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Classification of the Size Distribution of Soil Aggregates in Arid and Semi-arid Regions in East Asia

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Classification of the size distribution of soil aggregates in arid and semi-arid regions in East Asia

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Abstract: Broad-scale evaluation of wind erosion requires details of the spatial distribution of the primary factors controlling wind erosion, such as soil characteristics, vegetation cover and soil water conditions. Soil aggregates are one of the factors, and their size distributions have usually been mapped by assuming a one-to-one relationship with soil texture class. We dry-sieved 31 soil samples from arid and semi-arid regions in East Asia. Cluster analysis showed that the size distribution of aggregates varied even within a single soil texture class, mainly because of the difference in soil types, indicating that the above assumption does not hold in this region. Azonal aeolian sediments have typical well-sorted forms of size distributions, but zonal steppe soils show various patterns of size distribution. Parent material can be a good indicator to use to classify the size distributions of aggregates in steppe soils, loess materials and soils formed on newer (Quaternary and Cretaceous) igneous rock (finer soils), on sedimentary materials (coarser soils), and on ancient geological layers (complex, coarse particle size composition). Soil maps and geological maps of this region are readily available, so the mapping of soil aggregates in relation to these thematic maps should be efficient and practical.

Key Words: dry sieving, cluster analysis, wind erosion, China, Mongolia

INTRODUCTION

Erosion of soil by wind, which occurs in many arid, semi-arid and agricultural areas of the world, leads to land degradation and reduces air quality (Shao, Y., 2000). The arid and semi-arid regions of East Asia are among the most vulnerable to wind erosion (Gao, X. *et al.*, 2002). Wind erosion and dust entrainment into the air in East Asia have been intensively studied at large spatial scales in recent years (e.g. Nickovic, S. *et al.*, 2001; Shao, Y. *et al.*, 2002; Gong, S. L. *et al.*, 2003). The intensity of wind erosion depends on various factors, of which the most important are wind velocity, soil moisture, vegetation cover, surface roughness and particle size distribution (Chatenet, B. *et al.*, 1996). The sand drift intensity of single-sized, smooth, loose, dry particles can be estimated as a function of the friction velocity and the threshold friction velocity (Iversen, J. D. and White, B. R., 1982). Friction velocity is an index of the shear stress from atmospheric turbulence to the ground surface. Threshold friction velocity is defined as the minimum friction velocity required for the aerodynamic forces to overcome the retarding forces and to initialize the movement of soil particles (Shao, Y., 2000). Most of the recent advanced modelling frameworks for wind erosion estimation are based on these concepts.

Mass-size distribution of soil particles is one of the primary input parameters for advanced wind erosion models (Marticorena, B. *et al.*, 1997; Shao, Y. and Leslie, L. M., 1997), which estimate the fluxes (the total weight of moved soil particles per unit area and per unit time) of saltation sand and suspended dust. Particles with different diameters have different erodibilities. Experiments show that particles with a diameter of around 80 μm are the most erodible (Iversen, J. D. and White, B. R., 1982). Moreover, size distribution of soil particles affects erodibility through indirect processes, such as soil moisture and surface crusting (Shao, Y., 2000).

The distribution needed for the models does not correspond to traditional soil texture. The traditional particle distribution is seen only when soils are submitted to wet sedimentation techniques, which lead to the breakage of aggregates by the polar effects of water (Marticorena, B. *et al.*, 1997). All soils that contain colloidal materials contain aggregates, which are clusters of particles of different sizes that remain associated when the soil is stressed mechanically by tillage, raindrop impact or drying and wetting (Oades, J. M. and Waters, A. G., 1991). Therefore, the spatial distribution of the size distributions of soil aggregates must be mapped for broad-scale evaluation of wind erosion. However, there is hardly any information on the size distribution of aggregates at

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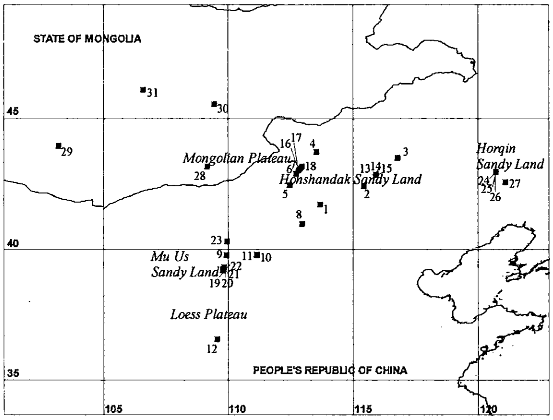

Figure 1. Sampling locations

large spatial scales, unlike other primary input parameters for wind erosion modelling, such as vegetation cover and soil moisture, for which remote sensing and modelling techniques are well developed. Owing to this scarcity, most models of wind erosion assume a one-to-one relationship between the size distribution of aggregates and the soil texture classification (Shao, Y. and Leslie, L. M., 1997; Marticorena, B. *et al*, 1997; Shao, Y. *et al.*, 2002), although the validity of this assumption is unknown.

Therefore, the accurate mapping of the size distribution of soil aggregates is one of the important pending issues for the broad-scale evaluation of wind erosion. We aimed to examine the validity of the above assumption and to establish methods for more accurate mapping of the size distribution of aggregates, by determining the size distribution of samples collected at various locations in northern and north-eastern China and Mongolia, and classifying the distributions in relation to the spatial information available at a broader scale.

1. METHODS

Sample locations

In the humid conditions, vegetation cover and soil moisture suppress wind erosion, while very dry conditions enhance wind-stable desert pavement and salt crust cover, also decreasing the activity of wind erosion (Pye, K., 1989 and Zhibai, D., 2002). Therefore, the intermediate condition, with less vegetation, less desert pavement and less salt concentration is most favourable to promoting the development of wind-erodible surfaces (Pye, K., 1989). In the target region, chernozems, kastanozems and calcisols by the classification of the World Reference Base for Soil

Table 1. Brief description of sampling locations. Soil types with an asterisk were identified from the SOTER soil map (FAO *et al.*, 1999); the others were identified by soil survey.

Sample No	Latitude	Longitude	Location	Landform	Soil type (WRB)	Texture
1	41:41:44N	113:40:10E	Eastern Mongolian Plateau	Hill slope	Kastanozems	Sandy Clay Loam
2	42:23:11N	115:24:09E	Eastern Mongolian Plateau	Flat land	Kastanozems	Loamy sand
3	43:28:51N	116:46:05E	Eastern Mongolian Plateau	Hill slope	Chernozems	Clay Loam
4	43:42:44N	113:30:41E	Central Mongolian Plateau	Flat land	Kastanozems	n/a
5	42:26:16N	112:27:34E	Central Mongolian Plateau	Flat land	Kastanozems	n/a
6	42:52:43N	112:42:20E	Central Mongolian Plateau	Flat land	Kastanozems	Loamy sand
7	43:01:23N	112:47:31E	Central Mongolian Plateau	Flat land	Kastanozems	Loamy sand
8	40:56:20N	112:56:06E	Yinshan Mountain	Hill slope	Kastanozems	Loamy sand
9	39:44:34N	109:55:08E	Ordos plateau	Hill slope	Kastanozems	Loamy sand
10	39:44:18N	111:08:34E	Northern Loess Plateau	Hill slope	Kastanozems	Loamy sand
11	39:45:21N	111:07:27E	Northern Loess Plateau	Hill slope	Kastanozems	Loamy sand
12	36.30:38N	109:32:25E	Central Loess Plateau	Flat land	Calcic Cambisols	Loamy sand
13	42:50:32N	115:53:08E	Honshandak sandy land	Sand dune	Arenosols	Loamy sand
14	42:50:33N	115:53:06E	Honshandak sandy land	Sand dune	Arenosols	Loamy sand
15	42:51:04N	115:53:10E	Honshandak sandy land	Sand dune	Arenosols	Loamy sand
16	43:05:06N	112:52:20E	Honshandak sandy land	Sand sheet	Arenosols	Loamy sand
17	43:05:06N	112:52:20E	Honshandak sandy land	Sand sheet	Arenosols	Loamy sand
18	43:09:06N	112:55:53E	Honshandak sandy land	Sand sheet	Arenosols	Sand
19	39:09:53N	109:46.35E	Mu Us sandy land	Sand dune	Arenosols	Loamy sand
20	39:12:21N	109:46:22E	Mu Us sandy land	Hill slope	Arenosols	n/a
21	39:16:51N	109:49:04E	Mu Us sandy land	Sand dune	Arenosols	Loamy sand
22	39:16:51N	109:49:04E	Mu Us sandy land	Sand dune	Arenosols	Loamy sand
23	40:16:44N	109:56:19E	Kupqi desert	Sand dune	Arenosols	Sand
24	42:56:16N	120:42:37E	Horqin sandy land	Upland field	Arenosols	n/a
25	42:56:26N	120:42:57E	Horqin sandy land	Sand dune	Arenosols	n/a
26	42:56:29N	120:42:52E	Horqin sandy land	Sand dune	Arenosols	n/a
27	42:33:12N	121:04:60E	Loess hill near Horqin sandy land	Flat land	Kastanozems	n/a
28	43:09:16N	109:08:30E	Central Mongolian Plateau	Flat land	Calcisols*	Loamy sand
29	43:57:17N	103:10:43E	Central Mongolian Plateau	Flat land	Calcisols*	Sand
30	45:33:11N	109:26:00E	Central Mongolian Plateau	Flat land	Kastanozems*	Sand
31	46:07:15N	106:35:18E	Central Mongolian Plateau	Flat land	Kastanozems*	Loamy sand

WRB = World Reference Base (FAO, 1998)
n/a = not available

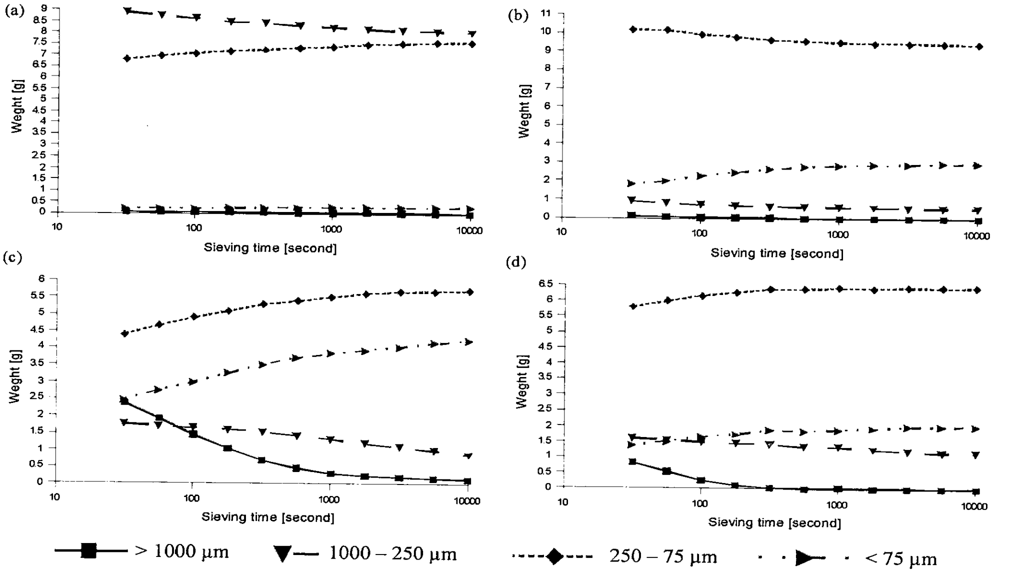

Figure 2. Time series of the soil weight on each sieve in a preliminary test of dry-sieving of (a) dune sand (sample no. 19), (b) castanozem (no. 2), (c) chernozem (no.3) and (d) loess (no. 12).

Resources (FAO, 1998) are considered erodible zonal soils (Quanguo-turang-puchahezuozhan, 1998). On the other hand, azonal soils, the formation process of which is mainly controlled by parent materials, such as sandy soils and loessal soils, in which aeolian processes are considerable as pointed out by many authors (e.g. Mabbutt, J. A., 1977), are also included in this study.

Thirty-one surface sediment samples (<5 cm depth) covering all the soil types which are considered erodible as explained above (Table 1), were collected in northern and north-eastern China and southern Mongolia (Figure 1). Most of the sampling points were selected on flat land or gentle slopes, to avoid the effect of micro-relief. The soil types without asterisks in Table 1 are compiled from the Chinese soil classification (Quanguo-turang-puchahezuozhan, 1998) determined by field survey by use of the correlation table attached to a soil and physiographic database for northern and central Eurasia (SOTER; FAO *et al.*, 1999). The soil types with asterisks are identified from a soil map in SOTER, without verification by field survey. Thirteen samples came from soil classified as kastanozems by WRB in the Mongolian Plateau and the Loess Plateau; 1 from chernozems; 2 from calcisols, 14 from arenosols in Honshandak Sandy Land, Horqin Sandy Land and Mu Us Sandy Land; and 1 from calcic cambisols (which corresponds to loess soils by Chinese soil classification) in the Loess Plateau.

	Sample No.	Dispersed (< 20 μm) [%]	Dry aggregate (< 38 μm) [%]
Dune sand	19	6.43	0.06
Castanozems	2	13.08	1.65
Chernozems	3	39.03	6.02
Loess	12	10.91	3.24

Table 2. The proportion of dispersed particles smaller than 20 μ m and dry aggregate smaller than 38 μ m.

Determination of the soil aggregate size distributions

Soil aggregates larger than 2 mm were removed by manual sieving, because large particles are not easily picked up by wind (Chatenet, B. *et al.*, 1996). The samples were sieved into seven soil classes—2000–1000, 1000–500, 500–250, 250–100, 100–75, 75–63 and 63–38 μm—with conventional stacked sieves on a vibration shaker machine. The optimum size of sample used for dry sieving depends on the number of sieves and the dimensions of the mesh apertures (Pye, K. and Tsoar, H., 1990). We considered 10 g appropriate.

There is no perfect method to determine the *in situ* size distribution of a soil (Chatenet, B. *et al.*, 1996), because (1) sampling itself may introduce bias, (2) aggregates do not have any characteristic size and are usually not stable, and (3) incomplete sieving may occur. In general, clay-sized particles and organic matter are the most important agents forming and stabilizing soil aggregates (Edwards,

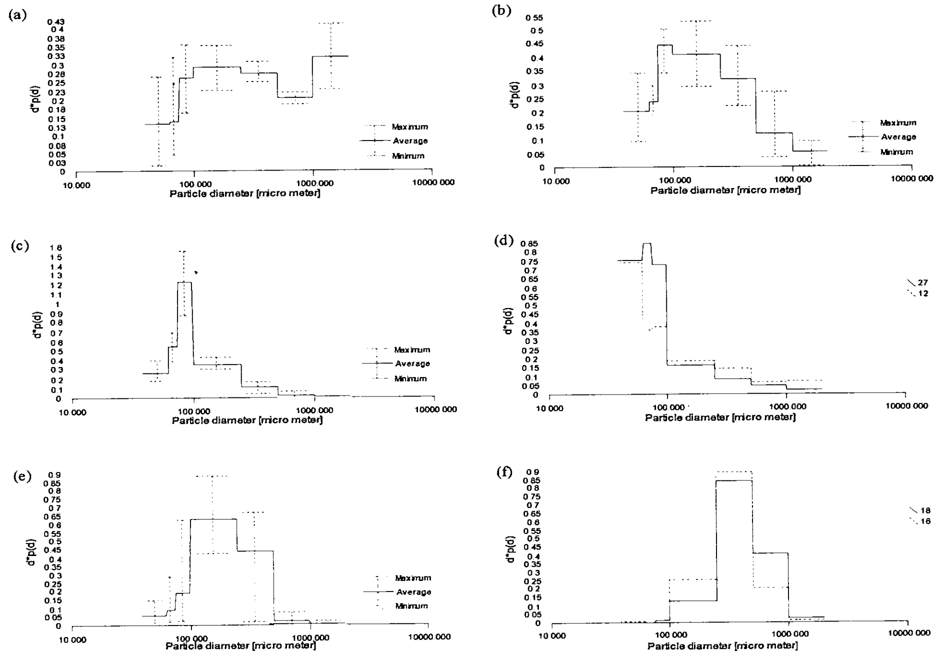

Figure 3. Six groups of size distribution of aggregates identified by cluster analysis. The averages and the ranges are shown for the groups including more than 3 samples.

A. P. and Bremner, J. M., 1967; Tisdall, J. M. and Oades, J. M., 1982), while, inorganic matter such as calcium carbonate, iron oxides and aluminium oxides can also bind particles (Hillel, D., 1998). The size distribution of aggregates is not a unique value for a soil sample, but varies with the composition of the aggregates, exogenous mechanical stresses, and stability in water. Therefore, in the ideal case for determining the size distribution of soil aggregates for the purpose of wind erosion study, aggregates that would be broken by aerodynamic drag should be broken in dry-sieving, and those aggregates that would not be broken by aerodynamic drag should remain in aggregate form. However, no studies consider the explicit relation between exogenous stresses due to dry sieving and aggregate breakage (e.g. Schjonning, P. 1992; Cammeraat, L. H. and Imeson, A. C., 1998; Boix-Fayos, C. *et al.*, 2001). The bias due to the sieving method should also be considered. Dalsgaard, K. *et al.* (1991) and Jinnai, K. *et al.* (1981) indicated that longer sieving does not improve separation efficiency, but the hammering effect of coarser particles is needed.

For sieving soil aggregates, those two viewpoints, aggregate breakage and separation efficiency in stacked sieves, should be considered. To determine the optimum duration of sieving, we performed a preliminary experiment with a sample each of dune sand (sample no. 19), castanozem (no. 2), chernozem (no. 3) and loess (no. 12). These samples did not reach equilibrium even after 10 000 s (2 h 46 min) sieving (Fig. 2), which is consistent with the results of Dalsgaard, K. *et al.* (1991) and Jinnai, K. *et al.* (1981). The chernozem was the slowest to approach equilibrium, and the difference in proportions between the initial and latter stages was also the largest. In contrast, dune sand changed the least with time. The figure shows that it was difficult to differentiate the changes because of separation by sieving and of aggregate breakage, except that large-aggregate breakage can be seen in the chernozems and loess samples.

However, even after 10,000-second sieving, a large proportion of small particles kept an aggregate form. Table 2 shows that the mass-proportion of the dispersed particles smaller 20 μ m (sum of the fractional weight of clay and silt), measured by the Pepit method, is considerably larger than that of dry aggregate smaller than 38 μ m. This means that an equilibrium exists at which the external force of sieving can no longer break the dry aggregate of the samples.

We settled on 20 minutes (1,200 seconds in figure 2) as

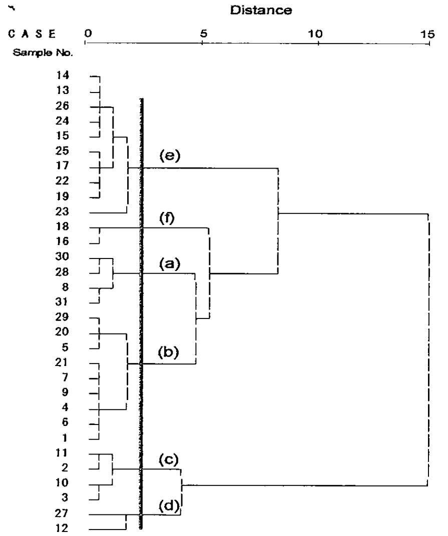

Figure 4. Dendrogram of the six clusters identified by cluster analysis.

the optimum duration for our experiment, managing both the completion of sieving and the avoidance of excessive aggregate breakage.

Cluster analysis

The weight of the fraction on each sieve was converted to a proportion of the whole for all soils, then we performed cluster analysis with Ward's method, in order to find out what types of size distribution of aggregates exist in the target region, and to identify what kind of background factors are the key to controlling the size distribution

2. RESULTS

Cluster analysis identified six groups of soils arranged on the basis of their size distribution of aggregates (Figure 3). The dendrogram in Figure 4 shows clear separation of these groups, with a jump in the distance between 2.5 to 4. Group *a* has a peak at over 1 mm, and a secondary peak at 100–250 μm. Four soils were classified into this group, three from steppe and desert-steppe in Mongolia, and one castanozem from the northern foot of the Yinshan Mountains. Group *b* is characterized by a peak at 100–250 μm and a larger range of particle size populations. This group consists mainly of castanozems from the Mongolian Plateau, plus a brown calcic soil from Mongolia. The soils in group *c* have a sharp peak at 75–100 μm, and hardly any other size population. Group *d* has a similar size distribution as in group *c*, but it also contains finer particles of less than 75 μm. Groups *e* and *f* are characterized by a sharp peak between 100 and 500 μm and almost no other size populations.

Table 3. Clusters and soil parameters. Soil types with an asterisk were identified from the SOTER soil map (FAO *et al.*, 1999); the others were identified by soil survey.

Cluster analysis Group	Sample No.	Soil type (WRB)	Soil type (Chinese)	Soil texture
a	8	Kastanozems	Castanozems	Loamy Sand
	28	Calcisols*	Brown calcic soils*	Loamy Sand
	30	Kastanozems*	Castanozems*	Sand
	31	Kastanozems*	Castanozems*	Loamy Sand
b	1	Kastanozems	Castanozems	Sandy Clay Loam
	4	Kastanozems	Castanozems	n/a
	5	Kastanozems	Castanozems	n/a
	6	Kastanozems	Castanozems	Loamy Sand
	7	Kastanozems	Castanozems	Loamy Sand
	9	Kastanozems	Castanozems	Loamy Sand
	20	Kastanozems	Castanozems	n/a
	21	Arenosols	Aeolian soils	Loamy Sand
	29	Calcisols*	Brown calcic soils*	Sand
c	2	Kastanozems	Castanozems	Loamy Sand
	3	Chernozems	Chernozems	Clay Loam
	10	Kastanozems	Castano-cinnamon soils	Loamy Sand
	11	Kastanozems	Castano-cinnamon soils	Loamy Sand
d	12	Calcic Cambisols	Loessal soils	Loam
	27	Kastanozems	Castanozems	n/a
e	13	Arenosols	Aeolian soils	Loamy Sand
	14	Arenosols	Aeolian soils	Loamy Sand
	15	Arenosols	Aeolian soils	Loamy Sand
	17	Arenosols	Aeolian soils	Loamy Sand
	19	Arenosols	Aeolian soils	Loamy Sand
	22	Arenosols	Aeolian soils	Loamy Sand
	23	Arenosols	Aeolian soils	Sand
	24	Arenosols	Aeolian soils	n/a
	25	Arenosols	Aeolian soils	n/a
	26	Arenosols	Aeolian soils	n/a
f	16	Arenosols	Aeolian soils	Loamy Sand
	18	Arenosols	Aeolian soils	Sand

WRB = World Reference Base (FAO, 1998)
n/a = not available

3. DISCUSSION

As pointed out in the Introduction, the broad-scale mapping of soil aggregates is one of the prerequisite issues for the broad-scale model simulation of wind erosion. Current broad-scale modelling of wind erosion assumes, without validation, that soil texture classification has a one-to-one relationship with the size distribution of aggregates, which is mapped on the basis of the spatial distribution of soil texture. However, our results contradict this assumption. Generally, soils in arid regions have coarse texture owing to the deflation of finer particles, a low supply of organic matter and low activity of chemical weathering. Most of the soil texture classes of our samples are coarse—loamy sand and sand in particular. Therefore, the soil texture of loamy sand and sand encompasses various arid soils: zonal steppe soils, loess soils and azonal aeolian sandy soils. These soils are distinctly different in origin and formation, which lead to different characteristics. Our results indicate that the classification of size distribution of soil aggregates on the basis of soil texture classification is not appropriate in arid and semi-

Table 4. Classification of steppe soils and corresponding information of climatie and parent material. Soil types with an asterisk were identified from the SOTER soil map (FAO *et al.*, 1999); the others were identified by soil survey. Annual rainfall is derived from a climate map (Zhongguo-Qixiangju, 1994; Ulsyn Geodezi Zurag Zuin Gazar, 1990). Parent material is derived from a geological map (Bureau of Geology and Mineral Resources, 1991; Ulsyn Geodezi Zurag Zuin Gazar, 1990).

Cluster Analysis Group	Sample No.	Soil Type (WRB)	Soil Type (Chinese)	Soil Texture	Annual rainfall [mm]	Parent Material	Geological era
a	8	Kastanozems	Castanozems	Loamy Sand	400	Metamorphic rock (gneiss)	Archean
	28	Calcisols*	Brown calcic soils*	Loamy Sand	75	Igneous rock (granodiorite)	Paleozoic
	30	Kastanozems*	Castanozems*	Sand	200	Igneous rock (diorite)	Paleozoic
	31	Kastanozems*	Castanozems*	Loamy Sand	250	Igneous rock (granodiorite)	Paleozoic
b	1	Kastanozems	Castanozems	Sandy Clay Loam	370	Metaclastics	Proterozoic
	4	Kastanozems	Castanozems	n/a	210	Clastics	Tertiary
	5	Kastanozems	Castanozems	n/a	250	Clastics	Tertiary
	6	Kastanozems	Castanozems	Loamy Sand	210	Clastics with marl	Tertiary
	7	Kastanozems	Castanozems	Loamy Sand	200	Clastics with limestone	Permian
	9	Kastanozems	Castanozems	Loamy Sand	400	Clastics	Cretaceous
	29	Calcisols*	Brown calcic soils*	Sand	125	Deposits	Cretaceous
c	2	Kastanozems	Castanozems	Loamy Sand	290	Igneous rock (granite)	Cretaceous
	3	Chernozems	Chernozems	Clay Loam	300	Igneous rock (basalt)	Quaternary
	10	Kastanozems	Castano-cinnamon soils	Loamy Sand	400	Loess	Quaternary
	11	Kastanozems	Castano-cinnamon soils	Loamy Sand	400	Loess	Quaternary
d	27	Kastanozems	Castanozems	Loamy Sand	400	Loess	Quaternary

n/a = not available

arid regions of East Asia, and must lead to considerable error in the estimation of wind erosion intensity.

Soil type can be a primary indicator for classifying soil aggregates, as seen in Table 3, in which aeolian soils are almost exclusively separated from other soils. Dune sand has a well-sorted size distribution of aggregates, as seen in Figures 3e and f (corresponding to groups *e* and *f* in Table 3). This is because on sand dunes, accretion from saltation predominates and gives well-sorted grains of between 0.125 and 0.25 mm (Mabbutt, J. A., 1977). Group *f*, which consists of soils from sand flats, is coarser than group *e*, in which most samples come from dunes. This result is consistent with the fact that coarser sands are found on sand flats than on sand dunes, because coarse gains concentrated at the surface resist arrangement into ripples, and prevent sand accumulation by increasing the saltation rate (Mabbutt, J. A., 1977).

In contrast to the results of aeolian sediments, the size distribution of steppe soils varied with samples (Figures 3a–d). To examine reasons for this variation, we considered the climate and parent material of the sample locations of the steppe soils (Table 4). The mean annual rainfall at each location was derived from a climate map (Ulsyn Geodezi Zurag Zuin Gazar, 1990; Zhongguo-Qixiangju, 1994). Parent materials were derived from geological maps (Ulsyn Geodezi Zurag Zuin Gazar, 1990; Bureau of Geology and Mineral Resources, 1991). In this study, parent materials for all soil samples are assumed to be consistent with the geology in geological maps, except sample 10 and 11, which were determined as loess in the field survey, although these locations lie inside an area of sedimentary deposits on the map. (These locations are within the "Dongsheng Uplift", where denuded sandstones are found, but loess is found here too.) Groups *c* and *d*, with well-sorted grains much finer than those of dune sands, can be regarded as an independent group, containing loess soils, steppe soils on loess materials and soils derived from newer (Quaternary and Cretaceous) igneous rocks. This size distribution shows the typical shape of loess materials. Loess consists of terrestrial windblown silt deposits. Its main source areas in China are the cold, dry deserts of northern and north-western China, where silt particles are produced by the combined action of frost and salt weathering. Through transport, a limited range of particle sizes is accumulated on the Loess Plateau, forming well-sorted sediment (Pye, K., 1987). A longer transport trajectory leads to the deposition of finer grains, as seen in the southern part of the Loess Plateau in contrast to the northern part (Quanguo-turang-puchahezuozhan, 1998). Our results also show this tendency, as seen in the fact that the sample collected in the middle of the Loess Plateau (Figure 3 (d), sample No. 12) has finer texture than the other loess materials that belong to group *c*. The reason why soils on igneous rocks consist of fine particles cannot be explained clearly, but may be related to the homogeneous crystal structures of these rocks. Group *a* has a complex size distribution, with a main peak from 1 to 2 mm and a secondary peak from 100 to 250 μm. The geological era of all samples classified into group *a* is very old, almost exclusively

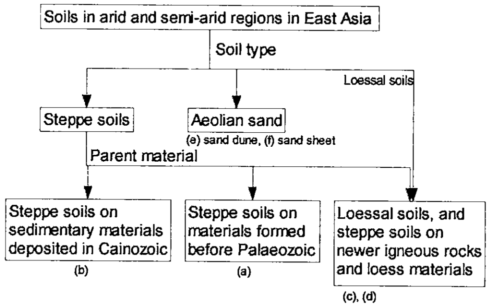

Figure 5. Possible classification of size distribution of aggregates from arid and semi-arid regions of East Asia on the basis of the cluster analysis.

before the Palaeozoic, whereas samples in other groups are Cainozoic and Mesozoic. Figure 5 summarizes the size distribution of aggregates in this region.

Many authors have used a fitting procedure based on multi-modal lognormal distribution to determine the mass-size distribution of sediment exposed to wind erosion (e.g. Chatenet, B. *et al.*, 1996), of emitted sand and dust near the surface (Alfaro, S. C. *et al.*, 1997, 1998), and of dust particles in the atmosphere (Gomes, L., 1990). The advantage of representing the size distribution by a multi-modal lognormal distribution is that it allows extrapolation of the particle-size information obtained from a limited number of soil samples to a broad region (Shao, Y., 2000). Most wind erosion models use the fitted form of size distribution (Marticorena, B. *et al.*, 1997; Shao, Y., 2001; Shao, Y. *et al.*, 2002). The multi-modal log-normal distribution is expressed by the equation

$$\frac{dP(d)}{d\ln(d)} = \sum_{j=1}^{J} \frac{w_j}{\sqrt{2\pi}\sigma_j} \exp\left(-\frac{(\ln d - \ln D_j)^2}{2\sigma_j^2} \right),$$

where P(d) is the probability distribution function, d is particle diameter, J is the number of modes, w_j is the weighting for the jth mode of the particle size distribution, and D_j and σ_j are the parameters for the log-normal distribution of the jth mode. The average size distributions for each group were fitted by means of a non-linear least-squares method, and are presented in Table 5, in order to use our results in wind erosion models.

CONCLUSIONS

We dry-sieved 31 soil samples from arid and semi-arid regions in East Asia. Cluster analysis showed that the size distribution of aggregates varied even within a single soil texture, mainly because of the difference in parent materials. Although most modelling studies of wind erosion assume a one-to-one relationship between soil texture class and the size distribution of aggregates, our results strongly contradict this assumption, which may cause considerable error in the estimation of wind erosion.

Azonal aeolian sediments have typical well-sorted forms of size distribution, but zonal steppe soils show various patterns of size distribution. The results indicate that parent material can be a good indicator to classify the size distributions of aggregates in steppe soils, loess materials and soils formed on newer (Quaternary and Cretaceous) igneous rock (finer soils), on sedimentary materials (coarser soils), and on ancient geological layers (complex, coarse particle size composition). Our results show that parent material is the primary factor determining the size distribution of aggregates. Therefore, the mapping of the distribution of soil aggregates as an input parameter for wind erosion models becomes possible, under the assumption that the parent material is consistent with the geology found in geological map. Soil maps and geological maps of this region are readily available, so the mapping of soil aggregates in relation to these thematic maps should be efficient and practical, though the assumption of the consistency of parent material and geology could lead to errors to some extent.

The detailed landform classification map is necessary for differentiating between the regions for group e and f,

Table 5. Estimated log-normal size distribution parameters for the six soil groups identified by cluster analysis. See equation and text for explanation of variables.

Groups	mode 1			mode 2			Sum of squares
	w_1	D_1	σ_1	w_2	D_2	σ_2	residual
a	0.7735	206.2	0.9978	0.2260	1208.3	0.2908	0.0037
b	0.0226	90.7	0.0411	0.9774	182.4	0.9782	0.0026
c	0.2278	84.7	0.1140	0.7722	103.0	0.7537	0.0003
d	0.7319	54.1	0.4544	0.2681	180.4	0.8853	0.0153
e	1.0000	207.5	0.5410				0.0033
f	1.0000	363.2	0.4606				0.0000

however, it is currently not available. Besides, this study is not successful providing clear criteria for differentiating between group *c* and *d*. Moreover, the small number of samples and our inability to consider the effects of microrelief prevented us from considering the variations within each cluster analysis group. Further systematic field survey is needed for more precise estimation of wind erosion.

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