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No-tillage controls on runoff: A meta-analysis

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ABSTRACT

Runoff from farmland is of great importance to both agricultural and environmental sustainability. In the present study, a meta-analysis was conducted to quantify the effectiveness of no-tillage (NT) in reducing surface runoff and to explore the factors controlling the effectiveness. Results showed that overall, NT significantly reduced runoff by 21.9% and 27.2% compared to reduced tillage (RT) and conventional moldboard plow (MP), respectively. The effectiveness of NT in reducing runoff was higher under simulated than natural rainfall, particularly as compared to MP. The reduction in runoff under NT was significant and greatest for moderate slope gradients (5–10%) relative to both RT and MP, but without statistical significance for both gentle (<5%) and steep (>10%) slope gradients. As compared to MP, the effectiveness of NT in reducing runoff decreased over time, whereas no such trend was found relative to RT. Compared to RT, NT significantly reduced runoff in soils with low clay content (<33% clay), while resulting in a slight but non-significant increase in runoff in soils with high clay content (≥33% clay). The effectiveness of NT in reducing runoff compared to RT did not vary with tillage direction. Runoff was significantly reduced by NT with crop residue retention relative to RT, but not with residue removal. Our results conclude that NT needs to be adapted to specific environmental conditions and management practices for improved controls on runoff.

1. Introduction

Runoff has important on- and off-site impacts such as soil water availability, sediment, nutrient, and biocide losses (Armand et al., 2009; Soane et al., 2012). No-tillage (NT) has been recommended for soil and water conservation, reduction in labor and energy costs as well as provision of many ecosystem services (e.g., carbon sequestration and soil biodiversity conservation) (Lal et al., 2007; Triplett and Dick, 2008). However, due to lack of soil mixing and surface application of crop residues, fertilizers, and agrochemicals, NT may increase the risk of nutrient and biocide losses in runoff (Holland, 2004; Cessna et al., 2013; Liu et al., 2014). Therefore, the effectiveness of NT in reducing runoff plays a critical role in both agricultural and environmental sustainability (Palm et al., 2014; Kirkegaard et al., 2014).

Although the benefits of NT to erosion controls are well recognized, increasing evidence suggests that NT is less effective in reducing surface runoff than soil erosion (Montgomery, 2007; Armand et al., 2009; Leys et al., 2010; Maetens et al., 2012). There are opposing mechanisms underlying the effect of NT on runoff. On the one hand, NT with residue retention can increase soil surface roughness, prevent surface crusting and sealing, and improve pore continuity, thus increasing infiltration and reducing runoff (Blanco-Canqui and Lal, 2009; Armand et al., 2009; Kahlon et al., 2013). On the other hand, continuous NT may increase bulk density and decrease macroporosity, thereby decreasing sorptivity and hydraulic conductivity (Alvarez and Steinbach, 2009; Fasinmirin and Reichert, 2011; Palm et al., 2014). Thus, previous results concerning the role of NT in reducing runoff are highly variable and inconsistent (Holland, 2004; Armand et al., 2009). Nevertheless, very few quantitative assessments regarding NT controls on runoff have been made (Maetens et al., 2012), though several narrative reviews are available (Armand et al., 2009; Soane et al., 2012; Palm et al., 2014).

The role of NT in reducing runoff reported in previous research varies greatly, indicating that the effectiveness of NT may depend on management practices such as residue management, tillage regimes and environmental conditions such as soil type and slope characteristics (Lal, 1997; Blanco-Canqui and Lal, 2009; Leys et al., 2010; Truman et al., 2011). However, little information exists regarding factors controlling the effectiveness of NT reducing runoff (Maetens et al., 2012). In addition, changes in soil properties

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after the introduction of NT need to be fully developed for a few years (Soane et al., 2012; Jemai et al., 2013). For instance, despite the improvement in chemical and biochemical properties, continuous NT may worsen soil physical conditions (Holland, 2004; Fasinmirin and Reichert, 2011; López-Garrido et al., 2014). Maetens et al. (2012) found that the effectiveness of NT in reducing runoff decreased over time in Europe and the Mediterranean. However, due to the limited number of long time-series (with only two studies applying NT over 5 years), it is not clear whether the temporal trend in the NT control on runoff is globally valid.

Meta-analysis is a promising way for combining independent experimental results to quantitatively estimate the direction and magnitude of a treatment effect (Hedges et al., 1999; van Kessel et al., 2013). Therefore, the objective of this study is to quantify the effectiveness of NT in reducing runoff and to explore the factors controlling the effectiveness of NT.

2. Materials and methods

2.1. Data collection

We used Web of Science for a comprehensive search of relevant peer-reviewed articles published before August 2014, using search terms either "no till*" or "zero till*", and either "runoff" or "run-off". The literature survey focused on runoff from field plots but excluded that from watersheds, as no two watersheds are hydrologically identical due to inherent differences in cropping systems, topography, and runoff characteristics (Williams et al., 2009). We treated different types of tillage as independent, even though they shared a common control in the same study. Runoff was summed, if it was measured multiple times in a growing season or by multiple rainfall runs, or was determined separately in wheeled and non-wheeled areas. One study in which runoff was zero in some treatments was excluded (Nyamadzawo et al., 2012), as zero values are not suitable for the present meta-analysis that used the response ratio as the effect size (Hedges et al., 1999). In order to examine the temporal trend in the effectiveness of NT, studies that reported only average runoff across multiple years were excluded. Data collection was not restricted to studies in which standard deviations were reported or could be inferred, as only 12% of observations gave the information across the dataset. In total, 77 papers were included in this analysis (see Appendices A and B in the Supplementary material for the reference list and site details, respectively) (Fig. 1).

In the present study, tillage systems were classified into three groups according to the intensity of soil disturbance caused by machinery during the primary tillage (Alvarez and Steinbach, 2009): (1) conventional moldboard plow (MP), (2) non-inversion reduced tillage (RT), in which the primary tillage was performed by chisel, disk, or rotary plow or, in several cases, hand hoe, and (3) NT, in which crops are sown directly into an untilled seedbed without any primary or secondary tillage (Fasinmirin and Reichert, 2011). Runoff was measured mainly by natural and simulated rainfall, while several studies that estimated runoff by the runoff equation were also included where runoff was calculated as the difference between rainfall amount and the sum of the total infiltration and surface storage (Appendix B in Supplementary material). Slope gradients were partitioned into three groups: <5, 5–10, and >10% (Lal, 1997). The duration of experiments was divided into three classes: <4, 4–10, and >10 years. We grouped tillage directions into two types: parallel to and across the slope. Soil clay content was separated into two categories: low (<33%) and high (≥33%) (Laganière et al., 2010).

2.2. Meta-analysis

The method of meta-analysis used in the present study followed van Kessel et al. (2013). The effect size was calculated as the natural log of the response ratio (R), which is the ratio of runoff in NT and in RT or MP (Hedges et al., 1999).

As stated above, only a small proportion of studies reported standard deviations, we weighted observations by the following function:

$$w_i = \frac{n}{y} \quad (1)$$

where w_i is the weight for the ith effect size, n is the number of field replicates, and y is the number of years for which the ith comparison was included in the dataset (van Kessel et al., 2013). We chose this metric because it not only avoids bias toward studies reporting results for multiple years, but favors field experiments that are well replicated.

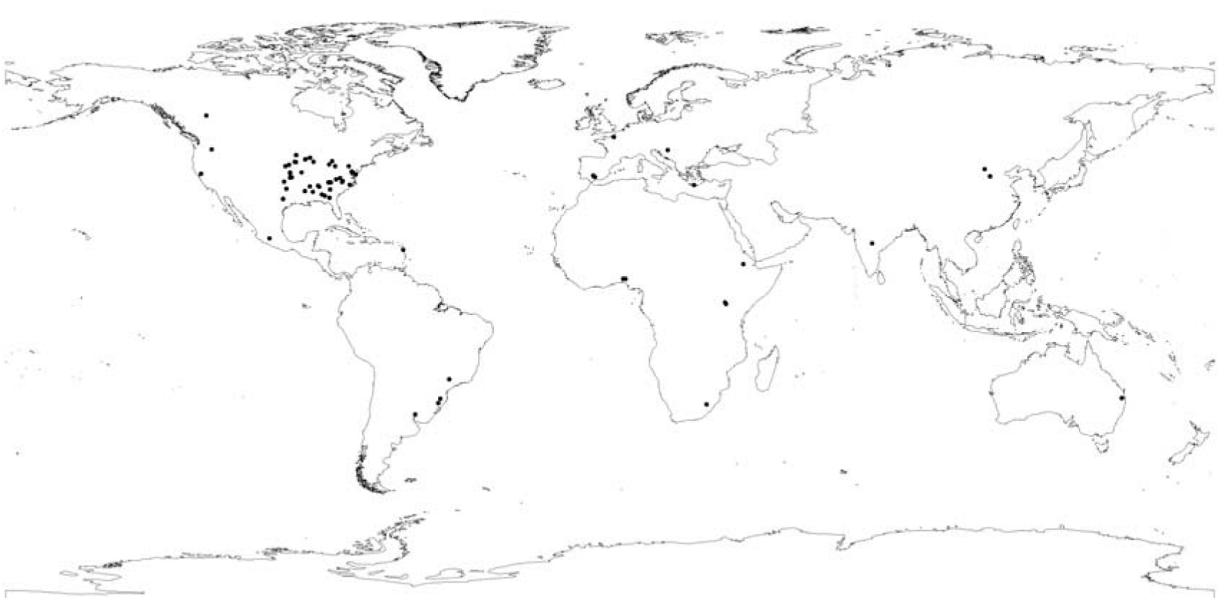

Fig. 1. Locations of studies included in this meta-analysis.