Use of ^{137}Cs to estimate rates and patterns of soil redistribution on agricultural land in Central-South Chile: models and validation

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Introduction

Soil conservation and sustainability is of maximum relevance to guarantee the increasing demand for food and raw materials in the world. Therefore, soil degradation and deterioration occurring during the past need to be evaluated. For this purpose, reliable techniques for quantifying soil erosion and sedimentation have to be improved. Developments made during the last decades in the use of the anthropogenic radionuclide ^{137}Cs as a tracer for determining rates and patterns of soil redistribution were considered by many authors as an important advance that overcomes many limitations of the conventional monitoring techniques (Loughran, 1989; Ritchie and McHenry, 1990; Quine, 1997; Walling, 1998).

The purpose of this research was to evaluate the applicability of the conventional ^{137}Cs technique and a simplified and faster method for estimating spatial distribution of medium-term soil erosion and sedimentation rates on agricultural land in Central-South Chile. The potential for using ^{137}Cs as a tracer in soil redistribution investigations had not been explored in Chilean soils.

Material and methods

Four study sites were selected in the Coastal Mountain Range in Central-South Chile (38°40'S, 72°30'W), where sustainable development of agricultural production need to be assessed due to erosion problems affecting this area. The mean annual rainfall at the study area is 1160 mm.y^{-1} and the typical soil type a Palehumult, Metrenco Series (IREN, 1970) containing about 65% clay and 7% organic matter (Ellies and Contreras, 1997). The study fields were under contrasting land use and management: crop land and semi-permanent grassland, both under subsistence and commercial management. The main characteristics of the sites are summarised in Table 1.

Site code	A	B	C	D
Use	Crop land	Crop land	Grassland	Grassland
Management	Subsistence	Commercial	Subsistence	Commercial
Surface (m2)	22000	4000	5000	2000
Slope (%) U; M; L*	6; 19; 7	13; 16; 3	9; 13; 7	36; 48; 17
Plough depth (m)	0.12±0.3	0.17±0.5	0.12±0.3	0.15±0.4
Density (kg m-3)	1250	1000	1180	1060
Sampling grid (mxm)	16 x 20	7 x 10	10 x 10	6 x 6

* Determined at the upper (U), middle (M), and low (L) sector of the site.

Table 1
Characteristics of the study sites.

To estimate the ^{137}Cs reference inventory, four appropriate sites that had been under herbaceous cover for at least four decades were chosen. For measuring the ^{137}Cs inventories, soil cores of 0.072 m in diameter were collected with an auger down to at least the penetration depth between June and August 1998. At the reference site samples were taken on a 6 m by 6 m grid. The grid spacing at the study sites are shown in Table 1.

To save time on the gamma analysis, the feasibility of measuring ^{137}Cs inventories of composite soil samples for estimating soil redistribution was also tested at all four sites. For this purpose, in October and November 1999 soil samples were collected at the same grid spacing as previously, but all cores from transects along the same contour line were bulked proportionally. The viability of this approach relies on the similar topography in parallel downslope transects, and on the almost uniform soil properties of each analysed site. Additionally, it is based on the assumption that soil redistribution occurred approximately to the same extend in parallel downslope transects of the field.

Soil redistribution rates were quantified using the refined mass balance model for cultivated soils incorporating soil movement by tillage described by Walling and He (1999), adapted to the site specific conditions of the studied fields. The time-course of the ^{137}Cs deposit within the study area was estimated on the basis of the annual deposit of ^{90}Sr and ^{137}Cs reported at the nearest site, located at 41°26′S, 73°07′W (Health and Safety Laboratory, 1977; Juzdan, 1988; Larsen, 1985; Larsen and Juzdan, 1986; Monetti and Larsen, 1991; UNSCEAR, 1982), and considering the activity ratio ^{137}Cs/^{90}Sr in deposition constant at 1.6 (UNSCEAR, 1982).

In order to examine the validity of the results obtained by the ^{137}Cs method, experimental erosion plots of 10 m^2 were installed in the upper part of the fields A and C for obtaining reference values of the annual sediment flux at the corresponding area. In addition, the results obtained by the ^{137}Cs method were compared with redistribution rates obtained by pedological observations, comparing the depths of the horizon of the area affected by soil redistribution with that of a reference area with scarce intervention.

Results and discussion

The measured reference inventory was 525±12 Bq.m^{-2} (σ= 94 Bq.m^{-2}, n=61, reference date: January 1998). The plough depth determined at the studied fields (Table 1) varied according to the tillage technique employed, ranging from 0.12±0.03 m depth at sites ploughed by animal traction to 0.17±0.05 m in sites ploughed by mechanical traction. The ^{137}Cs penetration depth ranged according to the position along the slope transects, from 0.12 m at eroded points to 0.34 m at points of sediment accumulation. Other values for the parameters required were taken from the literature (Walling and He, 1999) or estimated by using information on local soil properties and annual distribution and intensity of the rainfall.

Figure 1 represents the soil erosion (negative values) and deposition rates (positive values) estimated at the four analysed areas as a function of the field topography using the conventional grid framework sampling and evaluation of ^{137}Cs inventory at each point. The graphics were obtained using Surfer 7, and kriging geostatistics.

The results shown in Figure 1 allow a comparison of the modelled estimates of the net soil redistribution rates and their spatial distribution at the four studied sites.

At the crop land site under subsistence management (A) high erosion rates were observed at the upper border, due to repeated ploughing normal to the downslope gradient and due to the obstruction of sediment flux from the adjacent area into this field by a dense shrub fence. The other sector of high erosion rates is located in the area of maximum slope, which also promotes higher amounts of soil erosion. The sedimentation area is positioned at the sector of minimal slope located at hillfoot in water run-on sites. Intensive annual cultivation processes and frequent transit of animal plough systems could influence the high erosion rates obtained in this field (Schuller *et al.*, 1999).

Similar spatial distribution of soil erosion rates was observed on the crop land under commercial management (B): The highest erosion rates were estimated at the top of the field and at the sector of maximum slope. The highest sedimentation rates were obtained at a

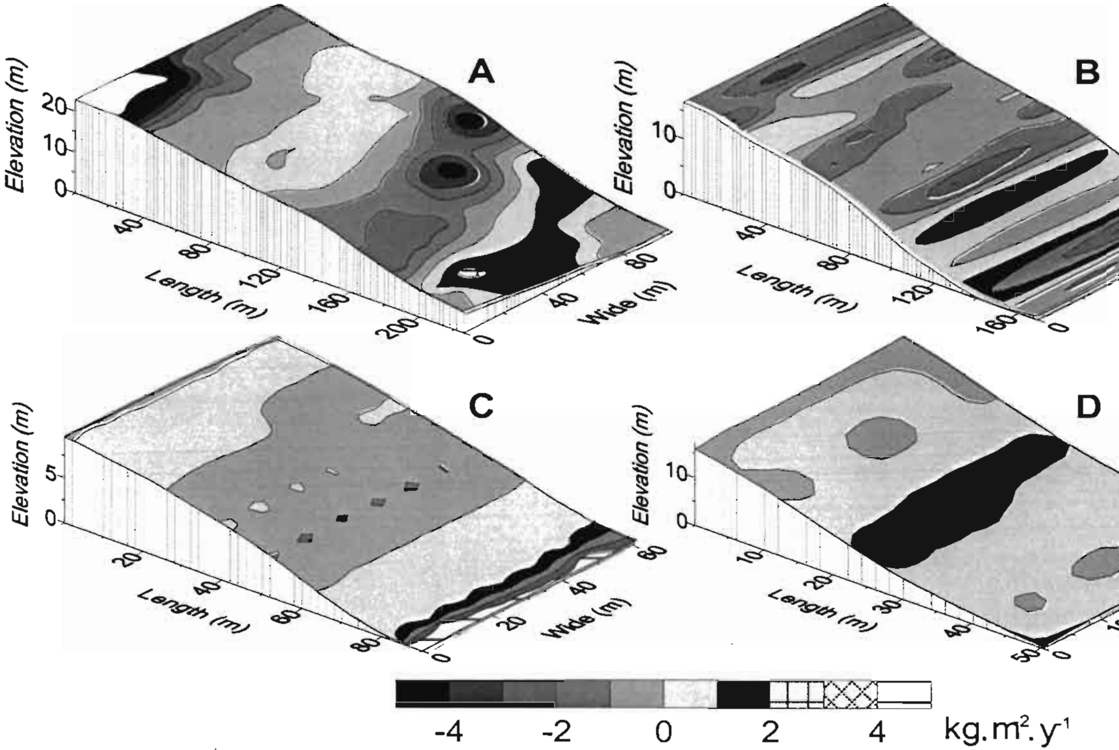

Figure 1

Soil redistribution rates estimated by ^{137}Cs inventory evaluation at grid points: crop land under subsistence (A) and commercial management (B), grassland under subsistance (C) and commercial management (D).

depression at the hillfoot. The erosion rates quantified in field B are lower than in field A. The soil loss estimated in field A is influenced by the site isolation from upper and lateral surrounding fields, which hinder sediment input into the study area. The field B is not isolated from surrounding crop fields, and therefore part of the soil loss could be compensated by sediment input moving from adjacent areas.

A form of expressing tolerable erosion is that the soil loss should not exceed their natural production (Hudson, 1971). Due to the difficulty in measuring this last parameter it is considered that the soil use is sustainable, when the annual loss does not exceed a thousandth of their total mass (Peralta, 1976). The values of the erosion rates measured in the crop land sites are mostly below this tolerable limit estimated at about 1 $kg.m^{-2}.yr^{1}$, but in sectors with large slope it exceeds this value by far.

At the semi-permanent grassland site under subsistence management (C) the areas showing the highest erosion rates are located in the middle sector of the field, where the slope is steepest. At this field, high sedimentation rates caused by sediment flow into an adjacent stream and by sediment accumulation during the swelling periods of the stream were observed at the hillfoot.

At the non-permanent grassland site under commercial management (D) the predominant process caused by soil movement was sedimentation. This area could be affected by deposition of sediments moving from an upper flat adjacent cultivated area, which was ploughed perpendicular to the hillslope of the grassland throughout several decades. The highest sedimentation areas were located in water flow concentration sites: at footslope and at the midslope where the inclination is maximal. The midslope sector is positioned at a concavity of lateral hillslopes, and could be therefore affected by sediment coming from lateral pronounced slopes. Both grassland sites are not isolated from the surrounding fields, and are probably affected by soil movement from and towards the adjacent areas.

As shown in Figure 1, the ^{137}Cs method allows to discriminate between the long-term soil redistribution processes according to the use (crop or grassland) and management (commercial or subsistence) of the soil.

The soil erosion rates estimated by the ^{137}Cs method were first compared with sediment flux measured at erosion plots during three years. The mean annual sediment loss determined with an experimental plot located at the upper sector of site A was 0.28 ± 0.08 $kg.m^{-2}.yr^{-1}$. The calculated erosion rate at the sampling points adjacent to the plot area varied from 0.09 to 0.6 $kg.m^{-2}.yr^{-1}$ (mean value 0.25 $kg.m^{-2}.yr^{-1}$). The sediment flux determined with the experimental plot simulating the management conditions of grassland C was 0.10 ± 0.03 $kg.m^{-2}.yr^{-1}$ and the calculated erosion rates at sampling points of similar slope in that grassland fluctuated between 0.04 and 0.19 $kg.m^{-2}.yr^{-1}$ (mean value 0.11 $kg.m^{-2}.yr^{-1}$). The annual sediment loss measured with erosion plots is in good agreement with the estimated erosion rates at adjacent positions in the fields. Nevertheless, the measured flux represents net soil export from the plots, because of their isolation from the soil redistribution processes operating in the surrounding area. Moreover, sediment flux is time dependent and therefore valid for the period for which it is calculated.

The soil redistribution rates quantified by the ^{137}Cs technique represent a time-integrated, medium-term, average for the last 40-45 years, and are therefore less influenced by extreme events. Additional redistribution rates obtained by pedological observations, which also consider the accumulative effect of past soil redistribution processes, are represented in Figure 2. The rates estimated by the pedological observations reflect a similar pattern of spatial distribution, in relation to the soil redistribution rates quantified by the ^{137}Cs method. Nevertheless, the values of erosion and sedimentation rates obtained by this method are expressed on relative scales, because of the difficulty in determining the period of cultivation of each field and the depth of the reference horizons. Therefore, additional medium-term estimations of erosion and sedimentation rates are required for validating the values estimated by the ^{137}Cs method. In the future, it is also necessary to study the applicability of the method under other climatic conditions and soil types occurring in Chile in which erosion is not so evident, in order to prevent it.

The erosion and sedimentation rates caused by tillage, water and the net rates obtained along the slope transect at each study site using the simplified ^{137}Cs inventory evaluation are represented in Figure 3.

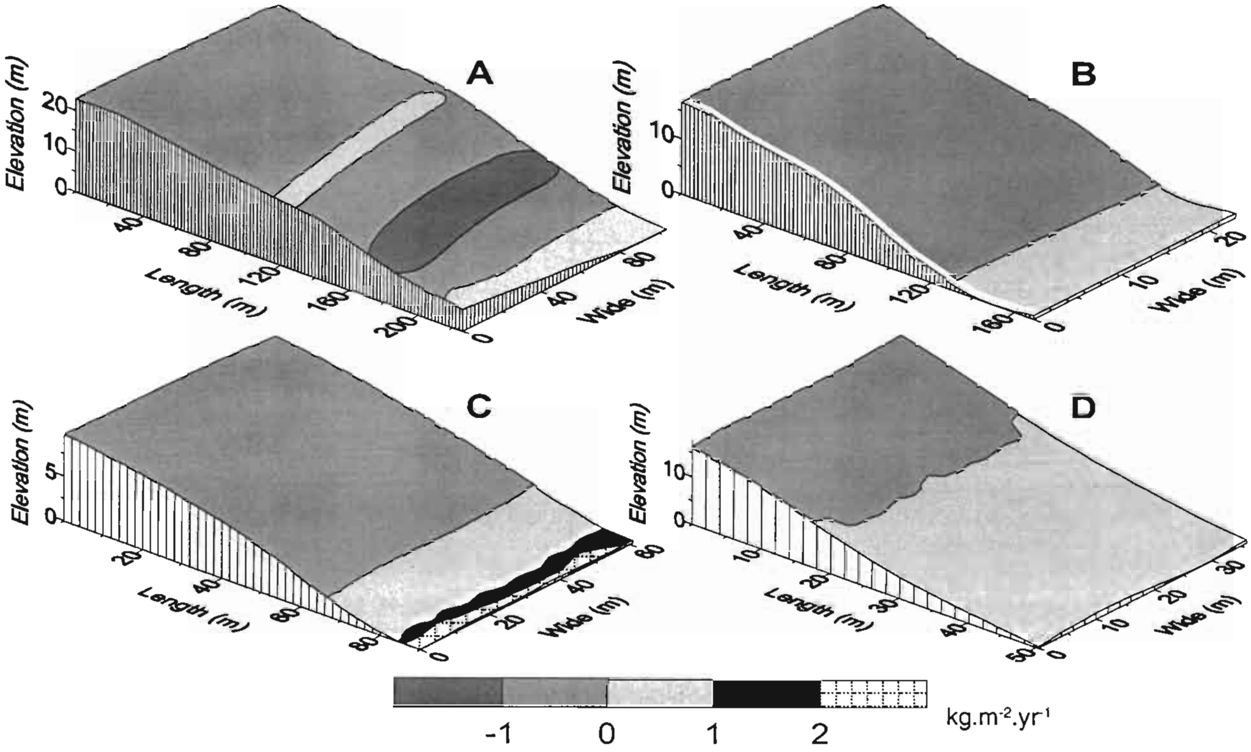

Figure 2

Soil redistribution rates estimated by pedological observations: crop land under subsistence (A) and commercial management (B), grassland under subsistance (C) and commercial management (D).

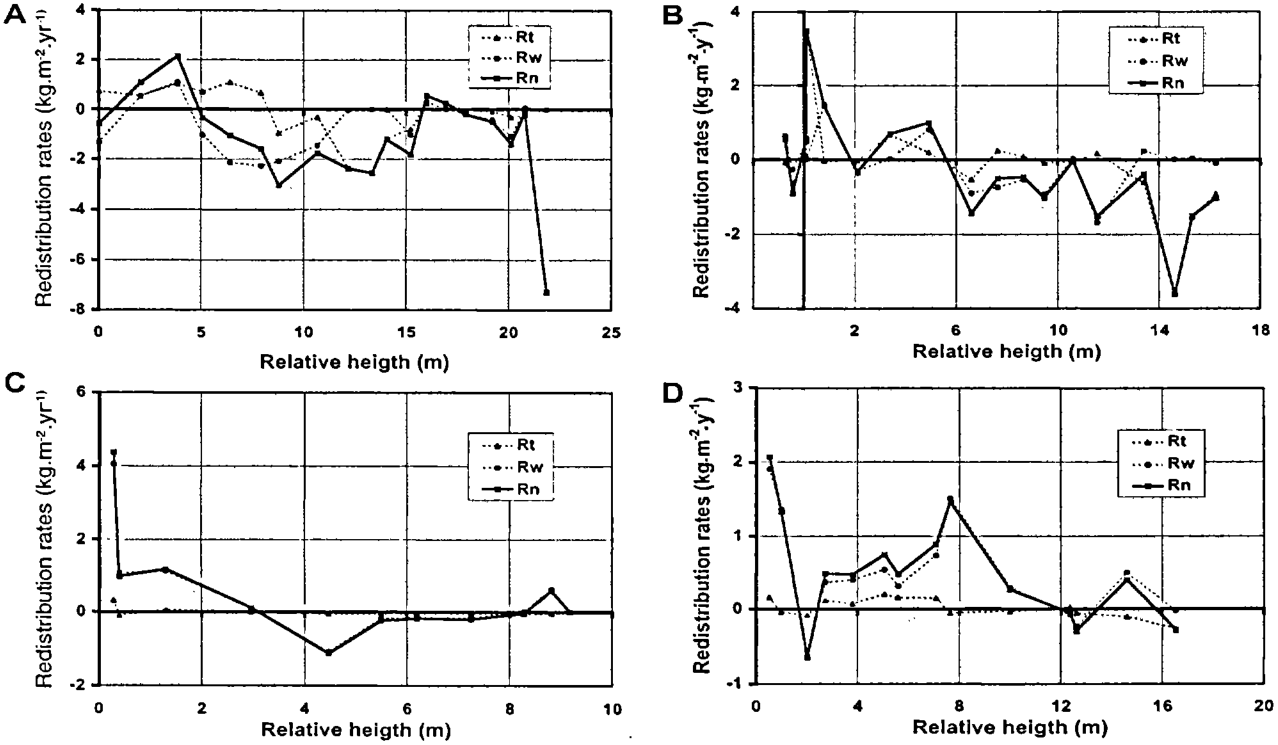

Figure 3
Soil redistribution rates caused by tillage (Rt), by water (Rw), and net rates (Rn) along the slope transect estimated by ^{137}Cs inventory evaluation at contour lines: crop land under subsistence (A) and commercial management (B), grassland under subsistence (C) and commercial management (D).

Comparing the mean redistribution rates estimated at similar altitude along the slope transects obtained by a ^{137}Cs inventory evaluation of individual samples collected in a grid pattern with the ones obtained by an inventory evaluation in composed samples taken at contour lines, the correlations between the redistribution rates caused by tillage, by water and net rates are strongly significant at the 0.01 level in each site, with exception of redistribution caused by water (significant at level 0.05) in site A. The simplified method is suitable for giving assessment on soil loss and sediment accumulation in areas exhibiting simple topography, showing almost similar slopes at constant-altitude transects. It reduces considerably the measuring time to estimate the soil redistribution.

The simplified method allows a fast estimation of soil redistribution rates, providing the possibility to estimate soil redistribution in larger areas in a shorter time. Nevertheless, the sampling and ^{137}Cs inventory quantification strategy must be selected according to the resolution of the required information, and extension and complexity of the landscape relief.

Aknowledgements
This study was supported by the Fondo Nacional de Investigación Científica
y Tecnológica, Chile (FONDECYT 1970662),
the International Atomic Energy Agency (IAEA CHI-8899),
and the Dirección de Investigación y Desarrollo,
Universidad Austral de Chile. The authors wish
to thank these institutions for their financial support.

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