Agriculture, Ecosystems and Environment 230 (2016) 231–241

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

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

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ARTICLE INFO

Article history:
Received 22 April 2015
Received in revised form 21 April 2016
Accepted 28 April 2016
Available online 21 June 2016

Keywords:
No-tillage
Runoff coefficient
Sediment concentration
Soil erosion

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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http://dx.doi.org/10.1016/j.agee.2016.04.033
0167-8809/

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.

$$RC = \frac{R}{P} \quad (1)$$

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).

$$SC = \frac{SL}{R} \quad (2)$$

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

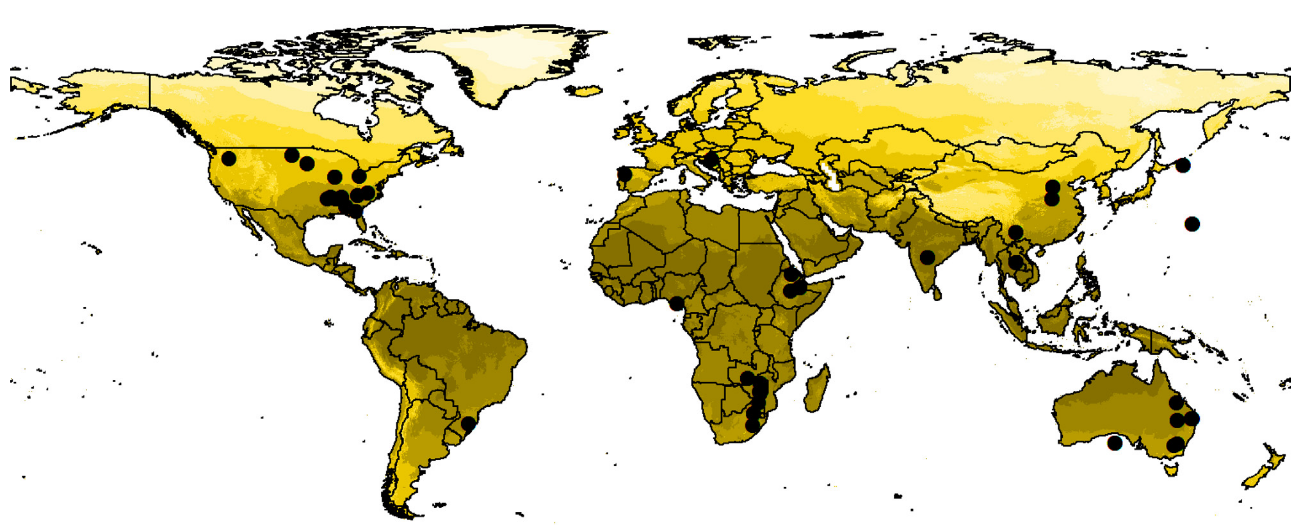

Fig. 1. The world map showing the research sites where the reviewed data were obtained.