Soil & Tillage Research 124 (2012) 226–232

Contents lists available at SciVerse ScienceDirect

Soil & Tillage Research

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

Soil roughness evolution in different tillage systems under simulated rainfall using a semivariogram-based index

Jaqueline Dalla Rosa [a,*], Miguel Cooper [a], Frédéric Darboux [b], João Carlos Medeiros [a]

[a] Soil Science Department, Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo (ESALQ/USP), Av. Pádua Dias, 11, P.O. Box 13418-900, Piracicaba, SP, Brazil
[b] INRA, UR 0272 Science du sol, Centre de recherche d'Orléans, CS 40001, F-45075 Orléans Cedex 2, France

ARTICLE INFO

Article history:
Received 19 October 2011
Received in revised form 13 May 2012
Accepted 3 June 2012

Keywords:
Tillage
Microrelief
Semivariograms
Rainfall
Roughness

ABSTRACT

Among the factors that contribute to greater changes in soil surface roughness are the tillage systems and rainfall conditions. This study evaluated the changes of surface roughness under different tillage systems and the application of artificial rain. The experiment was conducted in 2009 and 2010 for conventional tillage (CT), reduced tillage (RT) and no tillage (NT), in micro plots with 1 m × 1 m size for each treatment. Simulated rainfall with intensity of 80 mm h^{-1} was applied. Soil microrelief was measured with a portable laser scanner with a 1-cm horizontal resolution. The height readings were submitted to geostatistical analysis through the semivariogram method, and the index used to represent the roughness of the soil (RI) was extracted from the semivariograms. The RT and NT systems presented higher roughness in the first year, but in the second year, the greatest RI was observed in the NT system. The RI values in the same treatment differed between applied rainfalls only in NT for the second year. In CT, the RI did not differ between the applied rainfalls, but showed the same trend in the two years studied: initially an increase of roughness occurred until a maximum rain amount, then it decreased. Differences between the years studied occurred only in NT, which showed greater RI in the second year in comparison to the first one, CT and RT were similar and did not differ between the two years evaluated.

1. Introduction

The microrelief of the soil refers to the surface configuration of the soil. Roughness is defined as the height changes in reference to the general shape of the microrelief (Darboux, 2011), and roughness indices are specific metrics used for quantification of its components (e.g. vertical amplitude, spatial correlation). The knowledge of the dynamics of the microrelief is essential for a better understanding of soil erosion. The main processes related to water erosion, such as the water storage in depressions, soil detachment by shear stress or by the effect of raindrops and sediment transport, occur initially at the micro-scale level of the soil surface and are greatly influenced by the microrelief dynamics.

Different elements, ranging from individual grains, aggregates, clods, tillage, and landscape features, contribute to the microrelief at their respective scales (Huang and Bradford, 1992). In agricultural fields, soil tillage and rainfall conditions are the main contributors to changes in microrelief (Allmaras et al., 1966; Taconet and Ciarletti, 2007). Several studies have shown (1) that tillage increases roughness when compared to the no-tillage system and (2) that the rain was the main factor that caused its decrease (Bertol et al., 2006; Eltz and Norton, 1997; Lampurlanes and Cantero-Martinez, 2006; Panachuki et al., 2010; Zobeck and Onstad, 1987). In this context, soil conservation systems are employed due to a number of benefits to the soil, especially the potential to reduce soil erosion. Reduced tillage presented a great expansion in Brazil in recent years. Its increased use is a consequence of the promoted benefits compared to others tillage systems. Reduced tillage increases soil roughness (Bertol et al., 2006; Panachuki et al., 2010; Zobeck and Onstad, 1987), protects the soil surface with crop residues (Schultz, 1978) and improves machine operational yields and lowers fuel consumption (Hadlow and Millard, 1978). The larger roughness observed in this tillage system, associated with plant residues, acts as a strategy for soil and water conservation, because it (1) increases the soil ability to retain and infiltrate water, (2) reduces the speed and volume of runoff and, consequently, (3) reduces sediment losses (Mwendera and Feyen, 1994; Govers et al., 2000; Darboux and Huang, 2005; Bertol et al., 2006; Castro et al., 2006).

The most common form of expressing the roughness of a surface is through an index that represents by a single number the conformation of the soil surface. Numerous indices have been used in the literature. One of the first index that was defined is the random roughness index (RR) (Allmaras et al., 1966), which represents the random distribution of the microrelief. Used by many authors (Allmaras et al., 1966; Bertol et al., 2006; Garcia

* Corresponding author. Tel.: +55 19 3417 2150; fax: +55 19 3417 2110.
E-mail address: jaqueline.dr@gmail.com (J. Dalla Rosa).

0167-1987/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.still.2012.06.001

Moreno et al., 2010; Hansen et al., 1999; Jester and Klik, 2005; Kamphorst et al., 2000; Moreno et al., 2008; Onstad, 1984; Panachuki et al., 2010), this index is usually calculated by the standard deviation of heights after removal of the slope and tillage marks (hence, deviating from the original definition of Allmaras et al. (1966)). One of its major limitations is that it describes only the vertical component of the roughness, i.e. it does not consider the spatial organization of heights within the roughness (Huang and Bradford, 1992). According to Huang and Bradford (1993), it is important to select a roughness index that account for (1) the spatial correlation of soil topography and (2) its scale-dependent structure.

Another roughness index known as LD (limiting elevation difference) represents the mean of the absolute differences in height between two points of the soil surface (Linden and van Doren, 1986). It takes into account the spatial component of the roughness, and may represent the capacity of the soil surface to store runoff (Bertol et al., 2006). A third index employs the concept of tortuosity (Boiffin, 1984) and describes the relationship between the length of a profile of a soil surface and the distance between the initial and final points of this surface. It represents the capacity of some roughness to delay runoff, however, it may vary depending of the scale of measurements taken (Bertol et al., 2006).

Another way to express the roughness of the surface is using geostatistical techniques, such as semivariograms. The use of this method is common in soil roughness studies (Darboux et al., 2002; Eltz and Norton, 1997; Huang and Bradford, 1992; Linden and van Doren, 1986; Moreno et al., 2008; Vazquez et al., 2010). The semivariogram informs the relationship between the elevation differences and the length scales, given by the separation lag (Huang and Bradford, 1992). Such feature cannot be assessed with the RR index, because the RR index does not consider the spatial relationship between height measurements.

The objective of this study was to compare the surface roughness for different soil tillage systems and their evolution under simulated rainfall through two consecutive years. Surface roughness was quantified using an index based on semivariograms.

2. Material and methods

2.1. Experiment design and sample collection

The experiment was carried out in the municipality of Piracicaba/SP, Brazil (22°42′S, 47°36′W) in Arenic Haplustults (Survey, 2010) of loamy sand/clay texture, with the following particle size distribution: 164, 20 and 816 g kg^{-1} of clay, silt and sand, respectively, for the 0–5 cm layer. The climate of the study area according to Köppen's classification is Cwa. The relief is gently undulating and the altitude of the study site is 542 m. According with the weather station of ESALQ/USP, located close to the experimental area (22°42′S, 47°38′W) the mean annual precipitation for the last ten years was 1193 mm. The 3 maximum monthly rainfalls observed during this period occurred in March 2002, May 2005 and January 2008 with 104, 139 and 87 mm respectively (Base de dados meteorológicos, USP/ESALQ, 2011).

In November 2008, the initial soil preparation (plowing + harrowing three times) was carried out throughout the experimental area, as a form to homogenize the soil surface layer and afterwards, a cover crop was implanted (*Brachiaria decumbens* Stapf. – sown at haul without incorporation; sowing density of 13 kg ha^{-1}).

In April 2009, when the plants were in full stage of development, the cutting of the coverage was made with

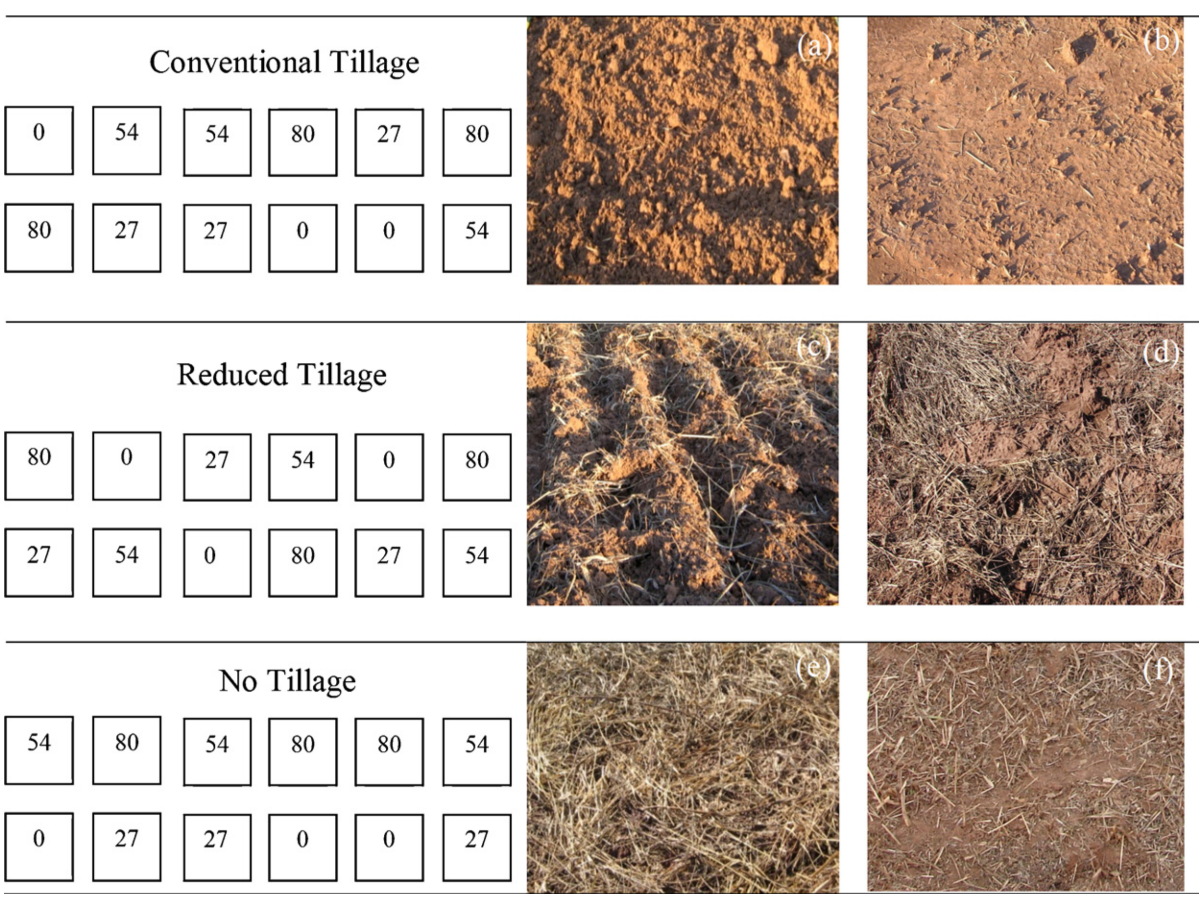

Fig. 1. Experimental design and details of the soil tillage systems. (a, c and e) Before rainfall (0 mm); (b, d, and f) after the rainfall (80 mm) and before roughness readings.

mechanical mowing and the regrowth was suppressed by herbicide application (4.0 L ha^{-1} of glyphosate). Experimental treatments were started in June 2009 and consisted in three soil tillage systems: conventional tillage (CT), tilled with a disk plow and a disk harrow (3 times); reduced tillage (RT), tilled with a heavy disk harrow with partial incorporation of the cover residues; and no tillage (NT), where the cover crop residues were left on the soil surface and the plot was not plowed. Each treatment consisted of a plot of 7 m $\times$ 30 m. Within each plot, 12 micro plots of 1 m $\times$ 1 m were installed, delineated and identified. A simulated rainfall was applied (0, 27, 54 or 80 mm) once on each micro plot making three replicates (Fig. 1). The cover crop of the RT and NT was not removed before application of the simulated rainfall. Micro plots had zero slope.

After performing the experiment in the first year, the experimental area lay fallow. In April 2010, when cover was in full stage of development, it was cut again, and the regrowth was controlled with herbicide until the completion of the till operations in June, in the same plots and following the same procedures used in 2009.

In all cases, the intensity of the simulated rainfall was 80 mm h^{-1} ($\pm$5 mm h^{-1}), performed with a rainfall simulator at 2.4 m above the ground. The simulator consisted of an oscillating nozzle, type VeeJet Spray Nozzle (H/U-80100, Spraying Systems, Co.).

The soil microrelief was measured twenty-four hours after the completion of the rainfall simulation, on the whole surface of each micro plot (individual surface area: 1 m^2). In the CT plots, readings were made directly on the soil surface, in the RT the residues semi-incorporated by tillage were not removed before the readings and in the NT system, the soil cover was removed manually using pruning scissors. Roughness measurements were obtained with a portable laser scanner adapted from Arvidsson and Bölenius (2006), in which each height reading (z) was made in a 10 mm $\times$ 10 mm (horizontal resolution) grid over the whole micro plot surface, hence totalizing 10.000 sampling points.

2.2. Roughness analysis

2.2.1. Semivariograms

Semivariograms are commonly used to represent soil roughness and allow to analyze the degree of spatial dependence between samples (Darboux et al., 2002; Eltz and Norton, 1997; Huang and Bradford, 1992; Linden and van Doren, 1986; Moreno et al., 2008; Vazquez et al., 2010). The data were subjected to geostatistical analysis by calculating the experimental semivariograms estimated up to 2/3 of the plot width (i.e. 69 cm). A semivariogram can be defined by the following equation:

$$\gamma(l) = \frac{1}{2N}\sum[z(x) - z(x+l)]^2 \quad (1)$$

where γ is the semivariance, l is the lag distance between points, $z(x)$ is the elevation in x and N is the number of pairs considered.

2.2.2. Roughness index

In this paper, the index used to represent the roughness of the soil (RI) was determined from the semivariograms. The RI was defined as the semivariance at the lag distance which separated the domain of strong spatial dependence (at short lag distances) and the domain of low spatial dependence (at greater lag distances). This index was chosen because several studies have demonstrated the importance of considering the spatial component and scale-dependency of the soil surfaces in the study of soil roughness (Darboux et al., 2002; Eltz and Norton, 1997; Huang and Bradford, 1992; Linden and van Doren, 1986; Moreno et al., 2008; Vazquez et al., 2010). In this study, no procedure of trend removal was carried out because (1) the micro plots had zero slope and (2) the ridges and furrows created by some of the tillage systems were considered as relevant features of the roughness.

2.3. Statistical analysis

With the semivariance data obtained from the semivariograms, the standard error (SE) of the mean was calculated from each distance through the following equation $\mathrm{SE} = dp/\sqrt{n}$. For the RI, the SNK test of means ($p < 0.05$) and regression equations were applied.

3. Results

3.1. Differences among treatments and applied simulated rainfalls

3.1.1. Roughness behavior and roughness index (RI) in 2009

A major distinction is observed between the treatments where no rain was applied (0 mm) (Fig. 2): the RT system showed the largest semivariances, followed by NT, and CT with the lowest semivariances. With the application of successive rainfalls, the CT system kept the minor semivariance, except at 54 mm, in which NT was very similar to CT. The greater semivariance in the RT is attributed to the till operations performed, which promoted the formation of mounds and depressions, and to the semi-incorporated residue cover, protecting it from the effect of the rain. The NT system also showed high semivariance, i.e. a high surface roughness.

The CT treatment was always the least rough and the RT and NT treatments the roughest (Fig. 3a). Comparing the tillage systems, at 0 and 27 mm of rain, RT and NT did not statistically differ from each other, but were higher than CT. As the rainfall increased to 54 mm, CT and NT did not differ and, RT was higher. At 80 mm of rainfall, all treatments were different from each other with the highest RI for RT (2131 cm^2), followed by NT (1399 cm^2) and then CT (773 cm^2). By comparison, the greater random roughness index (RR) in minimum tillage has also been reported by Panachuki et al. (2010) and Zobeck and Onstad (1987).

Observing each treatment independently there was no significant statistical difference in RI depending on the amount of applied rainfall (Fig. 3a). RI for RT and NT showed similar behavior during the application of rainfall. RI of CT had an initial increase in roughness up to 54 mm of rain, decreasing at 80 mm of rain, but these differences were not significant (Fig. 3a).

However, the regression analysis for the applied rainfall (Fig. 4), showed significant quadratic fitting for the CT (Roug. 2009 = 438 + 15.75x $-$ 0.15x^2), with determination coefficient R^2 of 0.83, where initially there was an increase of soil roughness with the increase of rainfall amount, up to a maximum rainfall of 52 mm, from which the RI decreases. On the other hand, other authors observed a constant reduction in the random roughness index (RR) with increased rainfall in conventional tillage (Bertol et al., 2006; Eltz and Norton, 1997; Magunda et al., 1997; Mwendera and Feyen, 1994).

3.1.2. Roughness behavior and roughness index (RI) in 2010

For all applied simulated rainfalls, the difference among treatments is very distinct (Fig. 5) except for rainfall of 27 mm where RT and CT were very similar. The NT treatment had the highest roughness, followed by the RT and CT, regardless of the amount of rain applied, thus, the highest semivariance was found in the NT system and the lowest in CT.

RI was similar between RT and CT, which had lower RI, while the NT system had the highest RI (Fig. 3b). For the rainfall of 0, 27 and 54 mm, CT and RT showed no statistical differences between each other, but they differed significantly from NT. For the rainfall of 80 mm, NT (RI = 2670 cm^2) and RT (RI = 1682 cm^2) did not differ, but CT (RI = 842 cm^2) was significantly lower. Observing each treatment, with the increase in cumulated rainfall, no significant

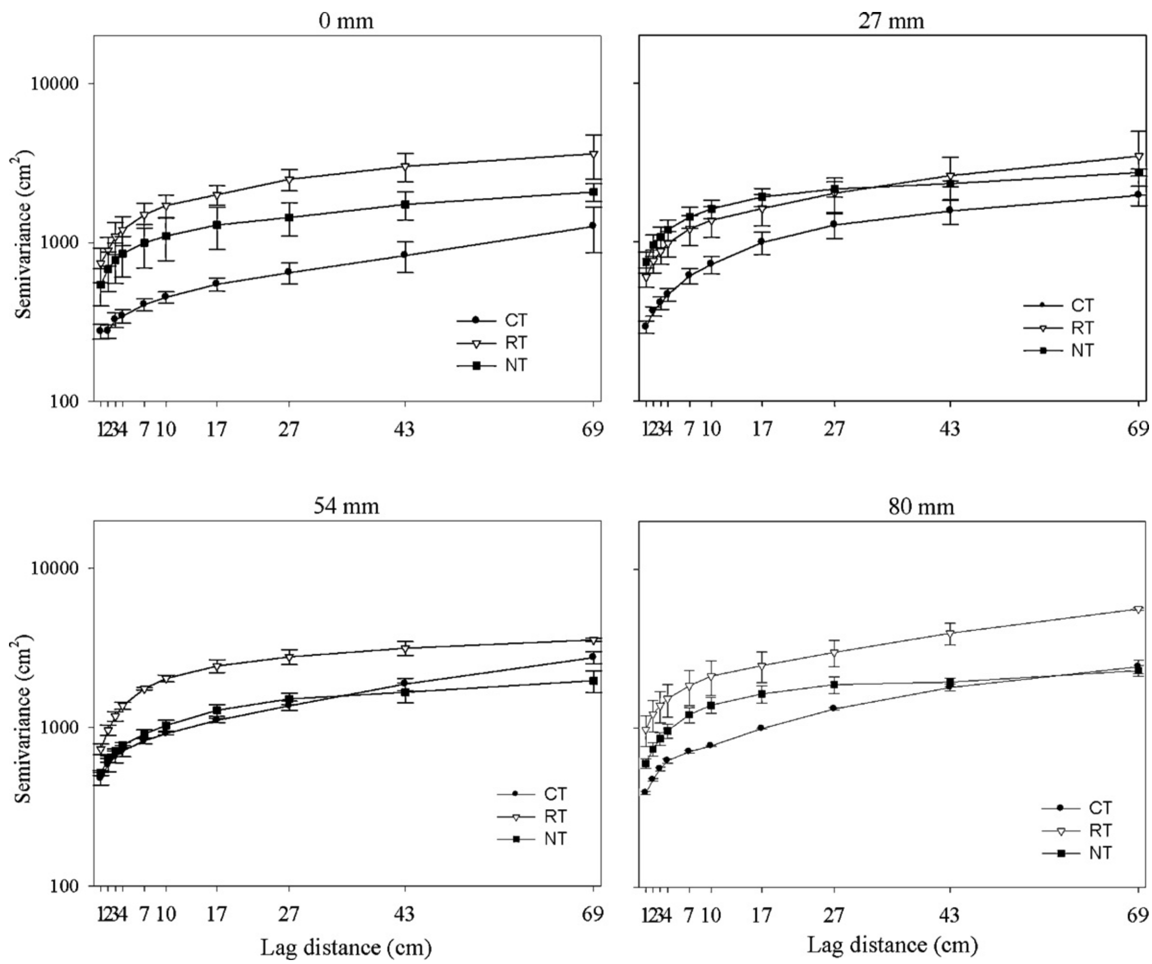

Fig. 2. Experimental semivariograms for the year 2009 for different soil tillage systems and applied rainfall. Conventional tillage (CT), reduced tillage (RT) and no tillage (NT). Bars are standard errors ($n = 3$).

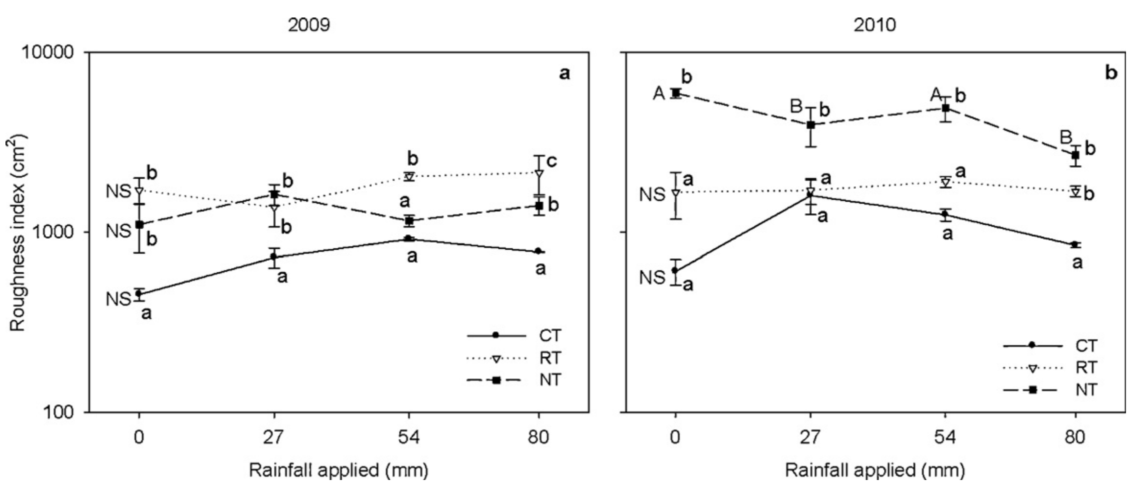

Fig. 3. Roughness index (RI) for different treatments and rainfall for (a) 2009 and (b) 2010. Lowercase letters indicate statistical differences between different treatments applied for the same rain and capital letters indicate differences between applied rainfall within each treatment. NS: not significant, by SNK test ($p < 0.05$). Conventional tillage (CT), reduced tillage (RT) and no tillage (NT). Bars are standard errors ($n = 3$).

differences of roughness were found for CT and RT, only NT showed differences between applied rainfall amounts (Fig. 3b).

Even if no statistical differences were found between the different amounts of applied rainfall taken independently, a significant quadratic relationship was found (Roug. 2010 $= 667.02 + 40.70x - 0.49x^2$) with determination coefficient R^2 of 0.58 (Fig. 4), demonstrating that RI initially increased up to a maximum at a cumulated rainfall of 41 mm and, then, decreased. So, basically, CT showed the same trend as in year 2009.

3.2. Comparison of the two years of study

RI showed similar results in the two years of study, with some specific differences. Overall, in 2009, conservation treatments

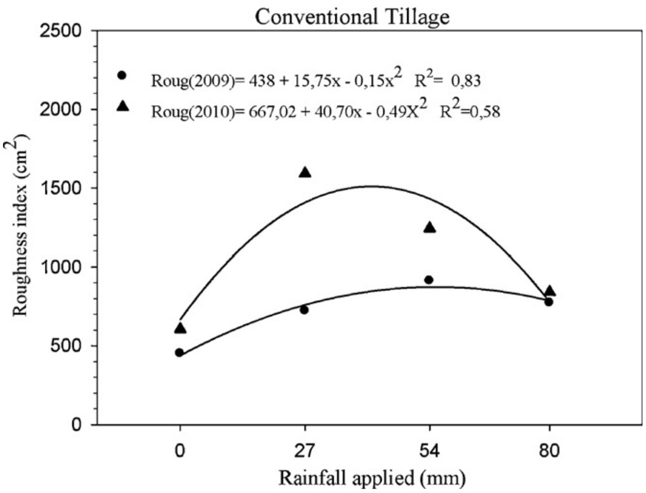

Fig. 4. Regression of the roughness index (RI) as a function of applied rainfall for both years of study.

(NT and RT) were similar, and showed higher RI than CT. In 2010, the CT and RT were statistically more similar and differed only with total rain amount of 80 mm (Fig. 3b), while the NT had higher RI.

The higher RI observed in the NT system, as occurred in 2010, is contrary to what other authors have observed (Bertol et al., 2006; Eltz and Norton, 1997; Linden and van Doren, 1986; Panachuki et al., 2010; Zobeck and Onstad, 1987). In general, NT systems, which do not undergo the influence of tillage, tend to show a decrease in roughness over the years of cultivation. The greater RI for NT may be explained by stems and residues of the cover plants that remained on the soil surface after the cut.

Comparing the effects of the two years (Fig. 6), RI of CT did not differ between the 2 years (2009: RI = 715 cm^2; 2010: RI = 1070 cm^2) and was the least rough system. RT also did not differ in the two years of study (2009: RI = 1809 cm^2; 2010: RI = 1735 cm^2) and presented higher RI than CT. Contrarily, RI of NT system was different in the two years (2009: RI = 1408 cm^2; 2010: RI = 4343 cm^2), with higher RI in the second year than in the first one. For both years, the behavior of RI for CT was similar, with an initial increase in RI (up to a maximum rainfall of 52 mm in 2009 and 41 mm in 2010), and subsequently a decrease with the cumulated amount of rainfall (Fig. 4).

4. Discussion

4.1. Effect of tillage system on soil surface roughness

Tillage can either increase or decrease soil roughness depending on the tillage operation and the roughness condition at the time of the operation (Zobeck and Onstad, 1987). Minimum tillage or reduced tillage, where the mobilization is performed using a chisel plow or disk harrow, is generally the tillage system that creates most roughness, followed by conventional tillage and no-tillage systems. In this sense, Zobeck and Onstad (1987) observed that the random roughness index varied from 5 cm for single tillage operations (offset disk) to 0.7 cm for no-tillage systems.

In 2009, the greatest surface roughness due to the effect of tillage (0 mm) occurred in the RT system (Fig. 2) and in NT in 2010 (Fig. 5). Similarly, RI in 2009 was higher in RT and NT, but in 2010 the highest RI occurred in NT. CT presented the lowest RI in the two years of the study (Fig. 3). Studying the same tillage systems, Panachuki et al. (2010) and Zobeck and Onstad (1987) found greater random roughness index (RR) in the minimum tillage

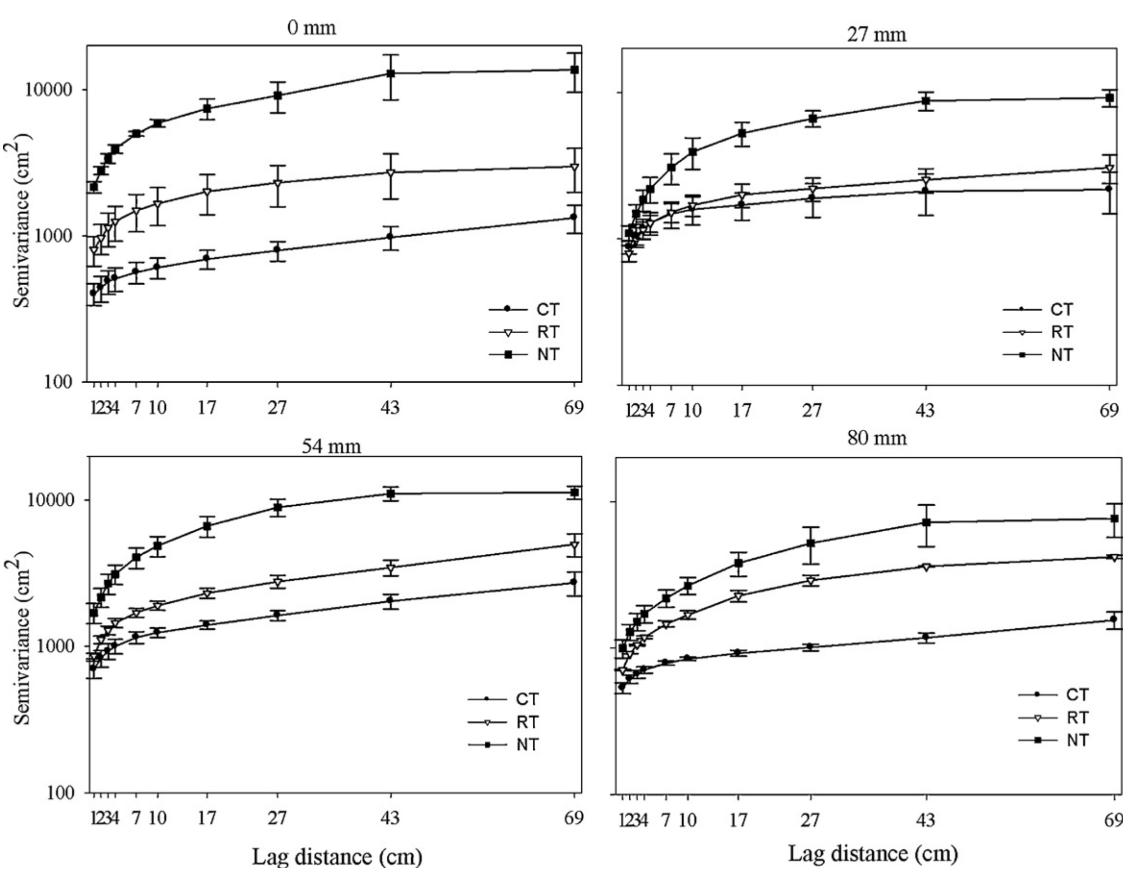

Fig. 5. Experimental semivariograms for the year 2010 for different soil tillage systems and applied rainfall. Conventional tillage (CT), reduced tillage (RT) and no tillage (NT). Bars are standard errors ($n = 3$).

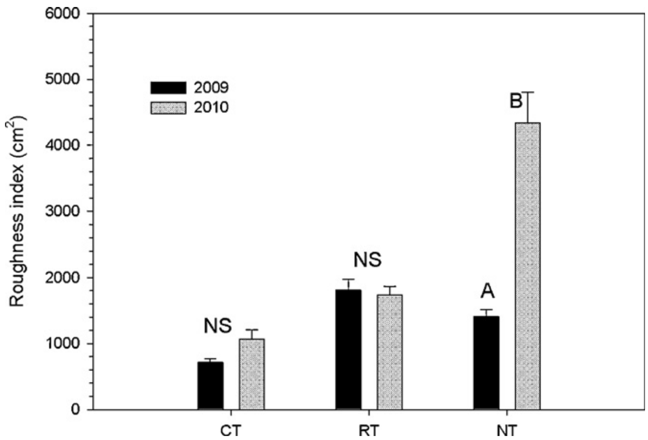

Fig. 6. Comparison of the roughness index (RI) of each treatment during the two years of the study. Different letters indicate difference for the same treatment in different year, and NS, no significant difference between the years, by SNK test ($p < 0.05$). Conventional tillage (CT), reduced tillage (RT) and no tillage (NT). Bars are standard errors ($n = 12$).

system, but they noted the conventional tillage as the intermediate and the lowest (RR) to no-tillage. However, Mwendera and Feyen (1994) observed after different soil tillage operations greater random roughness (RR) in systems that used ploughing and lower in no-tillage systems. de Oro and Buschiazzo (2011) emphasize also that the formation of clods, mainly in tillage systems that plow deeper, mobilizing the moister subsoil, can reduce the degradation rate of random roughness.

The occurrence of high values of roughness in the no-tillage system can be explained by the effects of plant residues on the soil surface and also by marks of tillage still present on the soil surface inherited from the initial phase of implantation of this treatment. Moreover, it is important to highlight that the roughness formed by plant residues, although more persistent in time, has less capacity to retain runoff water than the surface roughness caused by tillage (Bertol et al., 2006). In terms of erosion control and soil and water conservation, the association between the roughness caused by tillage and roughness of plant residues is most desirable (so-called semi-tillage). Plant residues on the soil surface act to dissipate the kinetic energy of rain drops, preventing direct impact on the soil surface; while the roughness caused by tillage is important in the retention and infiltration of surface water, in the decrease in runoff speed and volume, and retention of sediments produced by soil erosion (Castro et al., 2006). The combined effects of plant residues and roughness induced by tillage results in a greater conservation of the soil and water.

4.2. Temporal evolution of the roughness

The roughness evolution in time is influenced by the volume and intensity of rainfall, by runoff and soil type. The volume and intensity of rainfall generally decrease roughness (Bertol et al., 2006; Eltz and Norton, 1997; Magunda et al., 1997; Zobeck and Onstad, 1987), while the development of erosional features (microrills) that vary spatially can increase roughness (Huang and Bradford, 1992, 1993).

The RI in relation to applied rainfall amount in CT had the same behavior in the two studied years (Fig. 4). RI showed an increase up to a maximum rainfall of 52 mm in 2009 and 41 mm in 2010, decreasing after (Fig. 3). This initial increase could be attributed to fragmentation of larger aggregates or clods present in the soil surface, which in rainfalls up to 52 mm in 2009 and 41 mm in 2010 were broken but not completely destroyed, resulting in smaller aggregates, which were responsible for an increase in RI. Later, with increased rainfall, fragmentation increases leading to RI reduction. Nevertheless, these changes in RI were not enough to generate significant changes during the application of simulated rainfall (Fig. 3).

As the duration of the rainfall increases, the aggregates fall apart by the raindrop impact as well as by the loss of cohesive forces between soil particles, causing a decrease in RI (Fig. 3). Possibly, greater reductions in roughness would be observed with larger rainfall amounts. Panachuki et al. (2010) also noted that after the first simulated rainfall applied to CT, there was a small increase in the random roughness index, which decreased with subsequent rainfalls. The same trend was observed also by Eltz and Norton (1997) and Govers et al. (2000).

The formation of microrills as shown by Huang and Bradford (1993) may also increase the roughness, but no microrills were observed during this study, which is justified by the lack of slope of the area, and also by the high water infiltration of this soil.

Zobeck and Onstad (1987) emphasize that changes in the roughness during rains depend upon the distribution, shape and size of the aggregates which compose the soil surface, and the greater surface roughness occurred in the presence of a higher proportion of large aggregates (Rudolph et al., 1997). Among the degradation mechanisms by the action of rain, the breaking down by the raindrop impacts is a cumulative effect (Le Bissonnais, 1996), thus, additional rainfall application is needed for a greater soil disruption to occur. Greater reduction in the random roughness index (RR) in conventional tillage, minimum tillage and no-tillage, respectively, was also observed by Bertol et al. (2006) after the action of natural rainfalls. The authors emphasize that reduction of the RR, in conventional tillage, occurred after successive rain periods, after 229 mm of natural rainfall in a corn crop, and 350 mm in oats crop. Mwendera and Feyen (1994) also found reduced values of the random roughness index by the cumulative rainfall.

The conservationist treatments (RT and NT) showed a variation of increase and decrease of RI along the applied rainfalls, but both showed no significant differences in 2009 (Fig. 3). Only in 2010, did NT show significant differences between the rainfalls, reducing RI after 80 mm of applied rainfall. Possibly these variations and few changes in the conservation tillage systems are related to the presence of cover in these treatments, once the cover protects the soil surface avoiding large evolutions along the applied rainfalls. Furthermore, the cover crops in the conservation systems act positively in the soil and water conservation strategy.

5. Conclusions

The RT and NT systems presented higher roughness in the first year, but in the second year, the greatest surface roughness was observed in the NT system.

The RI values in the same treatment differed between applied rainfalls only in NT and in the second year. In CT, the RI did not differ between the applied rainfalls, but showed the same trend in the two years studied, initially an increase of roughness occurred until a maximum rain, then it decreased.

Differences between the years studied occurred only in NT, which showed greater RI in the second year in comparison to the first one, CT and RT were similar and did not differ between the two years evaluated.

The index used in this work (RI) satisfactorily represented changes in the roughness of the soil, due to the use of different tillage systems and simulated rainfall.

Future studies should detail the mechanisms of soil detachment in the rain and monitor the evolution of both aggregates and surface roughness, especially in conventional tillage systems.

Acknowledgments

Authors are thankful to São Paulo Research Foundation (FAPESP) for the scholarship and financial support (Projects 2006/57233-3 and 2008/53591-8).

References

Allmaras, R.R., Buerwell, R.E., Holt, R.F., 1966. Total porosity and random roughness of the interrow zone as influenced by tillage. USA, Conservation Research Report 7, 1–14.

Arvidsson, J., Bölenius, E., 2006. Effects of soil water content during primary tillage – laser measurements of soil surface changes. Soil and Tillage Research 90, 222–229.

Base de dados meteorológicos, USP/ESALQ Departamento de Engenharia e Biossistemas. http://www.leb.esalq.usp.br/postoaut.html (accessed 20.09.11).

Bertol, I., Amaral, A.J., Vazquez, E.V., Gonzalez, A.P., Barbosa, F.T., Brignoni, L.F., 2006. Relations of soil surface roughness with the rainfall volume and water aggregate stability. Revista Brasileira de Ciência do Solo 30, 543–553.

Boiffin, J., 1984. La dégradation structurale des couches superficielles du sol sous láction des pluies. Paris, INAPG, 1984, 320 pp. (Doctoral Thesis).

Castro, L.G., Cogo, N.P., Volk, L.B.D., 2006. Alterations in soil surface roughness by tillage and rainfall in relation to water erosion. Revista Brasileira de Ciência do Solo 30, 339–352.

Darboux, F., 2011. Surface roughness, effect on water transfer. In: Glinski, J., Horabik, J., Lipiec, J. (Eds.), Encyclopedia of Agrophysics.

Darboux, F., Huang, C.H., 2005. Does soil surface roughness increase or decrease water and particle transfers? Soil Science Society of America Journal 69, 748–756.

Darboux, F., Davy, P., Gascuel-Odoux, C., Huang, C., 2002. Evolution of soil surface roughness and flowpath connectivity in overland flow experiments. Catena 46, 125–139.

de Oro, L.A., Buschiazzo, D.E., 2011. Degradation of the soil surface roughness by rainfall in two loess soils. Geoderma 164, 46–53.

Eltz, F.L.F., Norton, L.D., 1997. Surface roughness changes as affected by rainfall erosivity, tillage, and canopy cover. Soil Science Society of America Journal 61, 1746–1755.

Garcia Moreno, R., Diaz Alvarez, M.C., Saa Requejo, A., Valencia Delfa, J.L., Tarquis, A.M., 2010. Multiscaling analysis of soil roughness variability. Geoderma 160, 22–30.

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

Hadlow, W., Millard, E.W., 1978. Minimum tillage: a practical alternative to ploughing in the South Africa Sugar Industry. In: Congress of ISSCT, 16, 1977, São Paulo, Proceedings, vol. 2. ISSCT, São Paulo, pp. 891–896.

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

Huang, C., Bradford, J.M., 1993. Application of a laser scanner to quantify properties of soil crusts. In: Poesen, J.W.A., Nearing, M.A. (Eds.), Catena Supplement. pp. 129–139.

Huang, C.H., Bradford, J.M., 1992. Applications of a laser scanner to quantify soil microtopography. Soil Science Society of America Journal 56, 14–21.

Jester, W., Klik, A., 2005. Soil surface roughness measurement—methods, applicability, and surface representation. Catena 64, 174–192.

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, 1749–1758.

Lampurlanes, J., Cantero-Martinez, C., 2006. Hydraulic conductivity, residue cover and soil surface roughness under different tillage systems in semiarid conditions. Soil and Tillage Research 85, 13–26.

Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. 1. Theory and methodology. European Journal of Soil Science 47, 425–437.

Linden, D.R., van Doren, D.M., 1986. Parameters for characterizing tillage-induced soil surface-roughness. Soil Science Society of America Journal 50, 1560–1565.

Magunda, M.K., Larson, W.E., Linden, D.R., Nater, E.A., 1997. Changes in microrelief and their effects on infiltration and erosion during simulated rainfall. Soil Technology 10, 57–67.

Moreno, R.G., Alvarez, M.C.D., Alonso, A.T., Barrington, S., Requejo, A.S., 2008. Tillage and soil type effects on soil surface roughness at semiarid climatic conditions. Soil and Tillage Research 98, 35–44.

Mwendera, E.J., Feyen, J., 1994. Effects of tillage and rainfall on soil surface roughness and properties. Soil Technology 7, 93–103.

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

Panachuki, E., Bertol, I., Sobrinho, T.A., Vitorino, A.C.T., de Souza, C.M.A., Urchei, M.A., 2010. Soil surface roughness under diferent management systems and artificial rainfall. Revista Brasileira de Ciência do Solo 34, 443–451.

Rudolph, A., Helming, K., Diestel, H., 1997. Effect of antecedent soil water content and rainfall regime on microrelief changes. Soil Technology 10, 69–81.

Schultz, L.A., 1978. Manual do plantio direto: técnicas e perspectivas. Porto Alegre, Agropecuária, 84 p.

Survey, S.S., 2010. Keys to soil taxonomy. In: Soil, S.S. (Ed.), Natural Resources Conservation Service. 11th ed. USDA, Washington, p. 338.

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

Vazquez, E.V., Vieira, S.R., De Maria, I.C., Gonzalez, A.P., 2010. Fractal dimension and geostatistical parameters for soil microrelief as a function of cumulative precipitation. Scientia Agricola 67, 78–83.

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