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The effect of herbaceous plant communities and soil textures on particle erosion of alluvial streambanks

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Abstract

Soil texture and plants are understood to be important determinants of erosion. However, there is a paucity of research on the quantitative effect of various soils, plants, or the interaction of the two, on streambank erosion. This study measures the influence of herbaceous plant communities and sandy loam, loam and clay loam soils on particle erosion rates. It demonstrates that the interaction of plants and soil are important. Seventy-one samples from the banks of 5 streams were tested using a flume. Multivariate regression analysis was used to analyze a dependent variable of erosion rate with independent variables of root density, soil texture, and plant communities. Autocorrelation was treated with the maximum chi-square method. Nebraska sedge (*Carex nebrascensis*) and Baltic rush (*Juncus balticus*) communities had the lowest erosion rates, followed by mixed sedge (*Carex lanuginosa*, *C. rostrata* and others) then mixed grass (*Poa pratensis* with *Deschampsia caespitosa*) communities. Silt had a negative effect on erosion for the Nebraska sedge, Baltic rush and mixed grass plant communities, but had no effect with the mixed sedge community due to a silt-by-sedge interaction. An increase in percent clay correlated with an increase in erosion. As percentages of clay or silt increased, root-volume density declined. Root-volume density was correlated negatively with erosion. Clay to silt ratio correlated negatively with erosion. Thus knowledge of both vegetation and soil texture are necessary to predict or manage streambank erodibility.

1. Introduction

Erosion and deposition are natural processes of stream morphology; however, they do not necessarily occur at equal rates. Variations in rates of erosion and deposition can lead to changes in channel width and depth which impacts stream management issues. For example, Platts et al. (1987) demonstrated the importance of channel width on fish habitat. As streambanks erode, the excess sediment disrupts aquatic life and changes stream shape. Headcuts can move up from a point of erosion, destroying meadows and worsening sedimentation problems.

On alluvial streams, plant roots protect against erosion by forming an interlocking mesh, holding soil in place and armoring against flowing water (Hadley, 1961; Smith, 1976; Gurnell and Gregory, 1984; Kamyab, 1991). Soil cohesion also reduces erosion. Past researchers have focused on the effects of soil and plants on erosion but rarely examine the effect of the two in combination. Previous field studies also tend to be qualitative rather than quantitative. As a result, land managers have little scientific evidence upon which to

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base revegetation and bioremediation decisions.

The purpose of this study is to quantitatively measure erosion rates as a function of soil texture, plant community, and the interaction of the two. The study focuses on particle or aggregate erosion as opposed to mass wasting.

There are few publications that measure streambank particle erosion in the field. Of the field studies that have been conducted, the reported erosion rates inherently include a combination of mass wasting and particle erosion (Smith, 1976; Kondolf, 1982; Dunne, 1988). As a result, the theoretical bases of the four hypotheses for this study are from other researchers' studies of mass wasting/particle erosion. These are:

(1) There is an inverse relationship between root density and particle erosion rate of a soil–root sample (Zimmerman et al., 1967; Swanson et al., 1982).

(2) Particle erosion rate is lowest with the Nebraska sedge (*Carex nebrascensis* Dewey), moderate with Baltic rush (*Juncus balticus* Willdenow), and highest with a mixed grass community of Kentucky bluegrass (*Poa pratensis* Linnaeus) and tufted hairgrass (*Deschampsia caespitosa* Palisot de Beauvois). This hypothesis is based on higher root mass and density of Nebraska sedge, followed by Baltic rush and Nevada bluegrass (*Poa nevadensis* Vasey ex Scribner) communities as reported by Manning et al. (1989).

(3) Soil texture and the interaction of soils and roots are both important factors of erosion. Clay soils are more cohesive and less erodible than sand (Bouyoucos, 1935; Glinski and Lipiec, 1990). Soil texture influences root systems by modifying aeration, water, and nutrient content and availability (Eavis, 1972; Ibanga et al., 1980; Bar-Yosef and Lambert, 1981; Stitt et al., 1982). Clayey and silty soils tend to inhibit root growth due to their small pore size (Taylor et al., 1966; Kramer, 1983; Glinski and Lipiec, 1990).

(4) Ratios among sand, silt and clay are significant determinants of erosion rate. Bouyoucos (1935), Trask (1959) and Schumm (1960) have used ratios of sand to clay or to clay and silt as indices of erodibility.

Preliminary findings reinforced the justification for this study; samples that had the highest amount of silt and clay had the lowest root density. Based on our hypotheses, fine grained soil should have low particle erosion rates, but conversely low root content would have high erosion rates. It was unclear what effect the soil–root combination would have on erosion.

2. Methods and materials

Bank samples were taken from five streams in order to obtain a wide range of soil and plant community types. Birch and Kingston Creeks are in the Toiyabe Mountain Range, and Barley Creek is in the Monitor Mountain Range in central Nevada. Dog and Slinkard Creeks lie on the eastern side of the Sierra Nevada Mountain Range in California (Fig. 1). This study expands a related study which used samples from a different but similar reach of Slinkard Creek (Kamyab, 1991).

In general the chosen sites are moderately entrenched to unentrenched, highly sinuous streams meandering through gently sloping meadows. Average channel widths range between 1.2 to 4.5 meters. Average stream depths at bankfull are between 0.6 to 1.0 meters. The meadow soils are non-gravelly, ranging between sandy loam, silt loam and clay loam. All but one of the four creeks conform to these characteristics. Kingston Creek, the exception, is more entrenched.

At each of the five stream sites, 10 to 20 sample

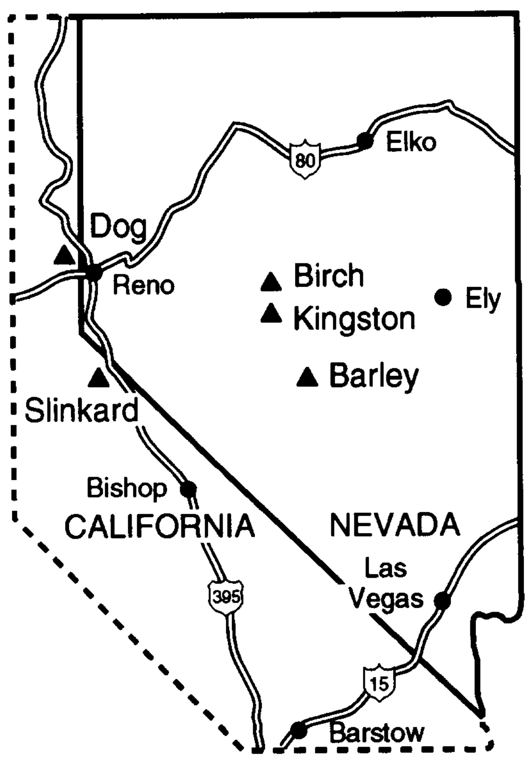

Fig. 1. Location map.

locations were chosen along typical sections of channel bank for a total of 80 samples. Because Kingston Creek has downcut enough in places to abandon its floodplain and become entrenched, some of these samples were elevated approximately 24 cm above the top of the active channel. Sample locations were approximately 4.5 to 7.5 m apart and situated mainly along straight reaches or the outside of meander curves. Locations were in relatively homogeneous plant communities which extended for at least 2 m along a streambank. Homogeneity was based on visual inspection. To determine species composition, a 20 cm ring was placed at each sample location and the encircled above-ground plant matter was clipped at ground level. The cut plants were identified and separated according to species. Soil–root samples were taken by driving a 7 cm diameter by 15 cm long corer into the top 15 cm of the trimmed location.

The cut plants taken from the field were oven dried and weighed. Species weight data were used with the Twinspan cluster analysis software to identify plant communities.

Sieve analyses and hydrometer tests (Gee and Bauder, 1986) were used to assess soil textures on a portion of each core sample. Organic matter was removed from the soil prior to doing the hydrometer tests.

To determine the root-volume density, a volume of 220 cm^3 was cut from the top 4 cm of each soil–root sample core. Soil was washed from the roots in a two stage process. The first washing was done by hand over a 180 μm screen. What remained in the screen was placed into a 50 cm tall, 8 cm diameter glass tube. Water was forced into the bottom of the tube, thus buoying up the less dense root matter, leaving sand in the bottom. The water with the suspended roots was poured off into the 180 μm screen. Root volume was measured by submerging the saturated roots in a 300 ml beaker of water. The displaced water level equalled root volume. Because all samples came from the same soil–root core volume (220 cm^3), the measurements represent root-volume density (root volume per soil–root volume). Root-volume densities of plant communities were compared with an analysis of variance using the Bonferroni method (Pfaffenberger and Patterson, 1987) and the results are reported in Table 3.

Particle erosion rates of the samples were measured in a laboratory flume. In preparation for the flume test, the lower 4 to 15 cm of each soil–root core was split lengthwise using a hacksaw. The sample was attached with nails to a plastic backing, oven dried at 60°C and weighed. To perform the tests the samples were saturated in tap water for 30 min then placed in a flume such that the flat side of a halved soil core was flush with, and part of, the wall of the flume. The top of the sample was submerged just below the surface of the water in order to simulate a top of bank position in a bankfull discharge event. Each flume test lasted 30 min. This was based on results of Kamyab (1991) who, in similar tests, found the maximum rate of erosion was obtained within 30 min. At the culmination of each flume test, the remaining soil–root sample was dried and weighed. The difference in weight constitutes loss due to erosion.

The flume was 60 cm wide by 25 cm deep, with a slope of 0.008. These settings yielded a similar shear stress on the channel walls as would be produced in the field under a bankfull event based on computations using:

$$T = GRs$$

where T is the shear stress, G is the specific weight, R is the hydraulic radius, and s is the slope of the energy grade line.

Field shear stress was predicted using the average bankfull hydraulic radius and slopes of the streams. The bankfull event was chosen based on the premise set forth by Dunne and Leopold (1978) that bankfull stage corresponds to the discharge which results in the average morphologic characteristics of channels.

Two pumps produced a flow of approximately 0.2 m^3/s (3380 gal/min), and a shear stress on the samples of 13.41 N/m^2. Shear stress, calculated as described above, was also estimated with a coarse, open-grained sand paper (Adalox A > 11, 36-D) covered metal plate. This was attached to a slightly flexible rod and placed in the flume wall where the sample faces had been. The force of flowing water pushed the plate sideways and activated a strain gauge attached to the rod. Displacement was measured with a meter (Baldwin Lima Hamilton, SR4). The force was then duplicated by hanging weights from the plate so that the amount and direction of displacement equalled that caused by the water.

Multiple regression analysis was used to determine the empirical relationship of erosion rate with plant and soil characteristics. The regression model included a dependent variable of percentage flume erosion rate, and independent variables of root-volume density, plant communities, soil texture (percent silt and clay) and the clay to silt ratio. Also included was a soil–plant interaction term that measures the combination of soil and plants working together.

The indicator variable method (Kennedy, 1985; Gujarati, 1988) was used in the regression model to quantify the effect of vegetation type on erosion. Indicator variables are used for qualitative (categorical) variables. In this method one indicator out of a group of indicators must be omitted from the regression equation. The t values and coefficients of the included variables are used to compare the effects of the included variables to the effect of the excluded one.

Initial regression analysis indicated that heteroscedasticity was present. The heteroscedasticity was removed by using the generalized least squares method (Kennedy, 1985; Gujarati, 1988). For the weighting we used the expected values of erosion (Y) from an original, heteroscedastic regression model. The original model was then divided by a transformation term of $1/Y^2$, yielding a homoscedastic model. As a result of this division the dependent variable, erosion, is relative erosion and has no units.

The results of preliminary regression models were highly unstable. The significance level and signs of estimated coefficients changed drastically when variables were added or removed. This instability results from combinations of correlations between the explanatory variables; however, it was unclear which variables or sets of variables were the source of the instability. Simple regressions between the variables did not reveal any R^2 values over 0.3480. The final regression was obtained with the "maximum chi-square" method often used with autoregression data (McClave, 1978). Maximum chi-square is used when the source of autocorrelation cannot be identified. In this method independent variables are initially identified for inclusion in a preliminary regression model. An initial model was estimated with root-volume density, soil percentage and plant community variables. The initial variables are chosen on a theoretical basis of what should explain the dependent variable. Additional explanatory variables are then added one at a time. Each successive model included the variable which had the biggest impact on the adjusted R^2. This process was repeated with remaining variables until no more impact was observed. Many possible soil–root and soil–plant interactions and ratios of soil textures were tested. No soil–root interaction was found to be significant. The only variables with significant impact on the initial model were the silt-by-mixed sedge community interaction and the clay to silt ratio.

3. Results

Plant communities identified by the Twinspan cluster analysis software were almost identical to groups chosen on the basis of field observations. The four plant communities identified were: (1) Nebraska sedge, (2) Baltic rush, (3) a mixed grass group (Kentucky bluegrass with tufted hairgrass), and (4) a mixed sedge group consisting of: woolly sedge (*Carex lanuginosa* Michaux), beaked sedge (*C. rostrata* Stokes) and small-wing sedge (*Carex festivella* Mackenzie). A list of species composition of the plant communities is given in Table 1. Table 2 lists typical plant communities for the stream sites.

Nearly 50% of the samples were sandy loam under the USDA classification system (Gee and Bauder, 1986). Of the remaining samples, 21% percent were composed of loam and 13% of clay loam. The rest were silty clay loam (6%), silt loam (4%), sandy clay loam (4%), sand (1%) and loamy sand (1%). Table 2 lists typical soil types for the stream sites.

A chi-square analysis showed that plant communities were not independent from soil types ($p \leqslant 0.005$). Nebraska sedge and mixed sedge communities were found mainly in loamy to sandy loam soils. The Baltic rush was mostly in sandy clay loam to sandy loam soils. Mixed grass samples were in clay loam, silt loam and silty clay loam soils.

The statistical analysis of erosion rates produced the following multiple linear regression model:

$$\begin{aligned} Erosion = {} & \underset{(0.001)}{88.02} - \underset{(0.01)}{9.37\,Rtden} - \underset{(0.001)}{2.16\,Silt} + \underset{(0.05)}{1.57\,Clay} \\ & - \underset{(<0.25)}{2.28\,Rush} + \underset{(0.01)}{26.34\,Grass} - \underset{(0.001)}{58.38\,Sedge} \\ & + \underset{(0.001)}{2.11\,Silt\text{-}by\text{-}sedge} - \underset{(0.025)}{59.00\,Clay/silt} \end{aligned}$$

R^2 adj. $= 0.59$ $\quad F = 13.49$

p values in parentheses

where:

Erosion	=	erosion rate measured in the flume test
Rtden	=	natural log of measured root-volume density
Silt	=	percentage of silt
Clay	=	percentage of clay
Rush	=	Baltic rush community type
Grass	=	mixed grass community type
Sedge	=	mixed sedge community type
Silt-by-sedge	=	interaction of % silt and mixed sedge community
Clay/silt	=	ratio of % clay to % silt

Baltic rush community type (*Rush*) has an insignificant p value, but was forced into the original regression equation (using the maximum chi-square technique) in order to determine its effect, if any, on erosion.

Root-volume density (*Rtden*) was negatively correlated with erosion in the multivariate analysis. One way ANOVA and Bonferroni tests showed that plant communities with higher average root-volume density had lower average erosion rates (Table 3).

Both percentage silt and clay are significant determinants of erosion. According to the regression coefficients, clay has a positive effect on erosion. Silt has a negative effect on erosion when the plant communities are Nebraska sedge, Baltic rush and mixed grass. It has almost no effect on erosion when the plant community is mixed sedge. This relationship is visually demonstrated in Fig. 2. The difference is due to the effect of the interaction of silt with mixed sedge (*Silt-by-sedge* variable). With the influence of this soil–plant interaction, the mixed sedge community has the lowest erosion rate of the four plant communities when silt is low ($<25\%$), but has the highest erosion rate when silt is above 40%.

Variability of erosion rate with soil composition is augmented by the clay to silt ratio. The ratio is negatively correlated with erosion; however, the degree of effect is dependent on the soil composition. As either clay increases or silt decreases there is less expected erosion.

According to the estimated partial regression coefficients, mixed sedge should be the least erodible due to its small estimated coefficient value. However, examination of the regression equation as a whole

Table 1
Plant communities

	Plant community			
	Nebraska sedge	Baltic rush	Mixed grass[a]	Mixed sedge
Dominant plants % range by wt. (average %)	1. Nebraska sedge 33–100% (76%) 2. Baltic rush 0–57% (10%)	Baltic rush 33–90% (60%)	1. Kentucky bluegrass 0–96% (48%) 2. Tufted hairgrass 0–91% (23%) 3. Idahoe fescue[d] 0–49% (5%)	1. Woolly sedge 46–100% (63%) 2. Beaked 0–84% (11%), small-wing sedge 0–88% (6%), flaccid 0–29% (3%)[f], and short-beak[c] 0–12 (1%)
Incidental plants	1. Blackcreeper sedge[b] 0–40% (4%) 2. Short beak sedge[c] 0–29% (2%)	1. Idahoe fescue[d] 0–45% (10%) 2. Swordleaf rush[e] 0–39% (5%)	1. Baltic rush 0–32% (5%) 2. Small wing sedge 0–53% (9%)	1. Baltic rush 0–39% (7%) 2. Kentucky bluegrass 0–38% (5%)

[a]The majority of the samples in this group were composed of 70 to 100% grass species.
[b]*Carex Praegracilis* Boott.
[c]*Carex simulata* Mackenzie.
[d]*Festuca idahoensis* Elmer.
[e]*Juncus ensifolius* Wikstrom.
[f]*Carex leptalea* Wahl.

Table 2
Comparison of stream site soil types and erosion rates

Stream	Typical plant communities	Typical soil type	Average erosion rate (% eroded over time)
Kingston Creek	mixed grass, some mixed sedge	loam, clay loam, silt loam and silty clay loam	53 a*
Barley Creek	mixed sedge, Baltic rush, some mixed grass	sandy clay loam and loam	29 b
Slinkard Creek	Nebraska sedge, Baltic rush, some mixed grass	loam, sandy loam, and clay loam	9 c
Dog Creek	Nebraska sedge	ditto	17 c
Birch Creek	Nebraska sedge	ditto	14 c

*Values with different letters are statistically different from each other at $p=0.05$ or better.

Table 3
Comparison of erosion rate and root density of plant communities

Plant community	Average root-volume density (ml/l)[1]	Standard deviation of root density	Average erosion rate (% eroded over time)	Standard deviation of erosion	No. of samples
Nebraska sedge	5.6 a*	2.03	14.51 d*	9.29	39
Baltic rush	6.3 a	1.76	14.67 d	17.00	8
Mixed grass	2.7 b	1.63	46.52 e	37.41	10
Mixed sedge	4.6 c	1.71	28.15 f	19.91	14

[1]Volume of roots per volume of soil-root core.
*Values with different letters are statistically different from each other at $p=0.1$ or better.

reveals that the negative estimated coefficient of the mixed sedge community (*Sedge*) is buffered by the positive estimated coefficient of the interaction term (*Silt-by-sedge*). The magnitude of effect that the positive interaction term has is dependent upon the percentage of silt. When the average measured percentage of silt (30.6) is used for the calculations, the result is that the mixed sedge community is less erodible than the mixed grass community, but more erodible than the Nebraska sedge and Baltic rush communities given identical soil types. This demonstrates that in order to understand the effect of the mixed sedge community, the entire regression model must be considered, including soil composition and plant–soil interaction. A one way ANOVA test supports what the full multiple regression model shows; using a one way ANOVA, the mean erosion rate of mixed sedge community samples is midway between the high rate of mixed grass and the lower Nebraska sedge and Baltic rush community samples (Table 3).

It was found that stream-grouped samples had equal variance of errors in the regression equation, and consequently each sample was treated independently. There is a possibility, however, that the 5 streams with their differing (but variable) soil types and plant communities should be analyzed as 5 replicates with the individual samples being subsamples. In addition to the plant and soil variation, there may be other unidentified stream characteristics that affect erosion. For example, the soils on Kingston Creek (predominately silty clay

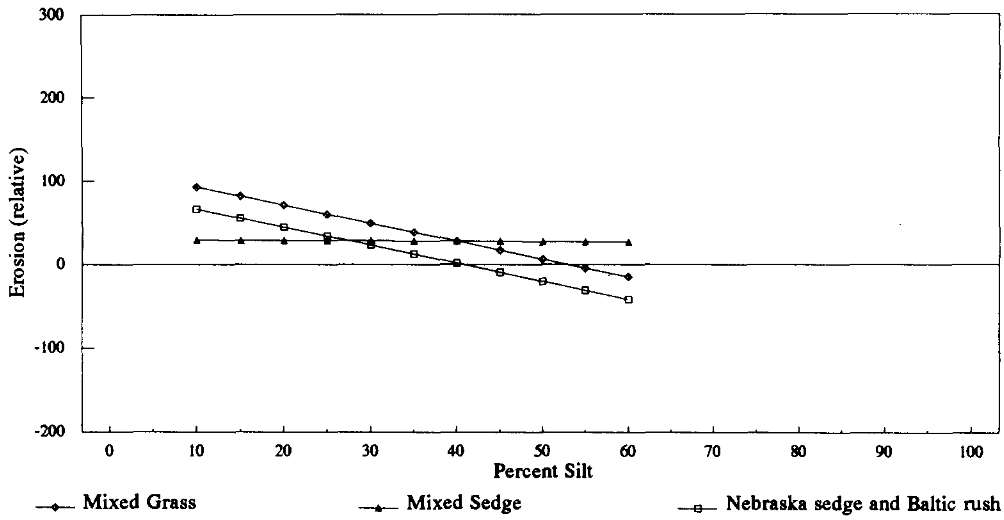

Fig. 2. Relationship between percent silt and erosion rate in the presence of the four plant communities as predicted by the regression model.

loam and silt loam) were drier and more friable, presumably due to a lowered ground water table resulting from stream entrenchment. The soil moisture difference may be an important determinant of root density (Bar-Yosef and Lambert, 1981; Manning, 1989) and in turn, erosion rate. A comparison of erosion means among stream groups using one way ANOVA and the Bonferroni method showed that Kingston samples had the highest ($p \leqslant 0.05$) erosion rates (53%), followed by Barley Creek (29%), and Slinkard Creek (9%). Erosion on Dog (17%), Birch (14%) and Slinkard (9%) Creeks were not statistically different from each other.

4. Discussion and conclusions

The purpose of using a flume to measure erosion rates is to be able to control the hydrologic regime. Admittedly, there are differences between measured flume erosion rates, and expected rates in a natural stream environment: First, there is higher velocity and probably higher erosion rates in the flume because the flume walls are smoother than streambanks, especially those where roughness is increased by above-ground vegetation and protruding roots; second, in removing the sample from the bank, there is a possible loss of stability that was offered by the surrounding soil–root mass; and third, there most likely is increased erosion occurring at the upstream and downstream edges of the sample. Although the sample face was placed flush with the flume walls at the commencement of each test, erosion of the sample produced a gap perhaps a few millimeters wide between the flume walls and the soil. This gap could produce an eddy behind the upstream (relative to the sample) flume wall. Although the eddy effect was too small to measure, many of the samples appeared to be more eroded on the edge closest to the upstream flume wall. Despite the differences between the laboratory and field erosion processes, the flume experiments allowed measurements of relative erosion rates between samples of differing soil/plant composition.

According to the regression coefficients, as percent clay increases, erosion increases. This finding contrasts with other studies reporting that clay correlates with increased soil strength (Bouyoucos, 1935; Glinski and Lipiec, 1990) and decreased streambank erosion (Grissinger et al., 1981). The finding may be explained by the influence of soil texture on root growth. Root density tends to decrease with increasing clay or silt content, while sand correlates with greater root density (Fig. 3). This is consistent with past studies where clay–silt soils were found to mechanically inhibit root growth (Taylor et al., 1966; Ibanga et al., 1980; Stitt et al., 1982). Soil texture is also known to influence soil moisture and soil nutrient status, which in turn affects root growth and density (Andrews and New-

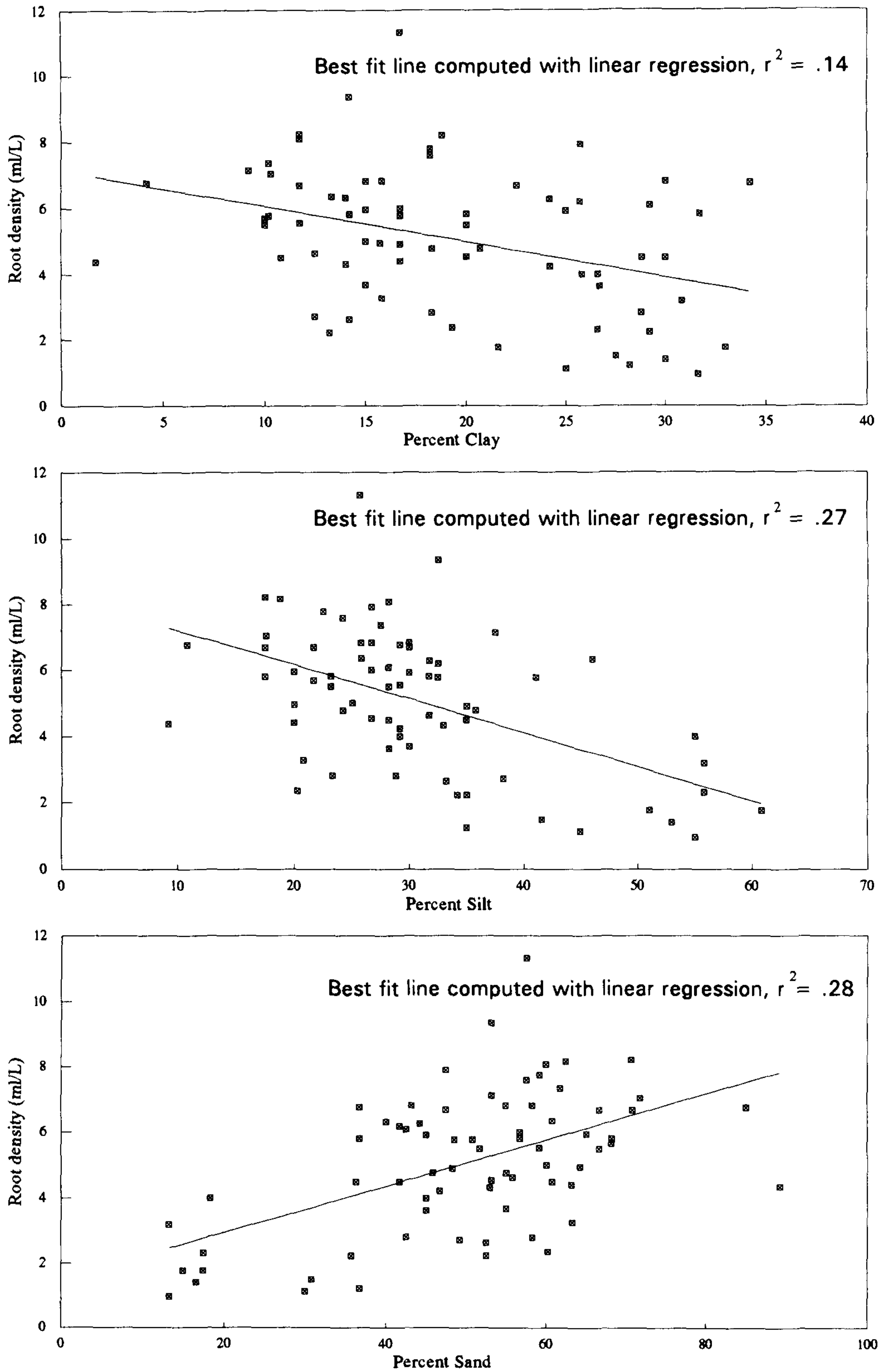

Fig. 3. Measured values of percent clay, silt, and sand, and root-volume density (density is volume of roots per volume of root and soil, ml l^{-1}).

man, 1970; Kramer, 1983; Glinski and Lipiec, 1990). The interplay of soil texture on root growth justifies why percent clay is positively correlated with erosion and why the silt-by-sedge interaction variable is significant in explaining erosion.

Observations made during the flume tests support the above findings. The samples were saturated by placing them in a pan of water before the flume tests. Nine of the samples, notably those with the highest clay–silt content, disaggregated into incohesive piles of mud. It was not possible to conduct a flume test on these samples. The root content of these samples was exceptionally low and not sufficient to hold the mud together. All but one of these samples were from the mixed grass plant community. It is conceivable that the fine textured soil limited root growth in these samples. From these data, however, it was not statistically possible to determine whether the low integrity was due to the high clay–silt content, the low root-volume density, or the mixed grass community type.

In conclusion, soil textures or plant communities alone do not determine the erodibility of an area. Soil–plant interaction can alter the effect of a soil or plant community on erosion. As a result, the presence of a cohesive soil or a certain plant community will not guarantee a stable streambank. It is largely believed that clayey soils are resistant to erosion, however this was not the case in this study. The reason may be that the effect of soil texture on root growth is playing a greater role in determining erodibility than previously suspected. Although the tendency is often to regard only soil types or plant communities when determining erodability, this study highlights the need to consider soils, plants and the interaction of the two in management decisions.

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References

Andrews, R.E. and Newman, E.I., 1970. Root density and competition for nutrients. Ecol. Plants, 5: 319–334.

Bar-Yosef, B. and Lambert, J.R., 1981. Corn and cotton root growth in response to soil impedance and water potential. Soil Sci. Soc. Am. J., 45: 930–935.

Bouyoucos, G.J., 1935. The clay ratio as a criterion of susceptibility of soils to erosion. Am. Soc. Agron. J., 27: 738–741.

Dunne, T., 1988. Geomorphologic contributions to flood control. In: V.R. Baker, R.C. Kochel and P.C. Patton (Editors), Flood Geomorphology. Wiley, New York, pp. 421–438.

Dunne, T. and Leopold, L.B., 1978. Water in Environmental Planning. W.H. Freeman, New York, 818 pp.

Eavis, B.W., 1972. Soil physical conditions affecting seedling root growth, I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam soil. Plant Soil, 36: 613.

Gee, G.W. and Bauder, J.W., 1986. Particle-size analysis. In: A.L. Page (Editor), Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. Agronomy Monograph, 9. 2nd ed. Am. Soc. of Agronomy, Madison, WI, Ch. 15.

Glinski, J. and Lipiec, J., 1990. Soil Physical Conditions and Plant Roots. CRC Press, Boca Raton, Fla., 244 pp.

Grissinger, E.H., Little, W.C. and Murphy, J.B., 1981. Erodibility of streambank materials of low cohesion. Trans. Am. Soc. Agric. Eng., 24: 624–630.

Gujarati, D.N., 1988. Basic Econometrics. 2nd ed. McGraw-Hill, New York, 705 pp.

Gurnell, A.M. and Gregory, K.J., 1984. The influence of vegetation on stream channel processes. In: T.P. Burt and D.E. Walling (Editors), Catchment Experiments in Fluvial Geomorphology. Proc. IGU Commission Meeting, Exeter and Huddersfield, UK, Aug. 16–24, 1981. Geo Books, Norwich, pp. 515–535.

Hadley, R.F., 1961. Influence of riparian vegetation on channel shape, northeast Arizona. U.S. Geol. Soc. Prof. Pap., 242-C: 30–31.

Ibanga, I.J., Bidwell, O.W., Powers, W.L., Feyerhern, A.M. and Williams, W.W., 1980. Soil consistence: effect of particle size. Soil Sci. Soc. Am. J., 44: 1124–1126.

Kamyab, I., 1991. Streambank stability prediction for C6 stream type reconstruction. Ph.D. thesis, Univ. of Nevada, Reno.

Kennedy, P., 1985. A Guide to Econometrics. 2nd ed., Basil Blackwell, Oxford, 238 pp.

Kondolf, G.M., 1982. Recent channel instability and historic channel changes of the Carmel River, Montery County, Calif. M.Sc. Thesis, Univ of California, Santa Cruz, 111 pp.

Kramer, P.J., 1983. Water Relations of Plants. Academic Press, New York, 489 pp.

Manning, M., Swanson, S.R., Suejcar, T. and Trent, J., 1989. Rooting characteristics of four intermountain meadow community types. J. Range Manage., 42(4): 309–312.

McClave, J.T., 1978. Estimating the order of autoregressive models: The maximum chi squared method. J. Am. Stat. Assoc., 73(36): 122–128.

Pfaffenberger, R.C. and Patterson, J.H., 1987. Statistical Methods for Business and Economics. 3rd ed. Richard D. Irw, Homewood, IL, 1246 pp.

Platts, W.S., Armour, C., Booth, G.D., Bryant, M., Bufford, J.L., Cuplin, P., Jensen, S., Lienkaemper, G.W., Minshall, G.W., Monsen, S.B., Nelson, R.L., Sedell, J.R. and Tuhy, J.S., 1987.

Methods for evaluating riparian habitats with applications to management. USDA For. Serv. Gen. Tech. Rep. INT-122: 177 pp.

Schumm, S.A., 1960. The shape of alluvial channels in relation to sediment type. U.S. Geol. Surv. Prof. Pap., 352-A: 17–30.

Smith, D.G., 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. Geol. Soc. Am. Bull., 87: 857–860.

Stitt, R.E., Cassel, D.K., Weed, S.B. and Nelson, L.A., 1982. Mechanical impedance of tillage pans in Atlantic Coastal Plains soils and relationships with soil physical, chemical, and mineralogical properties. Soil Sci. Soc. Am. J., 46: 100–106.

Swanson, F.J., Gregory, S.V., Sedell, J.R. and Campbell, A.G., 1982. Land–water interactions: The riparian zone. In: Edmonds, L. Robert (Editor), Analysis of Coniferous Forest Ecosystems in the Western United States. US/IBP Synthesis Series 14. Hutchinson Ross, Stroudsburg, Penn., pp. 267–291.

Taylor, H.M., Roberson, G.M. and Parker, J.F., Jr., 1966. Soil strength–root penetration relations for medium- to coarse-textured soil materials. Soil Sci., 102: 18–22.

Trask, P.D., 1959. Effect of grain size on strength of mixtures of clay, sand, and water. Geol. Soc. Am. Bull., 70: 569–580.

Zimmerman, R.C., Goodlett, J.C. and Comer, G.H., 1967. The influence of vegetation on channel form of small streams. Int. Assoc. Sci. Hydrol., 75: 255–275.