This is the pre-peer reviewed version of the following article Hydrological Processes, Vol.16(12), 2002, p.2339-2345, which has been published in final format at http://onlinelibrary.wiley.com/doi/10.1002/hyp.1006/pdf

Title: "Analysis of surface roughness in relation to soil loss and runoff at high rainfall intensities".

Authors:

O.J. IDOWU,[1] R.J. RICKSON[2] and R.J. GODWIN[3]

[1]Institute of Agricultural Research and Training, Obafemi Awolowo University, P.M.B. 5029 Ibadan, Nigeria.
E-mail: ojidowu@skannet.com
(Corresponding Author)

[2]Institute of Water and Environment, Cranfield University at Silsoe, Silsoe, Bedfordshire MK45 4DT, UK.

[3]Institute of AgriTechnology, Cranfield University at Silsoe, Silsoe, Bedfordshire MK45 4DT, UK.

Abstract:

The decay of roughness is an important factor governing surface processes such as infiltration and soil erosion. Thus the decay of surface roughness under different surface conditions was investigated and related to quantitative amounts of soil loss, runoff and sediment concentration in a laboratory experiment.

Rainfall with an intensity of 128 mm/h was applied to a bare or mulched surfaces of a sandy loam soil with known surface roughness at specified time intervals.

The decay of roughness as expressed by roughness ratio, in this experiment, was better predicted when related to an exponent function of square root of cumulative kinetic energy of rainfall rather than with the cumulative rainfall. The roughness decay equations in literature did not predict breakdown under mulched surfaces accurately. Thus the exponent parameters of the roughness decay equations were adjusted to reflect the reduced decay occurring under mulched surfaces.

In a bare soil, regression equations expressing soil loss, runoff and sediment concentration as a function of inital roughness were significant, but with low coefficients of determination, being 0.39, 0.12 and 0.36 respectively. In addition to initial roughness, cumulative kinetic energy of rainfall was further included in the regressions. This led to an increase in coefficients of determination being 0.81, 0.74 and 0.49 for soil loss, runoff and sediment concentration respectively.

Soil loss, runoff and sediment concentration as a function of initial roughness, final roughness and cumulative kinetic energy also gave significant regressions with coefficients of determination being 0.87, 0.85 and 0.51 respectively.

This work shows that soil loss and runoff could be predicted from bare soil surface provided the initial roughness and the energy of rainfall is known. However, field verifications of these relationships are needed under different tillage tools and under natural rainfall.

Introduction:

Tillage-induced roughness is an important factor, which affects many surface soil properties. Among properties affected by the state of the surface roughness includes porosity (Burwell et al., 1963; Johnson et al. 1979), soil thermal properties and solar radiation reflection (Cruse et al. 1980), infiltration of water into the soil (Magunda et al. 1997) and soil erosion (Johnson et al., 1979; Cogo et al., 1983).

The most studied aspect of surface roughness is its capacity to hold water temporarily in depressions thus affecting runoff during rainfall events (Podmore & Huggins, 1980; Moore & Larson, 1979; Mitchell & Jones 1978).

Several authors have shown that the amount of depression water storage is related to the level of roughness of the soil. However, tillage-induced roughness is very dynamic changing with successive rainfall during the growing season. Thus to be able to predict the effect of roughness on soil erosion, there is a need to understand the effect of rainfall on the decay of surface roughness and relate this changes in roughness to soil loss and runoff.

The decay of surface roughness has been found to decreased exponentially with increasing rainfall (Zobeck & Onstad, 1987, Romkens & Wang, 1987).

While some authors have chosen exponent function of cumulative rainfall to describe the decay of surface roughness (Zobeck & Onstad, 1987; Romkens & Wang, 1985), others have used the kinetic energy of rainfall (Morgan et al, 1993; Dexter, 1977; Burwell and Larson, 1969).

Zobeck & Onstad (1987) proposed an equation relating random roughness ratio (RRR) to an exponent function of cumulative rainfall (equation 1)

$$RRR = RR_f / RR_i = 0.89\ e^{-0.026\ P} \qquad [1]$$

RRR: Random roughness ratio

RR_f : Final soil roughness index (cm)

RR_i : Initial soil roughness index (cm)

P : cumulative rainfall (cm)

Equation 1 was derived based on the synthesis of some earlier works of Burwell & Larson 1969, Johnson et al., 1979, Onstad, 1984 and Steichen, 1984.

The equation 1 above explained 76% of the variations in the random roughness ratio among 418 data points for different primary tillage operations and soils.

The decay of surface roughness as proposed in European Soil Erosion Model (EUROSEM) (Morgan et al., 1993) is due to the kinetic energy of rainfall. Thus the equation relating random roughness ratio (RRR) to the square root of cumulative kinetic energy of rainfall is given below (equation 2).

$$RRR= RR_f /RR_i = * e^{-k \sqrt{E}} \qquad [2]$$

RRR: Random roughness ratio

RR_f : Final soil roughness index (%)

RR_i: Initial soil roughness index (%)

k : a constant = 0.7 (an average for most soils)

E : Cumulative kinetic energy of rainfall (kJ m^{-2})

Most of the studies relating to surface roughness decay have been tested with rainfall intensities less than 100 mm h^{-1}. However, in tropical regions, rainfall intensities well over 100 mm h^{-1}

normally occur during the growing season. The question arises if these roughness decay equations will still be valid for high intensity rainfall.

Another gap in knowledge is the case where surface mulches have been applied. Most of the roughness decay equations have focused on bare soil conditions. There arises a doubt whether these equations will be valid for mulched surfaces.

As the roughness get broken down, it is believed that there will be an increase in runoff volume generated from the soil surface thus giving rise to increased sediment losses.

While a lot of studies have focus on breakdown of roughness and at best related this breakdown to detention water storage and infiltration, very few studies have focused on the quantitative relations between roughness decay on one hand and soil loss, runoff and sediment concentration on the other hand. This work attempts to relate the roughness breakdown to soil losses and runoff from the soil.

Thus objectives of this study are

i. to test the effectiveness of some already existing equation in predicting roughness breakdown under high intensity rainfall,

ii. to adjust some already existing equation to predict roughness decay under mulched surfaces and

iii. to relate the decay of surface roughness to soil loss runoff and sediment concentration in the runoff.

Materials and Methods

Soil tray of dimensions 0.75 m x 0.5 m and 0.05 m deep and inclined to a slope of five degrees were used for this experiment. A sandy loam soil was collected from the field, air-dried and passed through a 10mm sieve. The soil was then brought to gravimetric moisture content of 12% before being compacted into the soil trays to give a bulk density of 1.4 Mg m^{-3}. The textural properties of the soil used are given in table 1.

Different surface roughness conditions were simulated using a hand trowel. Breaking the soil into large clods simulated a rough surface condition while a fine seed bed condition was simulated by breaking the soil into small clods. For the bare soil condition, 6 soil trays were prepared as fine seedbed while another six were prepared for rough seedbed.

Wheat straw was used as the surface mulching material. The rate of mulch application was 3 t/ ha. The mulch had moisture content of 14.5% at the time of application. To apply the mulch, the amount required was weighed out and spread uniformly over the soil surface, after the application of tillage treatments

Surface roughness ratio was measured using a fine chain method proposed by Morgan et al., (1993). The roughness ratio according to Morgan et al., (1993) is defined as the ratio of the straight line distance between two points on the ground to the actual distance measured over all the microtopographic irregularities. This can be expressed equationally as:

$$R = \frac{X - Y}{X}.100 \qquad [3]$$

R: Roughness index (cm/m or %).

Y: Straight-line distance between two points on ground surface (m).

X: The actual distance between the two points measured over all the microtopographic irregularities (m).

The chain was allowed to conform to the depressions and ridges created by the tillage along the marked axes. Three parallel axes were chosen across the width of the tray and two across the length of the tray. This gave a total of five chain measurements for each roughness determination. The roughness index was calculated from the mean of these five measurements using equation 3

Measurements on the bare soil (unmulched) treatments took place at the following time intervals (t): t = 0 (initial condition), t = 3, t = 6, t = 9, t = 12 minutes.

In the case of the mulched soil, roughness measurements only took place immediately after the application of the tillage treatment, before applying mulch and at the end of the rainfall application (t = 0 and t = 12). Surface roughness measurements were not taken at intervening times to prevent the dislodging of the mulch elements. The mulch materials were carefully removed from the soil surface after the last period of rainfall application and the surface roughness was measured.

A pressurized nozzle simulator was used to apply the rainfall. Simulated rainfall with an intensity of 50 mm h^{-1} was initially applied for 30 minutes to bring the soil to saturation. During this period, there was no runoff from the soil. Afterwards, simulated rainfall with an intensity of 128 mm /h was applied to the soil for twelve minutes to test the effects of the different treatments.

For the bare surface conditions, initial surface roughness was measured immediately after tillage and at every 3 minutes interval.

Runoff from the plot was collected into containers during the storm. After the storm, the runoff volume was estimated using a measuring cylinder. The runoff sample was then allowed to sediment after which the water was filtered off leaving the wet soil. The wet soil was transferred into an oven and dried at 110°C for 24 h.

Results and discussions

A. Roughness breakdown in bare soil

The actual breakdown of surface roughness in this experiment was compared with theoretical breakdown as calculated by equations 1 and 2. There was a significant correlation between the actual and predicted roughness for both equations. However, equation 2 gave a higher coefficient of determination (R^2=0.88) while that of equation 1 was 0.80. Predicted values of roughness were further compared with observed values using t-distribution test to find out if they differ statistically. It was found out that while the predicted values from equation 2 did not differ significantly from observed values, those from equation 1 were statistically different (Table 2). This indicates that equation 2, which relates the decay of roughness to square root of kinetic energy, has given more accurate predictions of roughness breakdown. This confirms the work of Saleh (1994) in which rainfall erosivity index (EI) was a better predictor of random roughness than the rainfall amount. Since equation 1 was developed mostly in the United States, the parameter constants, particularly the exponential decay parameter, may be a reflection of local conditions. If equation 1 is adjusted, the constant of the exponent in this equation changes from 0.026 to 0.199 to fit the data generated from this study. There is need to test equation 1 under different climatic and field condition to investigate how these parameters may be adjusted to predict the decay of roughness.

B. Roughness breakdown under the mulch

As expected, the decay of surface roughness under a mulch cover was far less than when the soil was bare. This was due to the dissipation of kinetic energy of rainfall by the mulch. Consequently, surface roughness was preserved longer under the mulch cover. Neither equation 1 or 2 gave reasonable predictions of the decay of roughness under surface applied mulch. Using a non-linear regression method on the roughness data generated in the laboratory, the constants of equations 1 & 2 for the surface mulched condition were found (equation 3 & 4).

$$RR_f = RR_i * 0.89 * e^{-0.002\,P} \qquad [4]$$

$$RR_f = RR_i * e^{-0.21 * \sqrt{E}} \qquad [5]$$

RR_f: Final soil roughness (cm)

RR_i: Initial soil roughness (cm)

P: cumulative rainfall (cm)

E: Kinetic energy of rainfall (kJ m^{-2})

From equation 3, it can be seen that the constant attached to the exponent, which was 0.026 in equation 1 has reduced to 0.002. Similarly the k - factor in equation 2 has been reduced from 0.7 to 0.2 in equation 4. This reflects the slowing down of the decay of surface roughness due to the mulching.

C. Predicting soil loss, runoff and sediment concentration from surface roughness.

A series of bivariate and multiple regression were performed to find out if soil loss, runoff and sediment concentrations from bare soil condition could be predicted from roughness values. A total of 24 data points were used to generate various regression equations given on Table 2.

Though the regression equations expressing soil loss, runoff or sediment concentration as a function of initial roughness were significant (Tab.2, equations 6-8), the coefficients of determination (R^2) were however low. Initial roughness explained just 39% of the variation in the measured soil loss, 12% in runoff and 36% in the sediment concentration. These relatively low R^2 implies that there are other significant variables apart from initial roughness controlling these dependent variables. As has been shown earlier, the decay of roughness is closely related to the cumulative kinetic energy of rainfall, thus, this variable was included in the regression. The regression equations now became a function of two independent variables, namely initial surface roughness and cumulative kinetic energy. The equations generated are listed in table2 equations 9-11. The regression between soil loss and the two independent variables gave a very high R^2 (0.81). For the runoff, the R^2 was 0.74. However for the sediment concentration, the R^2 was relatively low being 0.49. This shows that soil loss and runoff from a bare soil can be reliably predicted, if the initial roughness and the cumulative kinetic energy is known.

Adding final surface roughness to the independent variable (Table 2, equations 12-14) further expanded the regression equation. This led to an improvement in the predictive ability of the equation. The R^2 with soil loss as the dependent variable was 0.87, while for runoff and sediment concentration, it was 0.85 and 0.51 respectively. This shows that with the knowledge of these three variables (initial roughness, final roughness and cumulative kinetic energy), soil loss and runoff from a bare soil can be estimated. It is worth noting that final roughness can be reliably predicted using equation 2, therefore, only the values of initial roughness and cumulative kinetic energy are needed to use equations 12-14 on table 2.

Although these regression equations have been generated from a laboratory study with relatively few data points, thereby limiting it scope of application, however it gives an important focus on how soil loss and runoff may be predicted using roughness indices and kinetic energy of rainfall. There is need to test this empirical approach using field-measured values under different climatic zones.

Conclusions:

The decay of surface roughness was studied and related to soil loss, runoff and sediment concentration. The study led to the following conclusions:

1. The decay of surface roughness measured in this experiment was better predicted by an exponent function of the square root of cumulative kinetic energy of rainfall rather than cumulative rainfall.

2. The decay of surface roughness under mulch was not well predicted by equations being used for decay under bare soil surfaces. Thus the exponent parameters of the decay equations were adjusted based on measured values to reflect the slowing of roughness breakdown under mulched surfaces

3. Regression equations relating soil loss, runoff or sediment concentration to initial roughness gave low coefficient of determination, which were 0.39, 0.12, 0.36 respectively. This indicates that such equations could not reliably predict these dependent variables.

4. Regression equations relating soil loss, runoff or sediment concentration to initial roughness and cumulative kinetic energy gave high R^2 for soil loss (0.81) and runoff (0.74) but a relatively low R^2 for sediment concentration (0.49). This shows that runoff and soil loss can be reliably estimated from initial roughness and cumulative kinetic energy.

5. Regression equations using three independent variables: initial roughness, final roughness and cumulative kinetic energy gave a significant regression with soil loss, runoff and sediment

concentration. The R^2 of soil loss (0.87) and runoff (0.85) were very high showing that the addition of final roughness to the independent variables has improved the predictive ability of the equation for soil loss and runoff. However there was not much improvement in the prediction of sediment concentration, having an R^2 of just 0.51

6. There is need to test out this empirical approach to soil loss and runoff predictions under field condition with natural rainfall.

Acknowledgment:

Special thanks to Alex Vickers for assisting in setting up of rainfall simulators and collection of soil samples.

References:

Burwell RE, Allmaras RR, Amemiya M. 1963. A field measurement of total porosity and surface microrelief of soils. Soil Science Society of America Proceedings 27: 697-700.

Burwell RE, Larson WE. 1969. Infiltration as influenced by tillage-induced random roughness and pore space. . Soil Science Society of America Proceedings 33: 449-452.

Cogo NP, Moldenhauer WC, Foster GR. 1983. Effect of crop residue, tillage-induced roughness and runoff velocity on size distribution of eroded soil aggregates. Soil Science Society of America Journal 47: 1005-1008.

Cruse RM, Linden DR, Radke JK, Larson WE, Larntz K. 1980. A model to predict tillage effects on soil temparature. Soil Science Society of America Journal 44: 378-383.

Johnson CB, Mannering JV, Moldenhauer WC. 1979. Influence of surface roughness and clod size and stability on soil and water losses. Soil Science Society of America Journal 43: 4, 772-777.

Magunda MK, Larson WE, Linden DR, Nater EA. 1997. Changes in microrelief and their effects on infiltrationand erosion during simulated rainfall. Soil Technology 10: 1, 57-67.

Mitchell JK, Jones Jr. BA. 1978. Micro-relief surface depression storage: changes during rainfall events and their application to rainfall-runoff models. Water Resources Bulletin 14, 4, 777-802.

Moore ID, Larson CL. 1979. Estimating micro-relief surface storage from point data. Transaction of the American Society of Agricultural Engineers 22, 1073-1077.

Morgan RPC, Quinton JN, Rickson RJ. 1993. EUROSEM: A User Guide Silsoe College Cranfield University Silsoe, Bedford United Kingdom October 1993 EUROSEM User Guide Version 2.

Onstad CA. 1984. Effect of rainfall on tilled soil properties. American Society of Agricultural Engineers. Paper No. 84 -2525. Am. Soc. Agric. Eng., 6pp.

Podmore TH, Huggins LF. 1980. Surface roughness effects on overland flow. Transaction of the American Society of Agricultural Engineers 23, 1434-1439, 1445.

Saleh A. 1994. Decay of soil roughness by rainfall. American Society of Agricultural Engineers. Paper No. 942057. 15pp.

Steichen JM, 1984. Infiltration and random roughness of a tilled and untilled claypan soil Soil and Tillage Research 4: 251-262.

Zobeck TM, Onstad CA. 1987. Tillage and rainfall effects on random roughness: A review. Soil and Tillage Research 9: 1-20.