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Soil Aggregation and Wind Erosion: Processes and Measurements

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Abstract: The size distribution and stability of soil aggregates have a major influence on the wind erodibility of soils. From field and laboratory studies, we know that aggregate status is the result of external forces acting on the soil such as tillage, wetting and drying, freezing and thawing, and freeze drying. The effect of these forces varies with soil properties, cropping management, and the severity of the processes. As a result of these forces, soil aggregates may either increase or decrease in size as well as stability. The effects of moisture and temperature can cause significant changes in the aggregates and thus, the erodibility of a soil. In order to relate the forces acting on soils to different properties and to wind erodibility, standardized methods are needed to measure the aggregate size distribution and aggregate stability. Standardizing these methods would allow comparison of the effects of various treatments and soil types on the aggregate status. This paper reviews the processes and measurement of soil aggregation as it affects wind erosion.

Key words: Aggregate stability, aggregate size distribution, aggregation processes, Erodibility.

A soil aggregate is a group of primary soil particles that cohere to each other more strongly than to other surrounding particles (Kemper and Rosenau, 1986). Aggregation is the process by which soil primary particles are bound together. The primary soil particles (sand, silt, and clay) are usually bound together by natural cohesive forces of water-dispersable cements, as well as substances derived from root exudates and microbial activity.

The size distribution and stability of aggregates influence the soil's physical properties, including pore size distribution, bulk density, soil strength, and soil erodibility, as well as the processes that occur in the soil such as wetting and drying, freezing and thawing, and freeze drying (Skidmore and Powers, 1982). Aggregate size distribution is important in determining the amount and dimensions of pore space in soils. The size of pores affects the movement and distribution of water and air in the soil, which in turn, affect plant growth. Dry aggregate stability is the resistance of dry soil aggregates to breakdown from physical forces and is a measure of the coherence of particles within the aggregates (Skidmore and Powers, 1982). Aggregates with low stability fracture easily and break down into smaller sizes. Thus soil aggregate stability influences porosity, water retention, bulk density, infiltration, and the extent of soil surface exposed to precipitation (Cerda, 1996). The size and stability of aggregates also have major effects on a soil's susceptibility to wind and water erosion (Kemper and Chepil, 1965).

Wind erosion is a serious problem in many parts of the world. It is an especially severe problem in the arid and semi-arid regions. Areas most susceptible to wind erosion include much of North Africa and the Near East; parts of southern, central, and eastern Asia; the Siberian Plain; Australia; north-west China; southern South America; and North America (FAO, 1960). Wind erosion physically removes the most fertile part of the soil resulting in degradation of land, air and water quality. It has long been recognized that a soil consisting of bare, loose, dry, finely divided material is susceptible to wind erosion (Chepil, 1941). The basic causes of wind erosion are associated with the equilibrium between climate, vegetation, and soil (Chepil and Woodruff, 1963). The most important factor making the soil susceptible to wind erosion is the depletion or destruction of protective vegetation or plant residue on the land. Periods of low precipitation, high temperature, and high wind velocity are also important contributors to the severity of wind erosion (Skidmore, 1986).

In addition to protective vegetation, an increase in the size of aggregates increases a soil's resistance to the forces of the wind, not only by increasing the size of the unit exposed to the wind, but also through increased aerodynamic surface roughness (Chepil and Woodruff, 1963). The resistance of aggregates to abrasion by saltating particles affects the amount of soil movement by wind erosion. The greater this resistance, the longer aggregates remain on the soil surface, protecting the more erodible fraction. Therefore, the amount, stability, and placement of soil aggregates on the soil surface exert major influences on a soil's susceptibility to wind erosion. The purpose of this paper is to review the current state of knowledge of the processes that affect soil aggregate size distribution and dry stability as related to wind erosion, and methods of measurement of aggregate size distribution and stability.

Aggregation Processes Relevant to Wind Erosion

Several forces operating in the soil tend to cause changes in the aggregate status. Aggregates can break into smaller units or combine into larger ones by the action of rainfall impact, plant root growth, animal and machine traffic, abrasion from saltating particles, tillage and cropping history, wetting and drying, freezing and thawing, or freeze drying. These same forces can cause a change in the stability of aggregates. In addition to these forces, many factors or variables have been found to influence aggregate size distribution and stability. These factors include the primary particle size distribution, calcium carbonate content, and organic matter content (Chepil, 1953a, 1954a, 1955a and b). Each of these processes and factors affects wind erosion through its influence on aggregate size distribution and stability.

From wind tunnel tests, Chepil (1950) determined the relative erodibilities of soils as a function of the proportion of dry soil aggregates in various sizes. Aggregates greater than 0.84 mm in diameter were considered nonerodible in the range of wind speeds used in the tests. Relative wind tunnel erodibility was later converted (Fig. 1) to actual soil loss in a series of experiments on 69 fields near Garden City, Kansas, USA (Chepil, 1960). A soil with only one per cent of aggregates having diameters greater than 0.84 mm is 10 times more erodible than a soil with 53% of aggregates having diameters greater than

0.84 mm and almost 100 times more erodible than a soil with 77% of aggregates having diameters greater than 0.84 mm (Fig. 1). Similarly, dry aggregate stability can also differ a hundred- fold between soils (Skidmore and Powers, 1982).

Coarse textured soils do not contain enough silt and clay to bind sand particles into aggregates. Clayey soils develop aggregates, but weathering breaks them down and produces an erodible condition. Chepil (1953a) found that a clay content in the range of 15 to 27% with high amounts of silt is best for the development of aggregates which resulted in soils of reduced erodibility by wind. Clay content less than 15% generally impeded the formation of a good aggregate condition. As clay content increases to above 27%, aggregation generally decreases. Chepil (1955a) also found that as the proportion of silt increased and the proportion of sand decreased, the degree of soil cloddiness increased.

Soil organic matter often is associated with high levels of aggregation as well as structural stability. However, Chepil (1954a) claimed that decomposed organic matter increased the susceptibility of a soil to wind erosion. Although an increase in organic matter increased aggregation, the aggregates formed were limited to sizes that were erodible by wind. Chepil (1955b) also showed that wheat straw and green alfalfa in the process of decomposition increased soil cloddiness and decreased soil erodibility by wind. These aggregation trends were reversed after the straw was fully decomposed, and the erodibility of wind increased. He concluded that maintaining vegetative material on the soil surface was better for long-term aggregation than mixing residues into the soil where

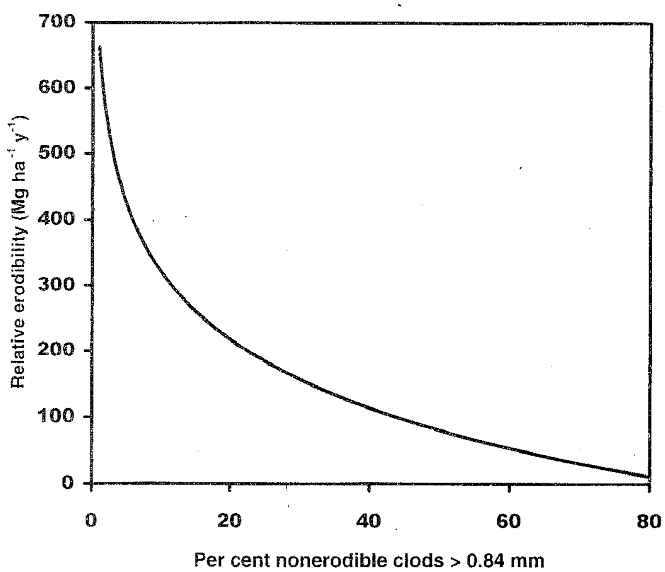

Fig. 1. Relationship between percent nonerodible aggregates > 0.84 mm and relative soil erodibility (Modified from Woodruff and Siddoway, 1965).

it decomposes more rapidly. Data from a 7-year study of summer fallow methods (Anderson and Wenhardt, 1966) show that the largest overwinter decrease in the erodible fraction (aggregates <0.84 mm diameter) occurred in treatments that left the highest residue amounts on the surface. Surface residues provide insulation and reduce the occurrence and depth of soil frost formation (Pikul *et al.*, 1986). Soil thermal properties can be altered by modifying reflectance, thermal conductivity, heat capacity, heat loss, and the shape of the soil surface (Voorhees *et al.*, 1981).

Modification of a soil's relative aggregate size status through tillage is one method of managing surface roughness (Chepil, 1953b; Lyles and Woodruff, 1962). Tillage can significantly alter a soil's aggregate size distribution. Variations in aggregate size distribution resulting from different implements were studied by Woodruff and Chepil (1958), Siddoway (1956), and Woodruff (1964), but soil water content was not considered as a factor in these investigations. Although available literature indicates that aggregate size distribution resulting from tillage operation depends on the soil water content at the time of tillage (Chepil, 1950; Gupta and Larson, 1982), there is little experimental data to support it. Tangie *et al.* (1990) and Wagner and Ding (1994) showed the water content at the time of tillage significantly affected the resulting aggregate size distribution. Maximum aggregate breakdown and the resulting minimum tillage-induced aggregate size distribution occurred near the optimum water content for compaction.

In humid areas, the addition of calcium carbonate or lime ($CaCO_3$) often increases soil aggregation. In arid areas, however, calcium carbonate has the opposite effect. On soils other than sands and loamy sands in arid areas, a 1 to 5% increase in calcium carbonate caused a substantial disintegration of soil cloddiness and a decrease in the stability of clods (Chepil, 1954a). This was thought to be caused by calcium carbonate weakening the cementing strength of clays. However, on sands and loamy sand soils, increases in calcium carbonate resulted in increased aggregation and stability. In these soils, calcium carbonate acts as a mild cementing agent similar to silt sized quartz in sandy soils.

During wind erosion, erodible particles less than 0.84 mm are removed continually in creep, saltation, and suspension. The suspension-size dust generated from aggregate abrasion tests was found to range from 14 to 27% of the whole soil and was related to parent soil clay content (Mirzamostafa *et al.*, 1998). The supply of particles is rarely exhausted because new erodible-size particles are created by abrasion. Thus, the presence of nonerodible aggregates alone does not determine field erodibility.

Aggregates that are susceptible to abrasive breakdown by saltating soil particles do not resist erosion. Rather, aggregates with low dry stability are broken down and contribute to the erodible-sized material; in some cases, this breakdown can be a significant source of erodible-size particles. Using a calibrated sandblasting device, Hagen (1984) studied the effects of particle speed, size, angle, and stability of the abrader on the abrasion resistance of aggregate "targets" of various stabilities. He found that sand abrader produced higher abrasive erosion than soil abrader and that impact angles of 15 to 30° caused more abrasion loss than did other angles. Abrasive erosion also increased as a power of the particle velocity. The power ranged from 1.5 for fragile aggregates to 2.3 for the most stable aggregates. The abrasive erosion decreased nonlinearly as aggregate stability increased.

In a separate experiment, Hagen *et al.* (1992) demonstrated that accurate abrasion coefficients can be calculated from dry aggregate stability. Soil loss correlated well with the aggregates' resistance to crushing according to the following equation:

$$Y = \exp(a + bX^{5/2} + c\ln(X), \quad R^2 = 0.97$$

where

$a = -2.07$
$b = -0.077$
$c = -0.119$
Y = abrasion coefficient (m^{-1})
X = ln [crushing energy ($J\ kg^{-1}$)] with lower limit 0.1.

This relationship (Fig. 2) provides a linkage between readily made measurements of crushing energy and the abrasion coefficients required for mathematical models of the vertical flux of abraded soil.

The Wind Erosion Prediction System (WEPS) currently being developed by the United States Department of Agriculture - Agricultural Research Service (Hagen, 1988, 1991a) requires the aggregate size distribution and stability to be represented accurately on a daily basis within the model. The aggregate size distribution is used not only to determine the amount of erodible material, but also to compute surface friction velocities as affected by aggregate-induced roughness. Roughness from aggregates also provides storage areas to trap saltating particles, thus removing them from the influence of the wind. Aggregate stability in WEPS affects the emission of loose aggregates from abrasive breakdown of large clods (Hagen, 1991b).

Changes in surface soil aggregate status over time can result in conditions highly conducive to wind erosion or can create a less erodible state. The stability and size distribution of soil aggregates are affected by the processes of wetting, drying, freezing, thawing, and freeze drying. These processes typically occur in repeated cycles of varying intensity throughout the year and can cause significant changes to the aggregate status of a soil (Layton *et al.*, 1993; Bullock *et al.*, 2001). Thus, changes in soil structure over winter can significantly affect erodibility of a soil. These processes are moderated by soil properties, particularly aggregate water content, as well as weather and plant residues. These overwinter processes are major causes of the highly erodible state many Great Plains soils of the United States exhibit in the early spring from February through May (Chepil, 1954b; Bullock *et al.*, 2001).

When a soil aggregate becomes wet, aggregate volume increases, depending on the clay content, and the swelling of clays and wetting of pore spaces disrupts structural bonds (Czurda *et al.*, 1997). As the soil dries, the water recedes into capillary wedges surrounding particle-to-particle contacts. The interfacial tension and internal cohesive tension pull adjacent particles together with great force as the soil dries and soluble compounds such as silica and organic molecules are concentrated in the liquid

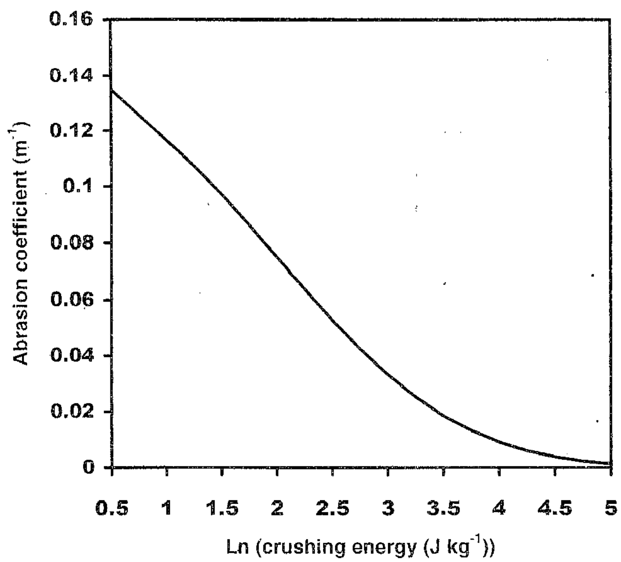

Fig. 2. Abrasion coefficient as a function of dry stability of soil aggregates (Modified from Hagen, et al., 1992).

phase. If, upon wetting, the soil water content increases to a point of saturation, a puddled state is reached in which consolidation results upon drying, even to the point of a massive state. However, if the soil is wetted to a low water content, aggregates tend to weaken and remain intact or become smaller upon drying. Such decay is especially notable with wetting and drying immediately following tillage. The precise water contents at which wetting and drying cause consolidation or disintegration are unknown.

In field studies, Bullock *et al.* (2001) found precipitation to be the key driving force in aggregation processes. This 3-year study investigated the effects of overwinter climatic factors on the geometric mean diameter of soil aggregates, percentage of aggregates < 0.84 mm in diameter, and soil roughness in southern Alberta, Canada. They concluded that the timing and form of precipitation provided useful insights into erodibility changes. During the "fall rain/snow" period, freeze thaw cycles were detrimental to soil structure, especially if accompanied by appreciable precipitation. The largest changes were observed during "winter snow" period when intermittent snowmelt probably increased soil water and allowed freeze thaw cycles to be more effective in aggregate breakdown. Freeze drying and aggregate abrasion by blowing snow may have also contributed to aggregate breakdown during this period. In the "spring snow/rain" period, while freeze thaw cycles and precipitation were still important in aggregate breakdown, heavy rains in the late spring were a factor in reaggregation.

Field data indicate that during winter, aggregates tend to degrade into smaller aggregates or consolidate into larger aggregates or even a massive structure (Chepil, 1954b; Bisal and Nielsen, 1964; Bisal and Ferguson, 1968). The differences in results were explained by differences in soil water content and the severity of the winter. Under low water contents, overwinter processes are not as effective in changing aggregate status. During wet winters, a high soil water content promotes consolidation during wetting and drying, as well as freezing and thawing. This often occurs in northern latitudes where the subsoil is frozen, thus trapping water at the surface during snow melt. As pore water expands during freezing, aggregate volume increases and disrupts structural bonds (Bisal and Nielsen, 1964). If the water changes to a liquid phase (i.e., thaws), pore collapse occurs and the soil resembles a viscous liquid or even enters a state of suspension. Upon drying, the consolidation action of decreasing matric potential results in a more stable aggregate structure. For water contents between the two extremes, overwinter processes have the highest potential to degrade aggregates into smaller and weaker units. Under these water contents, freezing causes ice structures to develop that push the aggregate apart. But upon thawing, not enough moisture is present to cause pore collapse and reconsolidation.

Under conditions of freeze drying, where soil water changes phase directly from a solid to a gas, the result is always destructive to aggregate size and stability (Tatarko, unpublished data). The severity of the effect depends on the water content at freezing. Upon freezing, ice crystals develop which disrupt aggregate bonds (Bisal and Nielsen, 1964; Hinman and Bisal, 1968). When drying in a frozen state, the soil retains its rigid structure in which pore collapse does not occur and the soil aggregates literally fall apart. The effects of freeze drying on aggregate size and stability are directly proportional to the water content when frozen (Starika and Benoit, 1995). The detrimental effects of freeze drying generally increases as aggregate size increases. When several repeated cycles of this process occur, the soil surface can be left in a highly erodible state during and after winter.

Aggregation Measurements Relevant to Wind Erosion

Dry soil aggregate stability and size distribution vary widely in time and space and are primary factors affecting wind erosion. Aggregate density has a minor influence, but is much less variable than stability and size distribution. For comparisons of size distribution or stability of aggregates, not only should the measurements of size and stability be well defined, but the disruptive forces used to determine them should be standardized as well. If the measurements are to have practical use, forces causing changes in aggregates should be related to forces expected in the field.

Aggregate size distribution

Soil at the surface is composed of aggregates and particles of various sizes. The relative amounts, by size class, of these components on a dry (air or oven) basis make up the aggregate size distribution (ASD).

The ASD was determined early in wind erosion research by sieving dry soil using hand or mechanically agitated flat sieves. In an attempt to standardize sieving and thus reduce operator error, Chepil and Bisal (1943) proposed a method that used a nested set of rotary sieves. This technique reduced the variance between two operators compared to hand sieving. This basic method is still used today, although several modifications have been made over the years to improve speed and accuracy of the sieve (Chepil, 1952, 1962; Lyles *et al.*, 1970; Fryrear, 1985). Lyles *et al.* (1970) proposed a modified rotary sieve and compared it, using non-abrasive materials, with the original rotary sieve as well as several of its modifications. They found that the modified rotary sieve significantly reduced average errors. This improved accuracy was attributed to giving major consideration to mesh length, the main factor controlling the time that material remains on the sieve mesh area.

With materials that abrade like soil aggregates however, size separation by sieving is less accurate because of a lack of a definable end point at which to stop sieving. Also, fragile aggregates like those from sandy soils, may disappear during sieving. However, such fragile aggregates contribute little to erosion resistance, thus their breakdown on the rotary sieve is of little practical consequence.

The rotary sieve as developed by Chepil (1962) and improved by Lyles *et al.* (1970) is the standard used in most wind erosion research to measure aggregate size distribution. According to Kemper and Rosenau (1986), some advantages of the rotary sieve are (i) it has the lowest variability of any method, regardless of size of sample; (ii) it causes less breakdown of aggregates than flat sieves; (iii) it is not subject to operator error; (iv) the sieves experience very little clogging; and (v) it is well suited to resieving soil to determine the relative resistance of the soil to mechanical breakdown.

The ASD in the past has been commonly and more simply represented as the per cent aggregates greater than 0.84 mm. This erodible fraction was used to determine the inherent soil erodibility in the wind erosion equation (Woodruff and Siddoway, 1965). However, it is well known that soil aggregates are a major component of random roughness and thus affect the surface threshold friction velocity (Chepil and Woodruff, 1963). More recent modeling efforts, therefore, attempt to account for the effect of the entire ASD on the erodibility of the soil (Hagen, 1991a). Also, to evaluate treatments, reducing the distribution to one or two parameters is desirable. Gardner (1956) and Kemper and Chepil (1965) proposed using the two parameters of geometric mean diameter (GMD) and geometric standard deviation (GSD) to describe the ASD.

Soil aggregates generally exhibit a log-normal size distribution. Gardner (1956) suggested a graphical approach to describing the distribution in which ASD is plotted on log-probability scale versus the log of the sieve diameter as the ordinate yielded straight lines. The GMD is the diameter at 50% oversize, and the GSD is calculated as the ratio of the size at 50% to the size at 15.9%. Gardner (1956) cautioned that the antilog of GSD has no statistical meaning when determined in this manner.

GMD and GSD also can be calculated as (Gardner, 1965; Campbell, 1985):

$$\text{GMD} = \exp\left[\sum_{(i=1)}^{n} m_i \ln d_i\right] = \pi\,(d_i)^{m_i}$$

$$\text{GSD} = \exp\left[\sum m_i\,(\ln d_i)^2 - (\ln \text{GMD})^2\right]^{0.5}$$

where,
m_i is the mass fraction in each aggregate size class i, d_i is the geometric mean diameter of class i, and π is the product operator.

Hagen *et al.* (1987) showed that for aggregate sizes that are distributed log-normally, the mass fraction of aggregates whose diameters are greater than or less than some diameter may be represented by the use of the error function of the normal distribution curve. This technique requires only two sieve cuts, from which the GMD and GSD can be calculated. Because these two parameters describe the size distribution of log-normally distributed aggregates, the mass fraction of aggregates greater than some user-selected diameter can be calculated easily. The two-sieve method is labor saving, but does not permit the easy detection of samples that deviate from a lognormal distribution. Therefore, a method of representing ASD as a modified log-normal distribution was presented by Wagner and Ding (1994). Their three and four parameter distributions can describe a wider range of field-sampled aggregate size distributions than a standard log-normal distribution, especially at the upper and lower tails.

Aggregate stability

Dry aggregate stability has been described by methods based on relative aggregate size reduction from applied forces, rupture stress, or energy required for size reduction. With relative size reduction, the aggregates were subjected to external forces in several ways. Chepil (1951) placed aggregates in metal cylinders and inverted them end-over-end 20 times. The stability was expressed as a percentage of the original weight of the soil retained on a 0.42 mm sieve. Chepil (1953c) also determined a relative measure of coherence by rotary sieving and dividing the weight of the soil material remaining on the sieve by the weight before sieving. Another method of size reduction was to vigorously sieve aggregates with flat sieves and express the aggregate stability as a weight percentage of sample remaining after five minutes over that remaining after one minute (Toogood, 1978). For the rupture stress measurement, aggregates were diametrically loaded between parallel plates (Rogowski and Kirkham, 1976; Skidmore and Powers, 1982).

The energy required for size reduction has been measured using several methods. The drop shatter method has been used to determine the amount of work required to subdivide aggregates into smaller units (Marshall and Quirk, 1950; Farrell *et al.*, 1967). With this method, air-dried aggregates are dropped from various heights onto a concrete floor. The amount of kinetic energy dissipated by shattering the aggregate then is related to the degree of fragmentation. Skidmore and Powers (1982) measured the energy required to crush an aggregate by integrating the area under the force versus distance curve. Boyd *et al.* (1983) developed a soil-aggregate crushing-energy meter (SACEM), for measuring the energy required to crush an aggregate between two horizontal plates. Although the SACEM provided useful information, it had limitations on the soil aggregate stabilities it could measure. The SACEM design later was modified to allow for a wider range of soil aggregate stabilities (Hagen *et al.*, 1995).

Skidmore and Layton (1992) studied different measures of aggregate stability. A related, unpublished study (Skidmore and

Layton, personal communication) evaluated four different measures of aggregate stability.

- Crushing energy/surface area (J m^{-2}) represents the work done in crushing an aggregate divided by the new surface area exposed, which gave energy per unit of surface area. The surface area was calculated using the arithmetic mean of the sieve size fractions and assuming the aggregates were spherical.
- Crushing energy (J kg^{-1}) is calculated by dividing the work done in crushing the aggregate by the mass of the aggregate being crushed.
- Rupture stress (kPa) is calculated by dividing the initial break force by the cross-sectional area of the aggregate. This requires an independent measure of aggregate density.
- Initial break force (N) is simply the force required for the initial fracture of an aggregate.

The relative variability of each method was: crushing energy < crushing-energy/surface area < rupture stress < initial break force. The sample numbers required to estimate the true mean within 25% of the mean at the 0.05 level were 10, 12, 20, and 22, respectively.

The initial break force is the easiest to measure but requires the greatest number of measurements. Aggregate stability measurements using rupture stress require a high number of aggregates and a separate measurement of aggregate density. The crushing energy/surface area method has the greatest range, more than two orders of magnitude between soft and stable soils. One drawback of this method is the amount of work necessary to measure the surface area exposed by crushing. However, it is probably the most meaningful scientifically because measuring the surface area exposed provides a measure of the magnitude of structural bonds broken by crushing (Skidmore, personal communication). Using the crushing energy method requires crushing the aggregate to the same end point each time. In spite of this, it requires the fewest aggregate measurements to estimate the mean. This measurement is extremely simple but requires special equipment for measuring energy. The crushing energy method is now used routinely in several laboratories for determining dry aggregate stability.

Summary and Recommendations

A soil's aggregate size distribution and dry stability exert a major influence on the wind erodibility of that soil. Larger or more stable aggregates resist the force of the wind and saltating grains more than smaller or weaker aggregates. The aggregation process is affected by soil constituents, management, cropping history, and weather. The most common methods currently used to measure aggregate status include the rotary sieving for size distribution and crushing energy for dry stability.

Our understanding of aggregation processes is far from complete. The influence of each soil constituent is only generally known. Mathematical models that predict aggregate size distribution and stability from a soil's intrinsic properties and cropping or management system would be helpful to the current wind erosion modeling efforts of the United States Department of Agriculture (USDA). Also, the influence of overwinter processes on soil aggregation is only understood in general terms and need to be quantified. Overwinter processes can leave the soil in a highly erodible state at a time when winds are the strongest and is thus an important process that needs to be better understood.

Likewise, soil aggregate measurement systems can be improved. A means of measuring aggregate size distribution that is non-destructive to clods is desirable. Rotary sieving is an abrasive process that, by its nature, changes the aggregate size distribution during sieving. A method to rapidly measure aggregate size of many aggregates with a minimum of disturbance of those aggregates will provide a more accurate assessment of aggregate size distribution. Also, measuring aggregate stability is a time consuming process and requires many repetitions to estimate the mean. However, if stability can be related to intrinsic soil properties and cropping history, as well as weathering processes, the need for direct measurement of aggregate stability could be reduced.

References

Anderson, C.H. and Wenhardt, A. 1966. Soil erodibility, fall and spring. *Canadian Journal of Soil Science* 46: 255-259.

Bisal, F. and Ferguson, W.S. 1968. Monthly and yearly changes in aggregate size of surface soils. *Canadian Journal of Soil Science* 48: 159-164.

Bisal, F. and Nielsen, K.F. 1964. Soil aggregates do not necessarily break down over winter. *Soil Science* 98: 345-346.

Boyd, D., Skidmore, E.L. and Thompson, J.G. 1983. A soil aggregate crushing energy meter. *Soil Science Society of America Journal* 47: 313-316.

Bullock, M.S., Larney, F.J., Izaurralde, R.C. and Feng, Y. 2001. Overwinter changes in wind erodibility of clay loam soils in southern Alberta. *Soil Science Society of America Journal* 65: 423-430.

Campbell, G.S. 1985. *Soil Physics with BASIC: Transport Models for Soil-plant Systems.* Elsevier, Amsterdam.

Cerda, A. 1996. Soil aggregate stability in three Mediterranean environments. *Soil Technology* 9: 133-140.

Chepil, W.S. 1941. Relation of wind erosion to the dry aggregate structure of the soil. *Science of Agriculture* 21: 488-507.

Chepil, W.S. 1950. Properties of soil which influence wind erosion: II. Dry aggregate structure as an index of erodibility. *Soil Science* 69: 403-414.

Chepil, W.S. 1951. Properties of soil which influence wind erosion: V. Mechanical stability of structure. *Soil Science* 72: 465-478.

Chepil, W.S. 1952. Improved rotary sieve for measuring state and stability of dry soil structure. *Soil Science Society of America Proceedings* 16: 113-117.

Chepil, W.S. 1953a. Factors that influence clod structure and erodibility of soil by wind: I. Soil texture. *Soil Science* 75: 473-483.

Chepil, W.S. 1953b. Factors that influence clod structure and erodibility of soil by wind: I. Water stable structures. *Soil Science* 76: 389-399.

Chepil, W.S. 1953c. Field structure of cultivated soils with special reference to erodibility by wind. *Soil Science Society of America Proceedings* 17: 185-190.

Chepil, W.S. 1954a. Factors that influence clod structure and erodibility of soil by wind: III. Calcium carbonate and decomposed organic matter. *Soil Science* 77: 473-480.

Chepil, W.S. 1954b. Seasonal fluctuations in soil structure and erodibility of soil by wind. *Soil Science Society of America Proceedings* 18: 13-16.

Chepil, W.S. 1955a. Factors that influence clod structure and erodibility of soil by wind: IV. Sand, silt, and clay. *Soil Science* 80: 155-162.

Chepil, W.S. 1955b. Factors that influence clod structure and erodibility of soil by wind: V. Organic matter at various stages of decomposition. *Soil Science* 80: 413-421.

Chepil, W.S. 1960. Conversion of relative field erodibility to annual soil loss by wind. *Soil*

Science Society of America Proceedings 24(2): 143-145.

Chepil, W.S. 1962. A compact rotary sieve and the importance of dry sieving in physical soil analysis. *Soil Science Society of America Proceedings* 25: 4-6.

Chepil, W.S. and Bisal, F. 1943. A rotary sieve method for determining the size distribution of soil clods. *Soil Science* 56: 95-100.

Chepil, W.S. and Woodruff, N.P. 1963. The physics of wind erosion and its control. *Advances in Agronomy* 15: 211-302.

Czurda, K.A., Ludwig, S. and Schababerle, R. 1997. Fabric changes in plastic clays by freezing and thawing. In *Soil Structure: Its Development and Function* (Eds. K.H. Hartge and B.A. Stewart), pp. 71-91. Advances in Soil Science. CRC Press. Boca Raton, FL, USA.

Farrell, D.A., Greacen, E.L. and Larson, W.E. 1967. The effect of water content on axial strain in a loam soil under tension and compression. *Soil Science Society of America Proceedings* 31: 445-450.

FAO. 1960. Soil erosion by wind and measures for its control. Food and Agriculture Organization, United Nations. *Development Paper No. 71*. Rome, Italy.

Fryrear, D.W. 1985. Determining soil aggregate stability with a rapid rotary sieve. *Journal of Soil and Water Conservation* 40: 231-233.

Gardner, W.R. 1956. Representation of a soil aggregate-size distribution by a logarithmic-normal distribution. *Soil Science Society of America Proceedings* 40: 151-153.

Gupta, S.C. and Larson, W.E. 1982. Modeling soil mechanical behavior during tillage. In *Predicting Tillage Effects on Soil Physical Properties and Processes* (Eds. P.W. Unger and D.M. Van Doren, Jr.), pp. 151-178. American Society of Agronomy Special Publication No. 44. American Society of Agronomy and Soil Science Society of America. Madison, USA.

Hagen, L.J. 1984. Soil aggregate abrasion by impacting sand and soil particles. *Transactions of the American Society of Agricultural Engineers* 27: 805-816.

Hagen, L.J. 1988. New wind erosion model developments in the USDA. *Proceedings of the 1988 Wind Erosion Conference*, pp. 158-164. Lubbock, Texas, USA.

Hagen, L.J. 1991a. A wind erosion prediction model to meet user needs. *Journal of Soil and Water Conservation* 46(2): 106-111.

Hagen, L.J. 1991b. Wind erosion mechanics: Abrasion of aggregated soil. *Transactions of the American Society of Agricultural Engineers* 34(3): 831-837.

Hagen, L.J., Schroeder, B. and Skidmore, E.L. 1995. A vertical soil crushing-energy meter. *Transactions of the American Society of Agricultural Engineers* 38(3): 711-715.

Hagen, L.J., Skidmore, E.L. and Fryrear, D.W. 1987. Using two sieves to characterize dry soil aggregate size distribution. *Transactions of the American Society of Agricultural Engineers* 30: 162-165.

Hagen, L.J., Skidmore, E.L. and Saleh, A. 1992. Wind erosion: Prediction of aggregate abrasion coefficients. *Transactions of the American Society of Agricultural Engineers* 36: 1847-1850.

Hinman, W.C. and Bisal, F. 1968. Alterations of soil structure upon freezing and thawing and subsequent drying. *Canadian Journal of Soil Science* 48: 193-197.

Kemper, W.D. and Chepil, W.S. 1965. Size Distribution of Aggregates. In *Methods of Soil Analysis* (Ed. A. Klute), Pt. I, pp. 499-510. American Society of Agronomy and Soil Science Society of America, Madison WI, USA.

Kemper, W.D. and Rosenau, R.C. 1986. Aggregate stability and size. In *Methods of Soil Analysis.* (Ed. A. Klute), Pt. I, pp. 425-442. American Society of Agronomy and Soil Science Society of America, Madison WI, USA.

Layton, J.B., E.L. Skidmore, and C.A. Thompson. 1993. Winter-associated changes in dry-soil aggregation as influenced by management. *Soil Science Society of America Journal* 57:1568-1572.

Lyles, L., Dickerson, J.D. and Disrud, L.A. 1970. Modified rotary sieve for improved accuracy. *Soil Science* 109(3): 207-210.

Lyles, L. and Woodruff, N.P. 1962. How moisture and tillage affect soil cloddiness for wind erosion control. Agricultural Engineering 43(3): 150-153,159.

Marshall, T.J. and Quirk, J.P. 1950. Stability of structural aggregates of dry soil. *Australian Journal of Agricultural Research* 1: 266-275.

Mirzamostafa, N., Hagen, L.J., Stone, L.R. and Skidmore, E.L. 1998. Soil aggregate and texture effects on suspension components from wind erosion. *Soil Science Society of America Journal* 62: 1351-1361.

Pikul, J.L., Zuzel, J.F. and Greenwalt, G.N. 1986. Formation of soil frost as influenced by tillage and residue management. *Journal of Soil and Water Conservation* 41: 196-199.

Rogowski, A.S. and Kirkham, D. 1976. Strength of soil aggregates: influence of size, density, and clay and organic matter content. *Med. Faculty Landbouww. Rijksuniv. Gent.* 41: 85-100.

Siddoway, F.H. 1956. *Annual Research Report.* Soil and Water Conservation Research Branch. United States Department of Agriculture-Agricultural Research Service in cooperation with Tetonia Branch Agricultural Experiment Station. University of Idaho. Moscow, USA.

Skidmore, E.L. 1986. Wind erosion climatic erosivity. *Climatic Change* 9(1.2): 195-208.

Skidmore, E.L. and Layton, J.B. 1992. Dry-soil aggregate stability as influenced by selected soil properties. *Soil Science Society of America Journal* 56:557-561.

Skidmore, E.L. and Powers, D.H. 1982. Dry soil-aggregate stability: Energy based index. *Soil Science Society of America Journal* 46: 1274-1279.

Starika, J.A. and Benoit, G.R. 1995. Freeze-drying effects on wet and dry aggregate stability. *Soil Science Society of America Journal* 59: 218-223.

Tangie, N.M., Wagner, L.E. and Slocombe, J.W. 1990. Effects of moisture content on aggregate size distribution. American Society of Agricultural Engineers Paper No. MC 90-102. St. Joseph, USA.

Toogood, J.A. 1978. Relation of aggregate stability to property of Alberta soils. In *Modification of Soil Structure* (Eds. W.W. Emmerson, R.D. Bond and A.R. Dexter), pp. 211-215. John Wiley and Sons, New York.

Voorhes, W.B., Allmaras, R.R. and Johnson, C.E. 1981. Alleviating temperature stress. In *Modifying the Root Environment to Reduce Cropping Stress* (Eds. G.F. Arkin and H.M. Taylor), pp. 217-266. Monograph 4. American Society of Agricultural Engineers. St. Joseph, MI, USA.

Wagner, L.E. and Ding, D.J. 1994. Representing aggregate size distributions as modified lognormal distributions. *Transactions of the American Society of Agricultural Engineers* 37(3): 815-821.

Woodruff, N.P. 1964. Residue maintenance by various types of farm machines. In *Wind Erosion Control on Cropland in the Great Plains States*, pp. 96-97. United States Department of Agriculture-Soil Conservation Service.

Woodruff, N.P. and Chepil, W.S. 1958. Influence of one-way-disk and subsurface-sweep tillage on factors affecting wind erosion. *Transactions of the American Society of Agricultural Engineers* 1(1): 81-85.

Woodruff, N.P. and Siddoway, F.H. 1965. A wind erosion equation. *Soil Science Society of America Proceedings* 29(5): 587-590.