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Soil crusting and surface runoff in agricultural land in Galicia (NW Spain)

Formación de costra y escorrentía superficial en suelos agrícolas de Galicia (NO España)
Encrostamento do solo e escorrimento superficial em solos agrícolas da Galiza (NW Espanha)

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ABSTRACT

This study discusses the soil surface conditions under which crusting and runoff are generated. A field survey was conducted in three agricultural districts in the province of A Coruña (Galicia, Spain), where the soils, developed over basic schists in a temperate-humid climate, are prone to crusting. A total of 168 freshly tilled surfaces and the cumulative natural rainfall since the last tillage operation were studied. The agricultural situations corresponded to primary and secondary tillage, crop seedbeds and pasture seedbeds. Stages of soil crusting were recorded by visual assessment, based on the estimation of the extent of structural, transitional and sedimentary crusting. The runoff was estimated by measuring the maximum distance reached by soil particles carried by the runoff and then deposited on the soil surface where there were no incisions on soil. Surface crusting was observed in all agricultural situations. The amount of accumulated rainfall required to form a fully sedimentary crust was variable, depending largely on the initial soil surface roughness. On average, 50, 150 and 350 mm of accumulated rainfall were required for soil surfaces with a low, medium and high roughness, respectively. The combination of three soil surface conditions (crusting stage, roughness and vegetation cover) was primarily responsible for the start of runoff formation.

RESUMEN

En este trabajo se analiza bajo qué estados de la superficie del suelo se forma costra superficial y escorrentía. El estudio se efectuó en parcelas agrícolas de la provincia de A Coruña (Galicia, España), cuyos suelos, formados sobre esquistos básicos en clima templado húmedo, son susceptibles al encostramiento. Se analizaron 168 superficies recién labradas en relación a la cantidad de lluvia acumulada desde la última operación de laboreo. Las superficies agrícolas analizadas engloban superficies de laboreo primario, laboreo secundario, lechos de siembra de cultivos y lechos de siembra de praderas. El estado de encostramiento del suelo se evaluó visualmente en base al grado de costra estructural, costra de transición y costra sedimentaria. La escorrentía se estimó midiendo la distancia máxima alcanzada por las partículas que han sido transportadas por la escorrentía y posteriormente depositadas en la superficie del suelo, cuando no hay incisiones en el suelo. Se observó encostramiento en todas las situaciones agrícolas. La lluvia requerida para la formación de una costra sedimentaria completa depende fundamentalmente de la rugosidad inicial de la superficie del suelo. La combinación de tres condiciones de la superficie (estadio de la costra, rugosidad y cubierta vegetal) es la principal responsable del origen de la escorrentía.

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RESUMO

Neste trabalho, foram analisadas as condições da superfície do solo sob as quais ocorre a formação de crosta e o escorrimento superficial. O estudo foi conduzido em terrenos agrícolas na província da Corunha (Galiza, Espanha), cujos solos formados sobre xistos básicos sob condições de clima temperado húmido, são suscetíveis à formação de crosta. Analisou-se num total de 168 superfícies recém lavradas a quantidade de precipitação acumulada desde a última operação de lavoura. As superfícies agrícolas analisadas incluiam superfícies de lavoura primária, secundária, e camas de sementes para culturas e pastagens. O estado de encrostamento do solo foi avaliado visualmente com base no grau de crosta estrutural, crosta de transição e crosta sedimentar. O escorrimento foi estimado medindo a distância máxima atingida pelas partículas que foram transportadas pelo escorrimento superficial e depois depositadas na superfície do solo, quando não se verificam incisões no solo. Em todas as situações agrícolas ocorreu a formação de encrostamento. A chuva necessária para a formação de uma crosta sedimentar completa depende essencialmente da rugosidade inicial da superfície do solo. A combinação de três condições de superfície (estágio de desenvolvimento da crosta, rugosidade e vegetação) é a principal responsável pela origem do escorrimento.

KEY WORDS
Conventional tillage, agricultural practices, roughness, sedimentary crust

PALABRAS CLAVE
Laboreo convencional, prácticas agrícolas, rugosidad, costra sedimentaria

PALAVRAS-CHAVE
Lavoura convencional do solo, práticas agrícolas, rugosidade, crosta sedimentar

1. Introduction

Surface crusting has been the focus of research on soil degradation for several decades (McIntyre 1958; Valentin and Bresson 1992). Crusting occurs in two steps: an initial aggregate breakdown period that occurs under rainfall (reorganization of particles into a denser and more continuous structure by filling and compaction) and a subsequent hardening phase during drying. Crust classification varies in the literature but there is an agreement on two major types: structural crust and sedimentary crust. Breson and Boiffin (1990) showed that both crust types correspond to two successive stages in a general pattern of crust development. The change from the first to the second stage depends on the soil surface response to rainfall. These authors distinguished three main stages of surface crusting: initial fragmentary stage (F0), structural crust (F1) and sedimentary crust (F2). This classification has further been refined by including intermediate crust stages (F12) with more precise measurements of the relative proportion of structural and sedimentary crust, and the addition of a stage that corresponds to altered sedimentary crust (F3) (Ludwig et al. 1995).

On cultivated soils, crust formation is a complex phenomenon dominated by a wide variety of factors involving soil properties, rainfall characteristics, flow conditions and agricultural practices (Le Bissonnais et al. 2005). Surface crust development may inhibit seedling emergence and crop development (Gallardo-Carrera et al. 2007). It has a strong influence on soil hydraulic properties and runoff rate (Augeard et al. 2007). Crusting also affects soil surface shear strength and roughness, which, together with vegetation cover, influence sediment detachment and transport processes. Other surface characteristics may also influence runoff and erosion: macropores, biological factors, the presence of rock fragments, and wheel tracks and other linear features derived from the tillage operations (Figueiredo and Poesen 1998).

Runoff and soil erosion associated with farming activities causes significant environmental problems, due to soil loss and diffuse pollution produced in the water resources. In Galicia (NW Spain), despite the existence of some information on erosion of cultivated soil (Valcárcel et al. 2003; Taboada-Castro et al. 2010), references on the soil crusting process and its influence on runoff and erosion have received little attention. Moreover, a good database of soil surface conditions under which runoff and/or erosion are generated is not available at present. Understanding the spatial heterogeneity and temporal dynamics of these surface conditions is a key point for modelling soil erosion by water of cultivated areas on hillslope and catchment scales (De Roo 1998; Cerdán et al. 2002).

The objectives of this paper are: (i) to study the relation between crust formation, under natural rainfall, and the agricultural practices representative of the Galician region, (ii) to determine the dominant soil surface conditions for the runoff occurrence.

2. Materials and Methods

2.1. Study area

A long-term experiment (1999 to 2006) was conducted on three agricultural districts of A Coruña province (Galicia, NW Spain). The climate is temperate humid, with a mean annual temperature of 13.7 °C. The mean annual rainfall varies between 1000 mm and 1400 mm, recorded mostly between October and April. Generally, rainfalls are of moderate or low intensity. In late spring and early summer, storms of high intensity (> 10 mm h^{-1}) are frequent, which can cause rapid soil crusting and even concentrated flow erosion. In the experimental area, annual rainfall ranged from 889 to 1389 mm, presenting substantial seasonal variation between years (**Table 1**). The mean annual rainfall of the study period was similar to the mean long-term value so it is considered that the study period represents normal conditions of rainfall, although summer and autumn were slightly wetter than usual.

The soils studied showed similar geologic and pedologic settings. Soil parent materials are basic schists of the "Órdenes Complex". Soils are relatively deep, acid and medium textured, mainly silty loam with high silt contents (55-65%) and moderate clay contents (10-20%). Main soil types are classified as Cambisol (IUSS 2014), relatively rich in organic matter (41 g kg^{-1}), although variable (9.5-91 g kg^{-1}).

Table 1. Seasonal and annual rainfall (mm) for the study period (1999-2006) and mean rainfall recorded for the 20 previous years. Winter includes December of the indicated year and January and February the following year

Year	Spring	Summer	Autumn	Winter	Annual rainfall
2006	154.2	110.6	788.3	336.1	1389.2
2005	247.8	93.8	512.2	380.2	1234.0
2004	195.0	147.3	365.6	181.4	889.3
2003	212.4	150.6	443.0	192.4	998.4
2002	235.4	106.0	575.6	349.6	1266.6
2001	503.0	155.6	225.0	242.0	1125.6
2000	272.6	128.2	711.9	242.8	1355.5
1999	331.3	106.2	458.6	156.9	1053.0
Mean rainfall for the study period	299.0	124.8	510.0	260.2	1164.0
Mean rainfall (1979-1999)	350.0	89.9	309.7	280.8	1037.7

2.2. Agricultural context

Agricultural production in Galicia is structured around the family farm. The main feature of the sector is its heterogeneity, due to the existence of a multitude of uses, diversity of production models, and different sizes and degrees of intensification of farms. Agricultural landscapes with a strong presence of traditional agricultural systems often coexist with “new agricultural landscapes” and landscapes of agricultural abandonment. The former are characterized by the small size of the fields, low level of mechanization and subsistence polyculture (cereals, maize grain, potatoes, pasture, horticultural crops are the main crops). The second are characterized by larger field sizes, higher levels of mechanization and the predominance of forages (maize and pastures) compared to other crops, the latter being a more intensive and more productive agricultural system than the previous one. Maize is the second forage crop after pastures in economic importance in Galicia, and has an increasing presence in Galician farms (Anuario de Estatística Agraria 2008). However, the size of the "new landscapes" remains much smaller than those in intensive agriculture regions of Spain and northern Europe. Often in the Galician region, larger fields are divided by farmers into smaller portions to order produce different crops at the same time.

Landscapes representative of the traditional and intensive agriculture systems of the Galician region were criteria for the selection of the study sites. Accordingly, within a radius of about 10 km, three agricultural districts were selected. In the study area, the inversion of the soil by ploughing and subsequent harrowing is used in the two types of agriculture systems mentioned. This results in bare soil prior to crop growth and little crop residue remaining on the soil surface. The main crop rotations were: (i) forage maize/fallow/forage maize; (ii) forage maize/forage pasture; other crop rotations also analyzed were forage maize/winter cereal or turnip and potatoes/winter cereal or turnip. Fields under primary or secondary tillage as well as winter fallow were also monitored. The type of crop and rotations selected are representative of the Galician region. Land use, roughness, surface crusting state, rate of soil cover by growing vegetation and runoff classes were observed for each surface.

In the study area soil management is conditioned by the cropping system in every season. In late winter (February) the soil is ploughed (primary tillage) and then left bare until spring (secondary tillage for seedbed preparation). In mid-spring (May), maize is planted in two different ways: in rows on a flat surface (forage maize) or on small ridges (grain maize). After maize harvest (September/October), the fields are either left un-tilled until February of the following year (often forage maize monoculture) or tilled in autumn for sowing forage pasture.

For minority crops, potatoes are planted using a ridge cultivation system in early spring, while the winter cereal and turnip are sown in autumn after several passes with a harrow, leaving a moderately rough surface. Therefore, the soil is unprotected (bare or with less than 20% vegetative cover) about seven months (February to June and October to November) during an agricultural year. In this situation, even low-intensity rainfall can promote soil crusting processes, as well as generate runoff and erosion.

Most of the sites were not homogeneous in terms of crops and tillage year after year since they were divided into small fields with different land occupation according to the farmers’ discretion. In addition, they also differ widely in size (0.9-8.9 ha) and slope (1-15%). In general, the size of the surfaces studied was less than 2 ha and the slope less than 10%.

2.3. Assessment of soil crusting

The dynamics of crust formation for 168 freshly tilled surfaces (F0) according to the natural rains cumulated since the last tillage operation was studied. Seventy-eight surfaces corresponded to primary and secondary tillage (39 ploughed, 29 harrowed, 10 milled), sixty-four to crop seedbeds (27 maize, 15 potatoes, 10 winter cereal and 12 turnip) and twenty-six to pasture seedbeds. This number of initial stages (168 freshly tilled surfaces) exceeded the number of initial fields because several initial states were generated in the same field throughout the year, as a consequence of: (i) the successive tillage operations performed within the same field to obtain a single type of crop or (ii) the subdivision of the field to yield several crops. Occasionally, some crop fields were left abandoned. For these reasons, the number of studied surfaces varied among years. A data set of 2500 soil surface observations (total number of semi-quantitative descriptions performed in the 168 freshly tilled surfaces) from 1999 autumn-winter 2006 was available.

The crusting stage, the surface roughness as well as the distance reached by the detached soil particles and displaced by runoff on interrill surfaces were visually assessed using the methodology proposed by Bresson and Boiffin (1990) and improved by Ludwig et al. (1995). Stages of soil crusting were based on the estimation of the extent of structural, transitional and sedimentary crust. The assessment begins immediately after the last tillage operation when the soil is freshly-tilled (F0). It ends when any of the following circumstances occur: (i) soil surface fully crusted (F2); (ii) non-crusted surfaces, but the soil cover by growing vegetation exceeds 70%; (iii) soil tillage that gives rise to a new initial state.

The evaluation of soil surface roughness was based on the manual measurement of elevation differences between depression bottom and outlet, and on the assessment of connectivity between depressions. Five roughness classes (**Table 2**) were distinguished according to Ludwig et al. (1995). They were used to characterize soil oriented roughness (roughness parallel to the tillage direction: OR) as well as soil random roughness (roughness caused by the random orientation of clods or aggregates on the soil surface: RR).

Table 2. Evaluation of surface roughness (the height difference between the deepest part of microdepressions and the lowest point of their divide, Ludwig et al. 1995), runoff and porosity class

Roughness class (cm)	Runoff class (m)	Porosity class (macropores m^{-2})
R0 = 0-1	R00 = 0 (no runoff)	P0 = no macropores
R1 =1-2	R01 = Up to 10^{-2}	P1 = 1 - 10
R2 = 2-5	R02 = 10^{-2} - 10^{-1}	P2 = 10 - 50
R3 = 5-10	R03 = 10^{-1} - 10^{0}	P3 = 50 - 100
R4 > 10	R04 = 10^{0} - 10^{1}	P4 = >100
	R05 = 10^{1} - 10^{2}	

The distance reached by the detached soil particles was visually assessed by measuring the tracks left by the runoff according to the scale shown in **Table 2**. The porosity class of the soil surface based on the number of macropores (visible to the naked eye) per square meter of surface (macropores density) was also estimated (**Table 2**). The frequency of visual observations varied from surface to surface, ranging from 3 to 11 and in most surfaces it was 5). Field observations were made after each important rainfall event and were particularly frequent when the soil was bare or with the crop in very early stages.

An average of 6 observations (or measurements) per surface were conducted at each visit.

3. Results and Discussion

3.1. Soil surface crusting

Two main crusting stages (**Figure 1**) are distinguished: (i) sedimentary crust (F2) i.e. well-developed crust covering over 90% of the field surface, and (ii) other intermediate crust stages (F12). In this last stage we include the first stages of crust formation, i.e. structural crust as well as the transition stages between the structural and sedimentary crust.

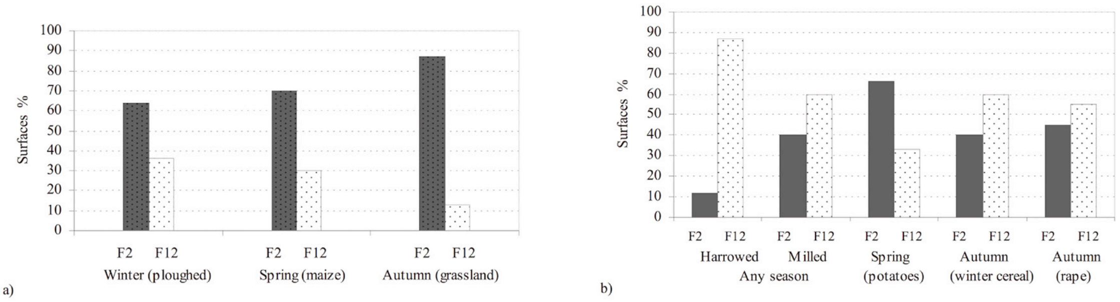

Figure 1. Percentage of surfaces affected by different surface crusting stages according to the agricultural situations in each season. (**a**) Primary tillage and major crops, (**b**) Secondary tillage and traditional crops. F2: sedimentary crust (continuous sedimentary crust in more than 90% of the surface); F12: Intermediate crust stages.

The results showed that these soils were crusted in all seasons. In the same field, depending on the cropping system, the surface can evolve several times a year which suggests that these soils are quite prone to surface crusting and is in agreement with their low structural stability (Taboada-Castro and Taboada-Castro 2003). Sedimentary crust is the dominant soil surface state (**Figure 1a**) in ploughed fields and main-crop seedbeds (maize and pasture). The low proportion of intermediate crusting stages indicates fast crusting dynamics, mainly during the pasture establishment periods. This tendency changes dramatically when referring to secondary tillage (harrowed or milled fields) and to traditional crops (with the exception of potato fields), where intermediate crust stages dominate (**Figure 1b**). These differences in behavior can be attributed, in the first case, to the short periods of time that field surfaces remain harrowed or milled, which generally makes accumulated rainfall insufficient to allow sedimentary crust development. On the other hand, winter cereal and turnip are sown during the rainy season thus allowing the soil to remain moist. This slows down surface degradation, since aggregate stability greatly depends on soil water content (Le Bissonnais et al. 1995; Fox 2004; Gallardo-Carrera et al. 2007). Moreover, these are fast-growth crops able to develop a dense vegetation cover in a short time period, which delays soil crusting.

While almost all tilled surfaces developed a crust within less than 2.5 months, the amount of accumulated rainfall required to reach a sedimentary crust was quite different (**Table 3**).

In this local case study, well-developed surface crusts were usually formed with less than 50 mm rainfall in pastures and less than 100 mm in milled fields, i.e. on fine seedbeds having low surface roughness (roughness classes: R0 and R1). Crusts developed with at least 150 mm rainfall in the rest of the agricultural situations (medium-roughness) except in ploughed fields (high roughness), which normally required amounts above 350 mm to form a sedimentary crust. These results suggest that initial roughness largely determines the rainfall amount required for crust development. However, in fields presenting the same initial roughness degree, variations in the amount of accumulated rainfall necessary for sedimentary crust development have been observed. In most cases, this variability can be attributed to the difference between: (i) tillage tools; (ii) crop state when the rains fall; (iii) rainfall characteristics; and (iv) inter-annual rainfall variations.

Table 3. Cumulated rainfall and soil surface conditions under which sedimentary crust was developed in different agricultural situations and time interval necessary for its formation

Agricultural situation[1]	[2]Cumulated rainfall (mm)			Soil surface conditions					Time interval from F0 to F2
				Roughness (cm)				VC	
	Mean	Min	Max	RRi	RRd	ORi	ORd	(%)	(months)
Ploughed fields (39)	358	287	450	5-10	4-8	10-20	10-20	0	2.5
Maize fields (27)	153	139	270	2-5	2-3	5-10; 10-20	5-10; 10-20	< 40	1.5 - 2
Pastures (26)	42	25	93	0-1; 1-2	0-1	1-2	1-2	< 20	0.5 -1
Harrowed fields (29)	183	113	286	2-5	2-3	2-5; 5-10	2-5; 5-10	0	1
Potato fields (15)	200	110	263	1-2	0-1	2-5; 5-10	2-5; 5-10	< 20	1
Winter cereal (10)	196	184	226	2-5	2-4	5-10; 10-20	5-10; 10-20	< 60	2
Milled fields (10)	74	47	102	1-2	0-1	0-1; 1-2	0-1; 1-2	0	1
Turnip fields (12)	187	167	212	2-5	2-4	2-5; 5-10	2-5; 5-10	< 40	1

[1] In parenthesis number of surfaces studied; [2] Cumulated rainfall from the last agricultural operation; RRi: initial random roughness; RRd: degraded random roughness; ORi: initial oriented roughness; ORd: degraded oriented roughness; VC: vegetation cover; F0: initial fragmentary state; F2: sedimentary crust.

3.2. Changes in surface roughness over time and runoff formation conditions

Surface roughness is a dynamic property that evolves rapidly under the influence of soil tillage and rainfall. Field observations indicated that random roughness (RR) was more susceptible to degradation by cumulative rainfall than oriented roughness (OR), which tends to remain relatively constant (**Table 3**). Surface roughness degradation results in the reduction of temporal water storage that in turn can increase runoff. Therefore, the roughness state influences the initiation and the pathway of surface runoff. On our fields, in the absence of soil incision by concentrated flow, the maximum distance reached by the soil particles displaced by runoff (estimated from the traces left by the runoff on the surface) ranged from 0 m to 10^2 m (R00 to R05) depending on the soil surface conditions according to different agricultural situations (**Table 4**). Thus, on rough surfaces these displacements were limited to short distances (10^0 m) since even when they are degraded they retain a high degree of roughness that can act as a physical barrier preventing the surface flow movement over long distances. In fact, several studies, including some carried out in Galicia (Lado et al. 1999), have shown that a rougher microrelief leads to a higher storage capacity of excess water on the soil surface, delaying runoff generation (Darboux and Huang 2005). In maize and potato fields these displacements, located at the bottom of the ridges, ranged from 10^{-1} (R02) to 10^2 m (R05) depending on the degree of surface degradation. In pastures, displacements of particles transported by runoff at hectometric scale (10^2 m, runoff class: R05) are widespread. The low degree of roughness of these seedbeds (≤ 2 cm), their compaction and their rapid crusting have a strong effect on sheet flow generation. However, maximum runoff distance of 10^2 m (R05) can be reached on freshly-tilled surfaces (F0) or on crusted-surfaces (F2), as long as in both situations substantial rainfall events occur.

Overland flow can become concentrated and cause soil incisions. Many factors are involved in these processes, among them, runoff-contributing areas and slope. Apart from these, tillage-induced linear elements (furrows, wheel tracks and backfurrows) promote flow concentration since they can collect and lead the water excess, mainly in those fields tilled parallel to the slope (Taboada-

Castro et al. 2008). Furthermore, initially-dry uncrusted surfaces or initially-dry or wet crusted, uncovered and with low roughness, were considered as prone to produce concentrated flow and soil incisions in the study area. From these considerations, rough ploughed-fields are not susceptible to being eroded as a consequence of the runoff generated within them.

As mentioned earlier, just days after sowing, many pasture seedbeds had a degraded surface resulting in a surface state highly prone to runoff generation. Previous studies carried out on some of these fields showed that the sedimentary crust reduces the infiltration rate about 10 times in comparison to the freshly-tilled surface (Taboada-Castro et al. 1999). Based on this assumption, one would expect that during the pasture's establishment period (autumn), runoff would be frequent even under low-intensity rainfall.

In summary, in our agricultural districts there was a close relation between farm management and the risk of runoff and erosion. Moreover, a cyclic variation of runoff risk relative to the weather conditions as well as to the type and sequence of agricultural operations was confirmed (Rodríguez-Blanco et al. 2010; Taboada-Castro et al. 2008). Considering an annual time scale, the maximum erosion risk occurs in spring due to the high number of tilled fields (subject to the occurrence of storms on surfaces having less than 30% vegetation cover) and in autumn when pasture was sown. In the latter, runoff and erosion can be important given the seedbed characteristics and the high possibility of rainfall events in this station. Erosion risk in summer is associated with storms when falling over dry, recently tilled soils i.e., restricted to bare fields after harvesting potatoes. The risk of erosion is reduced in winter crops since their

Table 4. Trend of soil surface conditions [a] and runoff classes [b] for the main agrarian situations

Main agrarian situation	Main soil surface conditions	Runoff classes (m)
Freshly tilled surfaces	Fragmented initial stage (F0) without rains Different degrees of roughness according to tillage tools used Bare soil High porosity (class P4)	0
Ploughed fields	Crusting surface (F2) High roughness (class R3; RR: 5-10) Bare soil Decrease of porosity (class P3)	10^0
Winter cereal fields/turnip fields	Intermediate crust stages (F12) Medium roughness (soil harrowed) Low or medium vegetation cover Medium porosity (P2)	10^0
Maize/potatoes fields	Intermediate crust stages (F12)/Sedimentary crust (F2) Low roughness Row crop Low vegetation cover Low porosity (P1)	10^{-1}; 10^0; 10^1; 10^2
Pastures	Sedimentary crust (F2) Without roughness and no macropores Soil bare or with low vegetation cover	10^1; 10^2

[a] Soil surface conditions both surface recently tilled (initial state common to all agricultural situations, differing only in degree of roughness) as others surfaces that reached the maximum stages of soil crusting. [b] Runoff classes are referred to the maximum distance reached by the soil particles displaced by runoff (estimated from the traces left on surface) when there are no incisions on soil.

medium rough seedbeds seal less rapidly and are covered in a short period of time by a dense vegetation cover that delays runoff generation. The vegetation cover could reduce the flow rate, as indicated in other studies (Cerdà 1999; Loch 2000; Rodríguez-Blanco et al. 2013, among others).

4. Conclusions

The dynamic of surface structure degradation by rainfall varies from year to year and with the soil use. It appears to be related to the variations in the timing of rainfall events and with the roughness grade. Freshly-tilled surfaces evolve over time, resulting in different soil crusting stages (intermediate crust stages or sedimentary crust) depending on the interactions between climatic, agricultural and edaphic conditions at a given time. On average, in our experimental area a sedimentary crust develops with accumulated rainfall about 350 mm on very rough surfaces, 150 mm on surfaces moderately rough and less than 50 mm on smooth and firm surfaces.

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