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Geochimica et Cosmochimica Acta 114 (2013) 81–93

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

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

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Received 19 September 2012; accepted in revised form 23 March 2013; available online 6 April 2013

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.

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0016-7037/$ - see front matter
http://dx.doi.org/10.1016/j.gca.2013.03.033

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})