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Impact of Antecedent Soil Moisture on Interrill Erosion

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Abstract: The impact of antecedent soil moisture content on soil erosion is a complicated phenomenon, which is still under argument with contradictions in research results. Hence, the objective of this study is to investigate the impact of antecedent soil moisture content to soil loss on clay soil by conducting two-year field experiments under natural rainfall on runoff plots with length of 10 meters, width of 3 meters, and uniform slope of 9%. Volumetric soil moisture sensors were used to log soil moisture changes, and soil moisture readings were used along with rainfall records to quantify the antecedent soil moisture conditions for each rainfall event. Results of this study show duration of the effective erosion event outranks the antecedent volumetric soil moisture content. Field study also suggests that accumulative rain falling within 48 hours (Pp_{48}) prior to an effective erosion event strongly correlated with soil loss per Rainfall-Runoff Erosivity Index (Soil Loss / EI_{30}), particularly when the duration of an effective erosion event is either between 3 ~ 7 hours or 10~ 30 hours. Hence, Pp_{48} can be considered as an alternative to replace antecedent soil moisture content in RUSLE 2's cover and management factor.

Keywords: interrill erosion; soil loss; antecedent soil moisture content; rainfall characteristics

1. Introduction

Soil erosion is one of the natural processes that shapes the landscape by the action of water and wind. It causes environment impacts such as (1). non-point source pollution resulted from soil loss carrying pollutants down the slopes, (2). reduction of soil fertility that affects crop yield, and (3). sedimentation in rivers and water bodies. [1–5] Quantification of soil loss has always been attracting researchers' attention, and the technology of soil loss estimation has changed from parametrized estimation like USLE [6,7] and Revised Universal Soil Loss Equation (RUSLE) [8] to processes-based simulations, for instance CREAMS [9], AgNPS [10], WEPP [11,12], SWAT [13]. Regardless the simplicity or complexity of models, soil loss estimation is still built upon the existing understanding of soil erosion processes.

Soil erodibility [5,14] defines the vulnerability of the soil when subjected to erosion. Physical and chemical properties of the soil were determined during soil formation through weathering processes [15]. On the other hand, soil improvement as well as human intervein; namely land grading, cover and crop management, and soil conservation, can alter soil erodibility. Putting into Universal Soil Loss Equation (USLE) terminology, these intervein are known as slope length factor (L), slope steepness factor (S), cover and management factor (C), and conservation factor (P), respectively, among which C factor is probably the most complicated parameter among all.

C factor has gone through development and revision for almost half a century. It has advanced from the original concept of USLE; namely C = Cc x Cs that considers the contributions from vegetation canopy and surface mulch, to RSUEL Version 2 (USDA-ARS, 2013); namely C = Cc x gc x Sr x rh x Sb x Sc x Pp x am that considers the effects from canopy and ground cover subfactor, random

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and artificial surface roughness subfactors, soil biomass subfactor, soil consolidation, ponding, and antecedent soil moisture subfactors.

Soil moisture content changes soil physical properties such as shear strength and aggregate stability, thereby alters the resistance to erosion [16,17]. A positive correlation has been found between soil moisture content and surface runoff [18–21]. Fortesa et al. (2020) [22] analyzed 5-year soil moisture and flow data at the catchment scale and found that 76% of flood events occurred in wet soil conditions. Massari et al. (2023) [23] analyzed data from Global Runoff Data Center (GRDC) as well as that from European Space Agency's Climate Change Initiative (CCI) and found that antecedent precipitation, soil moisture at surface and root zone, pre-storm river discharge, and pre-storm total water storage anomalies would affect the scale of flood events significantly.

Jadidoleslam et al. (2019) [24] applied Soil Moisture Active Passive (SMAP) to estimate surface soil layer's water contents from 38 watersheds (area ranges from 80 to 1,000 km^2) and to correlate soil water content with runoff coefficients. They found that runoff coefficients increased with the increase in antecedent soil moisture contents. In addition, runoff coefficient changed significantly under humid conditions. Schoener et al. (2019) [25] observed surface runoff from watersheds at different scales (2.8 m^2 and 2.8 km^2). The results showed a positive correlation between antecedent soil moisture content and runoff coefficient regardless the scales of the watershed. They also noted that antecedent soil moisture content had an influence on surface runoff during small rainfall events but produced less impact during heavy rainfall events.

While positive correlation between antecedent soil moisture and soil erosion or runoff generation has been reported [26,27], there are studies suggest otherwise. For instance, Castillo et al. (2003) [28] conducted study in eastern Spain using Time Domain Reflectometry (TDR) in three semi-arid small watersheds with different characteristics of vegetation to study the correlation between antecedent soil moisture and surface runoff. They found that the impact of antecedent soil moisture depended on rainfall intensity and soil permeability. In the case of high rainfall intensity or low soil permeability, surface runoff was not depended on the antecedent soil moisture content; whereas on the highly permeable soil, if a low-intensity rainfall event occurred, surface runoff was easily controlled by the moisture content of the surface soil and the influence of moisture content was relatively high.

Truman and Bradford (1990) [29] conducted a series experiments using rainfall simulator to test the splash erosion rates on air-dried and prewetted soils, and the result indicated that raise of soil moisture reduces the splash erosion rate, which might be related to promotion of soil sealing and aggregation stability [18,30]. Auerswald (1993) [31] indicated that increasing soil moisture from 10% to 30% reduced soil loss by 80% and suggested that soil moisture can decrease soil slaking. Ma et al. (2014) [32] found that transition of splash erosion rate in increasing soil moisture will decrease initially and then increase at the threshold moisture value of 15%.

Based on the contradictions in research results on the impact of antecedent soil moisture content to soil erosion, hence, the objectives of this study are (1). to investigate the correlation between antecedent soil moisture and soil loss and (2). to explore the feasibility of using rainfall parameters as alternatives to quantify the impact of antecedent soil moisture to interrill erosion.

2. Materials and Methods

2.1. Experiment Site and Preparation

The experiment site is in tropical climate zone at 120° 36′ 23″ N and 22° 38′ 41″ E. The average annual rainfall is about 2,022 mm [33]. Rain season usually begins in early May and lasts until late September. Soil at the experiment site consists of 18.84 % sand, 31.73 % silt, and 49.71 % clay and is classified as clay according to the United States Department of Agriculture (USDA) soil texture classification. The average organic matter content is 1.65 %.

Soil at the experiment site was first disked at least three times, residue including roots and ground vegetation were manually removed. Total of three runoff plots were prepared, and all runoff plots were remained bare throughout the rain season. Based on the past experiences rills seldom

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occur onsite when slope length is shorter than 10 m, therefore, each runoff plot was setup with 10 m in length and 3 m in width, and plot surface was leveled to the desired gradient of 9%.

The field study started in early 2019 and ended in late 2020, which covered two consecutive rain seasons. Due to plot availability, only one runoff plot was used in 2020, hence three runoff plots used in 2019 were considered as three replications. Disking was performed at the end of rain season to break any surface crust, and soil was randomly exchanged and mixed between plots prior to levelling.

A volumetric soil moisture sensor EC-5 was installed 10 cm below the ground surface at the mid-length of each runoff plot to monitor soil moisture contents. Volumetric soil moisture contents were automatically logged every 5 minutes throughout the entire study period.

2.2. Data Collection and Analysis

2.2.1. Rainfall

A 0.5-mm tipping-bucket rain gauge attached to a data logger was used to log the rainfall records and the records were used to extract rainfall characteristic including total precipitation (P, mm), maximum 30-minute rain intensity ($I_{30}max$, mm/h), event duration (Duration, h), time interval between two adjacent effective erosion events (TILR, h) (Figure 1), total precipitation within the past x hours prior to an effective erosion event (Ppx, mm).

Effective erosion events were delineated from rainfall records, and the effective erosion event refers to the definition given by Wischmeier and Smith (1978) [6]. When (1) the accumulated rainfall of an event exceeds 12.7 mm or more than 6.35-mm rain falls within 15 minutes and (2) the time interval between current and preceding events exceeds 6 hours, then the current event is considered as an effective erosion event. The begin time (T_b) and the end time (T_e) of an effective erosion event were used to extract the TILR and Duration.

TILR reflects the opportunity for soil to expose to natural drying process. Longer the TILR is, lower the antecedent soil moisture becomes. During the process of extracting TILR, some rain events that do not meet the criteria of effective erosion event may be inherently included. We choose to ignore these ineffective events by assuming that these events have no impact on antecedent soil moisture.

Duration is the length of time (in hours) that an effective erosion event lasts, which is the time span between T_b and T_e (Figure 1). Natural rainfall records may include rain-free intervals, and these intervals vary in length. Therefore, effective erosion event with longer Duration may include higher proportion of rain-free periods; conversely, shorter Duration events typically have less chance or lower proportion of rain-free periods.

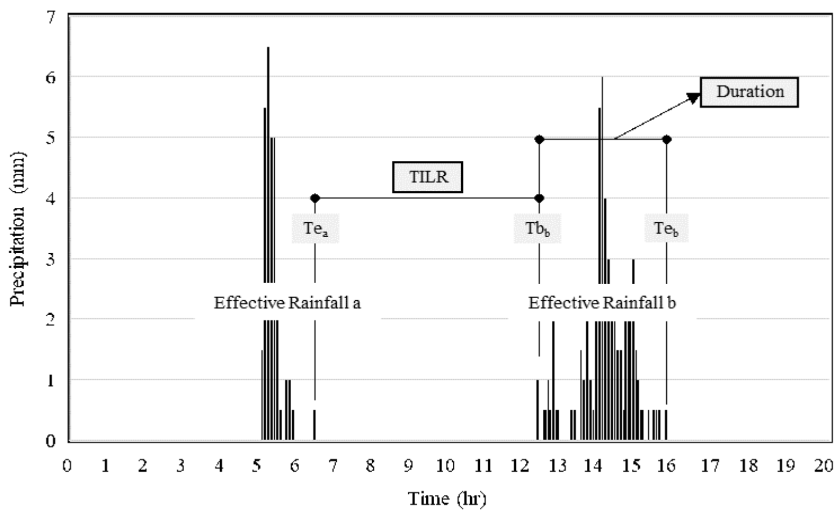

Figure 1. Delineation of effective erosion events, TILR, and Duration.

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Ppx represents the accumulated rainfall (in mm) within x hours prior to the beginning of an effective erosion event. Estimation of Ppx involves tracing backward in time from Tb by a specific "x hours" time range and summing up the rainfall amounts within, as illustrated in Figure 2. Five different time ranges; namely 12, 24, 48, 72, and 120 hours, were used in this study. Ppx reflects the amount of rain that soil receives before the occurrence of the rainfall event. If the "x hours" were chosen too short, it may overlook influential antecedent rainfall. Conversely, if it were chosen too long, it may include non-influential antecedent rainfall. Lastly, Rainfall-Runoff Erosivity Index (EI_{30}) was calculated based on the USLE definition proposed by Wischmeier and Smith (1978) [6].

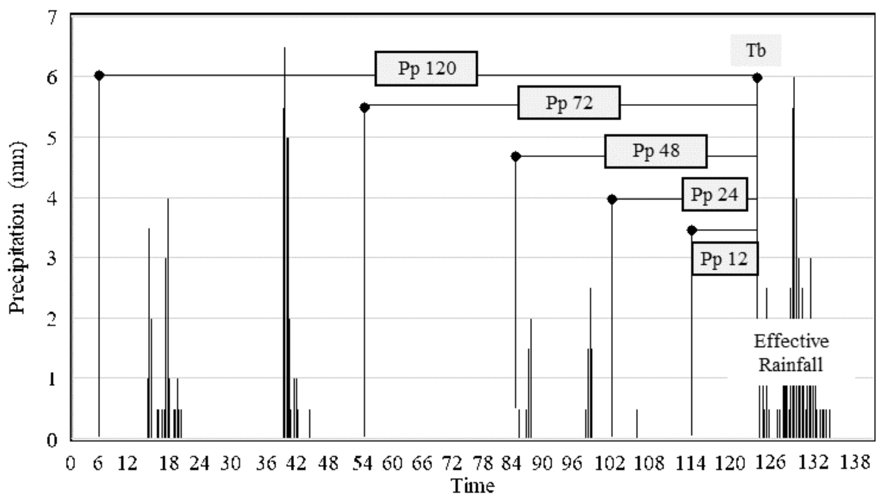

Figure 2. Determination of Ppx with different x-hr time range.

2.2.2. Runoff and Soil Loss

A collection tank was installed downstream of the runoff plot to collect surface runoff and soil loss. To accommodate large runoff volume exceeding the tank design volume, two partition walls were arranged inside the collection tank, which resulted a tank with three separate pools. A six-triangular-weir blade was installed on the rim of each partition wall. Excess runoff overflowing from five weirs were discarded and that from the remaining one overflew to the next pool. The rim of the second pool was also equipped with the same weir blade. Therefore, whenever runoff accumulated in the second and third pools, the runoff volume in the second pool was multiplied by 6 and runoff volume in the third pool was multiplied by 36, and then added to the runoff volume collected in the first pool, finally yielded the total runoff volume of the event.

Soil loss from a runoff plot was detained in the first pool except the suspended load. Runoff and soil loss collection was carried out by storm basis. Grab samples of detained sediment were taken from the first pool. Grab samples of suspended load were also taken from each pool. They were oven dried, back calculated using grab sample and detained sediment volume ratios then added together to get the total soil loss.

2.2.3. Antecedent Soil Moisture Content

To eliminate the effect of soil texture differences between runoff plots, volumetric soil moisture data were first normalized as follows:

$$NVSMC_i = \frac{VSMC_i - VSMC_{min}}{VSMC_{max} - VSMC_{min}} \quad (1)$$

where, $NVSMC_i$ = the normalized volumetric soil moisture content at time T_i, $VSMC_i$ = the volumetric soil moisture content at time T_i, $VSMC_{min}$ and $VSMC_{max}$ is the minimum and maximum volumetric soil moisture content detected during the rainy season, respectively.

T_i is the key point for analyzing the normalized antecedent volumetric soil moisture content (NAVSMC), and it must accurately represent the time right before the start of a rain event. It is

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slightly earlier than the beginning of the rain event (T_b). In this study, T_i is set approximately 5 to 10 minutes prior to the T_b.

3. Results and Discussion

Table 1 is the summary of the experiment results collected from 2019 to 2020, in which Precp. is the total precipitation of an effective erosion event, EI_{30} is the Rainfall-Runoff Erosivity Index, C is the runoff coefficient, NAVSMC is the normalized antecedent volumetric soil moisture content, Ppi is the accumulated rainfall within i hours (i = 1, 24, 48,72 and 120) prior to the beginning of an effective erosion event, and TILR is the time interval between two adjacent effective erosion events. Unit area soil loss (kg/m^2) and unit area runoff volume (mm) is the total soil loss and total runoff volume collected from an effective erosion event divided by the runoff plot area, respectively.

Table 1. Summary of field experiment results.

Event No.	Unit area soil loss	Unit area runoff volume	Precp.	EI_{30}	Soil loss / EI_{30}	C	NAVSMC	Pp12	Pp24	Pp48	Pp72	Pp120	Event Duration	TILR
	kg/m^2	mm	mm	MJ-mm / ha-h	(kg/m2) / (MJ-mm/ ha-h)	-	m^3/m^3	mm	mm	mm	mm	mm	h	h
1	0.080	9.60	34.0	391.75	0.020	0.28	0.15	0.0	9.0	9.0	9.0	9.5	3.17	213.00
2	0.214	9.20	34.0	391.75	0.055	0.27	0.20	0.0	9.0	9.0	9.0	9.5	3.17	213.00
3	0.313	17.02	34.0	391.75	0.080	0.50	0.51	0.0	9.0	9.0	9.0	9.5	3.17	213.00
4	0.177	19.58	39.0	451.04	0.039	0.50	0.13	0.0	0.0	0.0	34.0	43.0	3.33	68.83
5	0.346	19.43	39.0	451.04	0.077	0.50	0.18	0.0	0.0	0.0	34.0	43.0	3.33	68.83
6	0.440	18.72	39.0	451.04	0.098	0.48	0.47	0.0	0.0	0.0	34.0	43.0	3.33	68.83
7	0.972	61.85	87.5	2951.65	0.033	0.71	0.18	0.0	39.0	39.0	39.0	82.0	2.42	20.25
8	2.109	39.19	87.5	2951.65	0.071	0.45	0.22	0.0	39.0	39.0	39.0	82.0	2.42	20.25
9	0.890	77.77	87.5	2951.65	0.030	0.89	0.53	0.0	39.0	39.0	39.0	82.0	2.42	20.25
10	0.178	19.40	23.0	117.47	0.151	0.84	0.27	0.5	3.5	16.0	21.5	114.0	10.83	104.00
11	0.230	16.90	23.0	117.47	0.196	0.73	0.34	0.5	3.5	16.0	21.5	114.0	10.83	104.00
12	1.335	91.31	117.5	1731.80	0.077	0.78	0.28	0.5	3.5	16.0	21.5	114.0	61.33	11.08
13	0.679	21.39	117.5	1731.80	0.039	0.18	0.34	0.5	3.5	16.0	21.5	114.0	61.33	11.08
14	1.166	48.37	117.5	1731.80	0.067	0.41	0.56	0.5	3.5	16.0	21.5	114.0	61.33	11.08
15	2.969	93.65	402.5	7811.82	0.038	0.23	0.29	0.5	2.0	94.5	117.5	144.0	91.50	10.50
16	2.511	53.17	402.5	7811.82	0.032	0.13	0.25	0.5	2.0	94.5	117.5	144.0	91.50	10.50
17	1.689	106.28	197.5	2476.39	0.068	0.54	0.24	0.0	0.0	3.0	3.0	25.0	28.00	133.58
18	1.666	45.95	197.5	2476.39	0.067	0.23	0.38	0.0	0.0	3.0	3.0	25.0	28.00	133.58
19	1.944	114.89	197.5	2476.39	0.078	0.58	0.47	0.0	0.0	3.0	3.0	25.0	28.00	133.58
20	0.256	32.20	41.5	374.80	0.068	0.78	0.20	0.0	0.0	0.0	0.0	176.5	4.33	97.08
21	0.205	20.68	41.5	374.80	0.055	0.50	0.36	0.0	0.0	0.0	0.0	176.5	4.33	97.08
22	0.172	24.73	41.5	374.80	0.046	0.60	0.44	0.0	0.0	0.0	0.0	176.5	4.33	97.08
23	0.320	48.77	54.0	1070.56	0.030	0.90	0.28	0.0	0.0	0.0	0.0	0.0	13.08	121.42
24	0.269	21.05	54.0	1070.56	0.025	0.39	0.45	0.0	0.0	0.0	0.0	0.0	13.08	121.42
25	0.414	52.16	54.0	1070.56	0.039	0.97	0.50	0.0	0.0	0.0	0.0	0.0	13.08	121.42
26	0.041	8.55	11.5	23.52	0.176	0.74	0.26	0.0	0.5	54.0	54.0	54.0	5.75	18.67
27	0.044	3.97	11.5	23.52	0.189	0.35	0.43	0.0	0.5	54.0	54.0	54.0	5.75	18.67
28	0.042	8.74	11.5	23.52	0.180	0.76	0.49	0.0	0.5	54.0	54.0	54.0	5.75	18.67
29	0.051	15.28	19.5	59.37	0.085	0.78	0.27	0.0	0.0	0.0	11.0	65.0	1.67	54.50
30	0.104	12.95	19.5	59.37	0.175	0.66	0.42	0.0	0.0	0.0	11.0	65.0	1.67	54.50
31	0.105	16.30	19.5	59.37	0.178	0.84	0.49	0.0	0.0	0.0	11.0	65.0	1.67	54.50
32	0.279	39.50	54.5	578.57	0.048	0.72	0.11	0.0	0.0	0.0	0.0	0.0	3.50	167.00
33	0.228	23.92	54.5	578.57	0.039	0.44	0.31	0.0	0.0	0.0	0.0	0.0	3.50	167.00
34	0.195	35.72	54.5	578.57	0.034	0.66	0.41	0.0	0.0	0.0	0.0	0.0	3.50	167.00
35	0.108	14.31	29.0	361.82	0.030	0.49	0.02	0.0	0.0	0.0	0.0	0.0	1.42	307.33
36	0.208	14.95	29.0	361.82	0.058	0.52	0.40	0.0	0.0	0.0	0.0	0.0	1.42	307.33
37	0.126	16.78	29.0	361.82	0.035	0.58	0.43	0.0	0.0	0.0	0.0	0.0	1.42	307.33
38	6.405	453.29	551.0	11126.44	0.058	0.82	0.36	0.0	45.0	106.0	106.0	106.0	86.83	21.92
39	1.536	101.54	192.5	3204.80	0.048	0.53	0.40	0.0	0.0	0.0	18.0	538.0	58.50	52.58
40	1.099	51.77	62.0	1631.76	0.067	0.83	0.41	0.0	0.0	8.0	9.0	13.5	1.25	307.50
41	0.362	1.22	23.5	234.68	0.154	0.05	0.39	0.0	0.0	0.0	0.0	4.0	1.17	450.67

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42	0.613	50.35	170.5	1311.07	0.047	0.30	0.42	0.0	0.0	3.5	6.0	46.5	55.92	107.27
43	0.413	18.75	24.5	211.19	0.196	0.77	0.43	0.0	16.0	95.5	140.5	172.5	2.25	20.17
44	0.012	0.85	6.0	7.96	0.152	0.14	0.41	0.0	1.5	2.5	2.5	12.0	22.00	91.83
45	0.058	11.14	12.5	61.42	0.095	0.89	0.43	0.0	0.5	6.0	16.5	19.0	0.75	49.25
46	0.131	20.47	58.0	325.25	0.040	0.35	0.42	0.0	0.0	0.0	14.0	31.5	61.00	72.08
47	0.717	97.78	198.8	1785.67	0.040	0.49	0.44	0.0	0.5	17.5	44.0	58.0	81.67	22.83
48	0.009	0.05	5.6	7.72	0.116	0.01	0.43	0.0	4.0	4.2	11.6	176.6	6.67	16.58
49	0.105	9.42	11.6	65.44	0.161	0.81	0.41	0.0	0.0	0.4	6.0	10.0	0.83	47.00

Remark: Events 1~ 37 were replications, therefore, they shared the same rainfall parameters.

A positive correlation (Figure 3) exists between unit area runoff volume and unit area soil loss (R^2 = 0.8201). Surface runoff appeared as overland flow without noticeable concentrated flow behavior and no rills were found in runoff plots during field experiment periods. Therefore, within the scope of this study, surface runoff was mainly responsible for transporting the eroded soil.

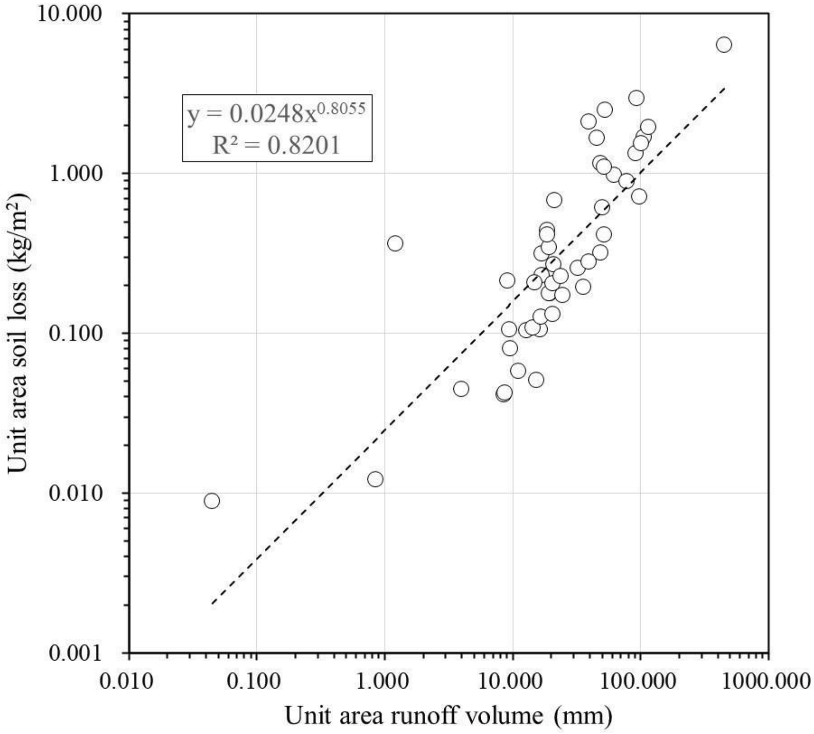

Figure 3. Relationship between unit area runoff volume and unit area soil loss.

Correlation analysis was also conducted between unit area soil loss, unit area runoff volume and the selected rainfall parameters; namely NAVSMC, Duration, Ppx and TILR. Results of correlation analysis (Table 2) indicate that unit area soil loss is strongly positive correlated with unit area runoff volume, precipitation, Duration, and Pp48. It is moderately positive correlated with Pp24 and Pp72, and it is weakly positive correlated with Pp12 and Pp120 but negative correlated with TILR. Weak and negative correlation was found between unit area soil loss and NAVSMC.

Time range x chosen to calculate Ppx affects the correlation analysis. The effective erosion events collected in this study seldom have any rainfall in 12-h time range before the occurrence of an effective erosion event. Therefore, most of the erosion events in Table 1 have zero rainfall in Pp12 column. On the other hand, Pp120 often includes additional rainfall events that were ineffective to erosion, which resulted in high amount of rainfall but less soil loss. If 72-h were chosen, the number of ineffective rainfall events included in Ppx calculations becomes less so that the correlation changes from weak positive to moderate positive; whereas Pp24 excludes some of the ineffective events that contributes soil weakening. Hence, Pp48 results the best performance in correlation analysis.

USLE sets the effective erosive rainfall segmentation condition at 6 hours to consider the possible impact from previous rainfall and believes that once the time interval exceeds 6 hours the impact of preceding rainfall can be ignored. According to the field observations and the results of soil moisture

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sensors from this study, the time required for soil moisture at 5-cm below the ground surface to return to a dry condition often exceeds 6 hours for clay soil. Therefore, we recommend that longer segment, i.e., TILR, for instance 48 hours, being used to delineate effective erosion events.

TILR to antecedent soil moisture content is somewhat similar to Ppx but it only counts the length of time between two adjacent effective rainfall events. Results of correlation between TILR and unit area soil loss (Table 2) show negative weak correlation. Shorter the TILR is, less chance the soil dries naturally. However, any ineffective rainfall may alter the soil wetness. Therefore, TILR; even through is easy to extract from rainfall records; fails to play contribution to soil erosion.

Duration is another rainfall characteristics considered in this study, and it is strongly positive correlated to unit area soil loss (Table 2) as expected. Nevertheless, Duration counts the entire time span of the rainfall event from T_b to T_e, but contribution from antecedent soil moisture to soil erosion primarily exists in the early stages of a rainfall event. For shorter-duration rainfall events, antecedent soil moisture content has larger impact on soil infiltration, whereas in longer-duration events, the influence of antecedent soil moisture diminishes.

Table 2. Summary of correlation analysis of field experiment results.

	Unit area soil loss (kg/m²)	Unit area runoff volume (mm)	Precp. (mm)	NAVSMC (m³/m³)	Pp_{12} (mm)	Pp_{24} (mm)	Pp_{48} (mm)	Pp_{72} (mm)	Pp_{120} (mm)	Duration (h)	TILR (h)
Unit area soil loss	1.000										
Unit area runoff volume	0.901	1.000									
Precp.	0.921	0.805	1.000								
NAVSMC	-0.023	0.031	-0.031	1.000							
Pp_{12}	0.223	0.037	0.318	-0.061	1.000						
Pp_{24}	0.534	0.524	0.321	-0.061	-0.063	1.000					
Pp_{48}	0.610	0.463	0.595	-0.013	0.310	0.512	1.000				
Pp_{72}	0.532	0.381	0.553	-0.020	0.310	0.403	0.945	1.000			
Pp_{120}	0.237	0.189	0.267	0.067	0.245	0.093	0.224	0.289	1.000		
Duration	0.652	0.560	0.823	0.089	0.529	0.058	0.441	0.455	0.344	1.000	
TILR	-0.233	-0.202	-0.264	-0.131	-0.279	-0.261	-0.441	-0.504	-0.418	-0.383	1.00

Amount of soil loss not only positively depends on the effective rainfall (Precp.) as well as Duration and negatively correlated with TILR but is also affected by Rainfall-Runoff Erosivity. Therefore, we further divide the soil loss per unit area by the corresponding Rainfall-Runoff Erosivity Index (EI_{30}) that is denoted as (Soil Loss / EI_{30}) hereafter. (Soil Loss / EI_{30}) quantifies how erodible soil becomes, which is also known as soil erodibility. We then plot (Soil Loss / EI_{30}) with respect to Pp_{48} but excluding data having Pp_{48} equals zero. The result that grouped in four Durations (Dur) is shown in Figure 4.

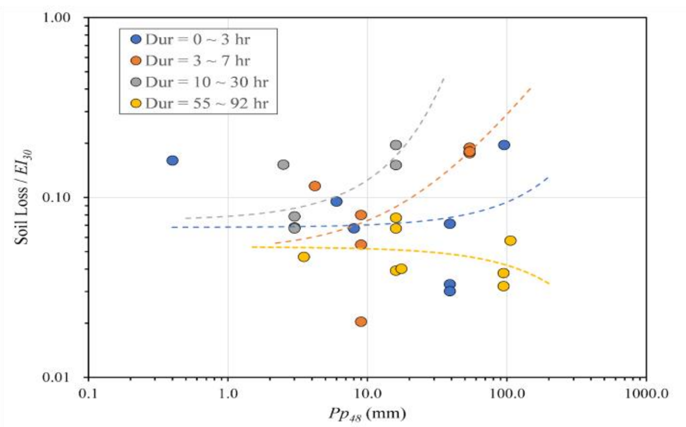

Figure 4. Trends of unit area soil loss per EI_{30} with respect to Pp_{48} that grouped by rainfall durations.

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Trends shown in Figure 4 indicate that total non-erosive rainfall that measured 48 hours prior to an effective erosion event (Pp_{48}) has less effect on clay soil's (Soil Loss / EI_{30}) when the Duration of effective erosion event exceeds 55 hours. When the Duration of effective erosion event is either between 3 ~ 7 hours or 10 ~ 30 hours, the Pp_{48} plays noticeable contribution to (Soil Loss / EI_{30}). Both trends follow the same pattern. However, Pp_{48} does not affect (Soil Loss / EI_{30}) for 0 ~ 3-h duration event when Pp_{48} is less than 20 mm.

We further conduct correlation analysis on (Soil Loss / EI_{30}) with respect to NAVSMC, Pp_{48}, and Duration by first excluding Pp_{48} equal zero and the result as well as the wind rose plot of correlation coefficients are shown in Table 3 and Figure 5, respectively.

Table 3. Correlation coefficients to (Soil Loss / EI_{30}).

Event with duration	0 ~ 3 hrs.	3 ~ 7 hrs.	10 ~ 30 hrs.	55 ~ 92 hrs.	0 ~ 7 hrs.	0 ~ 30 hrs.	All durations
NAVSMC	0.256	0.538	-0.086	0.296	0.386	0.295	0.230
Pp_{48}	0.319	0.880	0.759	-0.323	0.532	0.423	0.064
Duration	-0.325	0.808	-0.903	-0.508	0.402	-0.034	-0.466

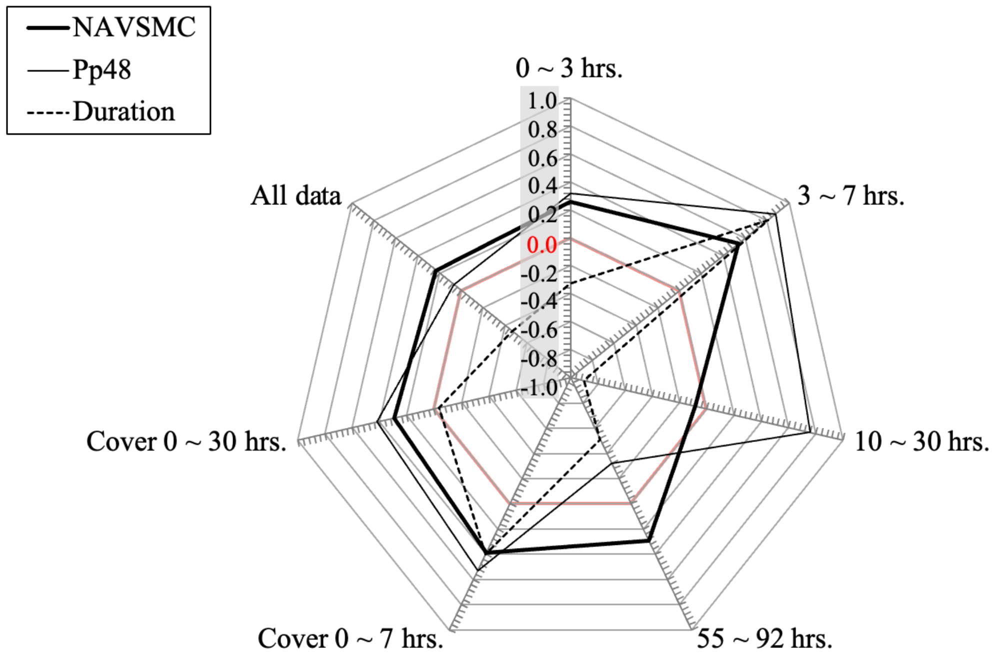

Figure 5. Windrose plot of correlation coefficients to (Soil Loss / EI_{30}).

From Table 3 and Figure 5 we found that normalized antecedent volumetric soil moisture content (NAVSMC) becomes moderately correlated with (Soil Loss / EI_{30}) while the duration of effective erosion event is within 3 to 7 hours. All three parameters become moderately correlated with (Soil Loss / EI_{30}) when effective erosion events with duration between 0 and 7 hours are considered. To eliminate the effect of Ppx, we only picked data having Pp_{12} = 0 from Table 1 and generated a scatter plot on (Soil Loss / EI_{30}) against the NAVSMC and the result is shown in Figure 6. Regardless of the dispersion of data in Figure 6, we found that data points were segregated into two groups. The division between these two groups is located at (Soil Loss / EI_{30}) = 0.15, therefore, we firstly identified common characteristics of the data points.

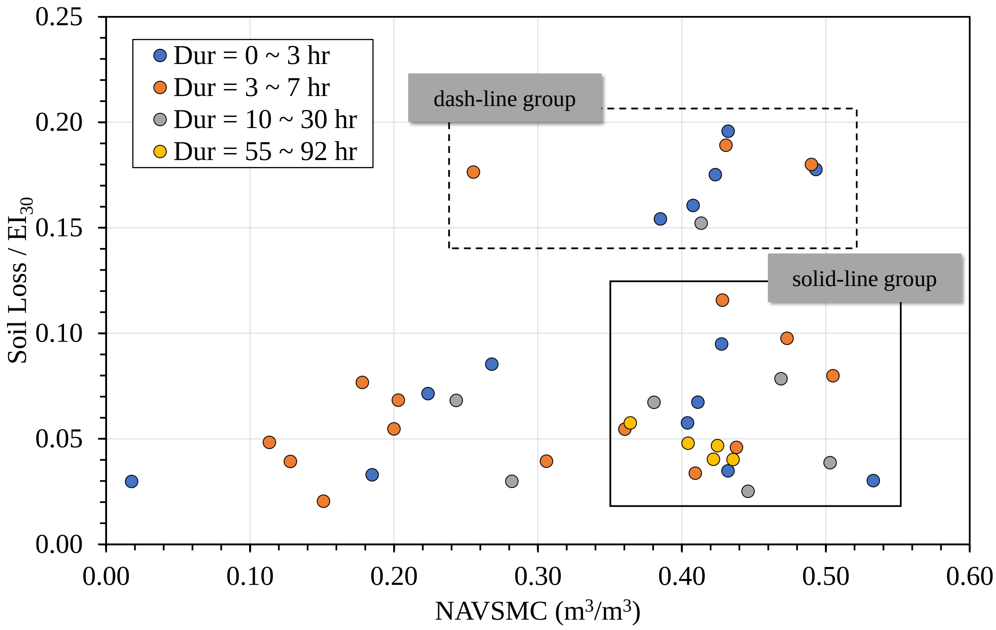

Figure 6. Soil Loss / EI_{30} vs. NAVSMC (All data).

Data points in the dash-line group are Events # 26, 27, 28, 30, 31, 41, 43, 45 and 50, and the data points in the solid-line group are Events # 3, 6, 9, 18, 19, 21, 22, 24, 25, 34, 36, 37, 38, 39, 40, 42, 46, 47, 48 and 49 (Table 1), respectively. We found that dash-line group shared the common characteristics of short Duration, short TILR, less rain, low average rain intensity, and low EI_{30} value. These events often occur after a low EI_{30} event. The solid-line group exhibits opposite characteristics to those of the dash-line group.

We further found that rainfall events with NAVSMC > 0.36 in Figure 6 (data of solid-line group) were associated with common characteristics of stronger storm. The average rainfall duration is 22.0 hours, approximately 3.5 time longer than the dash-line group (6.23 hours). The average rainfall amount is 103.1 mm, almost 5 times higher than the dash-line group (19.75 mm), and the average EI_{30} is 1570.14 MJ-mm/ha-h, which is 20 times higher than the dash-line group (78.7 MJ-mm/ha-h).

Furthermore, the average NAVSMC for these events is 0.41, slightly higher than the overall average of 0.35, while the average TILR is about 40.5 hours, roughly one-third of the overall average of 104.33 hours, and the average rain intensity is about 8.3 mm/h. According to the rain intensity classification from World Meteorological Organization (2018) [33], these events fell in the lower boundary of heavy rain category (average intensity between 7.6 and 50 mm/h).

Two scatter plots as that shown in Figures 7 and 8 were therefore drawn. Rainfall events having (Soil Loss / EI_{30}) > 0.15; i.e., dash-line group, were excluded in Figure 7, whereas data points in solid-line group were excluded in Figure 8.

The reasons we fit linear regression lines through three duration groups in Figure 7 are: (1). easy to see the general trends even the coefficients of determination are low, and (2). difficult to isolate the nonlinear effects of NAVSMC, if any, to soil vulnerability to erosion or soil erodibility since this study was conducted in field under natural rain conditions. From Figure 7, we found that 66.7% of the events occurred when NAVSMC was within the wilting point and field capacity. Dispersion of soil erodibility data expands to cover a wider range when NAVSMC exceeds 0.36, which is clearly illustrated in both Figures 6 and 7.

The trend shown on Figure 8 exhibits a high coefficient of determination with $R^2 = 0.7584$, from which we conclude that (1) the impact of normalized antecedent volumetric soil moisture content (NAVSMC) on soil erodibility is conditional, (2) the impact of antecedent soil moisture content on soil erodibility must be considered for long Duration, long TILR, higher average rain intensity and

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high EI_{30} events, and (3) the impact of NAVSMC to interrill erosion only exists in moderate to heavy rainfall events.

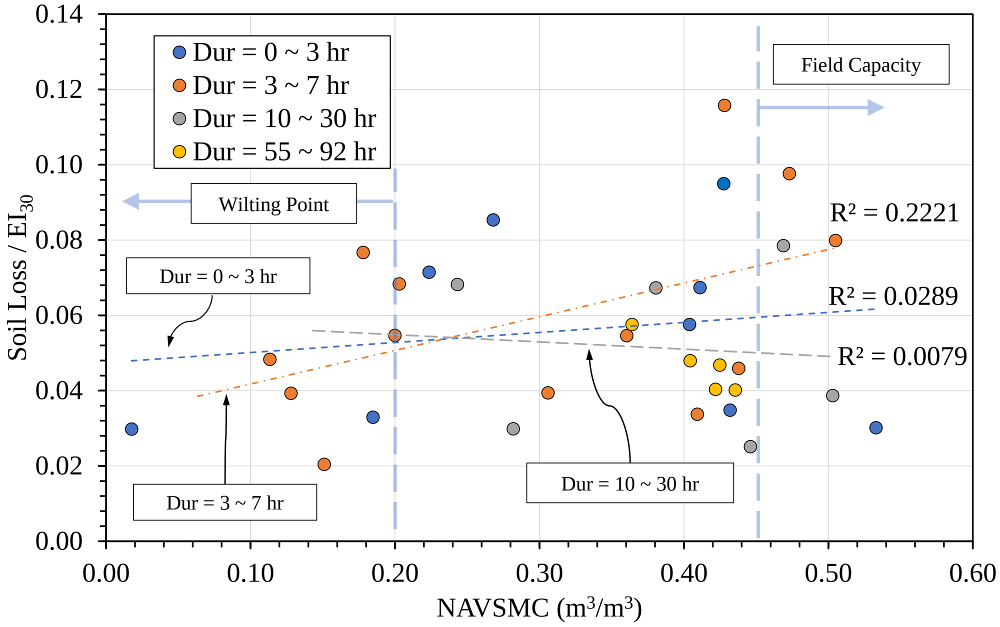

Figure 7. Soil Loss / EI_{30} vs. NAVSMC (excluding Soil Loss / EI_{30} > 0.15).

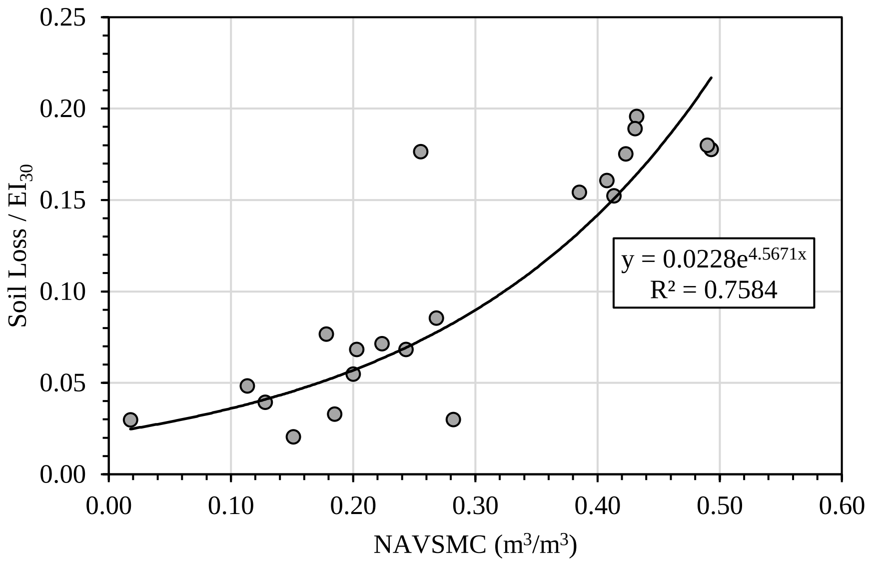

Figure 8. Soil Loss / EI_{30} vs. NAVSMC (excluding solid-line group in Figure 6).

Another intriguing argument arises regarding the impact of antecedent soil moisture conditions resulted from rainfall event duration. Soil moisture content tends to approach saturation in the later stage of a rainfall event, therefore, the influence of antecedent soil moisture content on soil erodibility should gradually decrease with increasing rainfall event duration. In other words, antecedent soil moisture conditions may have a significant impact on a 1-hour duration rainfall event but the impact can be almost negligible for a 100-hour duration rainfall event. To verify the influence, correlation analysis was again conducted and the correlation coefficients on (Soil Loss / EI_{30}) to NAVSMC are summarized in Table 4.

Table 4. Correlation coefficients of (Soil loss / EI_{30}) with respect to NAVSMC and other rainfall parameters.

Total event count	Duration range (h)	NAVSMC	Pp_{12}	Pp_{24}	Pp_{48}	Pp_{72}	Pp_{120}	Duration (h)	TILR (h)
49	0 ~ 91.5	0.259	0.035	-0.125	0.164	0.179	0.030	-0.302	-0.170
39	0 ~ 30	0.318	0.342	-0.155	0.451	0.476	0.283	-0.015	-0.323
30	0 ~ 10	0.438	-	-0.215	0.465	0.495	0.172	0.140	-0.344
26	0 ~ 5	0.435	-	-0.163	0.242	0.379	0.174	-0.433	-0.199
23	0 ~ 4	0.473	-	-0.196	0.222	0.359	0.447	-0.430	-0.226
14	0 ~ 3	0.419	-	-0.347	0.131	0.312	0.343	-0.186	-0.218

The results in Table 4 indicate that as the range of rainfall duration reaches to 0~5 hours, the correlation coefficients between (Soil Loss / EI_{30}) and NAVSMC increase, while the best correlation falls within 0~4 hours. In contrast, events with duration exceed 10 hours exhibit relatively lower correlations for all indexes. Therefore, we suggest that the impact of antecedent soil moisture content on soil erosion can be ignored for events with duration exceed 10 hours.

5. Conclusions

This study was conducted under natural rain for two consecutive rainy seasons at plot scale to investigate the impact of antecedent soil moisture content to soil loss on clay soil. Key points of the findings are summarized as follows:

1. Duration of the effective erosion event outranks the antecedent volumetric soil moisture content. Contribution of antecedent soil moisture content only affects the progress of erosion in the early stages of the rain event.
2. The accumulative rainfall (Pp) prior to an effective erosion event elevates the antecedent soil moisture content, that in turns affect the erosion process. Field study on clay soil suggests that accumulative rain falling within 48 hours (Pp_{48}) prior to an effective erosion event strongly correlated with soil loss per Rainfall-Runoff Erosivity Index (Soil Loss / EI_{30}) that also termed as soil erodibility. When the duration of an effective erosion event is either between 3 ~ 7 hours or 10~ 30 hours, Pp_{48} plays noticeable contribution to (Soil Loss / EI_{30}). However, Pp_{48} does not affect (Soil Loss / EI_{30}) for 0 ~ 3-h duration event when Pp_{48} is less than 20 mm. Hence, Pp_{48} can be considered as an alternative to replace antecedent soil moisture content in RUSLE 2's cover and management factor.
3. The effect of antecedent volumetric soil moisture contents to (Soil loss / EI_{30}) exists in rain events of lower rainfall duration, less rainfall amount, and low Rainfall-Runoff Erosivity Index. The characteristics of these events include average rainfall duration of 6.23 hours, average rainfall amount of 15.5 mm, average EI_{30} of 78.7 MJ- mm/ha-h, average time interval to preceding rain event within about 40.5 hours, and the average rain intensity about 8.3 mm/h. These events fall in the lower boundary of heavy rain category (average intensity between 7.6 and 50 mm/h).

Further studies are still needed to fully grasp the impact of antecedent soil moisture content on soil erosion, particularly on less clayey soils.

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