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Spatial variability of surface roughness and hydraulic conductivity after disk tillage: implications for runoff variability

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Abstract

Hydraulic conductivity and surface roughness were measured twice on freshly tilled soil immediately after each of two disk tillages. The objective was to measure the modification in their spatial arrangement induced by tillage. One hundred and thirteen points were measured on a 1600-m^2 area, each with a 1-m^2 sampling area. The average values for roughness and field saturated hydraulic conductivity, K_{fs}, differed significantly after each tillage. This was attributed to the different soil conditions at the time of tillage. Both magnitudes showed some degree of spatial autocorrelation, mostly in the tillage direction, but no cross-correlation. K_{fs} showed a periodic behavior in the direction perpendicular to the tillage rows that might reflect the effect of traffic. The spatial distribution of surface roughness was completely different after the two tillages made with the same equipment. The spatial distribution of K_{fs} after two tillages made with the same equipment were similar. An analysis with a runoff model suggests that the spatial modification of both K_{fs} and surface roughness by tillage is not capable, alone, to explain the lack of stability of runoff in replicated plots. Simulations suggest that the lack of stability in runoff among replicated plots might be explained by the spatial modification of surface tillage combined with an infiltration dominated by a bimodal model of surface crusting regulated by microrelief.

Keywords: Spatial variability; Surface roughness; Tillage; Hydraulic conductivity; Runoff

1. Introduction

It has been long recognized that physical and chemical soil properties show a significant degree of spatial variability, even at short distances. Paz-González et al. (2000) reported a coefficient of variation, CV, for the organic matter content, OM, of the topsoil of 24.1 and 9.8% for an uncultivated and cultivated plot, respectively, each plot 121 m^2 size. Diiwu et al. (1998) reported a CV of 14 and 8.2% for the OM content of the topsoil of a conventionally and zero tilled area, respectively, also in a relatively small area. Saturated hydraulic conductivity is considered one of the most spatially variable of soil properties, being usually log-normally distributed

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(e.g. Diiwu et al., 1998; Tsegaye and Hill, 1998; Anderson and Cassel, 1986; Vieira et al., 1981).

Vegetation has large impact on hydraulic conductivity and its spatial variability in cultivated fields (Mohanty et al., 1994). The effect of tillage on the spatial structure of saturated hydraulic conductivity is not clear from the literature. Logsdon and Jaynes (1996) reported how the increase in the variability induced by tillage made it difficult to determine the spatial structure of saturated hydraulic conductivity. Diiwu et al. (1998) indicated how tillage reduced the variability in saturated hydraulic conductivity compared to no tillage, thus increasing its spatial autocorrelation. The type of tillage applied may result in different types of spatial dependency in the infiltration characteristics, as shown by Cressie and Horton (1987). Saturated hydraulic conductivity varies not only spatially, but also temporally within the same field (Logsdon and Jaynes, 1996). In tilled fields this temporal variation is attributed, among other causes, to the modification of soil porosity induced by tillage (Logsdon and Jaynes, 1996; Tsegaye and Hill, 1998).

The interaction between surface microrelief and surface hydraulic conductivity has long been recognized and explained through various mechanisms, for instance, through the modification of the rate of surface sealing under rainfall (e.g. Brakensiek and Rawls, 1983). There has been active research on that interaction. Recently, Fox et al. (1998a,b) have shown how two different kinds of surface crusts, distributed according to the microrelief, may be created by tillage. These surface crusts, depositional on the depressions and structural on the mounds, result in magnitudes, extent and distribution of hydraulic conductivities that change during rainfall events, along with associated microrelief evolution.

Subtle differences induced by tillage have been used to explain the variation in runoff and soil loss among replicated, fallow plots (Hjemfelt and Burwell, 1984). A large coefficient of variation for seasonal runoff, between 30 and 50%, has been reported in replicated runoff plot experiments on fallow soil (Rüttiman et al., 1995; Hjemfelt and Burwell, 1984), even when a large number of replications were considered. For example, in the experiment reported by Hjemfelt and Burwell (1984) 40 plots, 3.2× 27.5-m in size with 3–3.5% slope, were located in a homogeneous area of 120×140-m on a silt loam soil and kept under identical fallow soil management. Hjemfelt and Burwell (1984) showed how the relative differences among replicated plots did not persist in time; a result corroborated by Rüttiman et al. (1995). Hjemfelt and Burwell (1984) suggested that the reason for this lack of stability in time of the relative differences among plots was that relative differences in soil properties affecting infiltration were modified each time a tillage operation was performed. Gómez et al. (2001), in a modeling analysis of the same experimental data, reproduced that lack of stability in time of the relative differences among plots only when assuming that after each tillage operation the spatial pattern of saturated hydraulic conductivity and random roughness was modified.

This large unexplained variability of the field runoff data hinders evaluation of simulation models, and several research projects in recent decades have explored the influence of the spatial variation of infiltration rate or hydraulic conductivity on runoff production using physically-based runoff simulation models (e.g. Smith and Herbert, 1979; Binley et al., 1989; Woolhiser et al., 1996). One of the difficulties in using these models that incorporate the spatial variability of soil properties into runoff generation is that they need to be parameterized from data coming from measurements made at the same scale as that of the computational grid. The distribution of the observed values depends on the sample size, or on the soil volume studied (Isaaks and Srivastava, 1989). When measuring K_s and infiltration rate, the measurement scale has been found to have a direct impact on the average values, too (Sisson and Wierenga, 1981; Shouse et al., 1994). The agreement between computational and measurement scale is not always easy to determine from previously published data, and this was one of the limiting factors in a previous work in which we tried to explain the CV in runoff among replicated plots of the experiment described by Hjemfelt and Burwell (1984) as a function of the spatial variability of K_s and surface roughness (Gómez et al., 2001). The experimental information about the temporal evolution of the spatial distribution of those two properties due to tillage is scarce, and limited mostly to 1-D transects (Logsdon and Jaynes, 1996). Without that information, to attribute the lack of temporal stability of the relative differences in runoff among plots to the modification of the spatial variability in K_s and surface roughness due to tillage remains hypothetical.

In this paper we present the results of an experiment aimed to measure the spatial distribution of surface roughness and saturated hydraulic conductivity of a fallow field after two consecutive tillage operations with the same implement under similar conditions. The objective was to determine if a modification of the spatial pattern of K_s and surface roughness occurred under that situation, and if such modification could provide a reason for the lack of relative differences in runoff in replicated plots, as hypothesized by Hjemfelt and Burwell (1984).

2. Materials and methods

2.1. Experimental set-up

An area 40×40-m was selected within an experimental field at the Purdue University Agronomy Farm (Tippecanoe County, Indiana) in the summer of 2001. The field had been kept fallow the previous cropping season, and the soil was classified as Drummer: Fine, silty, mixed, mesic Typic Haplaquolls (Ziegler and Wolf, 1998). The soil texture was silty clay loam, with a moderate infiltration rate and organic matter content around 2.7%. The field was tilled on July 16th using a disk plough, 5.5-m width, and 113 sampling points, hereafter locations, were marked on the freshly tilled soil. The sampling design consisted of 81 locations on a 3×3-m regular grid, mixed with two transects of 17 locations at 1.5-m distance in the tillage direction and perpendicular to it (Fig. 1). All the sample locations were 1-m^2. They were maintained free from traffic and trampling, and were covered by a plastic sheet, 1.5×1.5-m size, until the measurements were made. The field measurements took 7–9 days to be completed. Our objective with the plastic sheets was to avoid the effects of surface sealing on some of the plots caused by any rainfall that might occur during the experiment. In each location surface roughness, field saturated hydraulic conductivity, K_{fs}, and initial soil water content at 0–0.1-m depth were measured. Once all the locations were measured, the entire field was allowed to dry for 2 weeks and ploughed again using the same tillage equipment. Once tilled, the same sampling design was implemented, locating the sampling points at the same locations as previous through reference points maintained at the sides of

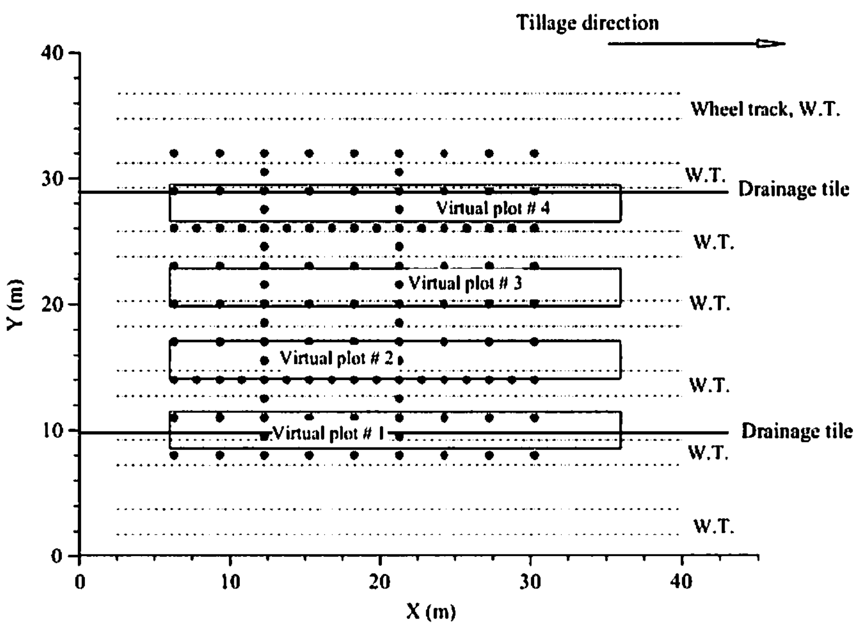

Fig. 1. Experimental set up, each point represents a 1×1-m^2 plot where K_{fs} and C_{rr} was measured. Virtual plots refers to USLE-type runoff plots simulated in Section 3.4.

the tilled area. The same experimental procedure (marking and protection of the sampling locations, measurement of surface roughness, K_{fs} and initial top soil water content) was repeated.

2.2. Surface roughness

Surface roughness was measured using the chain method (Saleh, 1993). The method is based on the principle that the surface distance between two points, L_2 will become larger as soil roughness increases. Therefore a chain of a given length, L_1, will traverse a shorter horizontal distance, L_2, when it follows a rough surface compared to a smooth one. Eq. (1) was used to calculate the roughness factor, C_{rr}:

$$C_{rr} = 100\left(1 - \frac{L_2}{L_1}\right) \tag{1}$$

Using Eq. (1) the non-oriented roughness caused by aggregates, C_{rr}, can be determined using measurements obtained in a direction parallel to the ridges (Gilley and Kottwitz, 1995). For each 1-m^2 location five C_{rr} measurements were made by carefully laying a linked roller chain along the ridge direction every 0.2-m. L_2 was 1-m for all measurements. The average of these five C_{rr} measurements was taken as the C_{rr} value for the 1-m^2 location.

Prior to the experiment, an assessment of the accuracy of the method was made measuring C_{rr} on four areas with different roughness (four replications each). The results showed an average coefficient of variation of 11% for C_{rr}, with the C_{rr} values ranging from 6.2 to 16.8. The most commonly used random roughness index, RR, (Allmaras et al., 1966) can be estimated from C_{rr} through the equation proposed by Gilley and Kottwitz (1995), where R (l m^{-2}) is total rainfall since last tillage, and RR is in units of mm:

$$RR = (1 - \exp[-4.82 \times 10^{-3}(R + 19)])C_{rr} \tag{2}$$

In our case, measuring immediately after tillage, R was zero.

2.3. Field saturated hydraulic conductivity

Field saturated hydraulic conductivity, K_{fs}, was measured using single ring infiltrometers. The measurement scale was chosen as 1-m^2 in order to avoid the problems between measurement and modelling scale. The single ring infiltrometer was chosen because it was the only type of infiltrometer of this size of which we had multiple, five, units available. This allowed performing all the field measurements in a reasonably short time span. For construction reasons the infiltrometers were of square shape, 1-m on a side. One of the characteristics of this kind of infiltrometers is that due to the ponded water they tend to overestimate the effect of macroporosity compared to rainfall conditions. The infiltrometers were inserted 0.1-m deep into the soil and cumulative infiltration was measured for a period of 3 h, keeping a constant water depth of 0.08-m. Care was taken to limit soil disturbance during ring insertion, pushing the rings gently into the soil and sealing any visibly boundary gap after the insertion with soil taken from the same field. Prior to flooding the infiltrometers, soil water content at the top 0.1-m was measured using TDR in the area outside, but near, the infiltrometer that had been kept under the protective plastic sheet.

One of the difficulties in interpreting single ring infiltrometers is that water flow into the soil is three-dimensional. This was taken into account using the generalized solution for single-ring infiltrometers of Wu et al. (1999). The method proposed by Wu et al. (1999) allows calculation of K_{fs} from the stabilized section of the cumulative infiltration curve. Eq. (3) was fit to the cumulative infiltration curves by the least square method using the data corresponding to the last 2 h of each measurement to insure steady-state infiltration

$$I = At + c \tag{3}$$

where I (mm) is cumulative infiltration; t (time unit) is time; h, A, and c are fitted parameters. K_{fs} was obtained solving

$$K_{fs} = \frac{A}{bf} \tag{4}$$

where b is a dimensionless constant equal to 0.9084 (Wu et al., 1999), and f can be estimated by:

$$f = 1 + \frac{H + 1/\alpha}{G^*} \tag{5}$$

where H (m) is the ponding depth of the water in the infiltrometer, α (m^{-1}) is the 'sorptive number' (Elrick and Reynolds, 1992). The α value for the Drummer soil was assumed to be $12\,\mathrm{m}^{-1}$, as suggested by Elrick and Reynolds (1992) for a soil of this texture. G^* was calculated according to

$$G^* = d + r/2 \quad (6)$$

where d is the ring insertion depth, and r is the ring radius. In our case r was taken as 1 m. Inspection of the experimental data showed that after 1 h, steady-state infiltration was reached in all the infiltrometers.

2.4. Statistical and geostatistical methods

The statistical moments considered in the analyses were mean, variance, CV, maximum values, and minimum values. The coefficient of skewness was used to decide whether or not a population resembled the normal frequency distribution. For a perfect normal frequency distribution, the coefficient of skewness is zero.

Spatial variability was assessed through the analysis of omni-directional and directional semivariograms (Isaaks and Srivastava, 1989; Goovaers, 1997) of the selected individual variables, as well as cross-semivariograms and maps obtained through ordinary kriging using the software package GS$^+$ (Gamma Design Software, Plainwell, MI). Experimental semivariograms, $\gamma(h)$, were calculated from a set of spatial observations, $Z(x_i)$, using

$$\gamma(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)}[z(x_i - z(x_i + h)]^2 \quad (7)$$

where h is the lag distance. The directions selected for the directional semivariograms were the tillage direction, along the X-axis on Fig. 1, and perpendicular direction. The selection of the lag intervals was made on the basis of classical rules (Isaaks and Srivastava, 1989).

Five different semivariogram models were examined: the linear, linear-sill, spherical, exponential and gaussian models. A subjective decision about the semivariogram model used was made based on the fit to the experimental semivariogram, judged by the square of the correlation coefficient (r^2) and the results of cross-validation (Goovaers, 1997).

In most cases the spherical model was chosen

$$\begin{aligned} \gamma(h) &= c_0 + c\left[1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3\right] & h \le a \\ \gamma(h) &= c_0 + c & h \ge a \end{aligned} \quad (8)$$

where c_0 represents the nugget variance, which consists of the variance at distances smaller than the minimum sampling distance plus the measurements error, c represents the structural part of the variance, and a represents the range, which is the maximum separation distance for which sample pairs remain correlated.

2.5. Analysis of stability of spatial patterns after tillage

To evaluate if tillage modified the pattern of spatial distribution of the measured soil properties after each of the disk ploughings, we compared visually the ordinary kriging (OK) maps of K_{fs} and C_{rr}. To quantify that stability, or lack of it, we also used the time stability parameter, λ, (Vachaud et al., 1985) defined according to Starr (1990)

$$\lambda_{ij} = X_{ij}/\bar{X}_j - 1 \quad (9)$$

where

$$\bar{X}_j = (1/n)\sum_{i=1}^{i=n} X_{ij} \quad (10)$$

where X_{ij} denotes the values of the magnitude analyzed at different locations (i) and different times (j), over n number of events. Starr (1990) and Vachaud et al. (1985) used this parameter to evaluate the stability in time of spatial differences in several soil properties measured at fixed locations. The index λ can be interpreted as an index of the relative differences at each measurement date (j). If the relative differences among different locations (i) remained stable in time, their λ values would rank similarly at each date, while they will change their rank from one date to another if there is a lack of such time stability.

2.6. Hydrological model

The impacts on runoff volume caused by changes in K_{fs} and RR after the two tillage operations were evaluated through a physically-based, storm event, runoff model previously described (Gómez et al., 2001). The model has two major components: (1) the infiltration algorithm was based on the Green and Ampt model using a time condensation approach, considering four soil layers and incorporating the reduction of surface hydraulic conductivity due to sealing. For the analyses described in this paper the model divided the area into square cells of 1.5 × 1.5-m, and used distributed parameters of K_{fs} and random roughness for every cell. (2) Surface runoff was computed by routing the excess water in the cell using the slope and aspect of each cell, and by solving the Manning's equation and the mass balance equation for each cell. Random roughness and K_{fs} are two of the most important parameters of the model and were determined from the field measurements, as was slope gradient. The remaining parameters were calibrated from published values. A list of those parameters and sources for calibration appeared in Gómez et al. (2001).

To analyze the impact of the modification of the spatial distribution of K_{fs} and surface roughness induced by tillage on the CV of runoff volume in replicated plots, a virtual experiment was performed. It consisted of numerical simulations using as input parameters the K_{fs} and roughness maps measured after each one of the two tillages alternatively. The rationale was that if there was a rearrangement of the spatial variability of those two properties due to tillage that was significant enough to induce clear spatial differences in runoff, the relative differences in runoff calculated for different areas of the field would change when using one map compared to the other. To do this four USLE-type plots were overlain on the field map, each plot 3-m wide by 24-m long (see Fig. 1). We considered that the effect of compaction in trafficked area below the freshly tilled layer would be incorporated in our infiltration measurements due to the relatively high resolution of the maps of K_{fs} and large area sampled by the infiltrometers. The 27 rainfall event dataset described by Hjemfelt and Burwell (1984) in a runoff plot experiment using 40 replications was used to simulate the runoff generation from these four plots. The same average values for the parameters previously calibrated in Gómez et al. (2001) were used. The maps of the spatial distributions of K_{fs} and RR used were those obtained through kriging from our experimental data. RR was obtained from C_{rr} through Eq. (2).

Prior to their use, these maps were normalized to the average K_{fs} and RR calibrated in Gómez et al. (2001) for the Hjemfelt and Burwell (1984) experiment. This was done by multiplying the individual K_{fs} values by the ratio of the calibrated K_{fs} to the experimentally measured average K_{fs}. Random roughness values, RR, were treated similarly. In this way the results of the simulation could be compared easily with previous experimental and simulation studies. To introduce in the simulations the modification of the spatial map of K_{fs} and RR by consecutive tillages, we used the maps measured after both the first and second tillage for each group of simulated rainfall events that occurred after each of the tillages described by Hjemfelt and Burwell (1984). Six tillages were performed in that experiment during the period covered by the 27 rainfall events. For rainfall events 1–4; 8–10 and 17–23 the maps measured after the first tillage were used, while those maps obtained after the second tillage were used for the remaining events.

The hydrological model incorporated the effect of microrelief on infiltration, as suggested by Fox et al. (1998a,b). The crusted hydraulic conductivity in each of the 1.5–1.5-m numerical cells used in the simulations was related to the random roughness, assuming that increased roughness translated to a larger extension of structural crusts, in this way controlling the fraction of depositional and structural crust (Fox et al., 1998a,b). This relationship took the form of

$$K_s = Ks_{str} f_{str} + Ks_{dep} f_{dep} \tag{11}$$

where Ks_{str} and Ks_{dep} are the hydraulic conductivities of the structural and depositional crusts, respectively, and f_{str} and f_{dep} are the fractions of the surface covered by structural and depositional crusts, respectively. Ks_{str} was 6.4 times greater than Ks_{dep}, as suggested by the ratio of hydraulic resistances measured by Fox et al. (1998b) for both kind of crusts on a soil of similar texture. Ks_{dep}, was estimated as the baseline K_s used for the simulation model previously calibrated (Gómez et al., 2001). The fraction f_{dep} was calculated from

$$f_{dep} = 1 - 16.67\text{RR} \tag{12}$$

Eq. (12) was developed considering that in a tilled soil with a random roughness (RR) of 0.03 m, Mellis et al. (1996) determined that 50% of the surface on a sandy clay loam soil showed depositional crust, while for a very smooth soil with a RR of 0.004-m 95% of the crusted surface was depositional. Thus Eq. (12) is an approximation based on published observations made on conditions similar to those represented by our numerical analysis. It is not a relationship that should be expected to hold on all soils and landscape conditions.

The model implemented in our simulations was an approximation of the more complex and dynamic interaction between both kinds of surface crusts described by Fox et al. (1998a,b), wherein differences in inundated areas depend on the water depth and surface microrelief, and where microrelief evolves with rainfall over very short time periods. Nevertheless, the model allows us to explore the implications of a surface hydraulic conductivity dominated by the microrrelief and its interaction with its spatial modification due to tillage.

3. Results and discussion

3.1. Surface roughness

The main statistical moments of the data are shown in Table 1. The average values of C_{rr} were significantly different ($P<0.001$) after the two tillages. There were also differences in the variance, with a larger variance after the second tillage, reflecting a greater data range. These differences were probably due mainly to variations in soil conditions at the time of tillage, since the plough, depth of plough, tractor and speed were similar for both tillage operations. Despite the fact that both tillages were performed at similar soil water contents, at the time of the first tillage the soil had been more disaggregated by the freezing and thawing cycles during winter and by previous spring tillage, while the second tillage was performed on a relatively more compacted soil due to the infiltration tests and the associate trampling around the infiltrometer locations. The coefficient of variation was similar in both cases, and not much different from the 18% reported for soil random roughness measured on 1×1-m plots by Potter (1990). The coefficients of skewness were near to 0, indicating probability distributions close to normal. For that reason, no transformation of the C_{rr} values was made prior to the computation of the semivariograms.

Table 1
Summary statistics of C_{rr}

	After first tillage	After second tillage
Mean C_{rr}	9.0	10.7
CV (%)	22.5	28.4
Variance	4.2	9.28
Maximum	15.0	18.2
Minimum	4.0	5.3
N	113	113
Skewness	0.27	0.51

Fig. 2 shows the directional semivariograms. The surface roughness measured through the C_{rr} parameter showed a significant degree of spatial autocorrelation. That autocorrelation showed to be anisotropic in its range for both tillage operations, with a larger range in the tillage direction (X-axis) compared to the Y-axis. We attribute this to the fact that the variability in the Y direction accounts for the effect of the overlapping of different passes of the 5.5-m width disc plough. Both variograms showed similar nugget values.

Fig. 3 shows the maps for C_{rr} obtained through ordinary kriging using the variogram models shown in Fig. 2. There are more areas with large C_{rr} values after the second tillage compared to the first one. It was also evident from Fig. 3 that the location of the areas with larger and lower roughness changed between the two consecutive tillages. Fig. 4 presents a quantification of that lack of correlation. If there had been a temporally stable spatial distribution of relative roughness, the areas with large and low roughness would remain approximately in the same spots, and their rank compared to the other spots would remain approximately the same. That would have been reflected in a significant correlation coefficient in the regression between the block λ values for the same areas, 9×9-m window, measured after each tillage. Such was not the case, as Fig. 4 shows.

Results shown in Figs. 3 and 4 suggest that the magnitude of the changes induced by tillage on soil roughness, and probably on porosity too, in the topsoil of replicated plots were great enough to introduce significant variability, spatial and temporal, among replicated plots. This result corroborates the hypothesis of Hjemfelt and Burwell (1984) and Gómez et al.

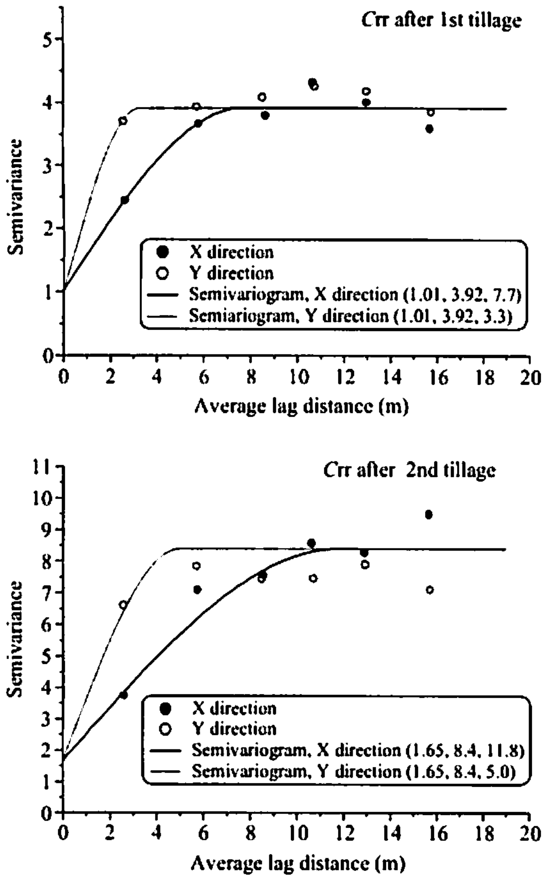

Fig. 2. Direccional semivariograms for C_{rr} after each tillage. Number between parenthesis are nugget, sill, and range.

(2001). In the current study we have measured such variability of surface roughness in small, homogeneous areas in which tillage was performed more uniformly than it could be in replicated plots, where equipment traffic has serious restrictions. These differences in roughness were measured with the relatively simple technique of the chain method, it could be that a portion of the significant nugget values shown in Fig. 2 were due to limitations in the accuracy of this technique compared to more sophisticated methods such as analysis of laser-scanned surfaces (Darboux and Huang, 2003).

3.2. Field saturated hydraulic conductivity

The main statistical moments for hydraulic conductivity are shown in Table 2. The average initial volumetric soil water content in the top 0.1-m for both rounds of measurements was the same, 19%, and no correlation was found between this initial soil water content and K_{fs} for individual plots (data not shown). There was a larger variance in K_{fs} after the first tillage, probably for the same reasons as those discussed above for surface roughness. The measured CVs were similar for both rounds of measurements, at approximately 50%. This CV was similar to values previously reported for tilled soils. Diiwu et al. (1998) reported 68% using undisturbed soil samples; Gupta et al. (1993) measured 50% using double ring infiltrometers, and Vieira et al. (1981) measured 40% using a single ring infiltrometer. All these values are much lower, however, than the 172% CV obtained by Tsegaye and Hill (1998) using undisturbed samples. The coefficients of skewness were significantly greater than zero, at 1.0 and 1.45, respectively, indicating an asymmetric right tail, while the log-normalized values presented a skewness coefficient close to cero. This is consistent with the log-normal frequency distribution described for K_{fs} in various experiments, (Logsdon and Jaynes, 1996; Diiwu et al., 1998). The average values of K_{fs} and Ln (K_{fs}) were different ($P<0.001$) after each tillage. These differences in the average K_{fs} values may be a consequence of differences in soil condition at the time of tillage as well as hypothetical differences in soil water content below the 0.1-m depth (not measured). To further reduce the skewness, K_{fs} values were log transformed by ln ($K_{fs}+10$) instead of ln (K_{fs}) prior to their geostatistical analysis.

Fig. 5 shows the directional semivariograms obtained for K_{fs}. They show a clear spatial autocorrelation in the tillage direction (X-axis) after both tillages, with a range between 10 and 11-m. The autocorrelation was anisotropic, and in the Y direction there was much less autocorrelation, and an apparent periodicity with an approximate 5.4 m period. Since the Y axis was perpendicular to the rows it is possible that our experimental semivariogram in the Y direction reflected the effect of past traffic patterns. Traffic pattern was also the explanation suggested by Logsdon and Jaynes (1996) and Mohanty et al. (1994), who also detected a periodicity in K_s measured in the direction perpendicular to tillage rows. Since we can not be conclusive about the explanation for that periodicity, for kriging purposes

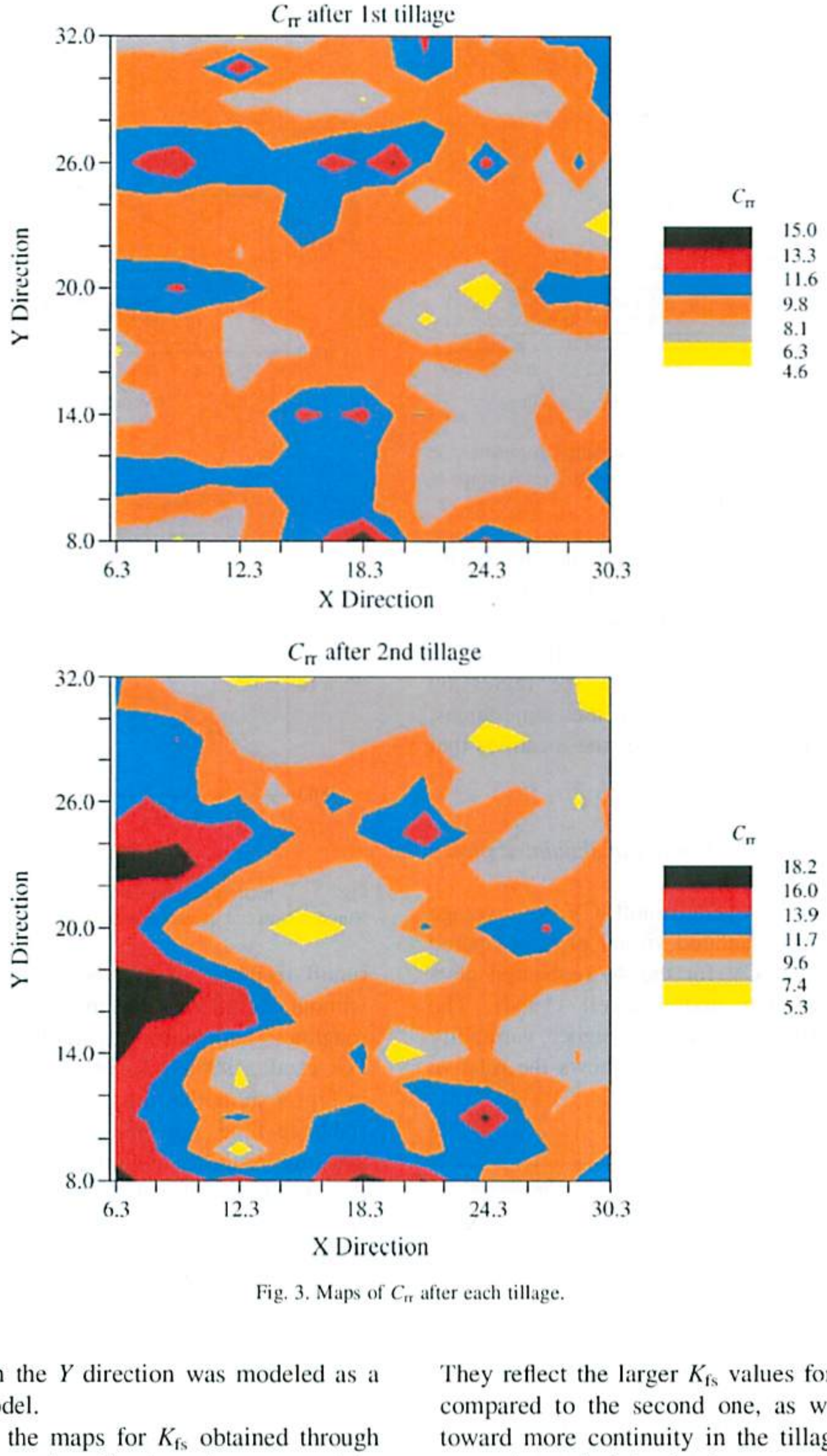

Fig. 3. Maps of C_{rr} after each tillage.

the variogram in the Y direction was modeled as a nugget effect model.

Fig. 6 shows the maps for K_{fs} obtained through ordinary kriging using fitted variogram models. They reflect the larger K_{fs} values for the first tillage compared to the second one, as well as the trend toward more continuity in the tillage direction and some the periodicity in the perpendicular direction.

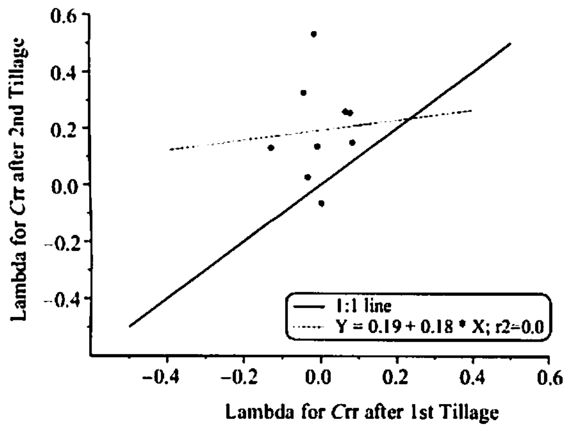

Fig. 4. Correlation between the time stability parameter, λ, corresponding to C_{rr}, after the first and second tillage. Average of all the points within a 9×9-m window.

It can also be noticed that some of the zones with larger K_{fs} appear in the same areas in both maps. This larger degree of temporal stability in the spatial distribution of K_{fs}, compared to C_{rr}, is reflected in the higher correlation coefficient from the regression between the λ block values for the same areas, calculated from the average K_{fs} of the locations that fall in a 9×9-m window (Fig. 7).

3.3. Implications on CV of runoff of simulated plots

Fig. 8 shows the event runoff CV vs. average runoff for the four simulated virtual plots compared to the experimental CV for the 40 replicated plots reported by Hjemfelt and Burwell (1984). The results follow similar trends of higher variability for smaller runoff events. Fig. 9 shows the relative

Table 2
Summary statistics of K_{fs}

	After first tillage	After second tillage
Mean K_{fs} (mm h^{-1})	62.3	34.8
Skewness	1.02	1.45
CV (%)	49.4	47.7
Variance	949.1	276.36
Maximum	145.1	92.6
Minimum	9.8	10.49
N	113	113
Mean Ln (K_{fs}) (mm h^{-1})	4.03	3.33
Skewness	−0.28	0.14

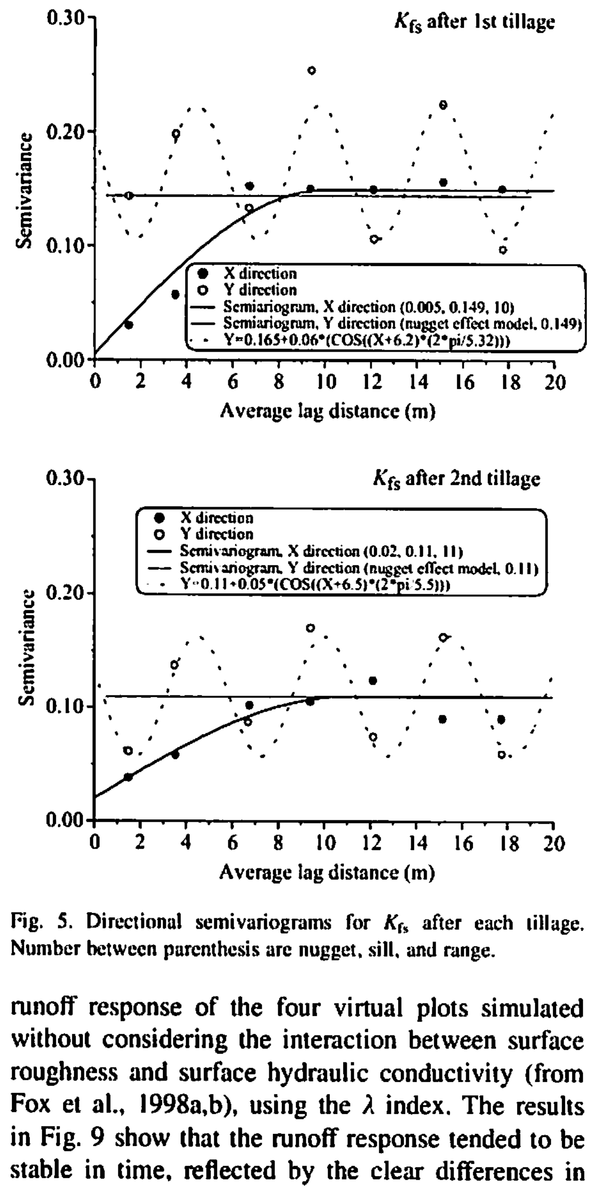

Fig. 5. Directional semivariograms for K_{fs} after each tillage. Number between parenthesis are nugget, sill, and range.

runoff response of the four virtual plots simulated without considering the interaction between surface roughness and surface hydraulic conductivity (from Fox et al., 1998a,b), using the λ index. The results in Fig. 9 show that the runoff response tended to be stable in time, reflected by the clear differences in the time stability parameter, λ, among the plots. Fig. 9 indicates that the relative ranking of the plots according to generated runoff did not change when changing the K_{sf} and C_{rr} maps that incorporated into the simulations the effect of the spatial arrangement due to tillage. These results contrast with the experimental results shown by Hjemfelt and Burwell (1984), which showed a lack of consistence in time of the runoff generation among different plots. Fig. 9 also shows a lower degree of time instability than the one obtained through simulated maps

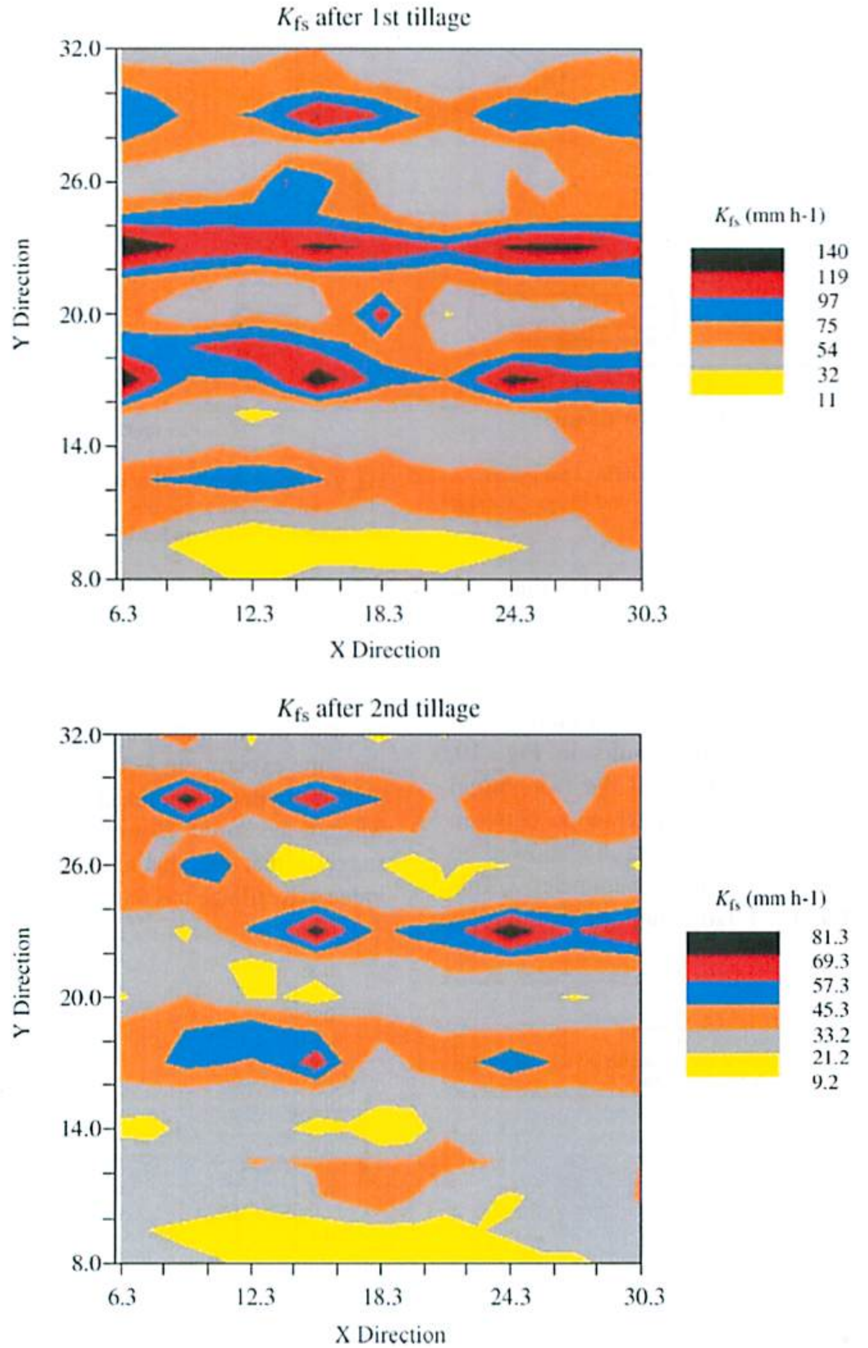

Fig. 6. Maps of K_{fs} after each tillage.

generated by Gómez et al. (2001). It is important to note that our experimental results of K_{fs} correspond to a particular situation: freshly tilled with infiltration on a completely submerged soil.

Fox et al. (1998a,b) showed how microrelief may play a dominant role not only in surface storage, but in regulating infiltration rate on tilled areas. Our results showed that surface roughness changed spatially with

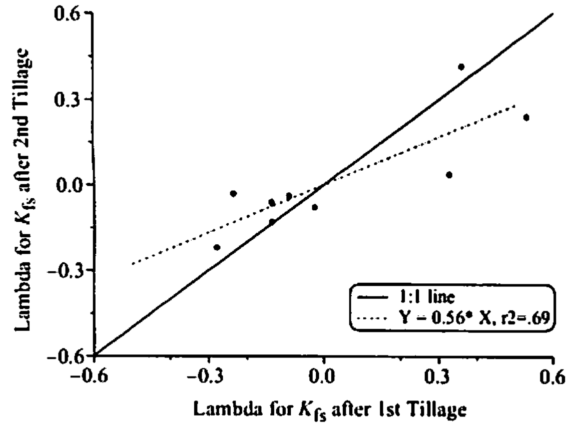

Fig. 7. Correlation between the time stability parameter, λ, corresponding for K_{fs}, after the first and second tillage. Average of all the points within a 9×9-m window.

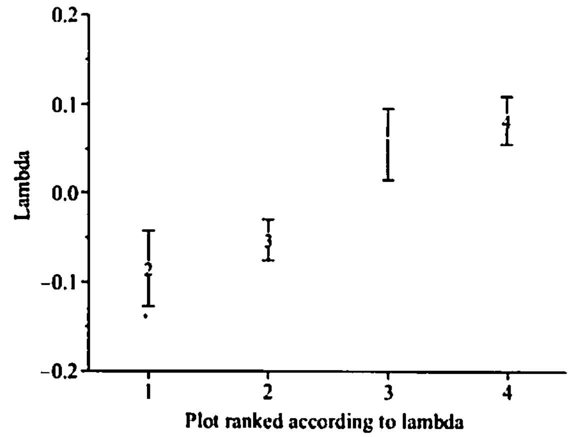

Fig. 9. Ranked time stability parameter, λ, for the four simulated plots corresponding to the 27 rainfall events. Vertical bars correspond to 90% confidence limits. Number refers to plot code.

tillage to a greater extent than did K_{fs}. To evaluate the implications of the phenomena described by Fox et al. (1998a,b) in runoff variability among plots, we repeated the virtual experiment considering the dominant role of microrelief in infiltration in the manner previously described. Results in Fig. 10, corresponding to runoff response of the four virtual plots simulated considering the interaction between surface roughness and surface hydraulic, showed no clear differences in the time stability parameter, λ. This is an indication that the relative ranking of the plots according to generated runoff changed when changing both the K_{sf} and C_{rr} maps as a function of tillage.

The previous analysis cannot be considered conclusive for several reasons. One is that the experimental data of K_{fs} and roughness does not come from the same experiment as the CV in runoff, and other is that the hydraulic conductivity of the surface crusts was not measured. However, our field measurements suggests that the spatial modification of infiltration induced by tillage has more to do with surface changes

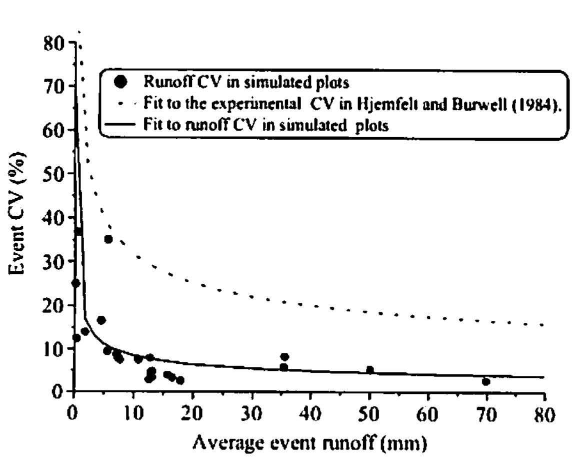

Fig. 8. CV in event runoff vs average event runoff for the four simulated plots. Dotted line shows the event runoff event for the 40 replicated plots of the experiment described in Hjemfelt and Burwell (1984) used as reference.

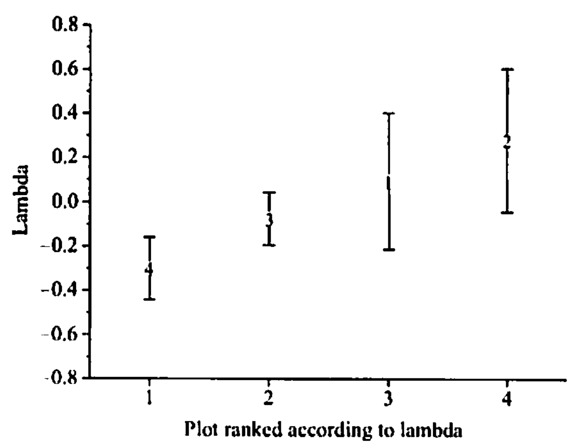

Fig. 10. Ranked time stability parameter, λ, for the four simulated plots corresponding to the 27 rainfall events assuming differences in hydraulic conductivity due to different kind of crusts related to roughness. Vertical bars correspond to 90% confidence limits. Number refers to plot code.

related to the modification of surface microrelief than to the effect of tillage on the freshly tilled K_{fs} of the soil. Our results showed how the spatial distribution of surface roughness over the field was modified by tillage, while the spatial distribution of freshly tilled K_{fs} was not appreciably modified.

The periodicity observed by Logsdon and Jaynes (1996) and Mohanty et al. (1994) indicates that trafficking may induce a lasting mark on the spatial distribution of K_{fs} and that the results observed by us in the current experiment may be expected as a general trend on tilled fields, especially in runoff plots where traffic is very much restricted. The K_{fs} measured in our experiment on freshly tilled soil indicates a restriction to infiltration below the plough layer that may not be obliterated by tillage. This restriction subsequently should intervene mostly when the wetting front reaches such depth during moderate to large rainfall events or during rainfall on previously moist soil. Hjemfelt and Burwell (1984) showed a large variability in runoff response among plots on wet soil even for large rainfall events, indicating that if such a restriction due to traffic existed, it did not play a significant role in controlling infiltration. This was probably due to the more limiting restriction to infiltration by surface sealing. The interaction among differently crusted areas has been proven under laboratory conditions. The coexistence of different kinds of surface crusts within the same tilled area has also been described in the field (e.g. Bielders et al., 1996). Such interaction induces a dynamic pattern of infiltration rate that depends upon the microrelief and water depth on the soil surface, and both of these magnitudes change during and between rainfall events.

All this taken together suggests that the lack of stability in time of the relative response in runoff plots might be explained by this dual crusting process associated with microrelief. The analysis with our simplified model suggests that result also (Fig. 10), although further experiments are needed to prove it. The infiltration pattern associated with the dual crusting model could also explain the positive correlation between rainfall intensity and apparent infiltration rate observed in fallow plots by Yu et al. (1997). Future analysis combining more numerically refined runoff-generation models, in the line of that described by Fiedler and Ramirez (2000), and combined field measurements of the evolution of microrelief and hydraulic conductivity under tilled conditions could provided more certainty about the hypotheses suggested in this paper. Such knowledge could improve our hydrological modeling capabilities. Future studies should include soils prone to surface sealing as the one described in this paper, as well as a soils not prone to sealing to be used as a control to test the null hypothesis.

4. Conclusions

The average values of surface roughness measured through the Saleh chain index and K_{fs} measured with ring infiltrometers changed after two tillages of the same area using the same equipment, probably because of differences in soil condition at the time of tillage. The spatial distribution changed substantially after each tillage only for surface roughness, and not for K_{fs}. Both surface roughness and K_{fs} showed larger spatial autocorrelation in the tillage direction, with a periodicity for K_{fs} in the perpendicular direction. This was attributed to the spacing between the wheeled areas in relation to the plough width. These results, combined with the results of a virtual experiment using a runoff generation model, suggest that the explanation for the lack of time stability in replicated runoff plots might be related to surface microrelief. The explanation that change in infiltration rates was related to microrelief evolution and water depth due to two different types of soil surface crusts with different hydraulic conductivities coexisting within the same tilled area seems feasible, although this hypothesis requires additional validation.

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