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Use of ^{7}Be to document soil erosion associated with a short period of extreme rainfall

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Abstract

Intensification and expansion of agricultural production since the 1970s have increased soil erosion problems in south-central Chile. Quantitative information on soil loss is needed for erosion risk assessment and to establish the effectiveness of improved land management practices. Since information from traditional sources, such as erosion plots, is limited, attention has been directed to the use of environmental radionuclides for documenting erosion rates. Cs-137 has been successfully utilised for this purpose, but only provides information on medium-term erosion rates. There is also a need to document event-related soil erosion. This paper outlines the basis for using ^{7}Be measurements to document short-term erosion and reports its successful use for quantifying the erosion that occurred within an arable field, as a result of a period of heavy rainfall (400 mm in 27 days) occurring in May 2005. The study field had been under a no-till, no-burning system for 18 years, but immediately prior to the period of heavy rainfall the harvest residues were burnt. The erosion recorded therefore reflected both the extreme nature of the rainfall and the effects of the burning in increasing surface runoff and erosion. The sampled area corresponded to that used previously by the authors to document the medium-term erosion rates associated with both conventional tillage and the subsequent switch to a no-till system. Comparisons between the erosion documented for the period of heavy rainfall in 2005 with these medium-term erosion rates permits some tentative conclusions regarding the importance of extreme events and the impact of burning in increasing the erosion associated with the no-till system.

Keywords: ^{7}Be; ^{137}Cs; Soil erosion; Extreme rainfall; No-till; Crop residue burning; Chile

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1. Introduction

Intensification and expansion of agricultural production since the 1970s have increased soil erosion problems in south-central Chile (CONAF, 1994). These problems relate to both on-site reduction in soil productivity, and therefore sustainable soil management, and to the off-site impacts of eroded sediment and problems of diffuse source pollution of water courses and degradation of aquatic ecosystems, and therefore to environmental protection (INIA, 2001; FAO,

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2002a,b). Cereals and legumes are the main crops of the region and the traditional land management practices are known to increase erosion risk. Burning of stubble and crop residues after harvest and subsequent ploughing and disc harrowing for seed bed preparation leave large areas of bare soil, often on slopes as steep as 15–20%, exposed to the heavy rains that occur during the winter period. In response to these problems, there has been a shift to minimum-till and no-till systems throughout much of the region (Acevedo, 2003).

Against this background, there has been an increasing need for quantitative information on rates of soil loss under both conventional and no-till/minimum-till systems within the region (Ellies, 2000). This information is needed in order to provide an improved assessment of erosion risk and its on-site and off-site impacts and to evaluate the effectiveness of no-till systems in reducing erosion. However, the information available from traditional sources, such as erosion plots, is very limited. With support from the International Atomic Energy Agency, attention has therefore been directed to the potential for using environmental radionuclides, and more particularly caesium-137 (^{137}Cs) measurements, as a means of obtaining information on past and recent erosion rates (see Schuller et al., 2004, 2007). Schuller et al. (2004) report the development of a novel approach for using ^{137}Cs measurements to compare erosion rates associated with conventional tillage and subsequent no-till operations at the same site, where the shift from conventional tillage to a no-till system occurred in the 1980s. Using this approach at a site on Buenos Aires farm in the Coastal Mountains of south-central Chile, Schuller et al. (2007) were able to demonstrate that the implementation of a no-till system, including crop residue management, reduced the net erosion rate by about 87%, thereby confirming the benefits of implementing no-till systems within the region.

Further investigation and evaluation of soil erosion problems in south-central Chile require information on several other aspects of erosion risk. These include assessment of the impact of high magnitude, low frequency rainfall periods on erosion and the potential role of post-harvest burning of crop residues in increasing erosion associated with no-till systems. In the first case, it is important to determine whether soil loss is an essentially continuous process or whether it is more discontinuous and dominated by those years in which the winter rains are particularly heavy. Equally, it is important to confirm that the no-till systems introduced to reduce erosion are as effective during periods of high magnitude rainfall as under more normal conditions. In the second case, the no-till system sometimes includes burning of the crop residues after harvest and there is concern that this may reduce the effectiveness of the no-till system in reducing soil erosion. In the standard no-till system, there is no burning of crop residues (NTNB – no-till, no burning). The residue of the harvested crop is left on the soil surface and direct seeding is undertaken using seed drills, which cut through the crop residue and open slots in the soil into which the seed and fertilizer are placed (see Schuller et al., 2007). Where burning of the crop residue is introduced (NTWB – no-till with burning), the residue is burnt in late summer (e.g. March), shortly after harvesting. This leaves the soil bare during the subsequent autumn rains, which commonly commence around May. The exposure of the bare soil to the autumn rains increases its susceptibility to raindrop impact and surface sealing. In addition, it is likely that the burning will increase the bulk density of the surface soil, through removal of organic matter, destroy the soil aggregates, thereby increasing the potential for soil crusting, and reduce the hydraulic conductivity of the surface horizons. There is also evidence that burning may result in hydrophobic conditions at the soil surface (Limon-Ortega et al., 2006). All of these changes are likely to lead to increased surface runoff and thus increased erosion risk.

In order to investigate further these aspects of soil erosion risk, there is a need for information on the short-term erosion and soil redistribution associated with individual periods of heavy rain. This would permit the relative contribution of periods of high magnitude, low frequency, rainfall to the longer-term soil loss to be established and the effects of introducing burning into the no-till system to be explored. In view of the past success of the authors in using ^{137}Cs measurements to document medium-term erosion rates in south-central Chile and the impact of the shift from conventional to no-till systems in reducing soil erosion rates, attention has been directed to exploring the potential for using beryllium-7 (^{7}Be) measurements to document the erosion associated with individual periods of heavy rain occurring during the autumn. In contrast to ^{137}Cs, ^{7}Be is a short-lived, naturally occurring, cosmogenic radionuclide with a half-life of only 53 days. This makes it particularly useful for documenting event-based erosion and it has been used successfully in such applications by several workers, including Wallbrink and Murray (1993), Blake et al. (1999), Walling et al. (1999), Wilson et al. (2003) and Schuller et al. (2006).

This paper reports the use of ^{7}Be measurements to document soil redistribution within a field at Buenos Aires farm in south-central Chile, associated with a period of very heavy rainfall in autumn 2005. The field investigated had been cultivated using a NTNB system for about 18 years, but, because of the slow decomposition of the residual stubble after the 2005 harvest, the crop residue was burnt in early March 2005, leaving the field bare at the onset of the autumn rains in May 2005. The results obtained therefore provide information on the role of high magnitude, low frequency, rainfall events in contributing to the longer-term erosion from the site and permit some preliminary conclusions regarding the influence of burning within NTWB systems in increasing soil loss.

2. Using ^{7}Be measurements to document short-term soil redistribution

2.1. Background

Beryllium-7 is a natural radionuclide generated through the cosmic ray spallation of nitrogen and oxygen nuclei in the stratosphere and upper troposphere (see Papastefanou and Ioannidou, 2004; Ioannidou and Papastefanou, 2006). It can therefore be assumed that, on a given date, the atmospheric concentration of ^{7}Be over a small area will be almost uniform (Doering et al., 2006). Beryllium-7 attaches to aerosol particles and is removed from the atmosphere by dry and wet fallout (Papastefanou, 2006). Wet fallout commonly accounts for about 97% of the total ^{7}Be deposition flux to the soil surface (Salisbury and Cartwright, 2005). Beryllium-7 reaches the soil surface primarily as the Be^{2+} ion, which is extremely competitive for cation exchange sites, because of its high charge density (Kaste et al., 2002). When ^{7}Be comes into contact with the soil, it is therefore rapidly and strongly fixed (Hawley et al., 1986; Wallbrink and Murray, 1996; Kaste et al., 2002) and remains predominantly in the upper centimetre of the soil profile (Blake et al., 1999; Walling et al., 1999; Doering et al., 2006). Existing field and laboratory evidence suggest that the initial vertical distribution of the ^{7}Be mass activity density, Bq kg^{-1}, within the soil is characterized by a strong exponential decrease with depth, with most of the radionuclide being found within the upper few millimetres of the surface soil (Walling and Woodward, 1992; Blake et al., 1999; Schuller et al., 2006). Because the half-life of ^{7}Be is short, relative to the rate of operation of processes potentially responsible for downward transfer of the radionuclide, it is rare to find ^{7}Be at depths of >2 cm and any ^{7}Be found below ca. 2 cm can usually be explained by the downward movement of soil particles through fissures formed during relatively dry periods (e.g. Olsen et al., 1985) and/or by bioturbation by soil fauna that can transport ^{7}Be to greater depths (e.g. Wallbrink and Murray, 1996; Kaste et al., 2007).

The successful use of ^{7}Be to document both the magnitude and spatial pattern of short-term (event-based) soil redistribution on agricultural land and the associated erosion and deposition has been reported by Blake et al. (1999) and Walling et al. (1999). The approach used is based on comparison of the ^{7}Be areal activity density, Bq m^{-2}, measured at a sampling point with a reference areal activity density determined for a nearby stable reference site, where neither erosion nor deposition has occurred. Depletion of the ^{7}Be areal activity density, relative to the reference value, provides evidence of erosion, whereas areas of sediment deposition are associated with increased areal activity densities. By coupling information on the extent of the decrease or increase in the areal activity density with information on the characteristic depth distribution of ^{7}Be within the surface soil of the reference site, the depth or amount of soil eroded or deposited can be estimated.

Taking account of the known rapid and strong fixation of ^{7}Be fallout to surface soils and of existing information regarding the depth distribution of ^{7}Be in soils, it can be assumed that the initial vertical distribution of the mass activity density of ^{7}Be within the soil will be characterized by an exponential decrease with depth. Based on this premise, Blake et al. (1999) and Walling et al. (1999) proposed a simple conversion model for estimating the intensity of soil redistribution from measurements of the extent of the increase or decrease in the areal activity density, relative to the reference value. The components of this model as presented by Schuller et al. (2006) are described below, using terms defined according to ICRU (2001).

2.2. The initial depth distribution of ^{7}Be in the soil

With x, kg m^{-2}, representing the mass depth of the soil measured from the surface (positive downward) and $C(x)$, Bq kg^{-1}, the mass activity density of ^{7}Be *at* mass depth x, the initial exponential depth distribution can be represented as:

$$C(x) = C(0)\exp(-x/h_o), \tag{1}$$

where $C(0)$ is the initial mass activity density of the surface soil (at $x = 0$) and h_o, kg m^{-2}, is the relaxation mass depth.

The reference areal activity density, A_{ref}, Bq m^{-2}, represents the initial total areal activity at an uneroded stable site or reference site in the study area:

$$A_{\mathrm{ref}} = A(0) = \int_0^\infty C(x)\mathrm{d}x = h_\mathrm{o}C(0). \tag{2}$$

Considering the initial distribution, the areal activity density *below* mass depth x, $A(x)$, Bq m^{-2}, is therefore:

$$A(x) = \int_x^\infty C(x)\mathrm{d}x = A_{\mathrm{ref}}\exp(-x/h_\mathrm{o}). \tag{3}$$

The relaxation mass depth term describes the shape of the initial depth distribution of both the mass activity density (Eq. (1)) and the areal activity density (Eq. (3)) of ^{7}Be in the soil. According to Eq. (3), the areal activity density below the relaxation mass depth is:

$$A(h_\mathrm{o}) = 0.368A_{\mathrm{ref}}. \tag{4}$$

63.2% of the total areal activity density of ^{7}Be will therefore be found within the 0 to h_o soil layer. Consequently, the greater the value of h_o, the greater the penetration of the radionuclide into the soil.

By measuring the mass activity density, C, in individual depth increments of the soil cores collected from the reference site and establishing the mass depth of each depth increment, the values of $A(x)$ for corresponding mass depths x down the reference profile can be calculated. Logarithmically transforming Eq. (3), h_o and the areal activity density A_{ref} can be deduced from a linear regression between Ln[$A(x)$] and x.

2.3. Estimating soil loss at a sampling point

Assuming that erosion has removed a thin layer of mass depth, R, kg m^{-2}, at a sampling point within the study site, the ^{7}Be areal activity density remaining at this eroded point, A, Bq m^{-2}, will be lower than A_{ref}. The soil mass eroded per unit area, R, is equal to the mass depth removed. By setting $x = R$ in Eq. (3), the remaining areal activity density at the sampling point can be calculated as:

$$A = A(R) = A_{\mathrm{ref}}\exp(-R/h_\mathrm{o}). \tag{5}$$

The mass of soil per unit area eroded from the sampling point, R, can therefore be calculated as:

$$R = h_\mathrm{o}\,\mathrm{Ln}\left(A_{\mathrm{ref}}/A\right). \tag{6}$$

2.4. Estimating sediment deposition at a sampling point

When the measured ^{7}Be areal activity density, A', Bq m^{-2}, for a sampling point within the study site exceeds A_{ref}, deposition is assumed to have occurred at this point. An estimate of the sediment mass deposited per unit area, R', kg m^{-2}, can be obtained by dividing the areal activity density in excess of A_{ref} by the mean ^{7}Be mass activity density of the deposited sediment, C_d, Bq kg^{-1}, i.e.,

$$R' = \left(A' - A_{\mathrm{ref}}\right)/C_\mathrm{d}. \tag{7}$$

The ^{7}Be mass activity density of the sediment eroded from a point, C_e, Bq kg^{-1}, can be estimated from the areal activity density lost at that point divided by the mass of sediment eroded per unit area, i.e.,

$$C_\mathrm{e} = \left(A_{\mathrm{ref}} - A\right)/R = A_{\mathrm{ref}}[1 - \exp(-R/h_\mathrm{o})]/R. \tag{8}$$

Consequently, the mean ^{7}Be mass activity density of the deposited sediment C_d can be estimated as the weighted mean mass activity density, C_e, of sediment mobilised from the upslope contributing area S:

$$C_\mathrm{d} = \frac{\int_S C_\mathrm{e}R\,\mathrm{d}S}{\int_S R\,\mathrm{d}S}. \tag{9}$$

Using the parameters A_{ref} and h_{o} established for the initial ^{7}Be vertical distribution in the soil (i.e., for the reference site) and Eqs. (6) and (7), the amounts of soil eroded or deposited at individual sampling points within a study area, and thus the spatial pattern of soil redistribution, can be established.

2.5. Key assumptions of the ^{7}Be technique

Use of the ^{7}Be method outlined above to estimate soil redistribution involves three key assumptions (see Walling et al., 1999; Schuller et al., 2006):

1. Prior to the erosion event to be investigated, any pre-existing ^{7}Be within the soil should be uniformly distributed across the study area.
2. The deposition of ^{7}Be fallout associated with the erosion event should also be spatially uniform across the study area.
3. The ^{7}Be deposited during an erosion event will be rapidly fixed by the soil particles and can only be redistributed by mobilisation and redistribution of soil particles.

Considering the first assumption, any pre-existing spatial variability of the ^{7}Be areal activity density introduced by soil redistribution caused by previous erosion events will rapidly disappear through radioactive decay, providing the erosion episodes are separated by a period of sufficient length (e.g. longer than ca. two half-lives). Contributions to the ^{7}Be areal activity density in the soil, associated with low intensity rainfall, that does not cause significant soil redistribution, can be assumed to be uniform. The second assumption can be expected to be fulfilled at the scale of a small field, where the spatial distribution of both rainfall input and ^{7}Be fallout can be considered to be spatially uniform. The third assumption has been widely confirmed by experimental investigations of the fixation of ^{7}Be fallout inputs by soil particles, such as those reported by Wallbrink and Murray (1996) and Blake et al. (1999).

Other important assumptions of the ^{7}Be technique include the assumption that the relationship between the activity density of ^{7}Be and mass depth documented for the reference site is representative of the main sampled area, and that there is no significant grain size selectivity in the mobilisation and deposition of soil particles. In the first case, there is a need to ensure that the soil properties, surface condition and surface hydrology of the reference site are essentially similar to those of the main sampled area. Use of mass depth, as an alternative to linear depth, when establishing the ^{7}Be depth distribution limits the importance of any minor contrasts in bulk density between the reference site and the main sampling site. In the second case, it is important to recognise that, as with other fallout radionuclides, ^{7}Be is likely to be preferentially associated with the finer soil particles (see He and Walling, 1996) and that selective removal of fines could invalidate the use of the relationship between the activity density of ^{7}Be and the mass depth to estimate the amount of soil removed by erosion. If selective erosion of fines occurs, the amount of erosion may be overestimated. Equally, if selective deposition of coarser particles with lower ^{7}Be activity occurs, Eq. (7) may underestimate the amount of deposition. Particle size correction factors, such as those employed in conversion models developed for use with ^{137}Cs measurements (see Walling and He, 1999), could be used to overcome this problem, but in most instances the precise relationship between the grain size distribution of the bulk soil and that of soil particles mobilised by erosion or deposited elsewhere on the slope, as well as the distribution of ^{7}Be activity density within the soil according to its grain size fractions will be unknown. Against this background, it is necessary to ensure that size selective mobilisation and deposition are likely to be of limited importance, or to incorporate an appropriate correction factor in the conversion model.

3. The study site and the sampling programme

3.1. The study site

The study site is the same as that used by Schuller et al. (2004, 2007) to document changes in soil erosion rates associated with the shift from conventional tillage to a NTNB system using ^{137}Cs measurements. They reported the medium-term erosion and deposition rates and their spatial distribution within the same site for the two periods with contrasting tillage systems. The conventional tillage period extended from the onset of ^{137}Cs fallout in 1954 to the shift to the NTNB system in 1986 and the NTNB study period extended from 1986 to 2003, the sampling year. The site is located within a cultivated field at Buenos Aires farm in the Coastal Mountains of south-central Chile (38°37′S

73°04′W). The soils are Araucano series Ultisols, Typic Hapludult (Soil Survey Staff, 1993) and are texturally classified as very fine clay (clay 45%, silt 34% and sand 21% within the upper 10 cm of the soil profile) (Centro de Información de Recursos Naturales – CIREN, 2002). This textural property is described as providing a high water retention capacity and plasticity within the soil profile. The topography of the sampled area comprises a 170-m long slope with a gradient of about 11%. The location is characterized by a temperate climate, with high rainfall intensities between autumn and spring and a mean annual precipitation of 1100 mm. A tipping bucket rain gauge installed at the site provided a continuous record of the precipitation with a resolution of 0.2 mm.

The present investigation was undertaken when the management of the field shifted to a no-till with burning of the crop residue (NTWB) system, two years after the study undertaken by Schuller et al. (2007). The field had previously been managed with a NTNB system for 18 years. After harvesting in early 2005 (summer) and before the wet season began, the crop residue remaining on the field was burnt in March 2005, leaving the soil bare until the onset of a period of very heavy rainfall in early May 2005 (autumn).

The rainfall record for the period between January 1 and June 1, 2005 is shown in Fig. 1. After a prolonged dry period with little precipitation, extending from January 1 to May 2, a period with an unusually high amount of precipitation occurred, extending from May 3 to 29, 2005. This period was characterized by a total rainfall of 400.5 mm in 27 days, including a 1-h period on May 18 during which 11.4 mm of rain fell. In the absence of a long rainfall record for the study site, it is not possible to provide a value for the recurrence interval of this period of heavy rainfall. However, based on the 52-year record of monthly rainfall for the measuring station at Temuco, some 45 km from the study site, it is estimated that a monthly rainfall of this magnitude has a recurrence interval of ca. 15 years. On May 30, one day after the termination of this period of heavy rainfall, the field was sampled for ^{7}Be measurements, using the methods described by Walling et al. (1999).

3.2. Field sampling and laboratory procedures

To determine the parameters A_{ref} and h_{o}, required for applying the ^{7}Be conversion model, a reference site, located within a flat area at the top of the study slope, and permanently under the same tillage system as the main sampled area, was identified. This reference site conformed to the standard requirements and represented an essentially flat stable area, which provided no visible evidence of the occurrence of either erosion or sedimentation during the period of extreme rainfall. Two sets of nine cores (10.6 cm in diameter and 4 cm long) were collected from this site at the intersections of the lines defining two 2 m × 2 m grids. To document the variation in areal activity density across the study slope, produced by erosion and deposition associated with the period of heavy rainfall, soil cores were collected from 10 to 11 sampling points located at 15-m intervals along three slope transects spaced 15 m apart (see Fig. 3). At each sampling point, two soil cores were collected, using the same corer as used at the reference site. Additionally,

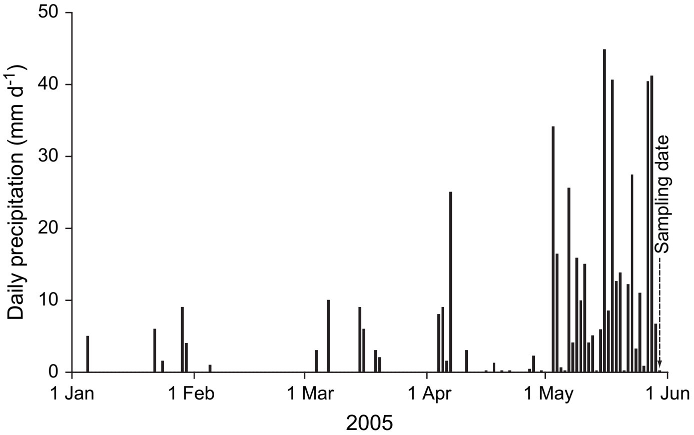

Fig. 1. The daily precipitation record for the study site for the period from January 1 to June 1, 2005. The arrow shows the date of collection of the soil samples used for ^{7}Be measurements (May 30, 2005).

along the lower part of the transects, where deposition of sediment might be expected, six cores were collected, in order to document the vertical distribution of ^{7}Be mass activity density and to observe the depth of ^{7}Be penetration into the soil.

To determine A_{ref} and h_{o}, each group of nine cores collected from the reference site was sectioned into 2-mm slices, and the slices from each group representing specific depth increments were bulked for measurement as a single composite sample. To document the depth of ^{7}Be penetration in the lower part of the transects, where deposition might be expected, the six cores collected from this area were sliced into 2-mm layers to a greater depth, to establish whether sediment containing ^{7}Be mobilised from upslope had been deposited at these sampling points. The six slices obtained for each depth increment were bulked for ^{7}Be measurement. A special device was used to facilitate slicing the cores. This device was designed and successfully used by Schuller et al. (2006) and comprised a piston (with the same diameter as the internal diameter of the core tube), the movement of which is controlled by a screw thread. The piston is inserted into the base of the core tube and can be used to extrude 1 mm of core per full turn of the screw. The 2-mm slices of soil extruded by rotating the screw two turns were separated from the remaining core using a sharp pallet knife.

The soil cores collected from the transects down the study slope were not sectioned, but were analysed as bulk cores. It was therefore necessary to determine the portion of the core that should be analysed, in order to maximize the gamma counting efficiency. If the cores were too shallow, they would not include the full inventory. If, however, they were too deep, the overall ^{7}Be mass activity density of the bulk core would be reduced (diluted) by incorporating soil containing no ^{7}Be. The vertical distribution of the ^{7}Be mass activity density observed at the reference site was used to determine the depth down to which the ^{7}Be concentration exceeds the detection limit (referred to as the penetration depth). Soil from above this depth, plus an additional 4 mm layer, was analysed to allow for the possible vertical extension of the ^{7}Be depth distribution, as a result of sediment deposition. These cores were subdivided, to recover the portion to be assayed, and the remainder of the core was discarded.

Prior to the measurement of their ^{7}Be activity, all samples were air dried and then dried for 48 h at 105 °C in an oven and weighed to determine the mass depth for each 2 mm depth increment. After sieving, each sample was mixed for 25 min using a shaker mixer (Turbula T2 F, Willy A. Bachofen Maschinenfabrik, Basel, Switzerland) to homogenize the ^{7}Be content. The samples (62–92 g) were then placed into 81.3 ml Petri dishes, in preparation for gamma counting. The ^{7}Be mass activity density (Bq kg^{-1}) of the samples was measured by gamma spectrometry using a Canberra high-purity Ge detector (Canberra Industries, Inc., Meriden, CT, USA) with a relative efficiency of 28%, at the Instituto de Física, Universidad Austral de Chile, Valdivia, Chile. The detector was calibrated for the selected measuring geometry using a standard gamma solution supplied by the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany). Spectra were analysed using Genie 2000 software (Canberra Industries, Inc., Meriden, CT, USA). Due to the low ^{7}Be concentrations in the soil samples analysed, the count time was set to 20 h per sample, which provided a detection limit of about 10 Bq kg^{-1} ($\pm$10% at the 95% level of confidence).

To assess the impact of burning the harvest residue on the density of the soil within the upper part of the profile (0–12 mm), four shallow soil cores were collected from the reference site after the burning and the measurements made on these cores were compared with those obtained for cores collected from the same location prior to the burning. These cores were sectioned into 2 mm depth increments, using the device described above, and the slices were air dried, oven dried at 105 °C for 48 h and subsequently weighed, to determine their bulk density and its depth distribution.

The change in the permeability of the soil caused by the burning of the crop residue was also assessed by comparing measurements of the saturated hydraulic conductivity (K_{sat}) obtained from representative points within the study area, before and after the burning. These measurements were made using a Guelph Permeameter (Soil Moisture Equipment Corp., USA, model 2800KI).

4. Results and discussion

4.1. Estimation of the magnitude of the soil redistribution associated with the period of heavy rainfall

During the four months prior to May 2005, the small amounts of precipitation documented for the study site (Fig. 1), coupled with the high water retention capacity of the soil, limited the potential for surface runoff generation and associated sediment mobilisation. The lack of both surface runoff and soil redistribution during this period was confirmed by field observations. The lack of soil redistribution ensured that the key assumption of an essentially uniform distribution of ^{7}Be areal activity density across the study field immediately prior to the onset of the period of heavy rainfall on May 3, 2005, was fulfilled.

The mean reference inventory measured for the two groups of cores collected from the reference site was 473 ± 50 Bq m^{-2}. The linear regression between the natural logarithm of the mean areal activity density, Ln[$A(x)$], and the mean mass depth, x, based on the two groups of sectioned cores collected from the reference site showed a high correlation coefficient ($r = 0.997$), which is significant at the 99% level of confidence, and confirms the expected exponential decrease of the areal activity density with depth. The values for the relaxation mass depth, h_o, and the reference areal activity density, A_{ref}, obtained from this relationship were 3.4 ± 0.1 kg m^{-2} and 499 ± 10 Bq m^{-2}, respectively.

The calculated relaxation mass depth indicates that, at the reference site, 63% of the total areal activity density was found in the soil above a mass depth of 3.4 kg m^{-2}, i.e., the upper 2.5 mm. Removal of the upper 1 mm (about 1.4 kg m^{-2}) of the soil by erosion would result in a 34% reduction in the ^{7}Be areal activity density at an eroding point. Due to the low value of the relaxation mass depth and the exponential depth distribution of the areal activity density, small amounts of erosion and deposition, associated with individual events or short periods of rainfall, will be reflected by significant decreases or increases in the areal activity density, relative to the reference value, A_{ref}. The ^{7}Be method is therefore highly sensitive to relatively small amounts of erosion and deposition.

Fig. 2 depicts the depth distribution of the mean ^{7}Be mass activity density (Fig. 2A) and the mean ^{7}Be areal activity density (Fig. 2B) at the reference site. The exponential form of both distributions is characterized by the relaxation

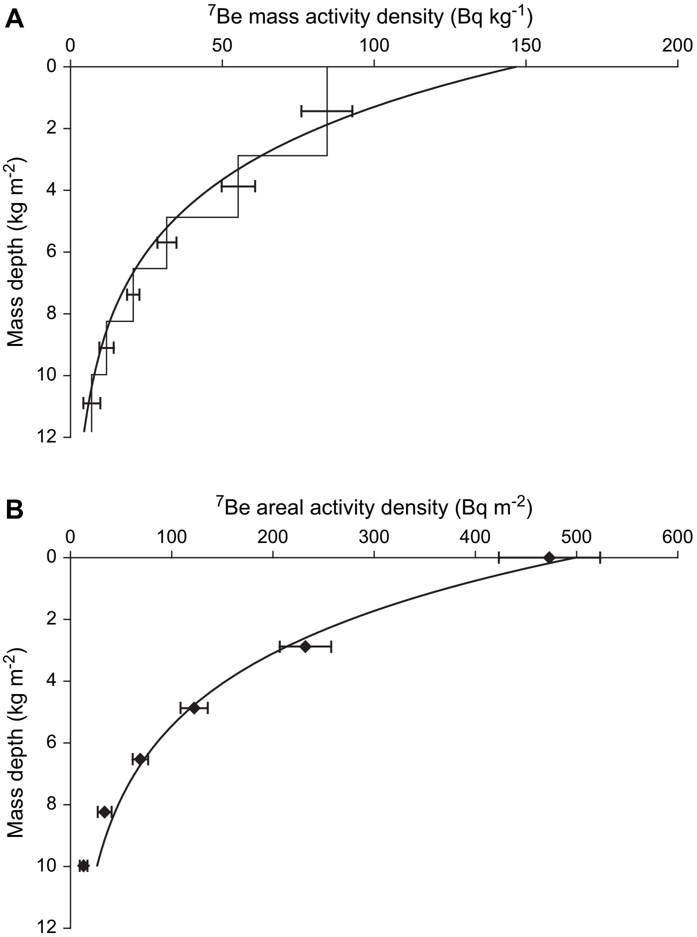

Fig. 2. The depth distribution of ^{7}Be at the reference site, showing (A) the exponential decrease of the ^{7}Be mass activity density and (B) the ^{7}Be areal activity density, with mass depth.

mass depth. By setting $h_o = 3.4$ kg m^{-2}, $A_{ref} = 499$ Bq m^{-2} and $C(0) = A_{ref}/h_o = 147$ Bq kg^{-1} (Eq. (2)) in Eqs. (1) and (3), the resulting expressions for the mass activity density and areal activity density are:

$$C(x) = 147\exp(-x/3.4) \text{ and}$$

$$A(x) = 499\exp(-x/3.4).$$

These functions are shown as continuous lines in Fig. 2A and B, respectively. Because the ^{7}Be activity falls below the detection limits at mass depth 11.8 kg m^{-2} (~12 mm), the ^{7}Be areal activity density contained below this depth was subtracted from the total areal activity density estimated using the linear regression, i.e.,

$$499 - \int_{11.8}^{\infty} 147\exp(-x/3.4)\mathrm{d}x = 483 \text{ Bq m}^{-2}.$$

The resulting value, 483 Bq m^{-2}, is in very close agreement with the mean areal activity density of 473 ± 50 Bq m^{-2} measured at the reference site and the former value was used as the reference areal activity density, when estimating the magnitude of soil redistribution.

Due to the time-variant nature of ^{7}Be reference inventories and their known global and regional variability, it is not possible to make direct comparisons between values reported for different locations. However, the reference inventory obtained for the study site, shortly after the period of heavy rainfall, is consistent with the magnitude of those reported for other studies undertaken in the southern hemisphere. Beryllium-7 areal activity densities reported in Australia vary from 176 to 778 Bq m^{-2} for undisturbed soils (Doering et al., 2006) and from 90 to 990 Bq m^{-2} for clear-felled areas (Wallbrink and Murray, 1996). For clear-felled forest soils in the River Region of Chile, a value of $A_{ref} = 573$ Bq m^{-2} was reported by Schuller et al. (2006).

The mean ^{7}Be areal activity density obtained for the lower part of the sampled transects, based on the composite samples produced by slicing the six individual cores, was 275 ± 10 Bq m^{-2}. This value is significantly lower than the estimated A_{ref}, and indicates that this zone of the slope experienced net erosion, with the sediment being transported towards a filter strip covered by native shrub vegetation, which formed the lower border of the cultivated field.

The magnitude (kg m^{-2}) and pattern of soil redistribution associated with the period of heavy rainfall occurring in May 2005, estimated from the ^{7}Be measurements for the 32 points (64 samples) located on the three slope transects using Eqs. (6) and (7), are shown in Fig. 3. Summary statistics for the data presented in Fig. 3 are provided in Table 1. Estimates of the uncertainty associated with these estimates, due to the precision of the laboratory measurements and the sampling procedures are provided in Table 1. These results indicate that about 81% of the sampled area experienced erosion, whereas deposition occurred over 19% of the area. The mean erosion estimated for the eroding area was 1.7 kg m^{-2} (17 t ha^{-1}) and the mean sedimentation for the areas experiencing deposition was 0.9 kg m^{-2} (9 t ha^{-1}). Combining these data, the net erosion from the sampled area was estimated to be 1.2 kg m^{-2} (12 t ha^{-1}), indicating that a large proportion of the soil mobilised by erosion from the sampled area during the period of heavy rainfall was transported beyond that area.

The results presented above confirm the potential for using ^{7}Be measurements to document soil redistribution associated with individual periods of heavy rainfall and the ^{7}Be technique should be seen as representing a valuable complement to ^{137}Cs measurements for soil erosion investigations in south-central Chile. The magnitude of the values of short-term soil redistribution presented above can usefully be compared with the longer-term values of mean annual net erosion of 0.14 kg m^{-2} year^{-1} (1.4 t ha^{-1} year^{-1}) and 1.1 kg m^{-2} year^{-1} (11 t ha^{-1} year^{-1}) reported for the study field under the NTNB system and the original conventional tillage system, respectively, by Schuller et al. (2007). These data indicate that, whilst the value of net erosion recorded for the 27-day period of extreme rainfall in May 2005 was an order of magnitude greater than the mean annual rate of net erosion reported for the field for the period of 16 years when it was managed with a NTNB system, it is little different from the mean annual rate of net erosion reported for the previous 32 years when the field was managed under a conventional system. Further discussion of the relative importance of the period of high magnitude rainfall and the burning of the harvest residue in influencing erosion within the study field is provided below.

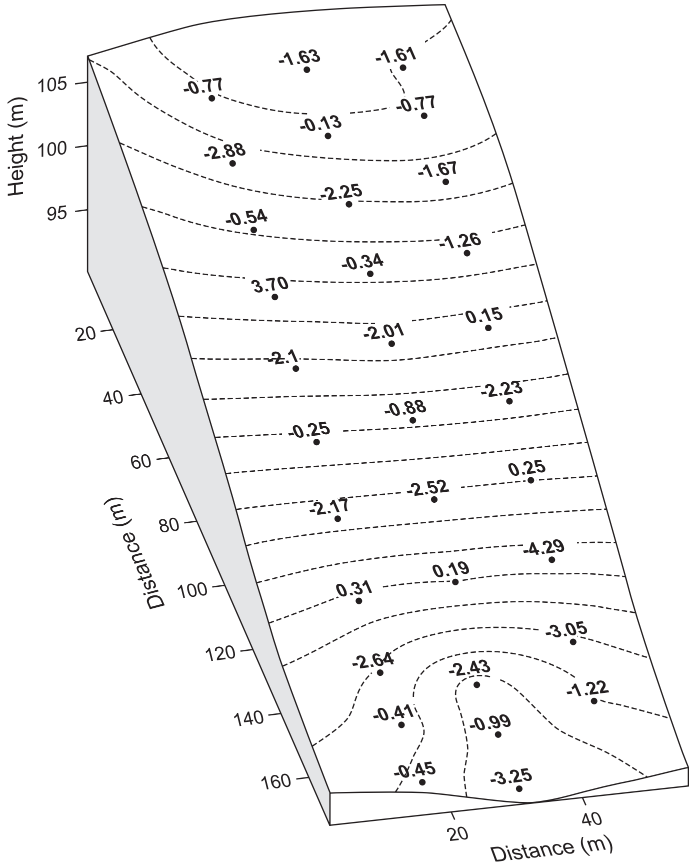

Fig. 3. The magnitude, kg m^{-2}, and spatial pattern of soil redistribution (erosion = negative values and deposition = positive values) in the study field associated with the period of heavy rainfall occurring in May 2005, estimated using the ^{7}Be measurements. The dashed lines represent contour lines with a 1-m height interval.

4.2. The impact of burning the crop residue

As indicated above, the net erosion documented for the period of heavy rainfall that occurred at the study site during May 2005 was almost an order of magnitude higher than the mean annual rate of net erosion associated with the preceding 16-year period, when the study field was managed under a NTNB system. The relatively high amount of net erosion associated with the period of heavy rainfall could be seen as reflecting both the extreme nature of the rainfall and the impact of the burning in modifying the NTNB system. It is not possible to ascribe a relative importance to these two controls, due to their close interaction and the availability of only a single measurement of event-based

Table 1
The soil redistribution documented for the study site for the period of heavy rainfall in May 2005 following burning of stubble, based on the ^{7}Be measurements

Zone	Amount
Eroding zone	
Mean erosion (kg m^{-2})	1.7 ± 0.2
Fraction of total area (%)	81
Aggrading zone	
Mean sedimentation (kg m^{-2})	0.9 ± 0.2
Fraction of total area (%)	19
Total area	
Net erosion (kg m^{-2})	1.2 ± 0.2

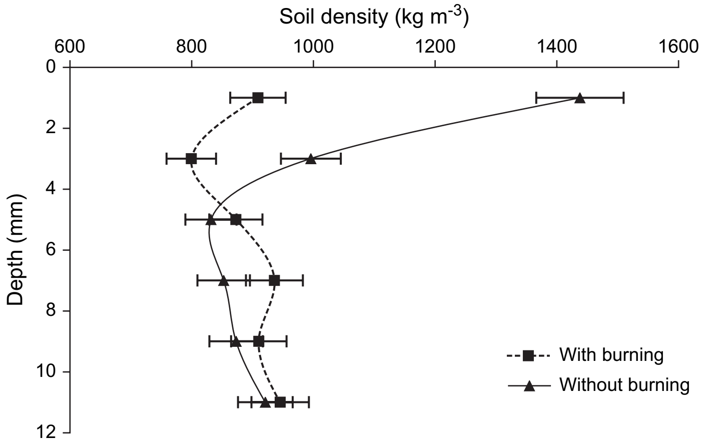

Fig. 4. The depth distribution of soil bulk density at the reference site measured prior to (■) and after (▲) the burning of the crop residue.

soil redistribution for a period of heavy rainfall. A more comprehensive measurement programme, based on an experimental (factorial) design and involving several periods of rainfall of different magnitude with the presence and absence of burning, would be necessary to isolate the effects of the two controls. Some tentative conclusions can, nevertheless, be drawn from the available information.

The literature contains many reports of studies that have demonstrated the adverse impact of burning crop residues in decreasing infiltration rates and increasing surface runoff and erosion (e.g. Steichen et al., 1987; Albrecht et al., 1995; Wuest et al., 2005), and the post-harvest burning in the study field prior to the period of heavy rain is likely to have had a similar effect. Fig. 4 depicts the change of the bulk density in the upper soil layer of the study field, caused by burning of the crop residues and provides clear evidence of the effects of the burning in increasing the bulk density of the upper 4 mm of the soil profile. The greatest effect is found near the surface and the bulk density of the upper 2 mm of the soil profile measured after burning the crop residue was found to be 1.6 times higher than the equivalent value for the period prior to burning. This change in bulk density reflects the partial destruction of the organic rich surface horizon, which can in turn be expected to increase the susceptibility of the soil to erosion by reducing infiltration and increasing surface runoff. The likely reduction in infiltration is further confirmed by the measurements of the saturated hydraulic conductivity of the soil (K_{sat}, cm h^{-1}) obtained prior to and after the burning of the crop residue. These showed a significant decrease as a result of the burning, reducing by almost 50%, from 7.85 to 4.24 cm h^{-1}. These values are consistent with the reports of increased saturated hydraulic conductivity associated with the adoption of NTNB management practices provided by other studies (e.g. Lipiec et al., 2006; Salako et al., 2006). In addition to the effects of burning the crop residue in increasing the bulk density of the surface soil and reducing the saturated hydraulic conductivity, it is likely that burning the crop residue destroyed the soil aggregates and the soil structure, increasing the occurrence of slaking and crust formation, which would further reduce infiltration (see Limon-Ortega et al., 2006).

The above evidence suggests that the burning of the crop residue immediately prior to the period of heavy rainfall had a significant effect in increasing surface runoff generation and associated soil redistribution. Because values of soil redistribution and net erosion are available for essentially the same area of the study field for the period of extreme rainfall and the preceding periods under NTNB and conventional tillage, it is useful to compare these data in more detail. However, when comparing the soil redistribution associated with the period of heavy rainfall with the medium-term mean annual soil redistribution rates for the NTNB and conventional tillage systems, it is important to consider in more detail the extent to which the period of heavy rainfall should be seen as an 'extreme event'. Both of these aspects are explored below.

4.3. The period of heavy rainfall as an 'extreme event'

In the absence of a long-term rainfall record for the study site, use has been made of the 52-year (1954–2005) record of monthly rainfall totals available for Temuco (38°45′S 72°38′W) some 45 km to the east of the study area.

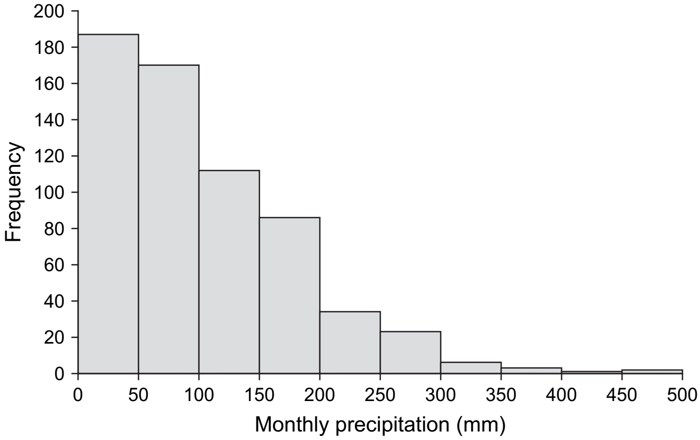

Fig. 5. A frequency distribution of monthly rainfall totals for Temuco, Chile, for the period 1954–2005.

Taking the period 1984–2005, for which records are available for both sites, the mean annual rainfall was 1150 mm for Temuco and 1100 mm for Buenos Aires farm, indicating that the two records are similar. However, the monthly rainfall total recorded at Temuco for May 2005 was 344.5 mm, a value that is somewhat lower than the 400.5 mm recorded for Buenos Aires farm during the same month. This situation emphasises the local variability of heavy rainfall, but it is, nevertheless, suggested that the longer-term record available for Temuco can be used to provide a meaningful assessment of the likely frequency of high magnitude monthly rainfall totals at the study site. Fig. 5 presents a frequency distribution of monthly rainfall totals based on the 52-year (624 month) record for Temuco, and this indicates that a monthly rainfall in excess of 350 mm was only recorded on six occasions and that a total in excess of 400 mm was only recorded on three occasions. This information emphasises the extreme nature of the 400.5 mm total recorded at the study site in May 2005, and, as indicated above, a monthly total of this magnitude has been estimated to have a recurrence interval of approximately 15 years. A monthly rainfall of 400 mm must therefore be seen as being of high magnitude, in terms of both absolute magnitude and its likely recurrence interval and clearly merits being described as an 'extreme event'.

4.4. Comparison of the soil redistribution caused by the period of heavy rainfall with the mean annual soil redistribution rates under NTNB and conventional tillage systems

Table 2 compares the soil redistribution documented at the study site for the period of heavy rainfall that occurred in May 2005 with the medium-term mean annual rates of soil redistribution for the study site under both NTNB (1986–2003) and conventional tillage (1954–1986), based on ^{137}Cs measurements, reported by Schuller et al. (2007). Because the downslope length of the sampled area was increased in the present study to incorporate an area of potential deposition, it is important that the comparison should be based on the same slope length (130 m) as used in the study reported by Schuller et al. (2007). The results obtained from the increased length of slope (170 m) sampled during the present study failed to show any deposition within the additional portion of the slope (Fig. 3) and the results for May 2005 presented in the first main column of Table 2 for both slope lengths are very similar, when the small differences are seen in the context of the uncertainty associated with the individual estimates. Further comparison of the soil redistribution associated with the three periods is therefore based on the 130 m slope length. Based on this comparison, several observations, related to the impact of both the burning of the crop residue and the heavy rainfall associated with the May 2005 event on soil redistribution rates within the study area, can be made.

(1) The net erosion associated with the period of heavy rainfall is of similar magnitude to the mean annual rate of net erosion from the study field during the period under conventional tillage. Because it reflects an extreme event, the net erosion associated with the period of heavy rainfall is likely to considerably exceed the longer-term

Table 2
A comparison of the soil redistribution documented for the study site for the period of heavy rainfall in May 2005, based on the ^{7}Be measurements, with estimates of the mean annual soil redistribution rate for the same area for the periods under NTNB (1986–2003) and conventional tillage (1954–1986) systems, derived using ^{137}Cs measurements

	No-till with burning For the 27-day period of heavy rainfall, estimated using ^{7}Be		*No-till, no burning* Mean annual values for a 16-year period estimated using ^{137}Cs, based on Schuller et al. (2007)	*Conventional tillage* Mean annual values for a 32-year period estimated using ^{137}Cs, based on Schuller et al. (2007)
Year	2005		1986–2003	1954–1986
Period	1 month		16 years	32 years
Precipitation	400 mm		1100 mm year^{-1}	1100 mm year^{-1}
Length of the slope (m)	170	130	130	130
Sampling points	32	27	34	34
Eroding zone				
Mean erosion	1.7 ± 0.2 kg m^{-2}	1.8 ± 0.2 kg m^{-2}	1.3 ± 0.2 kg m^{-2} year^{-1}	1.1 ± 0.2 kg m^{-2} year^{-1}
Fraction of total area (%)	81	78	57	100
Aggrading zone				
Mean sedimentation	0.9 ± 0.2 kg m^{-2}	0.9 ± 0.2 kg m^{-2}	1.4 ± 0.2 kg m^{-2} year^{-1}	0.0 kg m^{-2} year^{-1}
Fraction of total area (%)	19	22	43	0
Total area				
Net erosion	1.2 ± 0.2 kg m^{-2}	1.2 ± 0.2 kg m^{-2}	0.14 ± 0.2 kg m^{-2} year^{-1}	1.1 ± 0.2 kg m^{-2} year^{-1}

mean annual rate of net erosion associated with the NTWB system. It is therefore suggested that annual rates of soil erosion associated with the NTWB system are substantially less than under conventional tillage.

(2) The net erosion associated with the period of heavy rainfall is almost an order of magnitude greater than the mean annual rate of erosion from the study field during the period under NTNB system. Part of this increase reflects the extreme nature of the rainfall event and part the impact of burning the crop residues. However, if, following (1) above, it is assumed that the longer-term mean annual rate of soil loss under NTWB system is approximately 33% of that under conventional tillage (i.e., ca. 0.4 kg m^{-2} year^{-1}), it can be suggested that the net erosion associated with the extreme event is approximately three times greater than the mean annual rate of net soil loss under the NTWB system, whilst the latter is approximately three times greater than the mean annual net soil loss under NTNB. In this situation, it can be suggested that the extreme nature of the rainfall, rather than the burning of the crop residue, is the more important control on the high amount of erosion documented for the period of heavy rainfall. Under the above scenario, the mean annual net soil loss increases from 0.14 kg m^{-2} year^{-1} under NTNB to 0.40 kg m^{-2} year^{-1} under NTWB, but the period of extreme rainfall increases the annual soil erosion for the year including the study period to >1.2 kg m^{-2} year^{-1}. In absolute terms, the increase associated with the extreme rainfall is therefore about three times greater than that associated with the introduction of burning.

(3) There are important differences between the magnitude and nature of the soil redistribution reported for the three periods shown in Table 2. Under conventional tillage there was no net deposition of sediment within the sampled area. However, significant deposition occurred during both the period of NTNB and the period of heavy rainfall following the burning. In the case of the period under NTNB, the erosion rates documented for the eroding area were essentially the same as those estimated for the period of conventional tillage, but the occurrence of significant rates of deposition over nearly half (43%) of the sampled area resulted in a net erosion rate that is almost an order of magnitude less than that associated with the period under conventional tillage. The key impact of the introduction of the NTNB system was therefore to increase redeposition of the sediment mobilised from the eroding areas, rather than to reduce rates of erosion from those areas. In the case of the period of heavy rainfall in May 2005, which followed the burning of the harvest residue, the soil mobilisation, kg m^{-2}, within the eroding zone was greater than the mean annual rates reported for the periods under NTNB and conventional tillage, but, in contrast to the situation under conventional tillage, some deposition occurred over 22% of the sampled area and, as a result the net erosion was similar to the mean annual rate of net erosion reported for the period under conventional tillage.

5. Conclusions

The study reported clearly confirms the potential for using ^{7}Be measurements to document gross and net erosion on agricultural land in south-central Chile, associated with short periods of heavy rainfall. The information on event-related erosion generated by the ^{7}Be measurements provides a useful complement to that provided by ^{137}Cs measurements, which have been used previously by the authors to document the mean annual erosion rates associated with both conventional tillage and no-till systems. In combination, the two radionuclides provide a valuable means of investigating soil erosion and assessing erosion risk in the study area. Although the use of ^{7}Be measurements involves a number of important requirements and assumptions, related to both the preceding conditions and the occurrence of a discrete period of heavy rainfall that can be expected to cause significant erosion, the approach is likely to be applicable in many parts of the world, in addition to south-central Chile. The successful use of ^{7}Be measurements in a similar context has already been reported from the UK by Blake et al. (1999) and Walling et al. (1999), and from the USA by Wilson et al. (2003).

By documenting short-term erosion rates associated with individual periods of heavy rainfall, ^{7}Be measurements greatly extend the potential for using environmental radionuclides in soil erosion investigations. In the study reported here, for example, they have permitted a preliminary assessment of the impact of burning of the harvest residues within the no-till management system on erosion amounts and of the significance of extreme events in the longer-term erosion and sediment mobilisation from agricultural landscapes. A more rigorous experimental design, involving the monitoring of several events, would be necessary to provide definitive findings on these two facets of erosion risk in the study area, but the results obtained have permitted some preliminary conclusions regarding the importance of extreme events and the role of burning harvest residues in increasing erosion.

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