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Evaluation of disruption of sediment connectivity and herbicide transport across a slope by grass strips using a magnetic iron oxide tracer

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A B S T R A C T

The use of cover crops has been prescribed as a mitigation measure for offsite contamination, as they reduce sediment and agrochemical loads, thus reducing the hydrological connectivity of the land. However, there is the need to quantify its effectiveness for specific agrochemicals in broader range of conditions, to validate management for its safe environmental use. The objectives of the present study were: (1) to explore the use of simulated rainfall and magnetic iron oxide to understand the impact of vegetation strips on runoff and soil losses at the plot scale and, (2) to evaluate the effectiveness of vegetation strips in buffering sediment and herbicides coming from bare soil areas. The study encompasses six sets of rainfall simulations (three replications each) under four different soil management scenarios: dry vegetation cover sowed that year, dry vegetation cover two years after sowing, freshly-tilled soil, and tilled soil with a compacted surface due to rainfall and trampling. The experiments involved the use of a magnetic iron oxide as a sediment tracer to obtain a better understanding of the trapping efficiency of the vegetation strips. Three runoff plots were established on a hillslope under a Fluvisol alluvial terrace. Each of the plots contained three bare areas tagged with magnetic iron oxide and three strips with *Lolium multiflorum* L. The results indicate that by using cover crop strips, runoff and sediment losses were approximately 20% and 4%, respectively, of the losses measured in the bare compacted soil, while losses on the freshly-tilled surface were similar to that of the cover crop. Herbicide losses were greatly reduced by the cover crops, with losses ranging from approximately 0.1%–0.6% of the doses applied the day before on the bare area. Nevertheless, on the compacted bare soil, terbuthylazine, oxyfluorfen and diflufenican losses were 1.63%, 4.35% and 9.67%, respectively, of the dose applied the previous day. This can be explained because the tilled and compacted soil showed the highest cumulative runoff and soil losses values (28 mm and 248.9 $g\,m^{-2}$). The formation of micro-relief steps after the first simulation reduced the hillslope connectivity and, thus, the soil losses and runoff. Tracer selectivity from soil textures with fine particle size (clay) was observed, as there was an enrichment of these particles in the collected sediment. This study quantified the impact of cover crop strips on mitigating offsite herbicide contamination and improved our understanding of sediment redistribution at the hillslope scale.

1. Introduction

Water erosion and associated offsite contamination are major environmental risks in many Mediterranean crops such as olives or vineyards (Beaufoy, 2001; Gómez et al., 2011). The use of cover crops has been prescribed as a mitigation measure for both problems, as temporary cover crops in the orchard lanes have demonstrated their efficiency in reducing sediment and agrochemical loads (e.g. Gómez et al., 2009a,b). However, a great deal of uncertainty remains about quantifying its effectiveness, due to the limited number of studies available and the wide variability of cover crops observed under field conditions (Taguas et al., 2012; Gómez et al., 2017).

The growth of the phytosanitary sector from 1950 to 2000 provided farmers with a new tool to control spontaneous vegetation without repeatedly disturbing the soil structure. Herbicides have acquired a greater importance in recent years, facilitating the harvesting of permanent crops, controlling perennial species and reducing the frequency and depth of weed control through ploughing. Their importance relies in the fact that by using herbicides, the food productivity is stable and predictable (Ratola et al., 2014). Some of the herbicides used are known

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as pre-emergence or residual herbicides, and these remain in the soil for a certain period of time after their application, extending their action. However, inappropriate management of herbicides can lead to the pollution of the systems, causing toxicity if they reach the trophic chain and altering the natural equilibrium of the plant species in the contaminated ecosystems (Ding et al., 2010; Paganelli et al., 2010; Pal et al., 2010; Wittmer et al., 2010). The adsorption capacity of soil particles, together with their persistence, aggravates this risk. According to Lecomte et al. (2001), the dynamics of herbicide mobilization are influenced by the development of a surface seal. This seal formation limits the depth of the interaction between soil and runoff generation thus, influencing the mobility of the herbicide attached to soil particles. During a rainfall or an irrigation event, and as pesticides and herbicides can be bound onto soil particles, sediment losses become an important factor regarding environmental pollution (Chen et al., 2005; Mantzos et al., 2014). The temporal evolution of the herbicide concentration in the soil depends on the inherent characteristics of the herbicide molecule, the interactions with soil properties and environmental factors. For instance, rainfall and temperature have a significant importance for the herbicide biotic and abiotic degradation, reducing its volatilisation (Loos et al., 2012; Ratola et al., 2014). Also, the effect of application dates or the physico-chemical properties of each of the substances are crucial factors in the herbicide transport processes through the soil (Wauchope, 1978; Lecomte et al., 2001; Mantzos et al., 2014). Awareness of these variables and understanding the associated herbicide transport processes from agricultural soils to superficial water is a vital issue if we are to manage herbicides safely.

Grass strips are described as permanent vegetation or part of the crop rotation cycle which are set out along contour lines, separated by strips of arable land (van Dijk et al., 1996). From a hydrological perspective, they increasing roughness to reduce flow velocity and promote sediment deposition as well as adsorption by the vegetation. Strips of vegetation also act as filters which effectively prevent pesticides (Stehle et al., 2011), herbicides (Vianello et al., 2005), fertilizers (Withers et al., 2009) and runoff-sediment (Campo-Bescós et al., 2013) from entering streams or surface-water reservoirs.

Previous research indicates that it is expected that the degree of efficiency of grass strips in sediment trapping and in filtering will vary widely. For instance, Al-wadaey et al. (2012) found a reduction of 50% in sediment and phosphorus contribution by using filter strips of tall fescue and grasses, which covered, on average, 3% of the plot area. Kapil et al. (2010), in a review of the efficiency of filter strips on offsite sediment and pesticide contamination, found an average reduction of 45% in runoff volume (ranging from 0% to 100%) and an average of 76% in sediment mass (ranging from 2% to 100%). This variability reflected, among other issues, the fact that there are several factors such as slope, type of vegetation and its degree of development (Xiao et al., 2011; Thayer et al., 2012) which significantly affect the efficiency of filter strips. In addition, the development of micro-relief on the strip boundary led to the development of rill erosion, which eventually breached the strips and decreased their efficiency (Pankau et al., 2012). As an example of this large variability in the response, Martínez et al. (2006) showed how in situations of high rainfall intensity on saturated soils, cover crops can still be a significant source of nutrients to water streams.

As in other complex phenomena, a better understanding of the mechanisms controlling the hydraulics and sediment retention capacity of vegetation strips can be obtained from the calibration of models to extrapolate the available experimental data to such a wide variety of scenarios, which will, allow to improve the effectiveness of their use in farm conditions. This has been done with different modelling approaches, empirical e.g. RUSLE (Renard et al., 1997) and physically-based models, e.g.VFSMOD-D (Fox et al., 2010), but all rely on detailed experimental data to perform their calibration and validation. The use of different models can help us to understand the behaviour of pesticides and herbicides in the nature, as well as the performance of the vegetation strips when capturing the sediments. However, they might not be so efficient when determining the sources of those water streams pollutants. The location of sediment sources by using suitable fingerprinting properties has been noted as a good way of evaluating the effectiveness and proper functioning of vegetation filters at the catchment scale (Koiter et al., 2013). At the hillslope scale, sediment tracers are a complementary tool for detecting sediment sources and sinks. They can also be used for estimating the amount of erosion and for monitoring soil movement after water erosion events. This will lead to a better characterization of the system's performance and the different erosion processes taking place in it. Guzmán et al. (2010a) developed a tracing technique based on magnetic iron oxides which they successfully used to determine differences in erosion rates in an olive orchard at plot (Guzmán et al., 2013) and hillslope scale (Guzmán et al., 2015). This tracer could potentially be used for evaluating the trapping efficiency of vegetation strips in conditions similar to those found in orchards under Mediterranean conditions.

The objectives of the present study were twofold: (1) to explore the combined use of simulated rainfall and magnetic iron oxide in understanding the performance of vegetation strips in runoff and soil losses at the plot scale and, (2) to evaluate the degree of effectiveness of vegetation strips in buffering sediment and retaining herbicides from bare soil areas under different conditions, compared to a control situation without strips.

2. Materials and methods

2.1. Location and experiment design

Three runoff plots (A–C) were established in Córdoba, Spain (37° 51′ N, 4° 48′ W, Fig. 1), with an average annual precipitation of 600 mm. The plots were set up on a 15% Fluvisol slope (IUSS Working Group WRB, 2014) at 101 m.a.s.l. Soil texture was sandy loam (5% clay, 38% silt, 57% sand), with a 1.6 ± 0.2% organic matter content at the top 10 cm. Each plot was 6 × 14 m and was delimited with a 15 cm-high steel sheet to avoid runoff coming in from the surrounding plot. At the bottom of each plot (N–S gradient), the sheet was replaced with a steel channel connected to a pipe which collected runoff and sediment (Fig. 2).

In 2010, each plot was subdivided into 6 strips. Three of them (6 m wide and 2 m long) were sown to establish grass strips, while the other three (6 m wide and 2.7 m long) were kept bare using periodical tillage. The vegetation strips were sown at a seed density of 1.67 g m^{-2} of *Lolium multiflorum* L. (580 seeds per m^2) and fertilized with a dose of 80 kg ha^{-1} of N, P and K.

The experiment took place during the hydrologic years 2011/12 and 2012/13. The sediment was collected in a trap, following the design of MacDonald et al. (2001). Four sets of rainfall simulations were performed during the period June 2011 to November 2013, with different soil conditions (dry vegetation cover sown that year, dry vegetation cover two years after sowing, freshly-tilled soil (5 cm depth) and tilled soil with a compacted surface due to rainfall and trampling).

2.2. Soil tagging and herbicide application

In early June 2011, 178 kg of soil, with a background magnetic susceptibility of 1.76×10^{-7} m^3 kg^{-1}, were taken from the top 10 cm of the soil surface on the same slope outside the runoff plots. This soil was air-dried, sieved at 6 mm screen size and mixed by serial dilutions with 89 kg of synthetic magnetic iron oxide (Fe_3O_4), acquired as Bayferrox® 318 M, following the protocol established by Guzmán et al. (2010a).

A total of 29 kg of the mixture was spread by hand on each of the bare surface areas, raked to a depth of 5 cm and, finally, moistened with water using a sprinkler. After this procedure, the average magnetic susceptibility of the tagged strips in the plot was 7.71×10^{-6} m^3 kg^{-1}.