This paper was peer-reviewed for scientific content.
Pages 594-600. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001. Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Use of the Chain Set for Scale-Sensitive and Erosion-Relevant Measurement of Soil Surface Roughness

S.D. Merrill, C. Huang, T.M. Zobeck and D.L. Tanaka*

ABSTRACT

Soil surface roughness acts in erosion processes as an erodibility factor at one scale and a structural factor impacting wind or water erosivity at a higher but contiguous scale. Thus, roughness measurement must be multiscalar and scale-continuous. Use of chain-like devices to mechanically integrate roughness by the foreshortening of their length provides universally accessible and practical roughness measurement in the field. Computer simulation has shown that the use of a set of chains in which the linkage length of each individual chain is in a geometric progression will overcome the scale-indeterminacy that is inherent in using a single chain. Furthermore, the chain set will act as a nested set of scale filters to provide scale-sensitive roughness measurement.

Field measurements using a 6-member chain set with link lengths in a geometric progression ranging from 0.48 to 15.2 cm (recorded as chain roughness (CR), in percent) were compared with micro-topographic data from a laser scanner. Measurements were taken on 2 soil types under 4 tillages before and after attenuation of roughness by water application. Regressions of CR against log (link length) showed large declines in absolute slopes after erosion had occurred. This appears to be associated with greater decay of smaller-scale roughness elements (RE's) than larger ones, and shows the ability of the chain set to indicate qualitative changes in roughness caused by erosion. Chain set CR's and CR differences were regressed against two laser scanner-derived roughness indices – a standard deviation index (STDI) and a wind erosion process index (SAP30, area sheltered from abrader at < 30 deg.) Multiple regressions of scanner-derived indices against CR differences revealed a striking contrast between the SAP30 index's dependence on CR differences representing smaller-scale RE's versus the STDI index's dependence on CR differences representing larger-scale RE's. The chain set concept should be capable of providing measurement of joint soil and crop residue roughness effects.

INTRODUCTION

Soil wind and water erosion are natural, complex-chaotic dynamic processes (Goldenfeld and Kadanoff, 1999). The concept of soil surface roughness is central to scientific understanding of erosion processes. Soil micro-topography -- roughness -- acts at lower scale as an erodibility factor, determining resistance or vulnerability to erosion. At contiguous but higher scale, roughness becomes an erosivity factor, structurally mediating erosive energy of wind and water. As an erodibility factor, roughness acts inseparably with other perceived erodibility factors -- soil-inherent erodibility and cover factors (rocks, dead and live plant material). Thus, progress-enhancing measurement of soil roughness must be scale-sensitive and scale-continuous. Such measurement will greatly encourage implementation of multiscalar, hierarchical modeling and theory-building in soil erosion research (Werner, 1999).

Pin meters and profile meters - devices based on pin racks - were the former dominant means for measuring soil roughness (Zobeck and Onstad, 1987). Scale-sensitive and scale-continuous roughness measurement became possible over scales from 1 mm to 1 m with the advent of laser micro-topographic scanners (Huang and Bradford, 1990; Römkens et al., 1988). The analysis of surface roughness by fractal and other scale-inclusive models has been described by Huang and Bradford (1992).

Saleh (1993) introduced the chain method for measuring soil roughness. Chain roughness (CR: non-dimensional, percent) is determined by the degree of foreshortening of a roller chain laid on the soil surface:

$$CR = 100\,(1 - L2/L1) \qquad [1]$$

where L1 is the full length of the chain and L2 is the horizontal distance between chain ends when placed on the soil. Skidmore (1997) has pointed out that the chain technique could be subject to scale indeterminacy, noting that a very fine chain could yield the same CR value for a surface with many small roughness elements (RE's) as for a surface with a smaller number of larger RE's of the same shape. Skidmore's (1997) comments referred directly to ridge (oriented, machinery-generated) roughness, and Saleh (1997) responded that knowledge of the number of ridges should remove this particular indeterminacy.

*S.D. Merrill and D.L. Tanaka, USDA-Agricultural Research Service Northern Great Plains Research Laboratory, P.O. Box 459, Mandan, ND 58554. E-mail: C. Huang, USDA-ARS, National Soil Erosion Research Laboratory, Purdue Univ. 1196 SOIL Bldg., West Lafayette, IN 47907-1196; T.M. Zobeck, USDA-ARS, Plant Stress Laboratory, 3810 4th St., Lubbock, TX 79401-9750. *Corresponding author: merrills@mandan.ars.usda.gov

Based on a computer simulation study, Merrill (1998) concluded that any scale indeterminacy in single chain use could be overcome by using a set of chains in which the linkage lengths of individual chains are in geometric progression. Merrill (1998) also concluded that use of a chain set would yield information about the "fractal character" of soil roughness. "Fractal character" may be defined as the multiscalar size distribution of RE's relative to the largest sized RE's.

The purpose of this paper is to present results of field research comparing measurements made with the chain set to micro-topographic data collected with a laser scanner. Another purpose is to discuss concepts of scale-sensitive, scale-inclusive, and hierarchical measurement of soil roughness, and the role that the chain set can play in reaching these conceptual goals.

Theoretical Study

Randomly rough surfaces were simulated in a computer study as hemispherical RE's semi randomly placed upon a plane, as detailed by Merrill (1998). Placement of roller chains on surfaces was simulated as joined line segments. Link lengths of simulated chains were 0.89, 2.0, 4.5, 10, and 22.4 cm, and chain roughness values calculated per Equation 1 are designated CR0.9 through CR22.

The simulation of chain sets laid on surfaces of homogeneously sized RE's in Fig. 1 shows that the chain set acts as a nested set of scale filters. When the effective RE diameter approaches half the size of the chain link length, CR value drops by approximately 30%, and when RE diameter becomes about a third of link length, CR is lowered by about 70%. Thus, a chain set member integrates roughness for the range of scales between linkage length and the scale approaching chain length. The smallest-linked member of a chain set reports the effect of the greatest accumulation of RE scales, while the largest-linked member reports effect of the least RE scale accumulation.

The ability of the chain set to provide semi-quantitative information about "fractal character" is shown by simulation results of chain set layings on 3 surfaces of successively lesser homogeneity of RE size (Fig. 2). Plotting CR values versus log of link length reveals that the slope of regression progressively increases in absolute value as the size distribution of RE's becomes less uniform, i.e., the absolute regression slope increases as the degree of "fractal character" increases.

Approach to Field Experimentation

A chain set was constructed from ANSI standard roller chain so that each member was 92 cm in length: (1) chain with 0.476-cm links; (2) chain with 0.953-cm links; (3) 0.95-cm linked chain with every 2 links spot welded to form 1.91 cm links; (4) every 4 links welded to form 3.81-cm links; (5) every 8 links welded to form 7.62-cm links; (6) every 16 links welded to form 15.24-cm links.

Work was conducted on two kinds of soil, a sandy loam and a silt loam. The sites were given a pre-treatment consisting of moldboard plowing, harrowing, and rolling in the spring. Small, thrice-replicated areas were tilled with (a) a moldboard plow, (b) a tandem disk, or (c) a V-blade. Most measurements were made on these treatments; several measurement sets were taken on sandy loam soil tilled by field cultivator.

After tillage, approximately 1-m^2 areas were measured first by laser scanner and then by chain set (see Fig. 3). Elevation datasets were taken with a laser micro-topographic scanner (Huang and Bradford, 1990). Elevation was measured every 1 mm along 900-mm scan lines parallel to tillage direction; scan lines were 5 mm apart and the area covered was 850 mm long. Flour was used as an optical adjuvant. This is not recommended because the flour tended to form a crust on moist soil. Talcum powder is preferable, but due to availability, we used powdered sugar for later measurements (not reported here). Powdered sugar can, however, promote microbiological crusts.

Chain set members were laid successively over the measurement area taking care particularly with finer-linked members to follow micro-topographic irregularities, and horizontal reach was measured by caliper. Five parallel-to-tillage and 5 perpendicular sets of readings were made in

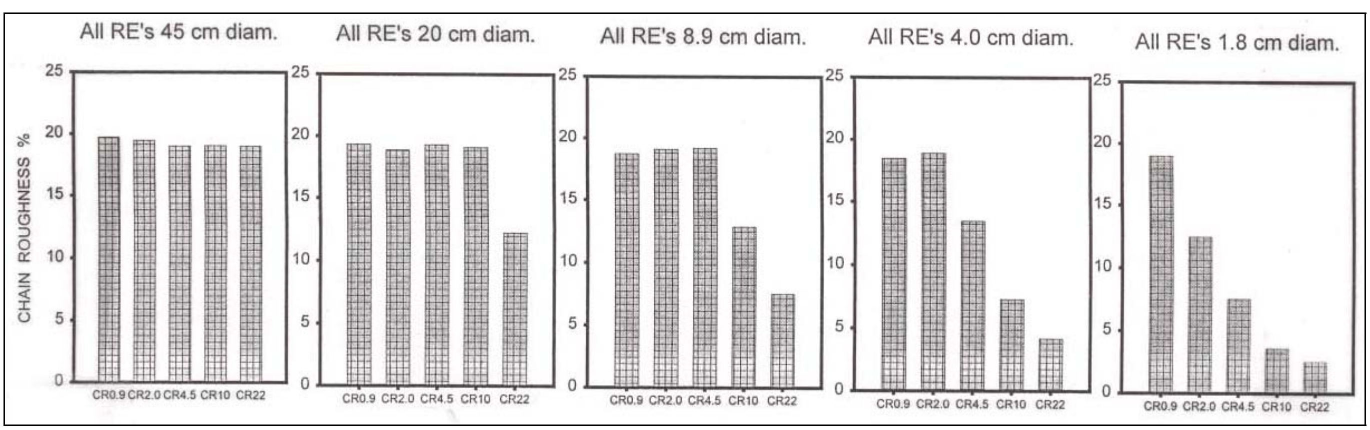

Figure 1. Results of computer simulation study in which a theoretical 5-member chain set was laid on surfaces with randomly positioned hemispherical RE's of homogeneous size (45% of area is covered by RE's).

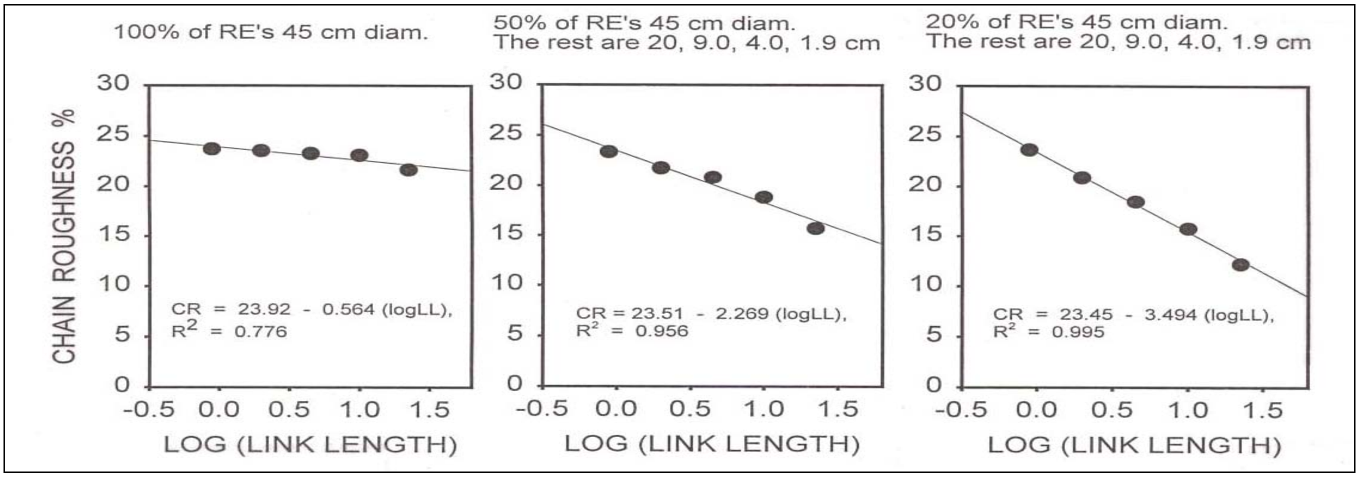

Figure 2. Results of computer simulation study in which a theoretical 5-member chain set was laid on surfaces with randomly positioned hemispherical RE's in which sizes were homogeneous (left); 50% of RE's were larger size (middle); and 20% of RE's were larger size (right). Chain roughness values are plotted vs. $\log_{10}$ of chain set member linkage length. (60% of area is covered by RE's).

each approximately 1-m^2 area. Areas at which chain set and laser scanner measurements had been taken were eroded by forceful application of water from a hose fitted with a bed-watering head, and subsequent measurements were taken after soil had dried somewhat.

Altogether 30 chain set - laser scanner dataset pairs were collected. The analytical software used data values at 5 mm by 5 mm intervals. Laser scanner datasets were analyzed by: (a) A standard deviation index was calculated by removing row and column effects before taking the deviation. This is similar in form to the traditional random roughness index (Zobeck and Onstad, 1987); (b) A wind erosion process-oriented index was calculated as the percent of area sheltered by micro-topography from abrader particle impact for angles 30 deg. or less from the horizontal. This was based on shelter angle distribution analysis described by Potter et al., 1990.

RESULTS AND DISCUSSION

Laying of individual chains or the chain set perpendicular to the direction of tillage measures both oriented roughness and random (non-oriented) roughness, whereas parallel layings measure the random component alone. Oriented roughness can be operationally defined as the difference between perpendicular and parallel chain layings. Fig. 4 (left) shows an example in which the oriented component was small compared to random roughness. No oriented roughness component was apparent in this case at the larger RE scales indicated by CR7.6 and CR15. Fig. 4 (right) illustrates a contrary example in which oriented roughness was approximately of the same magnitude as random roughness throughout the RE size scales indicated by the entire chain set.

The chain set will indicate qualitative changes in the size distribution of RE's after attenuation by water erosion (Fig.5). The slope of regressions of CR vs. log (link length) decline in absolute value from 7.5 to 1.8 (Fig. 5 left) and from 7.9 to 2.4 (Fig. 5 right). This appears to represent greater attenuation of smaller scale RE's compared to the larger scale RE's indicated by larger-linked members. Apparent attenuation of smaller scale RE's vs. larger scale ones was greater for the sandy loam soil compared to silt loam. This illustrates one of the most important abilities of the chain set: to yield indirect quantitative information about the qualitative changes (change in "fractal character") that occur as surface micro-topography is attenuated by erosion.

The R^2 values for regressions of CR values for individual chain set members against laser scanner-derived roughness indices are listed in Table 1. Values for STDI peak at the intermediate link size represented by CR1.9, but R^2 for SAP30 has highest value at CR0.5, representing he finest chain set member. Regressions of successive CR value differences between finest-linked chain and larger-value differences between finest-linked chain and larger-linked members against roughness indices produce R^2 values that are considerably higher for the SAP30 index than for STDI (Table 1). The chain set difference values appear to partially remove the influence of larger scale RE's represented by CR15. The higher level of predictability that CR difference values have for SAP30 compared to STDI indicates the greater dependence of the former process-oriented index on fine chain CR values which represent a scale-balanced range of RE's compared to the relatively upper-scale dominated STDI index.

Table 2 presents results of multiple linear regressions (a) for laser index prediction by CR values for individual chain set members in quadratic binomial form and (b) for prediction by binomials of individual CR values plus CR value differences. The pattern of results is similar to that shown in Table 1, with highest prediction for SAP30 occurring with the finest-linked part of the chain set. The highest R^2 value found overall for index prediction was 0.912 for SAP30 regressed against the polynomial in CR0.5 and $(CR0.5)^2$.

The relative dependence of SAP30 regressions on smaller-link CR values including smaller-scale RE influence versus STDI regressions dependence on CR's that exclude smaller scale RE influence is shown in higher detail by regression equations listed in Table 3. Eqs. 1A and 1B show

Figure 3. Illustrating chain set measurements being conducted in the field.

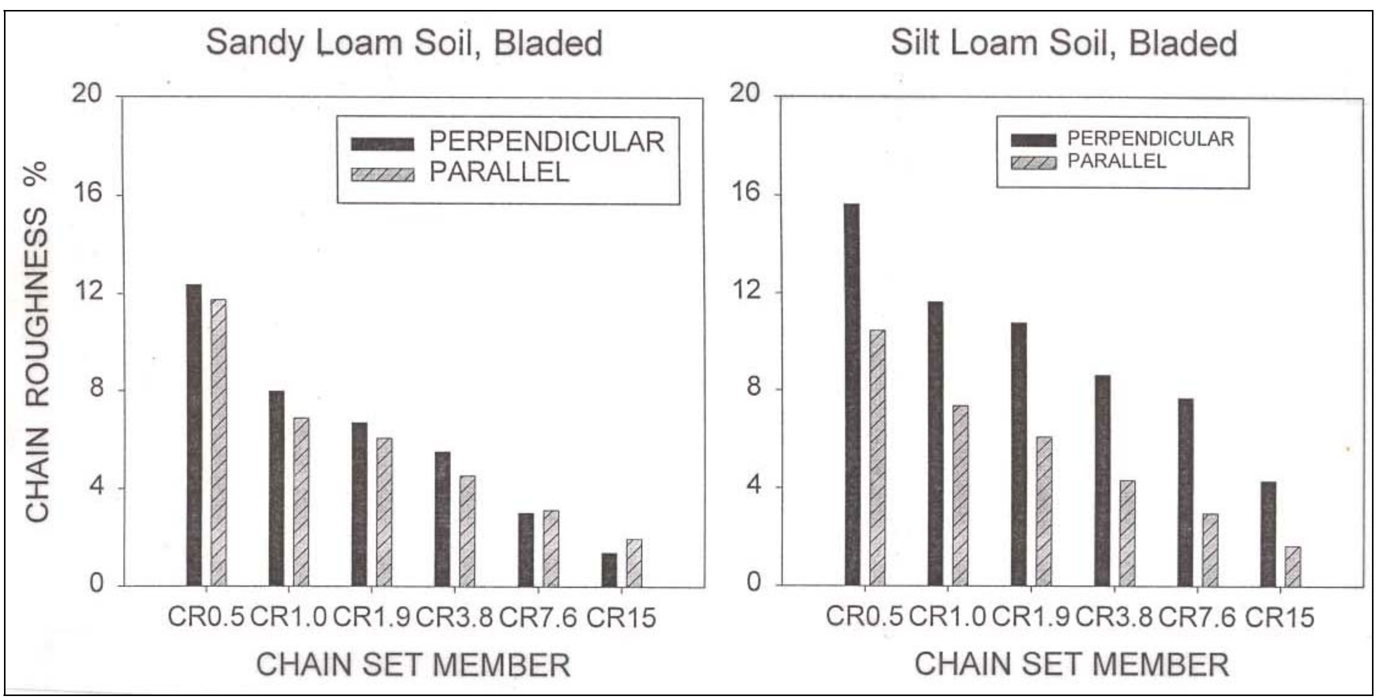

Figure 4. Field measurements by a 6-member chain set laid perpendicular and parallel to the direction of tillage. Each figure represents one replication of a tillage treatment before any significant rainfall or application of water.

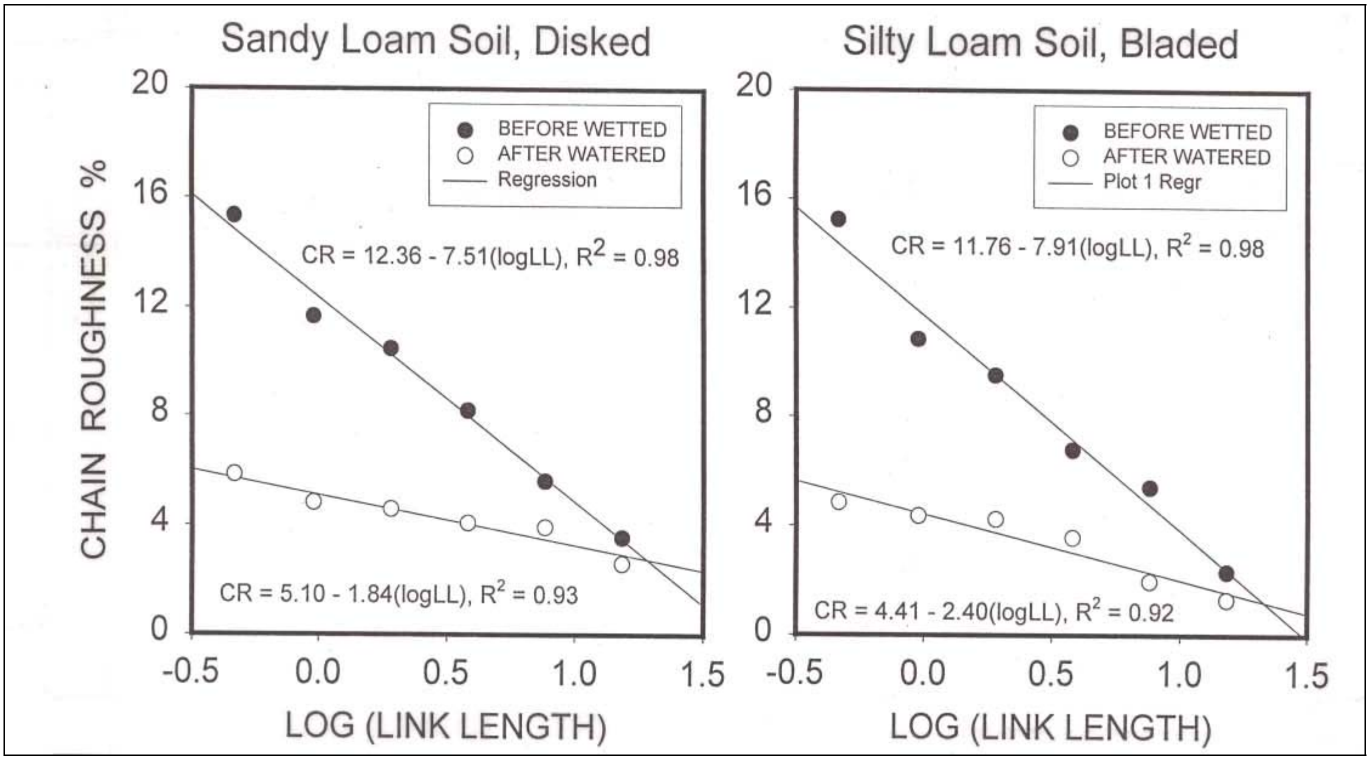

Figure 5. Results of field measurements by a 6-member chain set applied to single replications of tillage treatments before and after forceful, erosive application of water. Chain roughness values are plotted vs. log10 or chain set member linage length.

Table 1. R-squared values of regressions between single chain set roughness factors and laser scanner-derived indices for random roughness (standard deviation index, STDI) and shelter angle distribution (percent sheltered from abrader at 30 deg or less, SAP30). N = 30.

Laser Scanner-Derived Index	Chain Roughness Value					
	CR0.5	CR1.0	CR1.9	CR3.8	CR7.6	CR15
STDI	0.843	0.861	0.873	0.857	0.754	0.545
SAP30	0.854	0.717	0.653	0.647	0.515	0.275
	CR0.5-CR15	CR0.5-CR7.6	CR0.5-CR3.8	CR0.5-CR1.9		
STDI	0.693	0.672	0.622	0.466		
SAP30	0.859	0.846	0.860	0.796		

Table 2. R-squared values of multiple regressions between chain set roughness factors and laser scanner-derived indices for random roughness (standard deviation index, STDI) and shelter angle distribution (percent sheltered from abrader at <30º, SAP30). N = 30.

Laser Scanner-Derived Index	------------------------------------- Chain Set Roughness Factors -------------------------------------					
	CR 0.5 & $(CR\ 0.5)^2$	CR 1.0 & $(CR\ 1.0)^2$	CR 1.9 & $(CR\ 1.9)^2$	CR 3.8 & $(CR\ 3.8)^2$	CR 7.6 & $(CR\ 7.6)^2$	CR 15.0 & $(CR\ 15.0)^2$
STDI	0.859	0.872	0.874	0.865	0.755	0.563
SAP30	0.912	0.760	0.730	0.684	0.544	0.329
	CR1.0 & (CR0.5-CR1.0)	CR1.9 & (CR0.5-CR1.9)	CR3.8 & (CR0.5-CR3.8)	CR7.6 & (CR0.5-CR7.6)	CR15 & (CR0.5-CR15)	
STDI	0.866	0.885	0.878	0.870	0.865	
SAP30	0.904	0.891	0.887	0.873	0.877	

regressions with coarsest CR15 and single differences (CR0.5 - CR15), through Eqs. 2A and 2B with two CR differences to Eqs. 3A and 3B with three CR differences. Terms of polynomials are arranged with those representing contributions from finer-linked chain set members rightmost. The values of the partial regression coefficients show a striking and consistent pattern, confirming the dependence of the STDI index on more larger scale-representing CR values. In contrast, the dependence of the process-oriented SAP30 index on finer scale-including CR values is shown by the consistent increases in partial regression coefficient values for finer-linked members' terms.

These overall results indicate the inefficiency involved in using a standard deviation - random roughness type of index, such as STDI. Such indices are not only relatively scale-insensitive, but preferentially report effects of larger scale RE's. To make good use of scale-sensitive and scale-continuous roughness measurement, whether by low technology means such as the chain set, or by laser scanner, erosion process-oriented roughness indices must be developed and used. The SAP30 index from shelter angle distribution for wind erosive abrader process has been used. There is an immediate need for a general aerodynamic roughness length index. For water erosion relevancy, there is a need to use water retention, flow concentration and flow networking indices.

It has been shown that the chain set, which is a low-tech, field-practical device, can give effective prediction of roughness parameters measured by the higher-tech laser scanner. More importantly, the chain set can provide quantitative indication of scale-sensitive qualitative changes that occur as soil roughness is moved through stages of attenuation by wind or water erosion. The laying of the chain set could be made more reproducible and convenient through development of devices that will semi-automatically place chains on the surface and facilitate length measurement. Output of analog length measurements could be to a data logger.

The ratio of chain length to link length should not fall below some reasonable value, perhaps 15 or 30. By this criterion, the two largest-linked members of our working chain set were probably too short. The chain set becomes more useful as the range of scales over which it exhibits functionality becomes larger. Thus, larger-linked members of a chain set that can service a reasonably wide scale range should be of longer length than its smaller-linked members.

Roughness measurement that is scale-sensitive and functionally multiscalar, provides much greater understanding of the relationships between soil surface structure and erosion process. In this paper it was shown that the wind erosion-relevant abrader-sheltering index was distinctly better predicted by wider-scale-including fine-linked chain measurement than by smaller-scale-excluding coarse-linked chain measurement. Multiscalar, qualitative changes in soil surfaces undergoing rainfall erosion have been demonstrated by Huang (1998) through fractal-statistical analysis from laser scanner datasets. Current designs of roughness instruments provide measurement over a set area, typically 1 m^2, and lose statistical competence in the larger scales that approach the size limits of the device. To overcome this problem and to take full advantage of the scientific possibilities offered by multiscalar, scale-continuous measurement, future roughness devices must be designed to operate in a hierarchical manner. For the laser scanner and its probable stereoscopic, active-illumination using successors, this means a higher-resolution, smaller-scale sub-device operating within the domain of a lower-resolution, larger-scale parent device. For the chain set, it means a shorter, fine-chain subset applied to the area measured by a set of much longer chains that have a range of larger linkage lengths.

Roles for Chain Set-Like Devices

The chain set is a mechanical-computational device that is capable of performing scale-sensitive and scale-continuous integration of soil surface roughness over an area. Our research with the chain set has been conducted under bare soil conditions, but there is a need to make measurements of joint soil and prostrate residue roughness effects. The chain set concept appears capable of providing such measurement in an erosion-relevant manner. Research to develop such joint soil and residue roughness measurement is especially justified in the context of measuring and understanding soil erosion potentials in

Table 3. Regression equations for prediction of laser scanner-derived roughness indices by multiple chain set measurement parameters. N = 30.

Equation Number	Equation	R-square Value
1A	STDI =1.738 + **1.412***(CR15) + **0.791***(CR0.5-CR15)	0.865
1B	SAP30 =2.175 + **0.826***(CR15) + **1.985***(CR0.5-CR15)	0.877
2A	STDI =1.089 + **1.420***(CR15) + **1.169***(CR1.9-CR15) + **0.373***(CR0.5-CR1.9)	0.888
2B	SAP30 =3.257 + **0.812***(CR15) + **1.355***(CR1.9-CR15) + **2.682***(CR0.5-CR1.9)	0.895
3A	STDI =1.233 + **1.534***(CR15) + **1.257***(CR3.8-CR15) + **0.513***(CR1.0-CR3.8) + **0.421***(CR0.5-CR1.0)	0.881
3B	SAP30 = 3.755 + **0.782***(CR15) + **1.025***(CR3.8-CR15) + **1.447***(CR1.0-CR3.8) + **3.359***(CR0.5-CR1.0)	0.906

cropping systems that contain diverse crops that are alternatives to small grains in dryland agriculture. Another role for chain set-like devices that should be studied is the practical measurement of standing residue roughness effect. A lightweight form of a chain device with broad segments (i.e., a "linked strip") could be used for this purpose.

ACKNOWLEDGMENTS

The authors wish to acknowledge the excellent technical assistance principally of Mr. D. D. Schlenker, as well as that of Mr. M. A. Cervinski and Mr. L. F. Renner. The authors also acknowledge the contributions of Dr. T. W. Popham to software used for analysis of laser scanner datasets.

REFERENCES

Goldenfeld, N. and L.P. Kadanoff. 1999. Simple lessons from complexity. Science 284:87-89.

Huang, C.-H. 1998. Quantification of soil micro-topography and surface roughness. p. 153-168. *In* P. Baveye et al. (eds.), Fractals in Soil Science. CRC Press LLC.

Huang, C.-H. and J.M. Bradford. 1990. Portable laser scanner for measuring soil surface roughness. Soil Sci. Soc. Am. J. 54:1402-1406.

Huang, C.-H. and J.M. Bradford. 1992. Applications of a laser scanner to quantify soil micro-topography. Soil Sci. Soc. Am. J. 56:14-21.

Merrill, S.D. 1998. Comments on the chain method for measuring soil surface roughness: Use of the chain set. Soil Sci. Soc. Am. J. 52:1147-1149.

Potter, KN., T.M. Zobeck and L.J. Hagen. 1990. A micro-relief index to estimate soil erodibility by wind. Trans. ASAE 33:156-161.

Römkens, M.J.M., J.Y. Wang and R.W. Darden. 1988. A laser micro relief meter. Trans. ASAE 31:408-413.

Saleh, A. 1993. Soil roughness measurement: Chain method. J. Soil Water Conserv. 48:527-529.

Saleh, A. 1997. Reply to "Comments on chain method for measuring soil roughness". Soil Sci. Soc. Am. J. 61:1533-1535.

Skidmore, E.L. 1997. Comments on chain method for measuring soil roughness. Soil Sci. Soc. Am. J. 61:1532-1533.

Werner, B.T. 1999. Complexity in natural landform patterns. Science 284:102-104.

Zobeck, T.M. and C.A. Onstad. 1987. Tillage and rainfall effects on random roughness: A review. Soil Till. Res. 9:1-20.