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A wind tunnel experiment to explore the feasibility of using beryllium-7 measurements to estimate soil loss by wind erosion

Ming-Yi Yang [a,b,*], Des E. Walling [c], Xi-Jun Sun [b], Feng-Bao Zhang [a,b], Bo Zhang [b]

[a] *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, Shaanxi, China*

[b] *Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources, Yangling 712100, Shaanxi, China*

[c] *Geography, College of Life and Environmental Sciences, University of Exeter, Amory Building, Rennes Drive, Exeter EX4 4RJ, UK*

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Abstract

Sandy loess from the Wind–Water Erosion Crisscross Region on the Loess Plateau of China, an area with severe wind erosion, was collected for use in a wind tunnel experiment, to explore the feasibility of using ^{7}Be measurements to estimate the amount of soil lost through wind erosion. Wind erosion selectively removes the finer particles of soil. Use of procedures for estimating soil loss from ^{7}Be measurements developed for water erosion, which do not take account of this selective removal of fines, is therefore likely to result in overestimation of the amount of soil lost through wind erosion, because ^{7}Be is preferentially associated with the finer fractions of the soil. The results of the experiment, supplemented by measurements undertaken on two field plots in the study region demonstrated a well-defined power function relationship between S_e/S_o and A_{Be} (where S_e is the specific surface area of the soil at the eroded site; S_o is the SSA of the original soil and A_{Be} is the ^{7}Be activity remaining at the eroded site), with an exponent of ~0.75. It is proposed that a particle size correction factor P', based on the term $(S_e/S_o)^{0.75}$, can be incorporated into the procedure for estimating soil loss by wind erosion from ^{7}Be measurements. The estimates of soil loss obtained using the refined procedure were in close agreement with the measured values. Use of the ^{7}Be measurements to estimate soil loss without incorporating the particle size correction factor P' resulted in overestimation of the soil loss by ~14%. When P' was incorporated, the overestimation was reduced to ~2%.

1. INTRODUCTION

According to Oldeman (1994), wind erosion is an important cause of land degradation, and accounts for about 28% of the world's degraded land. In China, wind erosion represents a significant problem for about 16.7% (ca. $160 \times 10^4\,km^2$) of the national territory (Ci and Wu, 1997). In many regions of China, a combination of both wind and water erosion is responsible for land degradation and the region known as the Wind–Water Erosion Crisscross Region, located on the Loess Plateau of China, and hereafter referred to as the study region, is one such area experiencing severe land degradation (Tang et al., 1993). Average rates of surface lowering by wind erosion of 1.25 mm yr^{-1} have been reported for this region (Dong, 1998). In addition to reducing local land productivity, wind erosion results in important ecological and environmental problems, including dust storms, reduced visibility and the effects of increased levels of particulates on human health, which impact on sustainable social and economic development (Tang et al., 1993; Dong, 1998; Xu, 2000). Research to develop an improved understanding of wind erosion is therefore seen as an important priority in the study region.

* Corresponding author at: Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources, Yangling 712100, Shaanxi, China.

E-mail address: ymyzly@163.com (M.-Y. Yang).

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Estimation of the magnitude of soil loss by wind erosion is essential to evaluate the extent and intensity of wind-induced land degradation and the effectiveness of counter measures. Research undertaken in many different areas of the world has resulted in the development of a range of techniques and approaches for documenting and predicting soil loss by wind erosion. These include field monitoring, wind tunnel experiments and numerical models (Fryrear et al., 1991; Leys et al., 2001, 2002; Zobeck et al., 2003; Funk et al., 2004; Shi et al., 2004; Shao, 2009; Hagen, 2010). However, the available methods face significant limitations and constraints in terms of the period of time covered, practical demands, cost, reliability and accuracy (Shi et al., 2004). A key distinction can be made between two contrasting approaches to documenting wind erosion. The first approach involves measuring the amount of soil or dust transported by the wind, using traps or wind tunnel experiments, both in the laboratory and in the field. The resulting data are employed to infer the amount of soil lost from the land surface. The second approach attempts to measure the surface lowering caused by the wind erosion. Such measurements have been made using special equipment (Hai et al., 2009) and by employing fallout radionuclides. In the latter case, the reduction in the fallout radionuclide inventory caused by erosion is established by comparing an eroding site with a reference site and the degree of reduction is in turn used to estimate the amount of soil lost (Yan et al., 2003). Responding to a need to explore and develop improved methods for deriving accurate estimates of soil loss by wind erosion, we have focused on the second approach and, more particularly, the use of fallout radionuclides.

The anthropogenic fallout radionuclide cesium-137 (^{137}Cs) has been employed in soil erosion research for more than 40 years, as a means of documenting soil redistribution caused by water erosion. It overcomes many of the problems associated with traditional approaches for monitoring erosion and deposition on hillslopes (Loughran et al., 1989) and has therefore attracted increasing attention (Ritchie, 1998). The potential for using ^{137}Cs in wind erosion research was also recognized in the 1990s (Sutherland et al., 1991) and it has subsequently been successfully applied in several wind erosion investigations (Yan et al., 2000, 2001, 2003; Chappell and Warren, 2003; Van Pelt et al., 2007). These studies have demonstrated that ^{137}Cs can provide an effective tracer for estimating medium-term (30–50 years) average rates of wind erosion. However, it cannot provide information on short-term (seasonal) soil loss. There is therefore a need to explore the possibilities of using alternative fallout radionuclides in the study of wind erosion. The natural fallout radionuclide beryllium-7 is seen to offer considerable potential, because its fallout is essentially continuous and its short half-life means that it can provide information on soil loss by erosion over much shorter timescales than ^{137}Cs (i.e. days or weeks rather than decades).

Beryllium-7 (^{7}Be) is a naturally occurring cosmogenic radionuclide with a relatively short half-life of 53.3 days. It is produced in the stratosphere and upper troposphere as a product of the spallation of oxygen and nitrogen nuclei by cosmic rays (Lal et al., 1958). After production, ^{7}Be enters the environment through wet and dry deposition processes (Wallbrink and Murray, 1994; Ioannidou and Papastefanou, 2006; Hasegawa et al., 2007; Yi et al., 2007; Akata et al., 2008). When ^{7}Be reaches the land surface, it is rapidly and strongly fixed by soil particles and other ground cover and is readily detected in both soil and vegetation. Because the half-life of ^{7}Be is short, relative to the rate of operation of processes causing downward transfer of the radionuclide, it is rare to find ^{7}Be at depths >20 mm (Wallbrink and Murray, 1993; Walling et al., 2009). The vertical distribution of ^{7}Be within the soil profile is also characterized by a marked decrease in activity with depth (commonly exponential) within this shallow surface layer (Wallbrink and Murray, 1996; Walling et al., 1999, 2009; Shi et al., 2011a,b). When compared with ^{137}Cs, ^{7}Be inventories are more sensitive to short-term (i.e. event-based) redistribution of soil by surface erosion, due to the concentration of the radionuclide near the surface. Accordingly, the removal of a thin layer of soil will generally result in a significant change in the ^{7}Be inventory. However, the short half-life of ^{7}Be means that the soil inventory varies markedly through time in response to fallout inputs and radioactive decay, and this introduces problems in terms of the precise relationship between changes in the ^{7}Be inventory relative to the reference inventory and the soil redistribution rate (see Walling et al., 2009). Typical annual rates of soil loss due to wind erosion in the study region are about 1.25 mm yr^{-1} (Dong, 1998) and such erosion occurs mainly during the dry period (March–May), when the vegetation cover is sparse and the interception of ^{7}Be by plants is negligible (Zhang et al., 2011a). Beryllium-7 would therefore appear to offer considerable potential for estimating soil loss by wind erosion in this region of China. To date, however, the use of ^{7}Be in soil erosion investigations has been restricted to documenting soil redistribution by water erosion (Blake et al., 1999; Walling et al., 1999; Schuller et al., 2006; Navas et al., 2008; Sepulveda et al., 2008; Liu et al., 2011; Shi et al., 2011; Zhang et al., 2011b), and the authors are not aware of reports of its successful use to document wind erosion.

In the study reported here, the potential for using ^{7}Be measurements to document soil loss by wind erosion in the local region was explored. Sandy loess collected from the study region was used in a wind tunnel experiment to compare measurements of wind erosion rates based on the mass of sediment removed and transported by the wind with estimates of surface lowering derived from ^{7}Be measurements. The study aimed to extend existing work in using ^{7}Be in soil erosion investigations as well as to develop an improved understanding of the dynamics of wind erosion, in order to support the monitoring, control and prevention of soil loss by wind erosion in the local region.

2. MATERIALS AND METHODS

2.1. The experimental plots

The sandy loess used for the experiment was collected from the surface (0–15 cm depth) of a small area (15 m^2)

of sloping land in the Liudaogou watershed (38°46′ ~ 38°51′N, 110°21′ ~ 110°23′E), located 14 km west of Shenmu County in Shaanxi Province, China. The site lies within the study region. The soil was transported back to the laboratory, air-dried, well-mixed and then placed into five stainless steel plots (trays) (120 cm long × 80 cm wide × 35 cm deep). The soil was gently packed into the plots, layer-by-layer, to give an average bulk density of 1.36 g cm^{-3} and the surface of the plot was finally smoothed. Without further disturbance, these plots were placed close together outdoors in an open space at the Institute of Soil and Water Conservation at Yangling, Shaanxi Province, China for six months (from November 2009 to April 2010), to receive both wet and dry ^{7}Be fallout. In this period there was little wind, and the spatial distribution of ^{7}Be fallout over the area covered by the five plots (ca. 2.4 × 2.4 m) was assumed to be essentially uniform. One plot was selected as a reference and the other four were used for the wind tunnel tests.

2.2. Sampling of the reference plot before the experiment

Immediately prior to the wind tunnel experiment, depth incremental and bulk core samples were collected from the reference plot, in order to establish the ^{7}Be areal activity density or inventory and the depth distribution of the radionuclide. An area of 40 × 40 cm was selected on the plot and samples were collected from this area at 3 mm depth increments over the depth range 0–24 mm, using a purpose-built depth-incremental scraper plate sampling device, similar to that described by Campbell et al. (1988). With this device, the scraper blade can be progressively lowered by the required depth increment (e.g. 3 mm) and a thin layer removed. A final 6 mm depth increment was collected from the 24–30 mm depth. A core sampler with an internal diameter of 14.7 cm was used to collect four randomly located bulk core samples from the upper 3 cm of the soil profile in other areas of the plot. At the same time, 12 further bulk soil samples were collected from the 0–3 cm surface layer at random locations within the remaining areas of the plot, using a core sampler with an internal diameter of 3 cm. The latter samples were used to characterize the properties of the surface soil and were analyzed for moisture content, particle size distribution, specific surface area (SSA) and organic matter content (see Section 2.5). The moisture content was determined immediately after sampling by the oven drying method and provided a mean moisture content of 1.73 wt.%.

2.3. The wind tunnel experiment

The wind tunnel experiment was conducted in the inner wind tunnel of the Institute of Soil and Water Conservation, at Yangling, Shaanxi Province, China. The wind tunnel (Fig. 1) has a total length of 24 m and its main features are shown in Fig. 1. The test section (Fig. 1) has a cross-sectional area of 1 × 1.2 m. The wind speed can be varied continuously from 2 to 15 m s^{-1}. Soil mobilized during a test is collected using a vertical array of sediment traps (2 verticals and 5 horizontal rows) in the collecting section of the wind tunnel. Further details of this experimental facility are provided by Fan et al. (2011) and Zhao et al. (2012).

At the beginning of the experiment, the surface of the soil in the plot was set flush with the wind tunnel floor. Wind speeds of 10 m s^{-1} (run A) and 12 m s^{-1} (run B) were employed for the experiment. Extreme wind speeds ⩾17.2 m s^{-1} are on average recorded on 13.5 days per year in the study region, but such velocities were outside the capacity of the wind tunnel. The four plots were used in the wind tunnel experiment to provide two replicate runs for each wind speed. Wind erosion is strongly influenced by the moisture content of the soil (Chen et al., 1996) and in this experiment a constant moisture content, represented by that measured in the reference plot at the beginning of the experiment (1.73%), was ensured by undertaking all the wind tunnel runs in close succession within a single working day. The duration of the tests at each wind speed was 20 min. After each test run, the mobilized sediment collected by the sediment traps was recovered, oven dried at 105 °C and weighed (0.01 g), without further pretreatment. These samples were also analyzed for particle size composition, organic matter content and ^{7}Be activity (see Section 2.5), to permit comparison with the soil in the reference plot.

2.4. Sampling the plots after the test runs

After each test run, two types of sample were collected from the plots. The first group of samples was used for ^{7}Be analysis. They were collected from the 0–3 cm surface layer of the experimental plots using a core sampler with an internal diameter of 14.7 cm with the sampling points defined by a 25 × 30 cm grid (Fig. 2). This provided 12 samples from each plot and a total of 48 samples from the four plots. Four further samples (Fig. 2) were collected from the 0–3 cm surface layer adjacent to each of the 12 ^{7}Be sampling points, using a core sampler with an internal diameter of 3 cm. These four samples were composited to produce a single sample, which was assumed to be representative of the 0–3 cm surface layer at the ^{7}Be sampling point, and which was then analyzed to determine its particle size composition, specific surface area, and organic matter content (see Section 2.5). Twelve composite samples were collected from each of the four plots, providing a total of 48 samples.

2.5. Laboratory measurements

The total of 121 soil samples, collected from the reference plot and the four plots used for the experiments, were air-dried, ground, screened through a 1 mm sieve, to provide the <1 mm fraction and homogenised and weighed prior to analysis. The ^{7}Be analysis was carried out by gamma spectrometry in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, at the Institute of Soil and Water Conservation, in Yangling. Beryllium-7 mass activity densities (activities Bq kg^{-1}) were measured using a low background hyperpure coaxial germanium detector coupled to a multichannel analyzer system (EG&G ORTEC, Oak Ridge, TN). The ^{7}Be activity

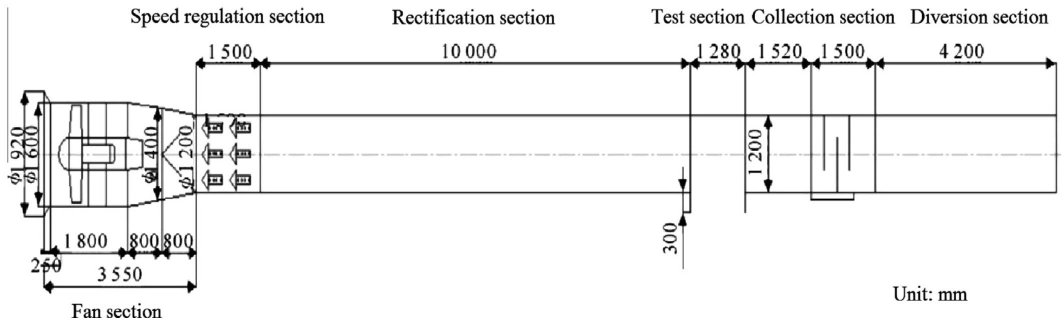

Fig. 1. The features of the wind tunnel.

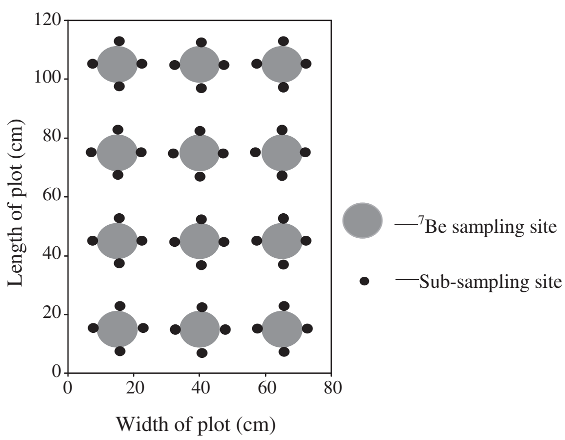

Fig. 2. The design of the sampling grid.

was measured at 477.6 keV with a count time of ~86,400 s. The detector was calibrated using a certified multi-radionuclide standard of a known activity (supplied by China Institute of Atomic Energy: ^{238}U, ±2.2%; ^{232}Th, ±2.7%; ^{226}Ra, ±3.2%; ^{210}Pb, ±2.9%; ^{40}K, ±2.7%; ^{137}Cs, ±0.4%; ^{60}Co, ±0.2%). The resulting measurements of ^7Be activity were typically characterized by a precision of ±5–6% at the 95% level of confidence. The measured ^7Be activities of the soil samples were converted to activities at the time of sampling of the reference plot using the appropriate decay constant.

With the exception of the samples used for ^7Be analysis, all remaining soil samples were divided into two parts. One part was screened through a 0.25 mm sieve, to provide the <0.25 mm fraction, prior to determining its organic matter content, by using dichromate oxidation with the application of external heat, with replicate measurements. The other part was analyzed to determine its particle size composition and specific surface area (SSA), using a laser granulometer (Mastersizer 2000, Malvern Instruments, Malvern, UK). The values of SSA provided by this equipment were estimated from the particle size distribution, assuming spherical particles. All samples were pretreated with hydrogen peroxide to remove organic matter and chemically dispersed using sodium hexametaphosphate, prior to particle size analysis.

2.6. Using ^7Be measurements to estimate soil redistribution rates

Walling et al. (1999) developed a simple model for using ^7Be measurements to estimate the soil loss by water erosion at a sampling point for the period of interest R_{Be} (kg m^{-2}), by comparing the inventory measured at the sampling point A_{Be} (Bq m^{-2}) with the local reference inventory A_{ref} (Bq m^{-2}) and assuming that ^7Be exhibits an exponential depth distribution in the soil profile i.e.

$$R_{Be} = h_0 \ln\left(\frac{A_{ref}}{A_{Be}}\right) \quad (1)$$

where h_0 (kg m^{-2}) is the relaxation mass depth, which reflects the shape of the exponential ^7Be depth distribution for the reference site. If the ^7Be inventory measured at the sampling point exceeds the local reference inventory, deposition is assumed to have occurred and the deposition rate R'_{Be} (kg m^{-2}) can be estimated as:

$$R'_{Be} = \frac{A_{Be} - A_{ref}}{C_{Be,d}} \quad (2)$$

where, $C_{Be,d}$ is the mean ^7Be activity of the deposited sediment (Bq kg^{-1}).

Use of this model assumes that the reduction in inventory relative to the reference inventory solely reflects erosion caused by the rainfall occurring shortly before the measurements of ^7Be inventory across the study site and that the reference inventory was spatially uniform across the site prior to that event (Walling et al., 2009).

In most published studies reporting the use of this model (e.g. Blake et al., 1999; Walling et al., 1999; Schuller et al., 2006; Sepulveda et al., 2008; Liu et al., 2011; Shi et al., 2011) it has been assumed that erosion causes removal of the bulk soil and the effects of selective removal of fine particles were not considered. However, wind erosion is a winnowing process that selectively removes the finer fractions of the soil. Since ^7Be is known to be preferentially associated with the finer fractions of the soil (Wallbrink and Murray, 1996; Taylor, 2012), use of Eq. (1) to estimate wind erosion rates is likely to result in significant overestimation of the erosion rate. There is therefore a need to modify the water erosion model presented in Eq. (1) to take account of preferential loss of fines, if a similar approach is to be used to provide reliable estimates of wind erosion rates. This modification is discussed below.

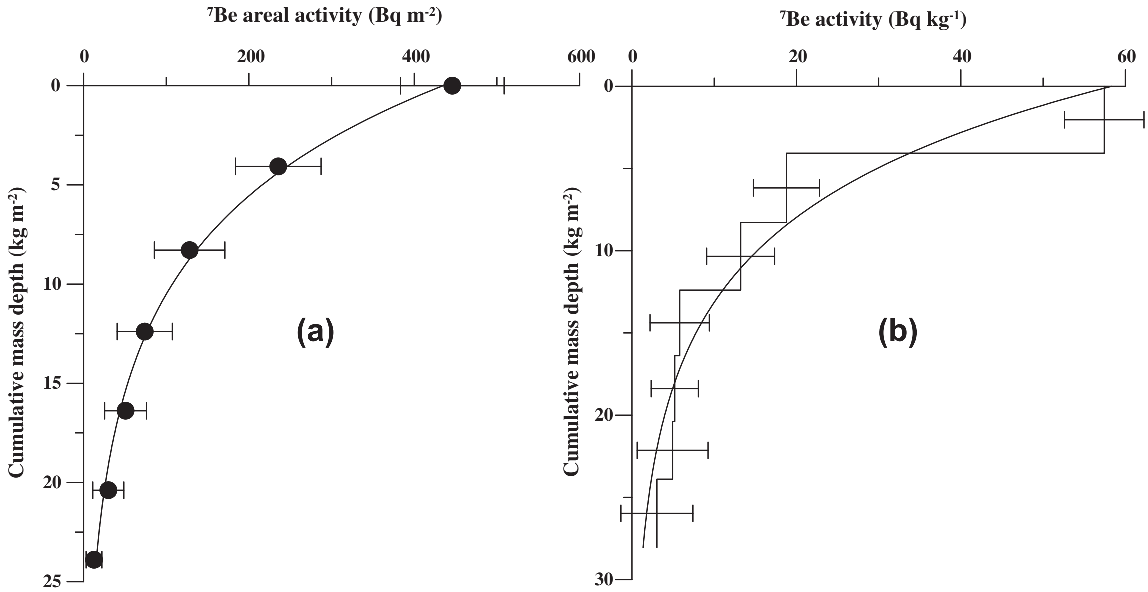

Fig. 3. The depth distribution of ^{7}Be in the reference plot, (a) ^{7}Be areal activity density, (b) ^{7}Be mass activity density.

3. RESULTS AND DISCUSSION

3.1. The depth distribution of ^{7}Be and the ^{7}Be inventory for the reference plot

As indicated above, a well-defined shallow exponential depth distribution of ^{7}Be in the surface soil provides the key to using ^{7}Be to document soil erosion. The depth distribution of ^{7}Be for the reference plot is shown in Fig. 3, and this is consistent with equivalent depth distributions reported both internationally and from elsewhere in China (Walling et al., 1999; Yang et al., 2006). Fig. 3 indicates that the ^{7}Be activity decreases rapidly with increasing depth, and is at a maximum in the shallow surface layer (0–3 mm). The exponential depth distributions fitted to Fig. 3 provide reasonably good fits to the measured depth distributions and are characterized by an h_0 value of 7.45 kg m^{-2}. The best-fit exponential relationships between ^{7}Be areal activity density (A_{Be}) and mass depth (x) and ^{7}Be mass activity density (C_{Be}) and mass depth for the reference plot were determined to be:

$$A_{Be}(x) = 435e^{-x/7.45} \quad (n = 7 \quad r^2 = 0.99) \tag{3}$$

$$C_{Be}(x) = 58e^{-x/7.45} \quad (n = 7 \quad r^2 = 0.91) \tag{4}$$

Because of the limited precision of measurements of ^{7}Be activity by gamma spectrometry (typically ±5–6% at the 95% level of confidence in the present study) and other sources of variability of the values obtained for the inventory of the reference plot, related to both sampling variability and soil heterogeneity, there is a need to take account of uncertainty in the final estimate of the reference inventory (Bq m^{-2}) obtained for the reference plot. The collection of the depth incremental samples from a relatively large area (40 × 40 cm) and the availability of measurements for four other cores reduces the potential impact of both sampling variability soil heterogeneity. Furthermore, precision errors associated with the measurements of the depth incremental samples are likely to cancel out. Taking account of the variation of the five values obtained for the reference inventory of the plot and the precision of the laboratory measurements of ^{7}Be activity, it has been estimated that the value of 446.0 Bq m^{-2} obtained for the reference inventory for the reference plot has an uncertainty of ±3% at the 95% level of confidence. The value of 446.0 Bq m^{-2} differs slightly from the total inventory calculated using Eq. (3) (434.6 Bq m^{-2}), but this difference falls within the ±3% confidence limit. The average of the two values (440 Bq m^{-2}) has been used to represent the reference inventory when estimating the soil loss from the four experimental plots.

3.2. Measurements of soil and ^{7}Be loss from the experimental plots

Table 1 provides information on the amounts of soil lost from the four experimental plots and the average percentage reduction in the ^{7}Be inventory for each plot. The amount of soil lost from the plots was similar for the two runs at a given wind speed, but, as expected, the loss increased at the higher wind speed. The increase was non-linear with a 20% increase in wind speed resulting in an average increase in soil loss of 29%. The measured soil losses were accompanied by a substantial reduction in the ^{7}Be inventories of the experimental plots, relative to the reference inventory, which provides the basis for estimating the amount of soil lost. Again, it is necessary to take account of the uncertainty of the final values of ^{7}Be inventory obtained for each of the experimental plots, which are required to estimate the soil loss. Since the mean inventory for each plot was based on measurements undertaken on 12 cores, the uncertainty associated with the final mean value, which reflects measurement precision, sampling variability and soil heterogeneity was again estimated to be

Table 1
The measured soil loss from the four experimental plots and the percentage reduction in ^{7}Be inventory for the four plots.

Plot	Wind Speed (m s^{-1})	Soil loss from plot (g m^{-2})	Mean ^{7}Be inventory* (Bq m^{-2})	Reduction of ^{7}Be inventory (%)
Ref.	0	—	440 ± 13	—
A-1	10	664	399 ± 12	9.3
A-2	10	634	401 ± 12	8.9
B-1	12	826	388 ± 12	12.0
B-2	12	842	386 ± 12	12.2

* Uncertainty at the 95% level of confidence.

~ ± 3%. The validity of this relatively low estimate of uncertainty is confirmed by the close agreement between the plot inventories documented for the replicate experiments and the consistent contrast between the values documented for the two different wind speeds (Table 1). The average increase in soil loss of 29% at the higher wind speed is associated with a further reduction of the ^{7}Be inventory of about 33%. Although one might expect the magnitude of the reduction in inventory to progressively decline as soil loss increases, due to the exponential depth distribution of ^{7}Be, the lack of a clear decline shown by these values reflects the limited depth of soil removed by erosion relative to the exponential depth distribution.

3.3. Comparison of the properties of mobilized sediment with those of surface soil from the reference plot

Fig. 4 and Table 2 compare the particle size composition of the mobilized sediment collected within the wind tunnel for the four experimental runs with that of surface soil (0–3 cm) from the reference plot. The grain size data summarized in Table 2 indicate that the mobilized sediment is, as expected, enriched in fines (<0.002 mm) and depleted in coarser (>0.050 mm) particles, as a result of the winnowing effect. The mean grain size distributions for runs A and B are superimposed on that for the surface soil from the reference plot in Fig. 4. This provides more information on the enrichment/depletion change point and indicates that mobilized sediment is enriched in particles <0.016 mm and depleted in particles >0.016 mm. Equivalent data for SSA and organic matter content are also presented in Table 2. The SSA values confirm the finer nature of the mobilized sediment, with the surface soil from the reference plot providing a mean SSA of 0.347 m^2 g^{-1}, whereas the equivalent average values for runs A and B are 0.413 and 0.424 m^2 g^{-1}, respectively. The values of organic matter content demonstrate that the mobilized sediment is enriched in organic matter. This is, again seen to be the response to a winnowing effect. In the latter case, the average organic matter of the mobilized sediment is 0.38%, whereas that of the original surface soil was 0.28%. The results also suggest that the degree of organic matter enrichment in the mobilized sediment increases slightly at the higher wind speed, although the magnitude of the increase is small and additional measurements would be required to confirm this trend as being statistically significant.

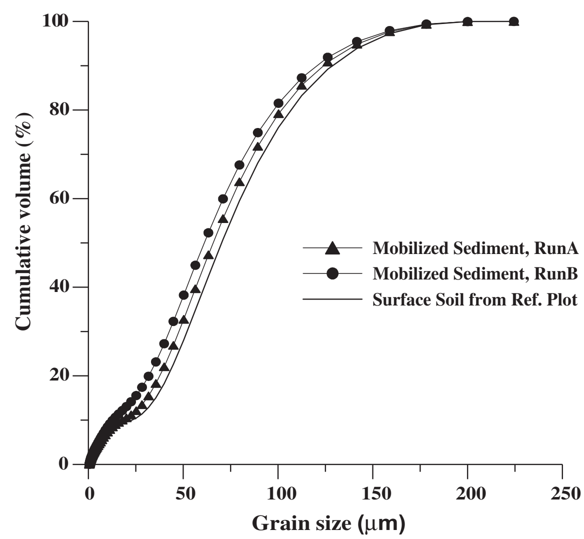

Fig. 4. Comparison of the mean particle size distributions of the sediment mobilized from the plots during the two replicate runs ($A = 10$ m s^{-1}, $B = 12$ m s^{-1}) with those of surface soil from the reference plot.

Table 2
Comparison of the properties of the sediment mobilized from the plots during the four wind tunnel runs with those of the surface soil (0–3 cm) of the reference plot.

Plot	Clay <0.002 mm (%)	Silt 0.002–0.05 mm (%)	Sand 1–0.05 mm (%)	SSA (m^2 g^{-1})	Organic content (%)	Average ^{7}Be activity (Bq kg^{-1})†
Ref.	5.5	49.2	45.3	0.347	0.28	14.8 ± 0.7/57.0 ± 2.9*
A-1	8.0	49.8	42.2	0.415	0.36	62.5 ± 3.1
A-2	7.9	48.7	43.4	0.410	0.37	62.0 ± 3.1
B-1	8.9	52.8	38.3	0.419	0.38	63.7 ± 3.2
B-2	9.0	50.8	40.2	0.429	0.40	64.1 ± 3.2

A and B denote the two wind speeds ($A = 10$ m s^{-1}, $B = 12$ m s^{-1}), 1 and 2 refer to the two replicate runs.
† Uncertainty at the 95% level of confidence.
* These values relate to the upper 3 cm and upper 3 mm of the soil within the reference plot, respectively.

Table 2 also presents values of ^{7}Be activity for the four samples of mobilized sediment (i.e. ca. 63 Bq kg^{-1}). It is difficult to compare these values with an equivalent value for the reference plot, due to the difficulty of selecting a value for the soil that is representative of the thin surface layer of soil that was mobilized by wind erosion. However, comparison of these values with the depth distribution of ^{7}Be activity presented in Fig. 3 suggests that the activity of the mobilized sediment is greater than the mean activity of the upper 3 mm of the soil of the reference plot (i.e. ~57.0 Bq kg^{-1}). This suggests that the sediment has been mobilized from a surface layer less than 3 mm in depth. The enrichment of the mobilized sediment in fines also means that its ^{7}Be activity is likely to exceed that of the original layer of soil from which it was mobilized. The data indicate that the ^{7}Be activity of the mobilized sediment is greater for the runs at the higher wind speed. Although an increased wind speed can be expected to result in the mobilization of a greater depth of soil, which will in turn be characterized by a reduced ^{7}Be activity, the noted increase in ^{7}Be activity of the sediment mobilized by higher wind speeds is consistent with the slightly greater values of SSA and percentage fines (<0.002 mm) associated with these samples. However, further replicate runs would again be required to test the statistical significance of these suggested trends.

3.4. The response of the physical and chemical properties and ^{7}Be inventory of the surface soil of the experimental plots to wind erosion

Table 3 provides information on the changes in physical and chemical properties of the surface soil on the experimental plots, as a result of the wind erosion generated using the wind tunnel. These data show that, when compared with the reference plot, the surface soil of the four plots exposed to wind erosion was coarser and evidenced a reduced organic content and that the ^{7}Be inventory was reduced by of the order of 9–12% (see Table 1). As expected, there is evidence that the surface soil of the plots subjected to a higher wind speed (i.e. plots 1B and 2B) is coarser (greater sand content, reduced silt content and reduced SSA) and shows a lower organic matter content and a greater reduction in the ^{7}Be inventory. The contrasts between the test plots (after being subject to wind erosion) and the reference plot, in terms of sand, silt and clay content and the ^{7}Be inventory, have been tested for statistical significance using one-way ANOVA (SPSS software) and the results are shown in Table 4.

Table 4 indicates that the mean differences between the sand and silt content and the ^{7}Be inventory of the test plots and the reference plot are significant at the 0.05 level. In the case of the clay content the difference was not statistically significant at the 0.05 level, because of the relatively low clay content of the original soil.

3.5. Using ^{7}Be measurements to estimate soil loss by wind erosion

Table 1 provides clear evidence that the wind erosion induced by the wind tunnel caused a significant reduction in the ^{7}Be inventory of the plots and there is need to explore further the precise relationship between the magnitude of the soil loss and the degree of reduction in the ^{7}Be inventory. This relationship will be influenced by the contrasts in particle size composition between the mobilized soil and the parent soil shown in Table 2. These contrasts reflect the winnowing of fines commonly associated with wind

Table 3
Changes in the physical and chemical properties of surface soil (0–3 cm) on the experimental plots after wind erosion.

Wind speed (m s^{-1})	Plot	Clay <0.002 mm (%)	Silt 0.002–0.05 mm (%)	Sand 1–0.05 mm (%)	Average SSA (m^2 g^{-1})	Average SOM (%)	Mean ^{7}Be inventory* (Bq m^{-2})
0	Ref.	5.5	49.2	45.3	0.347	0.28	440 ± 13
10	A-1	4.7	44.1	51.2	0.312	0.25	399 ± 12
	A-2	4.8	45.8	49.4	0.321	0.27	401 ± 12
12	B-1	4.9	42.6	52.5	0.302	0.24	388 ± 12
	B-2	4.7	39.4	55.9	0.298	0.23	386 ± 12

* Uncertainty at the 95% level of confidence.

Table 4
The results of one-way ANOVA for the mean difference between the sand, silt and clay and the ^{7}Be inventory of the test plots and the reference plot.

Plot		Clay		Silt		Sand		^{7}Be Inventory	
Group (I)	Group (J)	Mean difference (J–I) (%)	Sig.	Mean difference (J–I) (%)	Sig.	Mean difference (J–I) (%)	Sig.	Mean difference (J–I) (Bq m^{-2})	Sig.
Ref.	A-1	−0.8	0.062	−5.1	0.000*	+5.9	0.001*	−41.5	0.000*
	A-2	−0.7	0.098	−3.4	0.014*	+4.1	0.015*	−39.3	0.000*
	B-1	−0.5	0.196	−6.6	0.000*	+7.2	0.000*	−52.6	0.000*
	B-2	−0.8	0.066	−9.8	0.000*	+10.6	0.000*	−54.0	0.000*

* The mean difference is significant at the 0.05 level.

erosion. In general, smaller soil particles are characterized by an increased specific surface area and thus an increased capacity to adsorb radionuclides. He and Walling (1996) used laboratory experiments to demonstrate this particle size effect for the fallout radionuclides ^{137}Cs and unsupported ^{210}Pb and showed that, for a given soil or sediment, a clearly defined positive relationship existed between radionuclide activity and the SSA of subsamples with different grain-size compositions. This relationship was characterized by a power function. Wallbrink and Murray (1996) and Taylor (2012) have reported that ^{7}Be is similarly preferentially associated with the fine fraction and it would seem likely that the relationship between ^{7}Be activity and SSA can again be represented as a power function.

Walling and He (2001) developed a model for using ^{137}Cs measurements to estimate the soil erosion rate that incorporated the effects of size selective erosion (i.e. preferential mobilisation of fines). The particle size correction factor P was calculated as:

$$P = \left(\frac{S_m}{S_o}\right)^{v} \quad (5)$$

where S_m is the SSA of the mobilized sediment (m^2 g^{-1}); S_o is the SSA of the original soil (m^2 g^{-1}); and v is a constant with a value of ca. 0.65. Because the grain size composition of mobilized sediment is usually enriched in fine particles compared with the original soil, P is generally greater than 1.0.

A similar particle size correction factor, based on a comparison of the SSA of the mobilized sediment and the original soil, can be incorporated into the equations originally developed to derive estimates of soil loss by water erosion from ^{7}Be measurements and presented as Eqs. (1) and (2), to take into account the effects of winnowing of fines by wind erosion. However, although S_m can be readily estimated for the soil mobilized by wind erosion in the wind tunnel experiment, since that sediment is collected, it is difficult to estimate S_m in a standard field investigation involving ^{7}Be measurements, because the mobilized soil is unlikely to be collected. One of the key advantages of using fallout radionuclides, and more particularly ^{7}Be, to estimate soil loss by wind erosion is the potential to limit the field sampling to a single site visit and to visit sites adventitiously and retrospectively, based on reports of the occurrence of a period of significant erosion. In this context, the need to establish sediment collectors in advance of the period of erosion, could represent a major limitation. Furthermore, it must be recognized that the sediment trapped by a collector could originate from a wide area, extending well beyond the study site. This area could be characterized by a range of soil textures and magnitudes of soil loss. In this situation one, or a small number of samples of sediment from a collector, might not be representative of the soil lost from the study site itself. It therefore seems preferable to establish an alternative means of establishing P', which we now designate as the particle size correction factor for wind erosion. Instead of employing the SSA of the mobilized sediment (S_m), the SSA of the residual soil (S_e) can be used, since this will also be sensitive to preferential removal of fines by winnowing and can be linked directly to the study site and sampling point. Whereas S_m is greater than S_o, S_e is likely to be lower than S_o for eroded points. Table 5 presents the power function relationship between A_{Be} and S_e/S_o for the plots used in the wind tunnel experiment, where A_{Be} is the ^{7}Be inventory at the eroded point. In most cases the relationship provides a good fit to the data obtained from the experimental plots.

In order to test this approach further under field conditions in the study region, soil samples were collected from two representative cultivated slopes within the Liudaogou watershed in Shenmu County, Shaanxi Province. One slope was characterized by clay-loam soils and the other by sandy loam soils. At the former site, 21 samples of surface soil (0–30 mm) were collected along three parallel downslope transects ca. 70 m in length using a 14.7 cm diameter corer. The same procedure was used to collect 24 samples of surface soil from four transects ca. 35 m in length at the latter site. Samples were collected in November 2010 to establish the SSA of the surface soil prior to the wind erosion season (S_o). The slopes were resampled in May 2011 to establish the SSA of the surface soil after the wind erosion season (S_e) and the associated values of ^{7}Be inventory (A_{Be}). The relationships between the ^{7}Be inventory and the ratio S_e/S_o for these sets of samples collected from the two sites are presented in Fig. 5. These relationships, which cover the different erosion rates associated with the clay loam and sandy loam soils and therefore different degrees of reduction of the ^{7}Be inventory and different ranges of the ratio S_e/S_o, possess the same form and similar exponents to those reported in Table 5 for the more controlled conditions associated with the experimental plots. The sandy loam soils are clearly more susceptible to erosion, with the result that both the inventories measured at the end of the wind erosion and the ratio S_e/S_o are generally lower than for the clay loam soils.

Based on these findings, it is proposed that the particle size correction factor P' for incorporation into an equation for estimating soil loss by wind erosion from ^{7}Be measurements can be represented as:

$$P' = \left(\frac{S_e}{S_o}\right)^{v} \quad (6)$$

Developing Eq. (1), the selective removal of fine particles can be incorporated as follows:

Table 5
The relationship between A_{Be} (y) and S_e/S_o (x) for all sampling points on the experimental plots.

Wind speed (m s^{-1})	Plot	Fitted function	
10	A-1	$y = 433.7x^{0.78}$	($n = 12$, $r^2 = 0.97$, $p < 0.001$)
	A-2	$y = 426.7x^{0.79}$	($n = 12$, $r^2 = 0.77$, $p < 0.001$)
12	B-1	$y = 421.6x^{0.60}$	($n = 12$, $r^2 = 0.95$, $p < 0.001$)
	B-2	$y = 433.6x^{0.75}$	($n = 12$, $r^2 = 0.89$, $p < 0.001$)

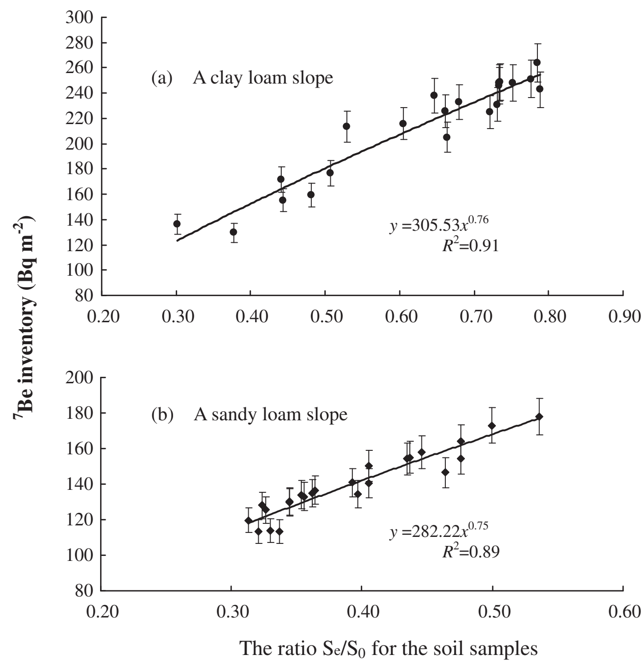

Fig. 5. The relationship between ^{7}Be inventory and the ratio of S_e/S_o for the soil samples collected from (a) a clay loam slope, and (b) a sandy loam slope in the Liudaogou watershed.

$$R_{Be,P'} = P'h_0 \ln\left(\frac{A_{ref}}{A_{Be}}\right) \quad (7)$$

where $R_{Be,P'}$ is the wind erosion rate (kg m^{-2}); A_{Be} is the measured total ^{7}Be inventory at the eroded site (Bq m^{-2}) and a positive value represents erosion.

For a depositional location, the deposition amount $R'_{Be,P'}$ can be estimated from the excess ^{7}Be inventory (defined as $A_{Be} - A_{ref}$) and the ^{7}Be concentration of deposited sediment $C_{Be,d}$.

$$R'_{Be,P'} = \frac{A_{Be} - A_{ref}}{P'C_{Be,d}} \quad (8)$$

Following Walling and He (2001), who proposed a generic value of ca. 0.65 for the parameter v in Eq. (8) when employed with ^{137}Cs measurements, the results presented in Table 5 and Fig. 5 suggest that a value of 0.75 can be assumed for parameter v in Eq. (7), when employed with ^{7}Be.

In the wind tunnel experiment S_m can be readily estimated for the mobilized and Eq. (7) also can be modified to incorporate the particle size correction factor P as follows:

$$R_{Be,P} = \frac{1}{P}h_0 \ln\left(\frac{A_{ref}}{A_{Be}}\right) \quad (9)$$

In this case a value of 0.75 can again been used for v in Eq. (5), as being applicable to ^{7}Be.

Table 6 compares the measured amount of soil loss by wind erosion from the plots placed in the wind tunnel, based on the collector, and the values estimated from the measurements of the change in ^{7}Be inventory, using the standard water erosion model (Eq. (1)) and the refined models incorporating the particle size correction (Eqs. (7) and (9)), for the different plots. The uncertainty associated with the values of A_{ref} and A_{Be} has been propagated through the calculations. As expected, the mean values of soil loss for the individual plots ($\bar{R}_{Be}$) calculated using Eq. (1) overestimate the measured values and are more than 11% higher than the measured values (R_e), with the degree of overestimation increasing for higher values of soil loss. The mean values of erosion rate for the individual plots ($\bar{R}_{Be,P'}$) calculated using the refined model incorporating a particle size correction factor based on the ratio S_e/S_o (Eq. (7)) show close agreement with the measured values (R_e) with the deviation of the estimated values from the measured values not exceeding +3% and averaging +2.2%. Similarly, the mean values of wind erosion loss for the individual plots ($\bar{R}_{Be,P}$) calculated using the refined model incorporating a particle size correction factor based on the ratio S_m/S_o (Eq. (9)) are in close agreement with the measured values (R_e). Here the difference between the estimated and measured values averages −1.9% and the deviation of measured and estimated soil loss decreases with increased wind speed.

The very close agreement between the values of soil loss estimated using the refined models incorporating a particle size correction factor (Eqs. (7) and (9)) and the measured values is seen to provide clear confirmation of the potential for using ^{7}Be measurements to estimate wind erosion rates. Furthermore, the use of the particle size correction factor P', based on the ratio of the SSA of the surface soil at the eroding point to that of the soil prior to erosion (i.e. Eq. (7)) is seen to provide results of similar accuracy to those provided by Eq. (9) which incorporates correction factor P based on the ratio of the SSA of the eroded soil to that of soil prior to erosion. As indicated above, use of the correction factor P' is seen to be preferable to the use

Table 6
Comparison of the measured soil loss from the experimental plots with the estimates of the soil loss from the experimental plots derived from the measurements of the change in ^{7}Be inventory.

Wind speed ($m\ s^{-1}$)	Plot	R_e ($g\ m^{-2}$)	Approx. soil loss depth (mm)	$\bar{R}_{Be}$* ($g\ m^{-2}$)	$(\bar{R}_{Be} - R_e)/R_e$ (%)	$\bar{R}_{Be,P'}$* ($g\ m^{-2}$)	$(\bar{R}_{Be,P'} - R_e)/R_e$ (%)	$\bar{R}_{Be,P}$* ($g\ m^{-2}$)	$(\bar{R}_{Be,P} - R_e)/R_e$ (%)
10	A-1	664	0.49	748 ± 31	+12.7	674 ± 28	+1.5	645 ± 27	−2.9
	A-2	634	0.47	707 ± 30	+11.5	652 ± 27	+2.8	615 ± 26	−3.0
12	B-1	826	0.61	958 ± 40	+16.0	846 ± 36	+2.4	823 ± 35	−0.4
	B-2	842	0.62	990 ± 42	+17.6	860 ± 36	+2.1	831 ± 35	−1.3

Notes: R_e is the measured soil loss; $\bar{R}_{Be}$ is the soil loss calculated using the ^{7}Be-based water erosion model (Eq. (1)); $\bar{R}_{Be,P'}$ is the soil loss calculated using the ^{7}Be-based wind erosion model incorporating particle size correction factor P' (Eq. (7)) and $\bar{R}_{Be,P}$ is the soil loss calculated using the ^{7}Be-based wind erosion model incorporating particle size correction factor P. (Eq. (9)).
* Uncertainty at the 95% level of confidence.

of P, since the former does not require the deployment of sediment collectors and avoids potential problems associated with the sediment obtained from the collector being unrepresentative of sediment mobilized from the study site itself. Practical issues associated with applying the approach based on Eq. (7) to the study region are considered further below.

3.6. Using the proposed approach in the study region

The climate of the study region located on the Loess Plateau of China, and particularly of the part of the region located in the north of Shaanxi Province, is very distinctive. The mean annual precipitation is about 400 mm, with annual totals ranging from ca. 108 mm (1967) to 819 mm (1965), and about 75% falling as rain from June to September. In winter, the land will commonly be snow covered from the end of November through to March. Snowmelt occurs relatively slowly and is rarely accompanied by rainfall. As a result the snowmelt rapidly infiltrates into the dry soil and does not cause surface runoff or erosion. After snowmelt, the soil rapidly dries out and wind speeds are high and, as a result, the soil is highly susceptible to wind erosion. Cultivation and planting of crops commences in May and the onset of the summer rain occurs in June. These climatic characteristics provide a good basis for using ^{7}Be measurements to quantify soil loss by wind erosion during the period of about one month between the end of snowmelt and the onset of cultivation and planting (i.e. April), which represents the main period of wind erosion in the region. The snowfall and dry deposition in the preceding months are generally sufficient to provide a significant and readily measured ^{7}Be inventory in the soil at the beginning of the period of wind erosion and the period of erosion is sufficiently short to provide meaningful estimates of erosion rates based on the reduction of the ^{7}Be inventory during the study period as a result of wind erosion. The results reported in Fig. 5 for the Liudaogou watershed confirm the existence of measurable ^{7}Be inventories at the end of the wind erosion season in soils subject to wind erosion. Since cultivation does not occur until May, the ^{7}Be inventory accumulated during the winter is not disturbed prior to the study period. Cultivation prior to May would negate the use of ^{7}Be measurements to estimate erosion rates during the period of wind erosion, since it would mix the accumulated ^{7}Be into the soil and destroy the original shallow depth distribution. The approach described by Walling et al. (2009) could be used to take account of problems associated with extending the period of interest associated with applying Eq. (7) from a few days to a few weeks, identified by those authors, in order to cover the entire period of wind erosion.

In the absence of erosion during the preceding winter months and rapid snowmelt, the ^{7}Be inventory of a study site is likely to exhibit limited spatial variability at the beginning of the period of wind erosion and this again conforms to the requirements for successful use of ^{7}Be measurements to estimate erosion rates. In this situation, it would be necessary to sample the study site immediately prior to the period of wind erosion to establish A_{ref} (Eq. (7)) and S_o (Eq. (6)), as well as the depth distribution of

^{7}Be which is needed to establish h_0. Alternatively, a small portion of the study area could be covered and protected from wind erosion, immediately after snowmelt, to permit measurement of these parameters. Samples collected at the end of the period of wind erosion would provide the required values of A_{Be} and S_e for use in Eqs. (6) and (7).

In the approach represented by Eq. (7) (and also Eq. (9)), it is important that the difference between A_{ref} and A_{Be} should be significantly greater than the uncertainty associated with these two values as a result of the precision of the measurements of ^{7}Be activity by gamma spectrometry, sampling variability and local and microscale variability in soil inventories (see Owens and Walling, 1996). This will largely depend on the amount of erosion and thus the magnitude of the reduction of the ^{7}Be inventory. However, uncertainty can also be reduced by replicate sampling to establish A_{ref} and a similar approach could be employed for A_{Be}, by collecting replicate samples at each sampling point. Since the precision errors associated with gamma spectrometry measurements are generally normally distributed, the mean of replicate measurements will be characterized by a smaller uncertainty than the individual measurements. It is important to recognise the potential for spatial variability of ^{7}Be fallout, particularly in arid and semi-arid areas (see Kaste et al., 2011) and for this reason study sites should be kept small and reference inventories should be established for individual sites, rather than for a wider area.

Typical annual soil losses due to wind erosion in the study area reported by Dong (1998) are of the order of 1.25 mm, which is equivalent to $\sim$1.7 kg m^{-2}. Such depths fall well within the vertical extent of the typical ^{7}Be depth distribution as represented by Fig. 3. Furthermore, such erosional losses are of a similar magnitude to those reported for the wind tunnel experiment (i.e. 0.63–0.84 kg m^{-2}) and this again confirms the viability of using ^{7}Be measurements to estimate wind erosion rates in the study region. The relatively high magnitude of the soil loss recorded for the short measurement periods associated with the wind tunnel experiment (20 min), when compared with the values reported for the entire period of wind erosion under natural conditions (ca. 1 month), are not unexpected, since similar findings have been reported by Dong (1998) when comparing results from wind tunnel experiments with field-derived estimates of annual soil loss attributable to wind erosion. The relatively high soil loss within a short period documented by the wind tunnel experiment reflects the continuous shear applied during this period. This contrasts with the sporadic occurrence of high levels of shear under natural conditions.

4. CONCLUSION

The wind tunnel experiment described in this contribution has provided a basis for incorporating a particle size correction factor into the procedure for using ^{7}Be measurements to estimate wind erosion rates, in order to take account of its winnowing effect. Comparison of the wind erosion rates estimated using this refined procedure with the measured values showed very close agreement and provides clear evidence of the potential for using ^{7}Be measurements to quantify wind erosion rates. Successful use of ^{7}Be measurements in wind erosion investigations requires that the local conditions, and particularly the timing of the wind erosion relative to ^{7}Be fallout and soil cultivation, are suitable for application of the approach. A preliminary assessment has demonstrated that these requirements are met by the study area and that the approach should prove successful if employed there.

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