Plant Root Effects on Soil Erodibility, Splash Detachment, Soil Strength, and Aggregate Stability

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Abstract. *The influence of dead roots on soil erodibility, splash detachment, and aggregate stability was studied in the laboratory using a rainfall simulator on a Mexico silt loam (fine, montmorillnitic, mesic, Udollic Ochraqualf). Soil was collected from four cropping treatments including alfalfa, Canada bluegrass, corn, and soybeans. Rainfall of 64 mm h^{-1} intensity was applied for 1 h during the first day. On the second day, a 30-min run of constant intensity (64 mm h^{-1}) was applied which was followed by four 15-min storms at intensities of 25, 100, 50, and 75 mm h^{-1}. Dead root mass and dead root length in the 0- to 0.15-m depth from the perennial crops (alfalfa and bluegrass) were much higher than those from annual row crops (corn and soybean). There was almost a five-fold difference in root mass and root length between alfalfa and soybeans. The study showed that dead roots did not affect runoff, but had significant effect ($p < 0.05$) on soil loss and sediment concentrations. However, the differences in soil loss and sediment concentrations were small relative to the differences in dead root mass and dead root length. Interrill erodibility (K_i) decreased as dead root mass and dead root length increased. There were exponential relationships between K_i and dead root mass, and K_i and dead root length. Dead roots had significant effects ($p < 0.05$) on soil shear strength, aggregate index, and dispersion ratio. Soil shear strength and aggregate index from alfalfa and Canada bluegrass were approximately 20 and 50%, respectively, higher than those from corn and soybean. Dispersion ratios from alfalfa and bluegrass were about 30% lower than those from corn and soybean. There was no significant difference ($p < 0.05$) in soil splash among the crops. Splash detachment was highest during the initial 10 min of the simulation and then decreased exponentially.*

Keywords. *Runoff, Soil loss, Sediment concentration, Interrill erosion, Soil properties.*

The rill-interrill erosion concept facilitates basic erosion mechanics and erosion modeling studies (Foster and Meyer, 1975; Lane et al., 1987). Rills are areas where flow concentrates in narrow channels a few centimeters wide because of natural topographical features, soil roughness, or tillage marks and tracks. Erosion from areas between the rills is defined as interrill erosion. Interrill erosion is affected by many factors including rainfall intensity (Meyer, 1981; Park et al., 1983), infiltration and runoff (Bradford et al., 1987), slope (Lattanzi et al., 1974; Singer and Blackard, 1982; Watson and Laflen, 1986; Meyer and Harmon, 1989), and residue cover (Lattanzi et al., 1974). Interrill erosion is also affected by soil properties including soil texture, organic-matter content, aggregate stability, and residual effects of crops and management practices.

Several research studies have been conducted to evaluate cropping effects on erosion under natural rainfall conditions. Laflen and Moldenhauer (1979) found that annual soil loss from corn following soybean was higher than that from corn following corn. Most of the annual difference occurred during the rough fallow and rapid growth periods. Alberts et al. (1985) did not find any difference in soil loss during the seedbed period between continuous soybean and continuous corn that were conventionally tilled. Field-scale rainfall simulation has also been used to evaluate the effect of prior cropping on soil loss. Results have ranged from those that have found a prior cropping effect (Oschwald and Siemens, 1976) to those that have not found an effect (Laflen and Colvin, 1981; Colvin and Laflen, 1981).

Erosion losses due to cropping effects could be a combination of many factors including prior cropping effects on the soil, the amount of residue incorporated by tillage, canopy and residue cover, and live and dead root biomass. To more carefully isolate the influence of each factor on soil detachment, a more controlled laboratory study is needed whereby all casual factors other than that related to the study are eliminated. Ghidey and Alberts (1994) studied the effects of cropping system and antecedent water content on interrill soil erodibility in the laboratory. They used disturbed soil which was sieved through a 9-mm sieve to remove residues and clods. Thus, the influence of cropping systems on factors such as microbial population, decomposed residue and root masses, and dead root mass on soil resistance to sealing and detachment by raindrops were not specifically measured.

Numerous research had been conducted to evaluate the effects of prior cropping systems, organic matter, and residue on aggregate size, aggregate stability, and soil erodibility (Alberts and Wendt, 1985; Bathke and Blake, 1984; Fahad et al., 1982; McCracken, 1984; Chaney and

Article was submitted for publication in August 1996; reviewed and approved for publication by the Soil & Water Div. of ASAE in December 1996.

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Swift, 1984). Gantzer et al. (1987) also studied the effects of soybean and corn residues on soil strength and splash detachment. However, very limited information is available on the effects of dead roots on soil erodibility, splash detachment, and aggregate stability.

The objective of this study was to evaluate the influence of dead roots on soil erodibility, splash detachment, and aggregate stability. Mathematical relationships were also developed that can be used in erosion models to predict the effect of dead root mass and dead root length on soil erodibility parameters.

MATERIALS AND METHODS

The study was conducted in a laboratory using soil boxes and a rainfall simulator. The soil boxes were 100 cm long and 30 cm wide. Soil depth was 10 cm overlaying 5 cm of sand. One end wall of these boxes was fitted with a V-shaped collector to collect and concentrate runoff into a continuous stream. Two perforated tubes in the bottom of each box allowed for air venting and drainage.

Soil was collected from plots located at the University of Missouri Midwest Claypan Experimental Farm near Kingdom City, Missouri. The soil was a Mexico silt loam (fine, montmorillnitic, mesic, Udollic Ochraqualf) with sand, silt, and clay contents of 5, 69, and 26%, respectively. Soil was collected from four cropping treatments selected to give a wide range in dead root parameters including alfalfa, canada bluegrass, continuous corn, and continuous soybeans. Four replications of each treatment were imposed in 1982 on 3-m wide × 27-m long plots. Soil was collected in the fall of 1988. Prior to soil collection, surface residue biomass was removed from the sample area before the 0- to 0.15-m layer was tilled with a rototiller. About 100 kg of soil was collected from each of the 16 plots, air dried, and sieved through a screen with 9-mm openings.

About 500 g of soil was taken from each plot sample for root mass and root length analysis. Roots were separated from the soil using a hydropneumatic elutriation system (Smucker et al., 1982). Root length was determined using the line intersect technique (Newman, 1966).

Soil subsamples were taken from each plot sample to determine the aggregate stability of the soil. The stability of air dry 2- to 1-mm aggregates was determined by wet sieving (Kemper and Rosenau, 1986), without vapor wetting prior to immersion. Aggregate Index (AI) was calculated using the equation:

$$AI = \frac{WSA}{WSA + WUA} \qquad (1)$$

where WSA is the weight of stable aggregates, and WUA is the weight of unstable aggregates.

Soil resistance to slaking and dispersion was also evaluated using Middleton's dispersion ratio and Middleton's dispersion ratio as modified by Olson et al., 1962. The dispersion ratio gives an index of stability of soil aggregates in water. The Olson et al. (1962) definition of dispersion ratio is:

$$DR20 = \frac{< 20\ \mu m \text{ undispersed}}{< 20\ \mu m \text{ dispersed}} \times 100 \qquad (2)$$

Middleton definition of DR is:

$$DR50 = \frac{< 50\ \mu m \text{ undispersed}}{< 50\ \mu m \text{ dispersed}} \times 100 \qquad (3)$$

In brief, the dispersion ratio is defined as the ratio of the mass of undispersed soil particles (either <50 or <20 μm) to the mass dispersed after adding the soil to a graduated cylinder and inverting end-over-end several times. The <50 μm and <20 μm dispersed fractions were measured using the pipette method.

The soil was firmly packed in the soil boxes to an average bulk density of 1.07 g cm^{-3} using a vibrational packing device. The soil box was then placed in a supporting stand at 4% slope. Rain was applied with a multiple intensity rainfall simulator, similar to that described by Meyer and Harmon (1979), with a single 80150 v-jet nozzle. Mean waterdrop diameter was 3.0 mm falling from a height of 2.5 m. To each box, rainfall of 64 mm h^{-1} intensity was applied for 1 h during the first day. On the second day, a 30-min run of constant intensity (64 mm h^{-1}) was applied. On day 2, the 30-min constant intensity event was followed by four 15-min storms at intensities of 25, 50, 75, and 100 mm h^{-1}. During each rainstorm, surface runoff was measured and sampled for sediment analysis. After runoff began, samples were collected at 2 and 3 min intervals in the first 5 min, and at 5-min intervals thereafter.

Soil splash samples were collected during the initial 60-min constant intensity (64 mm h^{-1}) run. Splash boxes, each with a 0.2-cm high × 2.5-cm wide rectangular opening, were mounted at 2-, 6-, and 10-cm heights above the soil surface on each side of the box. Splash boxes were changed quickly at 10-min intervals during the event. Soil splash was then quantitatively transferred from each splash compartment to glass dishes for oven drying and weighing on an analytical balance.

Four soil cores (56 mm × 33 mm high) were inserted into the soil prior to rainfall simulation. At the end of the variable intensity sequence, the soil cores were carefully removed for measurement of soil strength and bulk density. The samples were rewet with a 0.1 mole/L $CaCl_2$ -$MgCl_2$ solution and allowed to equilibrate for 12 h. About 5 h before the strength measurement, the samples were transferred to a tension table maintained at a 1 kPa soil water potential. Soil shear strength was determined with a Swedish fall cone device (60 g cone) (Al-Durrah and Bradford, 1981). Four measurements were made on each core and averaged before additional analysis was performed. Soil bulk density of each core was determined by standard methods.

Interrill detachment was described as being proportional to the power of rainfall intensity and slope factor (Meyer, 1981),

$$D_i = K_i I^b S_f \qquad (4)$$

where D_i is the interrill erosion rate (kg m^{-2} s^{-1}), K_i is the interrill erodibility parameter of the soil (kg s m^{-4}), I is the rainfall intensity (m s^{-1}), b is the exponent related to soil clay content (Meyer and Harmon, 1984), and S_f is the slope factor defined by Liebenow et al. (1990).

$$S_f = 1.05 - 0.85 \exp^{[-4\sin(\theta)]} \quad (5)$$

where θ is the slope angle.

The average erosion rates obtained from the 15-min variable intensity storms were used to evaluate equation 4. To fit equation 4 to the data using a linear relationship, both the erosion rate (D) and rainfall intensity (I) data were transformed into logarithms. The transformed data were then plotted and the resultant intercept and slope values were used to predict the K_i and b values of equation 4, respectively.

Interrill erosion has been approximately proportional to the square of rainfall intensity and the slope factor (Meyer and Harmon, 1984; Watson and Laflen, 1986; Ghidey and Alberts, 1994):

$$D_i = K_i I^2 S_f . \quad (6)$$

Recent studies has shown that interrill erosion can be well expressed in terms of rainfall intensity and runoff rate (Ghidey and Alberts, 1994),

$$D_i = K_i \, I \, R \, S_f \quad (7)$$

where R is the runoff rate (m s^{-1}). Erosion and runoff rates from variable intensity runs were also used to evaluate equation 7.

Results and Discussion

Root Parameters

Differences in dead root mass and dead root length among the four crops were highly significant ($p < 0.05$) (table 1). Dead root mass and dead root length in the 0- to 0.15-m depth from the perennial crops (alfalfa and canada bluegrass) were much higher than those from annual row crops (corn and soybeans). There was almost a five fold difference in root mass and root length between alfalfa and soybeans. Root length per unit weight of dry roots was 22.0, 32.0, 28.7, and 26.1 km/kg for alfalfa, Canada bluegrass, corn, and soybeans, respectively.

Day 1, Constant Rainfall Intensity Run

Runoff, soil loss, and sediment concentrations for alfalfa, canada bluegrass, corn, and soybeans on the first day of simulation (60-min constant intensity run at 64 mm h^{-1}) are given in table 2. Runoff and soil loss were expected to be lower from the perennial crops than those from the annual row crops. As expected, runoff, soil loss, and sediment concentration from alfalfa were significantly lower ($p < 0.05$) than from corn or soybean. However, runoff, soil loss, and sediment concentration from canada bluegrass were significantly higher ($p < 0.05$) than those from alfalfa and were similar to those of corn and soybean.

Table 1. Mean dead root mass and dead root length values* for alfalfa, Canada bluegrass, corn, and soybean

Crop	Root Mass (g m^{-2})	Root Length (m m^{-2})
Alfalfa	495a	10,858a
Bluegrass	384a	12,289a
Corn	150b	4,258b
Soybean	92b	2,364c

* Values containing the same letter are not significantly different at 5% level.

Table 2. Mean runoff, soil loss, and sediment concentrations* measured during the first day constant intensity run

Crop	Runoff (mm)	Soil Loss (g min^{-1} m^{-2})	Sed. Concent. (Mg kg^{-1})
Alfalfa	53.3b	12.3b	13,800b
Bluegrass	58.1a	16.0a	16,500a
Corn	57.1a	17.8a	18,600a
Soybean	55.8ab	14.9ab	16,000ab

* Values containing the same letter are not significantly different at 5% level.

Day 2, Constant Rainfall Intensity Run

On the second day 30-min run at 64 mm h^{-1} intensity there was no significant difference ($p < 0.05$) in runoff among the crops, but there were significant differences ($p < 0.05$) in soil loss and sediment concentrations (table 3). Soil loss and sediment concentration were lower from crops with higher dead root mass and dead root length, but the differences were small when compared to the differences in root mass and length. For instance, dead root mass and dead root length for alfalfa were approximately 5 times higher than those for soybeans, but the differences in soil loss and sediment concentrations between alfalfa and soybeans were only 17 and 16%, respectively

Interrill Erodibility, K_i

Erosion rates measured from the 15-min variable intensity (25, 50, 75, and 100 mm h^{-1}) storms were used to evaluate the K_i and b values given in equation 4. K_i values ($\times 10^{-6}$) for alfalfa, canada bluegrass, corn, and soybeans were 2.66, 2.52, 3.04, and 3.26 kg s m^{-4}, respectively. The K_i values from perennial crops were significantly lower ($p < 0.05$) than those from the annual row crops. The mean exponent, b, values were 2.12, 1.95, 2.14, and 2.13 for alfalfa, canada bluegrass, corn, and soybeans, respectively. There were no significant difference ($p < 0.05$) in the exponent, b, values among the crops, and they were all close to 2.0 which agrees with previous studies that found interrill erosion to be proportional to the square of rainfall intensity (Meyer and Harmon, 1984; Watson and Laflen, 1986; Ghidey and Alberts, 1994).

The differences in K_i values among the crops were small relative to the differences in root mass and root length. For instance, K_i value for soybeans was less than 20% higher than that for alfalfa, whereas the dead root mass and dead root length for alfalfa were four to five times higher than those of soybeans. The mean K_i values ($\times 10^{-6}$) when computed from equation 6 (intensity square relationship) were 2.66, 2.56, 3.02, and 3.32 kg s m^{-4} for alfalfa, canada

Table 3. Mean runoff, soil loss, and sediment concentrations* measured during the second day constant intensity run

Crop	Runoff (mm)	Soil Loss (g min^{-1} m^{-2})	Sed. Concent. (Mg kg^{-1})
Alfalfa	27.3a	12.4b	13,400c
Bluegrass	28.6a	13.5b	14,100bc
Corn	28.2a	15.7a	16,600a
Soybean	28.2a	15.0a	16,000ab

* Values containing the same letter are not significantly different at 5% level.

bluegrass, corn, and soybeans, respectively. There was a definite trend when K_i values were plotted against the dead root parameters. As dead root mass and dead root length increased, K_i decreased (fig. 1). The relationships between K_i and dead root mass, and K_i and dead root length, using equation 6 were best expressed exponentially.

The relationship between K_i dead root mass was:

$$K_i = 3.55\ e^{-0.71\ RTM}$$

$$r^2 = 0.63 \qquad (8)$$

where RTM is dead root mass in kg m^{-2}.

The relationship between K_i and dead root length was:

$$K_i = 3.62\ e^{-0.029\ RTL}$$

$$r^2 = 0.59 \qquad (9)$$

where RTL is dead root length in km m^{-2}.

The above relationships were determined using dead root mass and dead root length values measured from each plot. For each cropping treatment, soil samples were collected from four plots. When the mean values were used to define the relationships, better relationships were found between K_i and dead root mass ($r^2 = 0.83$), and K_i and dead root length ($r^2 = 0.92$).

Interrill erodibility values were also computed using equation 7. The mean K_i values ($\times 10^{-6}$) for alfalfa, canada bluegrass, corn and soybeans were 2.95, 2.81, 3.22, and 3.46 kg s m^{-4}, respectively. These values were slightly higher than the ones computed using equation 6, however, relationships similar to the ones expressed in equations 8 and 9 were observed when dead root mass and dead root length values were plotted against the K_i values computed from equation 7.

Soil Parameters

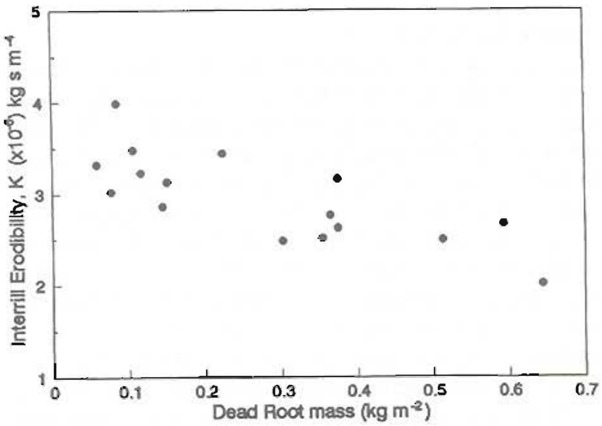
Bulk Density and Soil Shear Strength. There were no significant differences ($p < 0.05$) in bulk density among the crops measured in the soil within 50-mm × 33-mm high cores collected after the variable intensity sequence. Initial mean bulk density values were 1.06, 1.06, 1.07, and 1.07 mg m^{-3} for alfalfa, Canada bluegrass, corn, and soybean, respectively. At the end of the experiment, mean bulk density for alfalfa, Canada bluegrass, corn, and soybean were 1.10, 1.12, 1.11, and 1.10 mg m^{-3}, respectively. Dead root mass and dead root length had no significant ($p < 0.05$) effect on the final bulk density.

The effect of dead roots on the shear strength of the soil were significant ($p < 0.05$) (table 4). At the end of the experiment, soil shear strength was higher from soil samples with greater amounts of dead root mass and length. Mean soil shear strength for alfalfa and bluegrass were approximately. 22% higher than those for corn and soybeans.

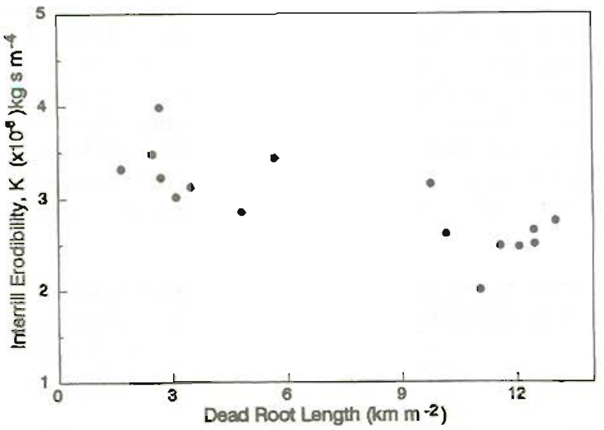
Dispersion Ratio and Aggregate Index

The effects of dead root parameters on aggregate stability such as aggregate index and dispersion ratio were significant ($p < 0.05$) (table 4). As dead root mass and dead root length increased, aggregate index increased and the dispersion ratios (DR20 and DR50) decreased. The aggregate index values for alfalfa and Canada bluegrass were twice those for corn and soybeans. DR20 and DR50 for alfalfa and bluegrass were approximately 40 and 35% lower than those for corn and soybeans, respectively.

There was no correlation between runoff and aggregate index or dispersion ratio, but there was a definite trend between soil loss and aggregate index, and soil loss and dispersion ratio. Soil loss decreased as aggregate index increased and dispersion ratio decreased. Our results support previous research findings that lower aggregate index and higher dispersion ratio values indicate increased susceptibility of the soil to erosion (Kemper and Rosenau, 1986).



(a)



(b)

Figure 1–Relationship between K_i and dead root mass (a), and K_i and dead root length (b).

Table 4. Mean soil strength, aggregate index (AI), dispersion ratio as defined by Olson (DR20), and dispersion ratio as defined by Middleston (DR%)*

Crop	Soil Strength (kPa)	AI	DR20	DR50
Alfalfa	5.14a	0.49a	6.7b	18.1b
Bluegrass	5.16a	0.48a	7.0b	16.0b
Corn	4.22b	0.21b	12.2a	25.4a
Soybean	4.23b	0.27b	11.1a	26.9a

* Values containing the same letter are not significantly different at 5% level.

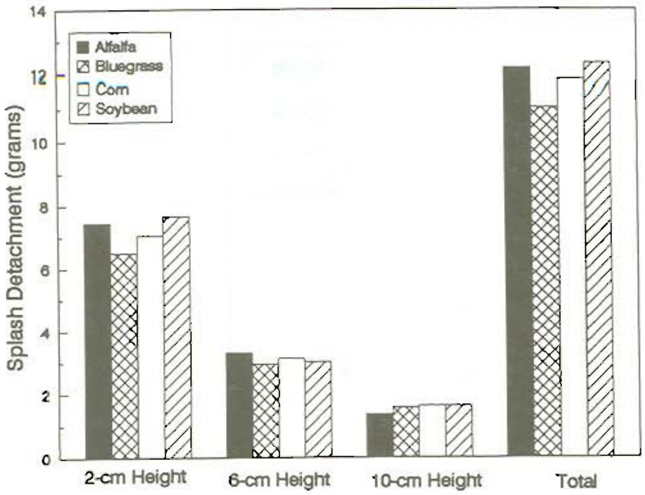


Figure 2–Soil splash collected 2-, 6-, and 10-cm heights above the soil surface.

Splash Detachment

Splash detachment at the 2-, 6-, and 10-cm heights, and total splash from the three heights measured during the first day constant intensity run are shown in figure 2. There were no significant differences ($p < 0.05$) in the total detachment among the crops. The total detachment measured at the three heights were 12.1, 11.0, 11.8, and 12.3 g for alfalfa, Canada bluegrass, corn, and soybeans. There were also no significant differences ($p < 0.05$) in splash detachment among the crops measured at 2-, 6-, and 10-cm heights. For each crop, about 60% of the splash was measured at the 2-cm height, 30% at the 6-cm height, and 10% at the 10-cm height.

Soil splash measured at 10-min time intervals during the one hour constant intensity run from the 2-, 6-, and 10-cm heights above the soil surface are given in figure 3. In all cases, splash detachment was highest during the initial 10-min of the simulation and decreased exponentially with time. The same trends were also observed when total splash detachments (sum of soil splash measured at the three heights) were plotted against time (fig. 4).

The effects of root parameters were not observed on splash detachment as they were on soil strength, aggregate stability, dispersion ratio, and interrill erodibility. Soil splash is mainly due to the forces of falling raindrops breaking down aggregates. The kinetic energy of raindrops falling at terminal velocity is from one to two orders of magnitude greater than the kinetic energy associated with gently flowing water (Hudson, 1981). Root mass and root length might have stabilized the aggregates to reduce erosion by runoff; however, these aggregates may not be stable when subjected to the impact of raindrops. Although there was variability in soil erosion among the crops due to differences in dead root mass and length, the effect was not observed on splash detachment.

Previous studies showed that splash detachment was highly correlated to soil shear strength (Cruse and Larson, 1977; Al-Durrah and Bradford, 1981; Al-Durrah and Bradford, 1982; Nearing and Bradford, 1985). In our study, splash detachment from crops that resulted in greater shear strength was not significantly different ($p < 0.05$) from

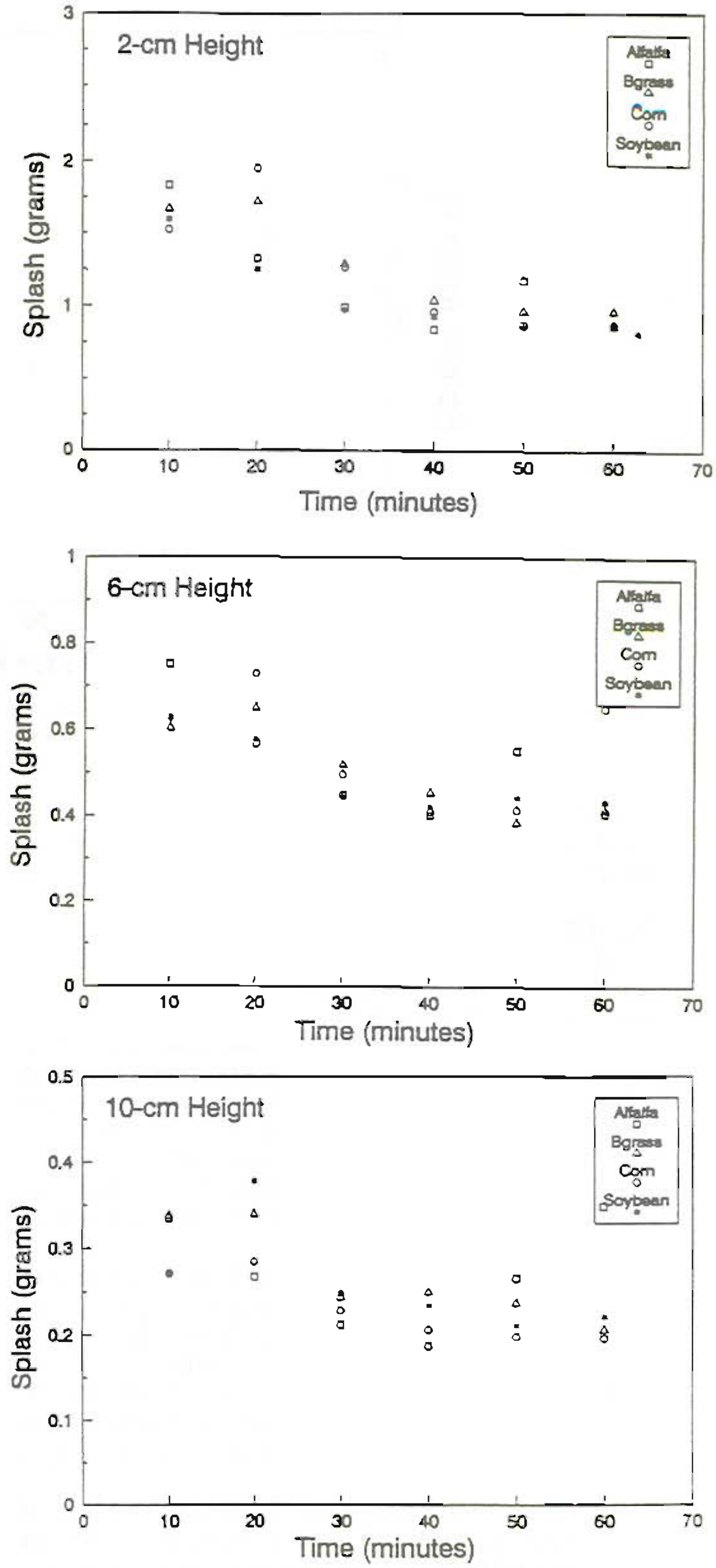


Figure 3–Splash collected in 10-min intervals at 2-, 6-, and 10-cm heights above soil surface.

crops with lower shear strength. Splash detachment was measured during the first day constant intensity dry run; whereas, the shear strength of the soil was measured at the end of the experiment after the variable intensity runs. Thus, it is difficult to conclude whether there was a

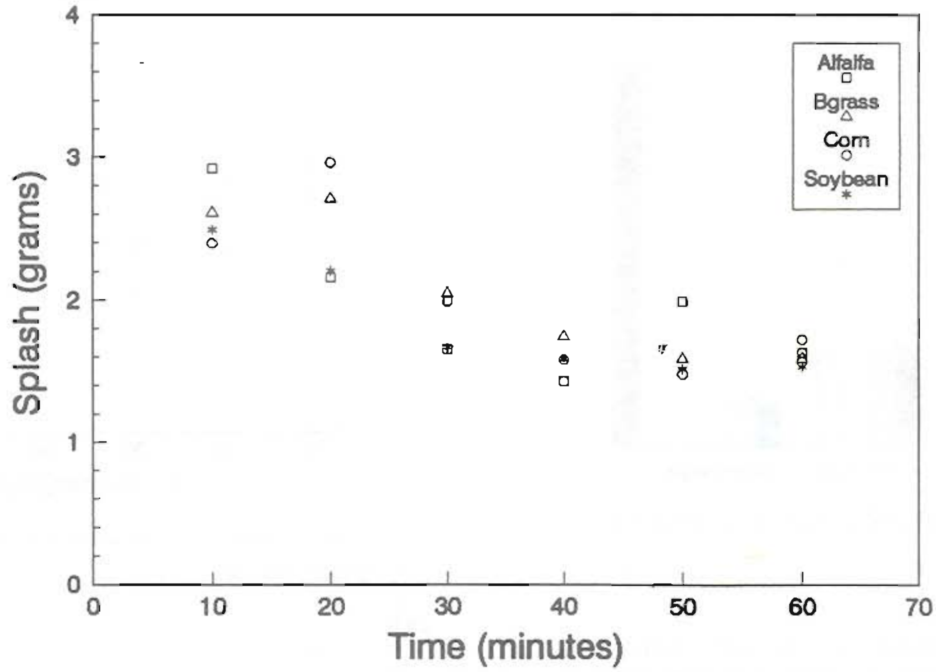


Figure 4–Total splash collected in 10-min intervals from 2-, 6-, and 10-cm heights above soil surface.

correlation between splash detachment and shear strength, since splash detachment was not measured during the variable intensity runs.

SUMMARY AND CONCLUSIONS

The effect of dead roots on runoff, soil erodibility, splash detachment, and aggregate stability were studied in the laboratory. We found that:

1. Dead roots had no effect on runoff but significantly influenced ($p < 0.05$) soil loss and sediment concentrations. Soil loss and sediment concentrations from annual row crops were significantly higher than those from perennial crops; however, the differences in soil loss among the crops were small relative to the differences in root mass and root length.
2. Interrill erodibility parameter, K_i, decreased as dead root mass and dead root length increased. There were exponential relationships between K_i and dead root mass and K_i and dead root length.
3. Dead roots had no effect on the soil bulk density, but significantly influenced soil shear strength. Soil strength increased as root mass and root length increased.
4. Dead roots significantly ($p < 0.05$) affected aggregate index and dispersion ratio. As the amount of root mass and root length increased, aggregate index increased, and dispersion ratio decreased.
5. The effects of dead roots were not observed on splash detachment as they were on soil strength, aggregate index, and dispersion ratio. Splash detachment was highest during the initial 10-min of simulation and then decreased exponentially.

The results obtained in this study have important implications for erosion scientists and modelers. The relationships between interrill erodibility, K_i, and root mass or root length observed in this study can be used in the erosion models such as WEPP to adjust predicted K_i values to temporal changes in either root parameters.

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