

# Use of $^7\text{Be}$ measurements to investigate the effectiveness of woody trash barriers in reducing sediment loss after forest clearcutting and their optimum spacing

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## 1. Abstract

Reliable information on the effectiveness of control measures in reducing soil erosion and sediment delivery to streams associated with forest clearcutting operations is needed to support the development of best management practices for soil and water conservation in forest areas. To address this need, attention focussed on an area exposed to highly erosive precipitation events immediately after final forest clearcutting and the installation of woody trash barriers to control soil erosion. Measurements of the cosmogenic radionuclide  $^7\text{Be}$  ( $T_{1/2} = 53$  d) in soil were successfully utilised to investigate the influence of barrier spacing on their effectiveness in reducing erosion and sediment transfer towards streams. The site selected for the study is located in south central Chile and is characterized by a mean annual rainfall of about 2300 mm and wet winters. Soil redistribution associated with a period of heavy rainfall was investigated on two plots 7.5 m wide and respectively 15 and 30 m long, oriented parallel to the predominant direction of surface runoff and bounded up- and downslope by trash barriers. The period of heavy rainfall (650 mm in 39 days) occurred between May and June 2006, and was preceded by a prolonged period with low rainfall. The results of the study indicate that a separation of 15 m between barriers is the most effective in reducing the net erosion and the sediment delivery ratio (0.09 kg m<sup>-2</sup> and ~20%, respectively), when compared to spacings of 30 m (0.3 kg m<sup>-2</sup> and ~80%, respectively). The results obtained using the  $^7\text{Be}$  technique were validated against direct measurements of soil loss or gain obtained using erosion pins.

## 2. Introduction

The export of forest products from Chile has increased by 69% during the last five years and now accounts for approximately 10% of total Chilean exports. As a result, the forestry economy in the country is characterised by intensification and expansion of plantations. This situation has increased awareness of soil erosion problems and encouraged the forest companies to promote soil conservation practices. To support the provision of improved guidelines for the design and use of woody trash barriers installed along contour lines to reduce soil erosion and sediment loss, a study has been started to assess the efficiency of such trash barriers and to establish their optimum spacing.

Soil redistribution and sediment transfer in areas bounded by the trash barriers have been quantified using the naturally occurring short-lived fallout radionuclide  $^7\text{Be}$  ( $t_{1/2} = 53.3$  d) and erosion pins. The potential for using  $^7\text{Be}$  to document short-term soil redistribution on recently harvested forest areas has been recently reported by Schuller et al. (2006).

## 3. Methods

### 3.1 The $^7\text{Be}$ method

By comparing information on the decrease or increase in the  $^7\text{Be}$  areal activity density relative to a reference value representative of a stable site experiencing neither erosion nor deposition, and using information on the characteristic depth distribution of the radionuclide within the surface soil, estimates of amounts of erosion and deposition can be obtained. This approach for using  $^7\text{Be}$  measurements to estimate erosion rates involves the following assumptions:

- That the deposition of  $^7\text{Be}$  fallout associated with the erosive event is spatially uniform.
- That any pre-existing  $^7\text{Be}$  present within the surface soil of the study area is also uniformly distributed across the area.
- That the  $^7\text{Be}$  deposited during the event is rapidly fixed by the soil at its point of receipt and can therefore only be mobilised by erosion of soil particles (Walling et al., 1999; Schuller et al., 2006).

The first condition can be expected to be fulfilled over a relatively small area, where the rainfall is uniform and where, after clearcutting, fallout inputs of  $^7\text{Be}$  will not be influenced by canopy interception and can therefore be assumed to be spatially uniform. In the second case, the cumulative fallout input to a relatively small area can again be assumed to be spatially uniform and the short half-life of  $^7\text{Be}$  means that any spatial

variability in the  $^7\text{Be}$  areal activity density introduced by soil redistribution associated with past erosive events will quickly disappear as a result of radioactive decay, provided that the erosive events are separated by a period of sufficient length. Considering the third condition, existing evidence suggests that in most environments  $^7\text{Be}$  fallout inputs will be rapidly and firmly fixed by the surface soil on receipt (Walbrink and Murray 1996; Blake et al., 1999). Because of its short half-life and short residence time in the soil,  $^7\text{Be}$  can be used to document short-term soil redistribution. Furthermore, its restricted penetration into the soil means that a substantial proportion of the areal activity density can be removed during a single runoff event and this increases the accuracy of the resulting erosion estimates (Wilson et al., 2003).

Based on the known rapid and strong fixation of  $^7\text{Be}$  fallout to surface soils (Wallbrink and Murray, 1996) and previously reported depth distributions of  $^7\text{Be}$  in soils (Blake et al., 1999; Walling et al., 1999; Schuller et al., 2006), it can be assumed that the initial vertical distribution of the areal activity density ( $A$ ,  $\text{Bq m}^{-2}$ ) of the  $^7\text{Be}$  within the soil will be characterized by an exponential decrease with mass depth ( $x$ ,  $\text{kg m}^{-2}$ ):

$$A(x) = A_{ref} \exp(-x/h_o),$$

with  $A_{ref}$  ( $\text{Bq m}^{-2}$ ) representing the initial total areal activity density at an uneroded stable site or *reference site* in the study area and  $h_o$  ( $\text{kg m}^{-2}$ ) the relaxation mass depth of the initial depth distribution of the  $^7\text{Be}$  areal activity density in the soil, i.e. the mass depth to which the areal activity density decreases to  $0.37 A_{ref}$ .

Based on measurements of the parameters  $A_{ref}$  and  $h_o$  at a reference site located close to the study area and on the areal activity density at the points to be studied, Blake et al. (1999) and Walling et al. (1999) proposed a model for converting measurements of the  $^7\text{Be}$  areal activity density into estimates of the soil redistribution. This approach was used for estimating the spatial distribution of erosion and deposition within the study plots.

### 3.2 The erosion pin method

The insertion of erosion pins in the soil leaving a defined initial length ( $L_o$ , m) exposed, permits determination of the amount of soil removed/deposited ( $R$ ,  $\text{kg m}^{-2}$ ) at that point by measuring the exposed length ( $L(t)$ , m) after a defined period ( $t$ ):

$$R = [L(t) - L_o] \delta,$$

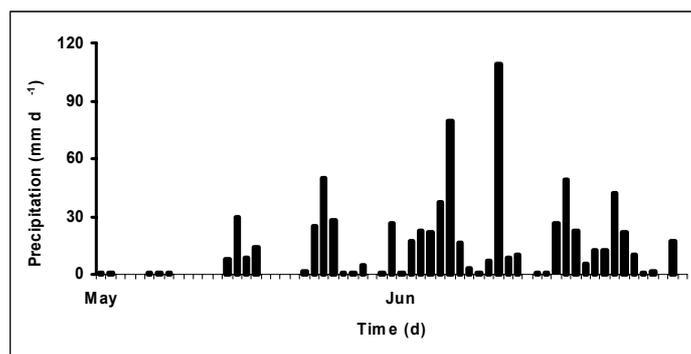
with  $\delta$ ,  $\text{kg m}^{-3}$ , being the density of the surface soil. If  $[L(t) - L_o]$  is found to be less than zero, erosion has taken place during the observation period and if  $[L(t) - L_o]$  is greater than zero, deposition will have occurred at the measuring point during the observation period.

### 3.3 Study site, sampling and laboratory procedures

The study site is located within the Forest Research Centre of the Universidad Austral de Chile ( $39^{\circ}44'25''\text{S}$ ,  $73^{\circ}09'58''\text{W}$ ), near the city of Valdivia, Chile. Soils in the area are Typic Paleudults (Ultisol) (CIREN, 2001), characterized by deep reddish brown clayey soils with a moderate to high infiltration capacity. The site has a mean slope of about 22%, a temperate climate with a mean annual rainfall of approximately 2300  $\text{mm y}^{-1}$  (Huber, 2004). Most rain falls between late autumn and early spring, when high rainfall intensities can occur. A digital rain gauge installed at the site provides a continuous record of precipitation with a resolution of 0.2 mm.

Clearcutting of the *Pinus radiata* plantation occurred during December 2005 (summer) and the soil remained covered by wood residues until the construction of trash barriers on early March 2006. To investigate the influence of the barrier spacing on the effectiveness of such barriers in reducing soil erosion and sediment transfer towards the drainage system, the trash was gathered into rows along contour lines, approximately 15 m and 30 m apart. The documented soil redistribution, was associated with the period of heavy rainfall occurring between May 14 and June 21, 2006 (650 mm in 39 d, Fig. 1), following a long period of low precipitation. The main storm events that occurred during this period were two consecutive events with intensities of 10.6 and 10.8  $\text{mm h}^{-1}$ , producing a total rainfall of 109 mm, that were recorded on June 11.

Soil redistribution associated with the period of heavy rainfall was investigated on two plots 7.5 m wide and respectively 15 and 30 m long, oriented parallel to the predominant direction of surface runoff and bounded up- and downslope by trash barriers. Shallow soil cores (4 cm deep) were collected from the plots at the intersections of a 1.7 m x 2.5 m grid in the case of the 15 m plot and a 3.3 m x 2.9 m grid for the 30 m long plot, using 10.6 cm diameter cylindrical plastic core tubes. At each grid intersection three soil cores were collected and these were subsequently bulked to be measured as a single sample. An adjacent flat area located within the harvested stand, that showed no evidence of erosion or deposition, was selected as a reference site and two sets of eight cores were collected using the same plastic core tubes, in order to determine the reference areal activity density,  $A_{ref}$ , and to characterize the relaxation mass depth of  $^7\text{Be}$  for the initial depth distribution,  $h_o$ . For the latter purposes, each set of 8 cores was sectioned into 2 mm slices in the laboratory and the slices representing specific depth increments were bulked for measurement as a single sample.



**Figure 1 Daily rainfall totals recorded during May and June 2006 using a rain gauge located at the study site**

#### 4. Results

For the vertical distribution of the mean  $^7\text{Be}$  areal activity density measured at the reference site on June 21, the reference areal activity was estimated as  $1120 \pm 60 \text{ Bq m}^{-2}$  and the relaxation mass depth as  $1.59 \pm 0.02 \text{ kg m}^{-2}$ , i.e.  $A(x) = 1120 \exp(x/1.59)$  ( $r=0.9993$ ).

A summary of the results obtained from the two study plots is provided in Table 1. Using the  $^7\text{Be}$  method on the 15 m plot, soil loss was documented at 15 out of the 20 sampled points (78% of the total area), and these points were characterized by a mean soil loss of  $0.47 \pm 0.1 \text{ kg m}^{-2}$ . Sediment deposition was documented at the remainder of the sampled points (22% of the total area), and the mean deposition for these points was  $1.3 \pm 0.2 \text{ kg m}^{-2}$ . Based on these values, the period of heavy rainfall resulted in a net soil loss from the plot of  $0.09 \pm 0.1 \text{ kg m}^{-2}$ . The overall sediment delivery ratio for the plot was estimated to be 24%. Using the erosion pins, a similar estimate of net erosion was obtained, with a sediment delivery ratio of 18%. In this case, 10 points were characterized by erosion, with a mean erosion of  $0.64 \pm 0.3 \text{ kg m}^{-2}$ , and the remaining points were characterized by deposition, with a mean deposition of  $0.59 \pm 0.3 \text{ kg m}^{-2}$ .

Based on the  $^7\text{Be}$  measurements obtained from the 30 m plot, soil loss occurred at 15 out of the 20 sampled points (72% of the total area), and these were characterized by a soil loss of  $0.41 \pm 0.1 \text{ kg m}^{-2}$ . Sediment deposition was documented at the remainder of the sampled points, and the mean deposition for these points was estimated to be  $0.16 \pm 0.1 \text{ kg m}^{-2}$ . For this plot the period of heavy rainfall resulted in a net soil loss of  $0.25 \pm 0.1 \text{ kg m}^{-2}$  and the associated sediment delivery ratio for the plot was estimated to be 84%. The erosion pins again provided a similar estimate of net soil loss, although the sediment delivery ratio was somewhat lower at 67%. In this case, 12 points showed evidence of erosion and were characterized by a mean soil loss of  $0.85 \pm 0.3 \text{ kg m}^{-2}$ , whilst seven points provided evidence of deposition and were characterized by a mean deposition of  $0.52 \pm 0.3 \text{ kg m}^{-2}$ .

**Table 1 Estimates of soil redistribution obtained using the  $^7\text{Be}$  and erosion pin methods for the 15 m and 30 m long plots bounded at their upper and lower limits by trash barriers (Period: May 14 to June 21, 2006; Rainfall: 650 mm)**

Method	$^7\text{Be}$	Erosion pin	$^7\text{Be}$	Erosion pin
Slope length bounded by barriers	15 m	15 m	30 m	30 m
Sampled area ( $\text{m}^2$ )	113	113	226	226
Number of sampled points	20	20	20	20
Mean erosion ( $\text{kg m}^{-2}$ )	$0.47 \pm 0.1$	$0.64 \pm 0.3$	$0.41 \pm 0.1$	$0.85 \pm 0.3$
Area affected by erosion (%)	78	53	72	61
Mean deposition ( $\text{kg m}^{-2}$ )	$1.3 \pm 0.2$	$0.59 \pm 0.3$	$0.16 \pm 0.1$	$0.52 \pm 0.3$
Area affected by deposition (%)	22	47	28	33
Net erosion ( $\text{kg m}^{-2}$ )	$0.09 \pm 0.1$	$0.06 \pm 0.3$	$0.25 \pm 0.1$	$0.35 \pm 0.3$
Sediment delivery ratio (%)	24	18	84	67

Although the estimates of net soil loss provided by the  $^7\text{Be}$  measurements and erosion pins are quite similar, particularly when the potential errors associated with both approaches are taken into account, the estimates of mean soil loss and mean deposition provided by the two approaches, whilst being of a similar order of magnitude, provide evidence of differences. In the case of the 15 m plot, the two approaches provide quite

similar estimates of soil loss from the eroding points, but the estimates of deposition provided by the  $^7\text{Be}$  measurements are higher than those provided by the erosion pins. For the 30 m plot, the situation is somewhat different, in that the estimates of both mean soil loss and mean deposition provided by the  $^7\text{Be}$  measurements are less than those provided by the pins. A greater number of measurements involving both erosion pins and the  $^7\text{Be}$  approach would be needed to explore more definitively the differences between the estimates provided by the two approaches. However, it is important to recognise that these differences could reflect both the spatial variability of soil redistribution within the plots and the different locations of the sampling points used for the two approaches, as well as more fundamental functional differences between the two methods. The latter include the fact that  $^7\text{Be}$  measurements provide an average value of soil loss or deposition for the  $265\text{ cm}^2$  represented by the three shallow cores collected from each sampling point, whereas the data provided by the erosion pins represent the average of three *point* measurements. Furthermore, disturbance of the soil during insertion of the erosion pins and their presence as small obstructions to surface runoff and sediment transport could mean that the results they provide are less representative of the 'natural' conditions.

The results presented in Table 1 provide clear evidence of the effect of extending the spacing of the trash barriers from 15 m to 30 m, in increasing erosion. The results obtained from the  $^7\text{Be}$  method indicate that the net erosion from the 15 m plot is  $0.09\text{ kg m}^{-2}$ , whereas the net erosion from the 30 m plot is  $0.25\text{ kg m}^{-2}$ . Although the values of mean erosion provided by the  $^7\text{Be}$  method are similar for both plots, the values for mean deposition are greatly reduced for the 30 m plot. This reduction in deposition on the 30 m plot and the associated increase in net erosion can be linked to the greater transport capacity of surface runoff on the longer plot. This may also account for the limited deposition observed at the base of the 30 m plot. The erosion pins provide similar evidence of increased net erosion from the 30 m plot. In this case the increased net erosion primarily reflects an increase in the mean erosion and a decrease in the area of deposition. Both can again be linked to greater erosion and sediment transport associated with a longer slope. The results obtained from this investigation show that, although the construction of linear trash barriers may be effective in reducing sediment delivery to watercourses, the soil erosion occurring within the intervening areas during periods of heavy rainfall could still represent a significant cause of soil degradation. A greater degree of replication is required to provide definitive findings, but the results obtained from this study suggest that a trash barrier spacing of 15 m is considerably more effective than a spacing of 30 m in reducing net soil loss and sediment delivery to watercourses. However, the design of such barriers should consider not only the spacing of consecutive barriers, but also their height and permeability.

This investigation has confirmed the potential for using  $^7\text{Be}$  measurements to investigate the efficacy of trash barriers in reducing net soil loss and sediment delivery from areas of forest harvesting. However, more extensive investigations are required to confirm the results obtained, to explore different barrier spacings and different methods of barrier construction, as well as to include a wider range of slope and soil conditions.

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