Quantifying the changes of soil surface microroughness due to rainfall-induced erosion on a smooth surface

Benjamin K. B. Abban et al.

NPG-2016-76

<u>RESPONSE TO REVIEW COMMENTS</u>

Dear Professor Daniel Schertzer:

We have reviewed the referee comments very carefully. Below we provide the detailed responses to these comments in the following sequence: (1) comments from referees, (2) author's response, and (3) author's tracked changes in manuscript, as suggested in the NPG guidelines. **Please note that the original comments provided by the reviewer are in black letters and our responses are in blue letters**. In addition to these responses, we provide the final form of the revised manuscript that reflects the proposed changes.

Reviewer #1:

We thank the reviewer for the insightful comments and suggestions. We believe that the edits in response to the comments have significantly improved the manuscript in terms of clarity, language, and structure.

Before beginning, we offer here a summary of our responses to the key concerns of the reviewer. More detailed responses are provided under the specific comments.

1. Do you have any replication of each experiment? Did you perform only one set of measurements per experiment?

> Three replicates of each rainfall intensity were performed. Repeatability was confirmed by evaluating changes in RR at specific cross-sections in the rainsplash dominated zone. It was found that on an average, the relative error of the RR ratios between replicates did not exceed 7%.

2. Do you overestimated the relevance of your results and reach conclusions that are not sufficiently proven by their data?

> Our discussion of the results has been adjusted to be more in line with the level of the analysis provided. Please see the specific comments below for each case.

A. When and where does microroughness matter?

Through these studies we were able to determine that microroughness really matters in these two cases: (1) when there is no cover, which is between harvest and planting; and (2) at the beginning of a storm event. We therefore offer only a small slice of the whole erosion process in this study under the controlled condition experiments.

B. Why perform controlled condition experiments?
Our experiments were designed to help us decipher the role of rainsplash on roughness by isolating it from the role of other processes such as runoff, variable water content, bare soil surface, texture, etc. Microroughness can lead to the formation of depression storage which can ultimately affect ponding and the formation of flow pathways.

General Comments:

The manuscript entitled "Quantifying the changes of soil surface microroughness due to rainfall-induced erosion on a smooth surface" (Reference number NPG-2016-76) authored by B.K.B. Abban, A.N. Papanicolaou, C.P. Giannopoulos, D.C. Dermisis, K.M. Wacha, C.G. Wilson, and M. Elhakeem presents results from a simulated rainfall experiment consisting of applying three different intensities to a smoothed bare soil surface. Authors calculated two widely-used indicators of surface roughness and discussed the implications of their results for modelling approaches.

The reported work is interesting and fits within the scope of Nonlinear Processes in Geophysics. However, the manuscript has an unusual organization and authors mixed methods with results and discussion. Moreover, relevant information is missing from the Materials and Methods section.

Another major concern that I have after reading this manuscript is the feeling that authors overestimated the relevance of their results and reached conclusions that are not sufficiently proven by their data, especially because of the number of events that they experimented (only three, one per rainfall intensity with no replications).

Finally, a few English mistakes must be corrected.

In the following lines, I provide the authors with some suggestions in order to improve their manuscript. They must correct them in order that this manuscript achieves the standard quality for being published in Nonlinear Processes in Geophysics.

Therefore, I recommend the rejection of this manuscript. However, if the editor feels that the research presented is of interest, I made a great number of comments and suggestions in the following pages.

Response:

Regarding restructuring, we have reallocated those areas identified by the reviewer as being out-of-place to the recommended spots. The specifics are provided in the comments addressed for the Materials and Methods and the Results.

We have also included more specifics regarding the methods used.

Those comments where the reviewer feels we have stretched too far in the relevance of our results have been adjusted to be more in line with the level of the analysis. Finally, the grammatical mistakes have been addressed with a thorough read following the edits.

Specific Comments:

1. Abstract: **The abstract must be greatly improved.**

Comment 1: Page 1, lines 13-14: "in agricultural landscapes", this is too general and does not describe what you have done. You did not study all agricultural landscapes, even not a few of them, just one and adapted to the smooth surface conditions that you were interested in.

Response:

We acknowledge that the expression "in agricultural landscapes" may be too general. The sentence (Page 1, lines 13-14) has been reworded as follows to be more precise:

"This study examines the rainfall induced change in soil microroughness of a bare smooth soil surface in an agricultural field."

Comment 2: Page 1, line 17: "representative intensities", representative of what? For instance, 75 mm/h is a very high intensity; does it frequently happen in your region?

Response:

The term "*representative intensities*" was based on the intensity recurrence intervals for Iowa using Huff and Angel (1992). The 30 mm/h event has a recurrence interval of ~0.25-yr, while the 60 mm/h event has a 20-yr recurrence interval. Finally, the 75 mm/h event has a 60-yr return period. Rainfall intensities of 75 mm/h usually appear in late May and June from convective thunderstorms in the study area, as seen from tipping bucket data near the test plot. Here, the Abstract (Page 1, lines 19-21) has been modified as follows and the citation placed in the reference list of the manuscript:

"Three rainfall intensities of 30 mm/h, 60 mm/h and 75 mm/h were applied to a smoothened bed surface in a field plot via a rainfall simulator. These intensities represent the range from typical to extreme rainfall intensities that appear in the region of study."

Reference

Huff, F. A. and Angel, J. R.: Rainfall Frequency Atlas of the Midwest. Midwestern Climate Center Research Report 92-03. Champaign, IL, 1992.

Comment 3: Page 1, line 21: I would remove "for initial microroughness length scales of 2 mm" since this is already stated in line 15 and you did not study any other length scales.

Response:

The phrase "*for initial microroughness length scales of 2 mm*" was removed.

Comment 4: Page 1, line 22: How can your results contradict literature when you have said that there is no literature for the surface conditions you have assayed?

Response:

We understand the reviewer's confusion here. What we meant to convey was that the results contradict the commonly adopted belief in the literature that microroughness decays with rainfall regardless of the initial roughness conditions (e.g., bare flat soil vs. bare disturbed soil). We modified the sentence (Page 1, lines 25-26) as follows:

"*This contradicts the commonly adopted notion in existing literature that a monotonic decay of soil surface roughness with rainfall is expected regardless of initial surface roughness conditions.*"

Comment 5: Page 1, lines 23-24: "Analysis shows", what analysis? This last sentence must be re-phrased and a conclusion should be added.

Response:

This last part of the abstract (Page 1, lines 24-28) has been modified to include a summary statement as follows:

"Findings show a consistent increase in roughness under the action of rainfall, with higher rainfall intensities resulting in higher relative roughness increase. This contradicts the commonly adopted notion in existing literature that a monotonic decay of soil surface roughness with rainfall is expected <u>regardless of initial surface roughness conditions.</u> The study results highlight the need for a better understanding of the phenomenon of microroughness evolution on a bare surface under rainfall action and its potential implications on hydrologic response."

Introduction: This section is well-written and provides enough information about the background of the presented work.

Response:

Thank you.

Comment 1: Page 1, line 29: You could remove "reported in the literature"

Response:

The phrase "*reported in the literature*" was removed.

Comment 2: Page 2, line 4: "From the outlined above" instead of "From the classes outlined above".

Response:

This change was made.

Comment 3: Page 2, line 7: What is "scape"? Is this a mistake? Should it be "scale"?

Response:

The term "*soil scape*" is used often in soil science, referring to a soil column. We have kept this term in the text.

See for example: Yaalon, D. H.: "The changing model of soil" revisited. Soil Science Society of America Journal, 76, 766-778, 2012.

Comment 4: Page 2, line 8: I am not sure if "enhancing" is the right word here.

Response:

The sentence was modified as follows to remove the term "*enhancing*" (Page 2, lines 13-15):

"*As a result, RR affects key hydrologic processes at the soil scape and ultimately at the hillslope scale (e.g., overland flow, infiltration), by affecting the depression storage and the associated runoff and erosion processes (Gómez and Nearing, 2005; Chi et al., 2012).*"

Comment 5: Page 2, line 10: I do not understand why you cite Paz-Ferreiro et al., 2008 here. Besides, according to the reference list, Allmaras (1966) should be Allmaras et al. (1966).

Response:

We cite Paz-Ferreiro et al., (2008) to support the claim that RR is the most widely used descriptor of soil surface roughness. We have also corrected the citation to "Allmaras et al. (1966)". The text now reads as (Page 2, lines 15-16):

"*According to Paz-Ferreiro et al. (2008), the RR index, which was first proposed by Allmaras et al. (1966), is the most widely used statistical microrelief index for the evaluation of soil surface roughness.*"

Comment 5: Page 2, line 21: "Few to none"? Not sure about this.

Response:

We have performed an exhaustive literature search of studies that involve the quantification of soil surface roughness. Few of the existing microroughness scale studies explicitly examine the interaction of rainfall with bare soil surfaces when the surface is initially smooth and undisturbed (e.g., in most studies the surfaces are either partially covered by vegetation or disturbed by tillage). We modified the sentence (Page 2, lines 28-29) to convey the above as follows:

"*Few existing studies, to the best of our knowledge, have explicitly examined the interaction of raindrop impact with bare soil surfaces for initial microroughness scales on the order of 2-5 mm.*"

Comments 6-7: Page 2, lines 22-23: "This condition"? Do you mean less than 2 mm? Here you say that initial microroughness scales less than 2 mm is the prevalent condition in agricultural hillslopes. However, I am not so sure that this is the prevalent state.

Response:

You are right, the sentence needed clarification. Our study explicitly deals with surfaces of initial roughness less than 2 mm. However, it is considered as an extreme condition and findings can be applicable to surfaces of the order of ~2-5 mm, which have been found to be common in agricultural landscapes according to pertinent studies (e.g., (Burwell et al., 1963; Allmaras et al., 1966; Burwell et al., 1969; Cogo, 1981; Currence and Lovely, 1970; Steichen, 1984; Unger, 1984; Zobeck and Onstad, 1987). The sentence was reworded as follows for more clarity (Pages 2-3, lines 29-2):

"*Surfaces with microroughness on the order of ~2-5 mm are common in agricultural landscapes where the soil is "smoothened" due to long, undisturbed exposure to rainfall impact, runoff, and freeze-thaw cycles (Burwell et al., 1963; Allmaras et al., 1966; Burwell et al., 1969; Cogo, 1981; Currence and Lovely, 1970; Steichen, 1984; Unger, 1984; Zobeck and Onstad, 1987; Abaci and Papanicolaou, 2009). Within these landscapes, soil surface conditions are usually bare in the period of the crop rotation between post-harvest and before plant growth is established, which approximately corresponds to 30-75% of the cyclic crop rotation period.*"

Comment 8: Page 2, lines 25-28: This portion of text about the models is not very well linked with the rest of the introduction. Moreover, you cite three studies. Huang and Bradford (1992), Rosa et al. (2012) and Zheng et al. (2014) that stated that RR increased

with rainfall, but later you do not discuss your results in the light of these three studies, why?

Response:

The studies of Huang and Bradford (1992), Rosa et al. (2012), Vázquez et al. (2008), and Zheng et al. (2014) provide quantitative indications that roughness can increase with rainfall, but they neither explicitly acknowledge the increasing trend nor link it to bare smooth surface conditions. Our goal herein is to highlight that phenomenon.

The part of the Introduction referring to these studies (Page 3, lines 3-14) was modified to outline their relevant findings:

"*There are some quantitative indications that under bare smooth surface conditions, soil surface roughness may actually increase under the action of rainfall. Specifically, the study by Huang and Bradford (1992) calculated the semivariance with respect to length scale before and after rainfall, and a slight increase in roughness with rainfall was denoted using the Markov-Gaussian model for a surface with low initial roughness. Rosa et al. (2012) introduced an index (called Roughness Index) estimated from the semivariogram to describe roughness, and the index increase with rainfall under specific conditions was observed and attributed to the fragmentation of aggregates and clods to smaller aggregates. Zheng et al. (2014) reported an increase in values of the RR after the application of rainfall on smooth soil surfaces. Finally, Vázquez et al. (2008) examined the evolution of the surface of three different soils during successive events. They reported that for two out of three soils, roughness increased for the first event, however decreased for the following events; the third soil showed scarce trend to either increasing or decreasing roughness due to successive rainfall events. Nevertheless, none of the above studies explicitly stated or acknowledged the increasing trend of roughness and its potential linkage to smooth bare soil surface conditions.*"

We have also added the Results further comparison between these studies and our own findings (Page 8, lines 5-19):

"*First, our study along with Vázquez et al. (2008) and Zheng et al. (2014), which were performed for the smooth surface initial condition, report an increase in RR with rainfall in general. Exception seems to hold for one soil surface of the study of Vázquez et al. (2008), as well as the smooth surfaces of Vermang et al. (2013) which show decaying roughness due to rainfall because of different soil type and rainfall conditions. Second, the present study indicates that the RR ratio becomes higher with higher rainfall intensity when the surface is classified as smooth, whereas the opposite tends to hold for soil surfaces classified as disturbed (Fig. 5, Table 1). Vázquez et al. (2008) and Zheng et al. (2014) recorded an increase in RR with rainfall but had significantly lower values of RR ratio than we did. This may be attributed to the fact that they applied lower rainfall intensity, and the initial microroughness conditions in their study were higher. Other studies not included in Table 1 have also shown increasing trends of roughness with rainfall, as quantified with the use of different indices. For instance, Huang and Bradford (1992) calculated the semivariograms for different surfaces and used fractal and Markov-Gaussian parameters to quantify the roughness. Markov-Gaussian analysis showed a relative increase in the roughness parameter for a surface of low initial roughness. Finally, Rosa* *et al. (2012) introduced the Roughness Index which is estimated from the semivariogram sill in order to quantify roughness, and observed its increase with rainfall under low initial roughness conditions. That increase was attributed to the fragmentation of aggregates and clods to smaller aggregates but was not linked to smooth bare soil surface conditions.*"

Comment 9: Page 2, lines 29-30: This is already stated in the former paragraph.

Response:

The sentence was removed.

Comment 10: Page 3, lines 3-9: This is a little bit messy from my viewpoint. Moreover, the two last sentences can be removed.

Response:

To clean the text, we shortened and reorganized the last part of the introduction. We highlight more the specific objectives (Page 3, lines 21-25), which read as follows:

"The key specific objectives of this study are (i) to quantify the soil surface microroughness of smooth bare soil surfaces before and after the effect of rainfall, and (ii) calculate the relative change in roughness for different intensities. To meet the two specific objectives we employ four commonly used indices, the RR index, the crossover length, the variance scale from the Markov-Gaussian model, and the limiting difference. The last three indices are alternate methods and used here to supplement the RR index analysis for relative change in roughness."

2. Materials and Methods: **This section lacks from essential information. Do you have any replication of each experiment? Did you perform only one set of measurements per experiment? It is not clear what geostatistical analysis has been performed.**

Response:

All tests were performed three times to ensure repeatability in terms of homogeneity in the raindrop distribution over the rainfed test area, steady state conditions in terms of runoff volumes, and the same soil water content at the inception of the tests. Figure 1b provides a glimpse of the complex set-up needed for the experiments and hence the level of work in these experiments. Raindrop distribution was tested with image analysis (Image J software) of rain splashes within painted areas in the plot to discern them from the rest of the soil background. A weir at the outlet of the plot ensured the occurrence of steady state conditions. The continuous monitoring of volumetric soil water content showed that we had the same water content at the start of the test. Agreement between the test replicates in terms of the key geomorphic and roughness features was found by evaluating changes in random roughness at specific cross sections.

Comment 1: Page 3, line 12: Maybe, you should give the geographical coordinates and elevation of your study area.

Response:

The geographical coordinates and elevation of the experimental plot are now provided (Page 3, lines 28-30):

"*This study was conducted on an experimental plot (Fig. 1b) of the U.S. National Science Foundation Intensively Managed Landscapes Critical Zone Observatory in the headwaters of Clear Creek, IA (41.74º N, -91.94º W and an elevation of 250 m above mean sea level).*"

Comment 2: Page 3, line 14: What do you mean by "mixed, superactive"?

Response:

The terms "*mixed*" and "*superactive*" are soil taxonomy nomenclature used by the USDA (https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf). The term "*mixed*" is related to the mixed nature of clay mineralogy, since these soils contain both smectite and illite. The term "*superactive*" is associated with the high degree of activity of cation exchange in the soil. The cation ion exchange capacity for these soils is between 15 and 30 Meq/100 g. Even though the goals of this paper do not include the effects of texture (since we only use one soil type) this information is helpful for the reader to judge the applicability of this study to their sites. We have added this info along with the textural characteristics of the soil (Pages 3-4, lines 30-2):

"*The soil series at the plot where the experiments were conducted is Tama (fine-silty, mixed, superactive, mesic Cumulic Endoaquoll) (http://criticalzone.org/iml/infrastructure/field-areas-iml/). It consists of 5% sand, 26% clay, 68% silt, and an organic matter content of 4.4%. The aggregate size distribution of the soil consists of 19% of the soil size fraction less than 250 μm, 48% between 250 μm and 2 mm, and 33% greater than 2 mm. These soils contain both smectite and illite, with high cation exchange capacity between 15 and 30 Meq/100 g.*"

Comment 3: Page 3, line 18: "to the plots", how many plots?

Response:

There was one experimental plot. This was a typo, which we have corrected.

Comment 4: Page 3, line 25: "widely accepted", by whom?

Response:

The Marhsall-Palmer distribution is an accepted relationship by the American Meteorological Society (http://glossary.ametsoc.org/wiki/Marshall-palmer_relation). The following reference was added in the text:

Marshall, J.S., Palmer, W.M.K.: The distribution of raindrops with size, Journal of Meteorology, 5, 165–166, doi:10.1175/1520-0469(1948)005<0165:TDORWS>2.0.CO;2, 1948.

Comment 5: Page 3, lines 27-29: This statement is too strong, even though rainfall characteristics were similar, other regions may have different soil types than the one studied here. What are the potential biases you are referring to in this sentence?

Response:

We agree with the reviewer that the direct comparison of our results may only be possible under similar soils examined in this study. This includes regions exhibiting semi-humid climate conditions and have mollisol soils. We have added the following caveat to the Discussion and Conclusions (Page 10, lines 20-23) and the citation to the reference list:

"*It is recognized that dryer, silty type soils may not exhibit the increase in RR shown here. Also, the role of sealing may be important on roughness development under bare soil conditions and needs further examination. Soil water retention characteristics of the soils under sealing and its implication to RR must be considered (Saxton and Rawls, 2006).*"

In terms of other potential biases between natural rainfall and the rainfall supplied by our simulators, a proper calibration must be performed to match the drop size. Drop size affects the terminal velocity and the kinetic energy of the falling rain. A poor calibration of the raindrop size distribution would affect the overall size and shape of the roughness formed. The sentence (Page 4, lines 15-17) has been modified as follows:

"*This level of attention was taken to minimize any potential biases compared to natural rainfall with respect to raindrop size distribution, and, thus, render the rainfall simulation experiments scalable to other regions experiencing the same type of soil, bare surface, roughness conditions, and natural rainfall characteristics.*"

Comment 6: Page 3, line 32: I would substitute "a priori the runs ensured that" for "before the runs confirmed that".

Response:

This change was made.

Comment 7: Page 4, line 1: This seems more like a result than materials and methods.

Response:

We agree with the reviewer. This sentence was removed from the Materials and Methods.

Comment 8: Page 4, line 3: What is CCD?

Response:

It is a charge-couple device camera that serves to transfer the electrical charge to the attached computer and to convert it into digital signal. "*Charge-couple device*" was used in the text instead of "*CCD*".

Comment 9: Page 4, line 5: I would use "by software" instead of "from the desktop, using a computer program".

Response:

The change was made.

Comment 10: Page 4, line 7: Please, provide the names and references for the specific software used.

Response:

The reference for the software is now provided in the text (Page 4, lines 26-29) as follows:

"*The information from each scan is converted into a set of (x,y,z) coordinates using a calibration file and the software developed from the USDA-ARS National Soil Erosion Research Laboratory for data transformation as explained by Darboux and Huang (2003).*"

Comment 11: Page 4, line 12: Remove "experimental" before "tests".

Response:

The word "*experimental*" has been removed.

Comment 12: Page 4, lines 12-13: Change the sentence to "Rainfall intensities were respectively 30, 60 and 75 mm/h for experiments 1, 2 and 3".

Response:

The text has been changed per the reviewer's suggestion.

Comment 13: Page 4, line 14: Is the duration of your rainfall events the same of the storms you are referring here? In fact, 75 mm/h during 5 hours means 375 mm in 5 hours, which seems too much. What is the return period of these events? I mean, are these storms really so usual?

Response:

No, the duration is not the same. However, because rainfall effects for the controlled experiments performed are isotropic it is the intensity that affects splash and RR (see all responses to comment 1 of reviewer 3). The 30 mm/h event has a recurrence interval of ~0.25-yr, while the 60 mm/h event has a 20-yr recurrence interval. Finally, the 75 mm/h event has a 60-yr return period.

Duration would only matter if the goal of the tests was to examine the role of runoff and shear on RR. Here the goal is to examine the role of KE on RR.

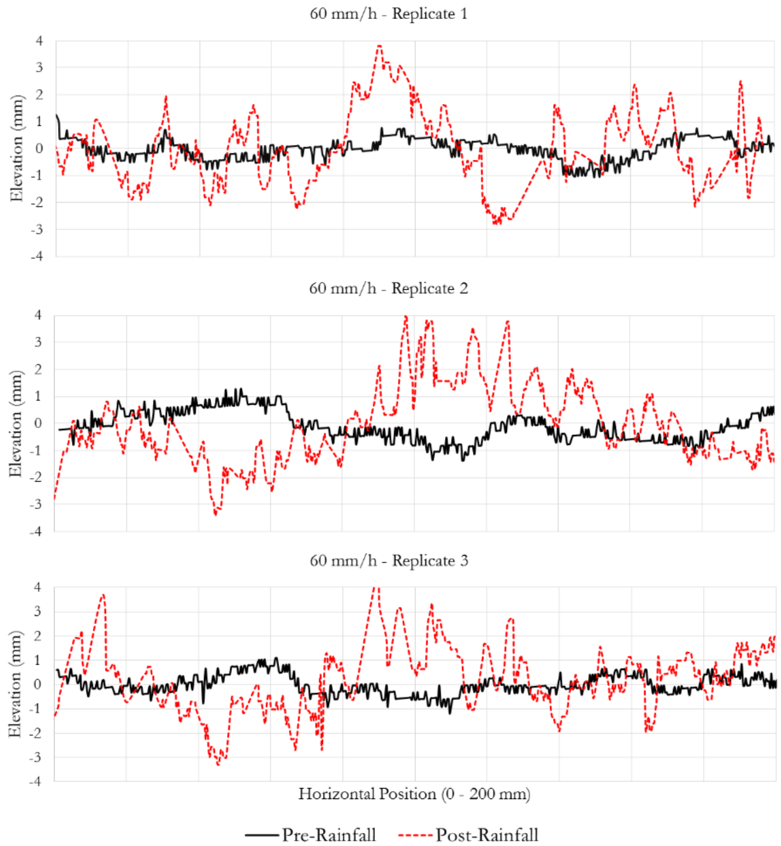
$$KE_i = \frac{1}{2} m_i v_{t\,i}^2$$

where mi is the mass of raindrop i (kg), v_{ti} (m/s) raindrop terminal velocity, ρ_i is the density of raindrop i (kg/m3), and V_i is the volume of the raindrop i (m^3) which assumes a spherical shape.

During each of the experiments, the rainfall intensity remained constant and the storm duration was chosen in order to reach steady-state conditions in terms of infiltration and runoff and thus obtain repeatable results in terms of roughness patterns. Three replicates of each rainfall intensity were performed, and repeatability was confirmed by evaluation of changes in RR at specific cross-sections in the rainsplash dominated zone, as shown below for the 60 mm/h case. We found that on an average, the relative error of the RR ratios between replicates did not exceed 7%. Per the reviewer's comment, we have added (Pages 5, lines 1-4):

"*Three replicates of each rainfall intensity case were performed, and repeatability was confirmed by evaluation of changes in RR at specific cross-sections in the rainsplash dominated zone. It was found that on an average, the relative error of the RR ratios between replicates did not exceed 7%.*"

	Pre-Rainfall RR (mm)	Post-Rainfall RR (mm)
60 mm/h - Replicate 1	0.42	1.44
60 mm/h - Replicate 2	0.55	1.59
60 mm/h - Replicate 3	0.37	1.40



Comment 14: Page 4, line 15: "Decagon soil moisture sensors", specify depth, how many and model.

Response:

Six 5TE soil moisture sensors were placed to a depth of 10 mm along the plot (Page 5, lines 4-5):

"*The volumetric soil water content was recorded with via six 5TE soil moisture sensors manufactured by Decagon Devices, Inc. and placed along the plot to a depth of 10 mm.*"

Comment 15: Page 4, line 16: What do you mean by 35%? What is the field capacity of this soil? Please, specify.

Response:

This value of 35% refers to the average initial volumetric water content at the plot. The field capacity for the soil is 38%. The sentence (Page 5, lines 5-7) reads as:

"*The initial volumetric water content was found to be the same for each experiment and approximately equal to 35% at the whole plot, where the field capacity of the specific soil is 38%.*"

Comment 16: Page 4, line 29: Remove "By definition".

Response:

The phrase was removed.

Comment 17: Page 4, line 31: "extracted" instead of "extract".

Response:

The word was replaced.

Comment 18: Page 4, line 32: "were" instead of "are".

Response:

The word was replaced.

Comment 19: Page 5, line 2: What is "its commonality found in the literature"?

Response:

The sentence has been reworded to better convey our message (Page 5, lines 30-31):

"*The RR index calculated from Eq. (1) was used in this study as the principal method to quantify soil surface roughness due to its frequent and widespread use in various studies and landscape models as a descriptor of microroughness.*"

Please note that additional indices were considered per the request of Reviewer 2.

Comment 20: Page 5, line 3: "was used" instead of "is used".

Response:

The phrase has been replaced.

Comment 21: Page 5, lines 8-12: This is not clear to me. Did you use all these methods? At the end of the sentence you say "among others", what do you mean? Do you imply that you used more methods than those indicated here?

Response:

We see how confusion may have arisen from our original statement. No, we did not use all the methods outlined. We have modified the sentence to read (Pages 5-6, lines 32-3):

"*If correlation exists within a certain spatial scale, RR will likely change with the changing window size of observed data (Paz-Ferreiro et al., 2008) and may be dependent on the resolution of the measurement device (Huang and Bradford, 1992). Thus, alternative scale-independent methods that consider spatial correlation have been developed by other researchers in order to address this issue.*"

Comment 22: Page 5, line 14: I would split this sentence in two. Instead of "with the advantage of its quantification being scale independent", I would use a point and then "It has the advantage of being scale independent".

Response:

The sentence was modified as suggested.

Comment 23: Page 5, line 16: "the semivariogram is a useful…" I do not think this sentence is really needed.

Response:

The sentence was removed.

Comment 24: Page 5, lines 22-25: it seems rather peculiar that you explain what a semivariogram is but not what the Hurst exponent indicates.

Response:

The Hurst exponent is briefly explained after Eq. (3). However, it is not extensively described because it is not of particular interest for this study. It has been shown to be less sensitive than crossover length when describing soil surface evolution influenced by rainfall (Vázquez et al., 2005). The text now reads as (Page 6, lines 26-27):

"*The generalized Hurst exponent is a less sensitive descriptor of soil surface evolution as influenced by rainfall (Vázquez et al., 2005), hence attention is mostly centered on the crossover length.*"

Comment 25: Page 5, line 28: "and 0 < H < 1", this should come before, when you refer to H and not after the crossover length.

Response:

This changed has been made.

Comment 26: Page 5, lines 32-33: I did not understand this sentence. Please, re-phrase it.

Response:

We rephrased these two sentences (Page 6, lines 27-30), which now read as follows:

"*Given the semivariogram plot calculated using Eq. (2), H and l can be extracted by fitting a power law relationship in the form of* $y = Ax^B$ *to the semivariance-lag distance data, where* $y = \gamma(h)$ *and* $x = h$*. According to Eq. (3), the B regression variable gives the generalized Hurst exponent value and the A regression variable yields the crossover length.*"

Comment 27: Page 6, lines 1-4: Could you, please, re-phrase this paragraph? I do not understand it properly, it is a bit confusing.

Response:

We have completely removed this paragraph to avoid confusion of the reader. Besides, it is explained in the Results section, please see Comment 8.

3. Results

Comment 1: Page 6, lines 6-14: This looks more like materials and methods than results.

Response:

We moved and modified this paragraph to the end of the section of Materials and Methods (Page 7, lines 13-19):

"In order to negate the effects of the differences found in initial microrelief amongst the three runs and compare rainfall induced changes in relative terms, the results from the rainfall experiments are presented in the form of ratios of the roughness indices. More precisely, the RR ratio, defined as the ratio of the RR index post-rainfall over the RR index prior to the rainfall (RR_{post}/RR_{pre}*), is calculated for each experiment. Semivariograms are plotted under pre- and post-rainfall conditions at the ROI to assess the spatial correlation of surface elevations. Along the same lines, ratios between pre- and post-rainfall conditions are calculated for the crossover*

length, the variance length scale of the Markov-Gaussian model, and the limiting difference to assess changes in microroughness along with the RR ratio."

Comment 2: Page 6, lines 12-14: Have these comparisons been performed against literature data? Did this literature provide ratios?

Response:

Yes, sections 3.1 and 3.2 are now updated and include more detailed comparisons with the cited studies. Figure 5 is updated to show the RR ratio versus the initial value of RR for our study along with the relevant studies considered. From Fig. 5 it is now clear that our study captures the behavior of RR for an initial range that was not covered before. In some of the studies (e.g., Zhang et al., 2014), ratios of the roughness indices were already provided, whereas in others they were calculated, since only the initial and final values of the indices were provided. Moreover, the study of Vázquez et al. (2008) which was previously missing from our study is now added to Fig. 5 and Table 1 and discussed in the text for completeness, since it involves quantification of RR for nearly smooth surfaces. Finally, cumulative rainfall amounts for each experiment are provided in Table 1 for a better inter-study comparison.

The updated Results section for the inter-study comparisons now reads as (Pages 7-8, lines 24-2):

"*Figure 5 shows the RR ratio, i.e., RR_{post}/RR_{pre}, with respect to the initial value of RR for the present study along with other studies that quantify rainfall induced microroughness changes. The dashed line at the RR ratio value of unity reflects no change in roughness, thus all points above that line show an increasing trend with rainfall, while all points below show a decreasing trend with rainfall. All the studies capture a wide range of initial RR values – up to 21 mm – and it is clear that our study captures the behavior of RR for an initial range that was not covered before. Figure 5 suggests that roughness may increase with raindrop impact for a range of low initial RR values (< 5 mm), while it consistently decays for high initial RR values (> 5 mm). It is acknowledged that the values of the roughness indices among different studies may reflect different conditions such as rainfall forcing and soil type. Specifically, Vázquez et al. (2007) used clay textured soil, Vázquez et al. (2008) used silt loam textured soil, while our study along with all the other studies cited conducted rainfall experiments for silty clay loam textured soil. Rainfall intensities and cumulative rainfall amounts varied significantly among studies.*"

The revised Figure 5 is below:

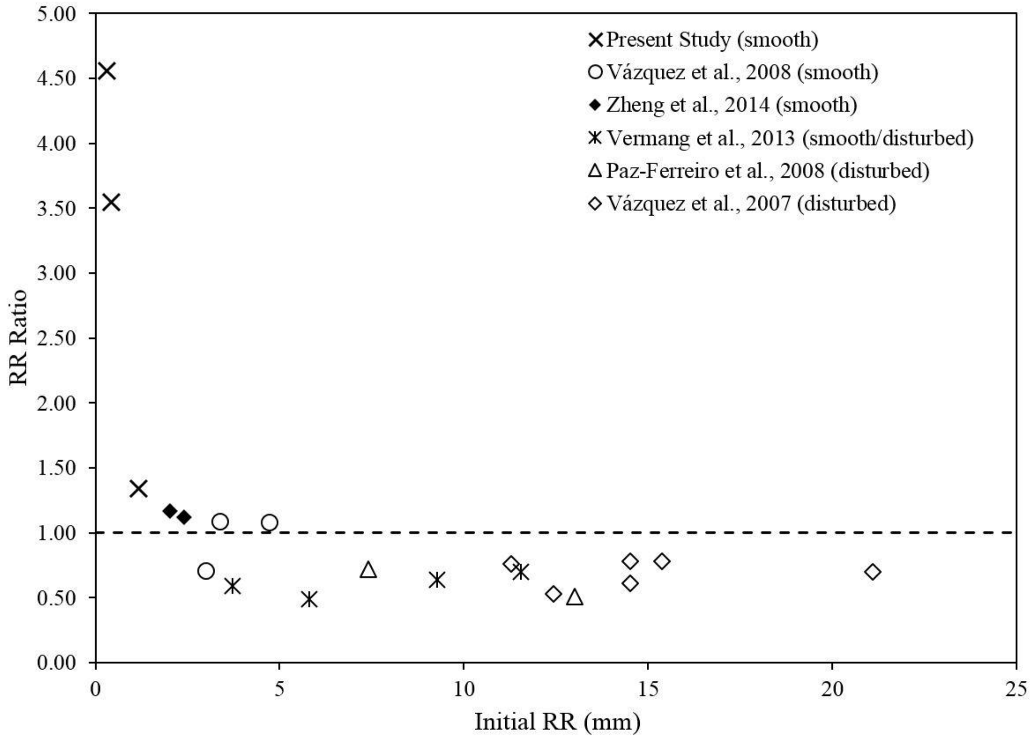


Figure 5: Random Roughness (RR) Ratio versus initial RR for this study and other selected studies.

Comment 3: Page 6, line 20: Have these experiments been performed only once?

Response:

This question was answered earlier under comment 13 in the Materials and Methods. Three replicates of each rainfall intensity case were performed.

Comment 4: Page 6, lines 21-23: Please, re-phrase this. It seems redundant.

Response:

The whole paragraph (Page 8, lines 3-19) which contained this phrase was modified to put our study into a context with the available literature. In doing so we eliminated the part that was considered redundant.

"*Table 1 summarizes the results of this study along with results from the selected studies in quantitative terms, documenting the RR index values before and after the rainfall events, the cumulative rainfall, as well as the associated RR ratio. Two inferences can be made from Table 1. First, our study along with Vázquez et al. (2008) and Zheng et al. (2014), which were* *performed for the smooth surface initial condition, report an increase in RR with rainfall in general. Exception seems to hold for one soil surface of the study of Vázquez et al. (2008), as well as the smooth surfaces of Vermang et al. (2013) which show decaying roughness due to rainfall because of different soil type and rainfall conditions. Second, the present study indicates that the RR ratio becomes higher with higher rainfall intensity when the surface is classified as smooth, whereas the opposite tends to hold for soil surfaces classified as disturbed (Fig. 5, Table 1). Vázquez et al. (2008) and Zheng et al. (2014) recorded an increase in RR with rainfall but had significantly lower values of RR ratio than we did. This may be attributed to the fact that they either applied lower rainfall intensity or the initial microroughness conditions in their study were higher. Other studies not included in Table 1 have also shown increasing trends of roughness with rainfall, as quantified with the use of different indices. For instance, Huang and Bradford (1992) calculated the semivariograms for different surfaces and used fractal and Markov-Gaussian parameters to quantify the roughness. Markov-Gaussian analysis showed a relative increase in the roughness parameter for a surface of low initial roughness. Finally, Rosa et al. (2012) introduced the Roughness Index which is estimated from the semivariogram sill in order to quantify roughness, and observed its increase with rainfall under low initial roughness conditions. That increase was attributed to the fragmentation of aggregates and clods to smaller aggregates but was not linked to smooth bare soil surface conditions.*"

Comment 5: Page 7, lines 4-5: How did you check this significance? Only by stating that difference is less than 10%?

Response:

A nonparametric test for spatial isotropy was performed per Guan et al., 2004 using the public domain R statistical package with 'spTest' library. A p-value less than 0.05 for all cases confirmed the spatial isotropy hypothesis. Thus, there would be no bias by taking one representative direction to calculate the semivariograms and the associated crossover lengths. The corresponding part of the paragraph was adjusted as follows (Page 8, lines 26-30):

"*Since the action of rainfall is isotropic and adds no systematic trend along any direction, no significant differences were expected between semivariograms. A nonparametric test for spatial isotropy was performed per Guan et al., 2004 using the public domain R statistical package with the 'spTest' library. The spatial isotropy hypothesis was confirmed ($p < 0.05$). Thus, there would be no bias in taking any direction to calculate the semivariograms and the associated crossover lengths.*"

Comment 6: Page 7, line 6: "representative semivariogram", that corresponds to which angle?

Response:

The semivariograms were chosen at the downstream direction that corresponds to an angle of 0 degrees. We have removed the term "representative".

Comment 7: Page 7, line 7: "semivariograms" instead of "semivariogram".

Response:

This change was made.

Comment 8: Page 7, lines 10-11: "which is considered sufficient to assume no spatial autocorrelation at the scale examined in this study", I do not get this; you checked all roughness for the 200 mm, so you should have accounted for lag distances less than 10 mm.

Response:

The semivariograms describe the mean variance of the elevation measurements for a range of lag distances and indicate the distance at which spatial autocorrelation ceases to exist. RR is independent of the window size, only if the window size significantly exceeds the spatial autocorrelation range, which is the case here. Our intent here was to point out that the window size of the ROI is sufficiently large enough to eliminate the effects of spatial autocorrelation of data on RR quantification. The last part of the paragraph (Pages 8-9, lines 33-5) has been rephrased as follows:

"*These lag distances are approximately 10 mm, so the selected 200 mm window size of the ROI is almost 20 times greater than the spatial autocorrelation range. This implies that the window size of the ROI falls at the scale of the semivariogram sill (which is defined as the near-constant value of semivariance at large lag distances where the semivariogram levels out – see horizontal dashed lines in Fig. 6). RR is directly related to the semivariogram sill (e.g., Vázquez et al., 2005; Vermang et al., 2013), therefore it can be considered independent of the selected window size, given that the latter far exceeds the spatial autocorrelation range.*"

Comment 9: Page 7, lines 16-17: "pre-rainfall values" instead of "pre-rainfall value for all three intensities".

Response:

The change was made.

Comment 10: Page 7, line 18: I would use "events" instead of "precipitation intensities".

Response:

The change was made.

Comment 11: Page 7, line 19-20: Please, check English and re-phrase this sentence.

Response:

The (Page 9, lines 9-11) sentence has been reworded as follows:

"*Complete agreement between the trends of the RR index and the semivariogram sill justify the use of the RR index as a representative and unbiased descriptor of microroughness.*"

Comment 12: Page 7, line 22: Remove "in existing literature".

Response:

The phrase has been removed.

Comment 13: Page 7, line 24: "reported" instead of "report".

Response:

The change was made.

Comment 14: Page 7, line 25: "found" instead of "in the crossover length reported".

Response:

This has been done.

4. Conclusions and Discussion: **This section is very weak and should be greatly improved. Besides, it should be entitled "Discussion and Conclusions".**

Response:

The title was changed to "Discussion and Conclusions". A great effort was made to improve this section in response to the reviewer's valuable comments. Please see the specific responses below.

Comment 1: Page 8, line 2: Are you sure that these experiments are "unique and novel". I am also concerned about the fact that you state that your experiments "mimic natural rainfall conditions" but you never described those natural rainfall conditions.

Response:

Very few studies have been designed to assess microscale variations under controlled conditions and thus record increases in RR with rainfall intensity. There are several rainfall simulator experiments out there; however, our experiments are unique in the sense that they were designed to help us decipher the role of rainsplash on RR by isolating it from the role of other processes such as runoff, variable water content, bare soil surface, texture, etc. They also mimic natural rainfall conditions, as described in the Material and Methods (Comment 4). We have modified the text to better describe the uniqueness of our experiments (Page 10, lines 2-5):

"*Few studies have been developed to assess microscale variation under controlled conditions to purposely examine increase in RR with rainfall intensity. Unique experiments are presented herein that were designed to help us decipher the role of rainsplash on increasing RR by isolating the role of other processes such as runoff, variable water content, bare soil surface, soil texture, etc*."

Comment 2: Page 8, lines 5-6: "which are confirmed as reliable descriptors of microroughness"; this is already known.

Response:

This phrase was removed.

Comment 3: Page 8, lines 7-9: I have doubts about this, you only performed your experiment once and considered a small surface where raindrop detachment prevails over runoff; were the same conditions in the other studies? Did they consider only raindrop detachment?

Response:

Experiments were performed 3 times. But we agree with the gist of your comment.

These lines probably come across too strong and may not reflect the main message of this study. As the spatial scale increases the effects of rainfall may not be dominant with time. When considering larger areas, runoff and concentrated flow (i.e., rills) will become more prevalent.

However, we all have to agree that during a storm, especially in the early part, there is a period when rainfall action may be more important than runoff, independent of location. It is hard to pinpoint the duration of that period because in some instances the soil may be saturated and runoff dominates right away. During that initial period, though, modeling the evolution of RR is important. This period is the focus of our controlled experiments and this study. The upslope area of the experimental plot provides the controlled conditions. We have therefore taken extra steps following a few other available studies (e.g., Zheng et al. 2014) to design tests where we can isolate the effects of rainfall on RR evolution. We discovered that RR does not always decay with intensity (and the kinetic energy of the raindrop) at all times but depending on the initial surface micorroughness condition RR can increase with time. This process can lead to the formation of depression storage which can ultimately affect ponding and lead to the formation of flow pathways.

All studies that reported on microroughness were performed at similar size experimental plots because this way they can isolate the effects of raindrop from runoff. Small plots suggest less area for runoff and formation of concentrated flow pathways. This is the reason in fact we have focused on a smaller section within the upper part of the plot where RR effects were dominant.

We have rephrased this statement to avoid confusion as follows (Pages 10, lines 12-17):

"The results obtained are consistent with findings of other studies that have examined length scales up to 5 mm. These length scales (i.e., ~2-5 mm) have been found to be common in agricultural landscapes that are subject to prolonged exposure to rainfall impact, runoff, and freeze-thaw cycles (Burwell et al., 1963; Allmaras et al., 1966; Burwell et al., 1969; Cogo, 1981; Currence and Lovely, 1970; Steichen, 1984; Unger, 1984; Zobeck and Onstad, 1987). Within these landscapes, the reported increase is expected to occur during the early part of the storm where rainsplash action may be more important than runoff."

Comment 4: Page 8, lines 11-12: What are the implications of this?

Response:

Please see the response to Comment 5 below, where the implications of localized microroughness residuals are better highlighted.

Comment 5: Page 8, line 13: "Roughness residuals infer depression storage residuals", what do you mean?

Response:

We suggest that localized microroughness residuals as shown from this study will leave additional depression storage at the surface prior to runoff generation. This may alter ponding and flow pathway patterns for storm events. The sentence (Page 10, lines 10-12) was altered to the following and the citations were added to the reference list:

"*Increase in microroughness further infers increase in depression storage at the soil surface prior to runoff generation (Kamphorst et al., 2000), which can affect ponding and flow pathway patterns especially at the onset of a storm event (Onstad, 1984).*"

Comment 6: Page 8, lines 15-20: I am not sure about this. Your results come from a limited number of experiments and you are implying that they have a strong importance in various disciplines and applications… it seems overestimating your findings.

Response:

We understand the reviewer's hesitation here and the potential overestimation of the findings' importance. This study's results, although being limited due to the level of work needed to complete them, consistently report a similar finding, which has been essentially undocumented to date. We feel that it will benefit and possibly further motivate environmental modeling and research, although maybe not directly other disciplines and applications. This part (Page 10, lines 26-28) has been modified as follows:

"*Our findings provide a better understanding of the highly dynamic phenomenon of soil surface microroughness evolution under the impact of rainfall. This study motivates further research on the extent of influence of the examined phenomenon and its mathematical formulation for modeling applications.*"

Comment 7: Page 8, lines 21-23: This must be further explained, I do not see your point.

Response:

We point out that soil surface roughness both depends on and affects hydrologic response. Localized increases in microroughness create additional depression storage at the surface (Kamphorst et al., 2000) with potential implications to flow and pathway patterns (Gómez and Nearing, 2005). However, the extent to which soil surface roughness increases would affect depression storage, ponding, and flow pathways is unknown and further research to quantify this effect is needed. To be more concise, the last part of the paragraph was modified accordingly (Pages 10-11, lines 30-3) and the citations added to the reference list:

"*Finally, this study and other studies demonstrate that the evolution of soil surface roughness in response to rainfall is dependent on initial roughness conditions and can contribute to hydrology, i.e., another factor shaping the soil surface (e.g., through runoff). Different behavior of surface roughness evolution, i.e., increase or decrease, depending on initial roughness conditions indicates a dynamic and nonlinear feedback between hydrologic response and surface roughness which may affect depression storage, ponding and flow pathways (Kamphorst et al., 2000; Gómez and Nearing, 2005). However, the extent to which soil surface roughness increase would affect depression storage, ponding, and flow pathways is unknown, and further research to quantify this effect is needed.*"

Comment 8: Page 8, line 24: Remove "study's".

Response:

It has been removed.

Comment 9: Page 8, lines 23-25: I really think that you are overestimating your results.

Response:

It has been shown through our own research and others (e.g., Gómez and Nearing, 2005) that due to the demonstrated interplay between roughness and hydrology at the microscale, we will see changes in runoff in terms of magnitude and timing. Most physically based models (e.g., WEPP) which assume a decrease in roughness following a rain event in all cases will have an error in the estimations of runoff and hence erosion. We do not infer that lack of consideration of our findings will necessarily or drastically affect hydrologic response. However, the addition of our results may address some of the discrepancies in the results. The last sentence (Page 11, lines 3-4) has been added:

"*Finally, this study and other studies demonstrate that the evolution of soil surface roughness in response to rainfall is dependent on initial roughness conditions and can contribute to hydrology, i.e., another factor shaping the soil surface (e.g., through runoff). Different behavior of surface roughness evolution, i.e., increase or decrease, depending on initial roughness conditions indicates a dynamic and nonlinear feedback between hydrologic response and surface roughness which may affect depression storage, ponding and flow pathways (Kamphorst et al., 2000; Gómez and Nearing, 2005). However, the extent to which soil surface roughness increase would affect depression storage, ponding, and flow pathways is unknown, and further research to quantify this effect is needed. Nonetheless, the current findings may help explain some modeling discrepancies in terms of depression storage and runoff predictions.*"

Comment 10: Page 8, lines 27-29: Yes, alright but is the initial roughness less than 2 mm? Besides, you indicate that Intensive Managed Landscapes have bare soil 75% of the time; it looks not very intensive…

Response:

As noted above, increase in surface roughness has been recorded for surfaces with initial microroughness of the order of 2-5 mm. Several studies have shown that landscapes with surface roughness of this order of magnitude are common in agricultural landscapes (Burwell et al., 1963; Allmaras et al., 1966; Burwell et al., 1969; Cogo, 1981; Currence and Lovely, 1970; Steichen, 1984; Unger, 1984; Zobeck and Onstad, 1987) due to long exposure to raindrop impact, runoff, and freeze-thaw cycles (Zobeck and Onstad, 1987; Abaci and Papanicolaou, 2009).

Depending on the management (i.e., tillage intensity), the period between harvest and planting where the surface cover is bare will vary from 40 days to 6 months. It is understandable, when seeing the long period of inactivity between harvest and planting, to have misgivings with the term "intensively managed landscapes". However, even though intensively managed landscapes have essentially bare soil conditions from harvest to planting, the level of work that goes into planting, harvest, fertilization and other amendments is quite extensive in a short window. This is also quite demanding for the soil and microbes living in the soil, thus the term "intensive".

Comment 11: Page 8, line 33: "landscape response to precipitation"; however, your study refers only to 200 mm^2 surface… is this not overestimating your results?

Response:

We understand the reviewer's concern. We were lax with our wording and speaking generally. The term "landscape response" may be a stretch, especially since our paper deals heavily with scales. As mentioned before, we believe that our findings are applicable to the early parts of storm events when rainsplash effects are most dominant for soil surfaces with roughness on the order of 2-5 mm. The sentence (Page 11, lines 11-13) has been reworded as follows:

"*To the extent that microscale processes are considered significant, we argue that such models should adequately capture the increasing and decreasing trends in soil microroughness during all stages of a storm event in order to accurately predict local response to rainfall.*"

Comment 12: Page 9, line 1: Again overestimating the importance of your results. How this slight increase in RR may affect erosion processes?

Response:

Indeed, the extent to which the increase in RR recorded herein can affect erosion processes is not yet known. However, it has been noted that different values of RR can affect flow pathways and runoff, which consequently can affect erosion processes (Gómez and Nearing, 2005). The above has been documented in the text (Page 11, Lines 13-15):

Furthermore, the following sentence has been removed in order not to overstate the importance of our results of the study:

"~~From this standpoint, our study provides a much-needed insight into processes other than tillage that can result in increasing soil surface roughness after the surface is smoothened through natural weathering or surface erosion processes.~~"

Comment 13: Page 9, line 4: This needs, at least, a reference.

Response:

This section was deleted in order to maintain better focus on the main message of the study.

Comment 14: Page 9, line 5: "new statistical analyses", what statistical analyses did you perform?

Response:

Again, in order not to divert from the main message of the study, we have removed the sentence.

Comment 15: Page 9, line 6: I am not sure about what you mean by "is present a priori".

Response:

The sentence was modified as (Page 11, line 16):

"*The majority of existing models assume that RR always decays over time with rainfall.*"

Comment 16: Page 9, line 7: "in the current paper" instead of "in the paper".

Response:

The change has been made.

Comment 17: Page 9, line 9: "is improved for current models", do you mean that is already done in current models?

Response:

Many existing models have parameterizations for the evolution of surface roughness (e.g., the Water Erosion Prediction Project, WEPP; Flanagan and Nearing, 1995). However, they do not account for the possibility that under certain microroughness conditions, rainfall may increase in roughness. Therefore, our study is calling attention to the need that current and future models must account for this condition of increasing roughness with rainfall over a smoothened surface. The ratios provided in this study are good first step for improving these models. The sentence (Page 11, lines 18-19) was reworded as:

"By providing the ratios of increase in roughness indices with rainfall intensity, the parameterization of the evolution of surface roughness with rainfall could be improved for current models."

Flanagan, D. C. and M. A. Nearing.: USDA-Water Erosion Prediction Project: Hillslope profile and watershed model documentation, 10, NSERL report, 1995.

Comment 18: Page 9, lines 11-12: "extension of the experiments in areas such as downslopes where concentrated flow and rilling are of importance" That you did not want to account in your study although you could have done in view of the surface of your experimental plot.

Response:

In this study, we examined only a small slice of the problem by isolating the effects of rainfall on roughness for smooth bare soil surfaces to get a better understanding on this phenomenon. It was considered as an essential first step before extending the study to include the combined effects of flow concentration, rilling, and rainfall on surface roughness. The last sentence (Page 11, lines 19-21) has now been improved based on the above:

"*Future research will provide a better understanding of the extent to which the initial increase in roughness in the early part of the storm could have an impact on flow pathways, runoff, and processes at subsequent parts of the storm.*"

5. References

Comments:

Eight references are not cited in the text. Please, check them and also edit the reference list according to the journal guidelines.

Page 10, lines 17-18: Chu et al. (2012) is not cited in the text.

Page 10, lines 20-23: Why did you use upper-case letters for the title of these publications?

Page 10, line 27: Why did you use capital letters for CATENA?

Page 10, lines 30-31: Why did you use upper-case letters for the title of this publication?

Page 11, lines 1-3: Le Bissonais (2016) is not cited in the text.

Page 11, lines 4-5, 10 and 17-18: Why did you use upper-case letters for the title of these publications?

Page 11, line 23: Why did you use capital letters for SOIL ORGANIC CARBON DYNAMICS?

Page 11, line 28: Potter (1990), this reference does not follow the style of the journal; the year of publication should come at the end.

Page 11, line 29: Why did you use upper-case letters for the title of this publication?

Page 11, line 32: Why did you use capital letters for CATENA? Besides, Römkens et al. (2002) is not cited in the text.

Page 12, lines 4-5: Remove the quotation marks.

Page 12, lines 8-9: Vázquez et al. (2006) is not cited in the text.

Page 12, line 11: Remove "European Geo-sciences Union (EGU)".

Page 12, lines 15-17: Vázquez et al. (2010) is not cited in the text.

Page 12, lines 18-19 and 25-28: Why did you use upper-case letters for the title of these publications?

Page 12, lines 22-28: Zhao et al. (2014), Zhao et al. (2016) and Zheng et al. (2012) are not cited in the text.

Response:

For the comments regarding the references, we have addressed them all as requested by the reviewer. In summary, we consistently followed the journal guidelines in terms of formatting, removed the uncited references, and added all new references during the major revision process of the manuscript. Please see the updated version of the References (Pages 12-15).

6. Figures

Comments:

Figure 1: Modify the caption to "(a) Types of soil surface microroughness. (b) Experimental plot. The rainfall simulator is placed above the bare soil surface and a base made of wood is put into place to facilitate the movement of the surface-profile laser scanner".

Figure 2: Modify the caption to "Setup of the experimental tests: (a) Rainfall simulators are mounted in series and a pump provides them with water from a tank; (b) rainfall simulators are placed and adjusted at a height of 2.5 m above the experimental plot surface to ensure drop terminal velocity is reached".

Figure 3: Indicate in the caption the interpolation technique that was used.

Figure 4: Why not a and b as in the former figures and you used left and right? You should define ROI in the caption. Besides, why "part"? If the whole experimental plot was 7 x 1.2 m is the whole plot what you are representing in the right-hand side of the figure and not only part of it.

Figure 5: Remove "considered herein". I think that you do not need to include experiments 1, 2 and 3 if you indicate the rainfall intensity. Remove the border of the figure and the second decimal from the Y-axis.

Figure 6: Remove "Spatial" and "considered herein". Use "region of interest" instead of "ROI".

Figure 7: Remove "considered herein". I think that you do not need to include experiments 1, 2 and 3 if you indicate the rainfall intensity. Remove the border of the figure and the second decimal from the Y-axis.

Response:

Regarding the comments to the figures, which are listed above, we have addressed them all as requested by the reviewers. These comments were all essential, but for the most part cosmetic and do not need further elaboration. Figure 5 was revised and is described in the Results Comment 2 above. Finally, Figure 7 was removed since it was considered as unnecessary. Please see the updated version of the figures (Pages 16-20).

Reviewer #2:

We thank the reviewer for the valuable input, which has significantly helped improve the quality of our manuscript. Our responses are provided below.

In summary:

1. We have significantly enhanced the flow, clarity, and precision of the text. The abstract is also very clear in terms of objectives, methodology, and findings.
2. We have put all our results into context, by providing all the relevant literature that has quantified soil surface roughness at the examined bare smooth soil surface conditions, explicitly acknowledging the studies with results that show the increase in roughness and added missing references (e.g., Kamphorst et al., 2000; Vázquez et al., 2008). We have also updated Fig. 5 to depict the changes seen in RR with respect to initial RR from our study and other studies.
3. We discussed the advantages by focusing on a single rainfall event rather than successive events in the context of this study.
4. We have added information regarding the soil characteristics considered in the study.
5. We have provided two additional commonly used indices for soil surface roughness. Their values and trends with rainfall are in good agreement with RR and crossover length, and in support of our conclusions.

General Comments:

This study analyses soil surface roughness evolution after a single event of simulated rainfall with three different intensities, namely 30, 60 and 75 mm/h. Two indices used to describe the magnitude of soil surface roughness indicate increasing values of this variable after rainfall addition.

In my opinion this manuscript does not contain significant results. This is because the experimental work has been limited to one rainfall event, and this is obviously a main weakness in any study about soil surface roughness evolution (either increase or decay). In addition, authors claim that the results are new, as they state that i) "Findings show a consistent increase in roughness under the action of rainfall for initial microroughness length scales of 2 mm" and ii) "This contradicts existing literature where a monotonic decay of roughness of soil surfaces with rainfall is recorded for disturbed surfaces". However, please note that i) again, the increase in roughness (instead of a expected decrease) has been found only for the first event. What about successive events); results are not reported. ii) Increases in soil surface roughness after simulated surface rainfall and for disturbed soil surfaces have been previously reported (Please, see Vidal Vázquez et al., 2008. Assessing soil surface roughness decay during simulated rainfall by multifractal

analysis. Nonlin. Processes Geophys., 15, 457–468). In this paper the evolution of the surface of three different soils was studied during successive events; two of the studied soils showed soil surface roughness increased after the first event (similar to your results)e second, but it decreased after the second and successive events; the third soil studied showed scarce trend to either increasing or decreasing surface roughness values following successive rainfall events.

Response:
There are a number of different reasons why our study focuses on the evolution of soil surface roughness under single storm events. First, the goal of our experiments is to offer generic, controlled conditions to isolate the effects of raindrop impact on roughness from other processes (i.e., runoff). We meet this goal by checking how raindrop impacts roughness under representative for the region rainfall intensities. We are focusing on single events as these experiments allow us to control the antecedent soil moisture conditions and initial bed surface structure. All single storm event experiments start from the same antecedent soil moisture conditions and initial bed surface structure to facilitate comparisons under different intensities and enable comparisons with the reported literature. We acknowledge that a single storm event represents a rather idealistic case scenario and that a series of storm events can be important and should be examined in future studies.

Specific Comments:

Comment 1: The obtained results should be put into context, with relevant references. This opinion is based in the fact that relevant studies about soil surface roughness, (including the previously cited Vidal Vázquez et al., 2008. Nonlin. Processes Geophys., 15, 457–468, and Kamphorst et al. 2000. Soil Science Society of America Journal 64(5): 1479.1458. By the way, these two manuscript present examples of soil surface roughness assessed by laser scanner as in your work. In the first work quoted (Vidal Vazquez et al., 2008) the magnitude of the roughness is not very different from that in your work and in the second (Kamphorst et al., 2000) several plots also are representative for conditions of rather low values of roughness.

Response:
Per the reviewer's suggestion, the results of our study have been put into context, adding the relevant references related to rainfall simulation experiments and the associated evolution of soil surface roughness for smooth surfaces.
First of all, we expanded our results and discussion to elaborate on the comparison with other studies. The study of Vazquez et al. (2008) has been added along with the already cited work of Huang and Bradford (1992), Rosa et al. (2012), and Zheng et al. (2014), all of them providing

indications that under certain conditions, roughness may increase with rainfall (See Page 8, lines 3-19 and Table 1).

We have created Figure 5 to better reflect the relevance of our results. It has been updated to show the rainfall induced relative change in RR with respect to the initial RR of the soil surfaces from our study and the studies outlined above. It is suggested that roughness may increase with raindrop impact for a range of low initial RR values (< 5 mm), while it consistently decays for high initial RR values (> 5 mm). It is also clear that our study captures the behavior of RR for an initial range that was not covered before.

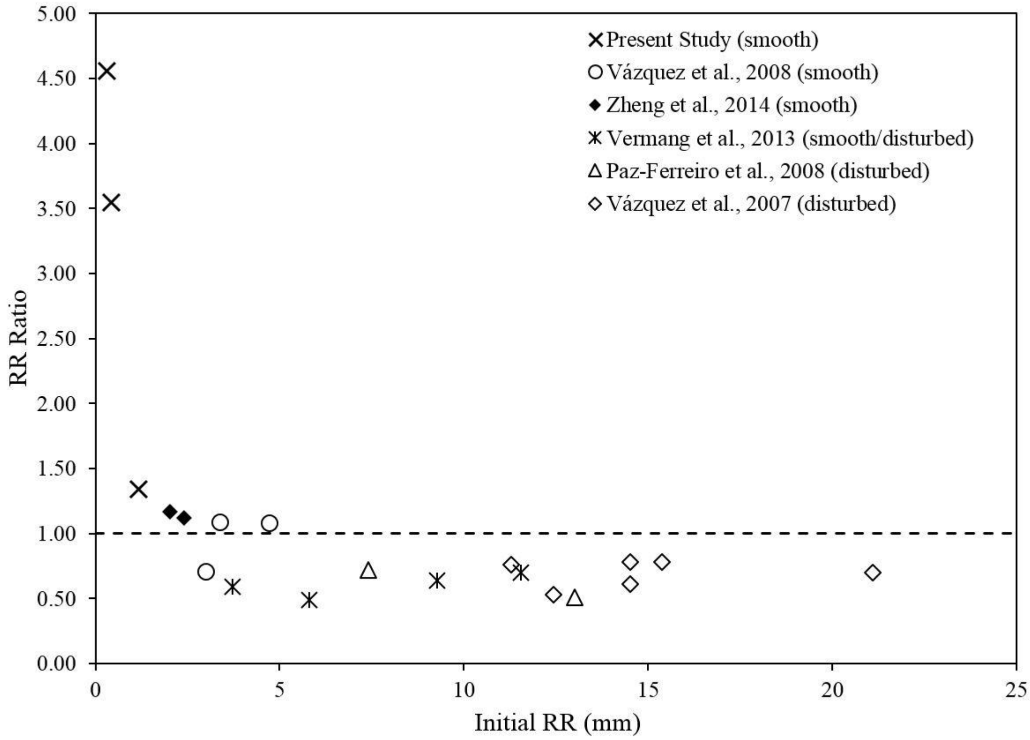


Figure 5: Random Roughness (RR) Ratio versus initial RR for this study and other selected studies.

Findings of Vázquez et al. (2008) have been added to Table 1. In addition, our results are discussed in the light of the other cited studies in the Results section.

Finally, the study of Kamphorst et al. (2000) has been added to the Discussion and Conclusions section of the manuscript in support of the relationship between microroughness and depression storage (Page 10, lines 10-12):

"Increase in microroughness further infers increase in depression storage at the soil surface prior to runoff generation (Kamphorst et al., 2000), which can affect ponding and flow pathway patterns especially at the onset of a storm event (Onstad, 1984)."

Comment 2: In my opinion, adding more experimental data (successive events) would allow that this manuscript reaches international standards.

Response:
We do acknowledge the importance of accounting for successive events but this is not the focus of the specific study as stated earlier. We are therefore not dismissive of the reviewer's request.

Having said that, it is also important to note that the labor and level of detail required to perform the experimental runs presented in the study is significant, as it can be seen in Fig. 1b and 2. It takes about 10 days to prepare and run each test. This is done for 9 runs, so roughly a period of 3 months.

In addition, any revision of this manuscript should address the following points:

Comment 3: Text should be ameliorated the text, which is not precise and provide a more clear presentation.

Response:
The text was substantially improved in terms of clarity, grammar, language and structure. A significant amount of effort has been put to enhance the flow and precision of the text. A number of modifications include: Correction of grammatical errors. We moved and modified the first paragraph of the Results of the previous version of the manuscript to the Materials and Methods section, since it is more relevant there (Page 7, lines 13-19). The last section was more appropriately renamed to Discussion and Conclusions. Results are presented in a clear manner, as explained in Comment 1 above.

Comment 4: Main corrections are expected in abstract, objectives and discussion and conclusion sections.

Response:
The abstract was significantly improved to clearly present our objectives, methodology, and findings (Page 1, lines 13-28). It is specified that our study focuses on a bare smooth soil surface in an agricultural field. Our study is also put into context with existing literature, and the need to

consider the cases where roughness can increase is highlighted, in light of the scarcity of studies that explicitly deal with rainfall induced change in roughness for the examined microroughness scales. Results from the additional indices examined were also added (see Comment 8).

The objectives of our study are now clearly stated (Page 3, lines 21-25):
"The key specific objectives of this study are (i) to quantify the soil surface microroughness of smooth bare soil surfaces before and after the effect of rainfall, and (ii) calculate the relative change in roughness for different intensities. To meet the two specific objectives we employ four commonly used indices, the RR index, the crossover length, the variance scale from the Markov-Gaussian model, and the limiting difference. The last three indices are alternate methods and used here to supplement the RR index analysis for relative change in roughness."

Major revision has been made in the Discussion and Conclusion sections (see Responses to Reviewer 1)**.** In a nutshell, comments where it seemed that we stretched too far in the relevance of our results have been modified or removed, to be more in line with the level of the analysis. Furthermore, we provide a better insight into the significance of our study, stating that our experiments were designed to isolate the role of rainsplash on roughness from other processes such as runoff, variable water content, bare soil surface, texture, etc. Through our study we were able to determine that microroughness and its change are significant when there is no cover, which tends to happen between harvest and planting, and at the beginning of a storm event. We also provide in a clearer manner the limitations of our study, as well as the next steps for further research in terms of a better understanding and quantification of the extent to which the initial increase in roughness in the early part of the storm could have an impact on flow pathways, runoff, and processes at subsequent parts of the storm.

Comment 5: Mechanisms and reason for the increase in soil surface roughness after one event simulated rainfall.

Response:
Changes in roughness during a storm event can be attributed to compression and drag force from the raindrop impact on the soil, angular displacement due to rainsplash, aggregate fragmentation, and differential swelling (Al-Durrah and Bradford, 1982; Warrington et al., 2009; Rosa et al., 2012; Fu et al., 2016). To the best of our knowledge, no study has quantified the co-play of the outlined processes as influenced by different soil types, rainfall characteristics (e.g., median diameter of raindrop), and initial roughness conditions. Therefore, the exact mechanisms and reasons that lead to the increase in soil surface roughness are unknown.
We now acknowledge the above in the manuscript (Page 10, lines 17-20):
"The exact mechanisms leading to increase in roughness are unknown. Changes in roughness during a storm event can be attributed to compression and drag forces from the raindrop impact

on the soil, angular displacement due to rainsplash, aggregate fragmentation, and differential swelling (Al-Durrah and Bradford, 1982; Warrington et al., 2009; Rosa et al., 2012; Fu et al., 2016).”

Comment 6: There are also unnecessary figures, regarding the experimental setup, as the methodology employed has been largely described before.

Response:
Thank you for the comment. Other reviewers have requested that we put more information about the experimental set-up. We deem that our figures regarding the experimental setup provide the reader with the necessary information and specifics to ensure repeatability of the experiments outlined. Future research may require the repetition of the same experiments to study the coevolution and interaction between rainsplash and runoff, in order to further determine their collective influence on the hydrologic processes. We have adjusted other sections of the paper if the concern relates to space. Specifically, we have removed Figure 5 of the previous version of the manuscript and added the Figure described in Comment 1.

Finally, we have removed Figure 7 since it was considered unnecessary.

Comment 7: Soil composition and main characteristics should be also reported in the material and methods section.

Response:
We have added more information on the soil used in our study (Pages 3-4, lines 30-2):
“The soil series at the plot where the experiments were conducted is Tama (fine-silty, mixed, superactive, mesic Cumulic Endoaquoll) (http://criticalzone.org/iml/infrastructure/field-areas-iml/). It consists of 5% sand, 26% clay, 68% silt, and an organic matter content of 4.4%. The aggregate size distribution of the soil consists of 19% of the soil size fraction less than 250 μm, 48% between 250 μm and 2 mm, and 33% greater than 2 mm. These soils contain both smectite and illite, with high cation exchange capacity between 15 and 30 Meq/100 g.”

Comment 8: Other significant roughness indices should be addressed, in addition to random roughness and crossover length.

Response:
Per the reviewer’s suggestion, we examined additional indices other than the RR and crossover length, which can capture soil surface roughness at the examined scales. Specifically, the variance length scale of the Markov-Gaussian model (Huang and Bradford, 1992) and the

limiting difference index (Paz-Ferreiro et al., 2008) were calculated. These specific indices were selected due to their common use for the quantification of soil surface roughness, as well as due to the fact that they can capture scale dependent characteristics of the soil surface. We found good agreement in the values and rainfall induced trends between all examined indices. Below we provide the major modifications we applied to the original manuscript:

Materials and Methods

A brief theory and references behind the introduced indices were added along with equations and specifics for their calculations (Pages 6-7, lines 31-12):

"The Markov-Gaussian model is a random process that has been adopted for the quantification of soil surface roughness (Huang and Bradford, 1992; Vermang et al., 2013). In that case, the semivariogram is written as an exponential-type function with the following form:

$$\gamma(h) = \sigma^2\left(1 - e^{-h/L}\right), \qquad (4)$$

where σ is the variance length scale, representing the roughness of a surface at the large scale, and L is the correlation length scale, which is a measure of the rate at which small scale roughness variations approach the constant value of σ. These indices are obtained by fitting the exponential-type function of Eq. (4) to the semivariogram obtained from Eq. (2).

Finally, the limiting difference (LD) index is another index adopted to quantify soil surface roughness. It is calculated from the first-order variogram (Linden and van Doren, 1986; Paz-Ferreiro et al., 2008), which is written in the form:

$$\Delta Z(h) = \frac{1}{n(h)}\sum_{i=1}^{n(h)}\left|Z(x_i + h) - Z(x_i)\right|, \qquad (5)$$

Then, a linear relationship is fitted between 1/ΔZ(h) and 1/h:

$$1/\Delta Z(h) = a + b/h, \qquad (6)$$

The limiting difference (LD) index is then calculated as $LD = 1/a$. LD has units of length, and represents the value of the first-order variance at large lag distances. It is considered as an indicator of soil surface roughness, thus adopted in the present study as an additional roughness index."

Results

The title of the subsection 3.2 was changed to "Changes in alternative roughness indices". Moreover, a paragraph was added at the end of that section, describing the findings obtained for the introduced indices (Page 9, lines 21-33):

"Table 3 lists the Markov-Gaussian variance length scale and the limiting difference indices for the three experimental tests, and their relative change after the rainfall. These indices show an increase with rainfall that is of the same magnitude and trend as the RR index and crossover length, and provide a supplemental analysis about the role of rainfall intensities on the relative increase in roughness. Our findings were compared against those reported in the literature. Huang and Bradford (1992) studied the evolution of soil surface roughness with the Markov-Gaussian variance length scale, and saw an increase of 6% in roughness for a surface of low initial roughness. Moreover, Paz-Ferreiro et al. (2008), who used the LD index to quantify soil

surface roughness, also recorded a 10% increase in the LD index for a low roughness conventional tillage soil surface. The higher relative increase in roughness seen in our study (Table 3) compared to other studies is attributed to the significantly lower initial roughness conditions in addition to different soil types and management.

Overall, the results provided suggest that all the indices employed in this study may be used interchangeably to characterize rainfall induced changes in soil surface roughness, and can capture an increase in soil surface roughness, especially for low microroughness scales on the order of 2-5 mm. For these microroughness scales, the relative increase in roughness is also shown to increase with rainfall intensity."

Tables

Table 3 below was added to the manuscript, presenting our findings regarding the last two indices that were introduced in support of the RR and crossover length:

Table 3: Summary of the rainfall induced change in the Markov-Gaussian variance length scale and limiting difference indices for the experimental tests of this study.

`	Cumulative Rainfall (mm)	Pre-rainfall σ (mm)	Post-rainfall σ (mm)	σ Ratio	Pre-rainfall *LD* (mm)	Post-rainfall *LD* (mm)	*LD* Ratio
30 mm/h	150	1.19	1.63	1.37	0.79	0.87	1.10
60 mm/h	300	0.42	1.52	3.62	0.26	0.87	3.39
75 mm/h	375	0.31	1.43	4.56	0.15	0.71	4.84

Based on the above I recommend to the editor either major revision or rejection of this manuscript.

Reviewer #3:

Our responses are provided below.

General Comments:
In this manuscript, the authors address the effect of rainfall velocity on soil-air roughness quantified via the random roughness (RR) parameter. They showed that as rainfall velocity increased from 30 to 75 mm/hr the random roughness index increased as well, which is in contrast to those reported in the literature. Although more experimental data on support are required to have a more conclusive conclusion, the manuscript is well written and well organized and suitable for publication in the journal. However, some moderate revisions are required before publication.

Response:
We thank the reviewer for the insightful comments and suggestions. We believe that the revisions we made in response to the comments have significantly improved the quality of the manuscript.

Minor Comments:

Comment 1: P3L23: Could the authors address/discuss on how changes in median diameter would affect air-soil roughness?

Response:
To respond to this great question, we have utilized the median drop diameter estimated for each intensity test to calculate the terminal velocity and mass of the rain drop (see Eq. (1d)). Several studies have shown that soil surface redistribution under the action of rainfall is dependent on the median raindrop diameter (e.g., Warrington et al., 2009; Fu et al., 2016). The kinetic energy (KE) corresponding to the median raindrop diameter is estimated using a collection of equations presented in Atlas et al. (1973), Begueria (2015), and Kathiravelu (2016):

$$\mathrm{KE_i} = \frac{1}{2}\mathrm{m_i v_{t\,i}^2} \qquad (1a)$$

$$m_i = \rho_i V_i \quad (1b)$$

$$V_i = \frac{4}{3}\pi\left(\frac{D_i}{2}\right)^3 \quad (1c)$$

$$v_{ti} = 9.65 - 10.3\exp(-0.6D_i) \quad (1d)$$

where m_i is the mass of raindrop i (kg), v_{ti} (m/s) is the raindrop terminal velocity, ρ_i is the density of raindrop i (kg/m^3), and V_i is the volume of the raindrop i (m^3) which assumes a spherical shape.

In our study, the calibration of the rainfall simulators with the disdrometer allowed us to match the median raindrop sizes that are predominantly found at the study site for all 3 intensities (see Table 1.1 below).

Table 1.1 Median drop diameters corresponding to the rainfall intensities of the experimental runs.

Rainfall Intensity (mm/h)	Median Drop Diameter (mm)
30	2.25
60	2.60
75	2.75

The rate of change in relative roughness (RR_{post}/RR_{pre}) and the other indices against intensity (summarized in Tables 1-3 of the manuscript) essentially reflects the effects of the median drop diameter on roughness.

Eqs. (1a-d) imply that for different intensity and median drop size diameter, both the terminal velocity and mass play an important role to the RR change due to different raindrop kinetic energy. The roughness index increases with intensity; however, the relative change in roughness reduces with increasing intensity, as shown in Fig. 1.1 and summarized in Table 1.2 below (these have not been included in the paper due to space requirements). A change in rainfall intensity from 30 mm/hr to 60 mm/hr results in a 16% increase in the median drop diameter which leads to a 165% increase in the RR ratio. However, a change in intensity from 60 mm/hr to 75 mm/hr results in a 6 % increase in median drop diameter which leads to only a 29% increase in the RR ratio.

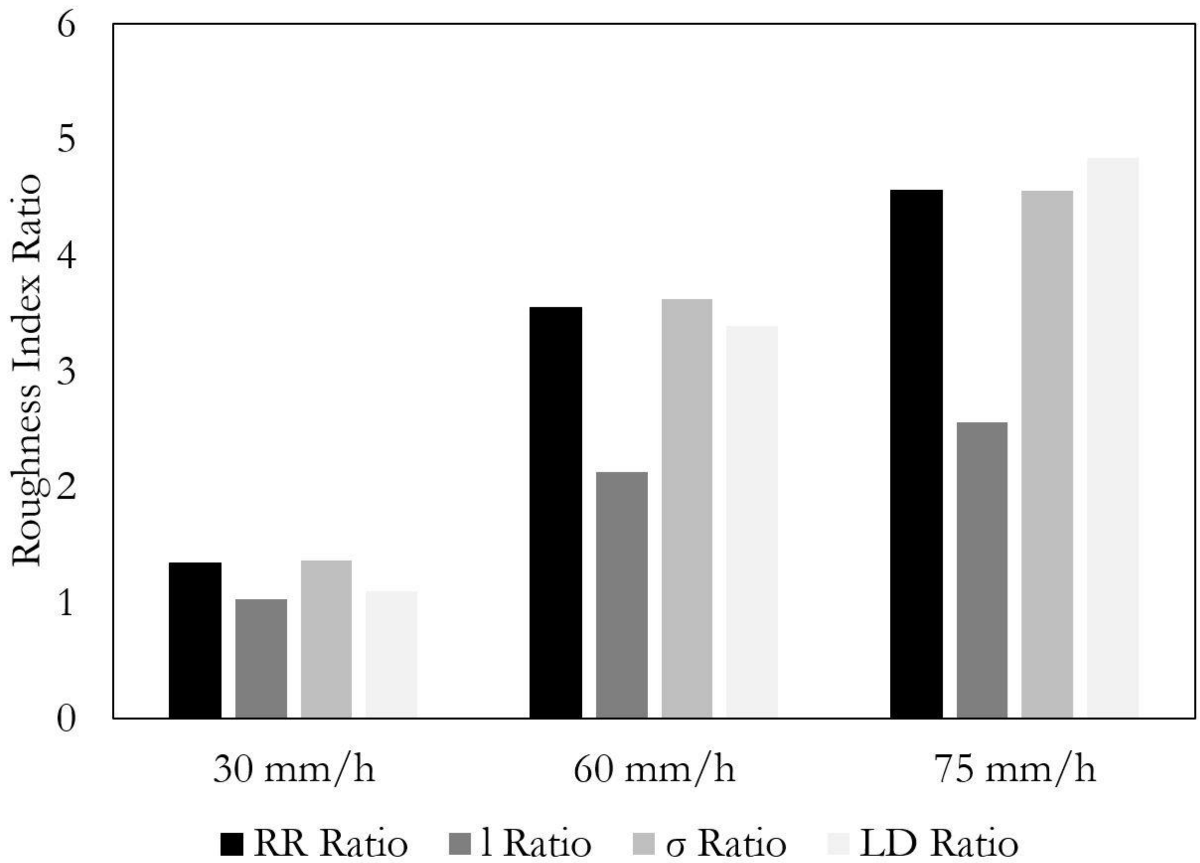


Figure 1.1 Relative ratios of the roughness indices as a function of rainfall intensity.

Table 1.2 Increase in median drop diameter

Change in Rainfall Rate	Increase in Median Drop Diameter	Increase in RR Ratio	Increase in l	Increase in σ	Increase in LD
30mm/h - 60 mm/h	16%	165%	107%	165%	207%
60 mm/h - 75 mm/h	6%	29%	20%	26%	43%

References

Atlas, D., Srivastava, R. C., and Sekhon, R. S.: Doppler radar characteristics of precipitation at vertical incidence, Reviews of Geophysics, 11, 1, doi:10.1029/RG011i001p00001, 1973.

Beguería, S., Angulo-Martínez, M., Gaspar, L., and Navas, A.: Detachment of soil organic carbon by rainfall splash: Experimental assessment on three agricultural soils of Spain, Geoderma 245–246, 21–30, doi:10.1016/j.geoderma.2015.01.010, 2015.

Kathiravelu, G., Lucke, T., and Nichols, P.: Rain Drop Measurement Techniques: A Review. Water 8, 29. doi:10.3390/w8010029, 2016.

Comment 2: P4L2: The authors should clearly state that with such a low resolution some rough features with scale less than 0.5 mm have not been captured via their laser scanner. As the title indicates the authors address soil surface microroughness, while the resolution of the laser scanner is 0.5 mm. How is it possible to capture microroughness with a scanner of resolution of millimeters?

Response:

We thank you for the comment. We have updated the text to include a sentence that clarifies that our analysis may not have captured microroughness features less than 0.5 mm.

We have added the following sentence to clarify the length scales that we captured (Page 4, lines 21-22):

"Horizontal and vertical accuracies of the laser are 0.5 mm. Thus, microroughness features less than 0.5 mm may not have been captured in the analysis."

Comment 3: Did the authors measure infiltration rate or even saturated hydraulic conductivity of the tested soil? If so, what is the infiltration rate?

Response:

In each test we placed soil moisture probes in order to continuously record volumetric water content and determine the steady-state infiltration conditions. This was roughly 2-3 hours after start depending on the rainfall intensity. We estimated the infiltration rate during all rainfall simulation runs by subtracting the measured runoff rates from the constant rainfall rates. As mentioned in the text, runoff was collected continuously at a downstream weir and rainfall rates were set to known constant value. This approach has been commonly used in plot experiments and provides a good estimate of the spatially averaged infiltration rates (e.g., Mohamoud et al., 1990; Wainwright et al., 2000). Below we provide the graph of the estimated infiltration rate with time for the 30 mm/h case (Fig. 3.1).

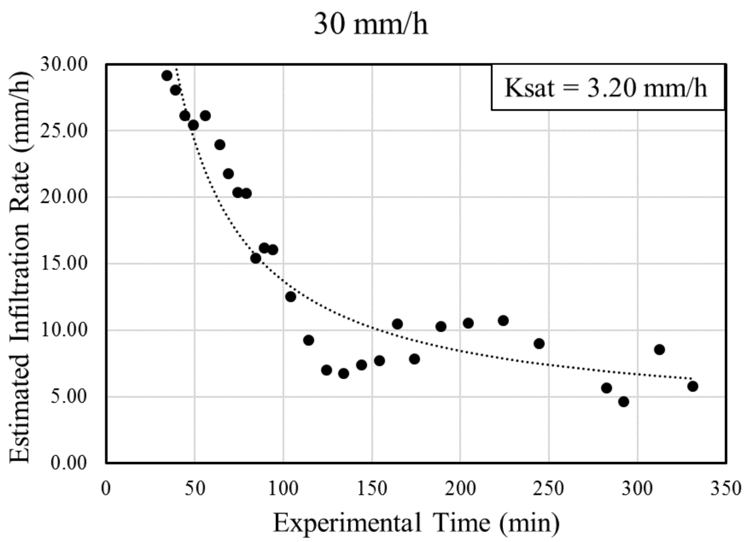


Figure 3.1 Estimated infiltration rate for the 30 mm/h case. K_{sat} was determined as 3.20 mm/h.

Averaged saturated hydraulic conductivity (K_{sat}) values ranged from 3.20 – 4.56 mm/h. In our previous study, we measured K_{sat} by means of semi-automated double ring infiltrometers at the field where this plot was located (see Papanicolaou et al., 2015). We found an average value of 4.0 mm/h, which is in agreement with our estimations.

The information outlined has been added to the text along with the cited references (Page 5, lines 8-13):
"The infiltration rate was estimated during all rainfall simulation runs by subtracting the measured runoff rates from the constant rainfall rates. This approach has been commonly used in plot experiments and provides a good estimate of the spatially averaged infiltration rates (e.g., Mohamoud et al., 1990; Wainwright et al., 2000). Averaged saturated hydraulic conductivity values ranged from 3.20 – 4.56 mm/h, which are in agreement with the averaged saturated hydraulic conductivity value of 4.3 mm/h measured by Papanicolaou et al. (2015a) using semi-automated double ring infiltrometers at the field where the study was performed."

Comment 4: P8L4-8: The authors stated that, "Analysis of soil surface roughness in the region where raindrop detachment dominates and under initial smooth surface preconditions for three rainfall intensities shows a consistent increase in the RR index and crossover length, which are confirmed as reliable descriptors of microroughness. This increase contrasts the findings of most available literature…" Please provide a few references from the literature for the last statement.

Response:

Per the suggestion of the other referees, we have removed the last statement because our findings do not contradict, but rather complement the existing literature by covering a range of initial microroughness that has not been captured before. That part of Discussions and Conclusion section now reads as follows, with references added to support it (Page 10, lines 12-17):
"The results obtained are consistent with findings of other studies that have examined length scales up to 5 mm. These length scales (i.e., ~2-5 mm) have been found to be common in agricultural landscapes that are subject to prolonged exposure to rainfall impact, runoff, and freeze-thaw cycles (Burwell et al., 1963; Allmaras et al., 1966; Burwell et al., 1969; Cogo, 1981; Currence and Lovely, 1970; Steichen, 1984; Unger, 1984; Zobeck and Onstad, 1987). Within these landscapes, the reported increase is expected to occur during the early part of the storm where rainsplash action may be more important than runoff."

Comment 5: Did the authors measure soil aggregate- or particle-size distribution? What is the range of particle sizes in mm?

Response:
Yes, the aggregate size distributions of the soil studied were measured. We found 19% of the soil size fraction less than 250 μm, 48% between 250 μm and 2 mm, and 33% greater than 2 mm.

We have added the aggregate size distribution of our soil along with other info for a clearer presentation (Pages 3-4, lines 30-2):
"The soil series at the plot where the experiments were conducted is Tama (fine-silty, mixed, superactive, mesic Cumulic Endoaquoll) (http://criticalzone.org/iml/infrastructure/field-areas-iml/). It consists of 5% sand, 26% clay, 68% silt, and an organic matter content of 4.4%. The aggregate size distribution of the soil consists of 19% of the soil size fraction less than 250 μm, 48% between 250 μm and 2 mm, and 33% greater than 2 mm. These soils contain both smectite and illite, with high cation exchange capacity between 15 and 30 Meq/100 g."

Quantifying the changes of soil surface microroughness due to rainfall-induced erosion on a smooth surface

Benjamin K.B. Abban[1], A. N. (Thanos) Papanicolaou[1,5], Christos P. Giannopoulos[1], Dimitrios C. Dermisis[2], Kenneth M. Wacha[3], Christopher G. Wilson[1], Mohamed Elhakeem[4]

[1]Hydraulics and Sedimentation Lab, Department of Civil & Environmental Engineering, University of Tennessee – Knoxville, Knoxville, TN 37996 USA
[2]College of Engineering, Department of Chemical, Civil & Mechanical Engineering, McNeese State University, Lake Charles, LA 70605 USA
[3]USDA-ARS – National Laboratory for Agriculture and the Environment, Ames, IA 50011 USA
[4]Abu Dhabi University, Abu Dhabi, P.O. Box 59911, United Arab Emirates
[5]Tennessee Water Resources Center, Knoxville, TN 37996 USA

Correspondence to: Prof. Athanasios (Thanos) N. Papanicolaou (tpapanic@utk.edu)

Abstract. This study examines the rainfall induced change in soil microroughness of a bare smooth soil surface in an agricultural field. Smooth soil surfaces with microroughness on the order of ~2-5 mm are common in agricultural landscapes subject to long, undisturbed exposure to rainfall impact and runoff and freeze-thaw cycles. There are quantitative indications in the literature that under such conditions, roughness may increase subject to rainfall action. The focus is on the quantification of soil surface roughness due to rainfall for initial microroughness length scales of 2 mm or less, which represent generic extreme conditions. These conditions have not been extensively examined in the literature as most studies have focused on disturbed initial surface conditions with roughness on the order of ~5-50 mm. Three rainfall intensities of 30 mm/h, 60 mm/h and 75 mm/h were applied to a smoothened bed surface in a field plot via a rainfall simulator. These intensities represent the range from typical to extreme rainfall intensity conditions that appear in the region of study. Soil surface elevations were obtained via a surface-profile laser scanner. Several indices were utilized to quantify soil surface microroughness, namely the Random Roughness (RR) index, the crossover length, the variance scale from the Markov-Gaussian model, and the limiting difference. Findings show a consistent increase in roughness under the action of rainfall, with higher rainfall intensities resulting in higher relative roughness increase. This contradicts the commonly adopted notion in existing literature that a monotonic decay of soil surface roughness with rainfall is expected regardless of initial surface roughness conditions. The study results highlight the need for a better understanding of the phenomenon of microroughness evolution on a bare surface under rainfall action and its potential implications on hydrologic response.This study sheds light on the interaction between rainfall and smooth bare surfaces and highlights the need for a better understanding of the phenomenon and its potential implications on hydrologic response.This study examines the rainfall induced change in soil microroughness of for a bare smooth soil surface in an agricultural field nin intensively managed agricultural landscapes. The focus is on the quantification of the roughness length under the action of rainfall for initial microroughness length scales of 2 mm or less, defined here as initial smooth surface conditions. These conditions have not been extensively examined in the literature as most studies have focused on initial disturbed initial surface conditions (bed surface conditions with initial length scales greater than 2 mm and varying between 5 – 50 mm). Three rainfall representative intensities namely of 30 mm/h, 60 mm/h and 75 mm/h were applied over to a smoothened bed surface at in a field plot via a rainfall simulator. These intensities represent the range from typical to extreme rainfall intensity conditions that appear in the region of study. Soil surface microroughness measurements were obtained via a surface-profile laser scanner. Two indices were utilized to quantify soil surface microroughness, namely the Random Roughness (RR) index and the crossover length. Findings show a consistent increase in roughness under the action of rainfall for initial microroughness length scales of 2 mm. This contradicts the dogmatic assumption in existing literature where that a monotonic decay of soil surface roughness of soil surfaces with rainfall is recorded for disturbed surfacesis expected regardless of initial surface roughness conditions. Analysis shows that on an average the RR and the crossover length post runafter the experimental tests increase on average by a multiple of 3.15 and 1.9, respectively, from their corresponding initial values apriori the runs. This study provides insight into the phenomenon of the interaction between rainfall and smooth bare surfaces which can result in increasing soil surface roughness, and aids the parameterization of models which account for the dynamic nature of soil surface roughness.

1 Introduction

Soil surface roughness influences many hydrologic processes such as flow partitioning between runoff and infiltration, flow unsteadiness, as well as soil mobilization and redeposition at scales ranging from a few millimeters to hillslope level (e.g. Huang and Bradford, 1990; Magunda et al., 1997; Zhang et al., 2014).

There are three distinct classes of microtopography surface roughness (Fig. 1a) reported in the literature for agricultural landscapes, each one of them depicting a representative length scale (Römkens and Wang, 1986; Potter, 1990). Following Oades and Waters (1991), the first class includes microrelief variations from individual soil grains to aggregates in the order of 0.053-2.0 mm. The second class consists of variations due to soil clods ranging between 2-100 mm. The third class of soil surface roughness is systematic elevation differences due to tillage, referred to as oriented roughness (OR), ranging between 100-300 mm.

From the classes outlined above, the first two classes are the so called random roughness (RR), and constitute the main focus of the present research. Contrary to OR, which changes seasonally and during crop rotations, RR changes on an event base (Abaci and Papanicolaou, 2009). RR reflects the effects of rainfall action on the soil surface and inherently varies in space and time. As a result, RR affects key hydrologic processes at the soil scape and ultimately at the hillslope scale (e.g., overland flow, infiltration), by altering affecting the depression storage and buffering or enhancingthe associated runoff and erosion processes (Gomez Gómez and Nearing, 2005; Chi et al., 2012). According to Paz-Ferreiro et al. (2008), the RR index, which was first proposed by Allmaras et al. (1966), is The the most widely used statistical microrelief index for the evaluation -of RR soil surface roughness. (Paz-Ferreiro et al., 2008) was initially proposed by Allmaras et al. (1966) Theas the standard deviation of the log-transformed residual point elevation data. In this study, the RR index was initially calculated per Allmaras et al. (1966) as the standard deviation of the log-transformed residual point elevation data. In this study, it is calculated according to Currence and Lovely (1970) as the standard deviation of bed surface elevation data around the mean elevation, after correction for slope using the best fit plane and removal of tillage effects ~~have been removed~~ in the individual height readings:

$$RR = \sqrt{\frac{\sum_{i=1}^{n}(Z_i - \bar{Z})^2}{n}}, \qquad (1)$$

where Z_i and $\bar{Z}$ are individual elevation height readings and their mean, respectively, and n is the total number of readings. Characterization of RR remains a challenge. Most of the available studies are limited to soil surfaces where the length scale exceeds the upper microrelief length scale of 2 mm corresponding to the first class. These studies usually include bed surface conditions with initial length scales of 5~~–~~-50 mm (e.g., Zobeck and Onstad, 1987; Gilley and Finkner, 1991). In these studies, a monotonic decay of roughness due to precipitation action is predicted, since rainfall impact and runoff "smoothen" the rough edges of soil grains, aggregates and clods, especially in the absence of cover (Potter, 1990; Bertuzzi et al., 1990; Vázquez et al., 2008; Vermang et al., 2013). Few ~~to none of~~ existing studies, ~~however,~~ to the best of our knowledge, have explicitly examined ~~however changes in RR~~the interaction of ~~rainfall~~raindrop impact with bare soil surfaces for initial microroughness scales ~~less~~ on the order of~~than~~ ~2-5 mm. Surfaces with microroughness ~~of~~on the order of ~2-5 mm ~~have been found to be~~are common in agricultural landscapes ~~Burwell et al., 1963; Allmaras et al., 1966; Burwell et al., 1969; Cogo, 1981; Currence and Lovely, 1970; Steichen, 1984; Unger, 1984; Zobeck and Onstad, 1987~~where the soil is "smoothened" due to long, undisturbed exposure to rainfall impact, runoff, and freeze-thaw cycles (Burwell et al., 1963; Allmaras et al., 1966; Burwell et al., 1969; Cogo, 1981; Currence and Lovely, 1970; Steichen, 1984; Unger, 1984; Zobeck and Onstad, 1987; Abaci and Papanicolaou, 2009). Within these landscapes, ~~This condition~~~~Bare~~ soil surface conditions~~s~~ are ~~with low roughness~~ ~~remains prevalent~~~~are locally pronounced~~ usually bare in the period of the crop rotation between post-harvest and before plant growth is established, which~~. This condition typically~~ approximately corresponds to 30-~~6~~75% of the cyclic crop rotation period.

~~cyclic crop rotations in agricultural hillslopes, where the soil is "smoothened" from due to long exposure to rainfall impact and runoff (Abaci and Papanicolaou, 2009).~~ There are some quantitative indications that under bare smooth surface conditions, soil surface roughness may actually increase under the action of rainfall. Specifically, the study by Huang and Bradford (1992) calculated the semivariance with respect to length scale before and after rainfall, and a slight increase in roughness with rainfall was denoted using the Markov-Gaussian model for a surface with low initial roughness. Rosa et al. (2012) introduced an index (called Roughness Index) estimated from the semivariogram to describe roughness, and ~~the index~~an increase of the index with rainfall was observed under specific conditions, and attributed to the fragmentation of aggregates and clods to smaller aggregates. Zheng et al. (2014) reported an increase in values of the RR after the application of rainfall on smooth soil surfaces. Finally, Vázquez et al. (2008) examined the evolution of the surface of three different soils during successive events. They reported that for two out of three soils, roughness increased for the first event, however decreased for the following events; the third soil showed scarce trend to either increasing or decreasing roughness due to successive rainfall events. Nevertheless, none of the above studies explicitly stated or acknowledged the increasing trend of roughness and its potential linkage to smooth bare soil surface conditions.There is some experimental evidence that under such conditions, RR may actually increase under the action of rainfall (Huang and Bradford, 1992; Rosa et al., 2012; Zheng et al., 2014). Finally, Vázquez et al. (2008) examine the evolution of the surface of three different soils during successive events. They report that for the two soils roughness increases for the first event, however decreases for the following events; the third soil showed scarce trend to either increasing or decreasing roughness due to successive rainfall events. The study of Kamphorst et al. (2000) examines soil surfaces obtained by laser scanning and find that there is statistically significant relation of roughness with maximum depression storage for low and high roughness surfaces. We herein examine changes in RR under rainfall impact for initial microroughness less of the order ofthan 2 mm. In hillslope scale erosion models this condition is not represented adequately. In fact, most models assume a static roughness or at best a monotonic decay of RR, leading to errors on storage, runoff, and sediment routing (Liu and Singh, 2004).

This study expands our knowledge base for changes in RR, by investigating the interaction of rainfall with soil surfaces of microroughness length scales less than 2 mm. The main goal is therefore to examine the postulate observed in the literature (e.g., Zheng et al., 2014) that rainfall action on surfaces with initial microrelief less than 2 mmon the order of 2-5 mm can could lead to RR increase. An increase in RR under these scales would further imply that rainfall action cannot completely eliminate the roughness of a surface, so roughness residuals would always exist at the locations where raindrop detachment is prevalent. Hereafter, for shortness, tests with initial RR close to or less thanon the order of 2-5 mm (first microroughness class) will be referred to as “smooth”, whereas tests with initial RR greater than 2 5 mm will be referred to as “disturbed”.

The key specific objectives of this study are (i) to quantify the soil surface microroughness of smooth bare soil surfaces before and after the effect of rainfall, and (ii) calculate the relative change in roughness for different intensities. To meet the two specific objectives we employ twofour commonly used indices, the RR index, and the crossover length, the variance scale from the Markov-Gaussian model, and the limiting difference. -The crossover length is anlast three indices are alternate methods and used here to supplement the RR index analysis for relative change in roughness (Paz-Ferreiro et al., 2008). A key specific objective of this paper is to quantify changes in the microroughness of smooth bare soil surfaces under different rainfall intensities. We will first use the RR index because of its widespread use as a descriptor of soil microroughness both in soil microrelief studies and in the majority of existing landscape models. Additionally, we will supplement our RR analysis with the fractal properties of the soil surface by means of the crossover length derived from semivariogram analysis, taking advantage of its scale independence. The pros and cons of the two methods are discussed under bare soil with minimal microroughness. These findings are discussed with the aim to enhance current formulations by providing updates on microroughness during a rainfall event under bare soil conditions.

2 ~~Experiments~~ Materials and Methods

2.1 Experimental Conditions

This study was conducted on an experimental plot (Fig. 1b) of the U.S. National Science Foundation Intensively Managed Landscapes Critical Zone Observatory in the headwaters of Clear Creek, IA (~~Fig. 1b~~41.74º N, -91.94º W and an elevation of 250 m above mean sea level). The soil series at the plot where the experiments were conducted is Tama (fine-silty, mixed, superactive, mesic Cumulic Endoaquoll) (http://criticalzone.org/iml/infrastructure/field-areas-iml/). It consists of 5% sand, 26% clay, 68% silt, and an organic matter content of 4.4%. The aggregate size distribution of the soil consists of 19% of the soil size fraction less than 250 μm, 48% between 250 μm and 2 mm, and 33% greater than 2 mm. These soils contain both smectite and illite, with high cation exchange capacity between 15 and 30 Meq/100 g.~~The term "mixed" is related to the mixed nature of clay mineralogy, since these soils contain both smectite and illite. The term "superactive" is associated with the high degree of activity of cation exchange in the soil. The cation ion exchange capacity for these soils is between 15 and 30 Meq/100 g.~~ The experimental plot was uniform in terms of downslope curvature, its gradient was 9% and the plot size was approximately 7 m long by 1.2 m wide.

The soil surface was prepared before each experiment by tamping using a plywood board to create a smoothened surface. Rainfall was applied to the plot~~s~~ using Norton Ladder Multiple Intensity Rainfall Simulators designed by the USDA-ARS National Soil Erosion Research Laboratory, IN. Figure 2 shows the setup for all the experimental runs considered in the present study. For each test, three rainfall simulators were mounted in series over the experimental plot (Fig. 2a) and approximately 2.5 m atop the plot surface (Fig. 2b) in order to ensure that raindrop terminal velocity was reached. Water was continuously pumped from a water tank under controlled pressure, and uniform rainfall was applied through oscillating VeeJet nozzles which provided spherical drops with median diameters between 2.25-2.75 mm and a terminal velocity between 6.8-7.7 m/s depending on the rainfall intensity~~ (see Table 1)~~. The distribution of raindrop sizes generated by the rainfall simulators was calibrated using a disdrometer and followed a Marshall-Palmer distribution (Elhakeem and Papanicolaou, 2009), which is a widely accepted distribution for natural raindrop sizes in the U.S. Midwest where the study was performed (Marshall and Palmer, 1948).~~ ~~ The calibration of the raindrop sizes was achieved by adjusting the pressure and swing frequency of the VeeJet nozzles.~~ Special care~~This level of attention was taken to minimize any potential biases ~~with respect~~compared to natural rainfall with respect to raindrop size distribution, and, thus, render the rainfall simulation experiments scalable to other regions experiencing the same type of soil, bare surface, roughness conditions, and natural rainfall characteristics.

Surface elevations were obtained prior to and after the completion of the experiments via an instantaneous digital surface-profile laser scanner (Darboux and Huang, 2003), developed by the USDA-ARS National Soil Erosion Research Laboratory, IN (Fig. 3a). Laser scanner measurements ~~a priori the runs ensured~~before the runs confirmed that the overall microrelief was less than 2 mm. ~~After the runs the measurements provided changes in microroughness under the action of rainfall.~~ Horizontal and vertical accuracies of the laser are 0.5 mm. Thus, microroughness features less than 0.5 mm may not have been captured in the analysis. Points were measured every 1 mm. The system consists of two laser diodes mounted 40 cm apart to project a laser plane over the targeted surface. The beam is captured by an 8-bit, high-resolution progressive scan charge-couple device~~CCD~~ camera with 1030 rows x 1300 columns and a 9 mm lens. The camera and lasers are mounted on a 5 m long carriage assembly and their movement on the carriage is controlled ~~from the desktop using a computer program~~by software that regulates the travel distance based on a user-specified distance (Fig. 3a). Information captured by the camera is recorded with an attached computer. The information from each scan is converted into a set of (x,y,z) coordinates using a calibration file and ~~specific~~ the software developed from the USDA-ARS National Soil Erosion Research Laboratory for data transformation as explained by Darboux and Huang (2003). The set of (x,y,z) coordinates obtained for each experiment are imported into ArcGIS 10.3.1 in order to create the corresponding Digital Elevation Models (DEMs) through inverse distance weighting interpolation and thereby visualize or analyze the surfaces (Fig. 3b). The resulting DEMs have a horizontal resolution of 1 mm and an accuracy of 0.5 mm in the vertical.

Three ~~experimental~~ tests of varying rainfall intensity were conducted on the experimental plot. ~~Experiment 1 had a rainfall intensity of 30 mm/h, Experiment 2 an intensity of 60 mm/h, and Experiment 3 an intensity of 75 mm/h~~Rainfall intensities were respectively 30, 60 and 75 mm/h for experiments 1, 2 and 3 ~~(Table 1)~~. These simulated intensities represent typical storms observed in the region of South Amana where the plot is located (Huff and Angel, 1992). Three replicates of each rainfall intensity case were performed until steady state conditions, and repeatability was confirmed by evaluation of changes in RR at specific cross-sections in the rainsplash dominated zone. It was found that on an average, the relative error of the RR ratios between replicates did not exceed 7%. ~~The initial soil~~The volumetric water content was ~~measured~~ recorded ~~with~~ via six 5TE ~~Decagon~~ soil moisture sensors manufactured by Decagon Devices, Inc. and placed along the ~~whole~~ plot ~~at~~to a depth of 10 mm. ~~and~~ The initial volumetric water content was found to be ~~the same~~similar for each experiment and approximately equal to 35% at the whole ~~whole~~ plot, where the field capacity of the specific soil is 38%. Each experiment was run for nearly 5 hours, sufficiently long to reach steady state ~~runoff and sediment~~conditions, as confirmed by weir readings and discrete samples taken at the outlet of the plot. The infiltration rate was estimated during all rainfall simulation runs by subtracting the measured runoff rates from the constant rainfall rates. This approach has been commonly used in plot experiments and provides a good estimate of the spatially averaged infiltration rates (e.g., Mohamoud et al., 1990; Wainwright et al., 2000). Averaged saturated hydraulic conductivity values ranged from 3.20 – 4.56 mm/h, which are in agreement with the averaged saturated hydraulic conductivity value of 4.3 mm/h measured by Papanicolaou et al. (2015a) using semi-automated double ring infiltrometers at the field where the study was performed.

~~Notice that t~~The initial microroughness length scale in Experiment 1 (1.17 mm) was greater than that of Experiment 2 (0.42 mm) and Experiment 3 (0.32 mm) – see Table ~~2~~1. This is attributed to the different timing of the experiment runs with respect to tillage. Experiment 1 was performed in early August, soon after harvest, so the soil surface had recently been disturbed. However, for Experiments 2 and 3 which were performed in late September, the soil presented less surface disturbance due to the cumulative action of rainfall within that period (Papanicolaou et al., 2015b). Therefore, despite tamping with plywood, remnants of tillage effects remained in Experiment 1 yielding different initial microroughness length scales than Experiments 2 and 3. All cases, however, exhibited initial microroughness length less than 2 mm corresponding to smooth surface bed conditions as confirmed with the laser scanner. Dry soil bulk density was 1.25 ~~k~~g/cm^3 for Experiment 1, and about 6% higher for Experiments 2 and 3 due to self-weigh consolidation of soil.

~~The left part of Fig. 4~~Figure 4a provides an example of the experimental plot at pre-rainfall and post-rainfall conditions. Since the focus of this research is only on plot regions where raindrop detachment is dominant over runoff, we are using the scanned profiles that correspond only to these upslope locations, which are shown ~~at the right part of~~in Fig. 4b. ~~By definition, n~~No rill formation ever took place in these regions. For scanned profiles within the Region of Interest (ROI) (i.e., a selected 200 mm x 200 mm window size), we extracted the data for further statistical and geostatistical analyses by utilizing the public domain R ~~package~~ software (https://www.r-project.org/). The geostatistics ('gstat') and spatial analysis ('sp') libraries ~~are~~ were imported to create sample semivariograms.

2.2 Soil Surface Roughness Quantification

The RR index calculated from Eq. (1) was ~~employ~~used in this study as the principal method to quantify soil surface roughness ~~Due~~ due to its ~~commonality found in the literature and its~~frequent and widespread use in various studies and landscape models as a descriptor of microroughness~~, the RR index calculated from Eq. (1) is used in this study as the first method to describe soil surface roughness~~. The RR index, however, requires that there is no spatial correlation between the surface elevations (Huang and Bradford, 1992).~~–~~ If correlation exists within a certain spatial scale, RR will likely change with the changing window size of observed data (Paz-Ferreiro et al., 2008) and may be dependent on the resolution of the measurement device (Huang and Bradford, 1992). Thus, alternative scale-independent ~~indices from~~ methods that consider spatial correlation have been ~~considered~~ developed by other researchers in order to address this issue. These methods include first-order variogram analysis (Linden and van Doren, 1986; Paz-Ferreiro et al., 2008), semivariogram analysis (Vázquez et al., 2005; Oleschko et al., 2008; Rosa et al. 2012; Vermang et al., 2013), fractal models based on Fractional Brownian Motion (Burrough, 1983a; Vázquez et al., 2005; Papanicolaou et al., 2012; Vermang et al., 2013), multifractal analysis (Lovejoy and Schertzer, 2007; Vázquez et al., 2008), Markov-Gaussian ~~Model~~ model (Huang and Bradford, 1992; Vermang et al., 2013), and two-dimensional Fourier Transform (Cheng et al., 2012), among others. We herein employ indices derived from the first-order variogram and the semivariogram as alternatives to the RR index. These include the crossover length, the Markov-Gaussian variance length scale, and the limiting difference.~~We herein employ the crossover length, the Markov-Gaussian variance length scale, and the limiting difference indices as alternatives to the RR index.~~

The crossover length derived from semivariogram analysis is an index~~-~~ that is commonly used in most recent soil microrelief studies to describe surface microroughness.~~, with~~ It has the advantage of its quantification being scale independent through the consideration of the spatial correlation between surface elevations (Vázquez et al., 2007; Paz-Ferreiro et al., 2008; Tarquis et al., 2008). The semivariogram ~~is a useful geostatistical tool developed to depict the spatial autocorrelation of data. It~~ is calculated from the following equation:

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [Z(x_i + h) - Z(x_i)]^2 \,, \quad (2)$$

where $\gamma(h)$ is the semivariance, h is the lag-distance between data points, $Z(x)$ is the elevation height value at location x and $n(h)$ is the total number of pairs separated by lag-distance h considered in the calculation. The semivariogram is the plot of the semivariance with respect to the lag-distance.

Key ~~fractal~~ indices for describing soil surface roughness can be derived from the semivariogram. Assuming a fractional Brownian motion model for describing soil surface roughness, as proposed in the pioneering work of Mandelbrot and van Ness (1968), the following expression for $\gamma(h)$ that incorporates the generalized Hurst exponent, H is obtained (Huang and Bradford, 1992; Vázquez et al., 2007; Paz-Ferreiro et al., 2008; Tarquis et al., 2008):

$$\gamma(h) = l^{2-2H} h^{2H}, \quad (3)$$

where H is a measure of the degree of correlation between the surface elevations at lag distance h with $0 < H < 1$ and l is the crossover length~~ and $0 < H < 1$~~. The crossover length is a measure of the vertical variability of soil surface roughness at the particular scale where the fractal dimension is estimated, hence greater roughness is associated with larger crossover length values and vice versa (Huang and Bradford, 1992). The generalized Hurst exponent is a less sensitive descriptor of soil surface evolution as influenced by rainfall (Vázquez et al., 2005), hence attention is mostly centered on the crossover length.

Given the semivariogram plot ~~that has been~~ calculated ~~from~~ using Eq. (2)~~ based on the elevation data~~, H and l can be extracted by fitting a power law relationship in the form of $y = Ax^B$ to the semivariance-lag distance data, where $y = \gamma(h)$ and $x = h$. According to Eq. (3), ~~The~~ the B regression variable gives the generalized Hurst exponent value~~, whereas~~ and the A regression variable yields the crossover length.

The Markov-Gaussian model is a random process that has been adopted for the quantification of soil surface roughness (Huang and Bradford, 1992; Vermang et al., 2013). In that case, the semivariogram is written as an exponential-type function with the following form:

$$\gamma(h) = \sigma^2 \left(1 - e^{-h/L}\right), \quad (4)$$

where σ is the variance length scale, representing the roughness of a surface at the large scale, and L is the correlation length scale, which is a measure of the rate at which small scale roughness variations approach the constant value of σ. These indices are obtained by fitting the exponential-type function of Eq. (4) to the semivariogram obtained from Eq. (2).

Finally, the limiting difference (LD) index is another index adopted to quantify soil surface roughness. It is calculated from the first-order variogram (Linden and van Doren, 1986; Paz-Ferreiro et al., 2008), which is written in the form:

$$\Delta Z(h) = \frac{1}{n(h)} \sum_{i=1}^{n(h)} |Z(x_i + h) - Z(x_i)|, \quad (5)$$

Then, a linear relationship is fitted between $1/\Delta Z(h)$ and $1/h$:

$$1/\Delta Z(h) = a + b/h, \quad (6)$$

The limiting difference (LD) index is then calculated as $LD = 1/a$. LD has units of length, and represents the value of the first-order variance at large lag distances. ~~-~~It is considered as an indicator of soil surface roughness, thus adopted in the present study as an additional roughness index.

In order to negate the effects of the differences found in initial microrelief amongst the three runs and compare rainfall induced changes in relative terms, the results from the rainfall experiments are presented in the form of ratios of the roughness indices. More precisely, the RR ratio, defined as the ratio of the RR index post-rainfall over the RR index prior to the rainfall (RR_{post}/RR_{pre}), is calculated for each experiment~~ and compared to existing literature~~. ~~Along the same lines, s~~Semivariograms are plotted under pre- and post-rainfall conditions at the ROI to assess the spatial correlation of surface elevations~~ and the associated crossover lengths are calculated~~. ~~Finally~~Along the same lines, ratios between pre- and post-rainfall conditions are calculated for the crossover length~~ ratio~~, the variance length scale of the Markov-Gaussian model, and the limiting difference~~ defined as the ratio of the crossover length post-rainfall over the crossover length prior to the rainfall (l_{post}/l_{pre}), is calculated for each experiment, compared to existing literature, and~~to assess~~ed as a descriptor of ~~changes in microroughness along with the RR ratio.

~~In this study, a 3rd order polynomial surface is optimally fitted within the predefined ROI, and RR is calculated as the standard deviation of the residuals from the aforementioned best fit surface based on Eq. (1). The semivariograms for the experiments confirm the suitability of the 200 mm square window in capturing surface elevations at a scale where no spatial correlation exists, as explained in the results below.~~

3. Results

~~This section presents the results from the rainfall experiments in the form of ratios of the roughness indices and it is organized as follows. First, the RR ratio, defined as the ratio of the RR index post-rainfall over the RR index prior to the rainfall (RR_{post}/RR_{pre}), is calculated for each experiment and compared to existing literature. Next, semivariograms are plotted under pre- and post-rainfall conditions at the ROI to assess the spatial correlation of surface elevations and the associated crossover lengths are calculated. Finally, the crossover length ratio, defined as the ratio of the crossover length post-rainfall over the crossover length prior to the rainfall (l_{post}/l_{pre}), is calculated for each experiment, compared to existing literature, and assessed as a descriptor of change in microroughness along with the RR ratio. The results are presented in the form of ratios to negate the effects of the differences found in initial microrelief amongst the three runs, thereby comparing changes in relative terms.~~

3.1 Changes in the RR index

Based on visual inspection of the DEMs ~~on the right hand side of~~in Fig. 4b, it is evident that roughness at the upslope regions increases with rainfall. Figure 5 ~~provides quantitative information and ~~shows the RR ratio, i.e., RR_{post}/RR_{pre}, with respect to the initial value of RR for the present study along with other studies that quantify rainfall induced microroughness changes. The dashed line at the RR ratio value of unity reflects no change in roughness, thus all points above that line show an increasing trend with rainfall, while all points below show a decreasing trend with rainfall. All the studies capture a wide range of initial RR values – up to 21 mm – and it is clear that our study captures the behavior of RR for an initial range that was not covered before. Figure 5 suggests that roughness may increase with raindrop impact for a range of low initial RR values (< 5 mm), while it consistently decays for high initial RR values (> 5 mm). which describes the change in roughness estimated within the ROIs with respect to the initial microroughness conditions. From Fig. 5 it can be seen that the resulting RR index is 1.34, 3.55 and 4.56 times higher than its initial value when rainfall is applied for Experiments 1, 2 and 3, respectively (also see Table 2). It is acknowledged that the values of the roughness indices among different studies may involve some experimental error and may reflect different conditions such as rainfall forcing and soil type. SpecificallyFor example, Vázquez et al. (2007) used clay textured soil, Vázquez et al. (2008) used silt loam textured soil, while our study along with all the other studies cited conducted rainfall experiments for silty clay loam textured soil. Rainfall intensities and cumulative rainfall amounts varied significantly among studies.

Table 2 1 also summarizes the effects of rainfall on roughness by means of the RR index for the present study along with other representative studies in existing literature, capturing the range of smooth and disturbed initial microroughness conditions found in the literature. The last column shows the RR ratiosummarizes the results of this study along with results from the selected studies in quantitative terms, documenting the RR index values before and after the rainfall events, the cumulative rainfall, as well as the associated RR ratio. From Table 2, tTwo main observations inferences can be made from Table 1. First, our study along with Vázquez et al. (2008) and Zheng et al. (2014), which were performed for the smooth surface initial condition, studies a report an consistent increase in roughnessin RR with precipitation occursrainfall in general. Exception seems to hold for one soil surface of the study of Vázquez et al. (2008), as well as the smooth surfaces of Vermang et al. (2013) which show decaying roughness due to rainfall because of different soil type and rainfall conditions. Second, the present study indicates that the RR index ratio becomes higher with higher rainfall intensitycumulative rainfall amountintensity when the surface is classified as smooth, whereas the opposite tends to hold for soil surfaces classified as disturbed (Fig. 5, Table 21). Vázquez et al. (2008) and Zheng et al. (2014) recorded an increase in RR with rainfall but had significantly lower values of RR ratio than we did. This may be attributed to the fact that they either applied lower cumulative rainfall amountintensity or the initial microroughness conditions in their study were higher. Other studies that are not included in Table 1 have also shown increasing trends of roughness with rainfall, as quantified with the use of different indices. For instance, Huang and Bradford (1992) calculated the semivariograms for different surfaces and used fractal and Markov-Gaussian parameters to quantify the roughness. Markov-Gaussian analysis showed a relative increase in the roughness parameter for a surface of low initial roughness. Finally, Rosa et al. (2012) introduced the Roughness Index which is estimated from the semivariogram sill in order to quantify roughness, and observed its increase with rainfall under low initial roughness conditions. That increase was attributed to the fragmentation of aggregates and clods to smaller aggregates but was not linked to smooth bare soil surface conditions.

The results outlined above for the use of the RR index as a descriptor of change in microroughness have been based on the assumption that there is no statistically significant spatial correlation in elevation readings between neighboring locations at the ROI, so they are valid only under this assumption. The following subsection outlines and discusses the results of the semivariogram analysis and ~~the crossover length~~additional indices in order to confirm this assumption and compare with the RR index method.

3.2 Changes in ~~the~~ alternative roughness indices ~~crossover length~~

Semivariograms and first-order variograms were obtained from geostatistical analysis and plotted at four different angles – 0°, 45°, 90°, and 135°– with respect to the downslope direction~~ in order to test isotropy~~ Since the action of rainfall is isotropic and adds no systematic trend along any direction, no significant differences were expected between semivariograms. A nonparametric test for spatial isotropy was performed per Guan et al. (2004) using the public domain R statistical package with the ‘spTest’ library. ~~A p-value less than 0.05 for all cases confirmed t~~The spatial isotropy hypothesis was confirmed ($p < 0.05$). Thus, there would be no bias in taking any direction to calculate the semivariograms and the associated crossover lengths.~~. The root mean square error of the semivariogram values at pre-rainfall and post-rainfall conditions was found to be less than 10%. Therefore, there were no statistically significant differences in the semivariograms, which implies that the roughness patterns for smooth initial conditions at the ROI remain isotropic after a rainfall event and can thus be examined with one representative semivariogram.~~

The ~~representative sample~~ semivariograms calculated at the ROI were chosen to be in the downslope direction at an angle of 0° and ~~calculated at the ROI~~ are presented for each experiment ~~are presented~~ in Fig. 6. The vertical dashed lines designate the lag distances above which the spatial autocorrelation of the elevations is not statistically significant. These lag distances are approximately 10 mm, so the selected 200 mm window size of the ROI is almost 20 times greater than the spatial autocorrelation range.~~.~~ This implies that the window size of the ROI falls at~~, which is considered sufficient to assume no spatial autocorrelation at the scale examined in this study~~the scale of the semivariogram sill (which is defined as the near-constant value of semivariance at large lag distances where the semivariogram levels out – see horizontal dashed lines in Fig. 6). ~~Hence,~~ RR is directly related to the semivariogram sill (e.g., Vázquez et al., 2005; Vermang et al., 2013), therefore it ~~is~~ can be considered independent of the selected window size, given that the latter ~~significantly~~far exceeds the spatial autocorrelation range.~~ of observed data considered.~~

~~Moreover, the semivariogram sill (which is defined as the near-constant value of semivariance at large lag distances where the semivariogram levels out – see horizontal dashed lines in Fig. 6) is directly related to the RR of the soil surface since it quantifies the mean variance in elevations at distances where spatial correlation is statistically negligible (Vázquez et al., 2005). It is seen from~~ Fig. 6 shows that the post-rainfall sills are greater than their corresponding pre-rainfall values~~ for all three intensities~~. Also, the difference in sills between pre- and post-rainfall conditions for the 30 mm/h precipitation intensity is much lower than those of the 60 mm/h and 75 mm/h ~~precipitation intensities~~events. These observations are in accordance with visual inspection of the surfaces as well as with the results noted earlier for the RR ratio (see Fig. 5, Table ~~2~~1).

~~Therefore, similar conclusions drawn from the RR ratio graphs can be drawn from the semivariograms~~Complete agreement between the trends of the RR index, the semivariogram sill, and visual inspection of the surfaces justify the use of the RR index as a representative and unbiased descriptor of microroughness.

Table 2 summarizes the results of this study along with results from ~~the selected~~other selected studies in quantitative terms, documenting the crossover length values before and after the rainfall events, the cumulative rainfall, as well as the associated crossover length ratio.~~Table 3 summarizes the impact of rainfall on the crossover length *l* at the ROI for our present study along with other representative studies in existing literature.~~ ~~As seen from the table, t~~The final roughness state of the bed surface after the application of rainfall (for ~~all~~ the studies considered herein), tends to have a crossover length in the range of 0.2~~—~~-4 mm. ~~However, t~~It is seen that the existing studies with initial disturbed surface conditions report~~ed~~ a decrease in the crossover length after rainfall, contrary to ~~the observed increase in the crossover length reported~~found ~~in~~ our study where we observe an increase for the initial smooth conditions (e.g., Vázquez et al., 2007; Paz-Ferreiro et al., 2008; Vermang et al., 2013).

~~Fig. 7 shows the crossover length ratio at the ROI with respect to rainfall intensity for our study.~~ Crossover length ratios greater than unity reflect an increase of soil surface roughness with rainfall. Similar to the RR ratio, the crossover length ratio is greater at the high precipitation intensity cases (~~Experiments 2 and 3~~60 and 75 mm/h) than at the low precipitation intensity case (~~Experiment 1~~30 mm/h)~~—also reflected in Table 3~~. ~~Overall, these results suggest that the crossover length, the semivariogram sill and the RR index, for scales where no spatial correlation exists, can be used interchangeably in order to characterize rainfall induced changes in microroughness.~~

Table 3 lists the Markov-Gaussian variance length scale and the limiting difference indices for the three experimental tests, and their relative change after the rainfall. These indices ~~also~~ show an ~~similar~~ increase with rainfall that is of the same magnitude and trend as the RR index and crossover length, and provide a supplemental analysis about the role of rainfall intensities on the relative increase in roughness. Our findings were compared against those reported in the literature. Huang and Bradford (1992) studied the evolution of soil surface roughness with the Markov-Gaussian variance length scale, and saw an increase of 6% in roughness for a surface of low initial roughness. Moreover, Paz-Ferreiro et al. (2008), who used the LD index ~~as an additional index~~ to quantify soil surface roughness~~.~~, ~~They~~also recorded a 10% increase in the LD index for a low roughness conventional tillage soil surface. The higher relative increase in roughness seen in our study (Table 3) compared to other studies is attributed to the significantly lower initial roughness conditions in addition to different soil types and management.

~~The laser measurements from the experimental runs were analyzed using all indices, namely, the random roughness, the crossover length, the Markov-Gaussian variance length scale, and the limiting difference. All indices show a consistent trend i.e., higher rainfall intensities result in higher relative increases in microroughness (Tables 1-3).~~ Overall, the results provided suggest that all the indices employed in this study may be used interchangeably to characterize rainfall induced changes in soil surface roughness, and can capture an increase in soil surface roughness, especially for low microroughness scales on the order of 2-5 mm. For these microroughness scales, the relative increase in roughness is also shown to increase with rainfall intensity. Our findings were compared against those reported in the literature. Huang and Bradford (1992) studied the evolution of soil surface roughness with the Markov-Gaussian variance length scale, and saw an increase of 6% in roughness for a surface of low initial roughness. Moreover, Paz-Ferreiro et al. (2008) used the LD index as an additional index to quantify soil surface roughness. They recorded a 10% increase in the LD index for a low roughness conventional tillage soil surface. Higher relative increase of roughness in our study (Table 3) compared to other studies, as seen in Fig. 5, are attributed to the significantly lower initial roughness conditions in addition to different soil types and management. Overall, these results suggest that all the indices employed in this study may be used interchangeably in order to characterize rainfall induced changes in soil surface roughness, for low microroughness scales on the order of 2-5 mm.

4. Conclusions and Discussion Discussion and Conclusions

Few studies have been developed to assess microscale variation under controlled conditions to purposely examine increase in RR with rainfall intensity. Unique experiments are presented herein that were designed to help us decipher the role of rainsplash on increasing RR by isolating the role of other processes such as runoff, variable water content, bare soil surface, soil texture, etc. We present unique, novel rainfall simulation experiments in this study that mimic natural rainfall conditions at the plot scale and capture microroughness evolution under bare surface conditions with microroughness in on the order of 2 mm. Analysis of soil surface roughness in the region where raindrop detachment dominates and under initial smooth surface preconditions for three rainfall intensities shows a consistent increase in the RR index and crossover length, which are confirmed as reliable descriptors of microroughness. This increase for microroughness length scales of the order of 2 mm. The results obtained are consistent with findings of other studies that have examined length scales up to 5 mm. These length scales (i.e., ~2-5 mm) have been found to be common in agricultural landscapes that are subject to prolonged exposure to rainfall impact, runoff, and freeze-thaw cycles (Burwell et al., 1963; Allmaras et al., 1966; Burwell et al., 1969; Cogo, 1981; Currence and Lovely, 1970; Steichen, 1984; Unger, 1984; Zobeck and Onstad, 1987). Within these landscapes, the reported increase is expected to occur during the early part of the storm where rainsplash action may be more important than runoff. contrasts the findings of most available literature and is mainly attributed to the initial roughness magnitude examined in this study; that is, smooth surface preconditions – defined herein as conditions of microroughness length scale close to 2 mm or less (first microroughness class) – as opposed to the existing literature that mostly deals with initial minimal roughness magnitudes in the range of 5-50 mm. Our TheseOur findings along with literature indicate suggest the existence of a characteristic roughness scale in the magnitude of 2-5 mm below which RR is expected to increase and above which RR is expected to decrease due to the action of rainfall. - It is further demonstrated that for low microroughness scales the relative increase in roughness increases with rainfall intensity. Another significant outcome of this study is the fact that the mere action of rainfall cannot completely smoothen out a bed soil surface, thereby a localized microroughness residuals will always remain at the locations where the action of runoff is low or absent. Roughness Increase in microroughness further infers increase in depression storage at the soil surface prior to runoff generation (Kamphorst et al., 2000), which can affect ponding and flow pathway patterns especially at the onset of a storm eventLocalized microroughness residuals further infer depression storage residualsthe existence of depression storage at the soil surface following a rainfall event, which can significantly alter the ponding and flow pathway patterns flow partitioning between infiltration and runoff at the hillslope scale especially at the onset of an a subsequent event (Onstad, 1984). The results obtained are consistent with findings of other studies that have examined length scales up to 5 mm. These length scales (i.e., ~2-5 mm) have been found to be common in agricultural landscapes that are subject to prolonged exposure to rainfall impact, runoff, and freeze-thaw cycles (Burwell et al., 1963; Allmaras et al., 1966; Burwell et al., 1969; Cogo, 1981; Currence and Lovely, 1970; Steichen, 1984; Unger, 1984; Zobeck and Onstad, 1987). Within these landscapes, the reported increase is expected to occur during the early part of the storm where rainsplash action may be more important than runoff. The exact mechanisms leading to increase in roughness are unknown. Changes in roughness during a storm event can be attributed to compression and drag force from the raindrop impact on the soil, angular displacement due to rainsplash, aggregate fragmentation, and differential swelling (Al-Durrah and Bradford, 1982; Warrington et al., 2009; Rosa et al., 2012; Fu et al., 2016). It is recognized that dryer, silty type soils may not exhibit the increase in RR shown here. Also, the role of sealing may be important on roughness development under bare soil conditions and needs further examination. Soil water retention characteristics of the soils under sealing and its implication to RR must be considered (Saxton and Rawls, 2006). Additionally, regions exhibiting different median raindrop diameters may experience different soil surface roughness evolution due to different aggregate fragmentation and rain splash effects (Warrington et al., 2009; Rosa et al., 2012; Fu et al., 2016).

Our findings provide a better understanding of the highly dynamic phenomenon of soil surface microroughness evolution under the impact of rainfall. OurThis study motivates further research on the extent of influence of the examined phenomenon and its mathematical formulation for modeling applications.This finding will benefits and further motivate a number of disciplines, from environmental modeling and research, to agricultural management, by providing a better understanding of the highly dynamic phenomenon of soil surface microroughness evolution under the impact of rainfall. For instance, current modeling tools of soil surface processes are likely tomay predict a total decay of soil surface roughness after subsequent rainfall events (e.g., Potter, 1990) which may not be the case.that will be translated to the absence of depression storage and are prone tomay overpredicting runoff (Liu and Singh, 2004). This may have implications on belowground processes within the soil column such as porous network formation and water nutrient diffusion (Hunt and Ghanbarian, 2016). drag forceFinally, this study and other studies demonstrate that the evolution of soil surface roughness in response to rainfall is dependent on initial roughness conditions and can contribute to hydrology, i.e., another factor shaping the soil surface (e.g., through runoff). Different behavior of surface roughness evolution, i.e., increase or decrease, depending on initial roughness conditions indicates a dynamic and nonlinear feedback between hydrologic response and surface roughness which may affect depression storage, ponding and flow pathways (Kamphorst et al., 2000; Gómez and Nearing, 2005). However, the extent to which soil surface roughness increase would affect depression storage, runoff, and flow pathways is unknown and further research to quantify this effect is needed. However, the extent to which soil surface roughness increase would affect depression storage, ponding, and flow pathways is unknown, and further research to quantify this effect is needed. Nonetheless, the current findings may help explain some modeling discrepancies in terms of depression storage and runoff predictions.Nonetheless, our study demonstrates that the evolution of soil surface roughness in response to rainfall is dependent on initial roughness conditions and can contribute to hydrology, i.e., another factor shaping the soil surface (e.g., through runoff). Different behavior of surface evolution depending on initial microroughness indicates a dynamic and nonlinear feedback between hydrologic response and surface roughness which may affect ponding, flow pathways, as well as the associated surface heterogeneity where localized smooth conditions are prevalent. This by no means suggests that lack of consideration of our findings will necessarily or drastically affect hydrologic response. However, it may be implemented to explain model discrepancies and motivate further research.Finally, our study demonstrates that soil surface roughness, which may be quantified by means of the RR index or crossover length, evolves in response to and in concert with rainfall, indicating a feedback where hydrologic response and surface evolution are interrelated. Our study's results further suggest that the response of soil surface roughness is nonlinear with respect to the hydrodynamic forcing and the related processes, depending on both the initial roughness condition and the applied rainfall energy and affecting ponding, flow pathways, as well as the associated surface heterogeneity.

On an annual basis, Abaci and Papanicolaou (2009) and Abban et al. (2016) highlight the importance of the seasonal variation of land cover on sediment output in agricultural Intensively Managed Landscapes (IMLs), indicating that during certain periods, the combination of high magnitude events and bare soil will severely increase erosion. This point is of high relevance here given the soil surface in agricultural IMLs is bare 30-75% of the time during the calendar year. Models simulating these periods at the microscale are likely to be sensitive to the treatment (and definition) of the soil surface microroughness, and thus, require an adequate determination of the soil surface roughness length scales for accurately modeling the hydrologic response of hillslopes. They must be able To the extent that microscale processes are considered significant, we argue that such models should adequately capture the increasing and decreasing trends in soil microroughness during all stages of a storm event in order to accurately predict local response to rainfall.tTo the extent that microscale processes are considered significant, we argue that such models shouldo adequately capture the increasing and decreasing trends in soil surface microroughness in order to accurately predict the landscape localized response to precipitation. The extent to which the increase in RR recordedr herein maycan affect erosion processes is not yet known. However, it has been noted that different values of RR can affect flow pathways and runoff, which consequently can affect erosion processes (Gómez and Nearing, 2005).

The unknown is the degree of change in RR that will significantly affect erosion processes.From this standpoint, our study provides an much-needed insight into processes other than tillagethe mechanism of the interaction between rainfall and a bare surface that can result in increasing soil surface roughness after the surface is smoothened through various processes, such as natural weathering or surface erosion processes. Particularly, our research feeds into the dynamics of areas morphological runoff zones on the landscape where raindrop detachment is prevalent (i.e. upslope and interrill areas) and known to contribute significantly to runoff and net sediment fluxes from the landscapeoverland flow hydraulics (Smith et al., 2011). Existing models may perform poorly in these areas and under bare certain conditions partially because the new statistical analysesbehavior we provide examine in the manuscript are is lacking. In fact, tThe majority of existing models assume that the random roughnessRR is present a priori and that italways decays over time over timewith cumulative rainfall amountrainfall. Few models consider the reverse condition where the soil surface is initially smooth as defined in the current paper and the random roughnessRR increases under the action of raindrop. By providing the ratios of increase in random roughness indicesand crossover length with rainfall intensity, the parameterization of the evolution of surface roughness with rainfall could be improved for current and future models is improvedcan be aided, at least by providing the physical ranges of the ratios for current models. Future research will complement the present efforts by quantifying the evolution of microroughness under the collective action of rainfall and runoff. provide a better understanding of the extent to which the initial increase in roughness in the early part of the storm could have an impact on flow pathways, runoff, and processes at subsequent parts of the stormThis will necessitaterequire a better understanding the of the interplay and the governing scaling laws of the various processes involved extension of the experiments in areas such as downslopes where concentrated flow and rilling are of importance.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

The present study was in parts supported by the National Science Foundation grant EAR1331906 for the Critical Zone Observatory for intensively managed landscapes (IML-CZO), which comprises multi-institutional collaborative effort. The authors, especially the corresponding author, would like to acknowledge the help provided by Dr. Chi-Hua Huang from the USDA-ARS National Soil Erosion Research Lab, West Lafayette, IN regarding the purchase of the laser system used in this research to map the RR. The fifth author was partially supported by the University of Iowa NSF IGERT program, Geoinformatics for Environmental and Energy Modeling and Prediction. This research was supported by the NASA EPSCoR Program [Grant #NNX10AN28A] and the Iowa Space Grant Consortium [Grant # NNX10AK63H]. Finally, the first author during part of this analysis has been supported by the USDA-AFRI grant. The data of this research are available to the interested reader upon written request to any of the first three authors.

References

Abaci, O. and Papanicolaou, A. N.: Long-term effects of management practices on water-driven soil erosion in an intense agricultural sub-watershed: monitoring and modelling, Hydrological Processes 23, 2818–2837, doi:10.1002/hyp.7380, 2009.

Abban, B. K., Thanos Papanicolaou, A. N., Cowles, M. K., Wilson, C. G., Abaci, O., Wacha, K., Schilling, K., and Schnoebelen, D.: An enhanced Bayesian fingerprinting framework for studying sediment source dynamics in intensively managed landscapes, Water Resources Research 52, 4646–4673. doi:10.1002/2015WR018030, 2016.

Al-Durrah, M. M., Bradford, J. M.: The mechanism of raindrop splash on soil surfaces, Soil Science Society of America Journal, 46, 1086, doi:10.2136/sssaj1982.03615995004600050040x, 1982.

Allmaras, R. R., Burwell, R. E., Larson, W. E., and Holt, R. F.: Total porosity and random roughness of the interrow zone as influenced by tillage, USDA Conservation Re. Rep., 7, 22, 1966.

Bertuzzi, P., Rauws, G., and Courault, D.: Testing roughness indices to estimate soil surface roughness changes due to simulated rainfall, Soil and Tillage Research, 17, 87–99, doi:10.1016/0167-1987(90)90008-2, 1990.

Burrough, P. A.: Multiscale sources of spatial variation in soil. I. The application of fractal concepts to nested levels of soil variation. Journal of Soil Science 34, 577–597, doi:10.1111/j.1365-2389.1983.tb01057.x, 1983a.

Burrough, P. A.: Multiscale sources of spatial variation in soil. II. A non-Brownian fractal model and its application in soil survey, Journal of Soil Science, 34, 599–620, doi:10.1111/j.1365-2389.1983.tb01058.x, 1983b.

Burwell, R. E., Allmaras, R. R., and Amemiya, M.: Structural alteration of soil surfaces by tillage and rainfall. Journal of Soil and Water Conservation, 21, 61-63, 1966.

Burwell, R. E. and Larson, W. E.: Infiltration as influenced by tillage-induced random roughness and pore space. Soil Science Society of America Journal, 33, 449, doi:10.2136/sssaj1969.03615995003300030032x, 1969.

Cheng, Q., Sun, Y., Lin, J., Damerow, L., Schulze Lammers, P., and Hueging, H.: Applying two-dimensional Fourier Transform to investigate soil surface porosity by laser-scanned data. Soil and Tillage Research, 124, 183–189, doi:10.1016/j.still.2012.06.016, 2012.

Chi, Y., Yang, J., Bogart, D., and Chu, X.: Fractal Analysis of Surface Microtopography and its Application in Understanding Hydrologic Processes, Transactions of the ASABE, 55, 1781–1792, doi:10.13031/2013.42370, 2012.

Cogo, N. P.: Effect of residue cover, tillage-induced roughness, and slope length on erosion and related parameters. PhD Dissertation, Purdue University, 344, 1981.

~~Chu, X., Yang, J., and Chi, Y.: Quantification of Soil Random Roughness and Surface Depression Storage: Methods, Applicability, and Limitations, Transactions of the ASABE, 55, 1699–1710, doi:10.13031/2013.42361, 2012.~~

Currence, H. D. and Lovely, W. G.: The analysis of soil surface roughness, Transactions of the ASAE, 13, 710–0714, 1970.

Darboux, F. and Huang, C.: An ~~Instantaneous~~instantaneous ~~Profile~~ profile ~~Laser~~ laser ~~Scanner~~ scanner to ~~Measure~~ measure ~~Soil~~ soil ~~Surface~~ surface ~~Microtopography~~microtopography, Soil Science Society of America Journal, 67, 92, doi:10.2136/sssaj2003.9200, 2003.

Elhakeem, M. and Papanicolaou, A. N.: Estimation of the ~~Runoff~~ runoff ~~Curve~~ curve ~~Number~~ number via ~~Direct~~ direct ~~Rainfall~~ rainfall ~~Simulator~~ simulator ~~Measurements~~ measurements in the State of Iowa, USA, Water Resources Management, 23, 2455–2473, doi:10.1007/s11269-008-9390-1, 2009.

Fu, Y., Li, G., Zheng, T., Li, B., and Zhang, T.: Impact of raindrop characteristics on the selective detachment and transport of aggregate fragments in the Loess Plateau of China, Soil Science Society of America Journal, 80, 1071, doi:10.2136/sssaj2016.03.0084, 2016.

Gilley, J. E. and Finkner, S. C.: Hydraulic roughness coefhcients as affected by random roughness, Transactions of the ASAE, 34, 0897–0903, doi:10.13031/2013.31746, 1991.

Gómez, J. A. and Nearing, M. A.: Runoff and sediment losses from rough and smooth soil surfaces in a laboratory experiment, ~~CATENA~~ Catena, 59, 253–266, doi:10.1016/j.catena.2004.09.008, 2005.

Guan, Y., Sherman, M., and Calvin, J. A.: A nonparametric test for spatial isotropy using subsampling, Journal of the American Statistical Association, 99, 810–821, doi:10.1198/016214504000001150, 2004.

Huang, C. and Bradford, J. M.: Depressional storage for Markov-Gaussian surfaces, Water Resources Research, 26, 2235–2242, doi:10.1029/WR026i009p02235, 1990.

Huang, C. and Bradford, J. M.: Applications of a ~~Laser~~ laser ~~Scanner~~ scanner to ~~Quantify~~ quantify ~~Soil~~ soil ~~Microtopography~~microtopography, Soil Science Society of America Journal, 56, 14, doi:10.2136/sssaj1992.03615995005600010002x, 1992.

Huff, F. A. and Angel, J. R.: Rainfall Frequency Atlas of the Midwest. Midwestern Climate Center Research Report, 92-03~~.~~, Champaign, IL, 1992.

Hunt, A. G. and Ghanbarian, B.: Percolation theory for solute transport in porous media: Geochemistry, geomorphology, and carbon cycling: Solute transport in porous media, Water Resources Research, 52, 7444–7459, doi:10.1002/2016WR019289, 2016.

~~Le Bissonnais, Y.: Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology: Aggregate stability and assessment of soil crustability and erodibility, European Journal of Soil Science, 67, 11–21, doi:10.1111/ejss.4_12311, 2016.~~

Kamphorst, E. C., Jetten, V., Guérif, J., Pitkanen, J., Iversen, B. V., Douglas, J. T., and Paz, A.: Predicting depressional storage from soil surface roughness, Soil Science Society of America Journal 64, 1749, doi:10.2136/sssaj2000.6451749x, 2000.

Linden, D. R., Van Doren, D. M.: Parameters for characterizing tillage-induced soil surface roughness, Soil Science Society of America Journal, 50, 1560, doi:10.2136/sssaj1986.03615995005000060035x, 1986.

Liu, Q. Q. and Singh, V. P.: Effect of ~~Microtopography~~microtopography, ~~Slope~~ slope ~~Length~~ length and ~~Gradient~~gradient, and ~~Vegetative~~ vegetative ~~Cover~~ cover on ~~Overland~~ overland ~~Flow~~ flow through ~~Simulation~~simulation~~.~~ , Journal of Hydrologic Engineering, 9, 375–382, doi:10.1061/(ASCE)1084-0699(2004)9:5(375), 2004.

Lovejoy, S. and Schertzer, D., 2007: Scaling and multifractal fields in the solid earth and topography, Nonlinear Processes in Geophysics 14, 465–502, doi:10.5194/npg-14-465-2007, 2007.

Magunda, M. K., Larson, W. E., Linden, D. R., and Nater, E. A.: Changes in microrelief and their effects on infiltration and erosion during simulated rainfall, Soil Technology, 10, 57–67, doi:10.1016/0933-3630(95)00039-9, 1997.

Mandelbrot, B. B. and Van Ness, J. W.: Fractional Brownian ~~Motions~~motions, ~~Fractional~~ fractional ~~Noises~~ noises and ~~Applications~~applications, SIAM Review, 10, 422–437, 1968.

Marshall, J. S., Palmer, W. M. K.: The distribution of raindrops with size, Journal of Meteorology, 5, 165–166, doi:10.1175/1520-0469(1948)005<0165:TDORWS>2.0.CO;2, 1948.

Oades, J. and Waters, A.: Aggregate hierarchy in soils, Australian Journal of Soil Research, 29, 815, doi:10.1071/SR9910815, 1991.

Oleschko, K., Korvin, G., Muñoz, A., Velazquez, J., Miranda, M. E., Carreon, D., Flores, L., Martínez, M., Velásquez-Valle, M., Brambila, F., Parrot, J.~~-~~ F., and Ronquillo, G.: Mapping soil fractal dimension in agricultural fields with GPR, Nonlinear Processes in Geophysics, 15, 711–725, doi:10.5194/npg-15-711-2008, 2008.

Onstad, C. A.: Depressional ~~Storage~~ storage on ~~Tilled~~ tilled ~~Soil~~ soil ~~Surfaces~~surfaces~~.~~, Transactions of the ASAE, 27, 729–732, doi:10.13031/2013.32861, 1984.

Papanicolaou, A. N., Tsakiris, A. G., and Strom, K.: The use of fractals to quantify the morphology of cluster microform, Geomorphology, 139-140:91-108, doi:10.1016/j.geomorph.2011.10.007, 2012.

Papanicolaou, A. N., Elhakeem, M., Wilson, C. G., Burras, C. L., West, L. T., Lin, H. (Henry), Clark, B., and Oneal, B.E.: Spatial variability of saturated hydraulic conductivity at the hillslope scale: Understanding the role of land management and erosional effect, Geoderma, 243–244, 58–68, doi:10.1016/j.geoderma.2014.12.010, 2015a.

Papanicolaou, A. N., Wacha, K. M., Abban, B. K., Wilson, C. G., Hatfield, J. L., Stanier, C. O., and Filley, T. R.: From soilscapes to landscapes: A landscape-oriented approach to simulate soil organic carbon dynamics in intensively managed landscapes,~~: SOIL ORGANIC CARBON DYNAMICS.~~ Journal of Geophysical Research: Biogeosciences, 120, 2375–2401, doi:10.1002/2015JG003078, 2015b.

Paz-Ferreiro, J., Bertol, I., and Vázquez, E. V.: Quantification of tillage, plant cover, and cumulative rainfall effects on soil surface microrelief by statistical, geostatistical and fractal indices, Nonlinear Processes in Geophysics, 15, 575–590. doi:10.5194/npg-15-575-2008, 2008.

Potter, K. N.~~, 1990~~: Soil properties effect on random roughness decay by rainfall, Transactions of the ASAE, 33, 1889–1892, 1990.

Römkens, M. J. and Wang, J. Y.: Effect of ~~Tillage~~ tillage on ~~Surface~~ surface ~~Roughness~~roughness, Transactions of the ASAE, 29, 0429–0433, doi:10.13031/2013.30167, 1986.

~~Römkens, M.J., Helming, K., and Prasad, S.: Soil erosion under different rainfall intensities, surface roughness, and soil water regimes, CATENA, 46, 103–123, doi:10.1016/S0341-8162(01)00161-8, 2002.~~

Rosa, J. D., Cooper, M., Darboux, F., and Medeiros, J. C.: Soil roughness evolution in different tillage systems under simulated rainfall using a semivariogram-based index, Soil and Tillage Research, 124, 226–232, doi:10.1016/j.still.2012.06.001, 2012.

Saxton, K. E. and Rawls, W. J.: Soil water characteristic estimates by texture and organic matter for hydrologic solutions, Soil Science Society of America Journal, 70, 1569, doi:10.2136/sssaj2005.0117, 2006.

Smith, M. W., Cox, N. J., and Bracken, L. J.: Terrestrial laser scanning soil surfaces: a field methodology to examine soil surface roughness and overland flow hydraulics, Hydrological Processes, 25, 842–860, doi:10.1002/hyp.7871, 2011.

Steichen, J. M.: Infiltration and random roughness of a tilled and untilled claypan soil. Soil and Tillage Research, 4, 251–262, doi:10.1016/0167-1987(84)90024-2, 1984.

Tarquis, A. M., Heck, R. J., Grau, J. B., Fabregat, J., Sanchez, M. E., and Antón, J. M.: Influence of thresholding in mass and entropy dimension of 3-D soil images, Nonlinear Processes in Geophysics, 15, 881–891, doi:10.5194/npg-15-881-2008, 2008.

Unger, P. W.: Tillage effects on surface soil physical conditions and sorghum emergence. Soil Science Society of America Journal, 48, 1423, doi:10.2136/sssaj1984.03615995004800060044x, 1984.

Tarquis, A.M., de Lima, J.L.M.P., Krajewski, W.F., Cheng, Q., and Gaonac'h, H.: "Nonlinear and scaling processes in Hydrology and Soil Science", Nonlinear Processes in Geophysics, 18, 899–902, doi:10.5194/npg-18-899-2011, 2011.

Vázquez, E. V., Miranda, J. G. V., and González, A. P.: Characterizing anisotropy and heterogeneity of soil surface microtopography using fractal models, Ecological Modelling, 182, 337–353, doi:10.1016/j.ecolmodel.2004.04.012, 2005.

Vázquez, E.V., Miranda, J.G.V., Alves, M.C., and González, A.P.: Effect of tillage on fractal indices describing soil surface microrelief of a Brazilian Alfisol, Geoderma, 134, 428–439, doi:10.1016/j.geoderma.2006.03.012, 2006.

Vázquez, E. V., Miranda, J. G. V., and González, A. P.: Describing soil surface microrelief by crossover length and fractal dimension, Nonlinear Processes in Geophysics, European Geo-sciences Union (EGU), 14, 223–235, 2007.

Vázquez, E. V., Moreno, R. G., Miranda, J. G. V., Díaz, M. C., Requejo, A. S., Paz-Ferreiro, J., and Tarquis, A. M.: Assessing soil surface roughness decay during simulated rainfall by multifractal analysis, Nonlinear Processes in Geophysics, 15, 457–468, doi:10.5194/npg-15-457-2008, 2008.

Vázquez, E.V., Vieira, S.R., De Maria, I.C., and González, A.P.: Fractal dimension and geostatistical parameters for soil microrelief as a function of cumulative precipitation, Scientia Agricola, 67, 78–83, doi:10.1590/S0103-90162010000100011, 2010.

Vermang, J., Norton, L. D., Baetens, J. M., Huang, C., Cornelis, W. M., and Gabriels, D.: Quantification of Soil soil Surface surface Roughness roughness Evolution evolution under Simulated simulated Rainfallrainfall, Transactions of the ASABE, 56, 505–514, doi:10.13031/2013.42670, 2013.

Warrington, D. N., Mamedov, A. I., Bhardwaj, A. K., and Levy, G. J.: Primary particle size distribution of eroded material affected by degree of aggregate slaking and seal development, European Journal of Soil Science, 60, 84–93, doi:10.1111/j.1365-2389.2008.01090.x, 2009.

Zhang, X., Yu, G. Q., Li, Z. B., and Li, P.: Experimental study on slope runoff, erosion and sediment under different vegetation types, Water resources management, 28(9), 2415-2433, 2014.

Zhao, L., Wu, J., Zhang, Q., and Wu, F.: Runoff, erosion and sediment particle size from smooth and rough soil surfaces under steady rainfall-runoff conditions, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 64, 623–632, doi:10.1080/09064710.2014.949297, 2014.

~~Zhao, L., Huang, C., and Wu, F.: Effect of microrelief on water erosion and their changes during rainfall: Microrelief Affect Erosion and Change during Rainfall, Earth Surface Processes and Landforms, 41, 579–586, doi:10.1002/esp.3844, 2016.~~

~~Zheng, Z.C. and He, S.Q.: Change of Soil Surface Roughness of Splash Erosion Process, in: Godone, D. (Ed.), Research on Soil Erosion, InTech, 2012.~~

Zheng, Z. C., He, S. Q., and Wu, F.: Changes of soil surface roughness under water erosion process: Soil surface roughness under water erosion, Hydrological Processes, 28, 3919–3929, doi:10.1002/hyp.9939, 2014.

Zobeck, T. M. and Onstad, C. A.: Tillage and rainfall effects on random roughness: A review, Soil and Tillage Research, 9, 1–20, doi:10.1016/0167-1987(87)90047-X, 1987.

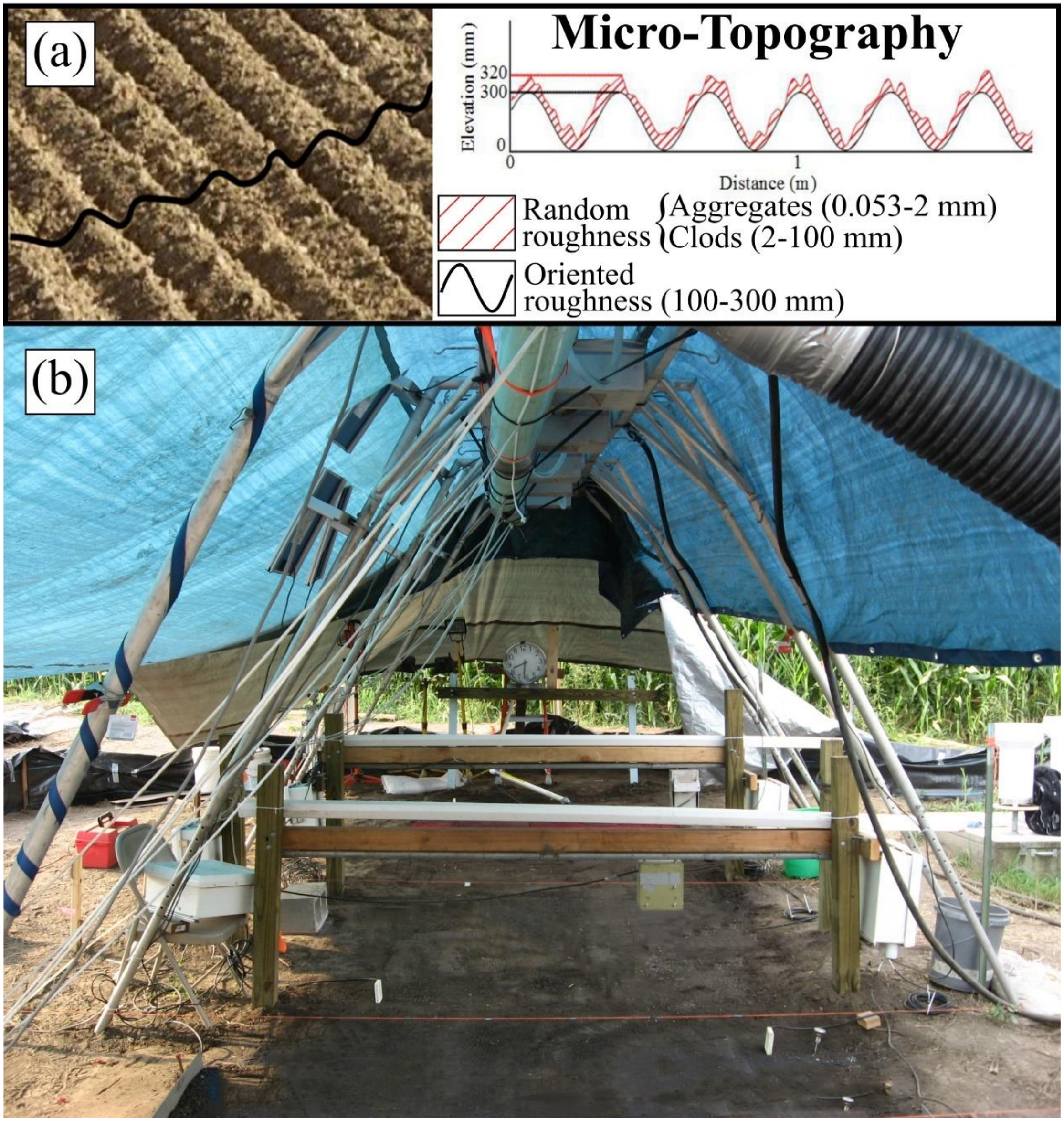


Figure 1: (a) ~~Definition sketch of soil surface roughness types~~Types of soil surface microroughness. (b) Experimental plot~~ where the experiments were conducted~~. The rainfall simulator is placed above the bare soil surface and a base made of wood is put into place to facilitate the movement of the surface-profile laser scanner.

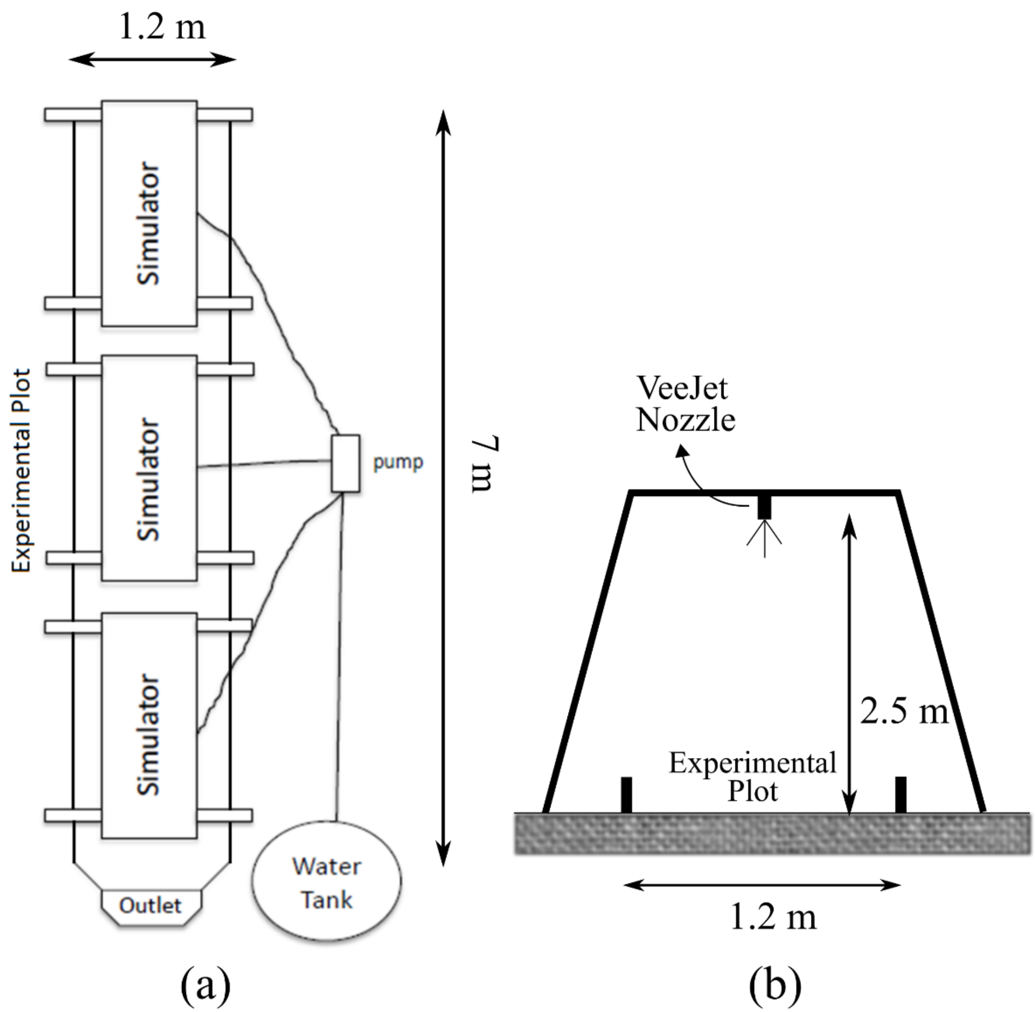


Figure 2: ~~Sketch of the setup for all of the experimental tests considered in this study.~~Setup of the experimental tests: (a) ~~The r~~Rainfall simulators are mounted in series and a pump ~~is utilized to~~ provides them with water from a ~~water~~ tank ~~throughout the experiments~~. (b) ~~The rainfall~~ Rainfall simulators are placed and adjusted at a height of 2.5 m above the experimental plot surface to ensure drop terminal velocity is reached.

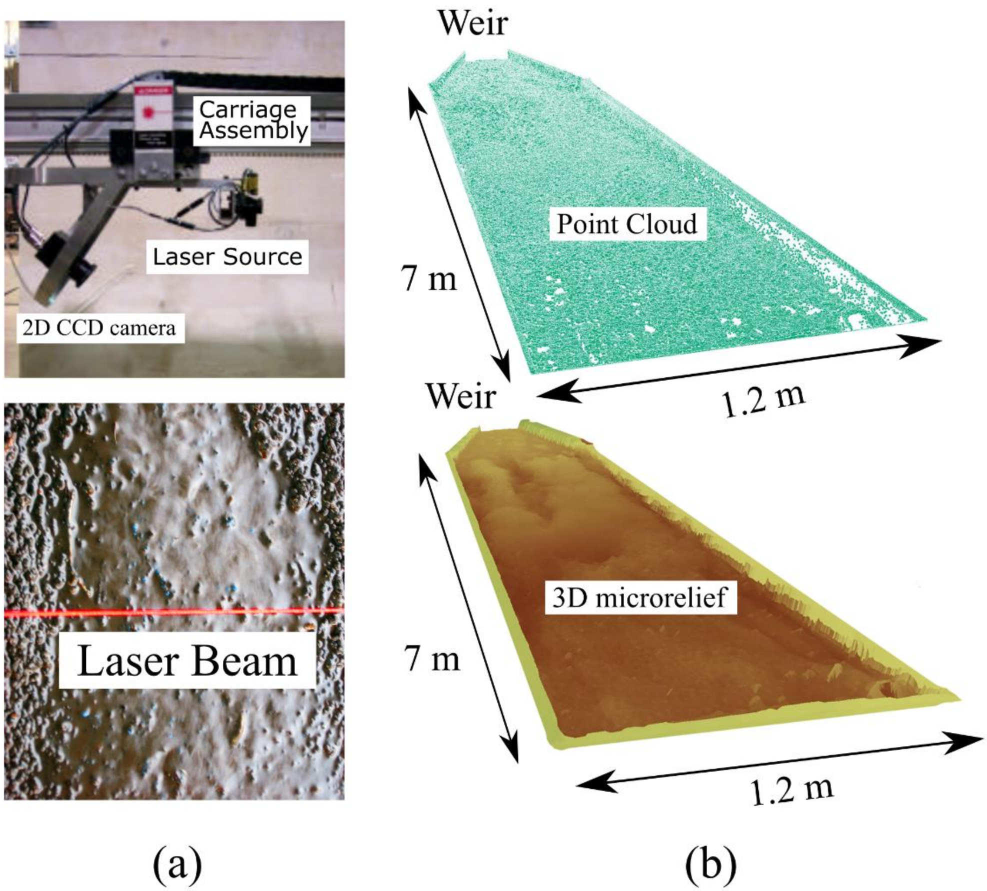


Figure 3: (a) Instantaneous digital surface-profile laser scanner used in the experimental runs and laser beam projected on the soil surface. (b) Cloud of (x,y,z) data acquired from the laser scanner for an experimental test along with the associated 3D representation of the soil surface microrelief through inverse distance weighted interpolation.

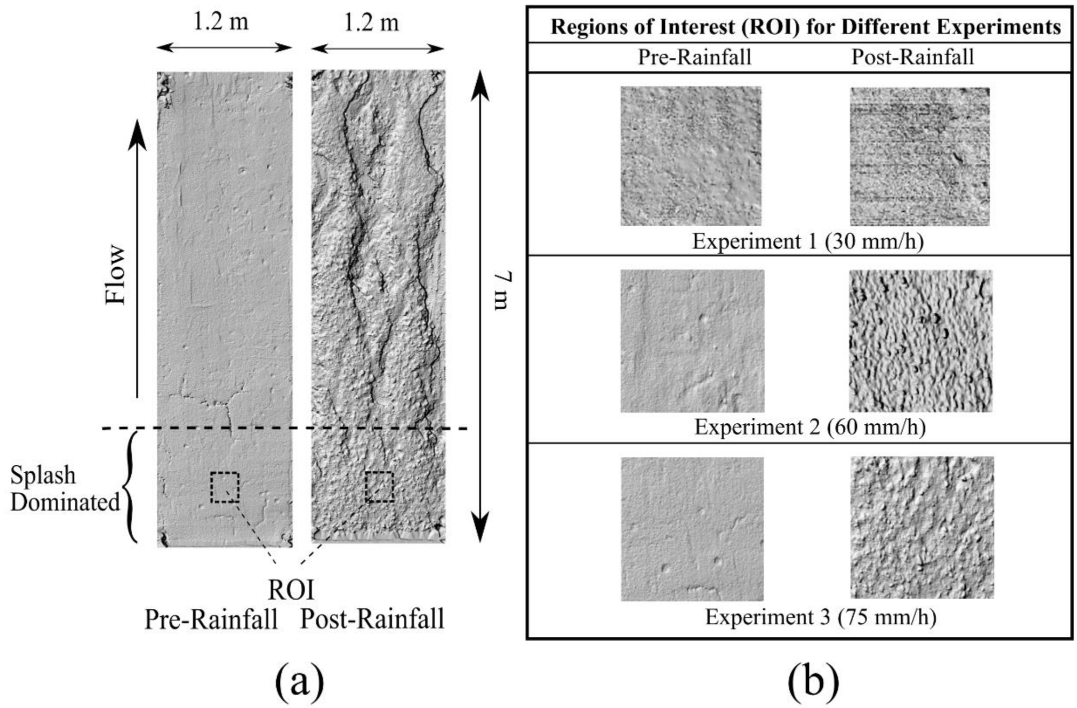


Figure 4: ~~Left~~(a)~~:~~ ~~Part of the e~~Experimental plot ~~of this study~~ under pre- and post-rainfall conditions for an experimental test. The dashed boxes indicate the extent of the Region of Interest(ROI), where raindrop detachment is dominant over runoff. ~~Right:~~ (b) Scanned profiles extracted from the laser-scanned areas of the three experimental tests considered, under both pre- and post-rainfall conditions.

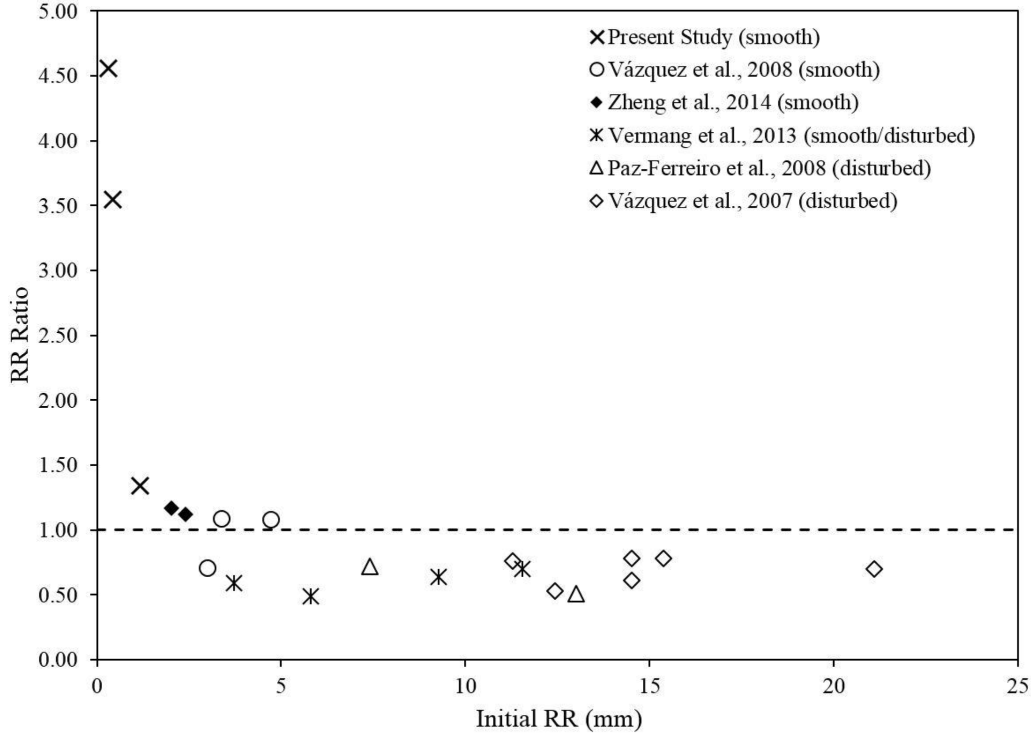


Figure 5: Random Roughness (RR) Ratio <u>versus initial RR for this study and other selected studies.</u>~~at the ROI for the three experimental tests considered herein.~~

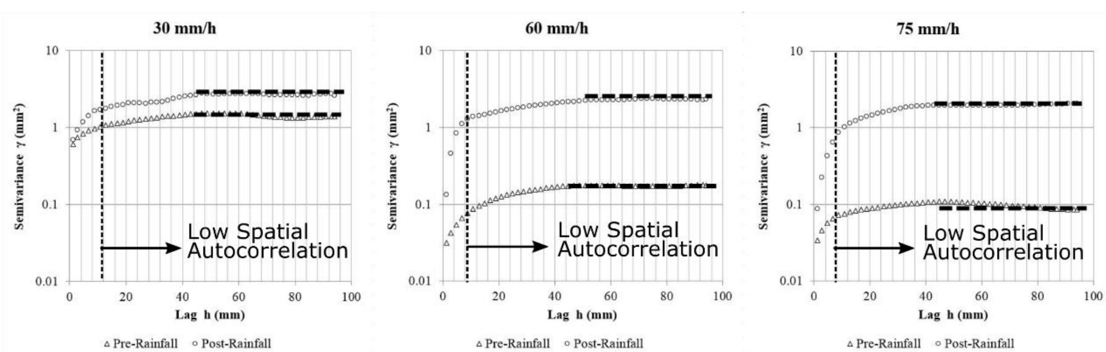
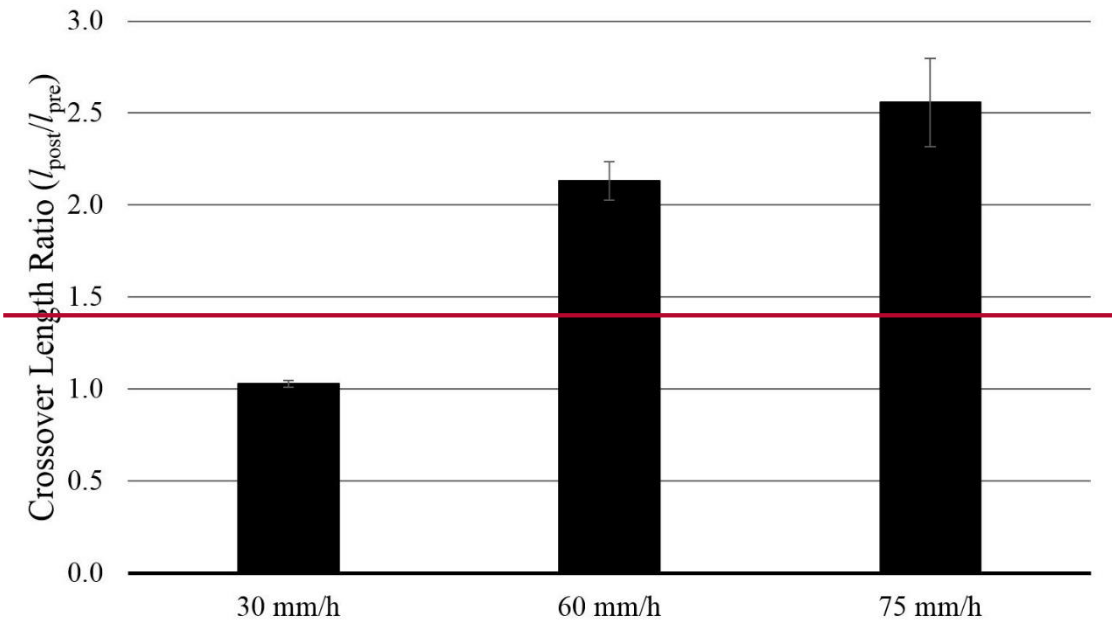


Figure 6: ~~Spatial s~~<u>S</u>emivariograms at the ~~ROI~~ <u>region of interest</u> for the three experimental tests ~~considered herein~~, under pre- and post-rainfall conditions. Horizontal dashed lines indicate the semivariogram sills and vertical dashed lines indicate the lag distance above which the spatial autocorrelation of the elevations is negligible.



~~**Figure 7: Crossover length (l) ratio at the ROI for the three experimental tests considered herein.**~~

~~Table 1: Conditions of experimental tests.~~

~~Characteristics~~	~~Experiment 1~~	~~Experiment 2~~	~~Experiment 3~~
~~Rainfall Intensity~~	~~30 mm/h~~	~~60 mm/h~~	~~75 mm/h~~
~~Duration of Experiment~~	~~5 h~~	~~5 h~~	~~5 h~~
~~Terminal Velocity~~	~~6.8 m/s~~	~~6.8 m/s~~	~~6.8 m/s~~
~~Median Drop Diameter~~	~~2.25 mm~~	~~2.25 mm~~	~~2.25 mm~~
~~Height of Drop~~	~~2.5 m~~	~~2.5 m~~	~~2.5 m~~

Table ~~2~~1: Summary of the rainfall induced change ~~of~~ in the RR index in the experimental tests of this study, as well as in experiments reported in the literature. Smooth conditions refer to initial microroughness on the order of 2-5 mm and disturbed conditions refer to initial microroughness greater than 5 mm. Cumulative rainfall amounts are also provided.

	Cumlative rainfall (mm)	Pre-rainfall RR (mm)	Post-rainfall RR (mm)	RR Ratio
Present Study (smooth)				
30 mm/h	150	1.17	1.57	1.34
60 mm/h	300	0.42	1.48	3.55
75 mm/h	375	0.32	1.46	4.56
Vázquez et al., 2008 (smooth)				
Soil MA4	85	3.39	3.70	1.09
Soil MA6	50	3.00	2.13	0.71
Soil LU1	195	4.72	5.10	1.08
Zheng et al., 2014 (smooth)				
Straight Slope	~60	2.01	2.35	1.17
Raking Cropland	~135	2.40	2.68	1.12
Vermang et al., 2013 (smooth/disturbed)				
Very Smooth	150	3.71	2.19	0.59
Smooth	150	5.80	2.82	0.49
Rough	150	9.27	5.92	0.64
Very Rough	150	11.55	8.13	0.70
Paz-Ferreiro et al., 2008 (disturbed)				
Minumum tillage (2003)	229	13.00	6.63	0.51
Minimum tillage (2004)	350	7.40	5.32	0.72
Vázquez et al., 2007 (disturbed)				
Disc Harrow	233	15.38	11.99	0.78
Disc Plow	233	21.09	14.69	0.70
Chisel Plow	233	11.29	8.60	0.76
Disk harrow + Disc Level	295	12.42	6.58	0.53
Disc Plow + Disc Level	295	14.51	11.38	0.78
Chisel Plow + Disc Level	295	14.51	8.83	0.61

Table ~~3~~2: Summary of the rainfall induced change ~~of~~ in the crossover length in the experimental tests of this study, as well as in experiments reported in the literature. Smooth conditions refer to initial microroughness on the order of 2-5 mm and disturbed conditions refer to initial microroughness greater than 5 mm. Cumulative rainfall amounts are also provided.

	Cumulative Rainfall (mm)	Pre-rainfall l (mm)	Post-rainfall l (mm)	Crossover length Ratio
Present Study (smooth)				
30 mm/h	150	0.71	0.73	1.03
60 mm/h	300	0.09	0.20	2.13
75 mm/h	375	0.15	0.39	2.56
Vermang et al., 2013 (smooth/disturbed)				
Very Smooth	150	2.07	1.07	0.52
Smooth	150	4.56	1.16	0.25
Rough	150	6.93	1.46	0.21
Very Rough	150	5.06	1.63	0.32
Paz-Ferreiro et al., 2008 (disturbed)				
Minimum Tillage (2003)	229	4.73	3.80	0.80
Minimum Tillage (2004)	350	5.49	1.69	0.31
Vázquez et al., 2007 (disturbed)				
Disc Harrow	233	7.69	2.86	0.37
Disc Plow	233	10.32	1.97	0.19
Chisel Plow	233	6.43	1.71	0.27
Disk harrow + Disc Level	295	6.69	1.19	0.18
Disc Plow + Disc Level	295	9.25	1.17	0.13
Chisel Plow + Disc Level	295	5.01	1.16	0.23

Table 3: Summary of the rainfall induced change in the Markov-Gaussian variance length scale and limiting difference indices for the experimental tests of this study.

`	Cumulative Rainfall (mm)	Pre-rainfall σ (mm)	Post-rainfall σ (mm)	σ Ratio	Pre-rainfall *LD* (mm)	Post-rainfall *LD* (mm)	*LD* Ratio
30 mm/h	150	1.19	1.63	1.37	0.79	0.87	1.10
60 mm/h	300	0.42	1.52	3.62	0.26	0.87	3.39
75 mm/h	375	0.31	1.43	4.56	0.15	0.71	4.84