RESPONSE TO REVIEW COMMENTS

Dear Professor Daniel Schertzer,

We have reviewed the comments you provided very carefully. We want to thank the reviewer for the in-depth comments, suggestions and corrections, which overall have greatly improved the overall quality of the manuscript. Our responses are provided below. **Please note that the original comments are in black letters and our responses are in blue letters**. In addition to these responses, we will provide a revised manuscript which reflects the proposed changes, as well as a copy with the tracked changes where revisions were implemented.

General Comments:

The revised version of this manuscript has been very much modified regarding the first version. Several points that were raised by reviewers and editor have been addressed. Thus, organization has been somewhat improved, complementary information has been provided in the material and methods section, new indices have been taken into account and a number of sentences have been rephrased or corrected in all the sections of the manuscript.

However, in my opinion, this manuscript is not acceptable in its present form and therefore I still recommend major revision or rejection. This is mainly because results presented here are only significant for a very particular situation, but in spite of this generalization without experimental support have been made. Subsequently, presentation of results (including results cropped from the literature) is neither clear nor concise; also results are not put in context of the previous existing experimental evidence and text is far from precise.

First, I recognize that the results provided are interesting. However, the intended generalization from experimental results of a particular or "unique" case is one of my main concerns. Therefore, I completely agree with a previous comment of a different reviewer, which stated: "(I have) the feeling that authors overestimated the relevance of their results and reached conclusions that are not sufficiently proved by their data". In my opinion this statement still remains absolutely valid for the current version of the manuscript. For example, several statements in the Abstract section are too vague, imprecise or even misleading. Also other statements in the Discussion and Conclusions section are too strong or even not supported by results and evidence

Response:

We thank Reviewer #2 for their comments and noting the improvements made. We acknowledge the concerns and have made every effort to remove any overestimations, generalizations, and conclusions that are not based on the results of the specific conditions examined in the study. We have made it clear in the paper, based on the results, where our opinions point toward the need for further investigations. Please see answers to the Specific comments below that addresses these (Abstract: Comment 4, Introduction: Comment 2, Results: Comment 4, Discussions and Conclusion).

Second, preparation of soil surface to obtain a smooth surface in this work could result in an important bias. To the best of my understanding "tamping using a plywood board" for smoothing is an uncommon method. Using such procedure compaction of soil aggregates and structural units should be expected. Compaction intensity should increase with increasing soil water content and strength of tamping. Subsequently, the evolution of small aggregates, resulting mainly from tamping, under simulated rainfall could be far away from that of aggregate beds prepared by methods commonly used in field and laboratory experiments.

Response:
We followed the tamping approach in order to have consistent initial conditions for the replicates we performed out in the field. This was so that if any bias was introduced it would be consistent, if not minimal, and would not affect the trends in the experimental results. We do acknowledge that there could have been some compaction of soil aggregates and some effects from the compaction intensity. This could be problematic if soil aggregation was the focus of this research. However, this is not the case here. We strongly believe that the increasing trend in roughness observed in this study did not arise due to tamping and was due to the initial smooth conditions. Furthermore, our efforts to ensure consistency is confirmed in the values of all roughness indices for the pre- and post-rainfall roughness, which are consistent both in trends and relative magnitudes. This is further addressed in our answers to the Specific comments below (Abstract: Comment 4, Introduction: Materials and Methods: Comment 1, Results: Comment 4). We also acknowledge the potential impact of compaction of soil aggregates in the Discussions section of the manuscript.

Specific Comments:

Abstract

Comment 1: Page 1, Lines 13 to 17. On the one hand it is stated that roughness of about 2-5 mm is common on agricultural landscapes, but on the other hand the focus of this

manuscript is on roughness of 2 mm or less. I don't understand the discrepancy between the problem to be dressed and the focus of the manuscript.

Response:
Thank you for pointing this out. We understand the confusion stemming from how the sentences were framed. Our motivation was to study length scales less than 5 mm, where increases in roughness have been reported (e.g., Vázquez et al., 2008; Zheng et al., 2014). Since most of the studies for these length scales had roughness ranging between 2-5mm, we chose 2 mm as our reference condition for our experiments (since it was the apparent lower limit). However, ensuring an exact roughness value of 2 mm in the field is difficult, hence the slightly less initial roughness values. The initial part of the abstract has therefore been modified as follows (Page 1, Lines 13-19):

"This study examines the rainfall induced change in soil microroughness of a bare smooth soil surface in an agricultural field. The majority of soil microroughness studies have focused on surface roughness on the order of ~5-50 mm and have reported a decay of soil surface roughness with rainfall. However, there is quantitative evidence from few studies suggesting that surfaces with microroughness less than 5 mm may undergo an increase in roughness when subject to rainfall action. The focus herein is on initial microroughness length scales on the order of 2 mm, a low roughness condition observed seasonally in some landscapes under bare conditions, and chosen to systematically examine the increasing roughness phenomenon."

Comment 2: Page 1, Line l5. What means "long undisturbed exposure to rainfall impact"?.

Response:
This phrase was removed to avoid confusion.

Comment 3: Page 1, Line 18. "generic extreme conditions" is too vague. Also, it is not clear, here and all over the paper if your focus is in extreme conditions or in conditions that are common in agricultural landscapes.

Response:
This phrase was removed. Now it is explicitly stated that the focus of this paper is on initial microroughness of the order of 2 mm.

Comment 4: Page 1, Lines 25 to 27. The statement beginning "this contradicts..." and ending "… roughness conditions" is awkward, as before noted by other reviewer. What is the meaning of "monotonic" in this context?. The "commonly adopted literature" (for examples Zobeck and Onstad, 1987, who analysed 483 data sets and since them several other works) is the result of hundreds, perhaps thousands of experimental evidence in

different soils with different roughness magnitude, texture, aggregate stability, soil water content etc. In contrast in the present work results are limited to three soil surfaces from a particular soil, and the results obtained may be biased by the soil preparation procedure.

Response:

Thank you. We acknowledge the awkwardness of the statement and have modified the sentence. Our intent was not to suggest a limitation of the other studies but merely to point out that there are some conditions, specifically smooth surfaces, which have not yet been examined in detail, hence the limited data. Our study is a first step towards acknowledging this gap and filling it. Whilst we acknowledge that the conditions we examine are limited, we do not agree that the trends we observed are biased or insignificant based on the soil preparation procedure as other studies with a different soil preparation procedure have also reported an increase in microroughness e.g., Vázquez et al. (2008) and Zheng et al. (2014) (see earlier response to your general comment).

We have modified our statements in response to the comment to convey this message by indicating that the outcome of the interaction between rainfall and a soil surface may be different for smoother surfaces comparatively to rough surfaces, and highlights the need for a better understanding of the interaction (Page 1, Lines 22-26):

"Findings show a consistent increase in roughness under the action of rainfall, with an overall agreement between all indices in terms of trend and magnitude. Although this study is limited to a narrow range of rainfall and soil conditions, the results suggest that the outcome of the interaction between rainfall and a soil surface can be different for smooth and rough surfaces, and thus warrant the need for a better understanding of this interaction."

Etc., etc., etc. Again, my comments are not exhaustive. Altogether, I feel this abstract as awkward.

Introduction

Comment 1: Page 2, Lines 10 to 21. Indeed, random roughness assessment requires correction for both, slope and tillage marks. This is clearly stated in lines 18 and 19, but not in lines 10 and 11. Text in Lines 10 to 21. Also, please consider if Equation 1 should be in the Methods section.

Response:

Now it is clearly stated that evaluation of the RR index was done after correction for both slope and tillage marks in the Introduction (Page 2, Line 7).

Equation (1) was moved to the Methods section (Page 5, Lines 14-19).

Comment 2: Page 2, Lines 28 to 29. Please, note that Kamphorst et al. (2000) analysed 48 seedbeds with a roughness of the order of magnitude that you mention. Again 48 is much higher than 3, and several different soils have been studied by Kamphorst et al. (2000). Therefore, even if your results may be of interest, the should be put in the context of the previous work about the studied topic, and care should be taken to avoid overestimation of their relevance.

Response:

We have modified the text, explicitly stating that other studies have examined soil surface roughness <5 mm. We have also removed the extrapolation to limitations of hillslope scale erosion models in regards to representation of storage, runoff and sediment routing. We however note that there is no contradiction between the Kamphorst et al. (2000) results and our findings.

We state explicitly in the manuscript that we focus on the quantification of rainfall induced change in soil microroughness for scales 2 mm or less to examine the potential increase in roughness as the evidence suggests. This focus is due to limited data available for examining this trend and the lack of acknowledgement of the trend in previous studies (Page 2, Lines 15-29):

"There are few studies that have examined surfaces with initial microroughness less than 5 mm, a low roughness condition observed seasonally in some landscapes under bare conditions (e.g., Kamphorst et al., 2000; Vázquez et al., 2008; Zheng et al., 2014). Hereafter, for shortness, tests with initial RR less than 5 mm will be referred to as "smooth", whereas tests with initial RR greater than 5 mm will be referred to as "rough". There are some quantitative indications that under bare smooth surface conditions, soil surface roughness may actually increase under the action of rainfall… However, none of the… studies explicitly stated or acknowledged the increasing trend of roughness and its potential linkage to smooth bare soil surface conditions. The main goal of this study is to examine changes in RR under rainfall impact for initial microroughness less than 2 mm, since this appears to be the lower limit of roughness scales examined in the literature."

Special care is taken throughout the text so as not to overestimate the relevance of our results.

Comment 3: Page 2, Lines 29 to 34 and page 3, Lines 1 to 2. Sentences beginning with "Surfaces with microroughness…" are too vague. In addition, please note that in conventional tillage between postharvest and plant growth there is seedbed preparation. In

these conditions seedbeds constituted by small aggregates are the best example of real "microroughnees" or smooth soil surface.

Response:

We agree that the statement may come across as vague. These sentences were removed to improve the clarity and precision of the manuscript.

Comment 4: Page 3, lines 12 to 16. Again, I don't understand that if the aim of the work is to address the microrelief in soil surfaces with aggregates of about 2-5 mm you are focusing on "the order of 2 mm o less".

Response:

The goal of this work has now been corrected to address rainfall effects on roughness at scales on the order of 2 mm (Page 2, Lines 28-29). As explained above, the observation from literature review that surfaces with microrelief < 5 mm can undergo an increase in roughness under rainfall and the lack of data for smooth conditions is the main motivation of the study. We acknowledge the narrow range of our studied conditions, yet we believe our study provides the first leap for further exploring the behavior of smooth surfaces, and motivates further research on how the interaction between a soil surface and rainfall would be affected by the initial roughness conditions, and which are the underlying physics.

Comment 5: Page 3, lines 19 and 20. Although "disturbed" nay be an antonym of "smooth", in the context of this work correct is "rough". Please, see also Table 1.

Response:

The work "disturbed" has been replaced by "rough" throughout the manuscript.

Comment 6: Page 3, line 22. "Different intensities" of which?

Response:

That part of the text was corrected to "different rainfall intensities".

Etc., etc., etc. Again, my comments are not exhaustive. Again, tightening up is required.

Response:

Done – the manuscript has been tightened up.

Material and Methods

Comment 1: Page 4, line 4. What about aggregate size distribution after tamping?. What about soil compaction before and after tamping? What about aggregate stability before and after tamping?. Aggregate stability is a very important issue in this particular soil, prepared with a particular procedure before laser scanning. This is because of the strong relationship between processes responsible for roughness and aggregate stability.

Response:
It is recognized that the soil preparation method in our study could have introduced some bias to the soil properties such as aggregate size distribution, compaction, and aggregate stability. Nonetheless, for the purpose this study was designed for, this preparation method ensured consistency in the initial and final roughness states, as confirmed by replications of our experimental runs. Therefore, the bias introduced to our results would be consistent, if not minimal. In addition, other studies with a different soil preparation procedure where aggregates were not potentially disturbed and the conditions mimicked natural soil surfaces have also reported an increase in microroughness (e.g., Vázquez et al., 2008; Zheng et al., 2014). This suggests that the increasing trend in surface roughness is not an "artifact" of our soil preparation procedure.

The text has been modified as follows to acknowledge the potential existence of a consistent bias introduced by our preparation method (Page 3, Lines 11-14):

"The soil surface was prepared before each experiment by tamping using a plywood board to create a smoothened surface. This was done to ensure a consistency in surface roughness between the experiments, as well as to ensure that any potential bias introduced in the plot preparation would be also be consistent, if not minimal. This was confirmed by the observed roughness of the experiment replicates..."

Comment 2: Page 5, Line 11. Average hydraulic conductivity was rather low compared to simulated rain intensity. This is very important, since in these conditions in a flat surface should be expected. What about water ponding in your experiment, given that your plots had a slope?. Ponding is known to interfere with roughness decay.

Response:
Ponding on the soil surface of the experimental plots within the region of interest was minimal throughout the experiments. This can be seen in the image below, which was taken at the later part of a simulated event. The minimal ponding is attributed to the smooth bare surface

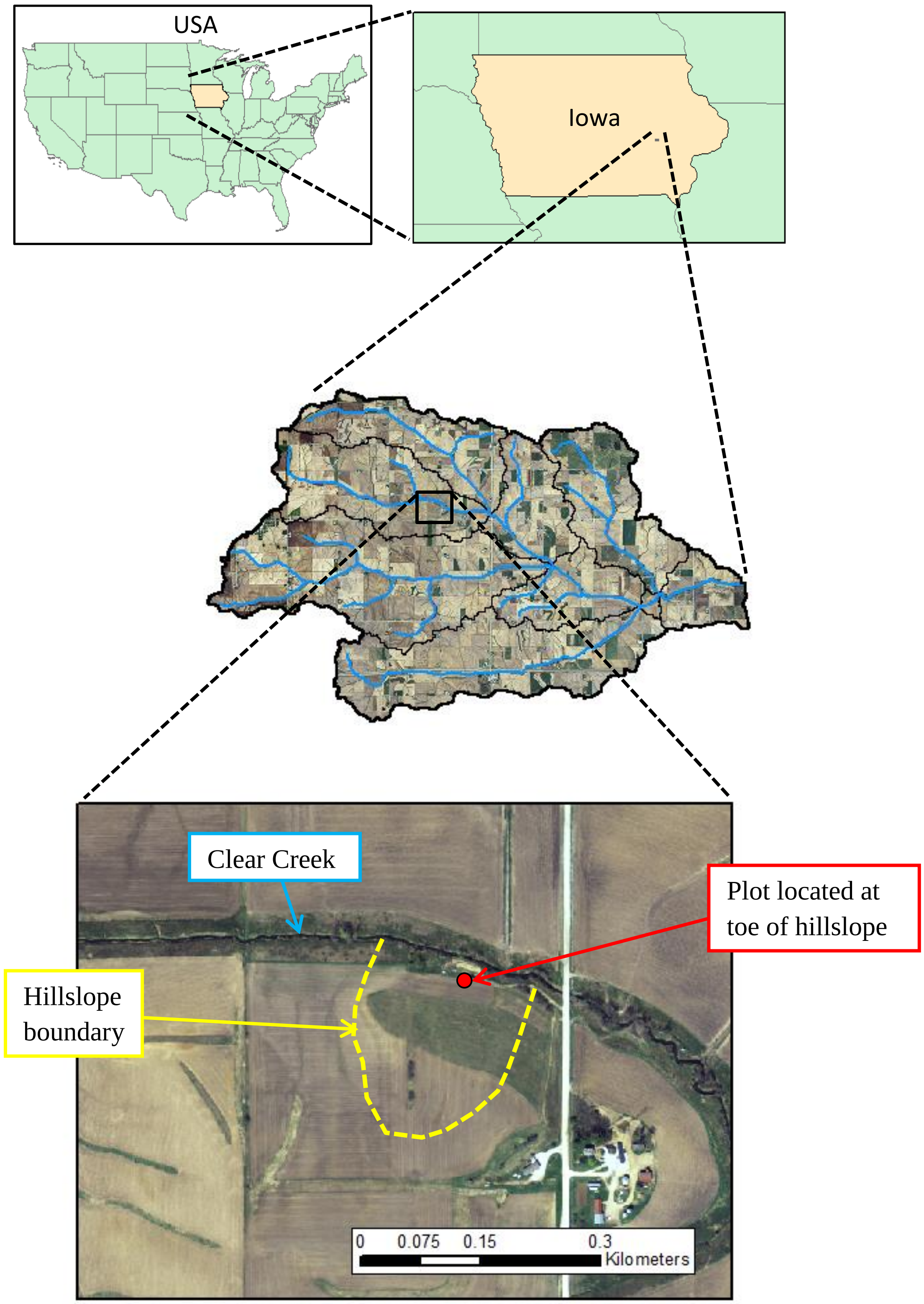
conditions and the high plot gradient of 9%, leading to low depressional storage. The above statement was added to enhance the precision of the text (Page 4, Lines 23-26):

"Although the average saturated hydraulic conductivity values were low with respect to the applied rainfall rates, minimal ponding was observed on the experimental plot, owing to the smooth bare conditions and the high plot gradient of 9%, which led to low depressional storage"

Comment 3: Page 5, Lines 15 to 18. The difference in initial roughness between experiment 1 and experiment 2 and 3, demonstrate roughness decay in your soil under natural rainfall. This is against your main hypothesis, which postulate roughness increase with increasing rainfall.

Response:
As it is stated in the text, the plots were located in an actual agricultural landscape and the plot for Experiment 1 had recently been disturbed by tillage, while Experiments 2 and 3 were performed later in the season. In between these periods, the effect of runoff from upslope areas is considered to have contributed to the decay in roughness over the prolonged period for which the plots for Experiments 2 and 3 were exposed. Therefore, roughness decay under natural rainfall was primarily because of the effect of runoff, and not the actual rainfall detachment process which is investigated in our study. The location of the plot in relation to the hillslope is shown on the map below to highlight this. This map has also been included in the manuscript as Figure 1. To avoid confusion regarding the decay, the statement below was added to the text (Pages 4, Lines 27-32).

"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 1. This is attributed to the different timing the experiment runs were performed 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 runoff from upslope areas on the plots arising from natural rainfall within that period (Papanicolaou et al., 2015b)."


USA
Iowa
Clear Creek
Plot located at
toe of hillslope
Hillslope
boundary
0
0.075
0.15
0.3
Kilometers

Location of experimental plot in relation to hillslope. The figure shows that the plot receive runoff from upslope areas of the hillslope.

Comment 4: Page 5, Lines 25. You stated that "no rill formation ever took place". But, what above "micro rills"?. I'm not sure above the absence of micro rills in your experimental conditions. Indeed, "traditional" works about soil surface roughness decay absolutely exclude the presence of soil erosion.

Response:

Visual evidence from the experiments confirms that rainsplash was the dominant process within the top part of the plot where our regions of interest were located (see figure provided in comment 2) and that the presence of micro rills was minimal. Given the very small flow rates at this location, even if microrills were present, the low stream power associated with their function would lead to little contribution to the alteration of soil surface roughness compared to the action of raindrop detachment (Kinnel, 2005). Furthermore, Kinnel (2005) noted that the impact of microrills is more prevalent for slopes gradients beyond 10%. We thus believe that our results were not affected by micro rills.

Comment 5: Page 3, Lines 3 to 24. I wonder if semivariograms, Hurst exponent, etc, have been calculated after removal of oriented roughness, i.e. tillage marks and also slope.
Etc., etc., etc. Again, my comments are not exhaustive. Again, tightening up is required.

Response:

Yes, correction for both slope and tillage marks was performed before the estimation of all the microrelief indices. This has also been added to the text where the various indices are described.

Results

I'm very concerned by the procedure used to compare results obtained in this work have with those of previous works. Results shown in Table 1 and in Figure 5 are misleading.

Comment 1: First, as before stated, hundreds of soil surfaces have been analysed for roughness decay in very different experimental conditions and this work only provide results for three soil surfaces measured under "unique" experimental conditions, which

perhaps lead to biased results. Moreover, you should include also the data you obtained showing roughness decay under natural rain conditions; this is given by the difference between initial roughness in Experiment 1, performed in earlier August (1.17 mm) and in Experiment 2 and 3, performed in late September (0.42 mm and 0.32 mm). This clearly show roughness decay in your soil with increasing natural rainfall isn't it?.

Response:

As discussed in Comment 3 of the Material and Methods section above, the decay in the initial roughness for Experiments 2 & 3 was influenced by runoff due to the position of the experimental plot on the landscape. As noted, Experiments 2 & 3 were performed at a later time of the year than Experiment 1. However, this difference in initial roughness is not an issue since the results are presented in a dimensionless form, i.e. the random roughness ratio (RR_t/RR_0; where RR_t is the random roughness after rainfall application and RR_0 is the initial random roughness).

Comment 2: Second, I don´t understand the criteria for selecting data from previous authors. In your answers to reviver's you stated that you only provide data for one simulation in order to focus on the analysis of raindrop impact. However, most experiments quoted in Table 1 and Figure 5 includes several successive events of natural or simulated rainfall. In addition, the selected data sets correspond to very heterogeneous initial conditions, texture, organic matter content, rainfall application, etc.

Response:

We acknowledge that because of the heterogeneous conditions of the experiments cited, Figure 5, and Tables 1 and 2 may present some confusion and can appear as misleading. Therefore, Figure 5 has been removed from the manuscript, while the Tables 1-3 have been modified. Table 1 now only includes results of our study along with results from the two studies focused on smooth initial surface conditions and reported an increase in roughness. With these changes, although the experimental conditions may still differ in Table 1, they do refer to smooth surfaces and similar soils, which support the increasing trend due to rainfall. Table 2 was merged with Table 3, presenting only results of our study with respect to alternative microroughness indices. The texts accompanying the Tables have also been modified accordingly.

Comment 3: Third, I don't understand the way in which calculations of RR ratio have been performed. For example, Vazquez et al (2007, 2008) quoted several measurements of RR for a given surface and you selected only one of them, apparently the last one. Why?.

Response:

The main goal of our study is to assess the steady-state conditions of roughness in order to get comparable results for different rainfall intensities. Therefore, we calculated the RR index between initial conditions and most final conditions in each experiment. For the experiments by other investigators (Vazquez et al., 2008) that examined a succession of events, we selected the roughness after the final succession since this was deemed as more closer to steady state conditions and, thus, more comparable to our study. With regards to the Vazquez et al (2008) study, selection of the intermediate storms relative the initial roughness would still have shown an increase in roughness for two of the three experiments that were performed. Only one of the experiments was an exception. We do agree with the reviewer however that a better understanding of the role of rainfall succession is needed in subsequent experiments. To put the studies we present into context, we elaborate further on the selection of the final roughness and the measurements and trends in the other studies (Page 7, 18-25):

"Table 1 summarizes the results of this study along with results from other studies focused on smooth surfaces, documenting the RR index values before and after the rainfall events, the cumulative rainfall, as well as the associated RR ratio. The present study, along with Vázquez et al. (2008) and Zheng et al. (2014) generally report an increase in RR with rainfall under the conditions examined. The Vázquez et al. (2008) study, however, differs from the present study and Zheng et al. (2014) in that it examined roughness evolution under successive rainfall events per run. Only the RR data collected on completion of the last rainfall succession in each run are presented in Table 1. The final RR values after the last rainfall succession were selected for being the more closely comparable to the steady-state conditions examined herein."

Comment 4: Summarizing, I'm sorry, but I have no evidence showing an effect of initial RR condition on the RR ratio. The interesting apparent exception found in your work may be the result of experimental biases and may be rather the result of an "artefact".

Response:

This comment has been addressed in our responses above. We think the issue of the bias has been addressed since there are several supporting evidence that this is not an artifact.

Comment 5: On the other hand, I have positive comment regarding subsection 3.2 (pages 8 and 9). Points raised here are important to further assess RR.

Response:

Thank you. We have overall tried to highlight more these points and the interesting findings of our work, avoiding generalizations and only stating what our results would imply and the needs for further investigation.

Discussion and Conclusions

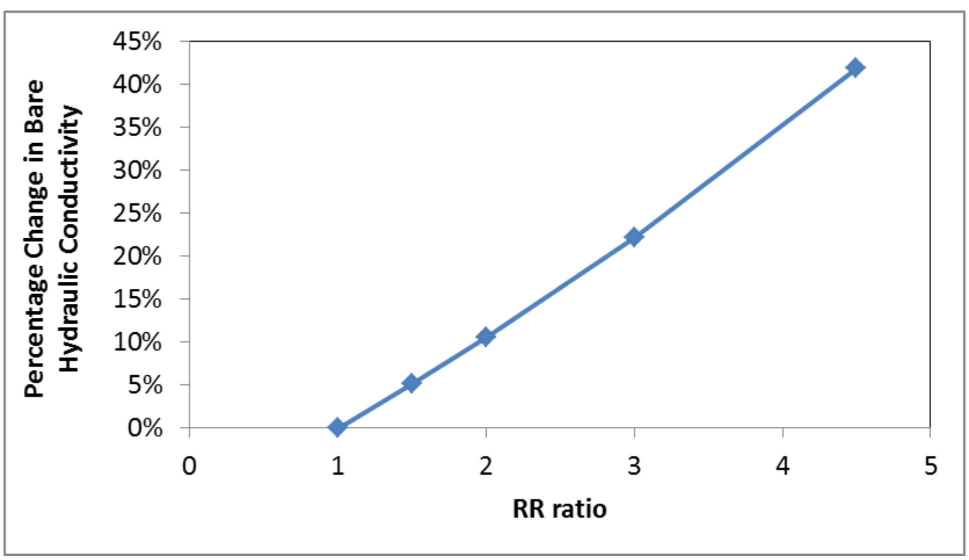
Comment: I can't review this section before the above mentioned points are addressed. However, please let me comment that the expected hydrological impact of a soil surface roughness in the order of 0.5 to 1 or 2 mm would be rather scarce. This is because of the expected digressional storage would be less than 1 mm per quadrat meter (Kamphost et al., 2000)

Response:

The impact of microroughness generation after a rainfall event can have a significant hydrological effect based on other factors besides digressional storage. As an example, we demonstrate this impact with a well-established pedotransfer function for the effects of soil crusting, roughness, and rainfall kinetic energy on the bare hydraulic conductivity, K_{br}, (Risse et al., 1995) that is employed in some overland flow models (e.g. WEPP; Flanagan *et al.*, 1995). The relationship is expressed as follows (Risse et al., 1995):

$$K_{br} = K_b\left[CF + (1 - CF)e^{-C.E_a(1-RR_t/RR_{t-max})}\right] \quad (1)$$

where K_b is the baseline hydraulic conductivity, CF is the crust factor, C is soil stability factor, Ea is the cumulative rainfall kinetic energy since the last tillage, RR_t is random roughness height, and $RR_{t\text{-}max}$ is the maximum random roughness height. Using the following typical values for our study site based on literature (Flanagan *et al.*, 1995; Chang, 2010): Ea = 10,000 J/m²; C = 0.0002 m²/J; $RR_{t\text{-}max}$ = 40 mm, we present the plot below for an initial RR_t value of 2 mm and minimal CF factor. The plot shows the percentage change in the bare hydraulic conductivity with increasing random roughness (RR) ratio. For the highest ratio observed in this study (4.5), we note that the percentage change in hydraulic conductivity can be as high as 42%. A paragraph has now been incorporated into the manuscript to present this potential impact.



Another example of where this roughness scale is important is on the mobilization of finer soil fractions and the estimation of the enrichment ratio (ER) for determining nutrient fluxes. The relationship between the change in roughness and the dislodgement/transport of finer sized fractions is poorly understood and for which a more detailed understanding is needed since the ER has been found to be particularly sensitive under the action of rainsplash (Papanicolaou et al., 2015). This factor has not been accounted for before and there is a need to build on our findings herein.

Per the comments brought up in the other sections related to generalization and overestimation of the results, the following sections have accordingly been removed from the Discussion section:

Page 11, Lines 12-13:
''~~It is further demonstrated that for low microroughness scales the relative increase in roughness increases with rainfall intensity.~~''

Page 11, Lines 15-21:
''~~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). 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).~~''

Page 12, Lines 14-15:
''~~Nonetheless, the current findings may help explain some modeling discrepancies in terms of depression storage and runoff predictions.~~''

Page 12, Lines 16-26:
''~~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 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. 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. 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).~~''

Page 12, Lines 27-32:

''~~The majority of existing models assume that RR always decays over time with rainfall. Few models consider the reverse condition where the soil surface is initially smooth as defined in the current paper and RR increases under the action of raindrop. 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. 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.~~''

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

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Abstract. This study examines the rainfall induced change in soil microroughness of a bare smooth soil surface in an agricultural field. The majority of soil microroughness studies have focused on surface roughness ~~Most studies have focused on initial surface conditions with roughness~~ on the order of ~5-50 mm and have reported a decay of soil surface roughness with rainfall. However, ~~Nonetheless,~~ there ~~are~~is quantitative ~~indications~~evidence from ~~other~~few studies suggesting ~~ing~~ that ~~S~~smooth ~~soil~~ surfaces with microroughness ~~on the order of ~2~~ less than 5 mm may undergo an increase in roughness when subject to rainfall action~~, yet these studies have focused on microroughness between ~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.~~ ~~Herein, T~~~~the~~The focus herein is on ~~the quantification of soil surface roughness due to rainfall for~~ initial microroughness length scales ~~of~~ on the order of ~~less than~~ 2 mm~~ or less~~, ~~–~~ a low roughness condition observed seasonally in some landscapes under bare conditions, and chosen to systematically examine the increasing roughness phenomenon~~where~~ ~~ich represent generic extreme conditions~~very limited literature data are available. ~~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~~ are 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~~ microroughness ~~were~~ ~~is~~are ~~obtained~~ recorded via a surface-profile laser scanner. Several indices ~~were~~ are utilized to quantify the soil surface microroughness~~ after correction for both slope and tillage marks~~, 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 an overall agreement between all indices ~~higher rainfall intensities resulting in higher relative roughness~~in terms of trend and magnitude~~ increase~~. Although this study is limited to a narrow range of rainfall and soil conditions, the results suggest that the outcome of ~~Owing~~

~~to the specificity of this study and the limited conditions examined, the results cannot be generalized over the whole range of soils and rainfall intensities, yet may imply that the dominant underlying physics of~~ the interaction between rainfall and a soil surface ~~are~~can be different for smooth and rough surfaces, ~~highlighting~~and thus warrant the need for a better understanding of ~~that~~this interaction. ~~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.~~

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) 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 outlined above, the first two classes are the so called random roughness (RR), and constitute the main focus of the present research. RR is quantified on a surface after correction for both slope and tillage marks. 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., infiltration, overland flow, ~~infiltration~~etc. ~~), by affecting the depression storage and the associated runoff and erosion processes~~ (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 most widely used statistical microrelief index for the evaluation of soil surface roughness. 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 in the individual height readings:~~

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

~~where Z_i and $\bar{Z}$ are individual elevation height readings and their mean, respectively, and n is the total number of readings.~~

Several studies have been performed to ~~Characterization of~~characterize RR ~~remains a challenge~~. Most ~~of the available studies are limited~~have focused on ~~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 microroughness 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). There are ~~several~~few studies ~~which~~that have examined surfaces with~~of~~ initial microroughness ~~on the order of ~2~~ less than 5 mm, a low roughness condition observed seasonally in some landscapes under bare conditions (e.g., Kamphorst et al., 2000; Vázquez et al., 2008; Zheng et al., 2014)~~, yet Fthere are noew existing studies, to the best of our knowledge,~~ which ~~have explicitly examined~~ ~~investigated the rainfall induced change in microroughness of soil surfaces below 2 mm.the interaction of raindrop impact with bare soil surfaces for initial microroughness scales on the order of ~2-5 mm. 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.~~ . Hereafter, for shortness, tests with initial RR less than 5 mm will be referred to as "smooth", whereas tests with initial RR greater than 5 mm will be referred to as "rough".

There are some quantitative indications that under bare smooth surface conditions~~ with microroughness between 2-5 mm~~, 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 an ~~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 an increase of the index with rainfall was observed under ~~specific~~ some conditions, and attributed to the fragmentation of aggregates and clods to smaller aggregates. Zheng et al. (2014) also 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~~However, none of the above studies ~~explicitly stated or~~ acknowledged and related the increasing trend ~~of~~ in surface microroughness to rainfall impact on smooth surfaces~~ and its potential linkage to smooth bare soil surface conditions~~.

~~We herein~~The main goal of this study is to examine changes in RR under rainfall impact for initial microroughness ~~of the order of~~less than 2 mm, since this appears to be the lower limit of roughness scales examined in the literature.

~~The main goal is to examine the postulate observed in the literature (e.g., Zheng et al., 2014) that rainfall action on surfaces with initial microrelief on the order of 2-5 mm could lead to RR increase. An increase in RR~~~~Based on the above,~~It is postulated that an increase ~~under these scales~~ in~~of~~ microroughness may occur under the action ~~as a result~~ of rainfall on pre-existing smooth surfaces~~ under the scales~~ ~~examined would~~ ~~may~~due to the nature of~~ further imply imply that~~ ~~the dominant underlying physics of~~ the interaction between rainfall and ~~a~~the soil surface~~ are different for smooth and rough surfaces~~~~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 on the order of 2-5 mm will be referred to as "smooth", whereas tests with initial RR greater than 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~~ ~~rainfall intensities.~~ To meet the ~~two specific objectives~~~~objectives~~goal, 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

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 (41.74º N, -91.94º W and an elevation of 250 m above mean sea level; Figures 1 and 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. 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. This was done to ensure a consistency in surface roughness between the experiments, as well as to ensure that any potential bias introduced in the plot preparation would be also be consistent, if not minimal. This was ~~It is acknowledged that this is not a standardized soil preparation procedure, yet special care was taken to ensure consistent, if not minimal, bias introduced to the soil parameters throughout the experiments, as~~ confirmed by the observed roughness of the experiment replicates.

Rainfall was applied to the plot using Norton Ladder Multiple Intensity Rainfall Simulators designed by the USDA-ARS National Soil Erosion Research Laboratory, IN. Figure ~~2~~ 3 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~~3a) and approximately 2.5 m atop the plot surface (Fig. ~~2b~~3b) 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. 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. 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.

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~~4a). Laser scanner measurements before the runs confirmed that the overall microrelief was less than 2 mm. 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 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 by software that regulates the travel distance based on a user-specified distance (Fig. ~~3a~~4a). 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 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~~4b). The resulting DEMs have a horizontal resolution of 1 mm and an accuracy of 0.5 mm in the vertical.

Three tests of varying rainfall intensity were conducted on the experimental plot. Rainfall intensities were respectively 30, 60 and 75 mm/h for experiments 1, 2 and 3. 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 volumetric water content was recorded via six 5TE soil moisture sensors manufactured by Decagon Devices, Inc. and placed along the plot to a depth of 10 mm. The initial volumetric water content was found to be similar for each experiment and approximately equal to 35% at the 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 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. Although the average saturated hydraulic conductivity values were low with respect to the applied rainfall rates, minimal ponding was observed on the experimental plot, owing to the smooth bare conditions ~~associated with the flattening of the soil surface~~ and the high ~~slope~~plot gradient of 9%, which led to low ~~soil surface roughness and~~ depressional storage.

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 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 runoff from upslope areas on the plots arising from natural rainfall within that period (Papanicolaou et al., 2015b)~~the soil presented less surface disturbance due to the cumulative action of rainfall runoff from natural rainfall within that period, since the experimental plot is located at a high energy environment where the effect of runoff can be significant (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~~, where runoff had negated a great part of disturbance due to tillage~~. This, however, is not an issue since all the results are presented herein in a dimensionless form (see Section 2.2 below on the index ratios). All cases, ~~however~~nonetheless, 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 g/cm^3 for Experiment 1, and about 6% higher for Experiments 2 and 3 due to self-weigh consolidation of soil.

Figure ~~4a~~ 5a 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 in Fig. ~~4b~~5b. ~~No r~~Rill formation ~~ever took place~~was not observed in these regions throughout the experiments. Visual observations confirmed that raindrop detachment was dominant~~, and the presence of micro rills was minimal, ensuring that~~ and the main driver of the change in soil surface roughness~~ was the raindrop impact~~. 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 software (https://www.r-project.org/). The geostatistics ('gstat') and spatial analysis ('sp') libraries were imported to create sample semivariograms.

2.2 Soil Surface Roughness Quantification

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. 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 in the individual height readings:

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

where Z_i and $\bar{Z}$ are individual elevation height readings and their mean, respectively, and n is the total number of readings. The RR index calculated from Eq. (1) ~~was used in this study as~~is 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. The RR index, however, requires that there is no spatial correlation between the surface elevations (Huang and Bradford, 1992). Hence, special care must be taken in adopting the RR index. If correlation exists within a certain spatial scale, the RR index 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. 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 (Huang and Bradford, 1992; Vermang et al., 2013), and two-dimensional Fourier Transform (Cheng et al., 2012), among others. We herein employ additional indices derived from the first-order variogram and the semivariogram as alternatives to the RR index, which is also utilized accounting for its limitations. These include the crossover length, the Markov-Gaussian variance length scale, and the limiting difference.

The crossover length derived from semivariogram analysis is an index that is commonly used in most recent soil microrelief studies to describe surface microroughness. 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 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 after correction for both slope and tillage marks 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 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. 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 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.

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:

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

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 with elevation data corrected for both slope and tillage marks (Linden and van Doren, 1986; Paz-Ferreiro et al., 2008), which is written in the form:

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

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

$$1/\Delta Z(h) = a + b/h, \tag{6}$$

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~~ that existed in the initial microrelief amongst the three runs due to the different timing of the experiments (see Section 2.1), 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.

3. Results

3.1 Changes in the RR index

Based on visual inspection of the DEMs in Fig. ~~4b~~5b, it is evident that microroughness ~~at the upslope regions~~in the splash-dominated region increases with rainfall. ~~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. For 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 1 summarizes the results of this study along with results from ~~the selected~~ other studies focused on smooth surfaces~~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, o~~The present~~ur~~ study, along with Vázquez et al. (2008) and Zheng et al. (2014)~~, which were performed for the smooth surface initial condition,~~ generally report an increase in RR with rainfall ~~in general~~under the conditions examined. The Vázquez et al. (2008) study, however, differs from the present study and Zheng et al. (2014) in that it examined roughness evolution under successive rainfall events per run. ~~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 shows decaying roughness due to rainfall because of different soil type and rainfall conditions.~~ Note that ~~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) performed successive rainfall simulations and recorded the values of roughness for each succession;~~ Only the RR data collected on completion of the last rainfall succession in each run conducted by Vázquez et al. (2008) are presented in Table 1. ~~in the present study the last succession~~ The final RR values after the last rainfall succession were selected for ~~the calculation of the final state of RR,~~ being the more closely comparable to the steady-state conditions examined herein. Although both Vázquez et al. (2008) ~~–~~and Zheng et al. (2014) recorded an increase in RR with rainfall, they ~~but~~ had significantly lower values of RR ratio than ~~we did~~the present study. This ~~may be attributed~~could be due to ~~the~~ several factors including, but not limited to, ~~that they either applied~~ lower applied rainfall intensity and amount, ~~or~~ the initial surface microroughness, and different soil conditions ~~in their study were higher~~ ~~different~~.

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 (i.e., the upper value where the semi-variance levels out), in order to quantify roughness, and observed ~~its~~ an 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. Overall, ~~it can be seen~~the experimental evidence suggests that the interaction between rainfall and smooth soil surfaces can lead to an increase in microroughness.

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~~. This condition was indeed not violated due to the choice in ROI. ~~.~~ The following subsection outlines and discusses the results of the semivariogram analysis and additional indices ~~in order to~~used to confirm the validity of ~~this~~ the assumption and their ~~compare~~ comparison with the RR index method.

3.2 Changes in alternative roughness indices

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 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 was determined in taking any direction to calculate the semivariograms and the associated crossover lengths.

The semivariograms calculated at the ROI were chosen to be in the downslope direction at an angle of 0° and are presented for each experiment in Fig. ~~6~~56. 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 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~~56). ~~-~~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.

Fig. ~~6~~ 56 shows that the post-rainfall sills are greater than their corresponding pre-rainfall values. 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 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 1). 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 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. The final roughness state of the bed surface after the application of rainfall (for the studies considered herein), tends to have a crossover length in the range of 0.2-4 mm. It is seen that the existing studies with initial disturbed surface conditions report a decrease in the crossover length after rainfall, contrary to 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). 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 (60 and 75 mm/h) than at the low precipitation intensity case (30 mm/h).~~

Table ~~3~~ 2 lists the crossover length, 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~~2) 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~~ smooth soil surfaces~~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 under the conditions examined herein. ~~, although this trend cannot be considered significant because of the low availability of data.~~

4. Discussion and Conclusions

Many studies have examined the response of rough surfaces to rainfall, and have reported a decay of roughness. Few studies have ~~been developed to~~ assessed microscale variation of smooth surfaces in response to rainfall under controlled conditions ~~to purposely examine increase in RR with rainfall intensity~~. ~~Unique~~ The experiments ~~are~~ presented herein ~~that~~ were designed to help us decipher the role of rainsplash on ~~increasing~~ RR for smooth surfaces with initial microroughness ~~below~~on the order of 2 mm by isolating the role of other ~~processes~~ factors such as runoff, variable water content, bare soil surface, and soil texture, among others~~etc~~. Our results show a consistent increase in roughness under the action of rainfall, with an overall agreement between all the roughness indices examined herein in terms of trend and magnitude. Our findings are consistent with findings of other studies that have examined length scales ~~up to~~less than 5 mm and ~~suggest~~ ~~may~~ suggest the possible existence of a characteristic roughness ~~scale~~ threshold ~~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. The value of this threshold ~~However, due the limited conditions examined, such threshold may not always exist and, in case it does, its value~~ may depend on the specific soil and rainfall conditions. A caveat of our study is that due to the limited range of conditions examined herein more experiments are needed to further solidify the conditions under which RR is expected to increase under rainfall action. ~~It is further demonstrated that for low microroughness scales the relative increase in roughness increases with rainfall intensity. Another significant~~An outcome of this study is the ~~fact that the mere action of rainfall cannot completely smoothen out a bed soil surface, thereby localized microroughness residuals will always remain at the locations where the action of runoff is low or absent. 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). 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). W~~ awareness that within ~~these~~ landscape regions~~s~~ where smooth surfaces are present, ~~the reported~~an increase in RR ~~is expected~~may ~~to~~ occur during the early part of the storm where rainsplash action ~~may be~~ is 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 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).~~

~~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, r~~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). Finally, the role of successive storm events on changing roughness for smooth surfaces is not covered in this study and needs to be examined.~~

~~Our findings provide a better understanding of the highly dynamic phenomenon of soil surface microroughness evolution under the impact of rainfall. T~~This study suggests that the ~~dominant underlying physics of~~effects of the interaction between rainfall and a soil surface ~~are~~can be different for smooth and rough surfaces, and highlights the need for a better understanding of ~~that~~the interaction due to its potential impact on hydrologic response. This potential impact is demonstrated with the following established pedotransfer function for the effects of soil crusting, roughness, and rainfall kinetic energy on the bare hydraulic conductivity, K_{br}, (Risse et al., 1995):

$$K_{br} = K_b\left[CF + (1 - CF)e^{-C.E_a(1-RR_t/RR_{t-max})}\right] \qquad (7)$$

where K_b is the baseline hydraulic conductivity, CF is the crust factor, C is soil stability factor, E_a is the cumulative rainfall kinetic energy since the last tillage, RR_t is random roughness height, and RR_{t-max} is the maximum random roughness height. Using the following typical values for the study site based on literature (Flanagan *et al.*, 1995; Chang, 2010): E_a = 10,000 J/m², C = 0.0002 m²/J, RR_{t-max} = 40 mm, the percentage change in bare hydraulic conductivity for increasing roughness can be estimated for an initial RR_t value of 2 mm and minimal CF factor. Performing the analysis for the range of random roughness ratios observed in this study (~1.3 – 4.5), the percentage increase in hydraulic conductivity is found to range between 5% –42%, which will have a significant impact on rainfall-runoff partitioning.

It is recognized that the soil preparation method in our study could have introduced some bias to the soil properties such as aggregate size distribution, compaction, and aggregate stability. Nonetheless, for the purpose this study was designed for, this preparation method ensured consistency in the initial and final roughness states, as confirmed by replications of our experimental runs. It is also recognized that drier, silty type soils may not exhibit the increase in RR shown here. Further, 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). Finally, the role of successive storm events on changing roughness for smooth surfaces is not covered in this study and needs to be examined.

The exact mechanisms leading to increase in roughness remain unknown and are not the focus of this study. However, changes in roughness during a storm event have been 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). 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). Future research should explore these mechanisms.

~~motivates further research on the extent of influence of the examined phenomenon and its~~and potential implementation in ~~mathematical formulation~~s ~~for modeling applications. For instance, current modeling tools of soil surface processes may predict a total decay of soil surface roughness after subsequent rainfall events (e.g., Potter, 1990) which may not~~ always ~~be the case. 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 although one would expect it to be minimal, more research is needed to quantify it under different conditions,~~

~~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.~~

~~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 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. 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. 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 majority of existing models assume that RR always decays over time with rainfall. Few models consider the reverse condition where the soil surface is initially smooth as defined in the current paper and RR increases under the action of raindrop. 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. 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.~~

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.

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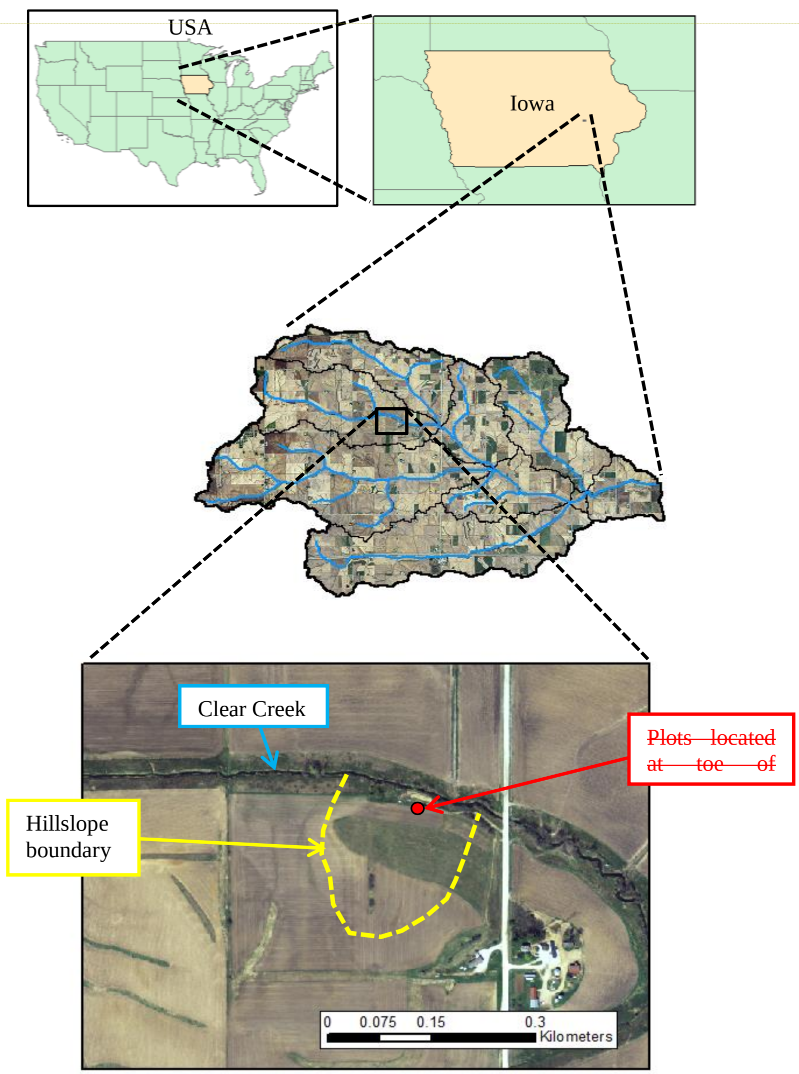

Figure 1:Location of experimental plot in the headwaters of Clear Creek, IA(41.74º N, -91.94º W)

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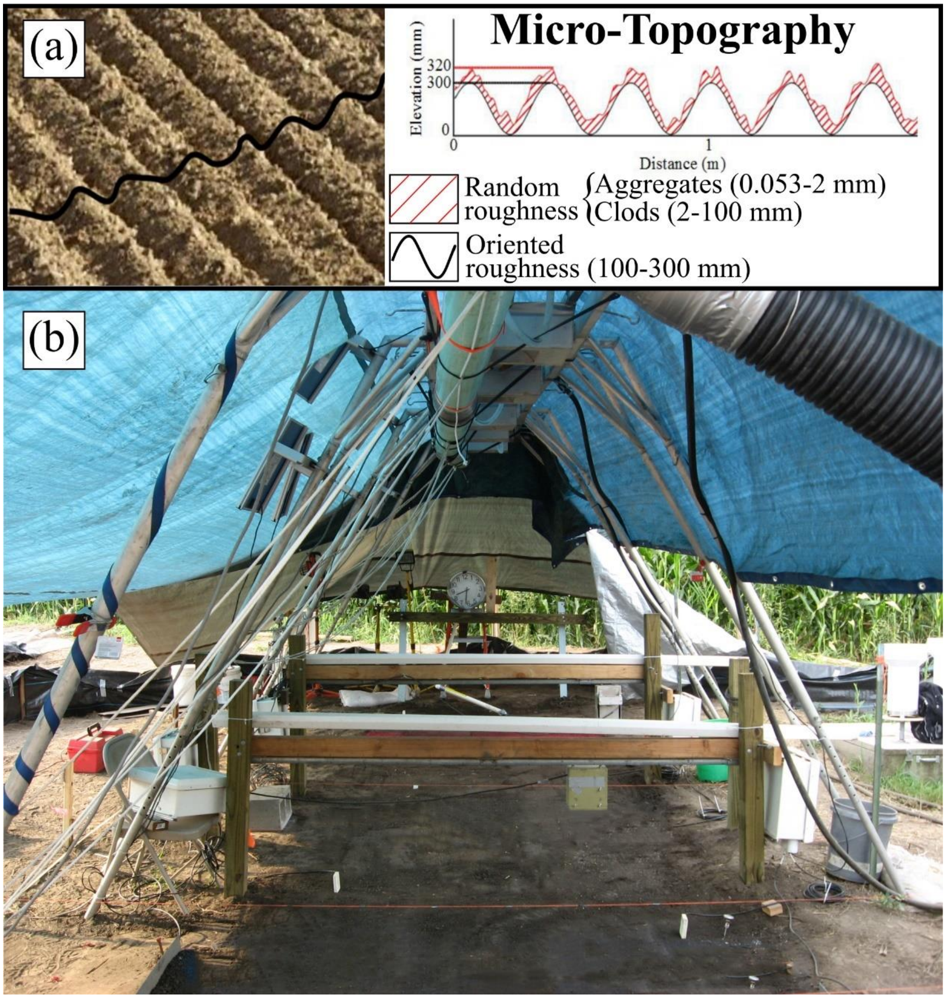

Figure ~~1~~2: (a) Types of soil surface microroughness. (b) Experimental plot. The rainfall simulator is placed above the bare soil surface and a base made of wood is put into place to facilitate the movement of the surface-profile laser scanner.

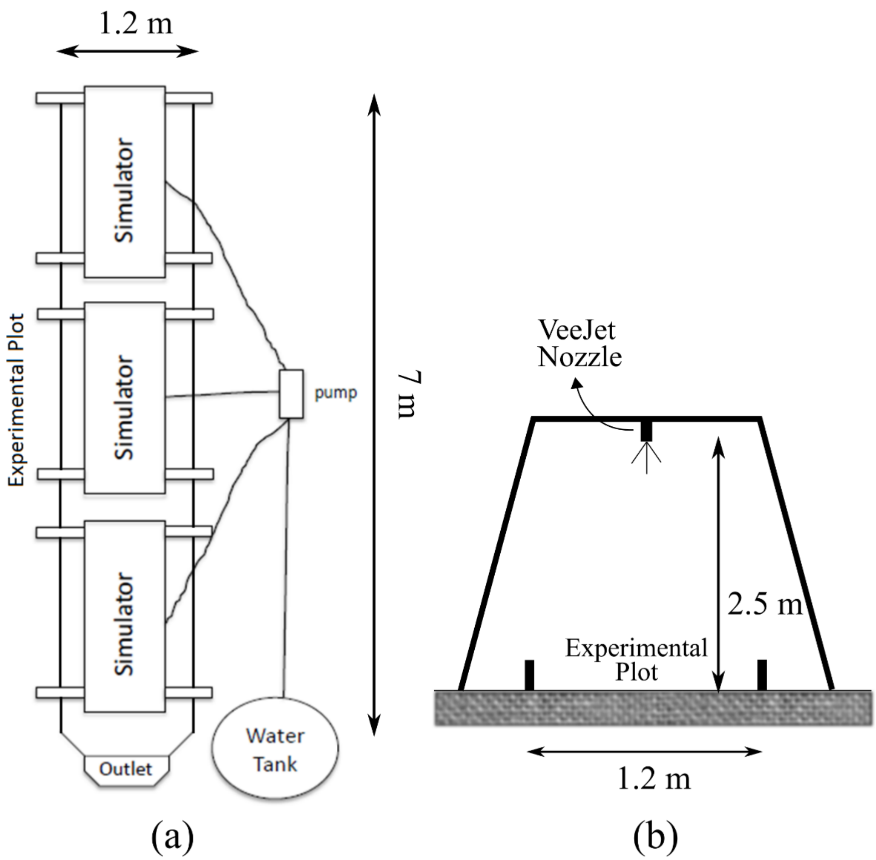

Figure ~~2~~3: Setup of the experimental tests: (a) Rainfall simulators are mounted in series and a pump provides them with water from a tank. (b) Rainfall simulators are placed and adjusted at a height of 2.5 m above the experimental plot surface to ensure drop terminal velocity is reached.

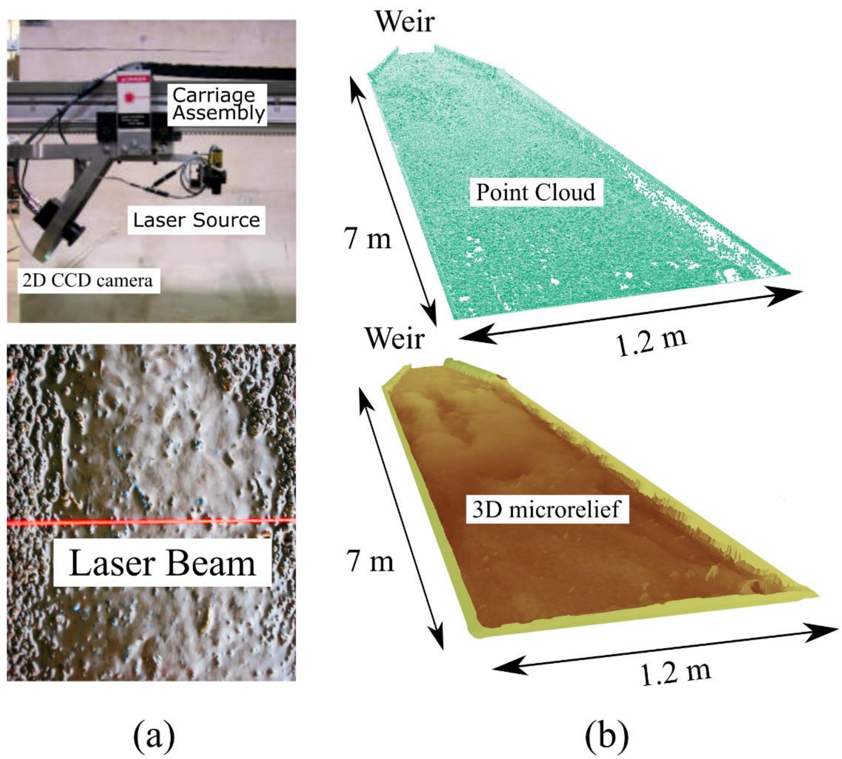

Figure ~~3~~4: (a) Instantaneous digital surface-profile laser scanner used in the experimental runs and laser beam projected on the soil surface. (b) Cloud of (x,y,z) data acquired from the laser scanner for an experimental test along with the associated 3D representation of the soil surface microrelief through inverse distance weighted interpolation .

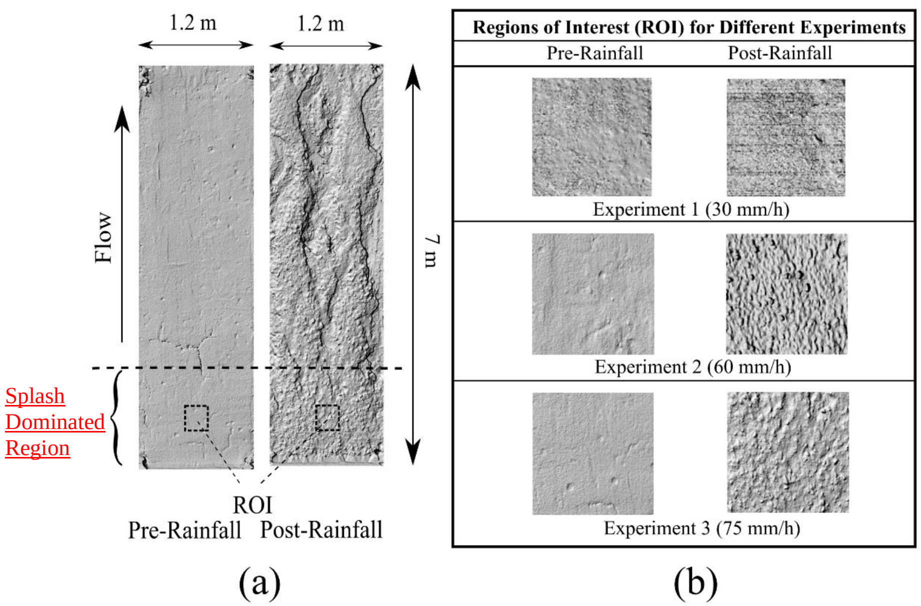

Figure 45: (a) Experimental plot under pre- and post-rainfall conditions for an experimental test. The dashed boxes indicate the extent of the Region of Interest (ROI), where raindrop detachment is dominant over runoff. (b) Scanned profiles extracted from the laser-scanned areas of the three experimental tests considered, under both pre- and post-rainfall conditions.

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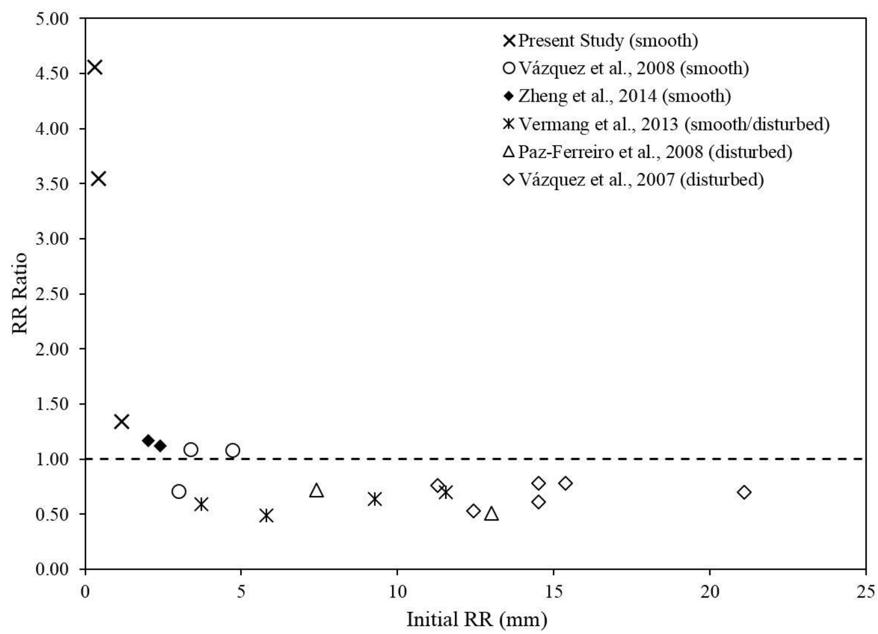

~~**Figure 5: Random Roughness (RR) Ratio versus initial RR for this study and other selected studies.**~~

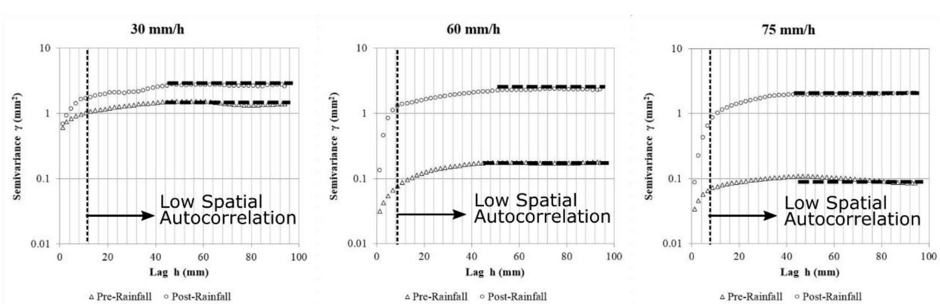

Figure ~~6~~56: Semivariograms at the region of interest for the three experimental tests, under pre- and post-rainfall conditions. Horizontal dashed lines indicate the semivariogram sills and vertical dashed lines indicate the lag distance above which the spatial autocorrelation of the elevations is negligible.

Table 1: Summary of the rainfall induced change 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~~ less than 5 mm ~~and disturbed conditions refer to initial microroughness greater than 5 mm~~. Cumulative rainfall amounts are also provided.

Rainfall Intensity (mm/h)	Cumulative Rainfall (mm)	Soil Type	Pre-rainfall RR (mm)	Post-rainfall RR (mm)	RR Ratio
			Present study		
30	150	silty clay loam	1.17	1.57	1.34
60	300	silty clay loam	0.42	1.48	3.55
75	375	silty clay loam	0.32	1.46	4.56
			*Vázquez et al., 2008**		
30	85	silt loam	3.39	3.70	1.09
30	50	silt loam	3.00	2.13	0.71
65	195	silt loam	4.72	5.10	1.08
			Zheng et al., 2014		
40	~60	silty clay loam	2.01	2.35	1.17
90	~135	silty clay loam	2.40	2.68	1.12

* The Vázquez et al. (2008) study looked at RR evolution under successive rainfall events, unlike the other two studies. Post-rainfall RR data presented for Vázquez et al. (2008) are those that were determined on completion of the last rainfall succession in each experiment.

Table 2: Summary of the rainfall induced change in the crossover length, the Markov-Gaussian variance length scale and limiting difference indices for the experimental tests of this study.~~Summary of the rainfall induced change 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.~~

Rainfall Intensity (mm/h)	Cumulative Rainfall (mm)	Pre-rainfall value	Post-rainfall value	Index Ratio
			l (mm)	
30	150	0.71	0.73	1.03
60	300	0.09	0.20	2.13
75	375	0.15	0.39	2.56
			σ (mm)	
30	150	1.19	1.63	1.37
60	300	0.42	1.52	3.62
75	375	0.31	1.43	4.56
			LD (mm)	
30	150	0.79	0.87	1.10
60	300	0.26	0.87	3.39
75	375	0.15	0.71	4.84

~~**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~~