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Tillage impact on soil erosion by water: Discrepancies due to climate and soil characteristics

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ABSTRACT

No-tillage (NT) is promoted for soil and water conservation, but research findings on overland flow and soil erosion are inconsistent across different ecosystems, with some studies showing no benefits of NT over conventional tillage (CT). A global literature review was conducted to quantify the impact of NT on water runoff, sediment concentration and soil losses. The objective was to identify the underlying causes of the variability in the performance of NT across different environments. Data from 282 paired NT and CT runoff plots from 41 research studies worldwide were analysed using meta-analysis and principal component analysis (PCA). Sediment concentration and soil losses were 56 and 60% lower under NT than CT, respectively. These tended to be greater under CT than NT on long plots (90% for sediment concentration and 94% for soil losses) and steepest slopes (79 and 77%, respectively). Greater differences in sediment concentration and soil losses between NT and CT were observed in low clay soils and under temperate climates. While on average there were no differences on runoff coefficient, NT decreased runoff coefficient by about 40% compared to CT in mulched soils, under cool climate (<10 °C), and for experiments done >5 years. Overall, the results indicated that NT has greater potential to reduce runoff and soil losses in temperate regions where soils of peri-glacial influence are relatively young, moderately weathered and fragile compared to the heavily weathered clayey tropical soils that are well aggregated and less erodible. The results of this study are expected to inform scientists, practitioners and policy makers on the links between land management and soil functioning processes. Policy makers and development implementers will be able to make informed choices of land management techniques for effective NT implementation, for instance by having more mulch input under warm climates.

1. Introduction

No-tillage (NT), also known as zero tillage or direct seeding, is a cropping method that eliminates mechanical seedbed preparation other than opening a narrow (20–30 mm wide) hole or furrow strip in the stubble of the previous crop for the placement of seeds with no other tillage being done thereafter (Fasinmirin and Reichert, 2011). NT is increasingly being seen as a possible component of sustainable agriculture as it improves soil infiltration by water and minimises soil water erosion as associated losses of fertile soil material (Huggins and Reganold, 2008). Other potential benefits of NT include climate change attenuation and adaptation as less carbon is exported from soils by water erosion (Muller-Nedbock and Chaplot, 2015) and through the decomposition of soil organic matter (Abdalla et al., 2015). For example, Cogle et al. (2002) observed a sharp decline in runoff rate from CT plots soon after tilling a crusting and hard-setting soil but the rates were comparable with NT after receiving a few storms. Similarly, Mchunu et al. (2011) observed higher water runoff in NT than in CT in the first half of the season and a reverse trend in the second half but overall, there were no differences in runoff between NT and CT.

Despite the contrasting findings about the performance of NT in soil and water conservation, the effectiveness of this practice in curtailing runoff and soil losses is intricately linked to the quantity of crop residue mulch retained on the soil surface (Bradford and Huang, 1994; Lal, 1984). A short-term study on NT mulch-based

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cropping systems in a semi-arid tropical environment in western Mexico (Scopel et al., 2005) showed huge improvements in soil losses reduction under NT with little amounts (20%) of surface residue cover. This finding complemented an earlier modelling conclusion that even small quantities of organic surface mulch had potential to significantly reduce overland flow in semi-arid tropical climates where rainfall variability is high (Scopel et al., 2004). Mchunu et al. (2011) attributed the 68% decline in soil losses by NT without mulch, under sandy loam soils (62% sand) to the formation of erosion resistant soil crusts.

The inconsistent performance of NT in reducing runoff and soil losses suggests that the environmental and land management conditions influence the effectiveness of NT in conserving soil and water. NT performance in improving soil physical properties that moderate runoff and soil loss may be controlled by interactions of topographical, climatic and soil factors. Elucidating the environmental factors that may influence the NT performance in controlling runoff and soil losses is, therefore, fundamental to the understanding of mechanisms by which NT reduces runoff and soil losses in cropped ecosystems. The knowledge gained would complement previous results from previous studies on the influence of NT on grain yield (Rusinamhodzi et al., 2011; Toliver et al., 2012) and N_2O emission (van Kessel et al., 2013).

Therefore, the objective of this study was, through meta-analysis to quantitatively compare the magnitude of annual runoff coefficient, sediment concentration and soil losses generated in NT compared to CT and to identify the effect of crop residue retention and main environmental factors (topographical, climatic, soil and soil management).

2. Materials and methods

2.1. Data base construction

A literature search was conducted within Science direct, Scientia Agricola, and Google Scholar using search terms such as no-tillage effects on runoff, no-tillage effects on runoff coefficient, no-tillage effects on soil erosion, soil loss(es) and zero tillage, direct seeding and runoff to identify research articles that investigate the impact of tillage on soil erosion by water. Two thousand and five hundred investigations were found. In recognition of the influence of spatial scale on runoff and soil loss processes (Chaplot and Poesen, 2012; Mutema et al., 2015) it was considered rational to limit the search to studies based on plot-scale measurements. We also only included the studies performed in-situ and based on paired comparisons between tilled and no-tilled soils. Forty-one research papers were retained with thirteen informing on residue retention (either the proportion of the soil surface coverage by mulch or mulch biomass in Mg ha^{-1} yr^{-1}). Papers were published between 1984 and 2012, from 282 runoff plots in 14 countries across the globe (Appendix A; Fig. 1). Rainfall simulation was used in 19 of the reviewed studies. Rainfall simulation is the artificial application of water onto an erosion plot in a manner that mimics the characteristics of natural rainfall such as energy, distribution, drop size distribution, duration and season (Williams et al., 2009). Rainfall simulations are as reliable as natural rainfall and they have an added advantage as research tools in that (i) they enable good control of rainfall parameters, (ii) give quick replicable results (Wilcox et al., 1986) and enable reproduction of extreme rainfall events such as those with a predicted return of more than 10 years.

Quantitative measurements of runoff, sediment concentration and soil losses as well as environmental parameters (topographical, climatic, soil and plot management variables) were compiled into the database. Measurements of runoff were recorded as volume per unit area (L m^{-2}) and soil loss was recorded as mass of sediment loss per unit area (g m^{-2}). The data on runoff and soil loss were directly extracted from tables and figures presented in the individual studies. When not given, runoff coefficient and sediment concentration were calculated using Eqs. (1) and (2) respectively.

$$RC = \frac{R}{P} \tag{1}$$

where: RC is runoff coefficient, which is a dimensionless value that indicates the fraction of rainfall that becomes runoff; runoff is the runoff depth (mm) and P is total depth of precipitation (mm).

$$SC = \frac{SL}{R} \tag{2}$$

where: SC is the sediment concentration (g L^{-1}) in runoff, which corresponds to the ratio of the soil losses (SL; g) to the total volume of runoff water (R; L).

Environmental factors that were considered relevant to the understanding of runoff and soil loss processes at each research site included topographical factors [i.e. longitude, latitude, altitude and slope gradient (S)], climatic factors [i.e. mean annual precipitation (MAP) and mean annual temperature (MAT)], soil factors [i.e. top-soil bulk density (BD), top-soil texture (CLAY, SILT

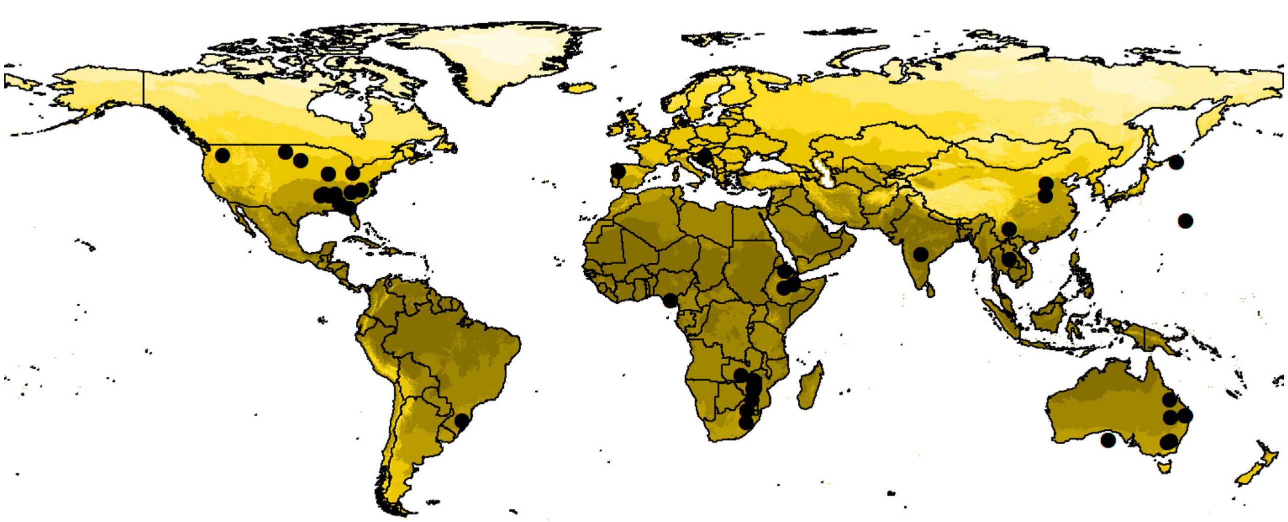

Fig. 1. The world map showing the research sites where the reviewed data were obtained.

and SAND) and soil organic carbon content (SOC)]. Management variables included soil surface mulch cover, duration/age of NT treatment and crop species grown in the experiment. Most of the environmental data were provided in the research articles. However, in cases where some data were not available, which was the case for 12 papers, these were retrieved from other research papers published at the same location. The missing climatic information was retrieved using global climate data from WorldClim (http://www.worldclim.org). Missing soil data was obtained from the Harmonised World Soil Database [HWSD] (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) that has information on fifteen soil properties for the topsoil (0–30 cm) and subsoil (30–100 cm). Only the soil data for the top layer (0–30 cm) were considered appropriate for the database. A challenge was encountered in five cases where data on site slope gradient (S) were not included in the publications. Table 1 presents the descriptive statistics for the topographical, climatic and soil factors extracted from the reviewed articles.

Categorical variable for the environmental and management factors used in the meta-analysis are presented in Table 2. The altitude in the studies ranged from 38–3890 m above sea level and were categorised as low (<700 m.a.s.l), medium (700–1400 m.a.s.l) and high (>1400 m.a.s.l), following the classification adopted by Sileshi et al. (2009). Four classes of slope gradient (S) and three for slope length were adopted from the Food and Agriculture Organisation (FAO) guidelines for soil description (FAO, 2006). Climatic zones (tropical, subtropical, temperate continental and temperate maritime) and MAT (low $\leq$10 °C, medium 10–20 °C and high >20 °C) categories were based on the Koeppen-Geiger climate classification system (Peel et al., 2007). The MAP categories were based on the FAO guidelines for agro-climatic zoning (Fischer et al., 2001). Soils were classified into three broad textural classes using the soil texture triangle (Brady, 1990). Categories for soil bulk density and SOC content reflect the prevailing levels of these soil properties in agricultural soils. Soil organic carbon content varies from <1% in heavily exploited soils to >2% in good soils (Gobin et al., 2011). Loveland and Webb (2003) cited the threshold SOC in agricultural soils at 2% (equivalent to 3.4% SOM) below which most soils may potentially undergo structural degradation (Seremesic et al., 2011; Musinguzi et al., 2013). However, it is important to note that thresholds for SOC content are site specific, influenced by complex interactions of climate, topography, soil texture and land use management (Musinguzi et al., 2013). Soil bulk densities ranging from 0.74–1.74 g cm^{-3} are typical in agricultural soils (Gupta and Larson, 1979). In addition to the environmental factors, management practices such as soil surface cover (with or without mulch), duration of NT treatment implementation and crop species used (cereals, legumes, cereal-legume rotations and other crops that included tobacco, cotton, canola, oil-seed rape, olives and sunflower) applied in the experiments were classified according to the practices adopted by the authors. Tillage studies conducted for periods <5 years were regarded as short-term (Rusinamhodzi et al., 2011) while those $\geq$10 years were considered long-term (van Kessel et al., 2013).

2.2. Multivariate statistical analysis

The effects of NT on runoff coefficient, sediment concentration and soil losses were analysed in comparison to a control, i.e. CT. Tillage practices that were reported as ploughing, contour ploughing, traditional tillage, deep tillage or very deep tillage were classified as CT. Practices such as zero tillage and direct seeding were classified as NT.

The runoff coefficient, sediment concentration and soil loss data were summarised using statistical meta-analytic model and further explored by performing a principal component analysis (PCA).

Principal component analysis (PCA) is a data analysis tool that transforms multivariate data into a new orthogonal (uncorrelated) coordinate system (principal components) in which the first coordinate (first principal component) accounts for the greatest data variability. The second greatest variability accumulates in line with the second principal component and so on (Jolliffe, 2002).

The multiple associations between runoff coefficient, sediment concentration and soil loss variables and environmental variables (topographical, climatic, soil and soil management) were further explored by performing principal component analysis (PCA) using Statistica software (Statsolf, 2004). The PCA technique extracts the most important information from a multivariate dataset and displays the relationships among variables as vectors in maps enabling visualisation of the otherwise multidimensional hyper-space. In this regard, PCA complements meta-analysis outcomes by portraying a multifactor picture of the patterns of relationships among inter-correlated variables.

2.3. Meta analysis

The impact of NT in controlling runoff coefficient, sediment concentration and soil losses was estimated by comparing the magnitude of the NT treatment mean $\left(\overline{X}^{NT}\right)$ to the CT (control) treatment mean $\left(\overline{X}^{CT}\right)$. A response ratio (Re) was calculated as the treatment effect size statistic using Eq. (3).

$$\mathrm{Re} = \left(\frac{\overline{X}NT}{\overline{X}^{CT}}\right) \tag{3}$$

Values of runoff above 1 indicated that NT treatment had greater mean runoff coefficient, sediment concentration or soil losses than CT. The response ratios were normalised by natural log transformation as shown in Eq. (4).

$$\mathrm{lnRe} = \ln\left(\frac{\overline{X}^{NT}}{\overline{X}^{CT}}\right) = \ln\left(\overline{X}^{NT}\right) - \ln\left(\overline{X}^{CT}\right) \tag{4}$$

MetaWin 2.1 software was used to compute mean effect sizes and generate 95% bootstrapped confidence intervals (CIs) using 4999 iterations (Rosenberg et al., 2000). Treatment effect sizes, i.e. NT *vs* CT, for each category were considered statistically significant if the 95% CIs did not overlap zero (Borenstein et al., 2009).

Table 1

Summary descriptive statistics for environmental factors (Long; longitude: Z; latitude: Alt; altitude: MAP; mean annual precipitation: MAT; mean annual temperature: ρ_b; bulk density: S; slope: soil particle distribution (clay, silt and sand) and SOC$_c$; soil organic carbon content from the 44 research sites.

Statistic	Topographic factors				Climatic factors		Soil factors				
	Long (°)	Lat (°)	Z (m)	S (%)	MAP (mm)	MAT (°C)	Clay (%)	Sand (%)	Silt (%)	ρ_b (g cm-3)	SOC$_c$ (g kg^{-1})
Minimum	−118.6	−35.1	38	1.00	400.0	4.0	1.0	4.8	3.6	1.0	0.7
Maximum	152	47	3890	25	2238	29	68	88	77	2	37
Mean	19.7	10.2	871	6.1	890.3	16.5	24.8	43.1	32.0	1.4	11.0

Table 2
Categorical variables used to describe physical and management conditions at experimental sites.

Categorical variable	Level 1	Level 2	Level 3	Level 4
Climate	Tropical	Subtropical	Temperate continental	Temperate maritime
Top-soil texture	Sand (<20% clay)	Loam (20–32% clay)	Clay (>32% clay)	
Mean annual precipitation	Low (<600 mm)	Medium (600–1000 mm)	High (>1000 mm)	
Mean annual temperature.	Low (≤10 °C)	Medium (10–20 °C)	High (>20 °C)	
Altitude	Low (<700 m.a.s.l)	Medium (700–1400 m.a.s.l)	High(>1400 m.a.s.l)	
Top-soil bulk density	Low (≤1.2 g cm^{-3})	Medium (1.2–1.6 g cm^{-3})		
Soil organic carbon content	Low (<1%)	Medium (1–2%)	High (>2%)	
Mean slope gradient	Very gently sloping (1.0–2.0%)	Gently sloping (2.0–5.0%)	Sloping (5.0–10.0%)	Moderately steep (15.0–30.0%)
Slope length	Short (<10 m)	Medium (10–15 m)	Long (>15 m)	
NT treatment duration	Short (<5 years)	Medium (5–10 years)	Long (>10 years)	
Soil surface cover	Crop residue cover	Bare soil (no mulch cover)		
Crop species	Cereals	Legumes	Cereal-legume rotation	Other (tobacco, cotton, canola, oil-seed rape, olives and sunflower).

Responses among categorical variables were considered statistically significant if the 95% CIs did not overlap each other. Many of the studies did not report any measure of variance for the response variables, thus an unweighted meta-analysis was performed (Johnson and Curtis, 2001). Although unweighted meta-analysis is less powerful than the weighted one, it allowed inclusion of a larger number of studies in the meta-analysis (Prieto-Benítez and Méndez, 2011).

2.4. Results

When averaged across soil and environmental conditions, there were no significant differences in runoff coefficient between NT and CT (Fig. 2A). However, separation of data by relevant categories of the individual selected soil and environmental factors revealed significant differences in runoff coefficient between NT and CT (Figs. 2A–5A). On average, soil erosion was significantly lower under NT relative to CT. NT reduced sediment concentration by 56% and for soil loss 60%, compared to CT (Figs. 2B–4B).

2.5. Effect of climate

Runoff coefficient was lower under NT than CT plots in temperate maritime and temperate continental climatic zones (−39% and −27%, respectively; Fig. 2A). In contrast, in subtropical and tropical regions runoff coefficient was 141% and 25% greater under NT than CT, respectively (Fig. 2A). Runoff coefficient was 27% and 33% lower under NT than CT in locations receiving >1000 mm and <600 mm MAP, respectively. In contrast, runoff coefficient was 31% greater in NT relative to CT in locations that received 600–1000 mm MAP. Runoff coefficient under NT was lower than CT (−33%) at low MAT (≤10 °C) while runoff coefficient did not differ between NT and CT at MAT >10 °C. Temperatures above 10 °C are characteristic of the subtropical and tropical climatic zones while those lower than 10 °C are typically experienced in the temperate regions.

Sediment concentration was also lower under NT compared to CT in temperate maritime and temperate continental climatic zones (−66% and −69%, respectively; Fig. 2B). However, there were no significant differences in sediment concentration between NT and CT in subtropical and tropical climatic zones. Soil losses exhibited a similar trend with climate, i.e. lower values under NT than CT in temperate maritime and temperate continental climatic zones (−80% and −58%, respectively) whereas no significant differences in subtropical and tropical regions (data not shown). Lower sediment concentration and soil losses under NT were observed in locations receiving >1000 mm and <600 mm mean annual precipitation (77% and 62% for sediment concentration, respectively). Sediment concentration was 56% and 73% lower in NT than CT in areas with mean annual temperature ≤10 °C and 10 < MAT < 20 °C, respectively. No significant differences in sediment concentration and soil losses existed between NT and CT were evident at higher mean annual temperature (>20 °C).

2.6. Effect of topography and slope length

A lower runoff coefficient (−19%) was shown in NT compared to CT in plots located at low altitudes (<700 m) whereas there were no significant differences at higher altitudes (>700 m). Sediment concentration under NT was 50% and 73% lower than CT at altitudes <700 m and 700 and 1400 m, respectively whereas there were no significant differences at higher altitudes (>1400 m).

Separation of data by slope gradient and slope length showed a decrease in runoff coefficient in NT compared to CT as slope gradient and slope length increased. For instance runoff coefficient was 35% and 52% lower in NT relative to CT on sloping (5–10%) and gently steep (10–30%) gradients, respectively while tillage had no impact on runoff coefficient on slopes <5%. Significantly impact of tillage on runoff coefficient (−26%) was shown in plots >15 m whereas no significant differences in runoff coefficient were observed in plot lengths <15 m.

Sediment concentration and soil loss under NT were lower relative to CT on moderately steep (10–30%), gently sloping (2–5%) and very gently sloping (1–2%) gradients (79%, 68% and 35% respectively for sediment concentration). In the case of slope length, significantly lower runoff coefficient (−26%) was shown in plots >15 m whereas no significant differences were observed in plot lengths <15 m. Sediment concentration and soil losses under NT were lower than under CT at all examined slope length categories with the largest difference (90%) being in 10–15 m long plots.

2.7. Soil properties

Top-soil factors (i.e. bulk density [BD], texture and SOC content [SOC$_{C}$]) influenced runoff coefficient (Fig. 3A). Runoff coefficient

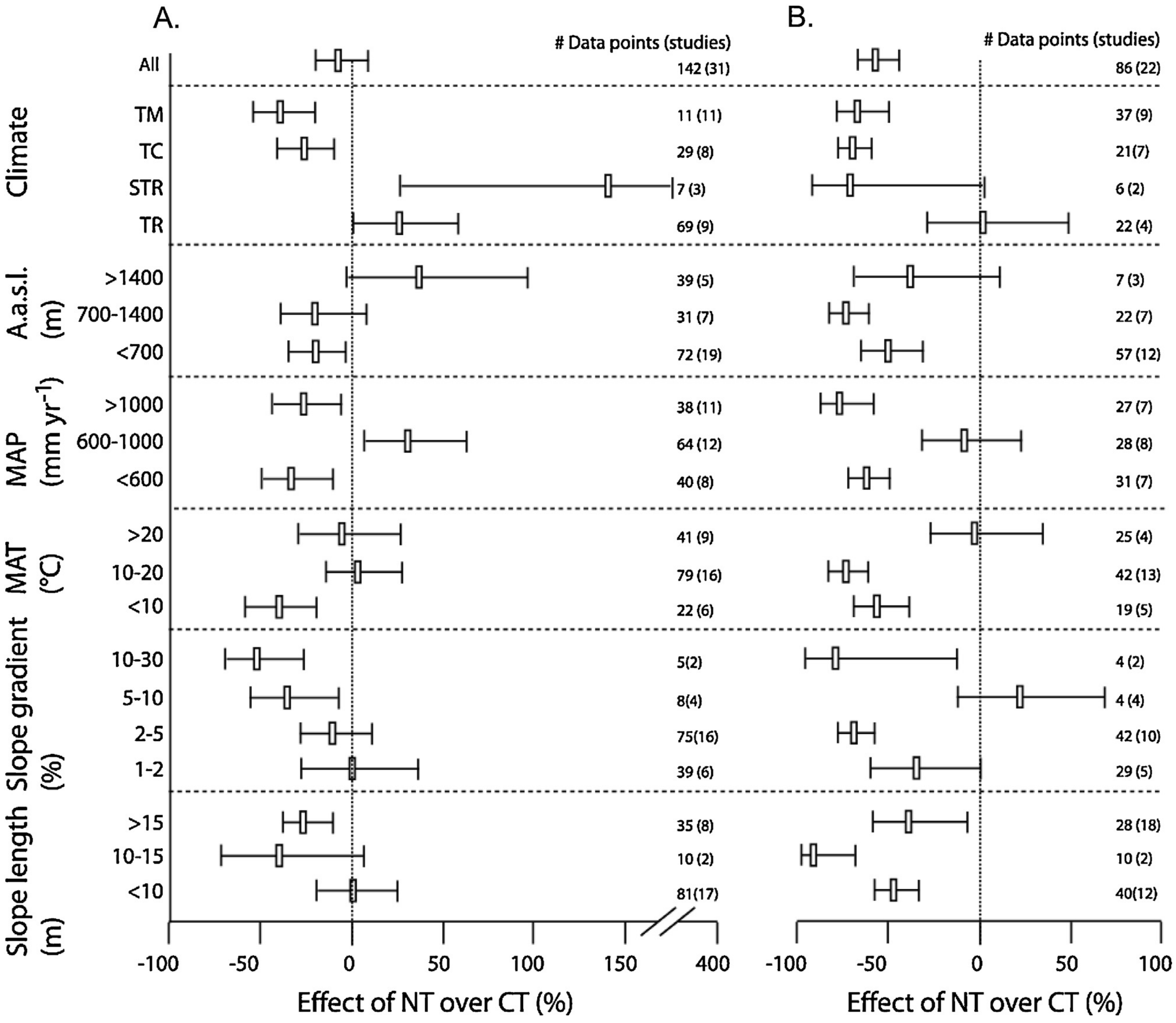

Fig. 2. Percentage change in runoff coefficient (A) and sediment concentration (B) in no-tillage (NT) compared to conventional tillage (CT) as influenced by climate (Temperate maritime: TM; Temperate continental: TC; Subtropical: STR; Tropical: TR), Altitude; meters above sea level (m.a.s.l.), Mean annual precipitation (MAP), Mean annual temperature (MAT), plot slope gradient and plot slope length. Negative values indicate that NT treatment had lower mean water sediment concentration (SC) compared to CT. Error bars are mean and 95% bootstrapped confidence intervals. Numbers correspond to the number of data points and of studies (in parenthesis).

was lower in NT relative to CT in sandy soils (−39%) whereas in clayey soils, runoff coefficient under NT was 33% higher than in CT. In soils with bulk density of 1.2–1.6 g cm^{-3}, runoff coefficient was 22% lower in NT than in CT while no difference was shown in soils with lower bulk density (≤1.2 g cm^{-3}). Runoff coefficient under NT in soils of low SOC$_C$ was 31% lower compared to CT whereas in soils with >2% SOC runoff coefficient in NT was higher by 35% compared to CT. Soil texture, bulk density and soil organic carbon content influenced sediment concentration (Fig. 3B). Sediment concentration under NT was lower than CT in loamy (−71%) and sandy soils (−53%). Sediment concentration under NT compared to CT was 66% lower in soils with bulk density of 1.2–1.6 g cm^{-3} while no significant differences in sediment concentration were shown in lighter soils (≤1.2 g cm^{-3}). Sediment concentration was lower under NT than CT for all SOC$_C$ categories, with the largest sediment concentration in soils with 1–2% SOC$_C$ (−84%) (Fig. 3B). Soil loss (product of runoff and sediment concentration; data not shown) in NT was 75% and 68% lower than in CT in loamy and sandy soils, respectively. Lower soil loss under NT than CT (−73%) was confined to soils with 1.2–1.6 g cm^{-3} bulk density. Soil loss in NT relative to CT decreased significantly in all examined categories of organic carbon content.

2.8. Soil management

Runoff coefficient was 41% lower under NT than CT in plots with mulch cover whereas there were no significant differences between NT and CT in bare soils (Fig. 4A). Plot management (i.e. soil surface cover, NT implementation duration and type of crops grown) had a significant impact on sediment concentration (Fig. 4B) and soil loss response to NT. For both mulched and bare soils, sediment concentration in NT was lower than CT (−55 and −56%, respectively), while soil loss under NT was 72 and 67% lower than in CT in mulched and bare soils, respectively

There was a tendency for runoff to be reduced with increasing duration after tillage abandonment. Runoff coefficient was 30% lower under NT compared to CT for medium (5–10 years) durations while it was and 39% lower longer-term (>10 years). In short-term

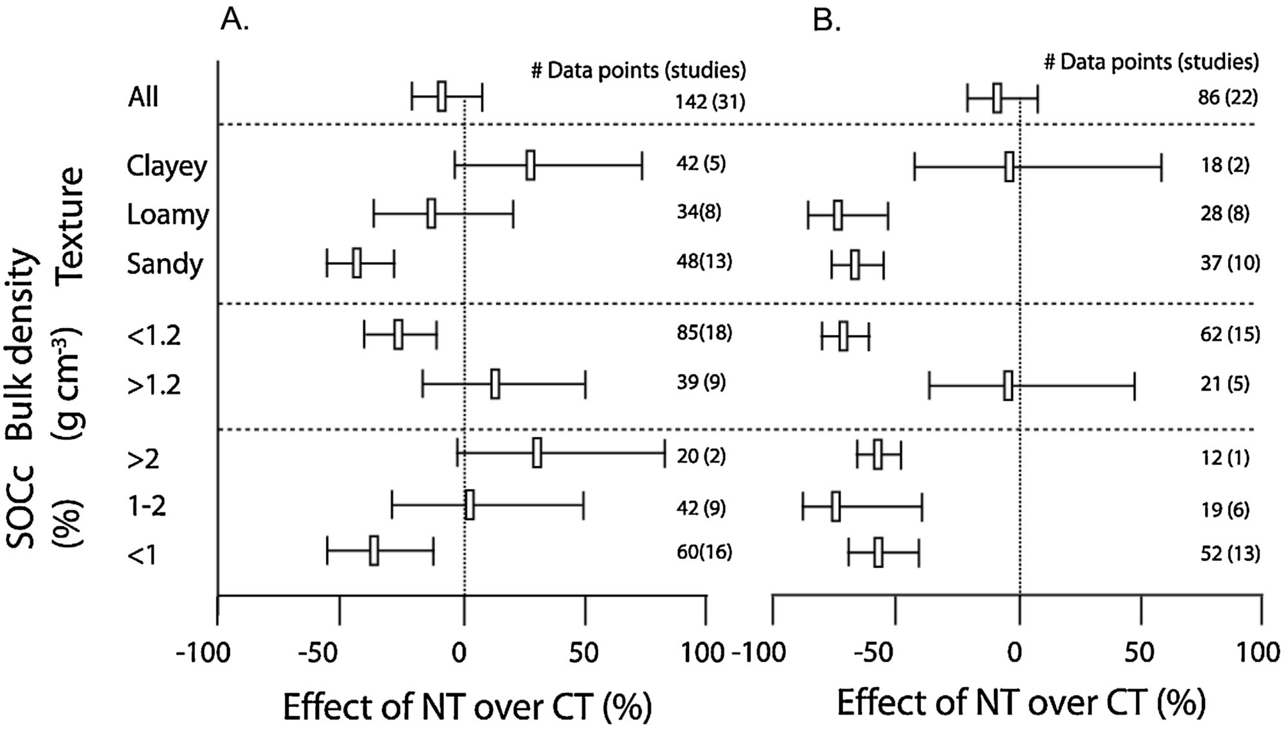

Fig. 3. Percentage change in runoff coefficient (A) and sediment concentration (B) in no-tillage (NT) compared to conventional tillage (CT) as influenced by soil texture, soil bulk density and soil organic carbon content (SOC_C). Negative values indicate that NT treatment had lower mean water SC compared to CT. Error bars are mean and 95% bootstrapped confidence intervals. Numbers correspond to the number of data points and of studies (in brackets).

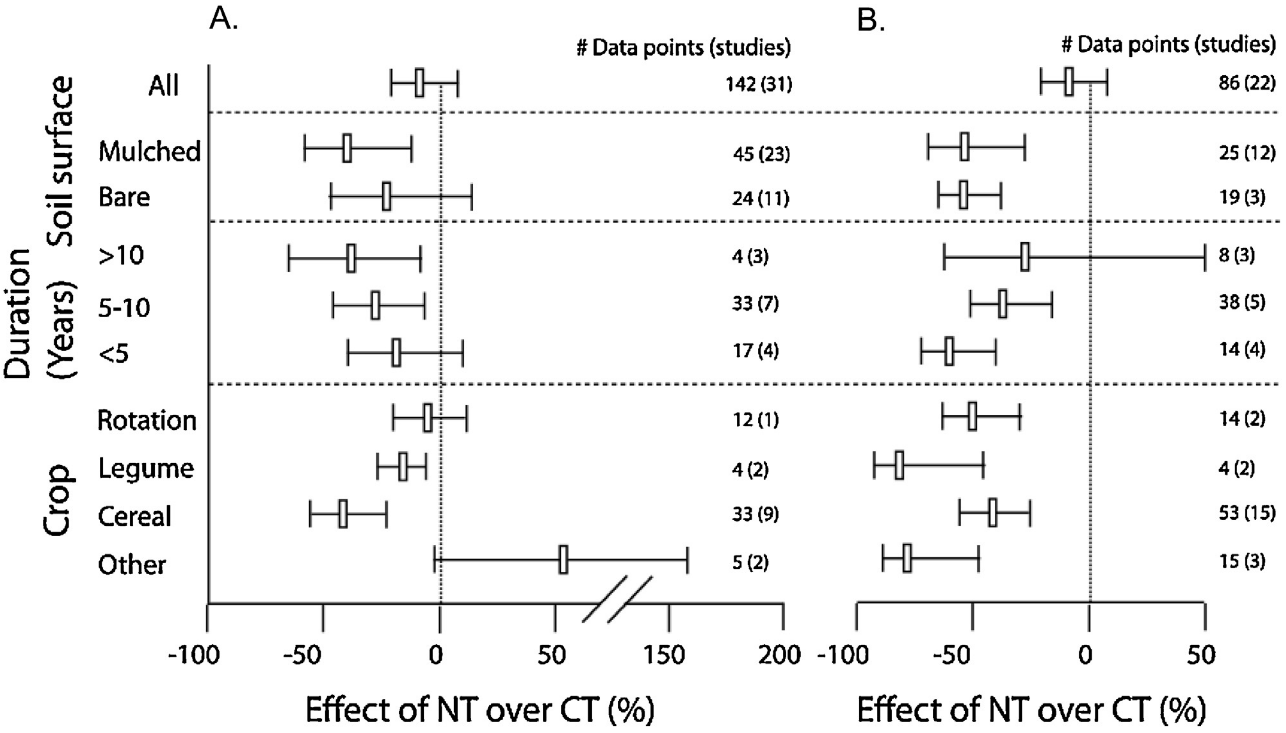

Fig. 4. Percentage change in runoff coefficient (A) and sediment concentration (B) in no-tillage (NT) compared to conventional tillage (CT) as influenced by soil surface mulching, duration since abandonment of tillage and crop type and rotation. Negative values indicate that NT treatment had lower mean water SC compared to CT. Error bars are mean and 95% bootstrapped confidence intervals. Numbers correspond to the number of data points and of studies (in brackets).

experiments (<5 years) there was no difference in runoff coefficient between NT and CT (Fig. 4A).

NT only reduced sediment concentration (Fig. 4B) and soil losses compared to CT in short-term (<5 years) and medium-term (5–10 years) experiments as compared to long term ones.

2.9. Crop species and crop rotations

When considering crop species, runoff coefficient was lower under NT compared to CT in cereals (−43%) followed by legumes (−17%) (Fig. 4A). In contrast, sediment concentration and soil losses under NT were the lowest for legumes (Fig. 4B), with for instance sediment concentration being 77% lower for NT than CT under legumes compared to 58% for cereal-legume rotations and 52% for cereal mono-crops.

2.10. Multivariate analysis

The two first axis of the PCA generated using the selected soil and environmental factors for the construction of the principal components (PCs) and the changes in runoff coefficient, sediment concentration and soil losses following tillage abandonment as secondary variables, explained 52% of the data variability (Fig. 5). Principal component one (PC1), which explained 31% of the data variance was positively correlated with NT treatment duration, altitude above sea level and slope gradient, and was negatively correlated with MAP, MAT and SOC_C. PC2 accounted for 22% of the data variability and was positively correlated with soil bulk density and negatively correlated with soil clay content. The effect of NT over CT for runoff coefficient, sediment concentration and soil losses exhibited negative coordinates on axes 1 and 2 which was interpreted as a greater efficiency of tillage abandonment to lessen runoff and soil erosion under steep carbon depleted sandy soils of low temperature and precipitation regions compared to clayey and carbon rich soils of the tropics.

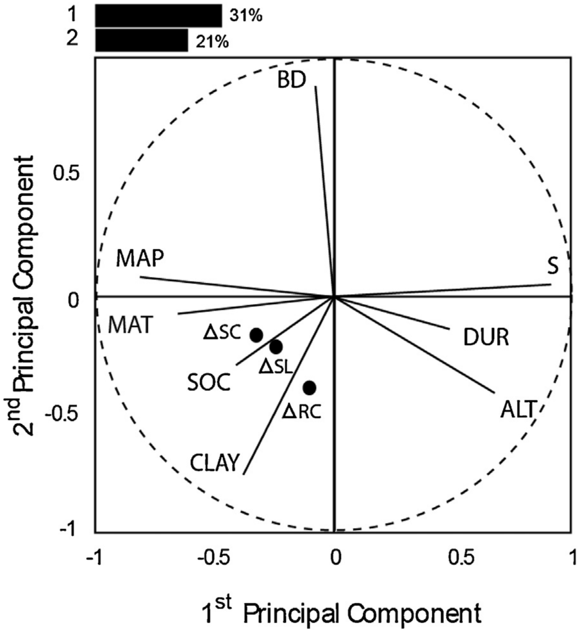

Fig. 5. Principal component analysis (PCA) scattergrams of environmental factors (active variables: DUR: duration since tillage abandonment; ALT: altitude above sea level; SOC: top-oil organic carbon content; Clay: top-soil clay content; BD: top-soil bulk density; MAT: mean annual temperature; MAP: mean annual precipitations; S: mean slope gradient) showing differences in RC, SC, SL and RC, SC and SL between NT and CT as supplementary variables (black circles). Negative Δ% values indicate that NT treatment had lower mean compared to CT.

3. Discussion

3.1. Impact of climate

No-tilled (NT) soils generated significantly less overland water flow and soil erosion compared to conventionally tilled (CT) soils in the cooler temperate climates whereas in tropical and subtropical climates there were generally no significant differences (Fig. 2). This is probably because the soils in temperate climates are moderately weathered and have a weaker structure compared to the heavily weathered and well aggregated tropical clay soils. Tropical soils are composed of predominantly enriched in clay mineral, whereas temperate soils tend to show a coarser texture of lower aggregation capacity (Six et al., 2002). However, tilling temperate soils highly compromises soils' aggregate stability leading to collapse of the soil structure. Therefore, application of NT in the temperate soils is hypothesised to reduce runoff and soil erosion because of the preservation of soil aggregates together with the enhancement of top-soil organic carbon storage, which both result in the improved stability of soil aggregates. On the contrary, NT is unlikely to significantly improve soil aggregation and structure in the already stable and erosion resilient clay and sesquioxide-dominated tropical soils (Potter et al., 2007).

The lower differences between NT and CT for runoff coefficient and soil losses in the warmer environments may be due to the fact that the tropics which are marked by high clay content are also the place of high temperature. The highest benefits of NT in reducing runoff and soil losses seemed to be confined to low (<600 mm yr^{-1}) and high (>1000 mm yr^{-1}) precipitations (Fig. 2). The low and high precipitation regimes typically reflects the nature of rainfall experienced in the tropical climatic zones which is often characterized by intense and highly erosive storms received at the start of the rainy season followed by prolonged low precipitation spells. The heavy storms lead to excessive runoff losses in NT due to reduced infiltration, possibly caused by soil sealing and crusting, whereas in CT the loosened soil, furrows and ridges increase the rate of infiltration due to mechanical rupture of surface crust (Woyessa and Bennie, 2004) and increased surface roughness (Rao et al., 1998) that intercepts water flow and provides depressions for temporary storage of overland flow during storms (Taye et al., 2013).

3.2. Impact of topography

The lower runoff coefficient, sediment concentration and soil losses per unit area under NT compared to CT with increasing slope gradient and slope length (Fig. 2) was expected as soil erosion increases with increasing slope gradient and slope length as steeper and longer slopes increase the velocity and connectivity of overland flow (Wilcox and Wood, 1989; Chaplot and Bissonnais, 2000; Chaplot and Bissonnais, 2003; Liu et al., 2001). The present study pointed to a linear increase in NT efficiency to reduce soil erosion with increasing slope gradient. In addition, the observed decline in runoff coefficient and soil losses per unit area with increasing slope length, under NT compared to CT concurred with findings made by Lal (1988) who compared runoff and soil loss in plots ranging from 20 to 60 m and reported a linear decrease in soil loss with increasing slope length under NT whereas, on the contrary, soil loss in CT increased as a power function of slope length. Wilcox et al. (2003) hypothesised that runoff and soil erosion reductions with increase in plot length depended on the degree of soil disturbance, implying that greater reduction in runoff and soil erosion with increasing plot length would be more pronounced in less disturbed than disturbed ones. This points to the ability of NT systems to change soil losses by water through a combination of decreased overland flow production and velocity and/or increase soil resistance to detachment the residue cover disrupts overland water flow connectivity (Moreno-de las Heras et al., 2010) and as biological crust of greater resistance to erosion develop on soil surface (Mchunu et al., 2011).

3.3. Impact of soil properties

Greater benefits of reducing runoff and soil losses by adopting NT compared to CT were observed in coarse-textured soils and relatively low soil organic carbon content (Fig. 3). Coarse-textured soils and soils with low SOC content tend to have lower aggregate stability but with higher proportion of macro-pores and thus infiltration by water than fine-textured soils (Gardner and Gerrard, 2003; Gil et al., 2013).

3.4. Impact of land management practices

Mulch cover reduced runoff under NT compared to CT whereas mulching had no impact on the NT efficiency to reduce soil erosion (Fig. 4). This was surprising, which Mchunu et al. (2011) explained to be influenced by the development of biological soil surface crusts on NT soils, with great potential to lessen soil detachment and this without the presence of residue mulching. NT impact on runoff was negligible in the initial years of NT treatment establishment (<5 years), probably because the effects of previous tillage would not have been completely eliminated and accumulation of organic matter and improved porosity and infiltration would not have taken root (Krutz et al., 2009; Toliver et al., 2012). In a short-term experiment, Al-Kaisi et al. (2005) recorded insignificant changes in SOC content in NT at the end of 3 years of treatment implementation. Significant accumulation of SOC were only realised within the top soil (0–5 cm) after 7 years (Krutz et al., 2009). In agreement, Sombrero and de Benito, (2010) reported significant increases in SOC content of 25% after 10 years of NT treatment establishment. However, while soil structure under NT might take several years to improve some mechanisms of greater soil protection against erosion following tillage abandonment may show effect almost immediately such as demonstrated by Mchunu et al. (2011) with protective biological crusts appearing within a few months of NT implementation. Bradford and Huang (1994) also concluded that undisturbed soil surfaces were generally resilient to erosion regardless of mulch cover.

On the contrary, NT benefits in decreasing soil losses relative to CT tended to decline with age of NT treatment suggesting a reverse of the trend portrayed in runoff. This observation implies progressive decline in NT performance in reducing sediment concentration and soil losses with increase in age of the NT treatment. This can be explained by the notion that annual SOC concentration in NT increases with time in the first few centimetres of the soil drastically improving soil aggregate stability and mechanical protection. However, accumulation of organic matter in NT continues to do so in the first few years (Lam et al., 2013) or until a new equilibrium is reached then declines exponentially thereafter (Bayer et al., 2006) exposing NT soils to risk of erosion.

Organic soil surface cover that remains undisturbed in NT plots stabilises soil aggregates and prevents soil particle detachment by dampening kinetic energy of raindrops (Ogban et al., 2008; Radford et al., 2008; Truman et al., 2009), minimising soil particle dispersion and crust formation (Unger et al., 1991; van Rensburg, 2010) and decreasing velocity of overland flow (Freebairn and Boughton, 1985; Wilcox and Wood, 1989; Defersha et al., 2011). Furthermore, crop residues release organic compounds, during decomposition, that are reported to have a binding effect on soil particles enhancing aggregate structural stability and preventing collapse of macro-pores (Rhoton et al., 2002) thus improving infiltration and soil resistance to detachment.

Though NT is seen to work only when combined with adequate mulching, surprisingly, the meta-analysis results showed that NT still performed better than CT in reducing soil loss even without mulch cover. This implies that there are other mechanisms that control overland flow and soil erosion in NT besides mulching. The question is: what are the other factors that reduce overland flow and soil erosion in NT besides maintaining surface cover?

Adoption of NT in cereal-based cropping systems provided a better opportunity to control overland water flow than systems that included legumes and other crops. This can be explained by possibly higher biomass quantities produced by cereals as reported in previous studies (Vachon and Oelbermann, 2011; Toliver et al., 2012) and/or a low rate of mineralisation of cereal stover due to high C/N ratio (Sangakkara and Nissanka, 2003). In a 10-year crop rotation study, Sombrero and de Benito (2010) recorded highest crop residue accumulation in a continuous cereal (cereal monoculture) in 8 of the 10 years compared to cereal-legume and cereal-fallow rotations, however, in the current study residue quantities were not monitored per se.

4. Conclusions

The main objective of this study, based on 282 runoff plots comparing NT and CT worldwide, was to quantify the benefits of applying NT on runoff, sediment concentration and soil losses and to identify soil and environmental factors that could be influencing variability in NT performance.

Results from the meta-analysis demonstrated that NT resulted in lower soil erosion relative to CT but there were no differences for overland flow. The differences in sediment concentration and soil losses increased with the increase in plot length and slope gradient. Additionally, greater benefits of tillage abandonment occurred in the coolest regions with soils of higher sand and silt content and thus lower aggregate stability, than under tropical clayey conditions of stable soil aggregates. Moreover, tillage abandonment impact on runoff and soil losses was irrespective of the retention level of crop residues as mulch, which pointed to the predominance of within soil mechanisms of control of soil infiltration by water and soil detachment. Based on these results, it is assumed that NT adoption in temperate climatic zones is likely to yield significant decline in soil erosion compared to tropical regions, despite current efforts to promote NT in tropical and subtropical regions. Finally, tillage abandonment impact was irrespective of the presence of mulch, implying that crop residues can be exported for other purposes e.g. biofuel production. More research is needed to better understand the underlying mechanisms influencing soil erosion and runoff under NT for the improved soil and water conservation.

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Appendix A. Description of the experimental site history, duration of the experiment, mode of precipitation and main results as reported in the articles reviewed in the study.

The main results R, SL and Y designate runoff, soil loss and crop yield respectively, ns stands for non-significant difference in R, SLOR Y between CT and NT. The tillage treatments CT and NT refer to conventional tillage and no-tillage, respectively.

Author	Year	Country	Site history	NT treatment duration	Mode of precipitation	Main results
Araya *et al.*,	2011	Ethiopia	Conventional tillage	3 yr	Natural rainfall	**R** CT > NT, **SL:**CT >NT, **Y**: NT > CT
Barton *et al.*,	2004	China	Experimental farm	4 yr	Natural rainfall	**SL**: CT > NT, **Y**: NT > CT
Basic *et al.*,	2002	Croatia	Commercial farm	5 yr	Natural rainfall	**SL:** T > CT> NT.
Bradford & Huang	1994	USA	15 + yr NT maize & soybeans	Event based	Simulated rainfall	**SL:** T > NT
Choudhary*et al.*,	1997	USA	32 yr continuous maize	Event based	Simulated rainfall	**R:** CT > NT, **SL:**CT >NT
Cogle*et al.*,	2002	India	Experimental farm	5 yr	Natural rainfall	**R:** NT > CT, **SL**: NT > CT
Engel et al.,	2007	Brazil	Soil erosion studies	Event based	Simulated rainfall	**R:**C T > NT, **SL**: CT > NT
Fleskens and Stroosnijder	2007	Portugal	Olive farm	Event based	Simulated rainfall	**R:** CT > NT,**SL**: CT > NT,
Hairston *et al.*,	1984	USA	Soybean production	2 yr	Natural rainfall	**R:** NT > CT, **SL:**CT > NT, **Y:** CT > NT
Jin *et al.*,	2008	China	30 + yr conventional tillage	2 yr	Simulated rainfall	**R:**CT > NT, **SL:**CT > NT
Kinnell	1996	Australia	Pasture-oats-wheat-lupins-canola rotation	Event based	Simulated rainfall	**R**: CT > NT [March], NT > CT [May]
Krutz *et al.*,	2009	USA		Event based	Simulated rainfall	**R:** CT > NT, **SL**: CT > NT
Li *et al.*,	2007	Australia	Old levee bank on experiment farm	6 yrs.	Natural rainfall	**R:** CT >NT, **Y:** NT > CT
Li *et al.*,	2008	Australia	Experimental farm	44 yr	Natural rainfall	**R:** CT > NT, **SL:** CT > NT,**Y**: NT > CT
Lindstrom et al.,	1998	USA	6 yr sod	4yrs	Simulated rainfall	**R:** CT > NT, **SL**: CT > NT
Malinda	1995	Australia		7 yr	Simulated rainfall	**R:** CT > NT
Mchunu *et al.*,	2011	South Africa	Conventional rain-fed maize on	1 yr	Natural rainfall	**R:** ns, **SL:** CT > NT
Munodawafa	2012	Zimbabawe	Experimental farm	9 yr	Natural rainfall	**R: C**T >NT, **SL**: CT > NT
Myers and Wagger	1996	USA	Experimental farm	2 yr	Simulated rainfall	**R**: NT > CT (yr), CT > NT(y2), **SL**CT> NT
Mzezewa and Van Rensburg	2011	South Africa	Experimental farm	Event based	Simulated rainfall	**R:** NT > CT
Nyamadzawo *et al.*,	2003	Zimbabwe	≈11 yr of 2 yr planted fallow rotations	2 yr	Simulated rainfall	**R:** ns, **SL**: ns,
Ogban *et al.*,	2008	Nigeria	Experimental farm	2 yr	Simulated rainfall	**R**:CT > NT, **Y**: CT > NT,
Rao *et al.*,	1998	India	Experimental farm	6 yr	Natural rainfall	**R:** NT > CT
Rhoton *et al.*,	2002	USA	9 yrs NT maize & cotton	Event based	Simulated rainfall	**R:** CT > NT, **SL**: CT > NT,
Rimal and Lal	2009	USA	22+ yr maize	Event based	Simulated rainfall	**R:** CT > NT, **SL**: CT > NT ns
Sasal *et al.*,	2010	Argentina	Tilled for 20 yr; 15 yr maize-soya-wheat-pasture rotation	1 yr	Natural rainfall	**R:** CT > NT
Thierfelder and Wall	2009	Zimbabwe & Zambia	Experimental farm	2 yr	Natural rainfall	**R:**CT >NT, **SL: C**T > NT, **Y:** NT > CT
Truman *et al.*,	2009	USA	Experimental farm	Event based	Simulated rainfall	**R**:CT > NT, **SL**: CT > NT,
Truman *et al.*,	2005	USA	10 yr T & NT	Event based	Simulated rainfall	**R:** CT > NT, **SL**:CT > NT
Tullberg *et al.*,	2001	Australia	Old levee-bank	4 yrs	Natural rainfall	**R:** CT > NT
Verbree *et al.*,	2010	USA	10+ yrs NT	Event based 2yr	Simulated rainfall	**R:** CT > NT, **SL**: CT > NT
Wang *et al.*,	2008	China	Traditional tillage maize monoculture	5 yr R; 2 yr SL	Natural rainfall	**R:** CT > NT, **SL:** CT > NT
Welderufael*et al.*,	2009	Ethiopia	Experimental farm	2 yrs	Natural rainfall	**R:** NT > CT.
Williams, *et al.*,	2009	USA	Ephemeral drainages	4 yrs	Natural rainfall	**R:** CT > NT, **SL**: CT > NT,**Y**: ns
Wood and Worsham	1986	USA	Experimental farm	2 yr	Natural rainfall	**SL:** CT > NT, **Y**: T > NT
Woyessa and Bennie	2007	Ethiopia	Conventional dryland maize production	2 yr	Natural rainfall	**R:** NT > CT
Woyessa and Bennie	2004	South Africa	Long-term tillage experimental site	Event based	Simulated rainfall	**R**: NT > CT, **SL:** NT > CT
Yang *et al.*,	2003	China	Intensified maize farming practices	20 yr	Natural rainfall	**SL**: CT > NT
Yu et al.,	2000	Thailand	–	3 yr	Natural rainfall	**R:** CT > NT
Zhang et al.,	2007	Australia	24 yr experiment	Event based	Simulated rainfall	**R:** CT > NT, **SL:**CT > NT

(*Continued*)

Author	Year	Country	Site history	NT treatment duration	Mode of precipitation	Main results
Zheng et al.,	2004	USA	10 yr wheat followed by 6 yr perennial vegetation	Event based	Simulated rainfall	**R:** NT > CT, **SL:** T > NT

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