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How effective are soil conservation techniques in reducing plot runoff and soil loss in Europe and the Mediterranean?

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A B S T R A C T

The effects of soil and water conservation techniques (SWCTs) on annual runoff (R_a), runoff coefficients (RC_a) and annual soil loss (SL_a) at the plot scale have been extensively tested on field runoff plots in Europe and the Mediterranean. Nevertheless, a comprehensive overview of these effects and the factors controlling the effectiveness of SWCTs is lacking. Especially the effectiveness of SWCT in reducing R_a is poorly understood. Therefore, an extensive literature review is presented that compiles the results of 101 earlier studies. In each of these studies, R_a and SL_a was measured on field runoff plots where various SWCTs were tested. In total, 353 runoff plots (corresponding to 2093 plot-years of data) for 103 plot-measuring stations throughout Europe and the Mediterranean were considered. SWCTs include (1) crop and vegetation management (i.e. cover crops, mulching, grass buffer strips, strip cropping and exclosure), (2) soil management (i.e. no-tillage, reduced tillage, contour tillage, deep tillage, drainage and soil amendment) and (3) mechanical methods (i.e. terraces, contour bunds and geotextiles). Comparison of the frequency distributions of SL_a rates on cropland without and with the application of SWCTs shows that the exceedance probability of tolerable SL_a rates is ca. 20% lower when SWCT are applied. However, no notable effect of SWCTs on the frequency distribution of RC_a is observed. For 224 runoff plots (corresponding to 1567 plot-year data), SWCT effectiveness in reducing R_a and/or SL_a could be directly calculated by comparing measured R_a and/or SL_a with values measured on a reference plot with conventional management. Crop and vegetation management techniques (i.e. buffer strips, mulching and cover crops) and mechanical techniques (i.e. geotextiles, contour bunds and terraces) are generally more effective than soil management techniques (i.e. no-tillage, reduced tillage and contour tillage). Despite being generally less effective, no-tillage, reduced tillage and contour tillage have received substantially more attention in the literature than the other SWCTs. Soil and water conservation techniques are generally less effective in reducing R_a than in reducing SL_a, which is an important consideration in areas where water is a key resource and in regions susceptible to flooding. Furthermore, all SWCTs show a more consistent and effective reduction of both R_a and SL_a with increasing R_a and SL_a magnitude, which is attributed to the reduced influence of measurement uncertainties. Although some significantly negative correlations between SWCT effectiveness and plot slope length, slope gradient or annual precipitation were found, the importance of these factors in explaining the observed variability in effectiveness seems limited. Time-series analyses of R_a during multiple years of SWCT application strongly indicate that no-tillage and conservation tillage become less effective in reducing R_a over time. Such an effect is not observed for SL_a.

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1. Introduction

Soil and water conservation techniques (SWCTs) have long existed as a means to combat the detrimental effects of soil loss through interrill and rill erosion (Morgan, 2005; Montgomery, 2007; Cerdà et al., 2009). The aim of SWCTs is to reduce both on-site runoff (R) and soil loss (SL) as well as the off-site consequences of erosion such as sedimentation of reservoirs, deterioration of water quality and flooding (e.g. Verstraeten and Poesen, 1999; Owens et al., 2005; Vanmaercke et al., 2011a). Recent research also focuses on the role of SWCTs in the conservation of various ecosystem functions of the soil and its role in bio-geochemical cycles, including carbon sequestration (e.g. Conley, 2000). Whereas the role of SWCTs in reducing soil loss is well recognised (e.g. Morgan, 2005; Boardman and Poesen, 2006), there is still a need to integrate SWCTs effectively into good agricultural and sustainable land management practices. This need is exemplified by the goals of recent policy developments such as the European Commission's Thematic Strategy for Soil Protection (European Commission, 2012). Furthermore, several international scientific projects focus on both quantifying the effectiveness of different SWCTs in reducing R and SL as well as on their successful implementation (e.g. DESIRE, 2007; Karlen, 2008; Louwagie et al., 2009; Römkens, 2010).

Successful SWCT application schemes are sufficiently effective in reducing R and SL to sustainable levels, while not being overdimensioned so that they are economically feasible. Implementing successful schemes therefore requires both qualitative assessments of the effects and applicability of SWCTs (e.g. Schwilch et al., 2011) as well as reliable quantitative data on of the R and SL reduction by the SWCT.

The most widely used measure to quantify the effectiveness of SWCTs in reducing SL is the soil loss ratio (SLR), i.e. the ratio of SL from a plot with SWCT application and SL from a reference plot with the same characteristics but without SWCT application (e.g. Cogo et al., 1984; Castillo et al., 1997; Gilley and Risse, 2000; Smets et al., 2008a). SLR values are similar to the widely used (R)USLE cover management (C) and support practice (P) factor (Renard et al., 1997). However, the calculation of C- of P-factors for specific soil conservation techniques is not straightforward and the validity of the empirical relations for C- and P-factors given by Renard et al. (1997) outside the Midwestern U.S.A. is uncertain. Quantification of SWCT effectiveness for other regions requires local measurements of SLR (e.g. Hessel and Tenge, 2008).

Furthermore, C- and P-factors apply only to SL and not to R. While runoff ratios (RR), the equivalent of SLR, have been used in some studies (e.g. Gilley and Risse, 2000), quantification of SWCT effectiveness remains mainly oriented at SL. Nevertheless, the term 'soil *and water* conservation techniques' implies that also an effect on runoff is expected or desired. Despite the limited attention, runoff reduction remains an important concern. On-site, conservation of plant-available water is an important issue for agricultural production (Wallace, 2000; Rockström et al., 2010) and may be a more important concern than soil loss, e.g. in areas where water is a key resource. Furthermore, sediment yield at the catchment scale is in many cases strongly controlled by the occurrence and magnitude of a few flood events (e.g. Gonzalez-Hidalgo et al., 2010). Hence, runoff reduction is a crucial part of integrated catchment management (Verstraeten and Poesen, 1999; Nyssen et al., 2010; Vanmaercke et al., 2010). In addition, runoff generation and soil loss for various land use types are closely related (Maetens et al., 2012) and information on the effectiveness of SWCTs in reducing R can also improve insights in their effectiveness in reducing SL.

There are also strong indications that the effectiveness of SWCT depends on environmental factors such as land use, saturated conductivity and storm size (Hessel and Tenge, 2008) or plot slope length (e.g. Gilley and Risse, 2000; Smets et al., 2008a,b) and plot slope gradient (e.g. Renard et al., 1997; Syversen, 2005). Nevertheless, very few quantitative assessments of the effects of these environmental factors on SWCT effectiveness in reducing R and SL have been made. Limited understanding of environmental effects on SWCT effectiveness in reducing R and SL also limits the incorporation of SWCT application in erosion models (e.g. Hessel and Tenge, 2008).

Finally, a comprehensive assessment of the effectiveness of SWCTs also needs to consider temporal aspects of SWCT application: the temporal variability in SWCT effectiveness and how this effectiveness evolves over the years since the initial application. The latter has been studied for the build-up of soil organic carbon (Hao et al., 2002), soil biochemical properties (Madejón et al., 2009) and crop yield (Van den Putte et al., 2010; Rusinamhodzi et al., 2011). However, no such study exists with respect to the long-term effects of SWCTs on R or SL.

An overview and meta-analysis of available field-measured data on the effectiveness of various SWCTs in reducing both R and SL can provide important additional insights and can improve our ability to model the effects of SWCT in reducing R and SL under various conditions. However, relatively few comprehensive overviews are currently available. A global assessment of SWCT effectiveness in reducing SL was made by Montgomery (2007), but this analysis does not include R nor does it allow quantification of the effectiveness of specific techniques. For Europe and the Mediterranean, available overviews of SWCTs effectiveness are very limited (Table 1). Several of the available overviews of erosion rates and their controlling factors do not consider SWCTs explicitly (Table 1). Furthermore, the reviews that consider SWCTs often do not include the effectiveness of SWCTs in reducing R. Studies that do consider R are limited to a few specific techniques (Table 1).

The objectives of this paper are (1) to provide an overview of field plot data on effectiveness of SWCT in reducing annual runoff (R_a, $mm^{-1}\cdot yr^{-1}$) and annual soil loss (SL_a, $Mg\cdot ha^{-1}\cdot yr^{-1}$) in Europe and the Mediterranean, (2) to quantify the effectiveness of different SWCT types in reducing both R_a and SL_a and to explore the effect of SWCTs on the relations between R_a and SL_a and (3) to explore the relations of SWCT effectiveness with some important variables that were reported in the experimental studies (i.e. magnitude of R_a and SL_a, plot length, plot slope gradient, annual precipitation (P_a, $mm\cdot yr^{-1}$), and the number of consecutive years of SWCT application).

2. Data collection

Annual runoff and soil loss data, measured on bounded plots where a SWCT was applied for Europe and the Mediterranean were collected from research papers, books, project reports and PhD. theses (Fig. 1). Each plot represents a combination of a soil type, a plot length, a slope gradient, and a land use type and is associated with one type of SWCT (Table 2). SWCTs were classified into three groups according to Morgan (2005) (Table 2). Only runoff and soil loss measurements from bounded runoff plots under natural rainfall, with a minimum length of 5 m were retained. Only annual data are considered: either plot data were collected during at least a full year, or the reported data could be extrapolated to represent a full year with a sufficient degree of reliability, i.e. when measurements were conducted for at least 80% of the year and rainfall was uniformly distributed throughout the year (Maetens et al., 2012), or