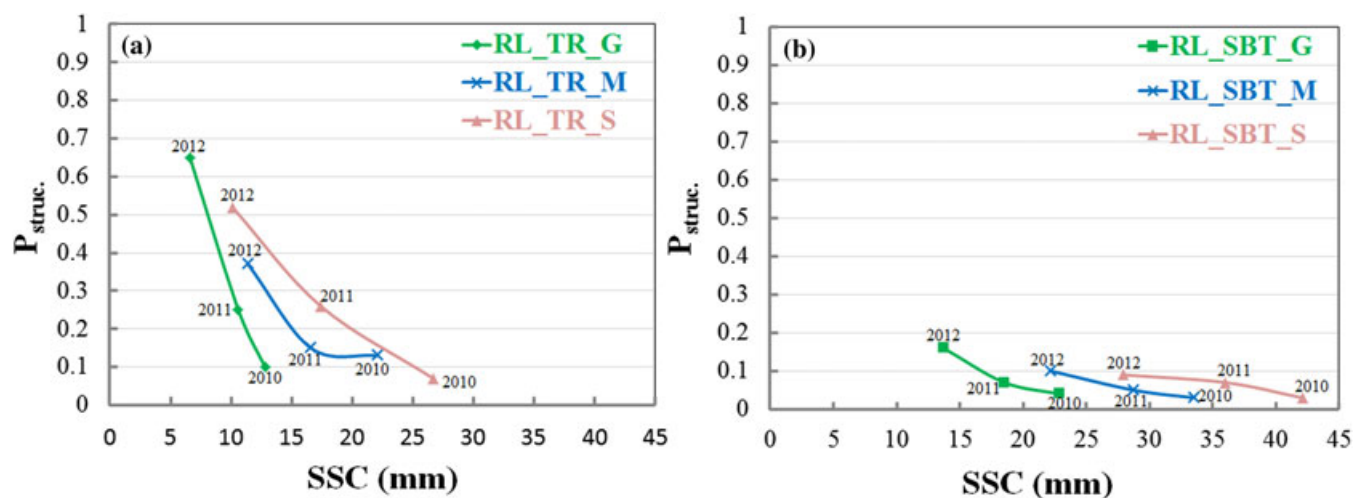


FIGURE 6 Evolution of support practice subfactors ($P_{struc.}$) in relation to the static storage capacity (SSC). The SSC were measured after plots installation in 2010 and immediately after successive rainy seasons in 2010, 2011, and 2012 for measures installed on rangeland (RL) plots with gentle (G), medium (M), and steep (S) slopes. (a) The relations for trenches (TR) and (b) the relations for stone bunds with trenches (SBT) [Colour figure can be viewed at wileyonlinelibrary.com]

cropland plots during this period are low mainly due to high infiltration rates in dry and freshly tilled soils (Tilahun et al., 2014) and the retention of surface runoff by the soil ridges and furrows (Taye et al., 2013). During the rainy season, vegetation cover in cropland increased from 0% at the beginning of the rainy season to over 73% on average (Taye, 2014), whereas for rangeland cover, percentage is variable in response to grazing pressure and remains low (28% to 36%) on average. Plots in rangeland were intensively grazed and compacted by trampling, and the recovery of surface vegetation cover was very slow.

Overall, the values obtained in this study appear consistent with C-factors reported for other (sub)tropical regions (Table S4). The C-factor values reported in (Table 3) for cropland sites range from 0.10 to 0.15 on average. These values are similar to those reported for cereal-based systems in Ethiopian (Hurni, 1985; Nyssen et al., 2009). Our C-factor values are smaller than the values reported for cassava-, maize-, coffee-, banana-, and bean-based systems in the tropics (Angima et al., 2003; Nill, 1993; Nill, Schwertmann, Sable-Koschella, Bernhard, & Breuer, 1996; Sulaiman, Mok, Maesschalck, & Jamal, 1983), which is likely explained by differences in cover-

management practices and rainfall conditions. For our rangeland sites, the average C-factor values calculated in this study are higher than the reported values for Ethiopia and Cameroon (ranging from 0.1 to 0.42; Nill, 1993; Nyssen et al., 2009). Also, Hurni (1985) reported a much lower value ($C = 0.05$) for rangelands in the subhumid central highlands of Ethiopia. This is most likely explained by the fact that the latter area is characterized by a more uniform rainfall distribution throughout the year and permanent vegetation cover, whereas the rangelands of our study area (and Tigray in general) are intensively grazed and subject to a climatic regime of long dry seasons and short but intense rainy seasons.

3.4 | Temporal variation of the P- and C-factor values

The support practice subfactor ($P_{\text{struc.}}$) values for trenches and stone bunds with trenches installed in rangeland increased with time due to a decrease of their effectiveness (Table 1, Figure 6). On average, $P_{\text{struc.}}$ subfactor value for trenches installed in rangeland was 0.10 in 2010 and increased to 0.51 in 2012 (Figure 7e, Table 1), whereas the

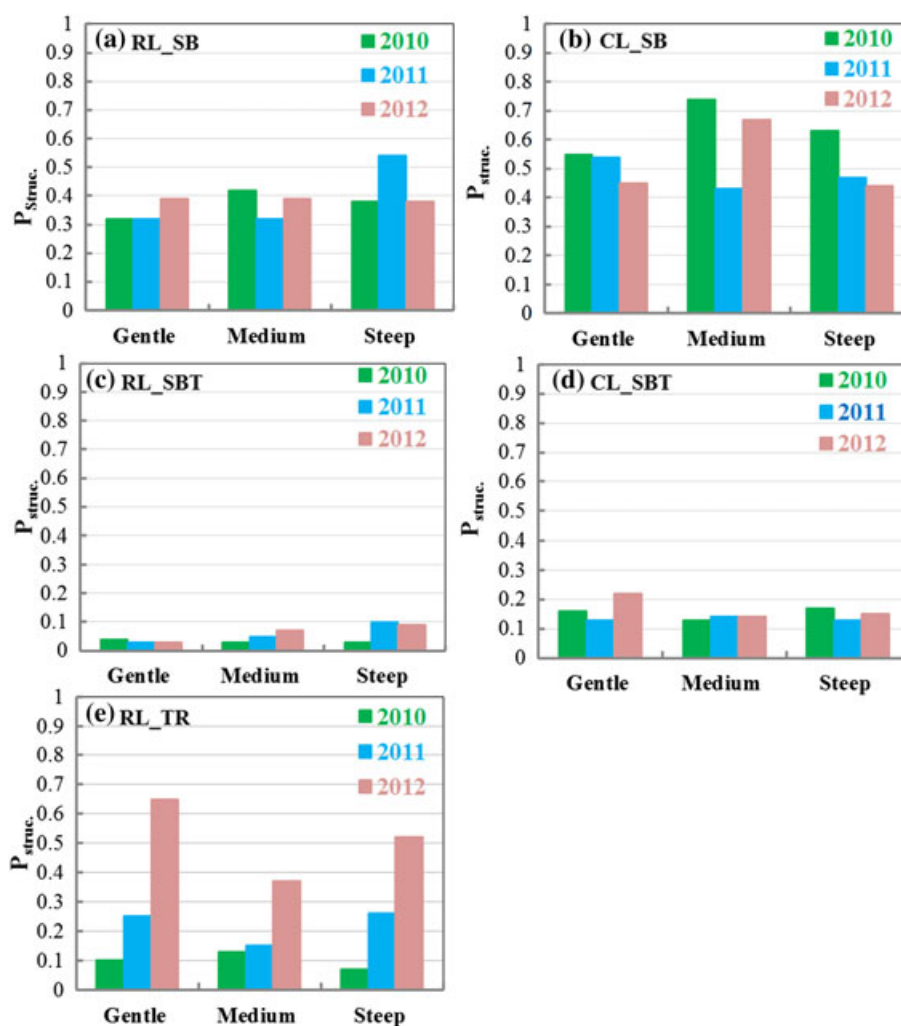


FIGURE 7 Support practice subfactor ($P_{\text{struc.}}$) values for soil and water conservation structures (a) for stone bunds in rangeland (RL-SB), (b) for stone bunds in cropland (CL-SB), (c) for stone bunds with trenches in rangeland (RL-SBT), (d) for stone bunds with trenches in cropland (CL-SBT), and (e) for trenches in rangeland (RL-TR) [Colour figure can be viewed at wileyonlinelibrary.com]

average P_{struc} subfactor value for stone bunds with trenches installed in rangeland increased from 0.03 in 2010 to 0.12 in 2012 (Figure 7c). These results are in line with the findings of Guzman et al. (2017), who applied the parameter-efficient distributed model to estimate the long-term (9 years) impact of Fany-juu (throw uphill) bunds on sediment concentration at the outlet of a small experimental catchment in the central Ethiopian Highlands. Their results also indicate that the effectiveness of these SWC structures declines over time and is negligible after 5 years. In contrast, there was no increasing trend of P_{struc} values over time for stone bunds and trenches installed in cropland (Figure 7d) with average P_{struc} values of 0.15 in 2010 and 0.17 in 2012 (Table 1). Stone bunds installed in both cropland and rangeland sites were less effective in controlling soil loss compared to the corresponding stone bunds with trenches (Taye et al., 2015). The mean P_{struc} values for stone bunds is 0.38 in rangeland and 0.55 in cropland, and their effectiveness remained nearly constant or with no clear trends (Figure 7a,b) over 3 years. The increase in P_{struc} values for the trenches and stone bunds with trenches installed in rangeland (Figure 7c,e) is attributed to infilling with sediments and losses of the SSC (Figure 6a,b) leading to a reduced runoff and sediment trapping efficiency over time. In general, the effectiveness of the SWC structures and their corresponding P_{struc} values are related to SSC and not related to their length density (Figure 4a,b).

The cover-management (C) factor values for the two land use types vary in response to land cover and slope gradients (Table 3). The rainfall depth during the monitoring period is also an important variable affecting the C-factor values. Overall, C-factor values evolve with the rainfall depth, vegetation cover, and crop type during the seasons, and these somehow explain variation between seasons. In the study area, rainfall depth and distribution are highly important for the recovery of the vegetation cover after the dry season. Earlier studies showed that vegetation cover in the northern Ethiopian Highlands progressively increases during the first weeks and months of the rainy season, resulting in significant decreases of sediment concentrations in the runoff as the rainy season progresses (Guzman et al., 2013; Taye, 2014; Vanmaercke et al., 2010).

4 | CONCLUSIONS

This study is the first to provide empirical data on P-factors for the common SWC structures (trenches and stone bunds) and C-factors for both cropland and rangeland in tropical semi-arid environments. The P- and C-factor values, however, show a wide range of year-to-year variations. In the case of the P-factor, this is due to a declining SSC and hence a decrease of the effectiveness of these SWC measures over time after implementation. In the case of the C-factor, it is explained by a change in vegetation cover in response to grazing and trampling compaction in rangeland and crop growth, tillage practices, and crop type in cropland. To address these P-factor variations, a relationship between the P-factor and SSC is proposed, which explains these variations for both land use types. There is no relation between the P-factor values and the length density of the SWC structures. Hence, for a reliable prediction of the P-factor values for the different SWC structures, a reliable estimate of SSC is

crucial. These results allow the prediction of the impacts of land management on soil erosion rates in Ethiopia and other similar environments.

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Additional Supporting Information may be found online in the supporting information tab for this article.

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