Soil-Inherent Wind Erodibility: Progress and Prospects

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Abbreviations

AASD, apparent aggregate size distribution; ARS, Agricultural Research Service; AS, aggregate stability; ASD, aggregate size distribution; EF, erodible fraction; GMD, geometric mean diameter; NEF, non-erodible fraction; PASD, potential aggregate size distribution; SIWE, soil-inherent wind erodibility; USDA, United States Department of Agriculture; WEPS, Wind Erosion Prediction System.

Introduction

Wind erodibility is the vulnerability or resistance of soil to erosion by wind . It consists of soil and plant factors. The plant factors of wind erodibility depend on live or dead vegetative materials covering the soil or standing upon it. The soil factors of wind erodibility consist of (a) soil surface wetness, (b) soil microtopography, referred to as *soil surface roughness*, and (c) *soil-inherent wind erodibility*.

When wind erodibility is not dominated by residue or crop cover, surface roughness, or surface wetness, then it is determined by non-structural, inherent properties of the surface soil itself, which we term *soil-inherent wind erodibility*. These properties have been termed *soil erodibility* in past discussions of wind erosion. We believe a better term for this complex property would be soil-inherent wind erodibility (SIWE). While SIWE is related to a range of soil physical and chemical properties, it may be defined by two interrelated components: *aggregate size distribution* (ASD), and *aggregate stability* (AS).

It appears that more information exists about how to model and predict wind erodibility factors other than SIWE than to model SIWE itself. The dynamics of SIWE are such that SIWE responds to plant growth and physical-environmental components, changes in crop and soil management, and periodic and chaotic changes in response to seasonal and multiyear weather cycles.

In dryland agricultural regions of the world, quasi-periodic to chaotic appearances of multiyear drought periods greatly accelerate wind erosion hazards. Under drought, residue production is minimal and wind erosion hazard becomes more determined by SIWE (Merrill et al., 199X; Merrill et al., 1996b). The design and structuring of research to understand SIWE has proven to be a very difficult challenge.

This paper reviews selected aspects of soil science literature that pertain to SIWE and discusses contributions to SIWE research originating at the USDA-Agricultural Research Service's (USDA-ARS) laboratory at Mandan, North Dakota. Sources of future progress in SIWE research are examined.

Soil Surface Properties: SIWE and the Rotary Sieve

There are a number of physical properties that relate to the wind erodibility of soil. These physical properties and factors are reviewed by Zobeck (1991), who lists them as: aggregate size distribution; bulk density; aggregate density; aggregate stability; crust thickness; relative area covered by crust and nonerodible and erodible material; amount of loose erodible material; and soil surface roughness. The definition of SIWE encompasses all of these properties except the last in the list, surface roughness. However, SIWE may be functionally defined and characterized by two of the properties, aggregate size distribution (ASD) and aggregate stability (AS).

Surface roughness and SIWE are often functionally inseparable. In tilled soils, the larger the size of soil aggregates in an ASD, the greater will the soil's surface roughness tend to be. The oriented roughness of soil ridges often implies a difference in SIWE properties on the ridge compared to between the ridges.

What we define here as SIWE is largely synonymous with measurements produced by rotary sieves, which were developed by W. S. Chepil (Chepil and Bisal, 1943; Chepil 1952; Chepil 1962). Rotary sieves are said to produce measurement of dry ASD, and the measurements are most often summarized as the *erodible fraction* (EF: percent less than 0.84 mm diameter), or if not as EF, as the *geometric mean diameter* (GMD; Gardner, 1956).

Although rotary sieves are operated at low rates of revolution, they do abrade soils. In the same paper reporting an improved form of the rotary sieve, Chepil (1952) advocated the use of the device to make operationally defined measurements of aggregate stability (AS) by multiple repassage through the sieve of fractions greater than 0.84 mm diameter. A physical definition of AS has been provided by E. L. Skidmore and colleagues, along with an instrument, known as the crushing energy meter, to carry out the measurements (Skidmore and Powers, 1982; Hagen et al., 1995). More precise measurements of AS require many determinations on individual soil aggregates with a crushing energy meter. As noted, less precise, relative assessments of AS may be performed with a rotary sieve (Chepil, 1952).

Soils can vary considerably in the their inherent aggregate stability (AS), and this will affect measurements of apparent ASD produced by rotary sieves. In a national study of soil properties related to wind erodibility (Zobeck, 1992), several soils from the Palouse region of the Pacific Northwest of the US were found to give high EF and low GMD values from rotary sieving due to inherently low AS. Because soil fractions produced by rotary sieving respond to AS as well as ASD, reporting of results as either *apparent aggregate size distribution* (AASD) or *potential aggregate size distribution* (PASD) will result in clearer understanding among users of such research results. The fact that the rotary sieve responds to both ASD and AS makes it a more valuable applied science instrument for producing results useful for predicting of wind erosion hazard. However, this characteristic of standard rotary sieves is a reason why future, basic research on the component properties of SIWE and their interrelationships should make use of special soil separation devices and precision crushing energy meters, as well as other instruments.

Research Methods

The SIWE-specific research conducted at the USDA-ARS, Mandan, ND location was carried out on a long-term conservation tillage experiment, details of which may be found in Black and Tanaka (1997), and also in Merrill et al. (1996a). Soils at the site are classified as Temvik-Wilton silt-loams (fine-silty, mixed Typic and Pachic Haploborolls). Starting in 1984, several cropping systems were initiated, including biennial spring wheat-fallow, from which measurements discussed here were taken. Tillage treatments were imposed on two series of plots, one series cropped on even-numbered years, the other cropped on odd-numbered years. Tillage occurred prior to seeding in May, and during the fallow year. Tillage treatments were triple-replicated and consisted of: (1) low-residue, primarily by offset disk; (2) conventional-till, primarily by tandem disk; (3) minimal-till, primarily by undercutter; and (4) no-till. Surface soil was sampled to a depth of about 2 cm approximately every 30 days when it was unfrozen and not covered by snow. After air drying, AASD was determined by rotary sieve (Chepil, 1962) on 1.1 kg samples.

Long-Term Climate Influences SIWE

Dryland agricultural regions like the Great Plains are subject to chaotically appearing wet-dry weather cycles with irregular periods of approximately 10 years to 20 years or more. Multiyear drought greatly accelerates wind erosion hazard by stunting growth of protective vegetation and by resulting in the disaggregation of surface soil. Thus, SIWE is changed by drought, as EF typically becomes higher and AS decreases.

There are few published studies detailing effects of multiyear weather cycles on SIWE. We will discuss three here. All three are from biennial spring wheat-fallow cropping in the Northern Great Plains.

Bisal and Ferguson (1968) measured sieve AASD from 1955 to 1967 on 3 texturally different soils in Saskatchewan, documenting effects of a multiyear drought in the late 1950's. Fig. 1, drawn from their study, shows average annual EF values from samples taken at various times during the year. They found that EF increased up to the late 1950's and then greatly decreased. Although seasonal changes in EF ranged over approximately 25 percentage units at the most, this was considerably less than the greatest multiyear change, which was on the clay soil and was over 55 percentage units.

Moulin and Townley-Smith (1993) measured sieve AASD from 1970 to 1984 in Saskatchewan on soil subjected to several mechanical tillage and no-tillage treatments. Relatively abundant precipitation was believed responsible for good soil aggregation and EF averages (measured in spring of the fallow year) of less than 10% in 1973 and 1974. Relatively low precipitation was associated with EF values of 40% to 60% in 1982 and 1983. EF value (defined as < 0.5 mm diameter) was significantly and negatively correlated with precipitation in the growing season of the year prior to sampling. Multiyear climatic effects on EF were considerably greater than tillage effects.

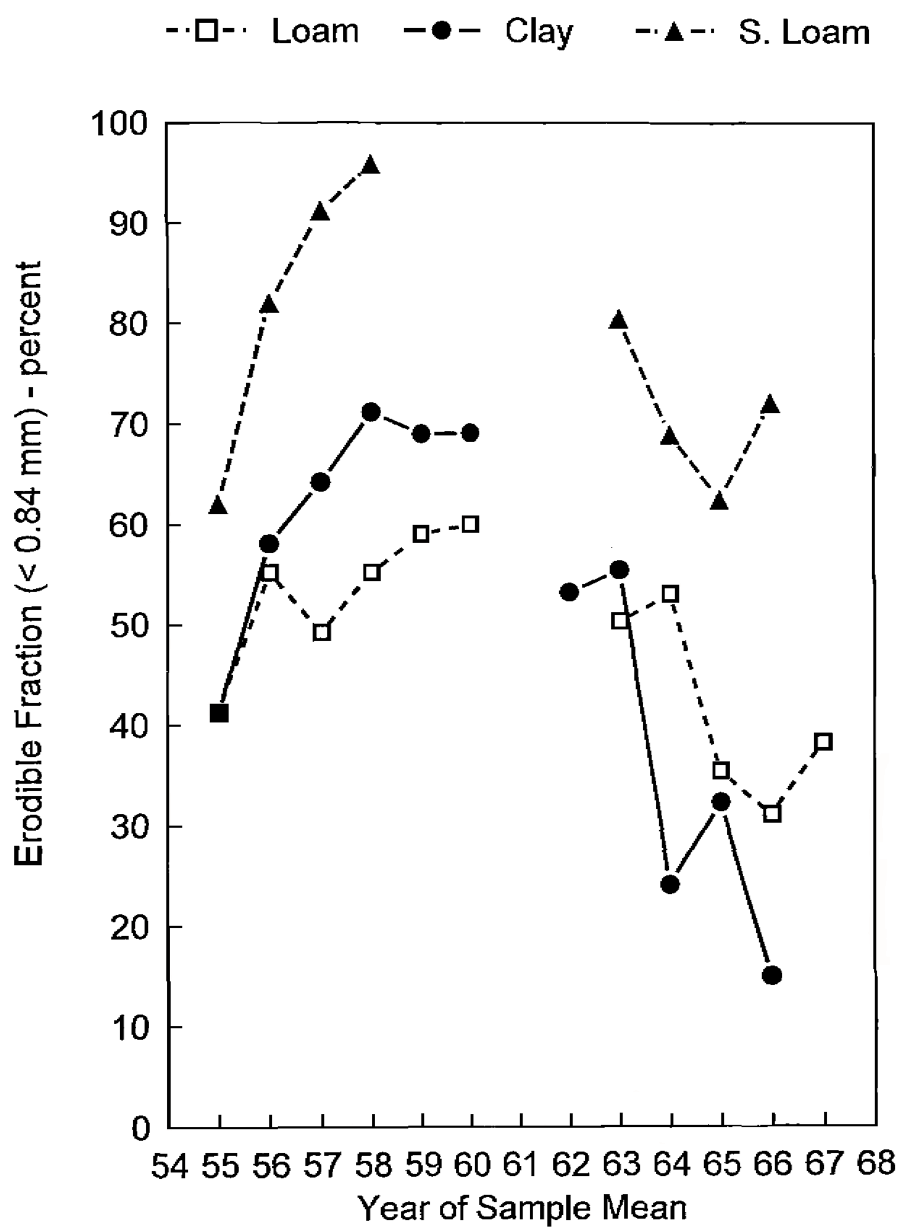

Figure 1. Average annual levels of SIWE measured as EF by rotary sieving. Samples were taken from farmers' and research center fields in biennial spring wheat-fallow cropping in Saskatchewan. *Drawn from*: Bisal, Frederick, and W. S. Ferguson. 1968. *Can. J. Soil Sci*. 48:159-164.

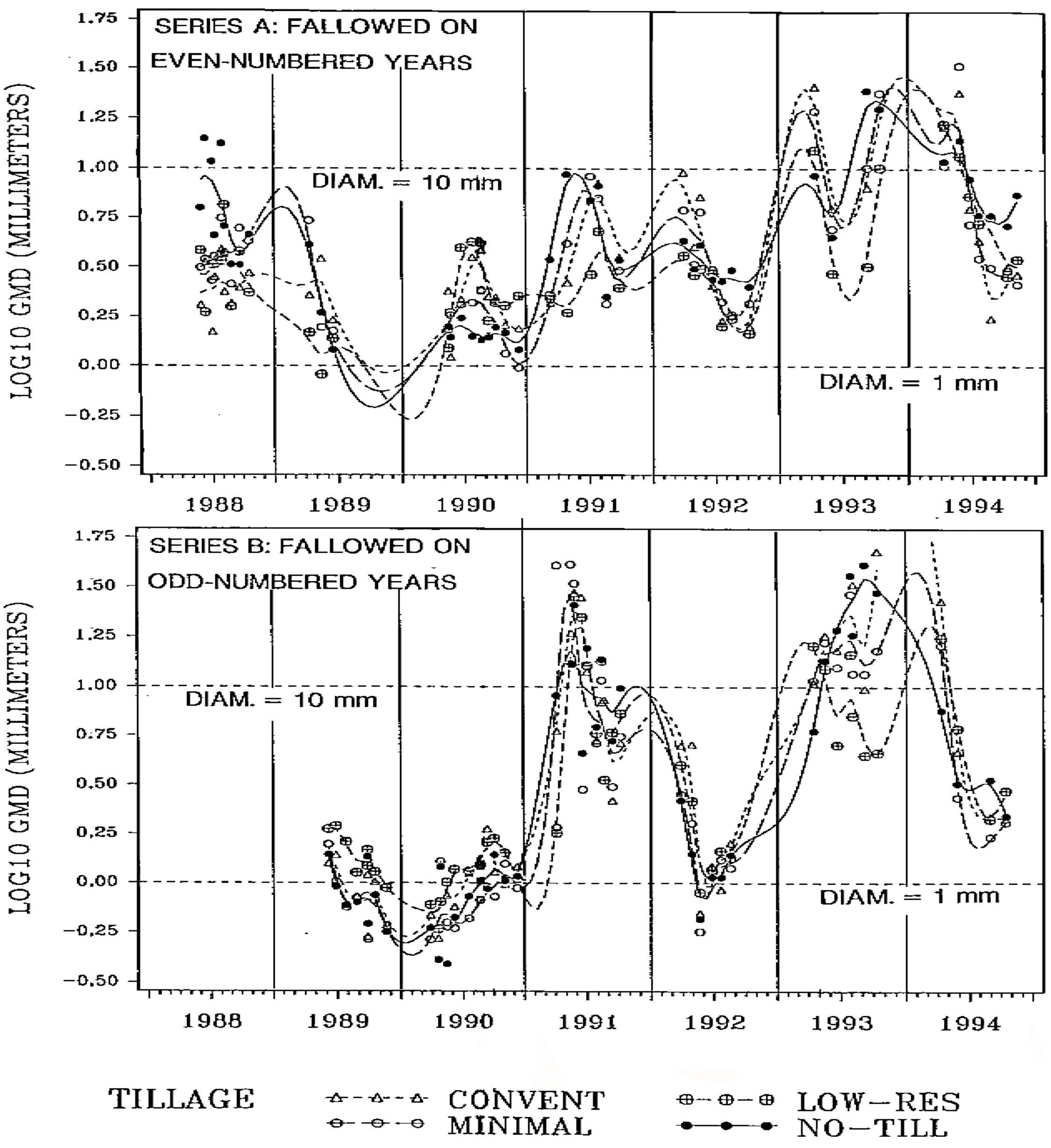

Figure 2. SIWE measured by rotary sieving and displayed as GMD's of aggregate size distributions in logarithmic scale vs. time for tillage treatments. A. Series A: measured in plots fallowed on even-numbered years. B. Series B: measured in plots fallowed on odd-numbered years.

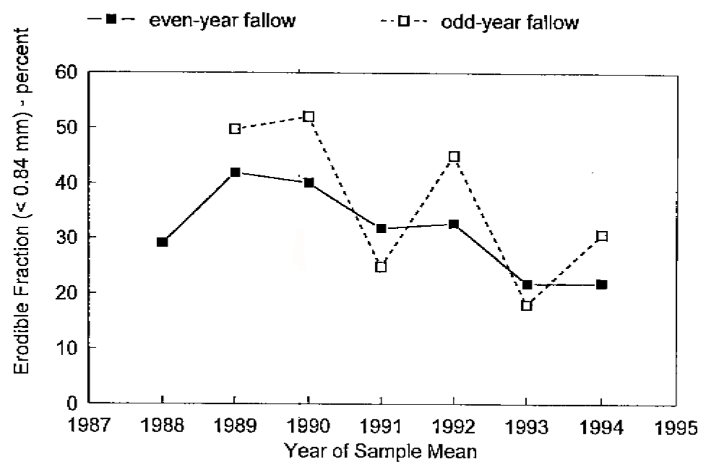

Figure 3. The same SIWE measurements shown in Fig. 2, but displayed as annual erodible fraction values averaged over tillage treatments.

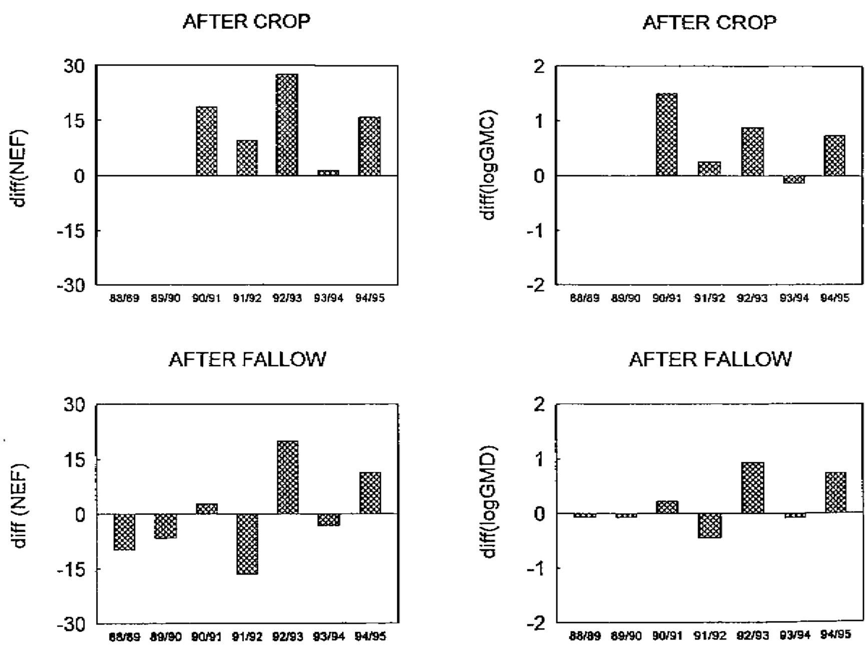

Figure 4. Overwinter differences (May minus October) in SIWE, as rotary sieve-mearsured AASD, and calculated as NEF difference (non-erodible fraction: 100 minus erodible fraction) and as $\log_{10}$ GMD differnce geometric mean diameter). Results are shown for after-fallow and after-crop winters under the biennial spring wheat-fallow cropping system. After-crop phase measurements were deficient or absent in winters 1988/1989 and 1989/1990.

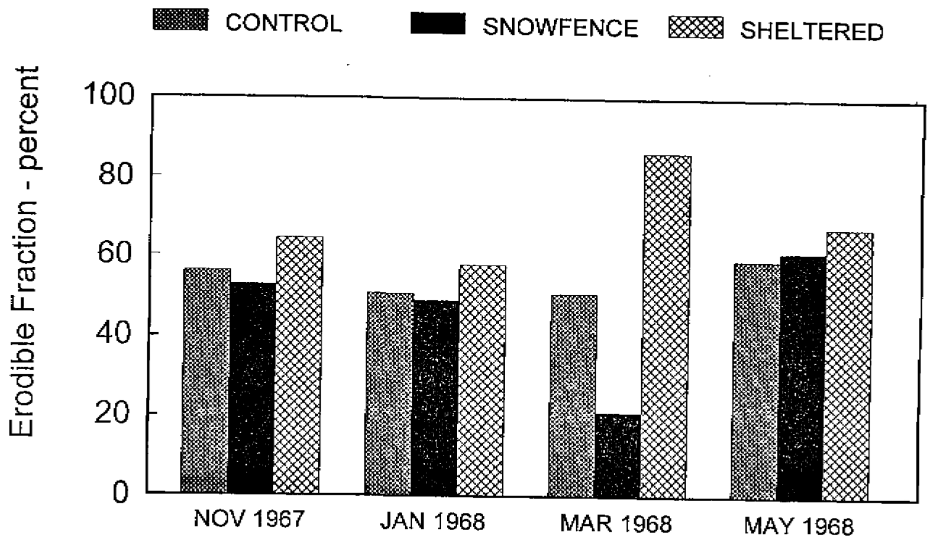

Figure 5. EF from rotary sieving in the after-fallow phase and early crop phase of spring wheat-fallow cropping under 3 snowcover control conditions. *Drawn from*: Anderson, C. H., and Frederick Bisal. 1969. *Can. J. Soil Sci.* 49:287-296.

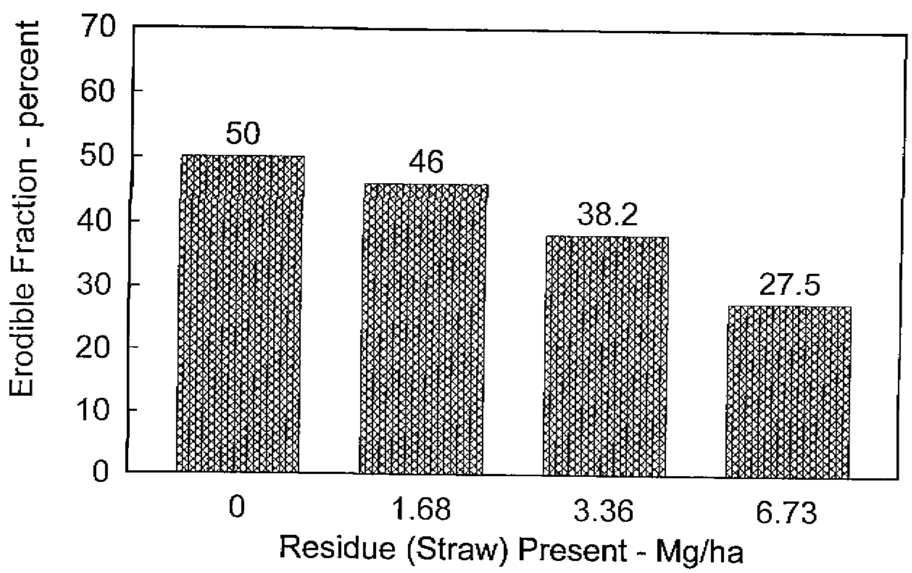

Figure 6. EF from rotary sieving measured in biennial winter wheat-fallow cropping in Montana after 8 years of maintenance of residue (straw) treatments which ranged from periodic removal (0 Mg/ha) to additions (3.7 and 6.7 Mg/ha). *Drawn from*: Black, A.L. 1973. *Soil Sci. Soc. Am. Proc.* 37:943-946.

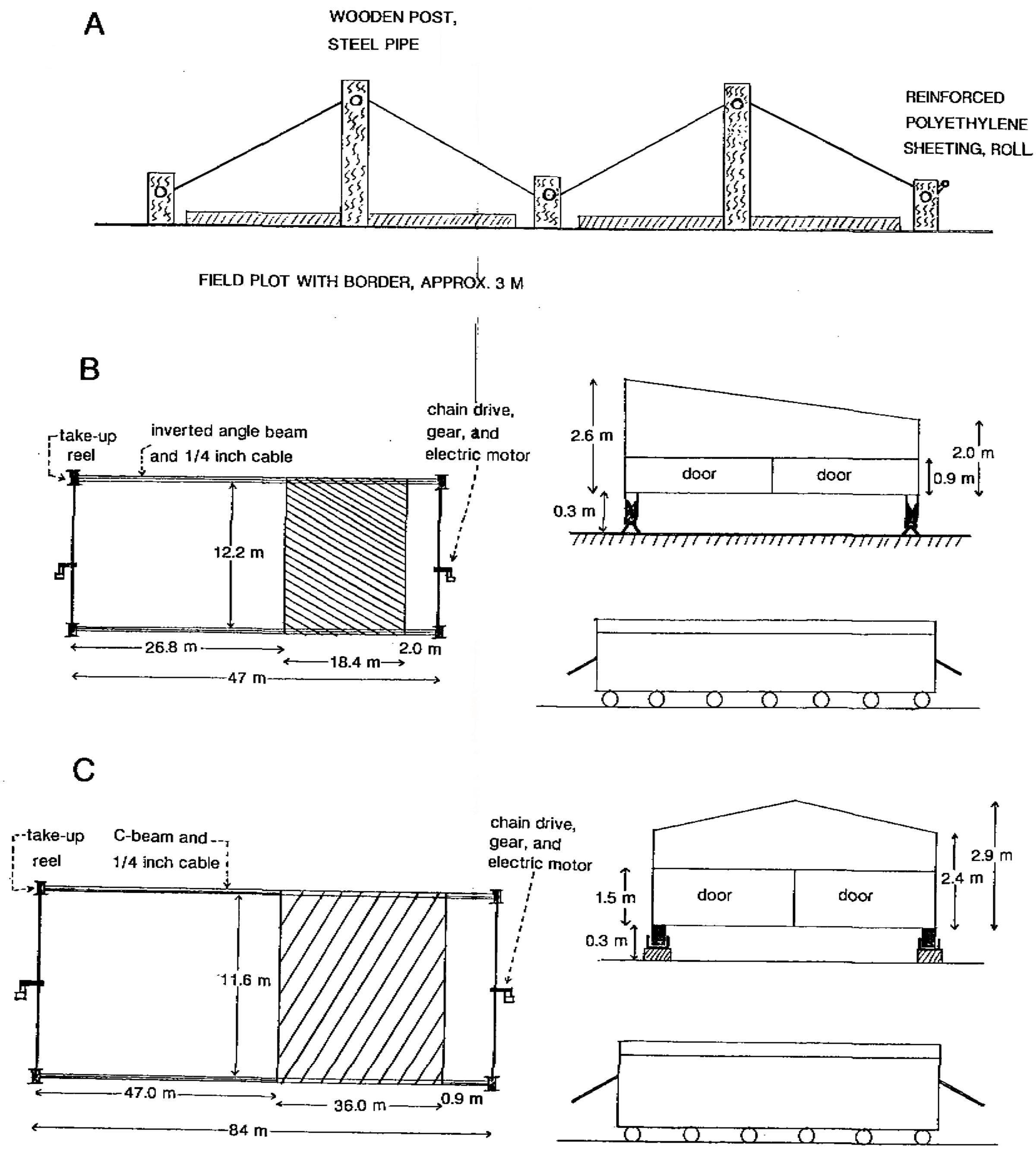

Figure 7. Low-cost, minimal rainout shelter constructed at USDA-ARS, Riverside, CA. B, C. Designs of rainout shelters constructed at USDA-ARS, Lubbock, TX. Not drawn to scale. A shelter has been constructed as in 7C with a single take-up reel at each end of the rail structure.

Merrill et al. (199X, 1996b) captured the effects of a multiyear drought on sieve-measured AASD (shown in Fig. 2 as $\log_{10}$GMD). Multiyear effects were considerably greater than tillage treatment effects. Some seasonal variances approached multiyear changes in size. The magnitude of AASD variances for plots fallowed on odd-numbered years outstripped variances for plots fallowed on even-numbered years. This is evidently linked to the circumstance that odd-year fallowed plots were in the after-crop phase overwinter following perturbation of the system by severe drought in 1988. Potential for overwinter soil aggregate building is greater following drought in the after-crop phase of the rotation than in the after-fallow phase (Merrill et al., 1995a; Merrill et al., 1995b). This is the mark of a complex chaotic system as the behavior of the system shows sensitive dependence upon initial conditions (Gleick, 1987).

Annual average EF values for the experiment of Merrill et al. (199X; 1996b) are shown in Fig. 3. The larger range in multiyear EF of this experiment was approximately 35 percentage units, which compares to largest and smallest ranges of about 55 and 30 percentage units for the observations of Bisal and Ferguson (1968) shown in Fig. 1.

Modeling the Dynamics of SIWE

The challenge of modeling and predicting SIWE lies in distinguishing multiyear climate effects from seasonal changes, and in distinguishing physical effects of environment and tillage from effects of crop growth and soil biological agents.

What may be called a classical pattern of seasonal change in sieve-measured SIWE was reported by Chepil (1954). Observations in winter wheat-fallow in Kansas indicated that under the climatic conditions of the area, non-conservation type tillage and crop growth promoted increased surface soil aggregation during the growing season, while overwinter periods with no snowcover and freeze-thaw effects caused disaggregation of surface soil. Armbrust et al. (1982) also reported predominantly disaggregative overwinter effects in Kansas. Larney et al. (1994) have reported disaggregative overwinter effects in spring wheat-fallow in Alberta.

However, as pointed out by Bisal and Nielson (1964), surface soil aggregates do not necessarily break down overwinter. Bisal and Ferguson (1968) observed both aggregative and disaggregative overwinter changes in Saskatchewan spring wheat-fallow, depending on soil type and phase of the cropping cycle. Anderson and Wenhardt (1966) observed predominantly aggregative overwinter changes in Saskatchewan. In research detailed below, Merrill et al. (1995a; 1995b) reported both aggregative and disaggregative overwinter effects in North Dakota.

Analyses of agronomic and climate influences on SIWE using regression and other modeling-type analysis have appeared in several reports. Zobeck and Popham (1990) reported regressions of AASD parameters with precipitation after tillage and bulk density for a sandy soil. Larney et al. (1994) reported regressions of sieve EF versus amount of crop residue present in spring for a spectrum of tillage methods in Alberta spring wheat-fallow. Merrill et al (1995a; 1995b) examined the relationships of overwinter changes in AASD parameters to weather and crop growth variables. A source of information and concepts about the modeling of SIWE may be found in the USDA-ARS Wind Erosion Prediction System (WEPS) model (Hagen, 1991). Particularly relevant to SIWE are the SOILS and TILLAGE submodels of WEPS.

The challenge of separating the effects of physical from crop growth factors in the modeling of SIWE dynamics is illustrated by work done at USDA-ARS, Mandan, ND in spring wheat-fallow. The work reported by Merrill et al (1995a) will be discussed here with additional data. Overwinter differences in sieve AASD (usually May minus October values) were analyzed as differences in $\log_{10}$GMD and as *non-erodible fraction* (NEF: 100 minus EF).

Annual overwinter differences in AASD measures averaged over tillage treatments are shown in Fig. 4. Differences for the after-crop phase were almost all positive, meaning that they are aggregative changes, indicating increases of average aggregate size. The presence of wheat stubble in all tillage treatments in the after-crop phase of the crop rotation evidently enhances surface aggregate formation overwinter. Overwinter differences in the after-fallow phase during the period 1988 to 1992 were predominantly negative, meaning that they were disaggregative. Effects of tillage were inconsistent and generally non-significant (Merrill et al., 1995a; Merrill et al., 1995b).

Correlation analyses of overwinter AASD differences versus various variables (Table 1) were set up so that a positive correlation coefficient value would indicate that the factor was appearing to give an expected aggregative effect. Generally, the highest correlations were with low fall AASD level, meaning that the potential for aggregate size increase and rebuilding was greatest when surface soil entered the fall in a relatively disaggregated state. Results for low number of effective freeze-thaw days closely followed results for snowcover days. Snowcover decreases freezing and thawing, of course. Overwinter meteorological factors, snowcover days and low effective freeze-thaw, and straw production were all positively correlated with overwinter differences for the after-fallow rotational phase. For the after-crop phase, significant weather or straw production correlations were negative, probably because correlations with the low fall AASD factor were relatively high. When data for the two phases of the rotation were combined, crop production factors gave higher overall correlation values than overwinter weather factors (Table 1).

Sources of Progress for SIWE Research

There are three sources of future progress in understanding SIWE dynamics and the role of SIWE in wind erosion hazard. The first is the continuation of SIWE observations in various cropping systems, under various climatic regimes, and on divergent soil types. Such efforts would be enhanced by concomitant research on the nature of the relationship between ASD and AS and on new methodologies for measuring components of SIWE.

A second source of progress lies in further use and analysis of several comprehensive SIWE data collections that currently exist. One such data collection was generated by a sieving study conducted at the USDA-ARS, Big Spring, TX laboratory. Led by D. W. Fryrear, the study is represented by a publication summarizing results from over 3000 samples at 120 locations across the United States (Fryrear et al., 1994). This report gives predictive equations linking basic soil properties to EF. Many of the locations are represented by 2 to 4 years of data collection.

Another collected database useful to researches into SIWE resulted from a USDA-ARS led effort to improve knowledge of soil factors related to wind erosion. Coordinated by T. M. Zobeck, data was collected for a number of soil-based wind erodibility factors, including rotary sieve AASD, AS by crushing energy meter, surface crust properties, and others (Zobeck et al., 1992). Samples were collected for 26 soils at 7 area locations representing a number of different cropping systems and US regions. Up to 4 years of data exits for some locations in this collection.

A third source of progress for SIWE research would be what might best be called action research: the direct manipulation of the field environment with respect to climatic and plant growth factors so that the whole process of gaining information and insight is accelerated and doesn't depend on chaotic patterns and events of long-term weather for producing useful observations.

Action Research for SIWE

Two examples may be cited of research in which elements of the field environment were actively manipulated so that effects on SIWE could be studied in a direct manner.

In the first example, Anderson and Bisal (1969) studied the effects of snowcover on rotary sieve-measured EF in spring wheat-fallow cropping in Saskatchewan. They increased snowcover on small plots with snowfencing or excluded snowcover with a small shelter that allowed wind to pass through. The results of the Anderson and Bisal (1969) study, summarized in Fig. 5, show that EF was significantly decreased at the end of the fallow period by enhanced snowcover, as compared to the control treatment. Absence of snowcover had the opposite effect, significantly increasing EF in the March samples. The effects were much less evident for other time periods.

In our second example, Black (1973) either removed flat residue -- the straw -- in a biennial spring wheat-fallow rotation, or added straw at two rates and lightly incorporated it with a stubble puncher. Straw removal or addition in this Montana experiment was carried out each spring in the fallow year of the rotation. After 4 crop-fallow cycles, rotary sieve-measured EF values (Fig. 5) show that SIWE was very significantly affected in the surface 0 to 5 cm of soil , with an average EF value of 50% for straw removal versus an EF of 28% for the higher straw addition. Although straw additions to this sandy loam soil undoubtedly decreased evaporation and enhanced snowcover, organic matter and soil nitrogen were also increased (Black, 1973).

The various actions that could be carried out to manipulate the field environment for SIWE research are listed:

A. <u>Rainfall</u>: decrease by rainfall shelter; increase by sprinkler irrigation.
B. <u>Snowcover</u>: decrease by snowout shelter; increase by snow fencing or skislope snowmaker.
C. <u>Crop residue</u>: decrease by removal; increase by addition of flat residue; alter residue-like effects by substitution of artificial (i.e., plastic) residue.
D. <u>Crop growth</u>: decrease in general manner by wider spacing; decrease more particularly by growth regulators and lethal or sublethal herbicide application; increase by higher seeding rate.
E. <u>Soil biology agents</u>: decrease effect by biocides, sterilants (i.e., methyl bromide); promote by application of a soluble carbon source with nutrients.
Manipulations of rainfall, snowcover, and crop residue in the field are all known and documented in soil science research; manipulation of crop growth and soil biology agents for the purpose of SIWE research is rather speculative.

Understanding the effects of multiyear wet-dry cycles on SIWE dynamics appears to be the greatest research need and the greatest research challenge. The limited number of existing reports that give quantitative information about long-term weather cycle effects demonstrates the essential scientific futility of depending upon serendipity and the chaotic appearance of multiyear droughts to achieve progress.

While research is needed on all the environmental factors affecting SIWE, the highest priority need appears to be the gaining of an understanding of comprehensive rainfall effects through control of rainfall in the field. Plant physiologists and other crop scientists have used rainout shelters for a number of decades to understand water stress effects. Soil erosion scientists should certainly consider using rainout shelters for study of SIWE and its relationship to other elements of wind erodibility. A number of rainout shelter designs are illustrated in Fig. 7. Fig. 7A shows a type of inexpensive shelter that should be suitable for shorter-term, more preliminary-type study. This type of shelter was used by researchers during the early 1970's at the USDA-ARS, U. S. Salinity Laboratory, Riverside, CA. Fig. 7B illustrates a relatively moderate cost rainout shelter constructed at the USDA-ARS, Lubbock, TX laboratory. Fig. 7C illustrates a larger shelter design which was also constructed at USDA-ARS, Lubbock, TX (T. M. Zobeck, personal communication). Upchurch et al. (1983) have discussed an advanced rainout shelter design in which two units parked on opposite ends of the rail structure move towards each other to cover the protected area. Foale et al. (1986) reviewed the general engineering principles of rainout shelter design.

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ACKNOWLEDGMENTS

The authors acknowledge the work of Mr. D. D. Schlenker with wind erodibility studies, and the supporting work of Mr. G. F. Quill. The authors thank Dr. T. M. Zobeck and colleagues of USDA-ARS, Lubbock, TX for providing information concerning rainout shelter design and construction.

Table 1. Correlation analysis in overwinter changes of apparent aggregate size distribution (AASD) versus agronomic and environmental variables. Overwinter differences in AASD measures were for May minus October values of log(10) of geometric mean diameter and of non erodible fraction (NEF: percent > 0.84 mm diameter).

		LOW FALL PRECIP.	SNOW COVER DAYS	LOW FREEZE -THAW	LOW FALL AASD	STUBBLE\ STANDING RESIDUE	STRAW PRODUC- TION	FLAT RESIDUE COVER
AFTER CROP	diff(NEF)	NS	NS	NS	0.88***	---	NS	---
n = 20	diff(logGMD)	NS	-0.50*	-0.44*	0.86***	---	-0.53*	---
AFTER FALLOW	diff(NEF)	NS	0.45*	0.45*	NS	NS	0.44*	NS
n = 28	diff(logGMD)	NS	0.40*	0.44*	0.42*	NS	0.39*	NS
FULL SET	diff(NEF)	NS	0.24+	0.29*	0.46**	0.43**	0.48***	---
n = 48	diff(logGMD)	NS	NS	NS	0.60***	0.29*	0.29*	---

Significance of correlation coefficients: NS, not significant; + < 0.10; * < 0.05; ** < 0.01; *** < 0.001.