Soil & Tillage Research 111 (2011) 142–153

Contents lists available at ScienceDirect

Soil & Tillage Research

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

Implications of scale, slope, tillage operation and direction in the estimation of surface depression storage

Jesús Álvarez-Mozos *, Miguel Ángel Campo, Rafael Giménez, Javier Casalí, Urtzi Leibar

Public University of Navarre, Dept of Projects and Rural Engineering Arrosadia, 31006 Pamplona, Spain

ARTICLE INFO

Article history:
Received 30 March 2010
Received in revised form 7 September 2010
Accepted 17 September 2010

Keywords:
Agricultural soils
Tillage
Surface roughness
Depressional storage

ABSTRACT

Many studies on soil microrelief, or roughness, have identified a multi-scale behaviour of roughness. However most of the literature on the surface storage of precipitation is based on experiments conducted over very small sampling areas, usually not large enough to reflect the large scale components of roughness. In this paper a 5 m long surface roughness profile database is studied with the main objective of assessing the scaling behaviour of surface storage and the role that surface slope and tillage direction play on this phenomenon. In particular, in was evaluated whether the measurement domain size (profile length) and resolution (sampling interval) had any influence on the calculated storage values. Results illustrate a multiscale behaviour of surface storage, with larger storage values obtained for longer profiles and smaller sampling intervals. Tillage operations significantly affect observed storage values and their variability. Tillage direction also had a significant role in the calculated storage values, however its importance decreased clearly over areas of increasing slopes.

1. Introduction

Soil surface roughness or microrelief plays an important role on a number of processes occurring at the soil–atmosphere boundary (Helming et al., 1998). Among others, the storage of precipitation in surface depressions is an important process with consequences on infiltration, runoff generation and erosion phenomena (Govers et al., 2000). Rough soil surfaces with many irregularities and cavities have more time for infiltration. Consequently, rough soil surfaces are expected to cause lower runoff and erosion rates than smooth soil surfaces.

The storage of precipitation in the soil surface has been generally parameterised using the so called maximum depression storage (MDS) which represents the maximum amount of water (in mm) that can be stored on the soil surface. The direct measurement of MDS is not straight forward since when pouring water at the soil it quickly infiltrates, especially in well structured soils. Therefore, generally MDS has been estimated from surface height measurements (either profiles or grids), using numerical algorithms that virtually fill soil depressions and subtract the original surface from the filled surface yielding the MDS value (Aguilar et al., 2009). In fact, there exist several algorithms that use different calculation methods but they are ultimately based on the same concepts; providing all of them very similar results (Kamphorst and Duval, 2001). Numerical MDS estimations have been compared with real MDS measurements using impermeable soil reproductions and results confirmed the adequacy of the numerical filling algorithms (Kamphorst and Duval, 2001).

Being an important process on the soil surface, surface storage has been included in many hydrological-soil erosion prediction models (DeRoo et al., 1996; Morgan et al., 1998). The estimation of MDS for a specific pixel or model unit is generally based upon the existing relationship between MDS and some roughness index. The most used roughness index is the so called random roughness (RR) which represents the standard deviation of surface heights. Different studies provide empirical regression equations between MDS and RR that have been implemented in a number of models (Kamphorst et al., 2000).

On the other hand, depression storage decreases for sloping surfaces. Early studies already ascertained the role of increasing slopes on MDS (Onstad, 1984), and provided regression equations where both roughness parameters and slope were taken into account for the estimation of MDS (Kamphorst et al., 2000).

However, most of the studies published on this topic are generally based on surface height profiles or grid measurements acquired on small plots up to 1 or 2 m (Carvajal et al., 2006; Aguilar et al., 2009). Recently, close-range photogrammetric techniques (Taconet and Ciarletti, 2007; Elbasit et al., 2009) and terrestrial laser scanning instruments (Heritage and Milan, 2009) have been used for obtaining high resolution digital surface models. Those techniques could potentially obtain point height data over larger areas. However, close-range photogrammetry has been generally

* Corresponding author. Tel.: +34 948169235; fax: +34 948169644.
E-mail address: jesus.alvarez@unavarra.es (J. Álvarez-Mozos).

0167-1987/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2010.09.004

applied to areas up to 1 m^2. Conversely, terrestrial laser scanners could survey areas up to 10–100 m^2, but so far those instruments produced poor results when measuring soil surfaces (Pérez-Gutiérrez et al., 2009); mainly because they seem to be very sensitive to the measuring geometry and, in particular, to the incidence angle (Soudarissanane et al., 2009).

Many studies on surface microrelief have identified a multi-scale behaviour of roughness, revealing that small profiles or sampling areas provide a limited description of surface roughness (Zhixiong et al., 2005; Verhoest et al., 2008). When large profiles or sampling areas are considered, low frequency components of roughness are sampled, resulting in larger values of most roughness parameters. Hansen et al. (1999) studied the variations of MDS values calculated from segments with increasing lengths (from 30 cm to 120 cm) and obtained more accurate storage estimates using longer segments. This issue can be of particular importance for the implementation of MDS on hydrological models. Generally, distributed models use spatial information (DEMs, land cover data, etc.) at spatial resolutions of 5 m at finest, so there is a scale gap between this pixel size and the size of the measurements upon which MDS calculating equations were obtained.

Another important characteristic of agricultural soils, not studied in detail so far, is the relation between surface storage and the direction of tillage rows. The angle between tillage rows and aspect direction (which represents the direction of the main slope), significantly affects runoff flow (Takken et al., 2001). However, as far as the authors know, the effect of tillage direction on MDS has not been quantified yet; furthermore the equations used to calculate MDS on most hydrological models do not include this variable.

In this paper we analyse an extensive dataset of 5 m long profile measurements acquired on winter cereal cropping agricultural areas with the following objectives: (1) to study the influence of height profile length and sampling interval on the obtained MDS values, (2) to investigate the variations of MDS when increasing slope gradients are considered and (3) to quantify how much MDS values can change over agricultural surfaces depending on tillage type and direction.

2. Materials and methods

2.1. Test site

The research was carried out over a small agricultural watershed called La Tejería which is located in the Spanish region of Navarre (Fig. 1). This watershed is part of the Experimental Agricultural Watershed Network of Navarre, created by the local Government of Navarre in 1993 and aimed at studying the impact of agriculture on the hydrological resources (Casali et al., 2008). The watershed can be considered representative of rain-fed cereal cropping areas in the region.

The watershed covers approximately 170 ha with quite homogeneous slopes of about 12%, and an altitude ranging from 496 to 649 m. Its climate is humid submediterranean, with a mean annual temperature of 13 °C. The average annual rainfall is about 700 mm distributed over approximately 105 days.

The prevailing soil class, *Vertic Haploxerept*, covers around 41% of the watershed. These soils are relatively shallow (0.5–1.0 m deep) with a top horizon clayey-silty in texture. The watershed is almost completely cultivated and the hedgerows and streams are the only areas covered by natural vegetation. The main crops are winter cereals (wheat, barley and oat) and, in a much lower proportion, rain fed vegetables (chickpeas and beans) and sunflower. The growing cycle normally starts in September when soil preparation and tillage operations are performed. Soil preparation operations are typical of conventional tillage systems and normally consist of (1) mouldboard ploughing, (2) first harrowing and (3) second harrowing. Afterwards (approximately around October), the cereal is sown and in some (few) fields the soil surface is compacted after sowing using a compacting roller.

2.2. Experimental protocol

Ten agricultural fields were selected over the watershed, with field sizes ranging from 3.0 ha to 7.3 ha (Fig. 1). Fields showed different tillage conditions changing during the experimental period, which started in September 2004 and finished in March

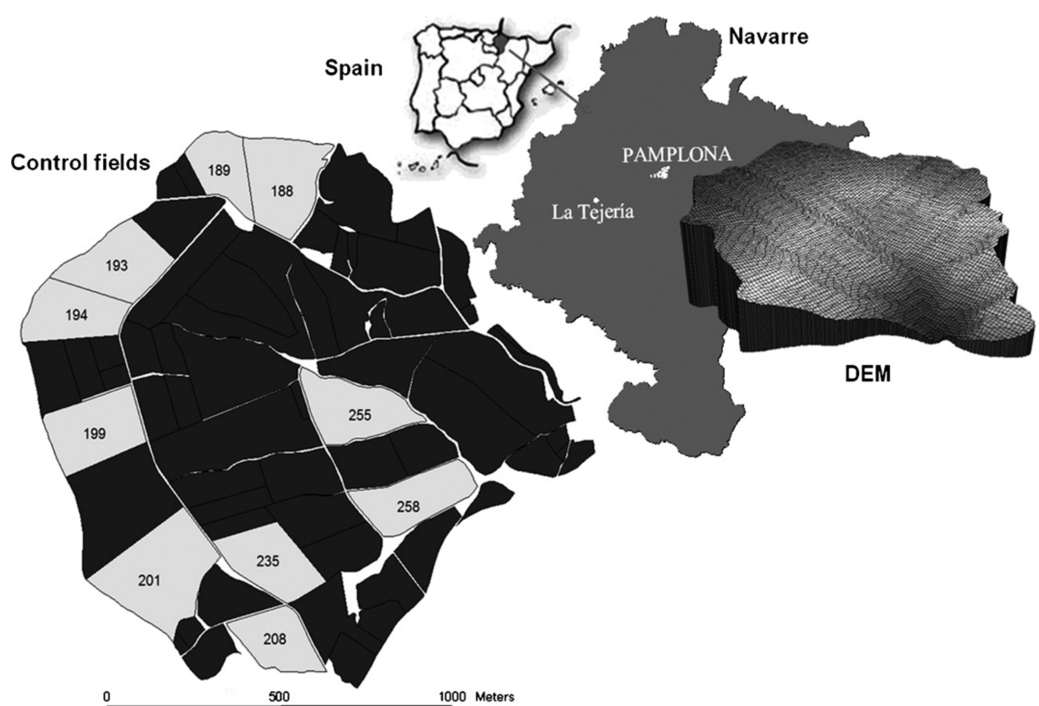

Fig. 1. Location of La Tejería experimental watershed, DEM and distribution of the control fields were surface profiles were measured.

Table 1
Description of the tillage classes found in the study area (ordered according to the typical sequence of tillage operations in the area).

Tillage class	Acronym	Description
Mouldboard plough	MP	Tillage operation performed with a plough with multiple mouldboards at a depth of 15–20 cm, resulting in soil inversion and a very rough surface
Harrowed rough	HR	Operation performed normally with a tine harrow to break soil clods and provide a smoother surface suitable for seeding
Harrowed smooth	HS	In cases where the first harrowing did not smoothen sufficiently the surface a second harrowing is applied
Roller compacted	RC	If the soil surface is still cloddy, some farmers compact the surface with a heavy compacting roller before sowing
Planted	P	Seeding operation performed with conventional sowing machinery, normally seed drills
Roller planted	RP	In few cases farmers compact the soil surface with a roller after sowing

2005. Table 1 briefly describes the tillage classes found in the watershed studied.

Surface height profiles (see Section 2.3) were measured over each experimental field in two directions: (1) parallel and (2) perpendicular to the tillage rows; with 4 repetitions on each direction. Ground measurements were performed on 8 dates: 22/sep/2004, 08/oct/2004, 24/oct/2004, 12/nov/2004, 28/nov/2004, 17/dec/2004 and 01/mar/2005. On the first three dates different tillage classes were measured, on the forth date the cereal crop was sown and hence the tillage class was 'Planted' for the rest of the study period (Table 2). In some measurement days a rather low number of profiles were acquired due to either severe weather conditions or technical problems. In total, a database consisting of 486 profiles was created.

During the research period, the accumulated precipitation was 382 mm, which can be considered normal in the region. As usual, precipitations were scarce on September and October and more frequent during winter months (Fig. 2).

2.3. Height profile measurements

Surface profiles were measured using an originally designed profilometer (Alvarez-Mozos et al., 2005). The instrument incorporates a laser sensor that measures the distance from a reference beam to the soil surface (Fig. 3). The laser profilometer consists of an aluminium beam, attached to two tripods at both ends. A laser sensor is placed on a small carriage that is moved along the beam driven by a small electric motor. The laser sensor has a vertical accuracy of 1.25 mm and a vertical measurement range up to 2 m, which makes it suitable for measuring exceptionally rough soils and other phenomena such as erosion rills and medium sized gullies.

The sensor is programmed to acquire and store height data every 5 mm in horizontal [or lateral] direction. The total length of acquired profiles is 5 m, and the beam can be dismantled in two pieces to be more easily handled and transported. Two plastic racks are attached to the aluminium beam; the former is used by the motor gear to move the carriage and the latter to provide a distance reference to the sensor and to indicate when measurements need to be stored. The instrument is connected to a power supply unit that also contains the data logger.

The processing of the profiles acquired is simple and fast. Once profiles are downloaded to a PC, the beam deflection is corrected using a parabolic curve fitted to a set of reference measurements determined previously in the lab. Each of the height profiles is corrected for the overall slope using regression analysis (considering a linear regression), so that an array of corrected height values is obtained. The profiles are then ready for the calculation of MDS or any other roughness parameter.

Table 2
Tillage class of the test fields on the different measurement dates.

Test field	22/sep/2004	08/oct/2004	24/oct/2004	12/nov/2004	28/nov/2004	17/dec/2004	01/mar/2005
188	Harrowed rough	Harrowed rough	Roller Compacted	Planted	Planted	Planted	Planted
189	Harrowed rough	Harrowed rough	Harrowed smooth	Planted	Planted	Planted	Planted
193	Harrowed rough	Harrowed rough	Planted	Planted	Planted	Planted	Planted
194	Harvested Crop	Harrowed rough	Harrowed rough	Planted	Planted	Planted	Planted
199	Mouldboard Plough	Mouldboard Plough	Mouldboard Plough	Planted	Planted	Planted	Planted
201	Harrowed smooth	Harrowed smooth	Roller Compacted	Planted	Planted	Planted	Planted
208	Mouldboard Plough	Mouldboard Plough / Harrowed rough	Mouldboard Plough / Harrowed rough	Roller planted	Roller planted	Roller planted	Roller planted
235	Harrowed smooth	Harrowed smooth	Planted	Planted	Planted	Planted	Planted
255	Harrowed smooth	Harrowed smooth	No Data	Planted	Planted	Planted	No Data
258	Harrowed rough	No Data	No Data	Planted	Planted	Planted	No Data

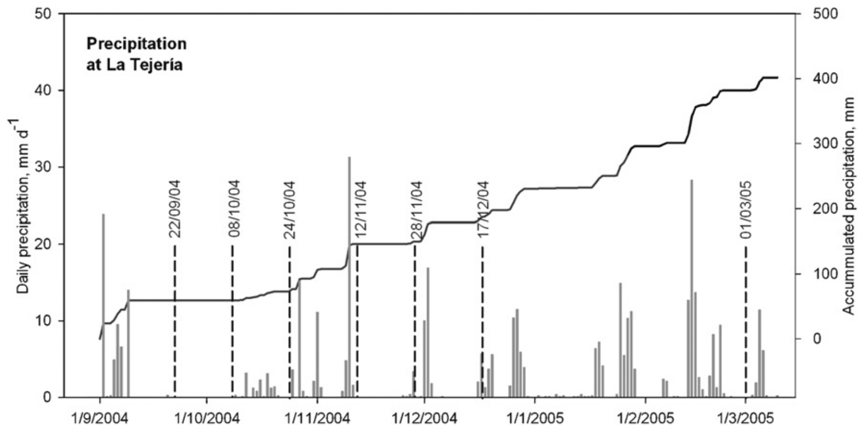

Fig. 2. Daily and accumulated precipitation recorded during the studied period. Measurement dates are shown with vertical dashed lines.

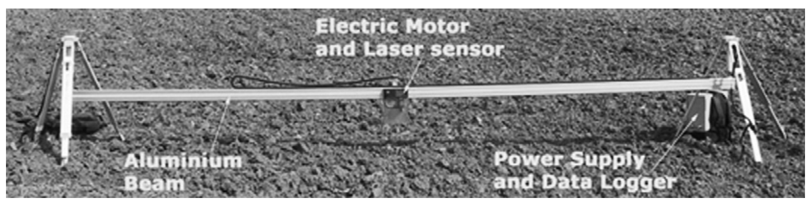

Fig. 3. Main components of the laser profilometer.

The main advantages of this instrument comparing to other roughness measuring methods are: (1) very high accuracy; (2) the soil surface remains unchanged during and after the measurement; (3) profile-data are directly downloaded, thus no post-processing is required; (4) the instrument is robust and can be adequately handled in the field; (5) it can record a very large number of profiles every working day.

2.4. Profile processing and determination of the maximum depression storage (MDS)

As explained earlier profiles were detrended using regression analysis, and thus represented perfectly horizontal conditions. For each profile the MDS was calculated using an ad hoc depression filling algorithm programmed in MATLAB. The algorithm recursively searches for pits or lower points in the profile, and determines the area needed to fill all the depressions up to their pour point (i.e. the water level at the moment they start to overflow). This filled area per unit length is assumed as the maximum amount of water storage in mm (Fig. 4).

In order to assess the influence of the measurement scale on the obtained MDS, both the influence of the domain size (profile length) and sampling interval (spatial resolution) were studied. The influence of the domain size was studied with the following analysis: 5-m long profiles were subdivided into shorter segments of length $L_i = 5/i$, where i is an increasing integer ($i = 1, 2, 3, \ldots, 10$); resulting in profiles with decreasing lengths $L_i = 5, 2.5, 1.67, \ldots,$ 0.5 m. Each profile segment was processed as explained above and its corresponding MDS value was obtained. Finally, for each segment length L_i the mean MDS (average value of MDS of all the segments of length L_i) and its standard deviation were calculated to show the dependence of MDS on L_i. Next, the influence of the

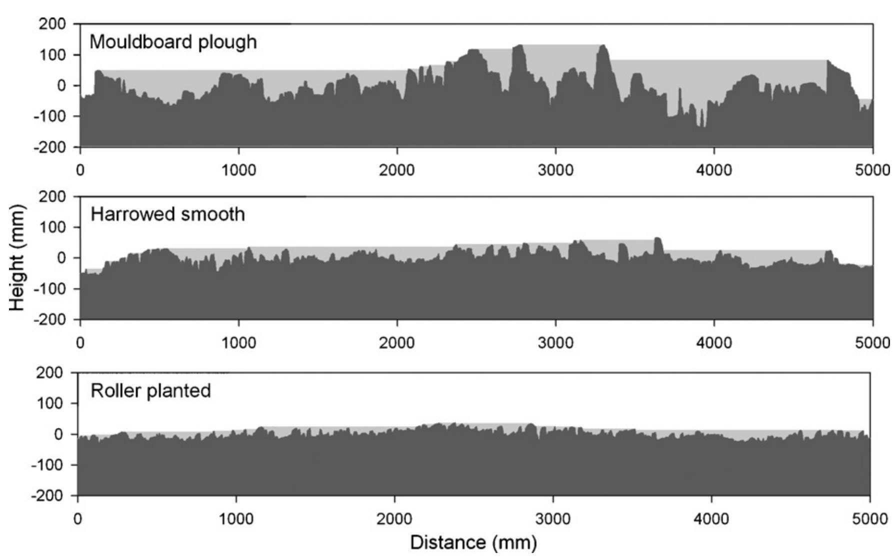

Fig. 4. Samples profiles of contrasting roughness measured in parallel to tillage rows. The areas filled by the MDS computing algorithm are shown.

sampling interval was evaluated following a similar analysis where MDS was calculated for profiles of increasing sampling intervals (decreasing resolution) of 5, 10, 25, 50, 75 and 100 mm. For each sampling interval the mean MDS and standard resolution were calculated.

The variations of average MDS with time were analysed to assess whether precipitation significantly reduced surface roughness and consequently MDS. Average MDS values for each tillage class were also calculated in order to obtain MDS values representative of typical tillage operations in rain-fed cereal growing areas.

In order to quantify the reductions in MDS with slope for the different tillage classes, profiles were successively relocated at increasing slope gradients (5%, 10%, . . ., 45%) and their corresponding MDS values were calculated.

Finally, it was investigated whether tillage direction (with respect to the terrain aspect or main slope direction) influenced the corresponding MDS values. With this aim MDS values were calculated again for profiles of increasing slope gradients but considering two possible scenarios: (1) tillage performed in the terrain aspect direction (i.e. tillage rows are parallel to the main slope) and (2) contour tillage (i.e. tillage rows are perpendicular to the main slope). These determinations were carried out using profiles acquired in parallel to tillage direction and in perpendicular, and comparing the MDS values obtained in both cases at different slopes.

3. Results and discussion

3.1. Scaling behavior of surface storage

3.1.1. Influence of the domain size (profile length)

For each profile and segment length the average MDS and its standard deviation were computed, as explained in Section 2.4. Fig. 5 represents the variation of MDS depending on the profile length for a sample profile (the same behavior can be observed on any of the measured profiles). It can be observed that MDS values change significantly depending on the length of the considered profile with MDS values increasing with larger profile lengths. The observed increasing trend describes an asymptotic shape with a larger slope for shorter profile lengths (below 2 m).

This increasing trend was already observed by Huang and Bradford (1990), who studied the scale dependency of surface storage using simulated Markov-Gaussian surfaces. In their review, Govers et al. (2000) also reported that surface storage measurements strongly depended on their measurement scale,

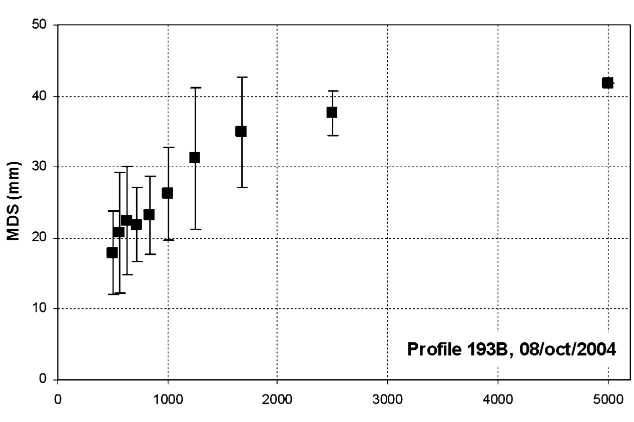

Fig. 5. Maximum depressional storage (MDS) variations depending on profile length for a sample profile. Points represent mean MDS values for each profile length and error bars its standard deviation.

being the size of the plot positively correlated with the obtained storage values. The dependence of MDS on profile length is a consequence of the multi-scale nature of surface roughness. Surface micro-topography consists of a superposition of roughness components with varying frequencies; thus, short surface profiles cannot reflect those low frequency components of roughness, which are only perceptible when profiles are long enough.

In order to compare this scaling behavior among different profiles and different tillage classes, a normalized storage value MDS′ was calculated for each profile segment. The normalization took as a reference the storage value obtained for each profile with a 5 m long segment, as shown in Eq. (1)

$$MDS'_{i,l,p} = \frac{MDS_{i,l,p}}{MDS_{5,p}} \quad (1)$$

where $MDS'_{i,l,p}$ is the normalized storage value for a segment i, with a certain length l and belonging to profile p; $MDS'_{i,l,p}$ is the non-normalized storage for that profile segment and $MDS_{5,p}$ is the storage value calculated for profile p with its maximum length (5 m). MDS′ takes values from 0 to 1 (the later for 5 m long profiles).

Using normalized storage values the increasing trend represented in Fig. 5 can be compared among different profiles and tillage classes. Fig. 6 represents the variation of MDS′ depending on profile length for each tillage class using profiles measured in parallel to tillage rows. Similar results are obtained with perpendicular profiles.

It can be observed that the length of the surface profile strongly affects the obtained MDS values in all tillage classes. For profile lengths of 1 m and lower, MDS is severely underestimated; this underestimation is stronger for rough tillage classes than for smooth classes. Over smooth surfaces profile lengths of 2.5 m could be sufficient to adequately calculate MDS. This can be explained by the absence of low frequency roughness components on these very smooth surfaces. On some of these tillage classes MDS values with 2.5 m profiles can be slightly larger than their corresponding 5 m value, but these differences are not considered statistically significant.

Similar results were obtained by Taconet and Ciarletti (2007), who evaluated the influence of the DEM size on the accuracy of several roughness parameters using close-range photogrammetric observations of a seedbed and a ploughed soil. They observed that as the measurement size increased (from 0.5 m to 3 m), the roughness parameters first increased abruptly and then oscillated around an asymptotic value taken as the true value. The authors observed that the minimum length necessary to reach a certain level of accuracy in the calculation of the roughness parameters was smaller for the seedbed than for the ploughed treatment.

3.1.2. Influence of the measurement resolution (sampling interval)

The results obtained show a decrease of MDS when sampling intervals increase from 5 mm to 50 mm. Similar results were reported in earlier studies considering different ranges of sampling intervals: from 1 mm to 20 mm (Carvajal et al., 2006), from 5 mm to 50 mm (Huang and Bradford, 1990), from 7.5 mm to 1 m (Martin et al., 2008). Conversely, Abedini et al. (2006) found an increase of the pond volume when sampling interval increased from 5 mm to 30 mm. Kamphorst et al. (2000) did not observe significant change in MDS when passing from a 5 mm to a 40 mm resolution.

In order to compare these results between different tillage classes, MDS values were normalized similarly as in the previous section. Fig. 7 shows that all tillage treatments yielded lower MDS values as sampling interval increased. The influence of the measurement resolution is relatively larger for smooth tillage treatments than for rough ones. The reduction in MDS when passing from a measurement resolution of 5 mm to 5 cm is around

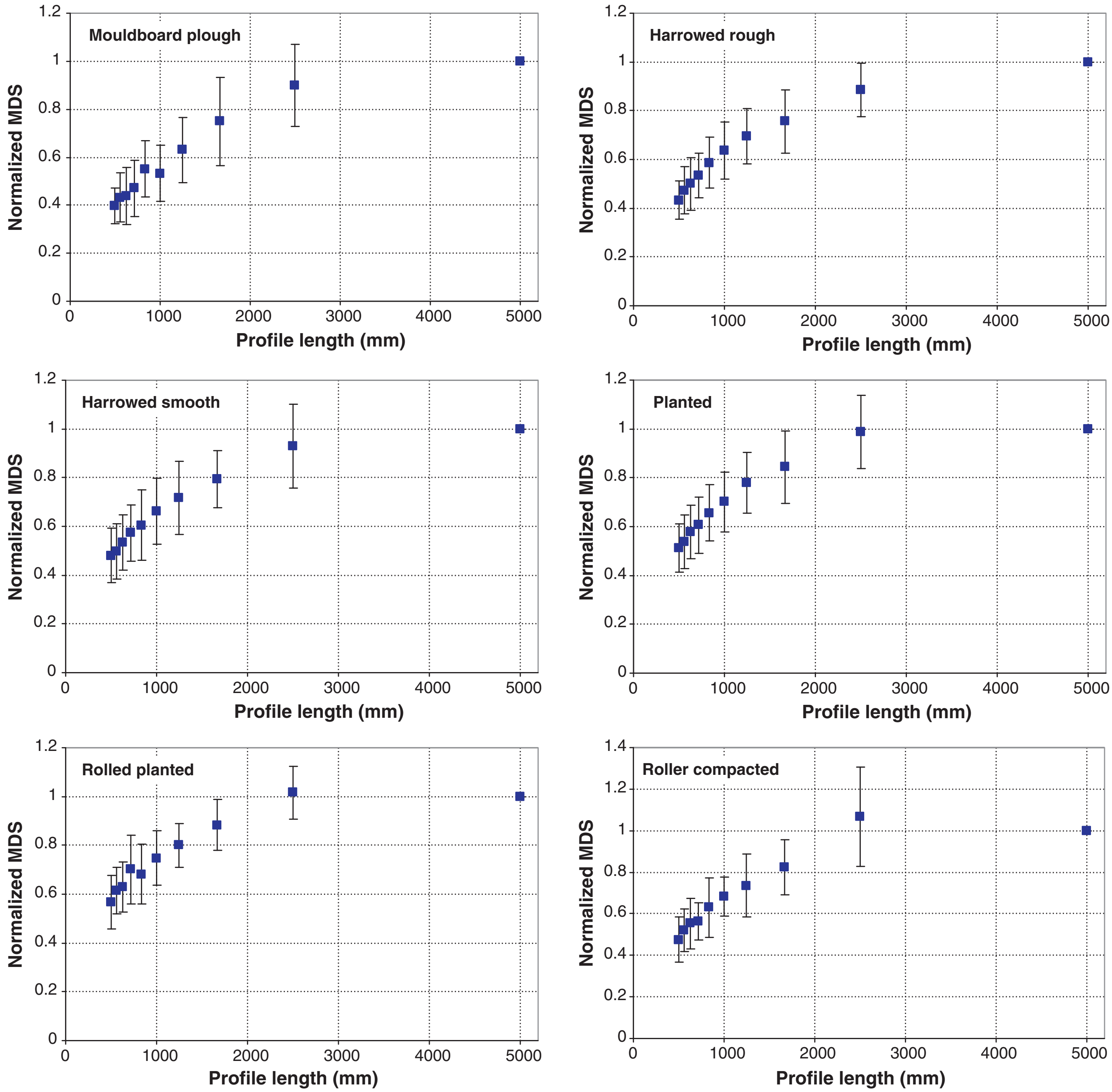

Fig. 6. Variation of the normalized maximum depressional storage (MDS′) depending on profile length for each tillage class. Points represent the average value of MDS′ for each profile length and tillage class and error bars its standard deviation.

a 10% for Mouldboard type surfaces and a 25% for planted ones. These results are directly related with the size of soil clods or aggregates controlling storage on each tillage class. On very rough surfaces clods can be larger than 10 cm, whereas on smooth ones they usually take only a few cm. Therefore, the effect of sampling resolution is stronger (relatively) in the later since at sampling intervals of 5 cm or larger small depressions might not be adequately represented. On rough surfaces depressions controlling MDS are larger and consequently, high resolution roughness components are not so relevant.

The error bars in Fig. 7 illustrate that the variability in the MDS measurements also increases as the sampling interval increases. Therefore, more accurate MDS estimates are to be obtained when high resolution measurements are used. Carvajal et al. (2006) obtained similar results and estimated that passing from a resolution of 5–24 mm implied and error close to 15% in the estimation of MDS for tilled soils.

3.2. Tillage class average MDS values

Average MDS values for each tillage class were calculated using 5 m long profiles. When horizontal conditions are considered profiles measured in parallel to tillage rows provide the most realistic estimate of MDS. Perpendicular profiles could provide overestimated MDS values, since water would normally flow following the tillage row direction (particularly for rough tillage classes). Consequently, all the parallel profiles for each tillage class are used to compute its average MDS value and standard deviation. Those values reflect the influence of tillage operations on MDS, and on its variability. Table 3 summarizes these results.

It can be observed that MDS values varied dramatically depending on the tillage operation performed. Average MDS ranged from values up to 60 mm in the roughest cases to 18 mm in rolled surfaces. These values are larger than those reported in earlier studies (Govers et al., 2000; Kamphorst et al., 2000). This could be a consequence of the larger profile lengths considered here but further studies need to be carried out to confirm this hypothesis. In fact, it has been reported that calculated storage values could be more affected by the processing of height data (in particular the boundary conditions considered) than by the variations of microrelief itself (Planchon et al., 2001).

Absolute MDS values should be interpreted with caution since Onstad (1984) observed that runoff would start well before all the depressions were filled to their maximum. In this sense, Kirkby (2001) highlighted the importance of the spatial distribution of surface storage capacity in runoff generation. The spatial distribution of surface storage led to more runoff than was indicated by a simple subtraction of mean storage capacity from rainfall ((Kirkby, 2001)). This is linked to the concept of connectivity and the location of preferential flow paths. The variability and spatial distribution of storage are key elements for interpreting its influence in runoff processes.

In this context, the variability of MDS seemed to be directly related to its average value. Tillage classes with large MDS showed a much higher standard deviation than surfaces with low MDS. This issue could have strong implications for modeling processes

Table 3
MDS statistics for the different tillage classes.

Tillage class	No.[a]	Mean MDS (mm)	Std. Dev. (mm)	Min. MDS (mm)	Max. MDS (mm)
MP	20	60.80	13.37	36.22	91.13
HR	43	45.49	10.57	21.06	71.59
HS	29	35.18	9.66	20.38	58.83
RC	8	26.15	7.06	16.51	39.88
P	143	25.39	7.69	8.86	47.98
RP	16	18.58	6.85	10.20	32.81

[a] Number of measurements per class.

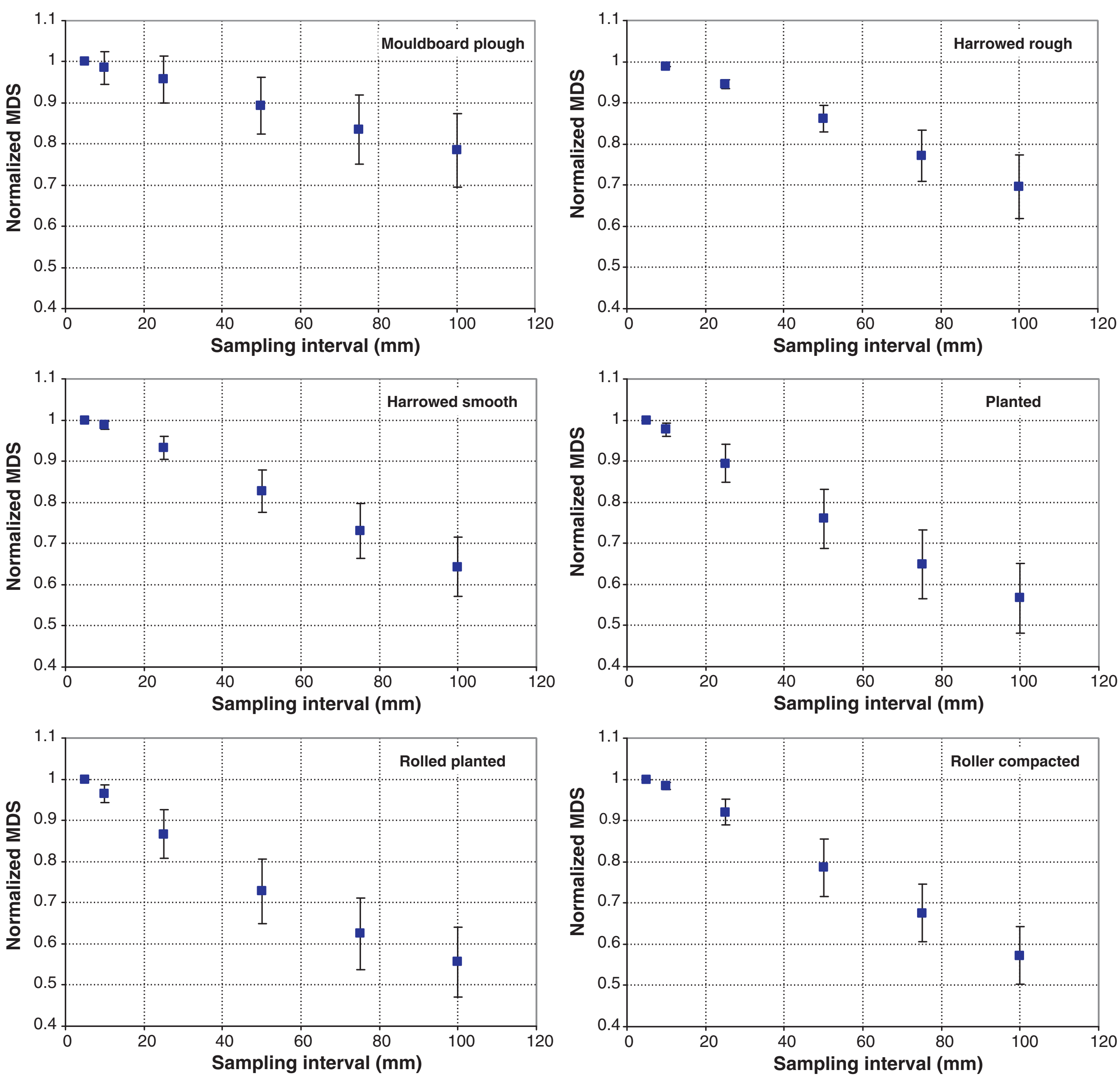

Fig. 7. Influence of the sampling interval on the normalized maximum depressional storage (MDS′) for each tillage class. Points represent the average value of MDS′ for each sampling interval and error bars its standard deviation.

where MDS is involved, resulting in much larger uncertainty when rough surfaces are considered.

Similar results have been observed in the past, for instance Abedini et al. (2006) measured MDS for three plot replicates of 1 m^2 and observed a coefficient of variation around 30%. Govers et al. (2000) reported a coefficient of variation for random roughness increasing from 15% to 35% for agricultural surfaces ranging from smooth to rough. Gomez et al. (2005) also reported a large spatial variability of soil physical properties such as surface roughness and hydraulic conductivity. In particular, they observed a coefficient of variation of 25% for roughness measurements acquired with the chain method over disk tillage plots. These high variability values were attributed to differences in soil conditions at the time of tillage. Arvidsson and Bolenius (2006) also observed significant variations in surface roughness for tillage treatments performed with the same implements but different soil moisture conditions. Differences in soil wetness and clay content, number of passes of the tillage tool and tractor speed might explain the variability observed for each tillage class.

3.3. Temporal variation of MDS on seedbed fields

Precipitation causes the smoothing of soil surfaces. Rain splash detaches soil particles and makes them fill the gaps in the soil surface, causing an overall reduction of surface roughness and hence of MDS (Guzha, 2004). Over cereal growing dry lands, once fields are sown, the soil surface remains poorly covered for several months until the emerging vegetation canopy effectively covers the soil. During this period soils are exposed to erosion processes. This is particularly true in temperate regions where those months correspond with a wet and cold season.

In order to assess whether precipitation significantly reduced surface storage only planted fields were investigated. Two of the control fields were already sown on the 24/October/2004, whereas the remaining were sown on the next measurement date, 12/November/2004 (Table 2). Therefore, five measurement dates were available for the analysis. Fig. 8 shows the temporal variations of MDS on those five dates. The first four dates showed no clear reductions in MDS and the variability of MDS on each measurement date was larger than any temporal trend observed. This result was expected since the accumulated precipitation recorded from 12/November/2004 to 17/December/2004 was less than 50 mm, so those variations were a consequence of the spatial variability of soil microrelief.

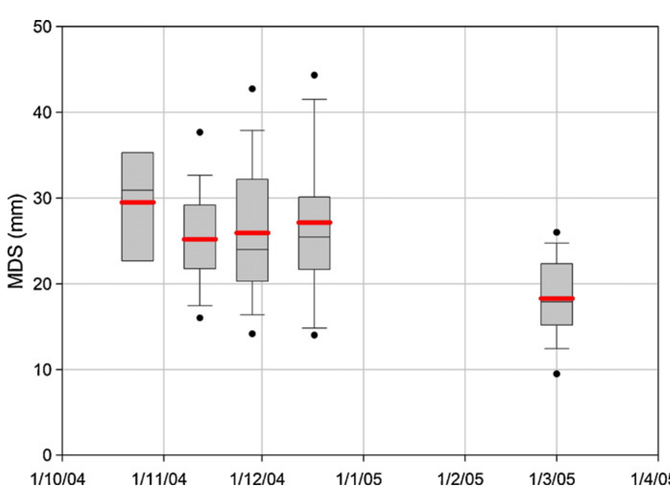

Fig. 8. Boxplots representing the variation of the maximum depressional storage (MDS) from November till March for planted fields. Dashed thick lines represent average values for each measurement date.

However, on 1/March/2005, after more than 200 mm of precipitation, observed MDS values were significantly lower than in December. On this last measurement date average MDS was 18 mm, whereas in the previous dates it was above 25 mm. After March, the vegetative cover was general sufficiently developed to protect the soil surface and surface smoothing was less likely to occur.

Experiments specifically designed to evaluate the reduction in surface roughness and depression storage with rainfall have been carried out in the past. The work of Zobeck and Onstad (1987) reviewed a number of previous studies and proposed an exponential trend relating the roughness decay with the cumulative precipitation which is generally accepted (Govers et al., 2000) and implemented in some erosion models (for instance, (Morgan et al., 1998)).

3.4. Influence of terrain slope and tillage direction on MDS

When an increasing slope gradient was imposed to surface profiles the calculated MDS decreased following an exponential trend. Fig. 9 shows the variation in MDS for increasing slope gradients when tillage is performed in the terrain aspect direction (using profiles measured in parallel to tillage rows). The variability observed for MDS decreases strongly with increasing slopes.

Using average MDS values for each slope gradient, exponential equations were fitted with a very high determination coefficient. The obtained equations are shown in Fig. 9. Similar exponentially decaying trends were observed by Huang and Bradford (1990) for both numerically generated and ground measured surfaces. Thompson et al. (2010) studied the role of microtopography in rainfall-runoff partitioning using a numerical model that considered a simplified one-dimensional hillslope with uniform sinusoidal microtopography. They observed large increases in the proportion of rainfall that infiltrated when a rough hypothetical hillslope with a 2° slope was compared with a perfectly smooth reference case (approximately doubling the percentage of rainfall that infiltrates). When a 10° slope was considered microtopography continued to exert an increase in infiltration relative to the reference smooth surface, but this increase declined (from a doubling to a 50% increase), primarily due to decreased storage volumes.

The decay of MDS for increasing slopes seems to be more marked for smooth tillage treatments than for rough ones. This is in accordance with the work of Darboux et al. (2002) who studied the influence of slope on depression storage using numerically generated surfaces and determined that the influence of slope depended on the roughness of the surface considered.

In agricultural areas the orientation of tillage ridges or furrows with respect to the slope is also crucial. In fact, the role that surface roughness plays in hydrological and erosion processes can be completely different depending on its orientation with respect to the slope Kirkby (2001). Therefore, it was assessed whether tillage direction had any influence on MDS over sloping terrains. With this aim MDS values were calculated for profiles of increasing slope considering two possible scenarios: (1) tillage performed in the terrain aspect direction and (2) contour tillage. This was done using profiles acquired in parallel and in perpendicular to tillage rows, and comparing the MDS values obtained in both cases. The results of the analysis are plotted in Fig. 10.

As expected, larger MDS values were obtained when contour tillage was considered. These increments (ΔMDS) were more prominent for rough classes, especially for 'Mouldboard plough' with differences up to 12 mm (Table 4). Smooth tillage classes showed smaller differences in MDS between both tillage strategies, generally below 3 mm. In the case of the 'Rolled planted' class, no relation was found between MDS and tillage direction, since very similar MDS values were obtained for both contouring and aspect

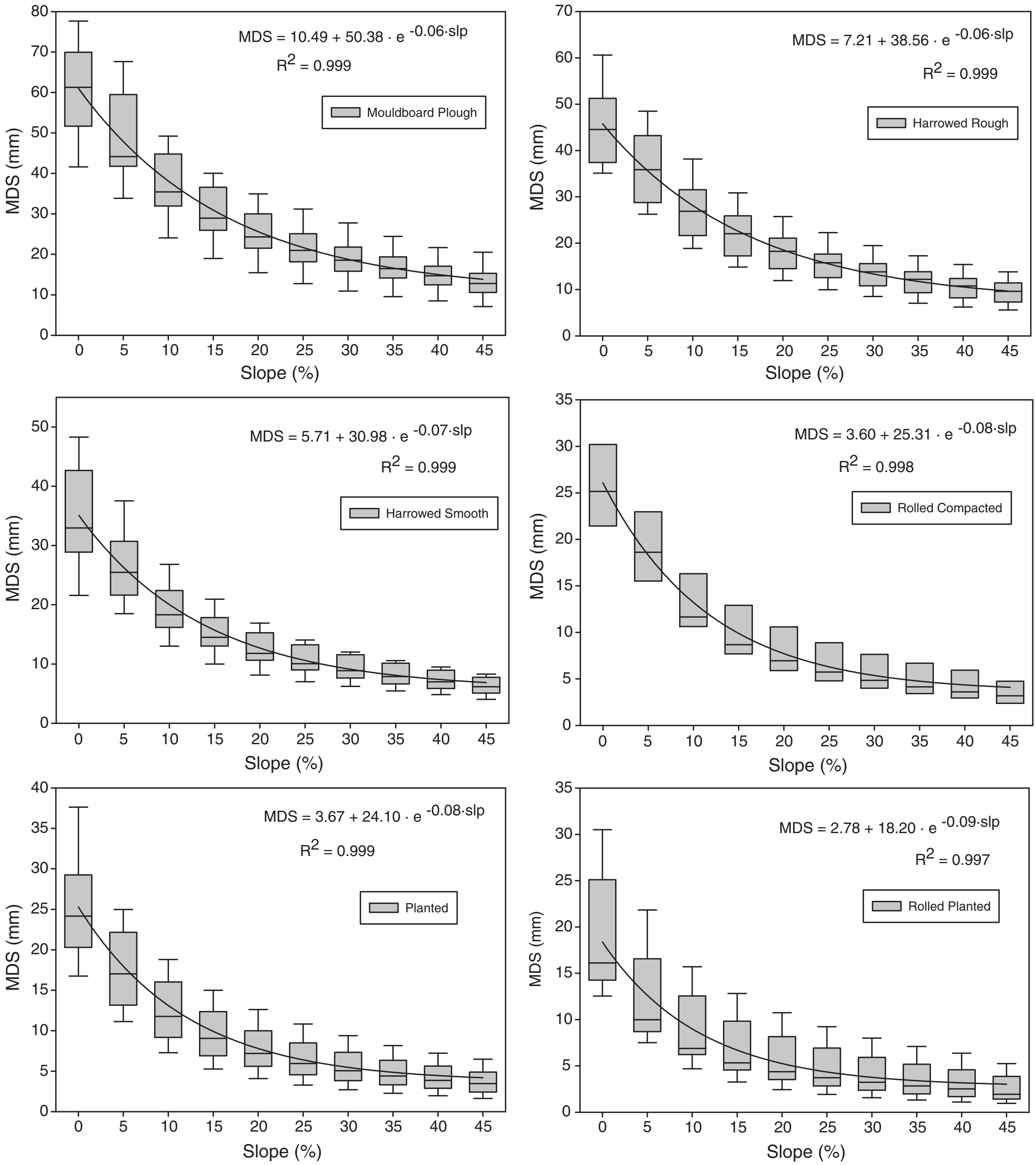

Fig. 9. Variation of the maximum depressional storage (MDS) with increasing surface slopes for each tillage class. The exponential curve fitted to each class is shown. Note the different vertical scales.

Table 4
Influence of tillage direction on MDS for increasing slopes. This table represents the differences in storage (ΔMDS, in mm) between contour tillage and tillage in the terrain aspect direction. ΔMDS values are given for each tillage class (MP, HR, etc.) and increasing slopes.

Tillage class	Slope (%)			
	10	20	30	40
MP	12.0	8.5	6.6	5.3
HR	4.1	2.6	1.7	1.2
HS	3.4	1.9	1.2	0.8
RC	2.0	1.5	1.1	0.8
P	2.4	1.5	1.0	0.8
RP	0.8	−0.1	−0.3	−0.3

direction tillage, leading to ΔMDS values close to 0 (Table 4). This behaviour is not surprising, since this class represented very smooth surface conditions where tillage rows were not even perceptible.

On the other hand, the ‘Rolled compacted’ class showed a different behaviour than the ‘Rolled planted’ class. In this case, the influence of tillage direction was appreciable and similar to that of the class ‘Planted’. It must be pointed out that ‘Rolled compacted’ consisted on a compacting roller operation performed after harrowing the soil. This was normally done when the previous harrowing operation produced a rather cloddy surface too rough to seed adequately. As a consequence this class produced a surface smoother than the harrowed classes but still similar in roughness to the ‘Planted’ class.

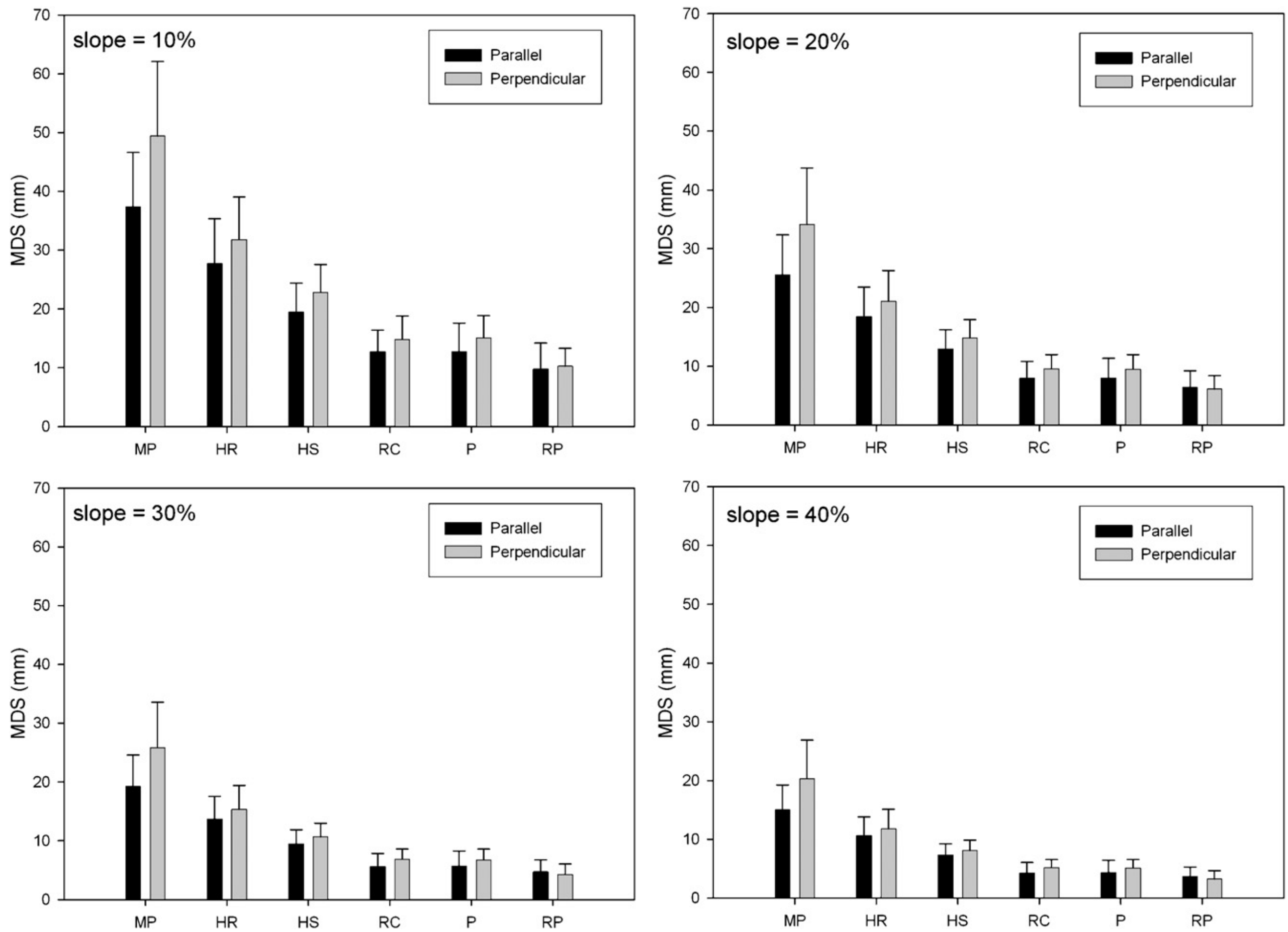

Fig. 10. MDS values computed for each tillage class considering tillage in the aspect direction (black bars) and contour tillage (grey bars), respectively.

Although slopes with contour tillage always had larger MDS values than those tilled in the aspect direction, ΔMDS significantly decreased as the slope increased. For a 40% slope ΔMDS was generally below 1 mm, except for 'Mouldboard plough' where it was around 5 mm. The experimental data used to obtain the RUSLE2 contouring subfactor are in accordance with these results. According to RUSLE2 contouring is most effective for slopes around 8% and for higher ridges (NRCS, 2008). Contouring has no effect for a 0% slope because flow direction is not defined. Besides, contouring has no effect beyond a maximum slope that is a function of ridge height, the value of this maximum slope ranges from 15% to 40% depending on ridge height and storm characteristics (NRCS, 2008).

Finally, it was explored whether an empirical relationship between ΔMDS and terrain slope existed. As explained above, ΔMDS values depended on the roughness of each tillage class (Table 4), hence rougher classes produced larger ΔMDS values. Therefore, in order to find a relationship between ΔMDS and the slope applicable to different tillage classes, the ratio $\Delta MDS_i/MDS_i$ was computed, where MDS_i is the mean storage value of tillage class i (shown in Table 3). This ratio was plotted against the slope and their relationship was evaluated (Fig. 11). The class 'Rolled planted' was not considered in this analysis, since no relationship between tillage direction and MDS could be observed in this case as explained above.

Fig. 11 shows two different decreasing trends. The first, representing the 'Mouldboard Plough' (MP) tillage class, shows a stronger influence of tillage direction on MDS with ΔMDS values approaching a 20% of the average MDS for a 10% slope. The remaining tillage classes follow closely a similar trend. In this case the influence of tillage direction is not that strong and ΔMDS values reach a 10% of the class-average MDS for a 10% slope.

The different behavior of the mouldboard class could be interpreted as a consequence of the particular configuration of this tillage tool. While the remaining tillage tools studied (harrow, sowing machine, etc.) consist of a number of spikes or harrows separated some centimeters and not very deeply inserted in the soil, the mouldboard consists of a steel blade which is inserted in the soil around 20 cm, producing an inversion of the soil profile and

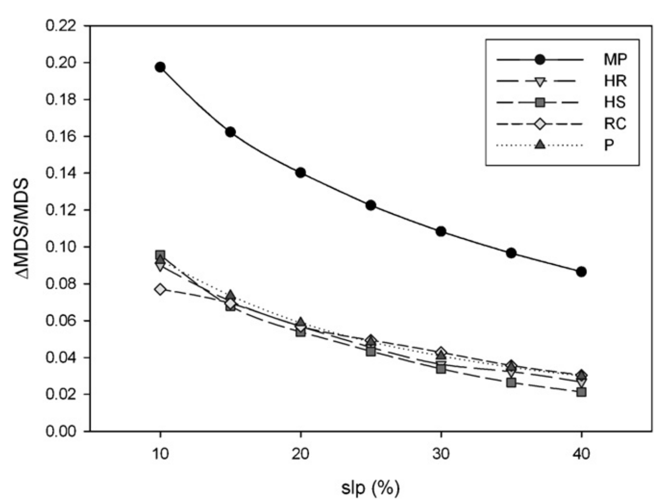

Fig. 11. Relationship between ΔMDS/MDS and the slope for the different tillage classes considered.

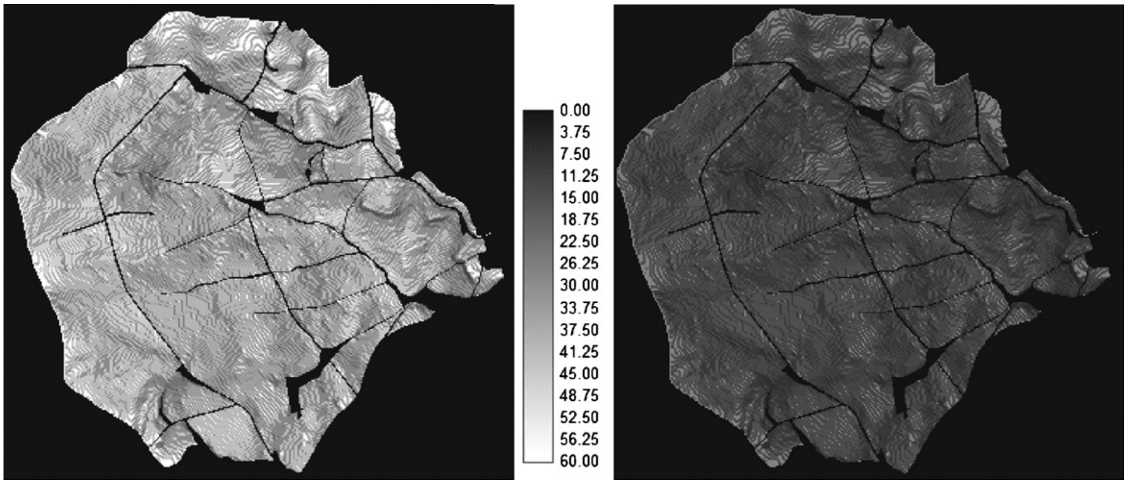

Fig. 12. Distribution of MDS considering two contrasting tillage states: (Fig. 10a, left) Mouldboard plough and planted (Fig. 10b, right).

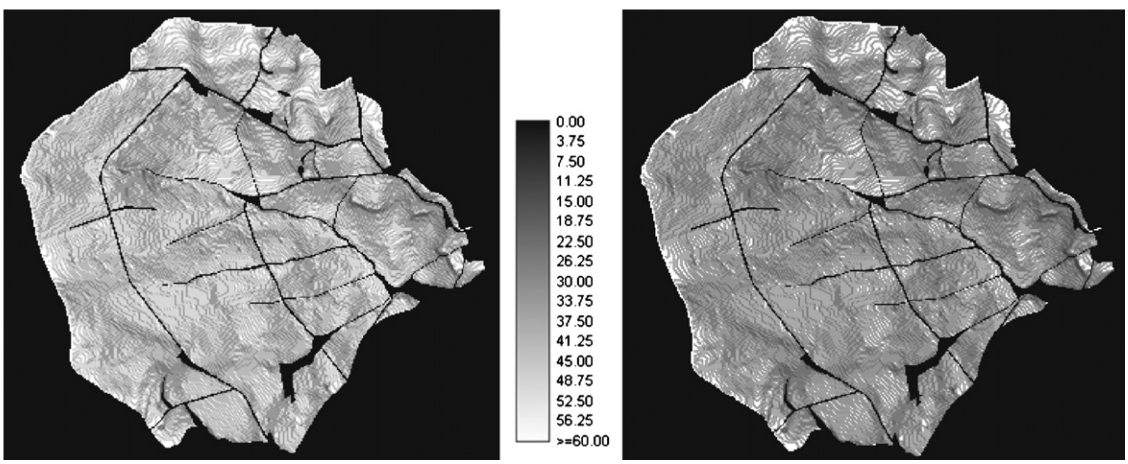

Fig. 13. Spatial distribution of MDS considering 'Mouldboard Plough' tillage and two hypothetical cases: (Fig. 11a, left) contour tillage and (Fig. 11b, right) tillage in the terrain aspect direction.

leading to a very marked directional roughness pattern. Consequently this tillage treatment produces the largest differences in roughness between tillage directions.

The two decreasing trends observed in Fig. 11 could be adequately fitted to an exponential type equation of the form of Eq. (2)

$$\frac{\Delta \mathrm{MDS}}{\mathrm{MDS}} = A\exp(-B\,slp) \qquad (2)$$

where for 'Mouldboard plough' $A = 0.254$ and $B = 0.028$ ($R^2 = 0.99$) and for the remaining tillage classes $A = 0.131$ and $B = 0.041$ ($R^2 = 0.96$). These equations could be useful for evaluating the effectiveness of contour tillage in promoting surface storage depending on the slope and tillage implement to be used.

In summary, in areas with steep slopes ΔMDS significantly decreased, so the effectiveness of contour tillage as a measure for runoff reduction on steep slope areas is dubious, at least with regard to the surface storage of precipitation.

3.5. MDS spatial distribution

Finally, it was possible to build maps representing the spatial distribution of MDS over La Tejería watershed using (1) average MDS values computed for each tillage class, (2) a 5 m resolution DEM and (3) ancillary information on tillage class and direction for each agricultural field. Fig. 12 illustrates the distribution of MDS considering two contrasting tillage states: Mouldboard plough (Fig. 12a) and Planted (Fig. 12b). It can be observed that the higher parts of the watershed (fields in the west) lead to slightly larger MDS values than the central parts; this is partly because tillage in the upper areas was mostly performed in contours.

Taking into account the soil preparation calendar generally followed on these areas, it was possible to estimate the MDS distribution over the watershed for a certain date (using average MDS values for each tillage class). On the other hand, these maps could be useful to evaluate the impact of agricultural management practices (tillage direction and type of implement used) on MDS and, subsequently, on infiltration and runoff generation. Fig. 13 shows the spatial distribution of MDS for two hypothetical cases where a primary soil preparation treatment (Mouldboard Plough) was performed (1) in contours (Fig. 13a) and (2) in the aspect direction (Fig. 13b). It can be observed that contour tillage lead to significantly higher MDS values over areas with moderate slopes.

4. Conclusions

Based on the results obtained on this study several conclusions can be drawn:

(1) Surface storage showed a multiscale behavior with increasing MDS values as the sampling domain and measurement resolution increased. The influence of the sampling domain was more marked for very rough surfaces. In any case, this issue needs to be taken into account in order to bridge the scale gap existing between MDS sampling sizes and DEM spatial resolutions.
(2) Tillage operations significantly affected the magnitude and variability of MDS. Rough surfaces showed larger MDS values, but also a significantly larger variability that should be taken into account when modeling hydrological processes and assessing model uncertainty.
(3) MDS decreased as rainfall smoothened the soil surface. As a result, at the end of the winter season MDS values could be significantly lower than at the time of sowing.
(4) Terrain slope dramatically influenced MDS with strong reductions on MDS for increasing slope gradients. The observed decreasing trends adequately fitted an exponential decay curve. This exponential decay seemed to be more marked for smooth tillage classes.
(5) Tillage direction influenced obtained MDS values. Contour tillage provided larger MDS values than tillage in the terrain aspect direction. However, the increment in MDS between contour tillage and tillage in the aspect direction was severely reduced as the slope gradient increased. In conclusion, contour tillage might not be a very effective runoff reduction measure for steep sloping areas.

Acknowledgements

This study was partly funded by the Spanish Government's National Scientific Research, Development and Technological Innovation Plan, project code CGL2007-63453. The authors acknowledge the two anonymous reviewers for their constructive comments and suggestions.

References

Abedini, M.J., Dickinson, W.T., Rudra, R.P., 2006. On depressional storages: the effect of DEM spatial resolution. Journal of Hydrology 318 (1–4), 138–150.

Aguilar, M.A., Aguilar, F.G., Negreiros, J., 2009. Off-the-shelf laser scanning and close-range digital photogrammetry for measuring agricultural soils microrelief. Biosystems Engineering 103, 504–517.

Alvarez-Mozos, J., Larranaga, A., Casali, J., 2005. Measurement and analysis of soil surface roughness over agricultural areas using a laser profile meter. Analysis of the temporal evolution of roughness as influenced by rainfall. In: I.A.O. Geomorphologists (Eds.), 6th International Conference on Geomorphology. International Association of Geomorphologists, Zaragoza, Spain.

Arvidsson, J., Bolenius, E., 2006. Effects of soil water content during primary tillage—laser measurements of soil surface changes. Soil & Tillage Research 90 (1–2), 222–229.

Carvajal, F., Aguilar, M.A., Aguera, F., Aguilar, F.J., Giraldez, J.V., 2006. Maximum depression storage and surface drainage network in uneven agricultural landforms. Biosystems Engineering 95 (2), 281–293.

Casali, J., Gastesi, R., Alvarez-Mozos, J., De Santisteban, L.M., de Lersundi, J.D., Gimenez, R., Larranaga, A., Goni, M., Agirre, U., Campo, M.A., Lopez, J.J., Doneezar, M., 2008. Runoff, erosion, and water quality of agricultural watersheds in central Navarre (Spain). Agricultural Water Management 95 (10), 1111–1128.

Darboux, F., Gascuel-Odoux, C., Davy, P., 2002. Effects of surface water storage by soil roughness on overland-flow generation. Earth Surface Processes and Landforms 27 (3), 223–233.

DeRoo, A.P.J., Offermans, R.J.E., Cremers, N.H.D.T., 1996. LISEM: a single-event, physically based hydrological and soil erosion model for drainage basins. 2. Sensitivity analysis, validation and application. Hydrological Processes 10 (8), 1119–1126.

Elbasit, M.A.M.A., Anyoji, H., Yasuda, H., Yamamoto, S., 2009. Potential of low cost close-range photogrammetry system in soil microtopography quantification. Hydrological Processes 23 (10), 1408–1417.

Gomez, J.A., Vanderlinden, K., Nearing, M.A., 2005. Spatial variability of surface roughness and hydraulic conductivity after disk tillage: implications for runoff variability. Journal of Hydrology 311 (1–4), 143–156.

Govers, G., Takken, I., Helming, K., 2000. Soil roughness and overland flow. Agronomie 20 (2), 131–146.

Guzha, A.C., 2004. Effects of tillage on soil microrelief, surface depression storage and soil water storage. Soil & Tillage Research 76 (2), 105–114.

Hansen, B., Schjonning, P., Sibbesen, E., 1999. Roughness indices for estimation of depression storage capacity of tilled soil surfaces. Soil & Tillage Research 52 (1–2), 103–111.

Helming, K., Römkens, M.J.M., Prasad, S.N., 1998. Surface roughness related processes of runoff and soil loss: a flume study. Soil Science Society of America Journal 62 (1), 243–250.

Heritage, G.L., Milan, D.J., 2009. Terrestrial laser scanning of grain roughness in a gravel-bed river. Geomorphology 113 (1–2), 4–11.

Huang, C., Bradford, J.M., 1990. Depressional storage for Markov-Gaussian surfaces. Water Resources Research 26 (9), 2235–2242.

Kamphorst, E.C., Duval, Y., 2001. Validation of a numerical method to quantify depression storage by direct measurements on moulded surfaces. Catena 43 (1), 1–14.

Kamphorst, E.C., Jetten, V., Guerif, J., Pitkanen, J., Iversen, B.V., Douglas, J.T., Paz, A., 2000. Predicting depressional storage from soil surface roughness. Soil Science Society of America Journal 64 (5), 1749–1758.

Kirkby, M., 2001. Modelling the interactions between soil surface properties and water erosion. Catena 46 (2–3), 89–102.

Martin, Y., Valeo, C., Tait, M., 2008. Centimetre-scale digital representations of terrain and impacts on depression storage and runoff. Catena 75 (2), 223–233.

Morgan, R.P.C., Quinton, R.E., Smith, H.W.A., Govers, G., Poesen, J.W.A., Auerswald, K., Chisci, G., Torri, D., Styczen, M.E., Folly, A.J.W., 1998. The European Soil Erosion Model (EUROSEM): Documentation and User Guide, Version 3.6. .

NRCS, 2008. Revised Universal Soil Loss Equation Version 2. USDA-Natural Resources Conservation Service.

Onstad, C.A., 1984. Depressional storage on tilled soil surfaces. Transactions of the ASAE 27 (3), 729–732.

Pérez-Gutiérrez, C., Alvarez-Mozos, J., Martínez-Fernández, J., 2009. Measuring surface roughness with terrestrial laser scanning. In: I.A.O. Geomorphologists (Eds.), 7th International Conference on Geomorphology. International Association of Geomorphologists, Melbourne.

Planchon, O., Esteves, M., Silvera, N., Lapetite, J.M., 2001. Microrelief induced by tillage: measurement and modelling of Surface Storage Capacity. Catena 46 (2–3), 141–157.

Soudarissanane, S., Lindenbergh, R., Menenti, M., Teuissen, P., 2009. Incidence angle influence on the quality of terrestrial laser scanning points. ISPRS—International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 38 (Part 3/W8), 183–188.

Taconet, O., Ciarletti, V., 2007. Estimating soil roughness indices on a ridge-and-furrow surface using stereo photogrammetry. Soil & Tillage Research 93 (1), 64–76.

Takken, I., Govers, G., Steegen, A., Nachtergaele, J., Guerif, J., 2001. The prediction of runoff flow directions on tilled fields. Journal of Hydrology 248 (1–4), 1–13.

Thompson, S.E., Katul, G.G., Porporato, A., 2010. Role of microtopography in rainfall runoff partitioning: an analysis using idealized geometry. Water Resources Research 46 .

Verhoest, N.E.C., Lievens, H., Wagner, W., Alvarez-Mozos, J., Moran, M.S., Mattia, F., 2008. On the soil roughness parameterization problem in soil moisture retrieval of bare surfaces from synthetic aperture radar. Sensors 8 (7), 4213–4248.

Zhixiong, L., Nan, C., Perdok, U.D., Hoogmoed, W.B., 2005. Characterisation of soil profile roughness. Biosystems Engineering 91 (3), 369–377.

Zobeck, T.M., Onstad, C.A., 1987. Tillage and rainfall effects on random roughness—a review. Soil & Tillage Research 9 (1), 1–20.