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Beryllium-7 in vegetation, soil, sediment and runoff on the northern Loess Plateau

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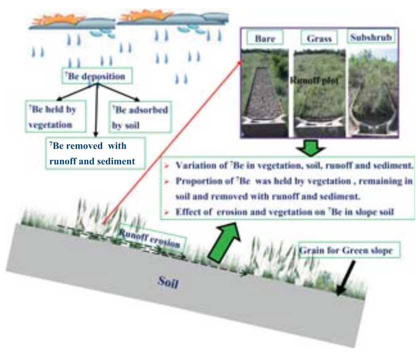
HIGHLIGHTS

- ^{7}Be activity in plant and soil varied significantly during rainy season.
- ^{7}Be inventory held by plant increased with increasing decayed cumulative rainfall.
- ^{7}Be mass activity in sediment decreased with increasing sediment amount.
- Soil erosion and vegetation affected markedly ^{7}Be inventory in the slope soil.
- Most of ^{7}Be remains in the slope soil at the end of the rainy season.

GRAPHICAL ABSTRACT



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ABSTRACT

Beryllium-7 (^{7}Be), as a potentially powerful tracer, was widely used to document soil redistribution and identify sediment sources in recent decades, but the quantity and distribution of ^{7}Be in vegetation, soil, sediment and runoff on the Loess Plateau have not been fully described. In this study, we measured ^{7}Be in vegetation, soil, sediment and runoff on the northern Loess Plateau of China and analyzed its variations during the rainy season to assess the potential of the ^{7}Be method for documenting soil redistribution and identifying sediment sources in a wide range of environments. The results indicated that vegetation, soil, and sediment samples showed higher levels and larger variations of ^{7}Be activities during the rainy season. The drying plants showed ^{7}Be mass activity that was more than three times higher than that of living and semi-decomposed plants. ^{7}Be mass activity in plants and sediment was much higher than in the soil. ^{7}Be activity in runoff water with a few submicron suspended particles varied slightly and was far lower than in plant, soil and sediment samples. The cumulative precipitation generally determined ^{7}Be inventory held by plants and soil. An inverse relationship was found between the ^{7}Be mass activity in sediment and the sediment amount. Globally, approximate 30% of the total ^{7}Be was held by plants in both the herbaceous and subshrub plots. Approximate 10% of the total ^{7}Be was lost with sediment from the bare plot. A very small proportion of ^{7}Be (1.18%–3.20%) was lost with runoff, and the vast majority of ^{7}Be was retained in the slope soil at the end of rainy season. Vegetation cover and soil erosion significantly affected the spatial distribution and variations of the ^{7}Be inventory in soil, providing a necessary condition for the development of a ^{7}Be method to document soil erosion on slopes with vegetation.

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1. Introduction

Cosmogenic ^{7}Be with a short half-life of 53.3 d is formed primarily in the stratosphere and upper troposphere as a natural product of cosmic-ray spallation of oxygen and nitrogen nuclei (Lal et al. 1958). Once produced, ^{7}Be rapidly forms BeO or $Be(OH)_2$ through ionic reactions, then attaches to sub-micrometer atmospheric aerosol particles and diffuses throughout the atmosphere until it is continuously delivered to the earth's surface by wet and dry deposition (Cho et al. 2007; Doering and Akber 2008; Ioannidou and Papastefanou 2006; Juri Ayub et al. 2012; Krmar et al. 2016; Papastefanou and Ioannidou 1995; Papastefanou et al. 1995; Wallbrink and Murray 1994; Zhang et al. 2013). Available evidence suggests that >90% of ^{7}Be deposition is delivered by wet deposition and that the magnitude of annual deposition fluxes varies primarily in response to the amount of annual precipitation and latitude (Wallbrink and Murray 1994). Upon reaching the earth's surface, ^{7}Be is rapidly and strongly adsorbed by ground cover and soil particles (Bondietti et al. 1984; Papastefanou et al. 1999; Wallbrink and Murray 1996; Zhang et al. 2012), and is commonly confined within the upper 20 mm of the soil (Blake et al. 1999; Schuller et al. 2010; Walling et al. 2009; Yang et al. 2006; Zhang et al. 2014). Due to its continual replenishment by fallout, its relatively short half-life, its restriction to a shallow surface layer and its ease of measurement by gamma spectrometry, ^{7}Be, alone or in conjunction with other radionuclides (^{137}Cs, ^{210}Pb, ^{234}Th and ^{40}K), has been successfully used as a tracer of soil particle transport processes, such as short-term or event-based soil erosion on bare slopes, sediment source identification, sediment transport rates and residence times, deposition and resuspension (Baskaran and Swarzenski 2007; Blake et al. 1999; Blake et al. 2002; Botwe et al. 2017; Le Cloarec et al. 2007; Matisoff et al., 2002; Matisoff et al. 2017; Matisoff et al. 2005; Saari et al. 2010; Walling 2013; Walling et al. 1999; Walling et al. 2009; Whiting et al. 2001; Wilson et al. 2003; Yang et al. 2013; Yang et al. 2006; Zhang et al. 2014; Zhang et al. 2018). However, there are still some uncertainties associated with the behavior of ^{7}Be in the soil and related environments, e.g., vegetation interception, root uptake, activity in different soil particle sizes, application on slopes with vegetation and loss due to runoff (Shi et al. 2013; Walling 2013). Knowledge of these behaviors of ^{7}Be in terrestrial environments is a fundamental component in extending the further use of the ^{7}Be method in a wide range of environments. Therefore, the first step in extending the use of the ^{7}Be method is to systematically study variations of ^{7}Be activity in vegetation, soil, sediment and runoff in local areas and to assess the potential of the ^{7}Be method in a wide range of environments.

^{7}Be activity in vegetation, which is mainly dependent on climatic conditions, i.e., on precipitation, and varied markedly between different growing periods, was significant, but the uptake by plant roots did not play an important role (Papastefanou et al. 1999). Wallbrink and Murray (1996) found that up to 55% of the ^{7}Be inventory was held by grass at sites with significant vegetation cover. Similar results were also reported by other researchers (Bettoli et al. 1995; Doering et al. 2006; Kaste et al. 2011). Vegetation growing in dry climates has lower ^{7}Be mass activity than vegetation growing in wet climates (Bondietti et al. 1984). Papastefanou et al. (1999) observed that ^{7}Be activity in grasses varied between 2.1 and 348.0 Bq kg^{-1} (average of 54.4 Bq kg^{-1}). A similar range of ^{7}Be mass activity in nine vegetable species from southwest Finland was reported by Lönnroth et al. (2007). Seasonal variations of ^{7}Be activity in plants were determined by precipitation and its temporal distribution (Pöschl et al. 2010; Sugihara et al., 2008). The differences in ^{7}Be mass activity between plant species were significant (Karunakara et al. 2003; Lönnroth et al. 2007; Zhang et al. 2011). Zhang et al. (2011) found that the mean ^{7}Be mass activity in plants ranked in order of highest to lowest was herbaceous, subshrubs and crop plants. In addition, previous studies also found that whole plant samples contained less ^{7}Be mass activity than leaf samples (Karunakara et al. 2003; Zhang et al. 2012).

The ^{7}Be inventory in a reference site, which is determined by the local characteristics of ^{7}Be deposition (Walling et al. 2009; Zhang et al. 2013), is greatly variable over time and space, from 200 to 1000 Bq m^2 on temperate and tropical land (Kaste et al. 2011). In general, ground cover and soil erosion significantly affected the ^{7}Be inventory in soil on the slope surface (Schuller et al. 2010; Shi et al. 2013; Wallbrink and Murray 1996). The mineral and organic particles in the surface soil strongly adsorbed ^{7}Be, and the finer particles had higher ^{7}Be activity than the coarser particles (Wallbrink and Murray 1996). ^{7}Be decreases exponentially with depth and is commonly confined within the upper 20 mm of the soil (Blake et al. 1999; Schuller et al. 2010; Walling et al. 2009; Yang et al. 2006; Zhang et al. 2014). The depth of ^{7}Be penetration may be primarily controlled by soil type, surface cover, plant roots, soil density, macrovoids, and structure (Wallbrink and Murray 1996). This distribution characteristic of ^{7}Be in the soil profile confirms its potential value as a label of surface soil to document soil redistribution and transition from sheet to rill erosion and to identify sediment source regions and land use (Matisoff et al., 2002; Whiting et al. 2001; Zhang et al. 2014).

^{7}Be mass activity in sediment decreased generally as rainfall proceeded and was consistent with the decrease in ^{7}Be mass activity in soil with depth (Wallbrink and Murray 1993; Yang et al. 2006; Zhang et al. 2014). Matisoff et al. (2002) observed that ^{7}Be mass activity was higher in suspended sediment derived from no-till sub-basins than those derived from conventionally tilled sub-basins and exhibited an inverse relationship with the suspended sediment concentration. Briefly, ^{7}Be mass activity in sediment intensively reflected the changes of erosion patterns, sediment sources, sediment transport rates, distances and residence times (Blake et al. 2009; Feng et al. 1999; Matisoff et al. 2017; Matisoff et al. 2005; Wallbrink et al. 1999; Walling et al. 1999; Whiting et al. 2001; Zhang et al. 2014).

The dissolved phase of ^{7}Be in water was analyzed. Bloom and Crecelius (1983) reported that the solubility of $^{7}Be^{2+}$ from submicron aerosols of air in seawater was a function of time and that ^{7}Be appeared to be strongly adsorbed on suspended matter and inorganic material at high suspended loads (>20 mg L^{-1}) and was only partially adsorbed at natural levels (~1 mg L^{-1}). Hawley et al. (1986) reported that the partitioning coefficient (K_d) of ^{7}Be in fresh water varied inversely with the solids concentrations at typical environmental values (up to 30 mg L^{-1}). At high solids concentrations (>100 mg L^{-1}), over 90% of ^{7}Be was associated with the solid phrase. Similar values were reported by Li et al. (1984). Matisoff et al. (2002) indicated that 99.9% of suspended solids removed by centrifuging accounted for 92.8% of the total ^{7}Be activity, 0.1% of the filtered solids accounted for 2.3% of the total ^{7}Be activity, and the dissolved phase of ^{7}Be in runoff contained 4.9% of the total ^{7}Be activity for the sample of 241 mg L^{-1} sediment concentration. The ^{7}Be dissolved phase in runoff and ^{7}Be in submicron suspended particles should receive more attention when using ^{7}Be as a tracer, especially for ^{7}Be in submicron suspended particles.

In conclusion, ^{7}Be activity in soil, vegetation, sediment and runoff were investigated and vary significantly. However, there is insufficient knowledge about the behavior of ^{7}Be after it enters terrestrial environments through wet and dry deposition processes. Specifically, we know little about the variations of ^{7}Be activity in vegetation, soil, sediment and runoff over time in relation to environmental conditions and how much ^{7}Be is retained in soil and vegetation or lost with sediment and runoff on slopes at a specific time. These knowledge gaps could affect using ^{7}Be as effective tracer for documenting soil redistribution and identifying sediment sources in a wide range of environments. Moreover, ^{7}Be activity in vegetation, soil, sediment and runoff varied with latitude and precipitation gradients under different climatic conditions, and more systematic analysis is required.

The Loess Plateau in Northern China is well known as one of the most severely eroded areas in the world (Li et al. 2016; Shi and Shao 2000; Zhang et al. 2017; Zhao et al. 2017). To date, although there have been several studies about using ^{7}Be as a tracer to document soil