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USO DE RADIONUCLEIDOS AMBIENTALES PARA CUANTIFICAR EL CAMBIO EN LA REDISTRIBUCIÓN DE SUELO DEBIDO A SISTEMAS DE LABRANZA CONTRASTANTES EN UN SUELO AGRÍCOLA

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RESUMEN

La intensificación de la producción agrícola en la zona centro-sur de Chile a partir de la década del 70 ha contribuido a incrementar la erosión del suelo y consecuentemente la degradación de este recurso. Para contribuir a revertir esta situación, se ha estimulado el cambio de sistemas de labranza tradicional a sistemas de cero labranza. En este escenario, surge la necesidad de cuantificar el impacto que ha tenido el cambio en el sistema de labranza sobre la tasa de pérdida de suelo, para lo cual se explora el uso del radionucleido ^{137}Cs.

En el marco de la presente tesis, se desarrollaron dos nuevos modelos matemáticos (estándar y simplificado) que basados en la distribución espacial y en profundidad del ^{137}Cs en el suelo, permiten estimar retrospectivamente el cambio en las tasas medias de redistribución de suelo asociadas al cambio en el sistema de labranza en un suelo agrícola. Los modelos propuestos fueron aplicados exitosamente en un sitio sometido a cambio en el sistema de labranza desde tradicional a cero labranza sin quema de residuos. El estudio se emplazó en un predio agrícola ubicado en la Cordillera de la Costa, Región de la Araucanía (38°37'S 73°04'O), el cual se caracteriza por presentar clima templado, una precipitación media de 1100 m a^{-1} y un suelo serie Araucano, orden Ultisol (Typic Hapludult).

El método simplificado tiene la importante ventaja de requerir (aparte de los parámetros de modelos tradicionales) sólo dos mediciones de ^{137}Cs por punto analizado: el inventario total de ^{137}Cs presente en el perfil de suelo y la concentración de ^{137}Cs en la capa de suelo homogenizada por aradura. En base a los resultados obtenidos, se estimó que a partir de la implementación del sistema de cero labranza incluyendo el manejo de residuos de cosecha, se redujo la tasa neta anual de erosión de suelo en un 87% respecto al periodo de labranza

tradicional (desde 1.1±0.2 kg m^{-2} a^{-1} a 0.14±0.2 kg m^{-2} a^{-1} respectivamente) y la fracción del área de estudio sujeta a erosión, desde 100% a 57%, lo que conlleva una significativa disminución de la pérdida de suelo y nutrientes desde el área estudiada. Estos resultados señalan los importantes beneficios del sistema cero labranza en términos de permitir un manejo sustentable del recuso suelo manteniendo su productividad y una disminución de los impactos asociados a la degradación de cursos de agua adyacentes.

Durante muchos años el sitio de estudio fue cultivado bajo cero labranza sin quema de residuos. Sin embargo, a comienzos del 2005, después de la cosecha y previo al inicio de las lluvias de otoño se sometieron a quema los residuos del cultivo, dejando el suelo desnudo sin cobertura vegetal hasta el inicio de un periodo de precipitaciones intensas (400 mm en 27 d) ocurrido en Mayo de 2005. Para estimar los montos y distribución espacial de la erosión y sedimentación asociados al periodo de precipitación intensa se utilizaron mediciones de ^{7}Be asociadas a un modelo de conversión de los inventarios de ^{7}Be en montos de redistribución de suelo. La erosión neta y fracción de pérdida de sedimentos desde el sitio de estudio (1.2±0.2 kg m^{-2} y 88% respectivamente) asociadas al periodo de precipitación intensa fueron considerablemente mayores que las estimadas para el mismo sitio durante el periodo previo de cero labranza sin quema (16 años) utilizando la técnica del ^{137}Cs (0.14±0.2 kg m^{-2} a^{-1} y 19% respectivamente). Los resultados obtenidos sugieren que la quema de residuos en el periodo estival incrementa la erosión del suelo durante la siguiente estación lluviosa, especialmente si ocurren eventos erosivos intensos. Por lo tanto, la quema de residuos de cosecha puede constituir una práctica no recomendable en el contexto de un sistema de cero labranza. El método del ^{7}Be provee una herramienta efectiva para documentar la erosión del suelo asociada con periodos individuales de precipitación intensa, contribuyendo al seguimiento y monitoreo del efecto de eventos erosivos puntuales sobre la redistribución de suelos desprovistos de cubierta vegetal.

La utilización de técnicas isotópicas, particularmente ^{137}Cs y ^{7}Be, para la cuantificación de la erosión y sedimentación del suelo, permiten estimar retrospectivamente la redistribución del suelo (a mediano plazo utilizando ^{137}Cs (años o décadas) y a corto plazo utilizando ^{7}Be (días o meses)) sobre la base de sólo un evento de recolección de muestras en el sitio de estudio, obviando la necesidad de mantener anualmente ensayos experimentales en el sitio y evitando alterar el desarrollo normal de las labores agrícolas sobre el mismo.

SUMMARY

Intensification of agricultural production in south-central Chile since the 1970s has caused problems of increased soil erosion and associated soil degradation. These problems have prompted a shift from conventional tillage to no-till system. Faced with the need to establish the impact of this shift in soil management on rates of soil loss, the use of caesium-137 (^{137}Cs) measurements has been explored. Two novel procedures for (a standard and a simplified method) using measurements of ^{137}Cs depth distribution to estimate rates of soil redistribution at sampling points under original conventional tillage and after the shift to no-till system have been developed. The methods have been successfully applied in a field where conventional tillage was shifted to no-till system in May 1986. The site is located in the Coastal Mountains of the Araucanía Region (38º37´S 73º04´W), and is characterized by Araucano series Ultisols (Typic Hapludult), a temperate climate and a mean annual precipitation of 1100 mm year^{-1}. The simplified method has the important advantage of requiring only two measurements per sampling point: the total ^{137}Cs areal activity density and the ^{137}Cs mass activity density in the upper part of the soil. The results obtained showed that the implementation of no-till practices, including crop residue management, coincided with a reduction in the net erosion rate by about 87% (from 1.1 ± 0.2 kg m^{-2} year^{-1} to 0.14 ± 0.2 kg m^{-2} year^{-1}) and the proportion of the study area subject to erosion from 100% to 57%, and therefore significantly decreased soil and nutrient loss. Reduced soil and nutrient loss has important on-site benefits, in terms of sustainable management of the soil resource and maintaining crop productivity, as well as reducing off-site problems associated with the degradation of river water quality.

For many years the study site was cultivated under a no-till without burning of crop residue system. However, after harvesting in early 2005 and before the wet season began, the crop residue remaining on the field was burnt, leaving the soil bare until the onset of heavy rainfall in the autumn. Following a prolonged dry period, a period of very heavy rainfall (400 mm in 27 d) occurred during May 2005. Beryllium-7 (^{7}Be) measurements, coupled with a conversion model which permitted estimates of amounts of soil redistribution to be obtained from the values of ^{7}Be areal activity density, were used to document the amounts and pattern of soil redistribution within the field associated with the period of heavy rainfall under no-till with burning of crop residue system. The net soil loss from the field associated with the period of heavy rainfall was considerably higher than the mean annual rate of soil loss from the field during the previous 16-y period of no-till, no-burn system estimated using ^{137}Cs measurements. The net erosion amount for the period of heavy rainfall was 1.2 ± 0.2 kg m^{-2}. This value is 8.6 times higher than the mean annual erosion estimated for the previous no-till system. The results obtained suggest that the burning of the crop residue in the summer increases soil loss during the following rainy season, especially if high magnitude erosive events occur. Burning of the crop residue may therefore be an undesirable component of the no-till system. The ^{7}Be method provides an effective means of documenting erosion associated with individual periods of heavy rainfall and investigating the influence of different tillage systems on soil redistribution amounts.

The use of isotopic techniques, particularly ^{137}Cs and ^{7}Be, for estimating soil erosion and sedimentation allow the evaluation of retrospective soil redistribution processes and their spatial distribution under contrasting agricultural systems based on a single visit to the study site, avoiding the need of periodical time consuming and expensive sampling procedures and the disturbation of the normal tillage practices.

1. INTRODUCCIÓN GENERAL

1.1. PROBLEMÁTICA

El reconocimiento explícito del sistema suelo como parte importante del ecosistema y responsable directo de la calidad y sustentabilidad de éste, ha estimulado una creciente preocupación por la protección de los suelos a nivel mundial. En este sentido, es relevante que estrategias para la protección de los suelos consideren la erosión como causa principal de la degradación de este recurso (Herrick et al., 1999; FAO, 2002b).

Estimaciones señalan que la erosión del suelo a nivel mundial alcanza aproximadamente 9.6 t ha^{-1} a^{-1}, de las cuales 3.4 t ha^{-1} a^{-1} son atribuidas a erosión hídrica y 6.2 t ha^{-1} a^{-1} a erosión eólica (Stallard, 1998). Según lo señalara Ellies (2000), en Chile la erosión afecta al 25% de la superficie total del país y alrededor del 60% de la superficie cultivable total, estimándose en ésta última una pérdida neta por erosión cercana a las 15000 ha a^{-1}.

A partir de la cuantificación de la magnitud de la pérdida de suelo se ha identificado a la agricultura como uno de los sectores productivos que más ha contribuido a la degradación de los recursos naturales. Por esta razón, se emprende el desarrollo de una agricultura sustentable basada en prácticas de manejo conservacionistas, que desde la perspectiva del control de la pérdida de suelo se conoce como agricultura de cero y mínima labranza.

Si bien, el impacto de la cero labranza sobre la tasa de erosión del suelo ha sido abordado ampliamente en suelos sujetos a esta práctica de manejo, existe la necesidad de cuantificar los cambios en las tasas medias de redistribución de suelo (erosión/sedimentación) producto de cambios en los sistemas de labranza ocurridos en un mismo sitio (bajo igual condición edafoclimática, topográfica, etc.).

El uso de radioisótopos como trazadores de la redistribución del suelo representa una opción interesante en la adopción de metodologías alternativas para cuantificar cambios en las tasas de redistribución de suelo asociadas a cambios en los sistemas de labranza, como también en la estimación de montos de redistribución de suelo producto de eventos erosivos recientes. El uso de ^{137}Cs y ^{7}Be permite proveer resultados retrospectivos en un mediano y corto periodo de tiempo respectivamente y su aplicación en un amplio rango de zonas edafoclimáticas (Walling et al., 1999; Walling y Collins, 2000; Wallbrink et al., 2003; Zapata, 2003).

1.2. HIPÓTESIS

1. El uso de ^{137}Cs como trazador permite cuantificar el cambio en las tasas medias de redistribución de suelo debido al cambio en el sistema de labranza ocurrido en un mismo sitio.

2. El impacto de un periodo de lluvia intensa sobre los montos de redistribución de suelo y su distribución espacial en un sitio sometido a cero labranza puede ser cuantificado en base a la distribución espacial del radionucleido ^{7}Be en el suelo.

1.3. OBJETIVOS

1.3.1. Objetivo general

Estimar el impacto del cambio en el sistema de labranza en un suelo agrícola sobre las tasas de redistribución de suelo.

1.3.2. Objetivos específicos

- Diseñar un modelo matemático, que basado en la distribución del ^{137}Cs en el suelo, permita estimar la distribución espacial de tasas medias de redistribución de suelo durante periodos de labranza contrastantes: inicialmente tradicional y posteriormente cero labranza.

- Estimar retrospectivamente el cambio en las tasas de redistribución de suelo producto del cambio en el sistema de labranza, utilizando para ello la distribución espacial y en profundidad del ^{137}Cs en el suelo.

- Determinar el valor del parámetro profundidad másica de relajación de ^{137}Cs en el corto plazo (h_0, kg m^{-2}) para suelo serie Araucano, orden Ultisol (Typic Hapludult) presente en el sitio de estudio.

- Aplicar la técnica de ^{7}Be para estimar montos y distribución espacial de la redistribución de suelo asociada a un periodo de precipitación intensa en un sitio sometido a cero labranza con quema de residuos. Analizar estos resultados en el contexto de los obtenidos utilizando ^{137}Cs.

1.4. ANTECEDENTES GENERALES

1.4.1. Radionucleidos ambientales como trazadores de suelo: concepto e historia

Se entiende por radionucleido a un elemento cuyo núcleo atómico puede desintegrarse y con ello emitir ondas electromagnéticas (radiación gama) y/o partículas (radiación alfa, beta o neutrones).

La primera aproximación realizada para analizar la relación entre redistribución de radionucleidos en el suelo y procesos de erosión fue llevada a cabo por Menzel en 1960, al estudiar la pérdida de ^{90}Sr desde parcelas de erosión. En los años 1965 y 1970, Rogowski y Tamura investigan el "comportamiento erosional" del ^{137}Cs al adicionarlo como trazador al suelo. Durante la década del 70, Ritchie y McHenry confirman el potencial del uso de ^{137}Cs en estudios de erosión y sedimentación del suelo al establecer una relación exponencial entre la pérdida de suelo y la de ^{137}Cs (Zapata et al., 2002).

A partir de estas primeras investigaciones, se amplía el uso de radionucleidos ambientales al reconocerlos como herramientas útiles tanto en la cuantificación de tasas de erosión del suelo como en modelos de sedimentación en cursos de agua. Algunos de ellos son: ^{137}Cs, ^{210}Pb, ^{7}Be, $^{239-240}$Pu, ^{14}C, ^{32}Si, ^{26}Al y otros. (Zapata, 2003).

1.4.2. Cesio-137

El ^{137}Cs es un radionucleido de origen antropogénico, producto de fisión nuclear con vida media de 30.17 años (Pfennig et al., 1995).

Este emisor gama, liberado a la atmósfera a través de pruebas de armas nucleares y emisiones desde reactores nucleares, fue inyectado a la estratósfera a partir del inicio de ensayos nucleares de alta potencia en 1952 (Ritchie y Ritchie, 1995). Como consecuencia de su difusión en la atmósfera y consecuente precipitación radiactiva a escala global se depositó en la superficie terrestre (Ritchie y McHenry, 1990; Beck y Bennett, 2002).

Investigaciones señalan que existe a escala local una relación directa entre los montos de los *inventarios*[1] de ^{137}Cs y la precipitación total anual (Tefry, 1975; Moroney, 1979; Cambray et al., 1983; Cawse y Horrill, 1986). Ello conduce a suponer un depósito uniforme de ^{137}Cs a escala local (Walling y Collins, 2000), hipótesis que constituye uno de los pilares fundamentales de esta técnica.

Una vez depositado en el suelo, el ^{137}Cs es fuertemente adsorbido por las arcillas y la materia orgánica (Tamura, 1964; Bachhuber et al., 1982, Livens y Baxter, 1988; He y Walling, 1996), observándose bajas tasas de migración vertical en varios tipos de suelo (Squire y Middleton, 1966; Frissel y Pennders, 1983; Schuller et al., 1997).

Debido a la rápida adsorción de este radionucleido -principalmente por la fracción mineral del suelo- la subsiguiente redistribución de ^{137}Cs es controlada prioritariamente por el movimiento de las partículas del suelo (Rogowski y Tamura, 1970a; McHenry y Ritchie, 1977; Ritchie y McHenry, 1990; Walling y Quine, 1993).

En general, los factores que influencian la redistribución de ^{137}Cs en el suelo son: dependencia temporal de la precipitación radiactiva, distribución vertical inicial de ^{137}Cs,

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[1] Actividad de un radionucleido (tasa de transformación nuclear del radionucleido o número de desintegraciones nucleares per segundo expresada en Becquerel, Bq) per unidad de superficie medida en una determinada fecha (Bq m^{-2}).

redistribución posterior al depósito debido a procesos mecánicos, físicos, químicos, biológicos y, selectividad en el tamaño de partícula (Ritchie y McHenry, 1990; Walling y He, 1999).

Por otra parte, la distribución vertical de ^{137}Cs en el suelo difiere entre un suelo no disturbado y uno disturbado (suelos cultivados o mecánicamente disturbados). En el primero, la *concentración*[2] de ^{137}Cs decrece exponencialmente en profundidad; en el segundo, el ^{137}Cs es mezclado homogéneamente hasta la profundidad de arado -encontrándose una concentración uniforme hasta esa profundidad- para luego decrecer exponencialmente (Walling y Quine, 1990; 1992; Basher at al., 1995; Owens y Walling, 1996; Sutherland, 1996; Sutherland, 1998; Correchel et al., 2005). Asociado a lo anterior, diversas investigaciones establecen que en suelos no disturbados, el ^{137}Cs se encuentra retenido mayoritariamente hasta los 20-25 cm de profundidad (Brown et al., 1981; Walling y Quine, 1990; Soileau et al., 1990; Basher et al., 1995).

La aplicación de la técnica del ^{137}Cs en suelos labrados anualmente comprende básicamente cinco etapas (Walling y Collins, 2000):

1. Recolección de muestras en el área de estudio con el fin de obtener información preliminar de la concentración de ^{137}Cs y su distribución vertical.
2. Recolección de muestras en sitios de referencia y en el área de estudio.
3. Establecimiento del *inventario referencial*[3] para el área en estudio, el cuál representa el inventario total en un sitio no disturbado y no afectado por procesos de erosión o sedimentación.
4. Medición de concentraciones de ^{137}Cs en las muestras de suelo, con el fin de obtener la distribución espacial del inventario de ^{137}Cs en el área en estudio.

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[2] Actividad de un radionucleido medida en una determina fecha per unidad de masa de suelo (Bq kg^{-1}).

[3] Actividad de un radionucleido medida en una determinada fecha per unidad de superficie en el lugar de referencia (Bq m^{-2}). Walling y Quine (1993), señalan que el sitio referencial debe ser no disturbado ni estar sujeto a erosión y/o sedimentación a partir del depósito del radionucleido y sólo se asume como disminución de la actividad el ajuste por decaimiento radiactivo.

5. Estimación de tasas de redistribución del suelo utilizando modelos específicos de conversión de la pérdida o ganancia de ^{137}Cs respecto al sitio de referencia en tasas de erosión o sedimentación del suelo.

Es importante señalar que la estimación de tasas de redistribución del suelo mediante esta técnica es altamente dependiente del establecimiento de una relación adecuada entre pérdida/ganancia de ^{137}Cs para cada punto -relativo al inventario referencial local- y la tasa de erosión/sedimentación respectiva (Walling y He, 1999). El establecer esta relación requiere conocer el comportamiento del ^{137}Cs en el suelo y la interacción de éste con los procesos de redistribución del suelo (Walling y Collins, 2000).

En el establecimiento del inventario referencial de ^{137}Cs debe considerarse la variabilidad espacial generada tanto como respuesta a cambios locales de clima, como también producto de la micro y macro topografía y su efecto en el transporte y almacenaje de agua dentro del perfil del suelo.

Respecto a esto, Owens y Walling (1996) reconocen que la variabilidad observada de ^{137}Cs en los sitios de referencia puede deberse a: variabilidad espacial al azar, variabilidad espacial sistemática, acuciosidad en el muestreo y precisión de la medición. En su investigación, ellos concluyen que la variabilidad espacial al azar es el factor más importante al analizar la variabilidad de ^{137}Cs. Además, se recomienda que el inventario referencial sea representado como un rango de referencia más bien que un valor único, expresándolo como la media más/menos dos desviaciones estándar (Owens y Walling, 1996).

Por otro lado, el coeficiente de variación (CV%), al entregar información acerca de la dispersión de una variable respecto a un valor central o de referencia, es una herramienta importante para conocer la variabilidad del elemento medido, estableciéndose rangos alto, moderado y bajo (> 36%, 16-35% y 0-15% respectivamente) (Mulla y McBratney, 1999). De acuerdo a resultados reportados en variadas investigaciones, se señala que el CV determinado para ^{137}Cs está dentro del rango moderado (Wilding y Drees, 1983; Bachhuber et al., 1987; Schuller et al., 1997; Basher, 1998; Sepúlveda, 1999; Pennock, 2000;), al igual que otras propiedades del suelo tales como densidad aparente, porcentaje de arena, limo y arcilla, carbono orgánico y nitrógeno total (Mulla y McBratney, 1999; Pennock, 2000).

Con esta información, se ha establecido que para propiedades moderadamente variables, deben ser colectadas entre 10 y 25 muestras para obtener una estimación de la media ± 10%, con un intervalo de confianza del 95% (Wilding y Drees, 1983; Bachhuber et al., 1987; Sutherland, 1994).

De este modo, la información entregada por indicadores estadísticos tales como la media y CV, junto a elementos de geoestadística (variograma y kriging), permiten obtener información acerca de la variabilidad y correlación espacial de la muestra, constituyendo herramientas importantes para la técnica del ^{137}Cs al aplicarlas tanto en el sitio de referencia como en el sitio de estudio.

1.4.2.1. Modelos de conversión de inventarios de ^{137}Cs en tasas de redistribución de suelo

En relación con las aproximaciones existentes para transformar los inventarios medidos de ^{137}Cs en tasas de redistribución del suelo, éstas pueden dividirse en empíricas y teóricas.

En el primer caso, se asume que la pérdida de suelo es proporcional a la pérdida de ^{137}Cs, relación derivada a partir de ensayos llevados a cabo en parcelas de erosión en los que se midió simultáneamente la pérdida de suelo y la de ^{137}Cs (Menzel, 1960; Rogowski y Tamura, 1965, 1970a, 1970b; Bernard et al., 1992), estableciéndose correlaciones empíricas entre ambas

(Elliot et al., 1984; Kachanoski, 1987; Elliot et al., 1990) que fueron confirmadas en estudios de campo (Ritchie et al., 1974; Ritchie y McHenry, 1975; Loughran et al., 1988). Estas ecuaciones fueron útiles para construir el conocimiento base sobre el comportamiento de radionucleidos ambientales en suelos, pero debido a presentar limitaciones importantes respecto a la representatividad de los resultados, hacen inapropiada su utilización.

Dada la necesidad de perfeccionar las aproximaciones empíricas, surgen los modelos teóricos, los cuales buscan representar la realidad considerando los factores que afectan al proceso en estudio. Walling y Quine (1990), definen estos modelos como el efecto total de todos los procesos de redistribución del suelo que operan desde el inicio de la precipitación radiactiva hasta el establecimiento de relaciones específicas en el área.

Entre los modelos teóricos se encuentra el llamado Modelo Proporcional, el cuál postula que el suelo perdido es directamente proporcional a la reducción del contenido de ^{137}Cs en el perfil del suelo, desde donde es modificado por las condiciones edáficas y ambientales tales como: densidad aparente, tiempo transcurrido desde el inicio del depósito y profundidad de arado (de Jong et al., 1983; Martz y de Jong, 1987; VandenBerghe y Gulinck, 1987; Walling y Quine, 1990). Esta ecuación es de simple aplicación, pero los resultados obtenidos con ella tienden a sobreestimar la pérdida del suelo, debido principalmente a que asumen una distribución uniforme de la concentración de ^{137}Cs en el perfil del suelo a través del tiempo y el espacio y, con ello, una pérdida uniforme de suelo en el tiempo.

Otro modelo teórico es el Balance de Masas. Éste propone que la pérdida tanto de suelo como de ^{137}Cs, puede ser entendida si se incorporan los factores involucrados en el movimiento de ^{137}Cs en el suelo, lo que provee una mejor descripción de los procesos involucrados (Walling y Quine, 1990, 1991, 1993; Walling et al., 1999). Este tipo de modelos requiere conocer parámetros específicos para su utilización, los que inducen a mayores posibilidades de error si no se determinan correctamente.

Una importante modificación contenida en este modelo es el considerar el efecto de la aradura en la redistribución de suelo. Quine et al. (1999) señalan que para cuantificar el impacto de la erosión en suelos cultivados se debe considerar la influencia de la translocación de suelo por aradura en la distribución espacial de ^{137}Cs y de este modo determinar la contribución de la erosión por aradura a la erosión total.

Como lo señala Quine (1999), la erosión por aradura representa un proceso erosivo específico y no sólo un medio de transporte de suelo o un incremento de la susceptibilidad de éste a ser erosionado por otro proceso. Por otro lado, la erosión hídrica y por aradura muestran diferentes dependencias topográficas. La primera ocurre preferentemente en concavidades y a longitudes mayores; y la segunda en superficies convexas (bordes, lomas) y a longitudes menores. Esto ha conducido a que se diseñen modelos de simulación capaces de estimar la redistribución de suelo por acción del agua y aradura independientemente (Quine, 1995, 1999).

1.4.2.2. Ventajas y desventajas de la técnica del ^{137}Cs

Según lo descrito por varios autores (Sutherland, 1996; Walling et al., 1999; Walling y Collins, 2000; Wallbrink et al., 2003; Zapata, 2003) las ventajas de la técnica del ^{137}Cs son:

- Las tasas estimadas de redistribución de suelo representan montos medios retrospectivos de los últimos 50 años en suelos cultivados durante este periodo. Al tratarse de tasas medias, éstas son menos influenciadas por eventos erosivos ocasionales extremos.
- Es posible obtener la distribución espacial de la redistribución de suelo en una unidad geográfica. Además, la técnica entrega información acerca de la tasa neta de redistribución de suelo y de los montos de pérdida de sedimentos desde el área estudiada.

- La recolección de muestras no produce mayor disturbación del área en estudio, no siendo necesario interrumpir o alterar labores agrícolas.
- Los resultados pueden ser utilizados en forma complementaria con modelos geoestadísticos y sistemas de información geográfica.
- Los montos de redistribución total de suelo representan la sumatoria de los efectos producidos por todos los agentes erosivos presentes en el área estudiada.
- Con el desarrollo de nuevos modelos para interpretar los datos obtenidos con esta técnica es posible cuantificar por separado la contribución de las labores agrícolas (erosión por aradura) y de la erosión hídrica en la redistribución de suelo.
- Es posible obtener información acerca del origen del sedimento movilizado y estimar el flujo de tasas de sedimentación hacia cursos de agua.
- La técnica tiene amplia aplicabilidad en diferentes medioambientes.

Respecto a otros modelos cuantitativos utilizados para estimar tasas de erosión de suelo tales como parcelas de erosión -método de evaluación directa- y la Revisada Ecuación Universal de Pérdida de Suelo (RUSLE) -método empírico de evaluación indirecta-, las principales limitaciones de estos modelos en relación a la técnica del ^{137}Cs son la representatividad de los resultados en el caso de las parcelas de erosión (Almorox et al., 1994; Morgan, 1997) y baja capacidad predictiva en condiciones de cero o mínima labranza en el caso del modelo RUSLE (Honorato et al., 2001).

Las limitaciones descritas para el uso de ^{137}Cs como trazador de la redistribución de suelo (Walling, 1998; Quine et al., 1999; Walling et al., 1999; He et al., 2002; Pennock y Appleby, 2002), son:

- En zonas con bajos inventarios de ^{137}Cs la variabilidad en los inventarios referenciales puede ser elevada, limitando la precisión del análisis de pérdida/ganancia de ^{137}Cs en cada punto medido respecto al valor del inventario de referencia.

- En la estimación de tasas de redistribución de suelo producidas por erosión hídrica esta técnica no es aplicable para flujo concentrado tipo cárcava.
- Los modelos entregan una aproximación indirecta que depende de la relación entre la redistribución de ^{137}Cs observada y la redistribución de suelo estimada.
- Los modelos existentes -hasta el inicio de esta tesis- no permitían estimar cambios en las tasas de redistribución de suelo producto de cambios en el sistema de labranza y uso del suelo.
- Necesidad de laboratorios especializados en espectrometría gama para medición de la concentración de ^{137}Cs en el suelo.

1.4.3. Berilio-7

El ^{7}Be es un radionucleido natural producido por el bombardeo de rayos cósmicos sobre núcleos de nitrógeno y oxígeno en la atmósfera, siendo su producción relativamente constante (Krishnaswami et al., 1980; Wallbrink y Murray, 1993; Jasiulionis y Wershofen, 2005). Este radionucleido de corta vida media (53.3 días), es removido de la tropósfera por decaimiento radiactivo y precipitación seca y húmeda, siendo esta última responsable del 97% del depósito de Be^{7} sobre el suelo (Salisbury y Cartwright, 2005).

De este modo, se establece una estrecha relación entre precipitación y depósito de ^{7}Be (Wilson et al., 2003), previéndose un depósito mayor en zonas cuya precipitación sea elevada, como también una variación estacional del depósito como resultado del lavado atmosférico causado por el aumento de la precipitación en el periodo de invierno (Salisbury y Cartwright, 2005).

En el sistema terrestre, este radionucleido ingresa como Be^{+2}, ion extremadamente competitivo por sitios de intercambio catiónico. Por tanto, una vez depositado, el ^{7}Be es rápida y fuertemente adsorbido por superficies de intercambio de los coloides del suelo y de la vegetación (Kaste et al., 2002).

En el perfil del suelo, este radionucleido presenta un decrecimiento exponencial en profundidad y se encuentra mayoritariamente concentrado en los primeros 10 mm, por lo que es capaz de proveer una buena discriminación entre el sedimento derivado de los primeros milímetros del suelo y el derivado desde profundidades mayores (Walling y Quine, 1995; citado por Zapata, 2003). Por esta razón, el ^{7}Be ha sido exitosamente utilizado como trazador de sedimentos en lagos, con el fin de determinar el origen de estos (Walling et al., 1999).

El método del ^{7}Be ha sido reconocido en años recientes como método eficiente para estimación de tasas de redistribución de suelo por diferentes autores, en diferentes países (Blake et al., 1999; Wallbring, 1993; Wilson et al., 2003). En Chile, la aplicabilidad de la técnica del ^{7}Be ha sido exitosamente implementada y validada en un suelo de uso forestal de la X Región, para la cuantificación de la redistribución de suelo asociada a eventos lluvia erosivos intensos durante el periodo de post-cosecha a tala rasa (Schuller et al., 2004; Iroumé et al., 2004; Schuller et al., 2006).

1.4.4. Líneas de investigación

De acuerdo a la bibliografía revisada es posible distinguir diferentes líneas de investigación -no obstante, todas ellas complementarias- que utilizan radionucleidos ambientales en investigaciones relacionadas con la redistribución de suelo.

Zapata et al. (2002) distinguen dos grupos básicos: estudios de erosión del suelo y estudios de sedimentación del suelo. Al analizar cada uno de estos grupos es posible diferenciar las siguientes tendencias:

Estudios de erosión del suelo:

- Desarrollo de modelos adecuados para estimar tasas medias de redistribución de suelo.
- Estudios de la posible relación entre la redistribución de suelo y la distribución del carbono orgánico del suelo.
- Validación de modelos de erosión hídrica utilizando la información entregada por algún radionucleido.
- Cuantificación de los efectos de prácticas agrícolas o procesos erosivos específicos en la tasa de redistribución de suelo.

Estudios de sedimentación del suelo (Zapata et al., 2002):

- Determinación de la cronología de los episodios erosivos.
- Cuantificación de la tasa neta de pérdida de suelo en una unidad geográfica.
- Identificación del origen del material sedimentado.
- Estimación del impacto de la erosión del suelo sobre el flujo de sedimentos a cursos de agua.

1.4.5. Erosión del suelo y actividad agrícola

La erosión del suelo representa un proceso físico de remoción de los constituyentes del suelo producido por el agua, viento, glaciares o acción geológica, y/o generado por la acción antrópica (Ministerio de Agricultura - Instituto Nacional de Investigaciones Agropecuarias - Comisión Nacional del Medioambiente, MINAGRI-INIA-CONAMA, 2001); siendo esta última responsable del proceso de erosión por aradura, que consiste en la pérdida y acumulación de suelo dentro de una unidad como resultado del movimiento neto de suelo producto de la variación en la translocación de éste originada por operaciones de labranza agrícola (Lobb et al., 2003).

En la agricultura convencional, la labranza del suelo representa uno de las labores fundamentales para la preparación de una adecuada cama de semillas, utilizando para ello implementos mecánicos que destruyen la estructura del suelo, causan compactación e indirectamente aceleran la oxidación de la materia orgánica y reducen la biodiversidad del suelo. Por tanto, la labranza tradicional ha sido descrita como la mayor causa de pérdida del suelo y desertificación en países en desarrollo, impactos ambientales que ponen en peligro tanto la seguridad alimentaria de la población como la salud del ecosistema (Organización de las Naciones Unidas para la agricultura y la alimentación, FAO, 2002a).

En términos numéricos, la erosión causada por aradura es responsable del 40% de la degradación universal de los suelos. En áreas cultivadas la erosión hídrica produce una pérdida de suelo del 40 al 60% y la erosión por aradura pérdidas entre el 20 y el 40% (FAO, 2002a).

La erosión por aradura produce un gran impacto en la erodabilidad del suelo a la acción del agua y del viento, facilitando la remoción del suelo por erosión hídrica (Lobb et al., 2002; Lobb, 2003; Lobb et al., 2003). Esto confirma la interacción existente entre los procesos de erosión del suelo, donde un proceso incrementa la erodabilidad o susceptibilidad del suelo a la acción de otro proceso erosivo.

1.4.5.1. Cero labranza como estrategia de conservación de suelos

Por conservación de suelos se entiende el uso y manejo del recurso a fin de mantener y/o mejorar su capacidad productiva, en función de sus aptitudes, limitaciones y potencialidades, de manera de evitar su pérdida y/o degradación, para el beneficio de las generaciones presentes y futuras (CONAMA, 1994).

Con este fin surge la agricultura sustentable, la que comprende técnicas y prácticas agrícolas que maximizan la productividad de la tierra y que al mismo tiempo minimizan los daños tanto al capital natural como a la salud humana. Este tipo de agricultura hace énfasis en técnicas regenerativas y de conservación de los recursos naturales dirigidas a minimizar el uso de insumos perjudiciales sobre el agroecosistema (FAO, 2002b). Los criterios que distinguen a la agricultura de conservación son: reducida o cero labranza, cobertura permanente del suelo y rotación de cultivos. A partir de ésta agricultura, se inicia la cero labranza en la década del 60 en Estados Unidos y en la década del 70 en Brasil.

En general, las características agroambientales de la agricultura de conservación son:

- La pérdida de suelo no excede la tasa de formación de éste.
- La fertilidad y la estructura del suelo se mantienen o se fortalecen.
- La biodiversidad es mantenida o fortalecida.
- Se incrementa la infiltración y por tanto se reduce la escorrentía superficial.
- Las emisiones de gases de invernadero se reducen.
- Los niveles de producción de alimentos se mantienen o mejoran.
- Se estimula el cuidado ambiental entre los usuarios de la tierra.

En Chile, la superficie sembrada con cero labranza se estima entre 130.000 y 200.000 hectáreas (Acevedo y Silva, 2003), destacándose que alrededor del 50% de la superficie triguera del país, entre las regiones VIII y IX, se cultiva con esta práctica (Vidal y Troncoso, 2002, citado por Acevedo, 2003). Según antecedentes recopilados por Acevedo (2003) la adopción de esta práctica conservacionista ha generado ventajas agronómicas, ambientales y también económicas.

1.4.5.2. Relación entre erosión y calidad del suelo

Se define calidad del suelo como la "continua capacidad del suelo para funcionar como un sistema viviente dentro de los límites del ecosistema y manejo del suelo, para sustentar la productividad biológica, promover la calidad ambiental del aire y agua y mantener la salud vegetal, animal y humana" (Doran et al., 1999).

De este modo, el concepto de calidad del suelo se basa en la multiplicidad de funciones y usos del suelo, y no sólo en un uso específico de éste (Singer y Ewing, 2000). Es así que, dado el dinamismo del sistema suelo y las relaciones que en él se generan, en lo que respecta a la erosión hídrica, ésta representa la interacción entre precipitación y suelo. Por tanto, la condición del suelo al momento de la interacción determina la magnitud del efecto erosivo generado (Norton et al., 1999).

La relación entre erosión y calidad del suelo está dada básicamente por tres aspectos: resistencia histórica a la erosión, resistencia actual a la erosión y recuperación posterior a la erosión. Las dos primeras intervienen en la erosión neta y las tres en su conjunto determinan el impacto de la erosión en las funciones del suelo y por tanto en la calidad de éste. La *resistencia* se refiere a la capacidad de un sistema para continuar funcionando sin cambio ante una disturbación (cualquier evento que cause un cambio significativo en el modelo normal de un ecosistema, pudiendo ser positivo o negativo). La *recuperación* está referida a la recuperación funcional de un sistema posterior a un proceso de disturbación (Herrick et al., 1999).

Se sugiere que los indicadores de calidad del suelo usados para precisar la calidad de éste deben ser utilizados respecto a los tres aspectos anteriormente señalados (Bautista et al., 2004).

1.4.5.3. Indicadores de calidad del suelo

Según lo señalan Dumanski et al. (1998), se entiende por indicadores a las variables que sirven para evaluar una condición y que conllevan información acerca de los cambios o tendencia de esa condición. Constituyen un instrumento de análisis que permite simplificar, cuantificar y comunicar fenómenos complejos (Soil Quality Institute, SQI, 1996).

En el caso del suelo, se reconoce que no existen criterios universales para evaluar los cambios en la calidad de éste (Arshad y Coen, 1992), criterios representados por indicadores tanto de propiedades físicas (textura, estructura, densidad aparente y otras), químicas (materia orgánica, nitrógeno, pH y otras) y biológicas (biodiversidad mesofauna edáfica, microorganismos del suelo) o procesos que ocurren en el suelo (SQI, 1996).

Los indicadores de calidad del suelo, según Hunnemeyer et al. (1997), deben permitir:

- Analizar la situación actual e identificar puntos críticos con respecto al desarrollo sostenible.
- Analizar posibles impactos antes de una intervención.
- Monitorear impactos de intervenciones antrópicas.
- Ayudar a determinar si el uso del recurso es sostenible.

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2. USE OF ^{137}Cs MEASUREMENTS TO ESTIMATE CHANGES IN SOIL EROSION RATES ASSOCIATED WITH CHANGES IN SOIL MANAGEMENT PRACTICES ON CULTIVATED LAND*

2.1. ABSTRACT

Intensification of agricultural production in south-central Chile since the 1970s has caused problems of increased soil erosion and associated soil degradation. These problems have prompted a shift from conventional tillage to no-till management practices. Faced with the need to establish the impact of this shift in soil management on rates of soil loss, the use of caesium-137 (^{137}Cs) measurements has been explored. A novel procedure for using measurements of the ^{137}Cs depth distribution to estimate rates of soil loss at a sampling point under the original conventional tillage and after the shift to no-till management has been developed. This procedure has been successfully applied to a study site at Buenos Aires farm near Carahue in the 9th region of Chile. The results obtained indicate that the shift from conventional tillage to no-till management has caused net rates of soil loss to decrease to about 40% of those existing under conventional tillage. This assessment of the impact of introducing no-till management at the study site must, however, be seen as provisional, since only a limited number of sampling points were used. A simplified procedure aimed at documenting the reduction in erosion rates at additional sampling points, based solely on measurements of the ^{137}Cs inventory of bulk cores and the ^{137}Cs activity in the upper part of the soil has been developed and successfully tested at the study site. Previous application of ^{137}Cs measurements to estimate erosion rates has been limited to estimation of medium-term erosion rates during

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the period extending from the beginning of fallout receipt to the time of sampling. The procedures described in this paper, which permit estimation of the change in erosion rates associated with a shift in land management practices, must be seen as representing a novel application of ^{137}Cs measurements in soil erosion investigations.

Keywords: Caesium-137; Erosion rates; No-till management; Chile

2.2. INTRODUCTION

In south-central Chile, intensification of agricultural production since the 1970s has exacerbated soil degradation processes such as erosion, acidification and loss of soil organic matter. Cereals and legumes represent the dominant crops and the traditional cropping systems in this region are largely based on conventional tillage, which involves burning of stubble after harvest, ploughing and subsequent disk harrowing operations for seedbed preparation. The existence of large areas of bare soil on steep lands with slopes of 15-20% during the fallow period, which is characterised by heavy and intense rainfall, has accelerated rates of soil loss, which in turn represent an important threat to crop productivity and sustainable soil use, as well as causing degradation of water quality in local streams and rivers. Soil management practices, such as those described above, have resulted in 33.5% of the total area of agricultural land in Chile being affected by erosion classified as ranging from serious to very serious (CONAF, 1994). Against this background, the introduction of no-till soil management practices has been viewed as a key strategy for the development of sustainable agricultural production. No-till practices are seen as a means of reducing soil and nutrient loss and associated diffuse source water pollution, as well as improving natural soil fertility and consequently soil quality (Borie et al., 2002; Rouanet et al., 2001; Pino et al., 2002; Acevedo, 2003).

Although it is generally accepted that soil erosion rates are likely to be significantly lower under no-till soil management practices than under conventional tillage, the precise magnitude of the reduction in soil loss associated with the introduction of no-till practices remains uncertain and there is currently a need to establish the extent of this reduction. Such information could be assembled using erosion plot experiments (e.g. Lal, 1994), but the representativeness of plot results in terms of the wider landscape is often questioned. Furthermore, the cost and time involved in establishing and operating plot experiments imposes constraints on the speed with which results can be obtained, the range of environmental and climatic conditions that can be covered and the period represented. This paper reports the development of an alternative approach to quantifying the changes in rates of soil loss associated with a shift in soil management from conventional tillage to no-till, based on measurements of caesium-137 (^{137}Cs) activity in the soil. This approach possesses the important advantages of being capable of application to a wide range of locations, as well as to different topographic positions in the landscape, and of providing retrospective results relating to an actual change in management practice at a study site. Furthermore, results can be assembled on the basis of a few site visits, thereby avoiding the need for lengthy periods of monitoring.

2.3. THE USE OF ^{137}Cs MEASUREMENTS TO ESTIMATE RATES OF SOIL LOSS

The use of ^{137}Cs measurement as a means of estimating rates of soil loss and patterns of soil redistribution in the landscape is now well established and documented (see Ritchie and McHenry, 1990; Walling, 1998, 2002; Schuller et al., 2003; Zapata, 2002). In brief, the approach is founded on the fact that in most environments the global fallout of ^{137}Cs derived from weapons testing that took place during the late 1950s and early 1960s was rapidly and firmly fixed by the surface soil. Subsequent redistribution of this radiocaesium fallout within the landscape occurred in response to the movement of soil and sediment particles, and measurements of the present day distribution of ^{137}Cs affords a means of quantifying rates of erosion and deposition associated with the period since fallout receipt. Estimates of erosion and deposition rates can be derived by measuring the ^{137}Cs areal activity density or inventory at a given location and comparing this with the equivalent reference value, which represents the areal activity density found at a stable undisturbed site experiencing neither erosion nor deposition. Where erosion has occurred, the measured areal activity density will be less than the reference value, whereas the measured areal activity density will exceed the reference value, where deposition has occurred. The magnitude of the difference between the measured and the reference areal activity density will be a direct reflection of the magnitude of the erosion or deposition rate and a range of conversion models has been developed to estimate erosion and deposition rates from a comparison of the two values (see Walling and He, 1999; Zapata, 2002). Different conversion models are required for cultivated soils and undisturbed (e.g. pasture) soils, since in the former case the radiocaesium will be mixed within the plough layer by tillage, whereas for undisturbed soils it will remain close to the surface. Loss of a given proportion of the reference areal activity density will therefore reflect a much higher erosion rate in the case of cultivated soil than for an undisturbed soil.

The estimates of erosion and deposition rate derived from ^{137}Cs measurements using the approach described above will relate to the entire period between the fallout input and the time of sample collection, and one frequently cited advantage of the approach is its ability to provide estimates of medium-term erosion rates that integrate the inter-annual variability associated with rainfall inputs and other environmental controls. This integration or temporal lumping could, however, also be seen as a limitation, in that it is not possible to quantify changing erosion rates associated, for example, with changes in land use or with shifts from drier to wetter conditions (or vice versa). In existing applications of the approach, use of a conversion model effectively assumes that the land use has remained essentially constant during the period involved. Faced with a requirement to document the change in the rate of soil loss associated with a shift from conventional tillage to no-till management, the approach has been modified to permit estimation of erosion rates associated with both the period of conventional tillage and the subsequent period when no-till practices were applied. To the authors' knowledge, this development of the ^{137}Cs approach represents the first attempt to use it to document changing erosion rates associated with a change in cultivation practice.

2.4. USING ^{137}Cs MEASUREMENTS TO DOCUMENT CHANGES IN SOIL EROSION RATES ASSOCIATED WITH CHANGES IN SOIL MANAGEMENT PRACTICES

The procedure developed for using ^{137}Cs measurements to document the change in erosion rate at a sampling point, associated with the change from conventional tillage to no-till management, involves estimation of the erosion rates associated with the initial period under conventional tillage, extending from the time of initial fallout to the time of the change in management practice, and with the subsequent period under no-till management, extending from the time of the change in management practice to the time of sample collection for ^{137}Cs measurements. It is based on measurements of the ^{137}Cs depth distribution at representative points within the study area. The following key elements are involved:

2.4.1. Estimation of the erosion rate during the no-till period

The erosion rate ($R_{nt}<0$) or sedimentation rate ($R_{nt}>0$) during the no-till period (kg m^{-2} y^{-1}) can be estimated by comparing the mass depth of the zone of homogeneous mixing associated with a measured ^{137}Cs depth distribution (h, kg m^{-2}) with the plough depth associated with the conventional tillage practices (H, kg m^{-2}). Assuming that the depth of the zone of homogeneous mixing would be equal to the plough depth at the time when conventional tillage ceased, the reduction or increase in h relative to H i.e. $[h - H]$ (kg m^{-2}), represents the total amount of erosion or deposition occurring during the period extending from the beginning of no-till management (t', y) to the time of sampling (t, y). The annual erosion or deposition rate R_{nt} can therefore be estimated as

$$R_{nt} = \frac{h - H}{t - t'} . \qquad (1)$$

2.4.2. Estimation of the erosion rate during the previous period of conventional tillage

The ^{137}Cs depth distribution in the soil at the end of the period of conventional tillage (i.e. at the beginning of no-till) can be reconstructed by assuming that the zone of homogeneous mixing would have extended to depth H and that the current mean ^{137}Cs concentration or mass activity density ($\overline{C}$, Bq kg^{-1}) in the upper part of the remaining portion of the zone of homogeneous mixing (i.e. down to $h' \leq h$) is a direct reflection of that existing in the plough layer at the end of the period of conventional tillage. The areal activity density (Bq m^{-2}) lost (negative value) or gained (positive value) during the subsequent period of no-till management can thus be estimated as

$$\left[h - H\right]\overline{C} . \qquad (2)$$

The total areal activity density $A(t')$ (Bq m^{-2}) at the measuring point at the end of the period of conventional tillage period (or the beginning of the period of no-till) (Bq m^{-2}) can be estimated as

$$A(t') = \left[A(t) - (h - H)\overline{C}\right] exp\left[Ln(2)(t - t')/T_m\right], \qquad (3)$$

where $A(t)$ (Bq m^{-2}) represents the areal activity density at the sampling point measured at the time of sampling and T_m is the half-life of ^{137}Cs (y).

The estimate of the total ^{137}Cs areal activity density at the end of the period of conventional tillage for a sampling point enables the erosion rate during the period of conventional tillage (R_{ct}) to be estimated using one of the conversion models for cultivated soils documented by Walling and He (1999). In this situation, it is simply assumed that the sample was collected at the same time as the shift from conventional tillage to no-till and that the estimated erosion rate applies to the period extending from the onset of ^{137}Cs fallout to that date.

2.5. A CHILEAN CASE STUDY

The procedure for assessing the change in the rate of soil loss associated with a shift from conventional tillage to no-till management practices described above has been applied to a study site in south-central Chile, where concern for soil degradation caused a shift from conventional tillage to no-till practices in 1986.

2.5.1. The study site

The study site represents a field located at Buenos Aires farm near Carahue in the Coastal Mountain range of the 9th Region of Chile (38°37´S 73°04´W). The site is characterised by Araucano Series Ultisols (Typic Hapludult), a temperate climate and a mean annual precipitation of 1100 mm y^{-1}. The field was under conventional management until May 1986, when there was a change to no-till management. In addition, a further site located close to the study field and with similar soils, but where conventional tillage has continued to the present, was selected for confirming the historical plough depth.

2.5.2. Sample collection and measurement

The soil samples for establishing the ^{137}Cs depth distribution and the areal activity density were collected between 2001 and 2002, from six points at 20 m intervals along a slope transect extending down the upper and middle portions of a slope, with the highest point located 5 m from the hilltop. The points were selected to be representative of an area likely to be susceptible to erosion under conventional tillage practices. At the neighbouring site, still under conventional tillage, equivalent samples were collected from two points located within a flat area close to the top of the field, shortly before the harvest period. All samples were cut with pallet knives from the upslope sides of pits about 1 m x 0.7 m excavated at the individual sampling points. Depth increments of 2 cm were employed in the upper and lower parts of the sampled profile, but this was reduced to 1 cm around the depth where the base of the original plough layer was expected to be located. The mass depth of each depth increment was estimated from the values of mass and surface area associated with the individual samples. The ^{137}Cs mass activity density of the soil samples was measured by gamma spectrometry using a high-purity Ge detector of 28% relative efficiency, in the Institute of Physics at the Universidad Austral de Chile, Valdivia, Chile. The samples were placed into 500 ml Marinelli beakers for counting and the detector was calibrated with standard solutions supplied by Physikalisch-Technische Bundesanstalt (PTB), D-38110 Braunschweig, Germany. Spectra were analysed using Accuspec B software from Nuclear Data (ND Instrumentation Division, Schaumburg, Illinois 60196, USA). Due to the low ^{137}Cs concentrations in the soils analysed, the count time for each sample was set to 20 h, which provided a detection limit of about 0.2 Bq kg^{-1} soil.

2.5.3. Estimation of the erosion rates

The soil erosion rates for the individual sampling points associated with the no-till period were estimated from the ^{137}Cs depth distribution using the method described above (i.e. Eq. (1)). The erosion rates associated with the period of conventional tillage were estimated using the procedure detailed above (i.e. Eqs. (2) and (3)) coupled with the mass balance conversion model incorporating soil movement by tillage described by Walling and He (1999). The values for the parameters required by the mass balance conversion model were measured or estimated based on those employed by Schuller et al. (2003) for a site in the same region with the same soil type, and similar annual precipitation, viz.,

reference areal activity density: 692 Bq m^{-2}, referred to May 1986,
particle size correction: 1.0,
proportion of annual ^{137}Cs fallout susceptible to removal by erosion prior to incorporation into the soil by tillage: 0.8,
relaxation mass depth: 5 kg m^{-2},
constant related to tillage practice: 210 kg m^{-1} y^{-1}.

2.5.4. Results

Fig. 2.1 shows the depth distribution of the ^{137}Cs mass activity density observed at the site currently under conventional tillage. It also demonstrates how the historical plough mass depth *H* is estimated by observing the depth to which ^{137}Cs is homogeneously mixed in the soil profile and assuming that ploughing depths have remained essentially similar since the 1980s. Based on Fig. 2.1, a value of 161.2 kg m^{-2} has been estimated for the historical plough depth *H* at the site now managed using no-till practices. Since *H* is defined as a mass depth, rather than a linear depth, it is not necessary to take account the potential differences in bulk density between the conventionally tilled site and the site with no-till management, where the bulk density might be expected to be greater some years after the cessation of regular ploughing.

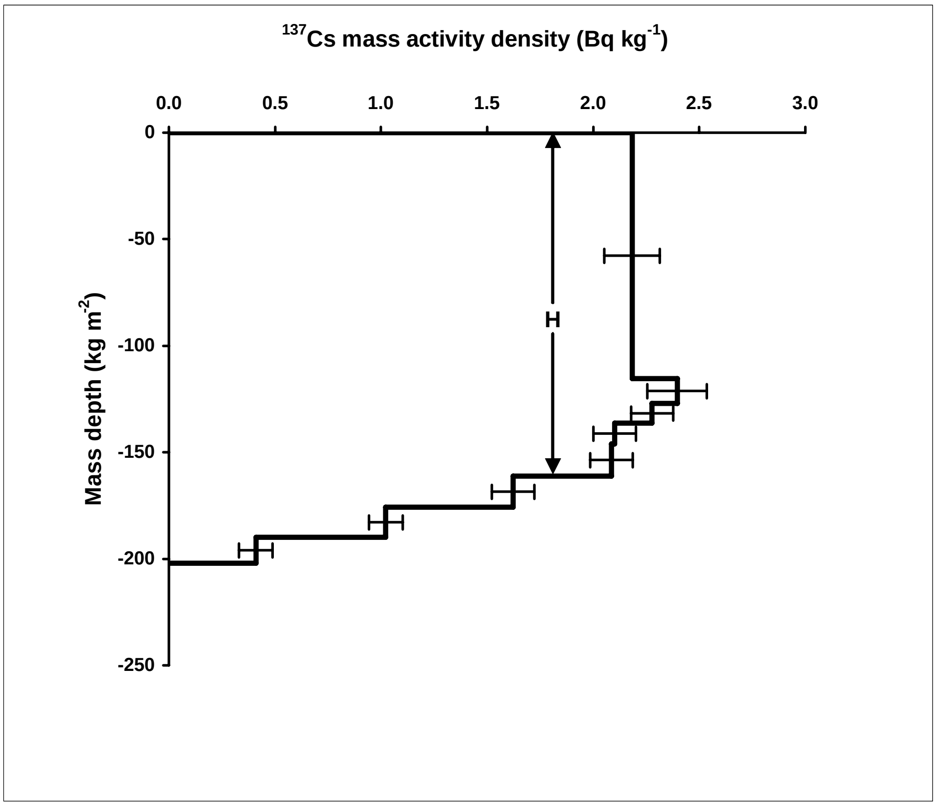

Fig. 2.1. The vertical distribution of ^{137}Cs mass activity density for a site currently under conventional tillage. *H* represents the observed plough depth.

Figures 2.2 and 2.3 present the depth distributions of ^{137}Cs mass activity density observed within the no-till site, for points experiencing erosion and deposition, respectively. In both cases, the ^{137}Cs depth distribution at the time of cessation of conventional tillage in 1986 has also been reconstructed using the approach outlined above. In Fig. 2.2 the depth to which the ^{137}Cs is currently found to be homogeneously mixed is smaller than the historical plough depth, indicating that erosion has occurred during the no-till period. In contrast, in the case of Fig. 2.3, the depth to which ^{137}Cs is found to be homogeneously mixed exceeds the historical plough depth, indicating that deposition has occurred at this site since the introduction of no-till management practices.

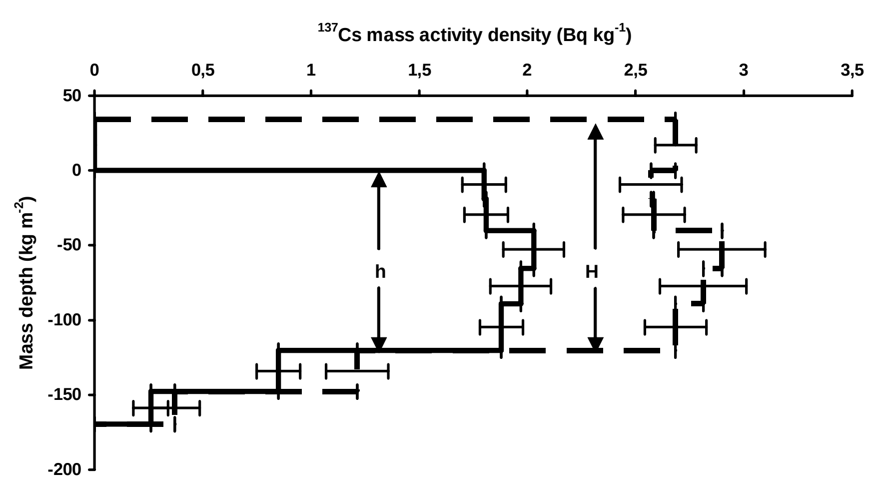

Fig. 2.2. The vertical distribution of ^{137}Cs mass activity density for a site experiencing erosion during the no-tillage period: ——— currently, and - - - - estimated at the beginning of the no-tillage period. *H* represents the historical plough mass depth and *h* the mass depth to which ^{137}Cs is currently found to be homogeneously distributed.

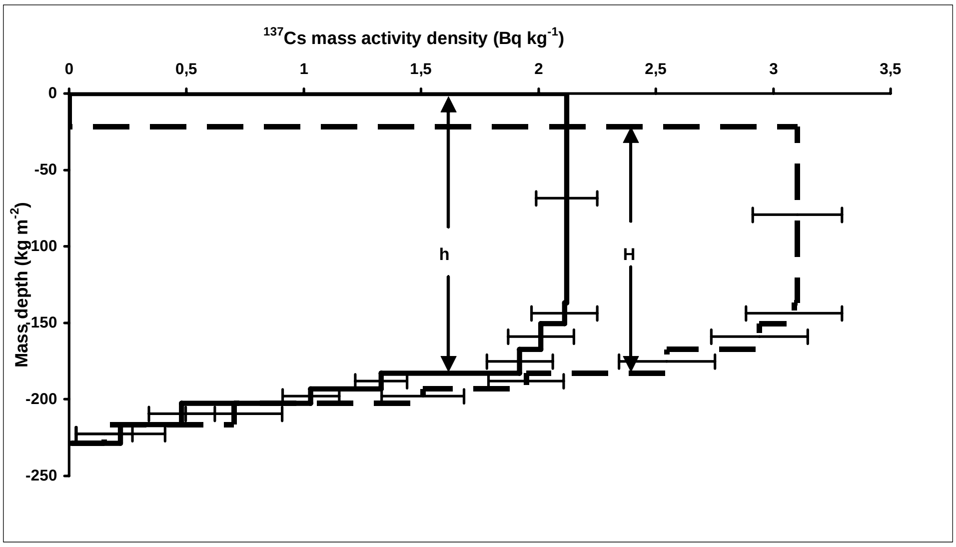

Fig. 2.3. The vertical distribution of ^{137}Cs mass activity density for a site experiencing deposition during the no-tillage period: ——— currently, and - - - - estimated at the beginning of the no-tillage period. *H* represents the historical plough mass depth and *h* the mass depth to which ^{137}Cs is currently found to be homogeneously distributed.

Erosion and deposition rates during the period of no-till management have been estimated by comparing the current depth to which the ^{137}Cs is found to be homogeneously mixed within the profile with the historical plough depth (i.e. Eq. (1)). Erosion and deposition rates associated with the period of conventional tillage have been derived by estimating the areal activity density at the time of cessation of conventional tillage using Eq. (3) and employing the mass balance conversion model, which takes account of tillage redistribution, presented by Walling and He (1999).

The estimates of erosion or deposition rate under conventional tillage and no-till management obtained for each sampling point along the transect within the no-till site are presented in Fig. 2.4. The values obtained for the period of conventional tillage indicate that soil loss occurred at all points along the sampled transect, producing a net erosion rate of -1.35 kg m^{-2} y^{-1} from the length of slope represented by the transect. For the period of no-till management, soil redistribution rates for the points along the sampled transect involve both erosion and deposition, producing an equivalent net erosion rate of -0.52 kg m^{-2} y^{-1}. These results suggest that the introduction of no-till management practices resulted in a significant reduction in the net rate of soil loss, with the net rate of soil loss under no-till being only about 40% of that under conventional tillage. However, this assessment of the impact of introducing no-till management procedures is based on only a small number of sampling points located along a transect which covered only part of the slope. A more intensive sampling programme, preferably involving both several sites and longer slope transects, would clearly be required to generate a more representative, and therefore, reliable assessment of the impact of the change from conventional tillage to no-till management on rates of soil loss from the study area.

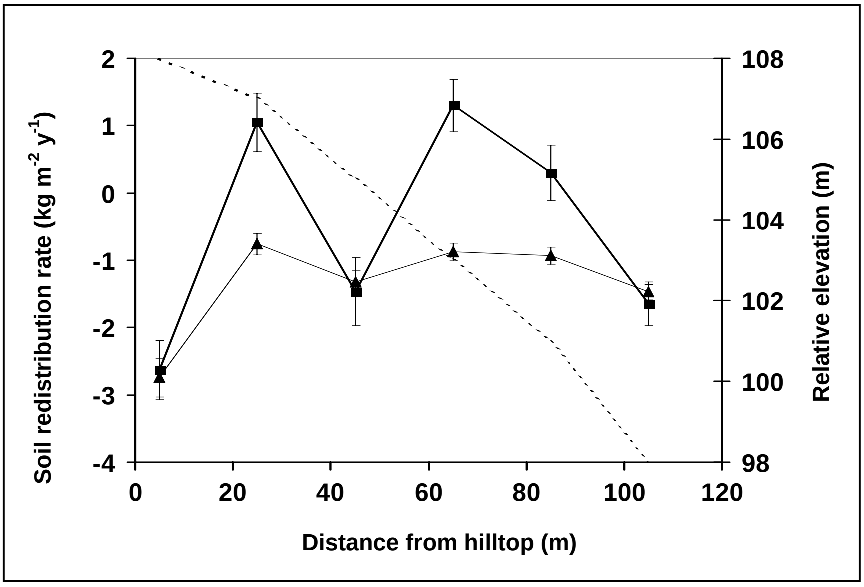

Fig. 2.4. Soil redistribution rates during the no-tillage ■ and conventional tillage ▲ periods, estimated from measurements of the ^{137}Cs depth distribution within an area currently under no-till. The dashed line ------ represents the relative elevation along the sampling transect.

2.6. DEVELOPMENT OF A SIMPLIFIED PROCEDURE TO PERMIT WIDER APPLICATION OF THE PROPOSED APPROACH

The procedure described above for estimating erosion rates associated with the periods of conventional tillage and no-till management requires appreciable effort, both in terms of the need to collect depth incremental samples and the resulting large number of samples requiring analysis for ^{137}Cs activity. The latter limitation is of particular significance in Chile, where ^{137}Cs activities are low and extended count times are required. A simpler approach that can be applied to additional sampling points in a study field to estimate the erosion rates associated with the periods under conventional tillage and no-till management, has also been developed.

The depth distributions of ^{137}Cs obtained for the six individual sampling points and for two additional replicate points along the slope transect at the site currently under no-till management indicated that only a small proportion of the total inventory was found below mass depth h, the depth to which the ^{137}Cs was found to be homogeneously mixed. In addition, a well defined linear relationship exists between A_h, the areal activity density down to h, and the total areal activity density, A. The well-defined relationship between these two variables shown in Fig. 2.5 ($r = 0.999$, $p < 0.01$) makes it possible to estimate A_h for additional points where only the total areal activity density, A, has been measured using bulk (unsectioned) cores.

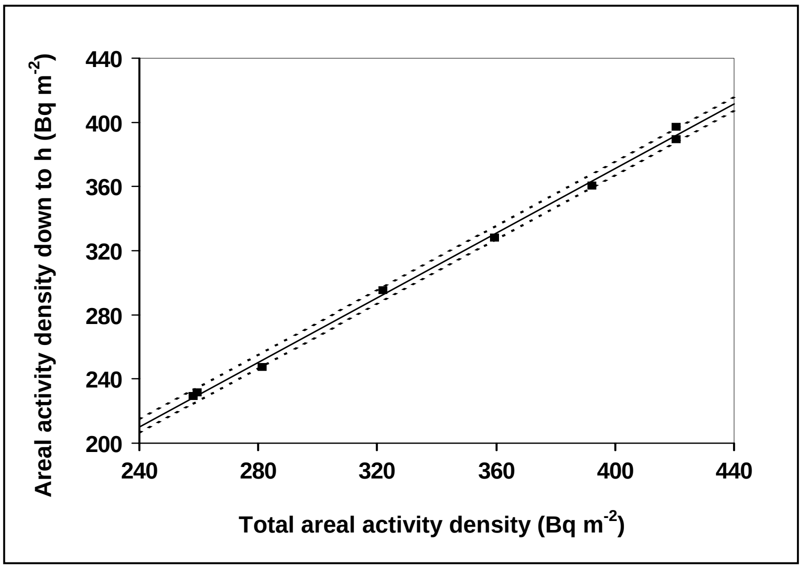

Fig. 2.5. The relationship between the ^{137}Cs areal activity density down to the mass depth, h, to which ^{137}Cs is found to be homogeneously distributed, and the total areal activity density, for the sampling points.

Assuming that the ^{137}Cs mass activity density will be effectively constant down to depth h and that the bulk density of the soil will also be almost constant down to this depth, due to the progressive compaction of the soil during the no-till period, h can be estimated using the relationship

$$h = \frac{A_h}{\overline{C}}, \tag{4}$$

where $\overline{C}$ (Bq kg^{-1}) is the mean ^{137}Cs mass activity density measured in the upper part of the soil profile (down to $h' \leq h$) at the sampling points. Using the relationship presented in Fig. 2.5 and Eq. (4), measurements of A and $\overline{C}$ at additional sampling points enables the key parameters for the ^{137}Cs depth distributions associated with the two management periods to be estimated for those points. These in turn allow the mean annual soil redistribution rates for the periods under conventional tillage and no-till management to be estimated.

In order to provide some validation of the use of the simplified method of estimating the erosion rates under conventional tillage and no-till management for additional points in the study field, based only on measurements of the total ^{137}Cs areal activity density of bulk cores and of the ^{137}Cs mass activity density in the upper part of the soil profile, these two variables have been calculated for the six depth incremental profiles sampled in the study field. The values of erosion rate for the contrasting management practices estimated using the simplified method are compared with those obtained previously using the more detailed depth incremental data in Fig. 2.6. As seen from Fig. 2.6, the erosion rates estimated using the original and the simplified methods are very similar, particularly when the uncertainties associated with the precision of the ^{137}Cs measurements are taken into account. Provided sufficient depth-incremental profiles can be sampled in a field to establish the relationship between A_h and A (cf. Fig. 2.5), the simplified method can be used to assemble information on the relative magnitude of the soil redistribution rate under conventional tillage and no-till management for additional points within a study area. The simplified approach has the important advantage of only requiring two ^{137}Cs measurements per sampling point and avoiding the need to collect depth incremental samples at all the points.

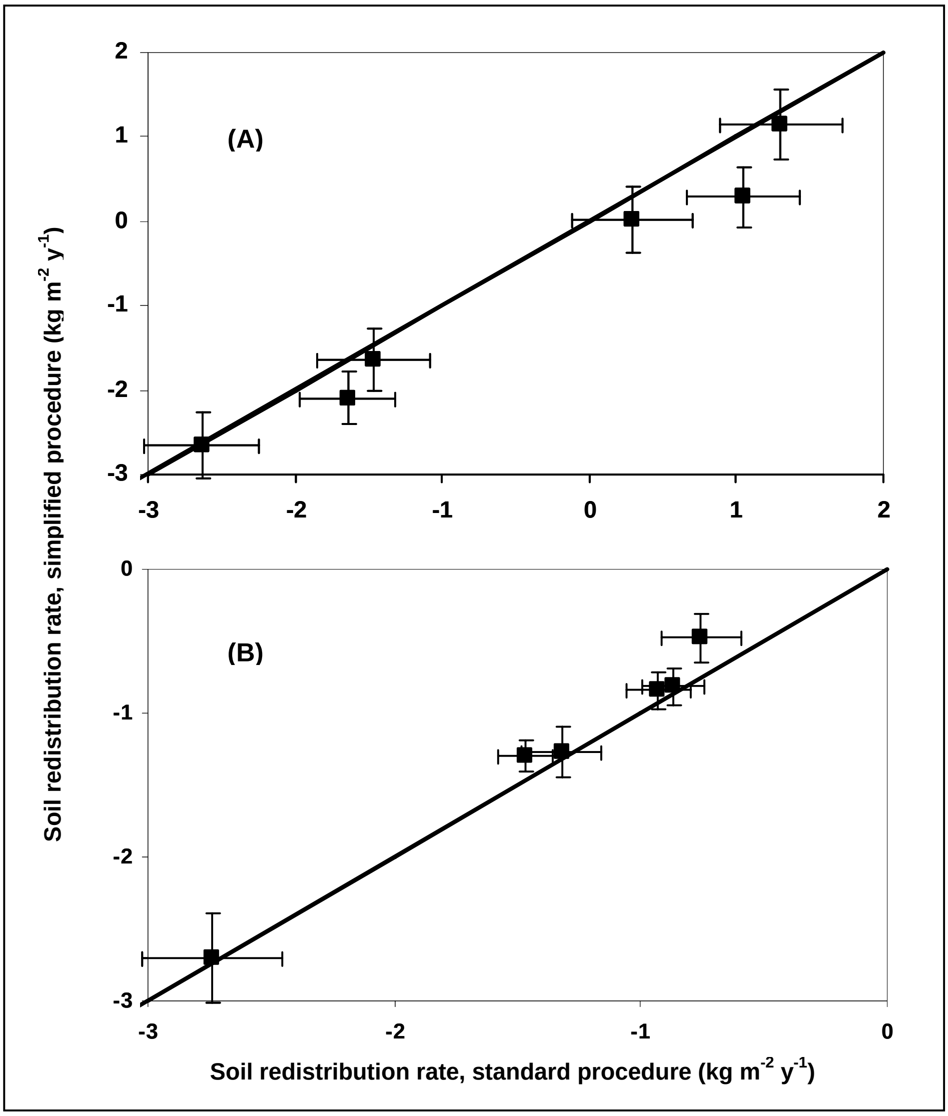

Fig. 2.6. The relationship between the estimates of soil redistribution under no-till management (A) and conventional tillage (B) obtained for the six sampling points in the study field using the simplified procedure and those based on the standard procedure, which requires information on the ^{137}Cs depth distribution. The uncertainties associated with the estimates of soil redistribution rate due to the precision of the ^{137}Cs measurements are shown.

2.7. CONCLUSION

Faced with the need to assemble information on the relative magnitude of rates of soil loss under conventional tillage and no-till management, in order to assess the effectiveness of the latter in controlling soil erosion and soil degradation, ^{137}Cs measurements have been shown to afford an effective means of quantifying the change in erosion rates associated with a shift from conventional tillage to no-till practices. By providing the potential to assemble the retrospective data from a range of points in the 'natural' landscape, where a change in land management practices has actually occurred, the ^{137}Cs approach offers important advantages over plot experiments. This application of ^{137}Cs measurements is thought by the authors to be the first attempt to use the approach to quantify *changing* erosion rates. As initially conceived, the approach is fairly demanding in terms of the need to collect and analyse depth incremental samples, in order to establish the depth distribution of radiocaesium at the sampling sites. However, a simplified approach is also proposed. This can be coupled with the standard approach in order to greatly increase the number of points within a study area that can be investigated, since it requires only two ^{137}Cs measurements per sampling point and avoids the need for detailed depth-incremental sampling. The approach has been successfully applied to a study site in south-central Chile. A greater number of sampling points covering a more extensive area would be required to provide a rigorous assessment of the precise impact of the change from conventional tillage to no-till management on rates of soil loss, but based on the results from the six sampling points available in this study, net rates of soil loss were shown to have been reduced to ca. 40% of those occurring under conventional tillage.

The approach described should be applicable to other study areas, both in Chile and elsewhere, where a change in soil management practices has occurred. However, application of the approach may be constrained by the requirement for relatively long periods under both conventional tillage and no-till management, in order to ensure that a measurable reduction in the total inventory occurs under conventional tillage and that the reduction in the depth of the plough layer as a result of erosion occurring during the period under no-till can be reliably quantified. Furthermore, the approach is not applicable to sampling points where deposition has occurred during the period under conventional tillage (i.e. where the areal activity density at the beginning of the no-till period exceeds the reference areal activity density and the depth of mixing exceeds the plough depth). In this situation, the plough depth *H* cannot be used to define the depth of homogeneous mixing at the end of the period of conventional tillage and it is therefore not possible to estimate the depth of erosion or deposition associated with the subsequent period of no-till cultivation.

2.8. ACKNOWLEDGEMENTS

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3. CHANGES IN SOIL EROSION ASSOCIATED WITH THE SHIFT FROM CONVENTIONAL TILLAGE TO A NO-TILLAGE SYSTEM, DOCUMENTED USING ^{137}Cs MEASUREMENTS[*]

3.1. ABSTRACT

Caesium-137 measurements have been used to document changes in the rate and extent of soil erosion associated with the shift from conventional tillage to a no-till system on a farm in south-central Chile. The study site is located in the Coastal Mountains of the 9th Region (38º37´S 73º04´W), and is characterized by Araucano series Ultisols (Typic Hapludult), a temperate climate and a mean annual precipitation of 1100 mm year^{-1}. A field, which was under conventional tillage until May 1986 and which was subsequently managed using a no-till system, was selected for the study. An approach for using ^{137}Cs measurements to quantify the medium-term erosion and deposition rates associated with the periods of contrasting land management documented previously was employed. This approach involves both a standard method and a simplified method, which permits a larger number of sampling points to be used. In this study, emphasis was placed on application of the simplified method, which has the important advantage of requiring only two ^{137}Cs measurements per sampling point. The results obtained for the study field showed that the implementation of no-till practices, including crop residue management, coincided with a reduction in the net erosion rate by about 87% and the proportion of the study area subject to erosion from 100% to 57%, and therefore significantly decreased soil and nutrient loss. Reduced soil and nutrient loss has important on-site benefits, in terms of sustainable management of the soil resource and

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[*] Schuller, P.; Walling, D.E.; **Sepúlveda, A.**; Castillo, A.; Pino, I. 2007. *Soil Tillage Res.* 94: 183-192.

maintaining crop productivity, as well as reducing off-site problems associated with the degradation of river water quality.

Keywords: ^{137}Cs; Soil erosion; Soil redistribution rates; Conventional tillage; No-till; Changing cultivation system; Chile

3.2. INTRODUCTION

In south central Chile, conventional tillage practices involve the burning of stubble after harvesting, ploughing and subsequent disk harrowing operations for seedbed preparation. These practices leave the soil bare for considerable periods before the crop cover develops and the bare soils can be subject to intense rainfall, which frequently causes soil erosion. This presents problems for the longer-term sustainability of both the soil resource and crop production, as well as contributing to the diffuse source pollution of water courses and river systems. The introduction of a no-till (also called reduced-tillage) system, is seen as a key strategy for reducing soil erosion and soil and fertiliser loss from agricultural land. No-till practices involve the management of crop residues, to ensure that the soil is partially covered with stubble and straw during the fallow period, and direct seeding, using seed drills which cut throughout crop residues and open slots in the soil, into which seeds and fertilizers are dropped. These practices are therefore currently being applied, in order to maintain and improve soil quality and to reduce soil and nutrient losses to water courses.

In order to assess the benefits of implementing no-till practices, there is a need to compare soil erosion and soil redistribution rates under conventional and no-till systems. Several attempts have been made to undertake such assessments in south-central Chile, and these indicate that soil erosion rates can be significantly reduced by implementing no-till practices on land previously under conventional tillage. The erosion rates reported for sites under a no-till system vary from 1 to 5 t ha^{-1} y^{-1}, whereas the equivalent values reported for areas under conventional tillage range between 9 and 20 t ha^{-1} y^{-1} (Del Pozo et al., 1993; Rodríguez et al., 2000; Merten et al., 2001; Uribe and Rouanet, 2002). On the Ultisols of the Coastal Mountains of south-central Chile, where over the 80% of the soils show evidence of compaction below the plough depth due to tillage operations, and where soil erosion rates are amongst the highest for any agricultural land in Chile (CONAMA, 2000; Ellies, 2000; INIA 2001), the implementation of a no-till system has also been shown to cause important improvements in soil quality, as reflected by an increase in aggregate stability (typically from ca. 17 to ca. 78%), and an increase in macroporosity (from ca. 12 to 17.5%) (Ellies, 2000). The national agencies responsible for environmental protection and improved agriculture have recognised that the main environmental and management problems in this part of Chile, and particularly the 9th Region, are associated with soil erosion (CONAMA, 2000; INIA, 2001). The implementation of a no-till system is seen as a valuable means of reducing these problems. However, there is need to assemble a larger body of information on the precise magnitude of the decrease in soil loss associated with the shift from conventional tillage to no-till systems, in order to provide a more rigorous confirmation of the likely impact, and therefore effectiveness, of such changes in land management.

The use of conventional approaches to assessing the changes in soil erosion rates associated with a shift from conventional tillage to a no-till system faces a number of important problems. These include, firstly, the need to extrapolate the findings from small bounded plots to larger fields or areas characterized by more complex topography, secondly, the need to take account of the considerable inter-annual variability of erosion rates and thus to consider whether information assembled for a short period (e.g. 1 or 2 years) is representative of more longer-term conditions, and, thirdly, the difficulty of obtaining information relating to 'before' and 'after' conditions on the same land. The establishment of long-term conventional plot experiments that might provide at least some of this information is likely to be heavily constrained by cost considerations, since such experiments are costly to install and require substantial resources to operate over an extended period of time. The work of Schuller et al. (2004) has, however, demonstrated the potential for using Caesium-137 (^{137}Cs)

measurements as an alternative approach to assembling information on the changes in soil erosion rates associated with a shift from conventional tillage to no-till systems. The use of the ^{137}Cs approach possesses four key advantages over conventional plot-based approaches for assembling such data. These are as follows:

1. The ability to generate information for individual fields or landscape units that is likely to prove more representative than the information provided by a small plot, particularly when assessing net soil loss and sediment delivery to water courses.
2. The ability to produce medium-term estimates of erosion rates associated with both conventional and no-till systems, that will take account of the temporal variability of erosion rates.
3. The ability to undertake 'before' (i.e. with conventional tillage) and 'after' (i.e. with a no-till system) investigations of the same field or study area.
4. The retrospective nature of the approach, which can provide information relating to medium-term erosion rates operating in the landscape over the past ca. 45 years on the basis of a single site visit for the collection of soil samples.

This contribution reports the results of using ^{137}Cs measurements to document the change in soil erosion rates associated with the shift from conventional tillage to a no-till system, within a representative field in the 9th Region of Chile by using the approach developed previously by Schuller et al. (2004). This comprised, firstly, a 'standard method' and, secondly, a 'simplified method', based on measurements of the ^{137}Cs activity of bulk cores. Both the standard method and the simplified method are briefly outlined below.

3.3. USING ^{137}Cs MEASUREMENTS TO ESTIMATE EROSION RATES UNDER NO-TILL AND CONVENTIONAL TILLAGE SYSTEMS

3.3.1. The standard method

3.3.1.1. Estimation of soil redistribution rates during the no-till period: The medium-term erosion rate ($R_n<0$) or sedimentation rate ($R_n>0$) at selected sampling points, associated with the no-till period (kg m^{-2} $year^{-1}$), can be estimated by comparing the mass depth of the zone of homogeneous mixing of ^{137}Cs in the soil ($h(t)$, kg m^{-2}) at the time of sampling (t, y), with the estimated plough depth (H, kg m^{-2}) at the time of cessation of conventional tillage (t', y). Assuming that the whole study area was affected by erosion during the conventional tillage period and that no ^{137}Cs fallout occurred during the no-till period, the depth of the zone of homogeneous mixing of ^{137} Cs in the soil at the time when conventional tillage ceased, t', would be equal to the plough depth H. The reduction or increase in $h(t)$ relative to H (i.e. $h(t)$ - H, kg m^{-2}) represents the total amount of soil erosion or deposition occurring during the period extending from the time of introduction of the no-till system to the time of sampling. The annual erosion or deposition rate R_n can therefore be estimated as:

$$R_n = \frac{h(t) - H}{t - t'} \tag{1}$$

3.3.1.2. Estimation of the erosion rates during the preceding period of conventional tillage: The ^{137}Cs depth distribution in the soil at the end of the period of conventional tillage can be reconstructed by assuming that the zone of homogeneous mixing would have extended to depth H and that the mean ^{137}Cs mass activity density ($\overline{C}$ (t), Bq kg^{-1}) in the upper part of the residual portion of the zone of homogeneous mixing (i.e. down to $h' \leq h$) at the time of sampling is a direct reflection of that existing in the plough layer at the end of the period of conventional tillage. The loss (negative value) or gain (positive value) in the areal activity density (ΔA, Bq m^{-2}) during the subsequent no-till period can thus be estimated as:

$$\Delta A = [h(t) - H]\overline{C}(t) \tag{2}$$

The total areal activity density ($A(t')$, Bq m^{-2}) at the measuring points at the end of the period of conventional tillage (or the beginning of the period of no-till) can therefore be estimated as:

$$A(t') = \left[A(t) - \{h(t) - H\}\overline{C}(t)\right] \exp\left[Ln(2)(t - t')/T_m\right] \tag{3}$$

where $A(t)$ (Bq m^{-2}) represents the areal activity density at each sampling point measured at the time of sampling and T_m (years) is the half-life of ^{137}Cs.

Comparison of the estimates of the total ^{137}Cs areal activity density at the end of the period of conventional tillage for the sampling points with the local reference value enables the erosion rate during the period of conventional tillage (R_c) to be estimated for these points using one of the conversion models for cultivated soils documented by Walling and He (1999). In this situation, it is simply assumed that the samples were collected at the same time as the shift from conventional tillage to no-till and that the estimated erosion rate applies to the period extending from the onset of ^{137}Cs fallout to that date.

3.3.2. The simplified method for extending the application of the standard method

The standard method, described above, requires appreciable effort, both in terms of the need to collect depth incremental samples and the resulting large number of samples requiring analysis for ^{137}Cs activity. The latter limitation is particularly significant for sites where ^{137}Cs activities are low and extended gamma count times are required. A simpler approach, that can be applied to additional sampling points in the study field to estimate the erosion rates associated with the periods under conventional tillage and a no-till system has also been proposed and validated by Schuller et al. (2004).

The depth distributions of ^{137}Cs obtained for individual sampling points along a slope transect at a site under a no-till system at the time of sampling, where the standard method was applied, indicated that only a small proportion of the total inventory was found below mass depth *h*. In addition, a significant linear relationship (r = 0.999, p < 0.01) was found between $A_{h,}$ the areal activity density down to *h*, and the total areal activity density, *A* (Schuller et al., 2004). The well-defined relationship between these two variables makes it possible to estimate A_h for additional points at the study site, where only the total areal activity density, *A*, has been measured using bulk (unsectioned) cores. Assuming that the ^{137}Cs mass activity density is approximately constant down to depth *h* and that the bulk density of the soil will also be almost constant down to this depth, *h*(*t*) can be estimated using the relationship:

$$h(t) = \frac{A_h(t)}{\overline{C}(t)} \tag{4}$$

where $\overline{C}$ (*t*) (Bq kg^{-1}) is the mean ^{137}Cs mass activity density measured in the upper part of the soil profile (down to $h' \leq h$) at the sampling points. Using the relationship between *A* and A_h, and Eq. (4), measurements of *A*(*t*) and $\overline{C}$ (*t*) at additional sampling points enables the key parameters for the ^{137}Cs depth distributions associated with the two tillage periods to be estimated for those points. These in turn allow the mean annual soil redistribution rates for the periods under conventional tillage and no-till practice to be estimated. This simplified approach was validated by Schuller et al. (2004), by demonstrating a very close correspondence between the results obtained using this method and those provided by the standard method for the same sampling points.

One limitation of the approach for comparing rates of soil loss under conventional tillage and under a subsequent no-till system, described above, is that it is not applicable to sampling points where deposition occurred during the period of conventional tillage, since this would result in the depth of homogeneous mixing exceeding the plough depth *H* at the beginning of the no-till period. This would make it impossible to estimate the rate of soil loss associated with the no-till period, since the method employed assumes that the depth to which appreciable ^{137}Cs activity is found at the onset of the no-till system corresponds to the plough depth *H*. For this reason the approach can only be used to assess the change in soil redistribution rate at sampling points that were eroding under conventional tillage. The approach is able to determine whether the introduction of a no-till system at these sampling points resulted in either an increase or decrease in the erosion rate or a shift to deposition.

3.4. STUDY DETAILS

3.4.1. The study site

The study site is the same as that used by Schuller et al. (2004) to trial the approach described above. It is located on a farm in the Coastal Mountains of the 9th Region of Chile (38º37´S 73º04´W), characterized by Araucano series Ultisols (Typic Hapludult), a temperate climate and a mean annual precipitation of 1100 mm y^{-1}. The field, cultivated annually for crop production, was under conventional tillage until May 1986, when there was a change to a no-till system. A second site, located close to the study site and with a similar soil type, but where conventional tillage had been practiced to the present, was selected to estimate the historical plough depth. Representative soil collected from the study field under no-till was also used to construct a small experimental plot (0.5 m^2) with zero slope at the University Austral de Chile Santa Rosa Experiment Station near Valdivia, in order to undertake experimental measurements of ^{137}Cs adsorption by the surface soil. The alternative location for these experimental measurements was necessary in view of the use of radioactive material, but the experiment was not dependent on the local conditions, apart from the soil.

In the region of the study site, significant atmospheric deposition of ^{137}Cs was last recorded in 1983 (Juzdan, 1988) and it can therefore be safely assumed that the existing ^{137}Cs inventory was mixed homogeneously within the plough layer by conventional tillage prior to the implementation of the no-till system. This is an important assumption of the approach proposed by Schuller et al. (2004).

3.4.2. Establishing the relaxation mass depth of the initial ^{137}Cs depth distribution

The use of the conversion models proposed by Walling and He (1999) to estimate the rate of soil loss at a sampling point during the period of conventional tillage necessitates specifying a value for the parameter representing the relaxation mass depth of the initial distribution of fallout ^{137}Cs in the soil profile, prior to its incorporation into the plough layer by tillage (h_o, kg m^{-2}). The estimates of soil loss generated by the models are sensitive to the value ascribed to this parameter and, in the absence of an empirical site-specific value for the study area, experimental measurements were undertaken as part of the study. These aimed to establish a value of this parameter, representative of the local conditions, and, more particularly, the local soils (Araucano series Ultisols) and the intense rainfall during winter. The measurements were undertaken on the 0.5 m^2 experimental plot described above. Cs-137 was applied to the surface of the plot using ^{137}Cs-labelled soil. The labelled soil was produced by adding a gamma standard solution supplied by the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany), containing about 350 Bq ^{137}Cs, to a 0.5 kg sieved soil sample, previously collected from the plot's surface. The amount of ^{137}Cs added to the labelled soil was calculated to minimise the amount used, whilst permitting reliable measurement of the ^{137}Cs depth distribution and thus the relaxation mass depth of the freshly added ^{137}Cs, using a Petri-dish measuring geometry with a corresponding detection limit of 10 Bq kg^{-1}. The labelled soil was transported without delay to the experimental site and applied uniformly to the plot. To replicate local conditions associated with conventional tillage, where soils commonly remain bare after seeding and exposed to the intense winter rainfall, the labelled soil was added to the plot in early July 2004.

3.4.3. Sample collection and measurement

In a previous study (Schuller et al., 2004), six depth incremental profiles and two replicates were collected along a slope transect at the study site, in order to establish the relationship between A_h and A. To extend the results of this earlier study, samples were collected from a greater number of sampling points covering a larger and more representative area of ca. 5000 m^2, which included five of the points sampled previously. This area was selected to be representative of an area likely to be susceptible to erosion during the period of conventional tillage. Additional bulk soil samples for establishing the total ^{137}Cs areal activity density A and the ^{137}Cs mass activity density $\overline{C}$ down to $h' \leq h$, were collected during 2003, from between seven and eight points, located at 15 m intervals along four additional parallel slope transects extending down the upper and middle portions of the slope (see Fig. 3.1). At each point, three 25 cm long and two 8 cm long cores were collected using an 7.6 cm diameter corer, in order to determine A and $\overline{C}$, respectively.

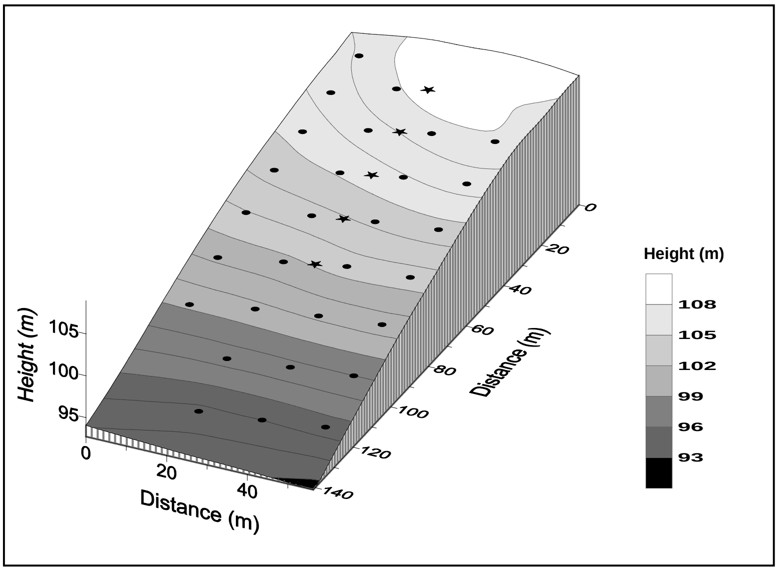


Fig. 3.1. The sampling points used for the study area within the sampled field. The points for which data from the previous study at the site described by Schuller et al. (2004) were used are marked by crosses.

At the additional site, located close to the study field where conventional tillage had continued to the present, depth incremental samples were collected to establishing the historical plough depth *H*, based on the ^{137}Cs depth distribution. A depth increment of 1 cm was used in the vicinity of the expected plough depth, in order to define this as precisely as possible.

From the 0.5 m^2 plot at the Santa Rosa Experiment Station, that had been labelled with ^{137}Cs, nine soil cores (4 cm long and 11 cm in diameter) were collected in spring 2004, 3.5 months after its labelling, when the crop began to sprout. During the sampling procedure, half of the labelled area was left undisturbed in order to permit future measurement of the long-term relaxation mass depth under the same soil and climatic conditions. The nine cores were sectioned into 2-mm slices in the laboratory and the slices representing specific depth increments were bulked for measurement as a single mixed sample. A special device, comprising a piston connected to a threaded rod which extruded the core from the core tube 1 mm per turn, was designed and constructed to undertake the sectioning.

All the soil samples were first air dried and then dried at 105°C in an oven, prior to being ground. To homogenize its ^{137}Cs content, each sample was mixed for 25 min using a shaker mixer (Turbula T2 F, Willy A. Bachofen Maschinenfabrik, Basel, Switzerland). After mixing, the bulk core and the 1 cm depth incremental samples collected to establish the plough depth were transferred to 500 ml Marinelli beakers and the 2 mm depth slice samples were placed in 81 ml Petri dishes, in preparation for counting. The ^{137}Cs analysis was undertaken by gamma spectrometry, using a Canberra high-purity Ge detector (Canberra Industries, Inc., Meriden, CT), with relative efficiency of 28%. The detector was calibrated for the selected measuring geometries and different soil densities by counting calibration samples prepared using a gamma standard solution supplied by the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany). The gamma spectra were analyzed using Genie 2000 software (Canberra Industries, Inc., Meriden, CT). Due to the low ^{137}Cs concentrations in the samples analyzed, the count time was set to 20 h per sample, which provided a measurement precision of better than ±10% at the 95% level of confidence. The ^{137}Cs detection limit for this measuring time was estimated to be approximately 0.3 Bq kg^{-1} for the Marinelli geometry and 10 Bq kg^{-1} for the Petri geometry employed.

3.4.4. Calculation procedures

The parameters A and $\overline{C}$ were calculated for each sampling point as the mean of the individual measured values of ^{137}Cs activity density in the samples collected at that point.

To determine the relaxation mass depth of the initial depth distribution of the ^{137}Cs in the soil, an exponential decrease of the ^{137}Cs mass activity density $C(x)$, Bq kg^{-1}, with mass depth x, kg m^{-2} was assumed, based on previously reported ^{137}Cs depth distributions in undisturbed soils (e.g. Schuller et al., 1997; Walling and He, 1999). The initial ^{137}Cs depth distribution can therefore be represented as:

$$C(x) = C(0)exp(-x/h_o) \qquad (5)$$

where $C(0)$ is the mass activity density of the surface soil (at $x=0$) and h_o the relaxation mass depth.

The areal activity density below depth x, $A(x)$, Bq m^{-2}, for the initial ^{137}Cs distribution is therefore

$$A(x) = \int_x^\infty C(x)dx = A(0)exp(-x/h_o) \qquad (6)$$

giving the total areal activity density, $A(0)$, Bq m^{-2}:

$$A(0) = \int_0^\infty C(x)dx = h_o C(0).$$

The relaxation mass depth, h_o, kg m^{-2}, describes the shape of the initial depth distribution of both the mass activity density (Eq. (5)) and areal activity density (Eq. (6)) of the ^{137}Cs in the soil. From Eq. (6) it follows that the areal activity density below the relaxation mass depth is $A(h_o) = 0.368A(0)$, and that initially 63.2% of the total areal activity density of the fresh deposited ^{137}Cs will be found within the 0 to h_o soil layer (or above h_o).

By measuring the mass activity density, C, in different 2 mm depth increments of soil collected from the labelled plot and establishing the mass depth of each depth increment, the values of $A(x)$ for the corresponding mass depths x can be calculated. Based on the logarithmic form of Eq. (6)

$$\ln[A(x)] = \ln[A(0)] - x/h_o \qquad (7)$$

h_o can be deduced from a linear regression between the calculated values of Ln[$A(x)$] and x.

3.4.5. Estimation of soil redistribution rates

A_h was estimated for each sampling point using the linear regression between A_h and A documented for the study site by Schuller et al. (2004) i.e.

$$A_h(t) = 1.006A(t) - 31.5 \qquad (r = 0.999, p < 0.01)$$

Soil redistribution rates during the no-till period were estimated using Eqs. (4) and (1).

The erosion rates associated with the period of conventional tillage were estimated using Eq. (3) coupled with the mass balance conversion model incorporating soil redistribution by tillage developed by Walling and He (1999). The reference inventory used for the calculations was based on that determined previously for a neighbouring site (Schuller et al., 2003), taking account of the influence of local variation in annual precipitation. This value 525±12 Bq m^{-2} for 1998, whilst relatively low from a global perspective, was consistent with existing understanding of the dependence of ^{137}Cs areal activity density on the local mean annual precipitation for the 9th and 10th Regions of Chile (Schuller et al., 2002).

3.5. RESULTS

3.5.1. Historical plough depth

Fig. 3.2 depicts the ^{137}Cs depth distribution observed at a point susceptible to erosion, located within the site where conventional tillage has continued to be practiced until the present day. Using this information and the ^{137}Cs depth distributions documented at other eroding locations within the site, the historical plough depth for the study site was estimated to be 170 kg m^{-2}, based on the mean mass depth of the zone of ^{137}Cs homogeneous mixing in the annually ploughed soil.

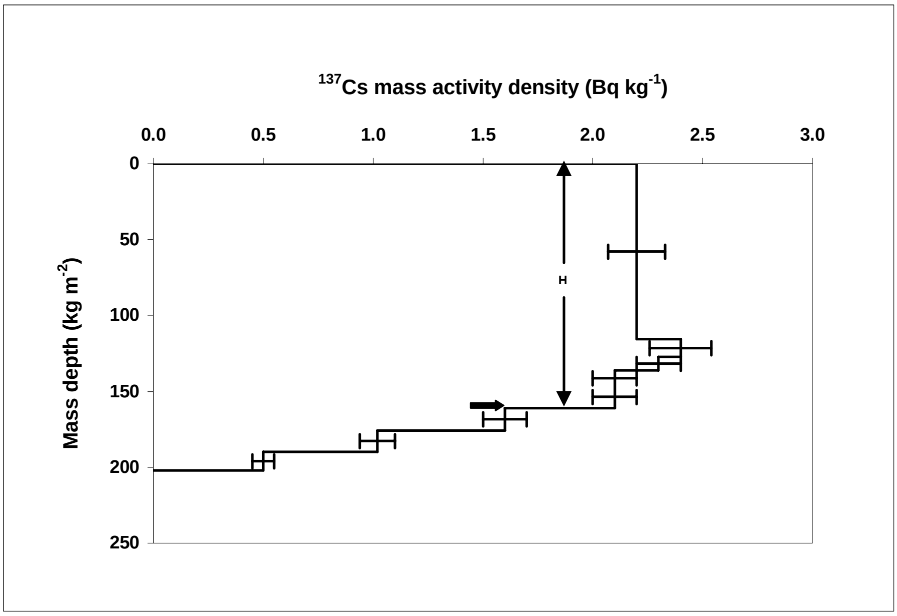
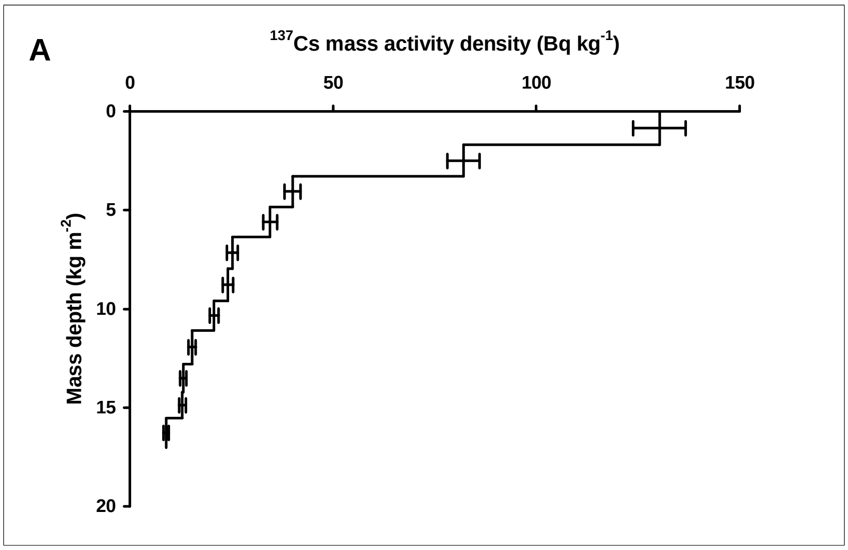


Fig. 3.2. Determination of the historical plough mass depth *H* (kg m^{-2}) under conventional tillage practice, for conditions similar to those of the study area.

3.5.2. The relaxation mass depth of the initial ^{137}Cs depth distribution

Fig. 3.3 presents the results of the experiment aimed at establishing the relaxation mass depth of the initial ^{137}Cs depth distribution. It shows the depth distribution of the ^{137}Cs in the soil, 3.5 months after the surface of the plot was labelled. During this period the soil remained bare and undisturbed and the precipitation recorded for the local area was 798 mm. The relaxation mass depth determined from Fig. 3.3 is 6.2±0.3 kg m^{-2}, which corresponds to a depth of approximately 8 mm. This value is a little higher than that suggested as a typical value (~4 kg m^{-2}) by Walling et al. (2002) and this may reflect the high rainfall received at the study site and/or the properties of the local soils.



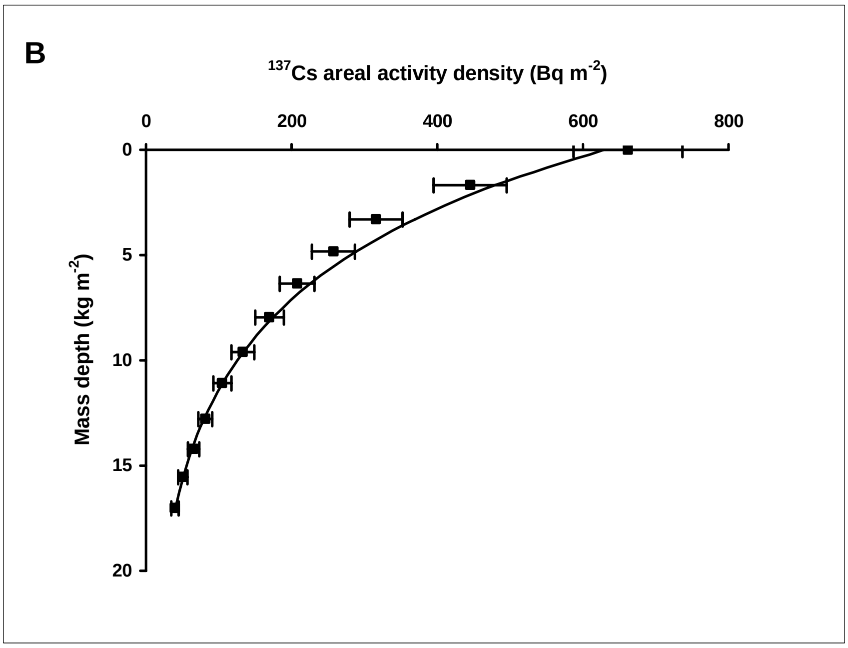


Fig. 3.3. (A) The initial distribution of fresh fallout simulated by applying ^{137}Cs labelled soil to the small plot at the Santa Rosa Experiment Station, and (B) the determination of the short-term relaxation mass depth for ^{137}Cs, using the results represented in Fig. 3.3A.

3.6. SOIL REDISTRIBUTION RATES

The parameters used in the mass balance conversion model incorporating soil movement by tillage developed by Walling and He (1999), that was employed to calculate erosion rates during the period of conventional tillage, are listed below:

- Reference inventory: 700 Bq m^{-2} (May 1986).
- Year of sample collection: 1986.
- Proportion factor (γ): 0.8.
- Relaxation mass depth: 6.2 kg m^{-2}.
- Plough depth: 170 kg m^{-2}.
- Tillage flux (φ): 210 kg m^{-2} $year^{-1}$.
- Particle size correction: 1.0.

The results obtained during this study for the 29 sampling points in the study field, using the simplified method have been combined with those obtained from the previous application of the standard method for a single slope transect (five points) within the same area, to provide information from five slope transects. Fig. 3.4 presents the spatial distributions of the soil redistribution rates obtained for the conventional tillage period (A) and no-till period (B). These were mapped using a kriging procedure. Summary statistics for the study area relating to the periods of conventional tillage and no-till have been derived using an areal weighting procedure applied to the soil redistribution rates estimated for the 34 sampling points within the study area and these are presented in Table 3.1.

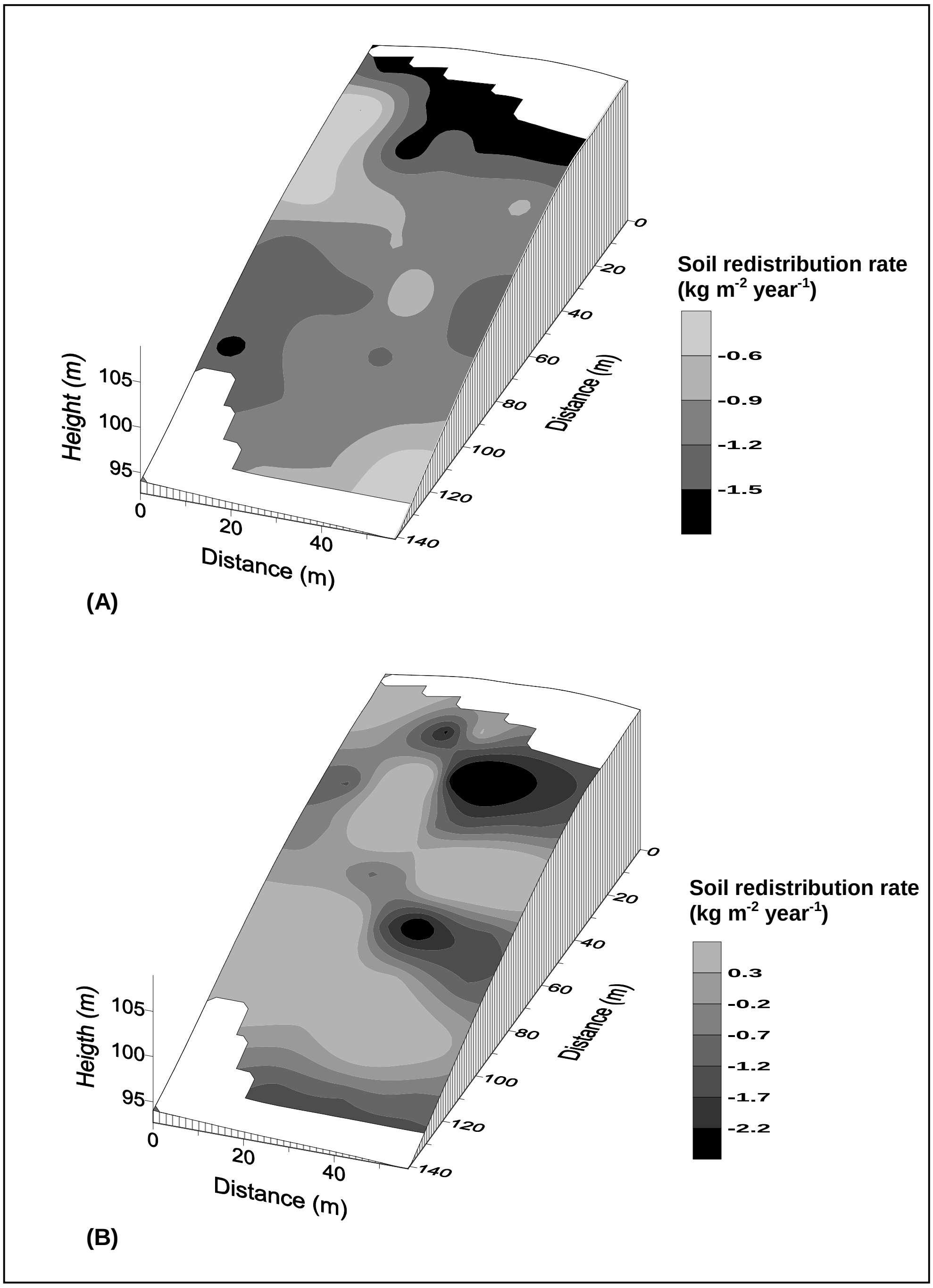


Fig. 3.4. The spatial patterns of mean annual erosion (negative values) and deposition (positive values) rates, established for the study area using ^{137}Cs measurements, for the period of conventional tillage (A) and during the subsequent period of no-till management (B).

Table 3.1. The soil redistribution rates for the two periods under contrasting tillage systems, documented using ^{137}Cs measurements.

	Conventional tillage period	No-till period
Eroding zone		
Mean erosion rate (kg m^{-2} year^{-1})	1.1±0.2	1.3±0.2
Fraction of total area (%)	100	57
Aggrading zone		
Mean sedimentation rate (kg m^{-2} year^{-1})	0.0	1.4±0.2
Fraction of total area (%)	0	43
Total area:		
Net erosion rate (kg m^{-2} year^{-1})	1.1±0.2	0.14±0.2
Sediment delivery ratio (%)	100	19

For the conventional tillage period, extending from the beginning of ^{137}Cs fallout in 1954 to the shift to no-till practice in 1986, an area-weighted mean annual erosion rate for the study area of 1.1 kg m^{-2} year^{-1} (11 t ha^{-1} year^{-1}) was estimated. This value is seen to be representative of the upper and middle portions of the study field where erosion was expected to be the predominant soil redistribution process during the conventional tillage period. The results obtained corroborate this assumption, because all points investigated in the area evidenced erosion and the study area was therefore characterized by a sediment delivery ratio of 100%.

During the no-till period extending from 1986 to 2003, only 57% of the study area was affected by erosion, and this was characterized by an area-weighted mean erosion rate of 1.3 kg m^{-2} year^{-1}. The remainder of the areas was affected by deposition, with an area-weighted mean annual deposition rate of 1.4 kg m^{-2} year^{-1}. These results demonstrate that in the study area the shift from conventional tillage to a no-till system has caused soil erosion to decrease significantly to produce a net erosion rate of about 0.14 kg m^{-2} year^{-1}, a gross erosion rate of

0.73 kg m^{-2} $year^{-1}$, and a sediment delivery ratio of ca. 16%. Interestingly, the results obtained from the ^{137}Cs measurements show that within the study area, the shift to a no-till system caused erosion rates in parts of the area to increase. This increase might reflect compaction in some areas as a result of the cessation of cultivation. This would be most likely to occur in those areas where previous erosion had caused the highest rates of soil loss and thus soil degradation (e.g. reduced organic matter content and increased bulk density), and could result in local increases in surface runoff. However, this increase was coupled with a shift from erosion to deposition over more than 40% of the study area, with the result that the sediment delivery ratio decreased and both the gross and net soil loss from the study area decreased. In terms of soil degradation, the increased rates of soil loss over parts of the area must clearly be seen as undesirable, but >40% of the study area now experiences no soil loss and, equally importantly, the export of soil towards the stream network has been reduced to ca. 13% of that occurring during the period of conventional tillage. Overall, therefore, the introduction of no-till management can be seen to have coincided with a significant reduction in both gross and net soil loss within the study area and to have greatly reduced the potential for diffuse source pollution of the local watercourses by eroded sediment.

Although the results presented above clearly demonstrate that the shift to a no-till system coincided with a reduction of both gross and net erosion rates and the area subject to erosion, it is important to consider whether the change in soil erosion associated with the no-till period could reflect the influence of other factors, and, more particularly, reduced annual rainfall. A plot of the medium-term record of annual rainfall totals for Temuco Airport, some 45 km from the study site is presented in Fig. 3.5. The mean annual rainfall for this measuring station over the period 1960 to the present is ca. 1230 mm, and therefore a little higher than the 1100 mm reported for the study site. However, it is thought that both stations would have experienced similar trends in annual rainfall over the past 40 years. Fig. 3.5 indicates that the years since 1986 and the introduction of a no-till system at the study site have generally been marked by reduced annual rainfall, with the mean for the period 1986 to 2003 being 1151 mm and ca. 11% lower than that for the preceding period extending from 1960 to 1985 (i.e. 1290 mm). It is clear that the reduced annual rainfall associated with the period since the introduction of no-till is likely to have contributed to the reduced soil loss during this period, but in view of the substantial length of the period (18 years) and the occurrence of many years with annual rainfall totals similar to those associated with the preceding period under conventional tillage, it is suggested that the shift to a no-till system represents the primary cause of the reduced rates soil loss and sediment delivery documented for the period under a no-till system.

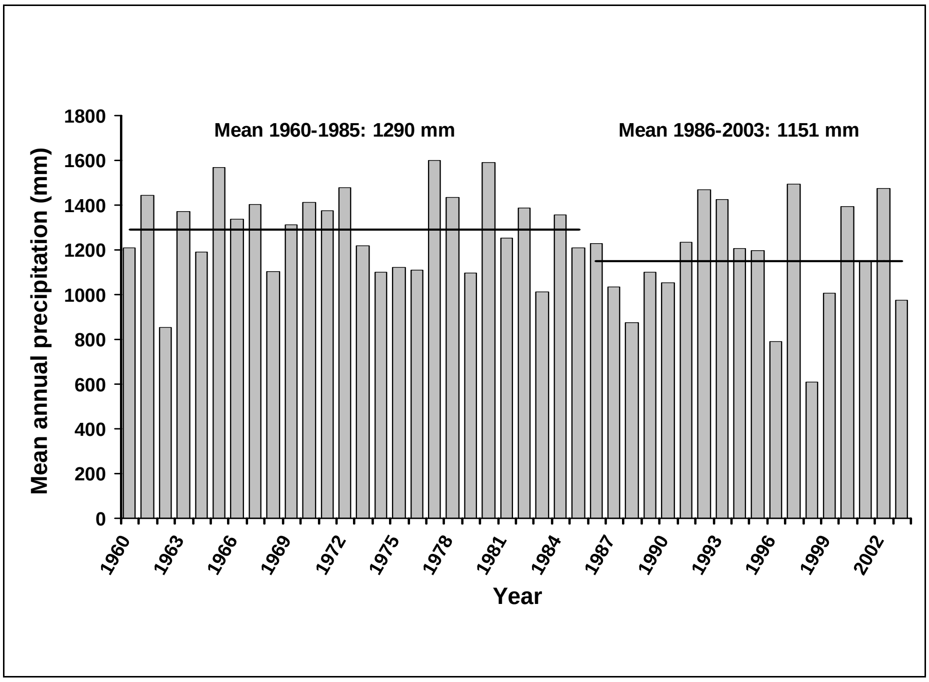


Fig. 3.5. A comparison of the mean annual rainfall at Temuco Airport for the part of the period of record when the study field was under conventional tillage, with that for the period after the introduction of a no-till system (i.e. post 1986).

3.7. CONCLUSION

Cs-137 measurements provide a valuable alternative to conventional techniques for assessing the impact of changes in land management on soil erosion rates. The simplified method for using ^{137}Cs measurements to establish the change in erosion rates associated with a shift from conventional tillage to a no-till system, developed by Schuller et al. (2004), has the important advantage of only requiring two ^{137}Cs measurements per sampling point and of avoiding the need to collect depth incremental samples at all points, to estimate the soil redistribution rates for the periods covered by each tillage system. Since it requires far fewer ^{137}Cs measurements, the simplified approach also allows data to be assembled for a larger number of sampling points and thus from a larger area, thereby providing a more rigorous assessment of the changes in soil erosion rates associated with the change in tillage system.

The simplified method for using ^{137}Cs measurements to establish the impact of a change in tillage practice on soil erosion rates was successfully employed in a study of a field located on a farm in south-central Chile. The results demonstrated a significant decrease in the rate of net soil loss and the portion of the study area subject to erosion, as well as in the sediment delivery ratio for the study area. The shift from conventional tillage to a no-till system was associated with a decrease in the net soil loss from the study area, by 87% and the proportion of the study area subject to erosion decreased from 100% to 57%. Although some of this reduction in the proportion of the study area subject to soil erosion and in the rates of net soil loss might reflect the lower annual rainfall totals at the study site since 1986, it is suggested that most of the reduction reflects the influence of the shift from a system of conventional tillage to a no-till system. The reduced soil loss has important benefits for the sustainable use of the soil resource and the reduced sediment delivery ratio will result in a reduction in sediment transfer to the local watercourses, which will in turn reduce the offsite effects of soil erosion and, more particularly, diffuse source pollution associated with sediment inputs to the stream network. These changes clearly demonstrate the potential environmental benefits of a shift from conventional tillage to a no-till system.

3.8. ACKNOWLEDGEMENTS

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4. USE OF ^{7}Be TO ESTIMATE THE IMPACT OF A PERIOD OF INTENSE RAINFALL ON SOIL REDISTRIBUTION WITHIN A FIELD UNDER A NO-TILL AND BURNING OF CROP RESIDUE SYSTEM[4]

4.1. ABSTRACT

For many years a field located in south central Chile (38°37'S 73°04'W, mean annual rainfall 1100 mm) was cultivated under a no-till without burning of crop residue (NTNB) system. However, after harvesting in early 2005 (summer) and before the wet season began, the crop residue remaining on the field was burnt, leaving the soil bare until the onset of heavy rainfall in the autumn. Following a prolonged dry period, a period of very heavy rainfall (400 mm in 27 d) occurred during May 2005. Beryllium-7 (^{7}Be) measurements, coupled with a conversion model which permitted estimates of rates of soil redistribution to be obtained from the values of ^{7}Be areal activity density, were used to document the amounts and pattern of soil redistribution within the field associated with the period of heavy rainfall under no-till with burning of crop residue (NTWB) system. The net soil loss from the field associated with the period of heavy rainfall, estimated from the ^{7}Be measurements, was considerably higher than the mean annual rate of soil loss from the field during the previous 16-y period of no-till, no-burn system estimated using ^{137}Cs measurements. The net erosion amount for the period of heavy rainfall was 1.2±0.2 kg m^{-2}. This value is 8.6 times higher than the mean annual net erosion rate estimated for the previous tillage system. The sediment delivery ratio associated

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[4] Preliminary version of:
Sepulveda, A. et al., Use of ^{7}Be to document soil erosion associated with a short period of extreme rainfall, J. Enviro. Radioact. (2007), doi: 10.1016/j.jenvrad.2007.06.010.

with the soil redistribution resulting from the period of NTWB was 88%, whereas the sediment delivery ratio associated with the soil redistribution occurring during NTNB was only 19%. The results obtained suggest that the burning of the crop residue in the summer increases soil loss during the following rainy season, especially if high magnitude erosive events occur. Burning of the crop residue may therefore be an undesirable component of the no-till system. The ^{7}Be method provides an effective means of documenting erosion associated with individual periods of heavy rainfall and investigating the influence of different tillage systems on soil redistribution amounts.

Keywords: ^{7}Be; ^{137}Cs; No-till; Soil erosion; Burning crop residue; Chile

4.2. INTRODUCTION

Existing studies and investigations of soil loss have confirmed that agriculture is the main production system contributing to the degradation of natural resources (FAO, 2002a). For this reason, sustainable agriculture based on conservation management practices is being promoted worldwide. From the perspective of soil loss and soil degradation, sustainable agricultural practices commonly involve no-till or reduced tillage systems (FAO, 2002b). The aim of such conservation tillage systems is to maintain a balance between soil conservation and crop production, reducing tillage to the minimum necessary to fulfil this purpose (Birkás et al., 2004).

In order to promote effective soil resource conservation, it is important to investigate and assess the changes in soil rates associated with changes in the tillage system. The radionuclides caesium-137 (^{137}Cs) ($t_{1/2}$ = 30.17 a), unsupported lead-210 (^{210}Pb) ($t_{½}$ = 22.2 a) and beryllium-7 (^{7}Be) ($t_{1/2}$ = 53.3 d) provide valuable tools for use in documenting soil redistribution rates over different timescales. More specifically, use of the cosmogenic, short-lived radionuclide ^{7}Be provides an effective means of documenting the soil loss associated with individual erosive events (e.g. Wallbring and Murray, 1993; Blake et al., 1999; Wilson et al., 2003; Schuller et al, 2006a), whereas ^{137}Cs and unsupported ^{210}Pb can be used to provide estimates of longer-term erosion rates (Zapata, 2002; Walling and He, 1999).

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 at a given date its atmospheric concentration 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 deposited at the soil surface (Salisbury and Cartwright, 2005). The ^{7}Be reaches the soil surface mainly as the Be^{2+} ion, which is extremely competitive for the cation exchange sites, because of its high charge density (Kaste et al., 2002). As ^{7}Be comes into contact with the vegetation canopy and the soil it is rapidly and strongly fixed (Hawley et al., 1986; Wallbrink and Murray, 1996, Kaste et al., 2002) and remains predominantly in the vegetation canopy and in the upper centimetre of the soil profile (Blake et al., 1999; Walling et al., 1999; Doering et al., 2006). Existing evidence suggests that the initial vertical distribution of the ^{7}Be mass activity density, Bq kg^{-1}, within the soil is characterised by an exponential decrease with depth, with most of the radionuclide being contained within the upper few millimetres of the surface soil (Walling and Woodward, 1992; Blake et al., 1999; Schuller et al., 2006a). Any ^{7}Be found at a depth greater than 10 cm can be explained by the downward movement of soil particles though fissures in the soil surface formed during relatively dry periods (Olsen et al., 1985) and/or by bioturbation by soil fauna that can transport ^{7}Be to greater soil depths (Wallbrink and Murray, 1996).

The three key assumptions associated with the use of the ^{7}Be method to estimate soil redistribution are as follows (Schuller et al., 2006):

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

Considering the first assumption, any pre-existing spatial variability of the ^{7}Be areal activity density caused by previous erosion events will rapidly disappear by radioactive decay, providing the erosion episodes are separated by a period of sufficient length (i.e. longer than two half-lives). Contributions to ^{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 cultivated field, where the spatial distribution of both rainfall input and ^{7}Be fallout can be treated as uniform. This assumption restricts the applicability of the ^{7}Be method to soils where the interception of ^{7}Be fallout by the vegetation canopy is negligible i.e. the method is primarily applicable to bare soils. 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 Blake et al. (1999) and Wallbrink and Murray (1996).

For many years, a crop field located at Buenos Aires farm in south central Chile, was managed using a no-till and no burning of crop residue (NTNB) system. Schuller et al. (2007) have reported the use of ^{137}Cs measurements to document the longer-term (16-y) erosion rates under this system. However, after harvesting in 2005 and shortly before the commencement of the wet season, the crop residue remaining on the field under the no-till system was burnt. The objective of the present research is to investigate whether the burning of the harvest residue causes soil redistribution rates to increase when compared with those documented for the period prior to the introduction of burning (Schuller et al., 2004). For this purpose, the ^{7}Be method proposed by Blake et al. (1999) and by Walling et al. (1999) was employed. The investigation also provided an opportunity to use the ^{7}Be method to assess the soil redistribution associated with a discrete period of very heavy rainfall following the burning of the cop residue.

4.3. MATERIALS AND METHODS

4.3.1. The ^{7}Be method for documenting short-term soil redistribution: Conversion of ^{7}Be areal activity density measurements into soil redistribution estimates

The model proposed by Blake et al. (1999) and Walling et al. (1999) for agricultural land was used to convert ^{7}Be areal activity density measurements into estimates of soil redistribution. This approach is based on comparison of the ^{7}Be areal activity density, Bq m^{-2}, measured at a sampling point with the reference areal activity density associated with a nearby undisturbed and stable reference site, were neither erosion nor deposition are thought to have occurred (Schuller et al., 2006). The initial depth distribution at the stable reference site can be described by the exponential function

$$C(x) = C(0)\exp(-x/h_o) \qquad (1)$$

with x, kg m^{-2}, representing the mass depth measured from the soil surface (positive downward), $C(x)$, Bq kg^{-1}, the mass activity density of ^{7}Be **at** depth x, $C(0)$ the initial mass activity density of the surface soil (at $x=0$) and h_o, kg m^{-2}, the relaxation mass depth. Using this expression, the reference areal activity density, A_{ref}, Bq m^{-2}, is defined as

$$A_{ref} = A(0) = \int_0^\infty C(x)dx = C(0)h_o \qquad (2)$$

Therefore, the areal activity density **below** mass depth x, $A(x)$, Bq m^{-2}, is

$$A(x) = \int_{x}^{\infty} C(x)dx = A_{ref} \exp(-x/h_o) \tag{3}$$

The relaxation mass depth, h_o, describes the shape of the initial depth distribution of the ^{7}Be mass activity density (Eq. (1)) and areal activity density (Eq. (3)). By setting $x = h_o$ in Eq. (3),

$$A(h_o) = A_{ref} \exp(-1) = 0.37A_{ref} \tag{4}$$

it follows that 37% of the total areal activity density of ^{7}Be is contained below the relaxation mass depth.

If soil erosion processes remove a thin layer of mass depth R, kg m^{-2}, at a sampling point, the remaining areal activity density A, Bq m^{-2}, at that point will be lower than A_{ref}. The soil mass depth eroded per unit area at the point is equal to the mass depth R, kg m^{-2}, removed and can be deduced by setting $x = R$ and $A(R) = A$ in Eq. (3), i.e.:

$$R = h_o \mathrm{Ln}\left[\frac{A_{ref}}{A}\right]. \tag{5}$$

For sampling points within the study site, where ^{7}Be areal activity density A', Bq m^{-2}, is higher than A_{ref}, deposition is assumed to have occurred. In this case, the sediment mass deposited per unit area R', kg m^{-2}, can be estimated as

$$R' = (A' - A_{ref}) \,/\, C_d \tag{6}$$

where C_d, Bq kg^{-1}, represents the ^{7}Be mass activity density of the deposited sediment. C_d can be estimated as the weighted mean of the ^{7}Be mass activity density of sediment eroded from each point C_e, Bq kg^{-1}, within the upslope eroding area S, m^2:

$$C_d = \frac{\int_S C_e R dS}{\int_S R dS} \tag{7}$$

C_e can be calculated from the areal activity density lost at each point divided by the mass of sediment eroded per unit area at the corresponding point:

$$C_e = \frac{A_{ref} - A}{R} = \frac{A_{ref}(1 - e^{-R/h_0})}{R} \tag{8}$$

4.3.2. Study site and laboratory procedures

The study site selected is the same as that used by Schuller et al. (2004, 2007) to document changes in soil erosion rates associated with the shift from a 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 period extended from 1986 to 2003, the sampling year. The study site is located within crop field at Buenos Aires farm in the Coastal Mountains of south-central Chile (38º37'S 73º04'W). The soils are Araucano series Ultisol, Typic Hapludult (Centro de Información de Recursos Naturales-CIREN, 2002) and are texturally classified as very fine clay (Soil Survey Staff, 1993). This textural property is described as providing a high water retention capacity and plasticity along the soil profile. The topography of the site comprises a 170 m long slope 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 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). As indicated above, the field had previously been managed with a NTNB system for many years. This tillage system involved leaving the residue of the harvested crop on the soil surface and direct seeding using seed drills which cut throughout crop residues and open slots in the soil to place the seed and fertiliser (Schuller et al., 2007). 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 rainfalls in early May (autumn). The rainfall record for the period between January 1st and June 1st, 2005 is shown in Fig. 4.1.

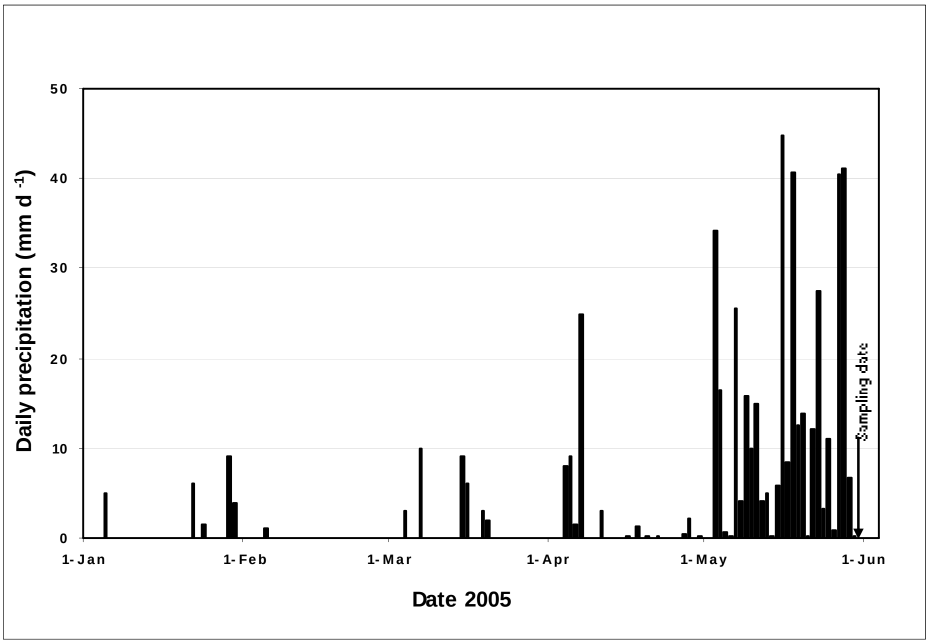

Fig 4.1. The daily precipitation record for the study site for the period from January 1st to June 1st, 2005. The arrow shows the date of collection of the soil samples used for ^{7}Be measurements (May 30, 2005).

After a prolonged dry period with little precipitation extending from January 1st to May 2nd, a period with an unusually high amount of precipitation occurred from May 3rd to 29th, 2005, producing a total of 400 mm in 27 days, including a 1-h period on May 18th during which 11.4 mm of rain fell. On May 30th, immediately after the period of heavy rainfall, the field was sampled for ^{7}Be measurements. The soil sampling was undertaken using the methods proposed by Walling et al. (1999).

To determine the parameters A_{ref} and h_o, a reference site located in a flat area at the top of the study slope (undisturbed stable area, not visible affected by soil erosion or sedimentation processes) was identified. From this site, nine soil cores (10.6 cm in diameter and 4 cm long) and nine replicate cores, were collected at the intersections of two 2 x 2 m grids. To evaluate the variation in areal activity density down the study slope, associated with erosion and deposition, samples were collected from 10 to 11 sampling points located at 15 m intervals along three slope transects spaced 15 m apart (see Fig. 4.2). At each sampling point, two soil cores were collected using the same corer as used for the reference site. Additionally, along the lower part of the transects, where deposition of sediment could be expected to have occurred, six cores were collected, in order to document the vertical distribution of ^{7}Be mass activity density and to observe the ^{7}Be penetration depth in the soil.

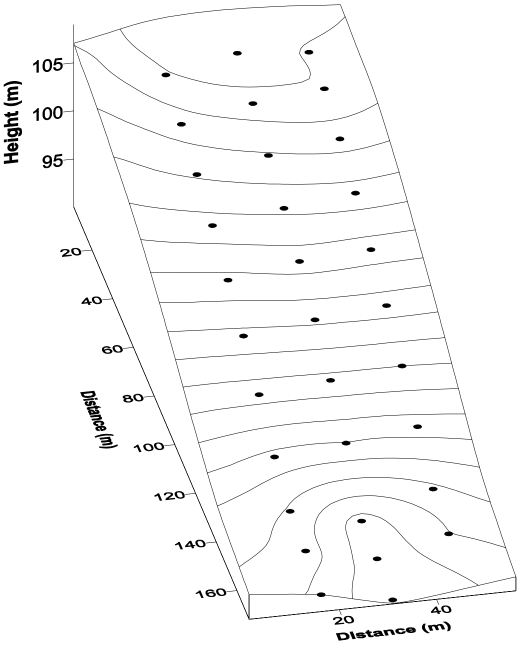

Fig. 4.2. Distribution of the sampling points at the study site.

To determine A_{ref} and h_o, each group of nine cores collected at the reference area was sectioned into 2-mm slices, and the slices representing specific depth increments for each group were bulked for measurement as a single composite sample. To document the ^{7}Be penetration depth at the base of the slope, the six cores collected from this area were also sliced into 2-mm layers, with each slice representing a specific depth increment being bulked for measurement. A special device was used for slicing the cores. This comprised a piston (with the same diameter as the internal diameter of the soil corer tube) moved by a screw thread. The piston is inserted into the base of the soil corer tube and can be used to extrude 1 mm of core per full turn of the screw. The slice of soil extruded by rotating the screw two turns (2 mm) is separated from the remaining core using a sharp pallet knife. The described tool was designed and successfully used by Schuller et al. (2006).

For the soil samples collected along the slope transects it was necessary to determine the depth to which the bulk cores should be collected, in order to maximize the counting efficiency. If the cores were too shallow, they would not include the full inventory. If, however, they were too deep, the ^{7}Be mass activity density of the bulk core would be reduced by mixing the ^{7}Be found in the upper part of the core with soil from a greater depth 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. The remainder of the core from greater depth was discarded.

Prior to the measurement of ^{7}Be activity, all the soil samples were air dried, then dried at 105ºC for 48 h 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 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, Meriden, CT) of 28% relative efficiency, 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). 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} (± 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 to 12 mm), four shallow soil cores were collected at the reference zone after the burning and these were compared with 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 dried at 105ºC for 48 h and weighed, to determine the depth distribution of the bulk density.

The change in the permeability of the soil caused by the burning of the crop residue was also assessed by comparing measurements of the hydraulic conductivity (K_{fs}) undertaken both before and after the burning. These measurements were made using a Guelph permeameter (Soil Moisture Equipment Corp., model 2800KI).

4.4. RESULTS AND DISCUSSION

4.4.1. Estimation of the magnitude of the soil redistribution

During the four months prior to May 2005, the amount and time-distribution of the precipitation documented for the study site (Fig. 4.1) provided no opportunity for significant erosion. The low daily precipitation totals, coupled with the high infiltration rates associated with the unsaturated soil conditions (from January to April) meant that no surface runoff and associated soil redistribution occurred and thus ensured a spatially uniform distribution of the ^{7}Be areal activity density across the study field immediately prior to the start of the period of heavy rainfall.

The linear regression between the natural logarithm of the mean areal activity density, $\mathrm{Ln}[A(x)]$, and the mean mass depth, x, based on samples and replicates collected at the reference site is shown in Fig. 4.3. The correlation coefficient $r = 0.997$, which is significant at the 99% level of confidence, confirms the hypothesis of an exponential decrease of the areal activity density with depth for undisturbed soils. The values obtained from this relationship for the relaxation mass depth, h_o, and the reference areal activity density, A_{ref}, were 3.4±0.1 kg m^{-2} and 499±10 Bq m^{-2} respectively.

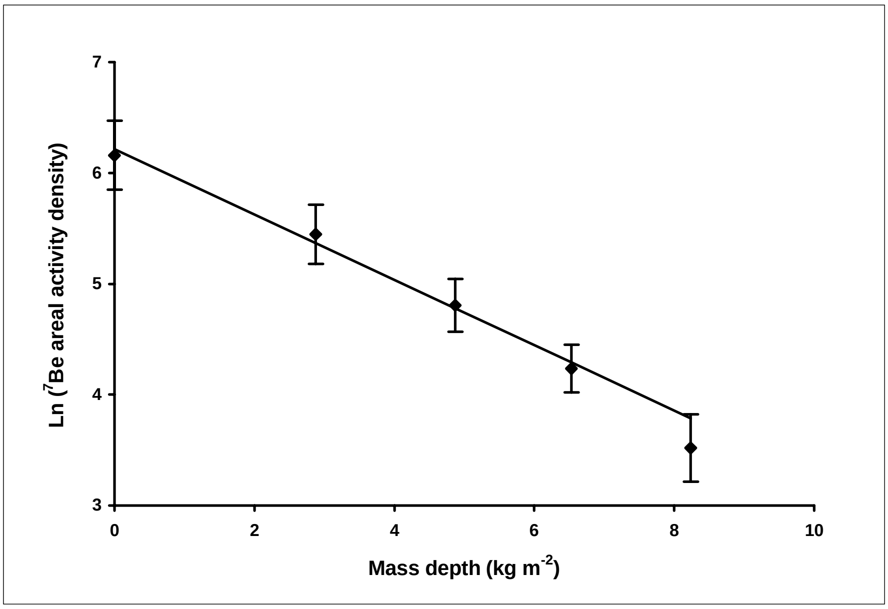

Fig. 4.3. A linear regression between the natural logarithm of the ^{7}Be areal activity density and the mass depth based on the sectioned cores collected from the reference site.

The calculated relaxation mass depth indicates that 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, at the reference site. 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 eroding points. Due to the exponential depth distribution of the areal activity density, the ^{7}Be method is very sensitive to surface erosion and soil redistribution, i.e. to the decrease or increase in the areal activity density relative to the reference value A_{ref} and is able to document the small amounts of erosion and deposition associated with short periods of time.

The reference inventory obtained for the study site is consistent with other values for studies undertaken in the southern hemisphere. ^{7}Be areal activity densities reported in Australia varied 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 soils (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).

Figure 4.4 depicts the depth distribution of the mean ^{7}Be mass activity density and the mean ^{7}Be areal activity density at the reference site. The shape of both distributions (Fig. 4.4 A and 4.4 B) are described by the relaxation 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 Eq. (1) and (3), the resulting expressions for the mass activity density and areal activity density are

$C(x) = 147 \exp(-x/3.4)$ and
$A(x) = 499 \exp(-x/3.4)$,

respectively. These functions are shown as continuous lines on Fig. 4.4 A and B, respectively. The ^{7}Be activity falls below the detection limits at mass depth 11.8 kg m^{-2} (~ 12 mm); for this reason, 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.:

$$499 - \int_{11.6}^{\infty} 147 \exp(-x/3.4)dx = 483 \text{ Bq m}^{-2}$$

This value is in very close agreement with the mean areal activity density of 473±50 Bq m^{-2} measured at the reference site. The calculated value of 483 Bq m^{-2} was used as the reference areal activity density.

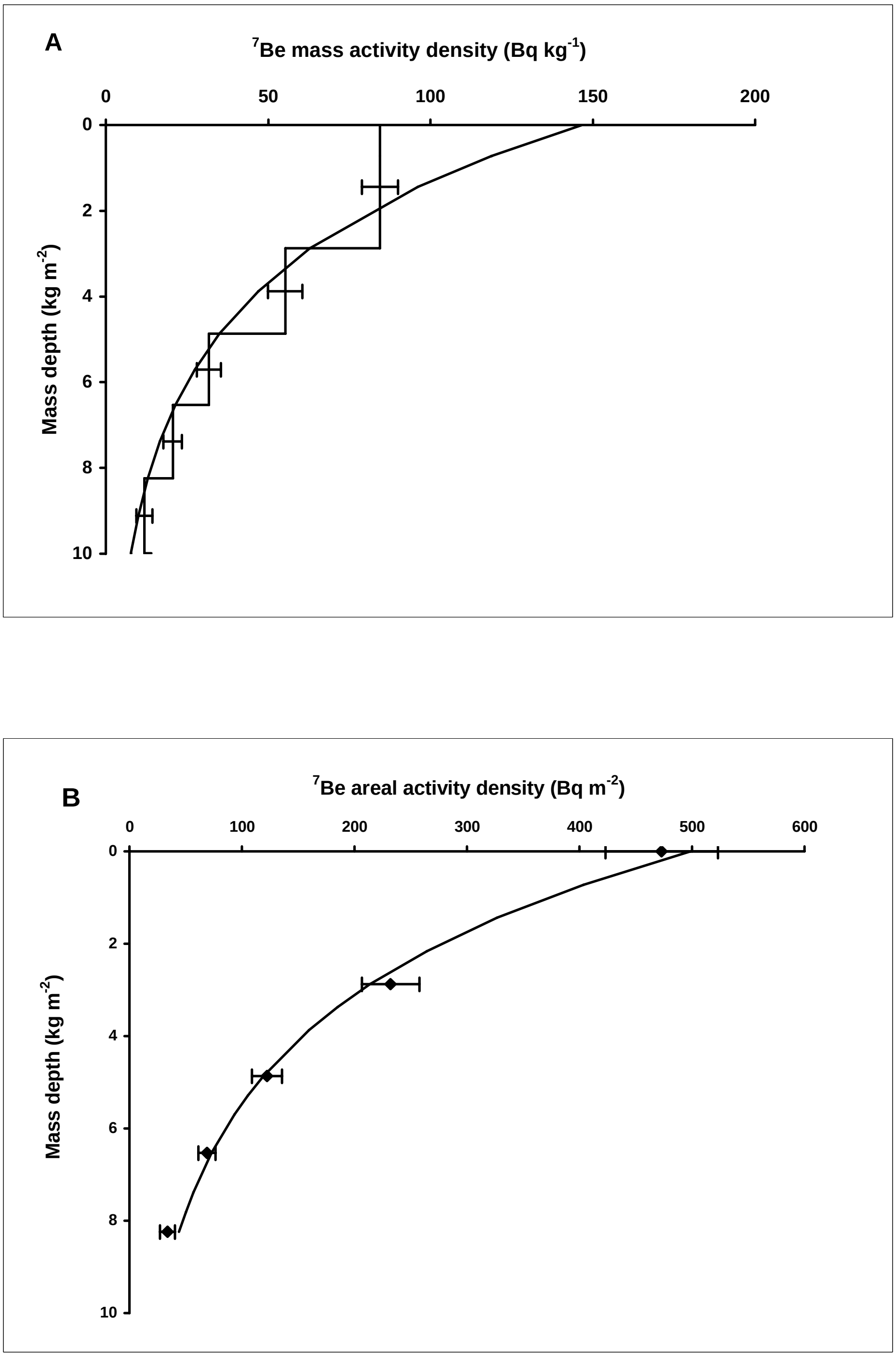

Fig. 4.4. The depth distribution of ^{7}Be at the reference site, showing: (A) the exponential decrease of the ^{7}Be mass activity density with mass depth and (B) the ^{7}Be areal activity density versus mass depth.

At the lower end of the sampled slope transects, the mean ^{7}Be areal activity density, based on the composite samples provided by slicing the six individual cores was 275±10 Bq m^{-2}. This value is significantly lower than the estimated A_{ref} and indicates a net soil loss from this zone of the slope transects, with the sediment being transported towards a filter strip covered by native shrub vegetation located at the lower border of the field.

The magnitude and pattern of soil redistribution associated with the period of heavy rainfall occurring in May 2005, estimated using the ^{7}Be method (Eq. (5) and (6)) for the 32 points (64 samples) located on three slope transects, are shown in Fig. 4.5.

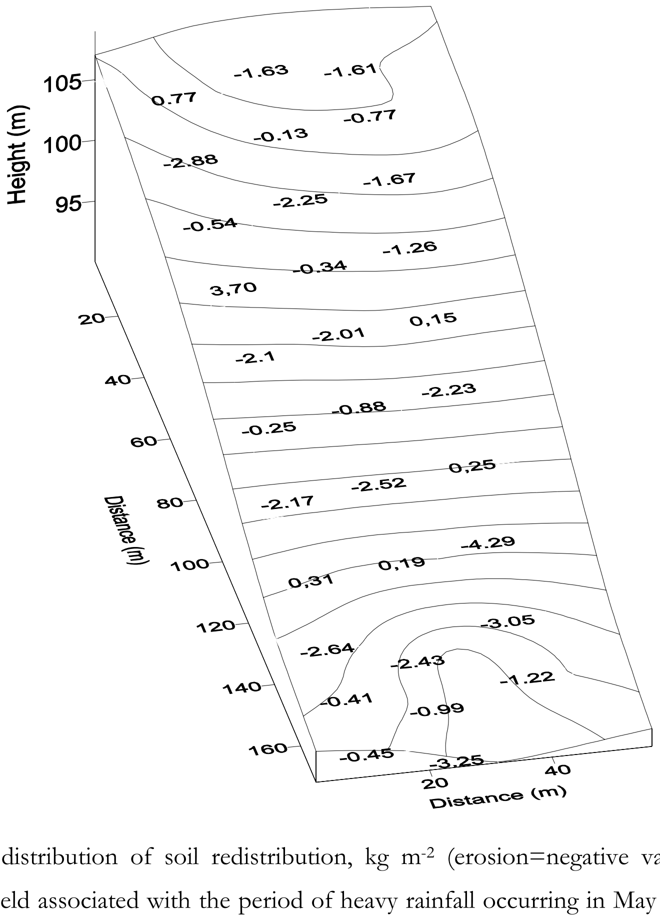

Fig. 4.5. The spatial distribution of soil redistribution, kg m^{-2} (erosion=negative values, deposition=positive values), in the study field associated with the period of heavy rainfall occurring in May 2005, estimated using the ^{7}Be measurements.

The summary statistics for the soil redistribution associated with the period of heavy rainfall occurring erosion in May 2005, after the crop residue had been burnt are presented in Table 4.1. These can be compared with the estimates of longer-term soil redistribution rates, based on ^{137}Cs measurements, obtained for the same field for the preceding 16-y period, when it was under a NTNB system and reported by Schuller et al. (2007). These data are also listed in Table 4.1.

Table 4.1. Comparison of the soil redistribution documented for the study site for the period of heavy rainfall in May 2005 following burning of the crop residue, based on ^{7}Be measurements, with previous estimates of mean annual soil redistribution rates under a NTNB system based on ^{137}Cs measurements (Schuller et al., 2007).

	No-till with burning (for a one month period of heavy rainfall, , estimated using ^{7}Be)	***No-till without burning*** (mean values for a 16 y period estimated using ^{137}Cs, Schuller et al., 2007)
Year	2005	1986-2003
Period	26 d	16 y
Precipitation	400 mm	1100 mm y^{-1}
Sampling points	32	34
Slope length (m)	170	130
Eroding Zone		
Mean erosion	1.7±0.2 kg m^{-2}	1.3±0.2 kg m^{-2} y^{-1}
Fraction of total area (%)	81	57
Aggrading zone		
Mean sedimentation	0.9±0.2 kg m^{-2}	1.4±0.2 kg m^{-2} y^{-1}
Fraction of total area (%)	19	43
Total area		
Net erosion	1.2±0.2 kg m^{-2}	0.14±0.2 kg m^{-2} y^{-1}
Sediment delivery ratio (%)	88	19

The results obtained for the soil redistribution caused by the period of heavy rainfall during May 2005 for the whole length (170 m) of the slope (table 4.1) are coincident within the uncertainty range with the results obtained for the same period for a reduced length (130 m) similar to that investigated for the NTNB system period.

Table 4.1 demonstrates that the net soil loss documented for the single period of heavy rainfall (400 mm) in May 2005, which followed burning of the crop residue, is substantially higher than the mean annual soil loss for the study site over the past 16-y under a NTNB system reported by Schuller et al. (2007). The pattern of soil redistribution documented for the period of heavy rainfall in May 2005, which is shown in Fig. 4.5 is characterized by a dominance of erosion across the study area. 81% of the area was affected by erosion and the mean erosion within this area was 1.7±0.2 kg m^{-2}. Deposition occurred over only 19% of the area, where the mean sedimentation was 0.9±0.2 kg m^{-2}. Because of the dominance of erosion, which can be related to both the heavy rainfall and the bare unprotected soil surface, and the limited area of deposition, the period of heavy rainfall in May 2005 was characterized by a high sediment delivery ratio of 88%. During the previous 16-y under a NTNB system, the mean annual soil redistribution rates were similar in magnitude to those associated with the period of heavy rainfall in May 2005, although the latter relate to a much shorter (1 month) period. However, the proportion of the area affected by erosion during the two periods is very different. During the 16-y period, when the study area was managed using a NTNB system, much of the soil mobilised by erosion was redeposited within the study area and the areal extent of the area experiencing erosion is very similar to that for deposition. As a result the sediment delivery ratio is relatively low (19%), indicating that only a small proportion of the mobilised sediment was moved beyond the study area and towards the stream network.

After burning of the harvest residue the susceptibility of the soil surface to raindrop impact increases and the sealing of the surface, the increased bulk density and the reduced hydraulic conductivity promote the generation of surface runoff. Together these effects increase both the mobilisation and transport of sediment within the study area. The net erosion associated with the one month period of heavy rainfall that occurred after the burning of the harvest residue was 8.6 times higher than the mean annual erosion associated with the previous 16-y period of NTNB system of the study area (1.2±0.1 kg m^{-2} and 0.14±0.2 kg m^{-2} y^{-1}, respectively). Furthermore, the aggrading zone associated with the period of heavy rainfall accounted for only 19% of the total area, whereas the equivalent area for the 16-y period under NTNB system was 43%.

Figure 4.6 depicts the change of the bulk density in the upper soil layer caused by burning of the harvest residues. The soil density measured for the first two millimetres of the soil profile immediately after the burning of the crop residue at the study site was found to be 1.6 times higher than the soil density measured for the same depth prior to the burning. This change in bulk density is ascribed to the partial loss of the organic rich surface horizon, the removal of which increases the susceptibility of the soil to erosion.

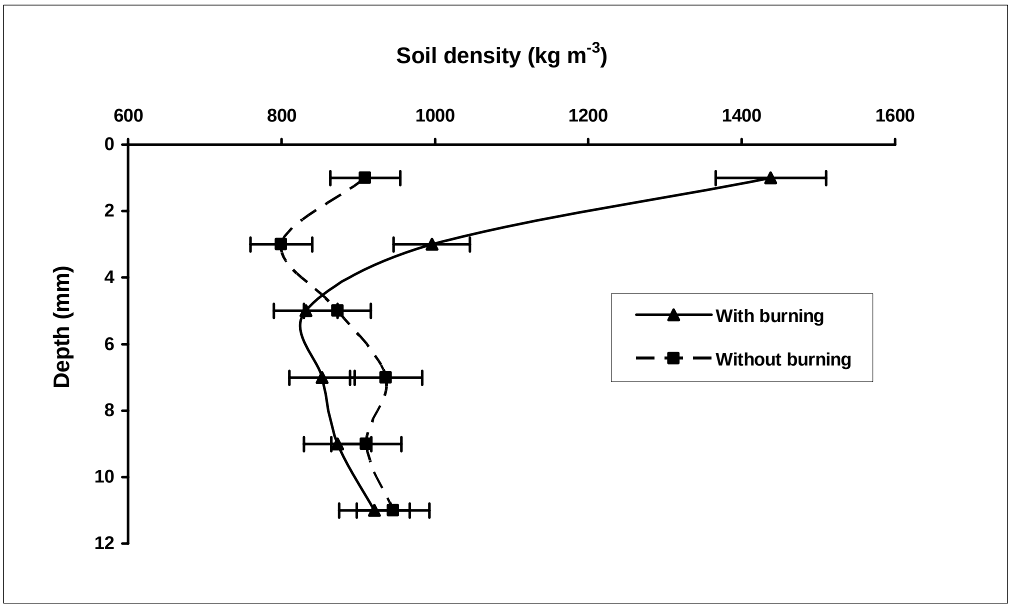

Fig. 4.6. The depth distribution of soil bulk density at the reference site measured prior to (■) and after (▲) the burning of the crop residue.

The estimates of the soil hydraulic conductivity (K_{fs}, cm h^{-1}) obtained prior to and after the burning of the crop residue showed a significant reduction as a result of the burning, reducing from 7.85 to 4.24 cm h^{-1}, respectively. These values indicate that the velocity of soil moisture movement within the soil profile after burning was substantially reduced and they are consistent with the reports of increased hydraulic conductivity associated with the adoption of NTNB management practices provided by other studies (e.g. Lipiec et al., 2006; Salako et al., 2006). Additionally, Limon-Ortega et al. (2006) concluded that burning of the crop residue destroyed the soil aggregates and the soil structure leading to the possibility of slaking and crust formation, which would further reduce infiltration.

According to Kaste et al. (2002), $^{7}Be^{+2}$ ions reaching the soil surface are extremely competitive for cation exchange sites because of their high charge density, and they are therefore rapidly sequestered by exchange sites. After burning of the crop residues, the upper 2 mm of the soil was characterised by a 60% higher bulk density than the soil below. The reduction of the pore space in the surface soil layer could act as a surface seal reducing the infiltration of water into the soil and promoting the mobilisation and downslope transport of ash containing ^{7}Be. The burning may also have promoted hydrophobic conditions at the soil surface, thereby further increasing runoff and sediment mobilisation and transport. For soils with a compacted surface layer, the ^{7}Be technique affords a very sensitive tool for estimating soil loss or deposition, because the loss or gain of very small depths of soil is likely to be clearly marked by a change in the areal activity density.

The higher magnitude of sediment mobilisation and delivery from the burned slope, as compared with that associated with the preceding NTNB system, emphasises that burning of the crop residue can be undesirable. Laflen and Colvin (1981) demonstrated that the erosion rate decreases exponentially with an increase in the harvest residue cover.

4.4.2. The relative importance of the period of heavy rainfall and the burning of the crop residues in explaining the high erosion amounts obtained for the study site.

Hypothesis: The synergistic effect of the extreme nature of the rainfall event and the burning of crop residues accounts for the high erosion amounts obtained for the period under NTWB. This is based on two key factors:

- 400 mm of precipitation fell in May 2005. Available records indicate that a monthly precipitation total of this magnitude or greater has only been recorded in the local region on three occasions during the 52 year period (624 months) 1954-2005 (see Fig. 4.7). The long-term monthly precipitation record for the Temuco precipitation measuring station (38°45`S 72°38`W), which is located 45 km from the study site, emphasizes the extreme nature of this monthly precipitation total. This period of extreme rainfall was characterized by high erosive energy, with a maximum intensity of 11.4 mm h^{-1} on May 18th (Fig. 4.1).

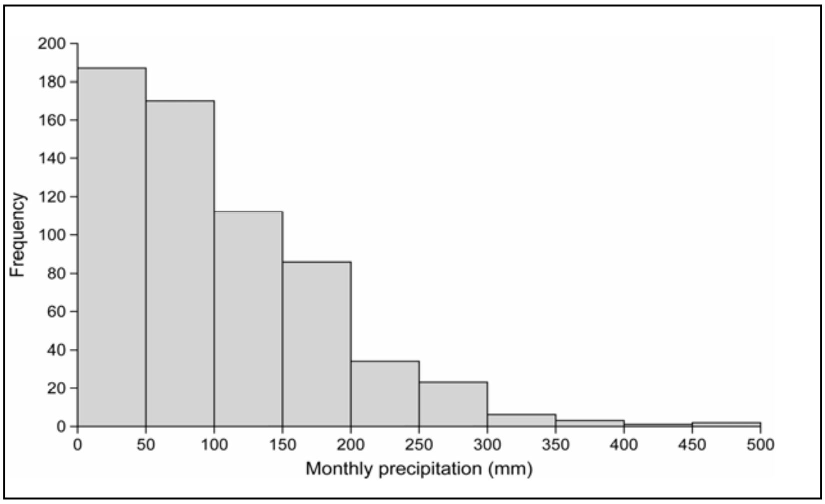

Fig. 4.7. A frequency distribution of monthly rainfall totals for Temuco, Chile for the period 1954-2005.

- The impact of the burning on the surface soil properties is reflected in the documented values of soil density and infiltration rate obtained prior to and after the burning. The changes involved are in agreement with those reported by Gyasi-Agyei (2006) and indicate that a water-repellent layer was formed at the soil surface. This promoted an increase in surface runoff. This change was coupled with a reduction in soil cohesion due to the burning of the organic matter, which resulted in the field surface being highly erodible and having limited resistance to raindrop impact. In addition, due to the burning of the crop residues, the soil surface was covered by ash, which provided a primary adsorption site for the ^{7}Be fallout associated with the extreme event. Given the low cohesion of the ash and the high soil erodibility, the surface layer of the soil and the associated ^{7}Be were readily mobilised, resulting in the high erosion amounts documented for the period under NTWB. In this sense, the ^{7}Be method provides a very sensitive and useful technique for documenting soil erosion associated with the burning of crop residues.

The differences in net soil erosion between NTWB and NTNB therefore reflect several factors. The study period for NTWB corresponds to a period of only one month, with high magnitude erosive rainfall falling on a highly erodible soil surface covered by ash and therefore resulting in a high amount of erosion. In contrast, the study period under NTNB, which covers a 16 year period with no burning of crop residues is more representative of the average climatic conditions for study area. Hence, the estimate of net soil erosion obtained for this period represents the mean annual soil redistribution that characterize the response of the Araucano series soil type in the Coastal Mountain of south-central Chile to the soil conservation strategy based on no-till system.

4.5. CONCLUSIONS

The impact of a period of heavy rainfall (400 mm month^{-1}) on soil redistribution within an area recently subjected to the burning of the crop residue was estimated using the ^{7}Be method. The net erosion documented for the period of heavy rainfall was 1.2±0.2 kg m^{-2}, and this is 8.6 times higher than the mean annual rate of net soil loss estimated previously for the same site for a 16-y period under a NTNB system. The increased amount of net soil loss reflects both increased sediment mobilization and an increase in the efficiency of downslope sediment transfer, as marked by an increase in the sediment delivery ratio from 19% under the NTNB system to 88% for the period of heavy rainfall after the burning of the crop residue. Based on the current findings, it would seem that burning of the crop residues in the autumn could promote soil loss during the following rainy season, especially if intense rainfall events occur. Such burning may therefore be an undesirable component of no-till management practices.

The investigation provides a useful demonstration of how ^{7}Be measurements can be used to document soil erosion associated with individual events or short periods of heavy rainfall and how such information can be used to complement information on medium-term soil redistribution rates provided by ^{137}Cs measurements. Equally, by providing a means of documenting erosion associated with individual events under different tillage systems the ^{7}Be method can provide valuable empirical evidence for use in assessing the efficacy of different soil conservation and sediment control strategies.

4.6. ACKNOWLEDGEMENTS

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5. DISCUSIÓN GENERAL Y CONCLUSIONES

5.1. ANÁLISIS

La intensificación de la producción agrícola en la zona centro-sur de Chile a partir de la década del 70 ha contribuido a incrementar la erosión del suelo y consecuentemente la degradación de este recurso. Para contribuir a revertir esta situación, se ha estimulado el cambio de sistemas de labranza tradicional a sistemas de cero labranza. En este escenario, surge la necesidad de cuantificar el impacto que ha tenido el cambio en el sistema de labranza sobre la tasa de pérdida de suelo, para lo cual se explora el uso del radionucleido ^{137}Cs.

De acuerdo a investigaciones anteriores, la redistribución de ^{137}Cs en una unidad geográfica permite obtener una estimación realista y retrospectiva de la erosión y sedimentación media del suelo ocurrida en los últimos 50 años, al entregar tasas de redistribución de suelo y su distribución espacial (Walling y He, 1999; Schuller et al., 2000). Una de las limitaciones en el uso de ^{137}Cs como trazador de la redistribución de suelo era que los modelos existentes -hasta el inicio de esta tesis- no permitían estimar cambios en las tasas de redistribución de suelo producto de cambios en el sistema de labranza y/o uso del suelo.

En el presente trabajo se logró desarrollar dos nuevos modelos matemáticos que basados en la distribución espacial y en profundidad del ^{137}Cs en el suelo, permiten estimar retrospectivamente el cambio en las tasas medias de erosión y sedimentación asociadas al cambio en el sistema de labranza en un suelo agrícola. En particular, los modelos propuestos fueron aplicados exitosamente en un sitio sometido a un cambio en el sistema de labranza, desde tradicional (LT), periodo 1954-1986, a cero labranza sin quema de residuo (CLSQ), periodo 1986-2003 (año de recolección de las muestras).

El estudio se emplazó en un predio agrícola ubicado cercano a Carahue, Región de la Araucanía, coordenadas 38°37'S 73°04'O, el cuál se caracteriza por presentar clima templado con una precipitación media de 1100 m a^{-1} y un suelo clasificado como serie Araucano, orden Ultisol (Typic Hapludult). La zona de emplazamiento del estudio presenta suelos altamente susceptibles a la erosión (Rovira, 1984), con alto contenido de arcilla que garantiza una alta retención de ^{137}Cs en los primeros centímetros del perfil del suelo, disminuyendo así su dilución en profundidad (Schuller *et al.*, 1997) y montos de precipitación que aseguran un depósito importante de ^{137}Cs en la zona (Schuller *et al.*, 2002).

El primer modelo desarrollado, método estándar (Capítulo 2), además de los parámetros propios de los modelos propuestos por Walling y He (1999), requiere de la determinación de dos parámetros fundamentales: la profundidad másica histórica de arado (H, kg m^{-2}) determinada en un sitio de referencia sujeto a LT hasta la fecha de recolección de las muestras y la profundidad másica a la cual el ^{137}Cs se encuentra distribuido homogéneamente en el perfil del suelo a la fecha de recolección ($h(t)$, kg m^{-2}) determinada en calicatas practicadas en cada punto analizado del sitio en estudio. La determinación de ambos parámetros demanda extenso tiempo de muestreo y medición de la concentración del ^{137}Cs en incrementos de profundidad. Mediante el uso de profundidades másicas (kg m^{-2}) se obvian las correcciones de profundidad (m) debidas a la variabilidad espacial de la densidad aparente del suelo en cada punto analizado y se corrigen las diferencias de profundidad debido al cambio en la densidad aparente en suelos arados anualmente y los sometidos a cero labranza.

Durante el periodo de CLSQ, la tasa de redistribución de suelo (R_{cl}, kg m^{-2} a^{-1}) es estimada en base a la profundidad másica de pérdida o ganancia de suelo ($[h(t) - H]$, kg m^{-2}) ocurrida desde el inicio del cambio de labranza (t', a) hasta la fecha de muestreo (t, a). Durante el periodo de LT, la distribución de ^{137}Cs en profundidad puede reconstruirse asumiendo que la zona de mezcla homogénea hasta el inicio del periodo de CLSQ se extendió hasta *H* y aplicando a continuación los modelos tradicionales de conversión desarrollados por Walling y He (1999). Debido a que el modelo estándar requiere una profundidad másica de referencia de homogenización de la concentración de ^{137}Cs en profundidad en el año de cambio del sistema de labranza, sólo puede ser aplicado en sitios sometidos a erosión durante el periodo de LT. En estas condiciones, al arar anualmente el suelo, el ^{137}Cs habrá sido mezclado periódicamente en forma uniforme hasta la profundidad de arado. Por esta razón, en el sitio de estudio se seleccionó un área expuesta a procesos de erosión previo al cambio en el sistema de labranza, la cual comprende una superficie 6700 m^{-2} (71% del área total del sitio) con 11% de pendiente y 130 m de longitud.

Si bien, el método estándar constituye una técnica innovadora en la cuantificación del cambio en las tasas medias de redistribución de suelo debido al cambio en el sistema de labranza, la estimación de tasas de redistribución de suelo para el periodo de labranza tradicional y de cero labranza obtenidas mediante este procedimiento, demanda gran trabajo en terreno y laboratorio en términos de recolección de muestras en incrementos de profundidad y medición/evaluación de la actividad de ^{137}Cs contenida en cada una de ellas. Esto tiene un impacto significativo sobre la operatividad del método en grandes extensiones. En particular, en Chile, dado los bajos inventarios de ^{137}Cs en el suelo que han sido reportados para distintas latitudes (Schuller et al., 1997; Schuller et al., 2003; Schuller et al., 2004) y la consiguiente necesidad de mayor tiempo de espectrometría gama (aproximadamente 20 horas por muestra), limita la aplicación del método estándar a pequeñas áreas o transectos de pendiente.

A fin de ampliar la representatividad de los resultados puntuales obtenidos con el método estándar, se desarrolló un segundo modelo: método simplificado (Capítulo 2 y 3). Este método, basado en el anterior, permite extender la evaluación de tasas de redistribución de suelo a un área más extensa y por lo tanto más representativa.

El método simplificado se basa en la relación lineal altamente significativa (r=0.999, p<0.01) determinada durante el desarrollo del método estándar entre el inventario total de ^{137}Cs presente en el perfil del suelo, $A(t)$ (Bq m^{-2}), y el inventario de ^{137}Cs hasta profundidad $h(t)$, A_h (Bq m^{-2}), medidos ambos a la fecha de muestreo en cada punto analizado:
$A_h(t) = 1.006A(t) - 31.5$. Por su parte, $h(t)$ puede ser estimada al asumir que la concentración de ^{137}Cs, $C(t)$ (Bq kg^{-1}), es constante hasta $h(t)$, siendo $h(t) = A_h(t)/C(t)$.

De este modo, el modelo simplificado, permite determinar $h(t)$ sin necesidad de medir la concentración de ^{137}Cs en incrementos de profundidad, utilizando únicamente dos variables por punto de muestreo: inventario total de ^{137}Cs presente en el perfil de suelo a la fecha de recolección ($A(t)$, Bq m^{-2}), determinado mediante cilindros metálicos de largo tal que capturen todo el ^{137}Cs presente en el perfil de suelo y la concentración de ^{137}Cs en la capa de suelo homogenizada por aradura ($C(t)$, Bq kg^{-1}), determinada utilizando cilindros metálicos de 8 cm de longitud.

El método simplificado fue validado comparando los valores de tasas de redistribución de suelo obtenidas para los periodos de LT y CLSQ con las obtenidas previamente utilizando la técnica más detallada del método estándar para los puntos analizados por ambos métodos. Mediante la aplicación de ambos métodos se obtuvieron resultados coincidentes de erosión y sedimentación dentro del intervalo de error asociado a los resultados.

La aplicación del método simplificado requiere del establecimiento previo de la relación entre $A(t)$ y $A_h(t)$ y por lo tanto de un análisis basado en muestras colectadas en incrementos de profundidad. Cumplido este requisito, el método simplificado permite obtener separadamente las tasas medias de redistribución de suelo ocurridas en periodos contrastantes de labranza agrícola en un mismo sitio mediante un procedimiento considerablemente más eficiente en términos del tiempo necesario para la recolección y medición de la concentración de ^{137}Cs presente en las muestras.

Producto del cambio en el sistema de labranza, los resultados muestran una clara reducción (87%) en la tasa neta de erosión de suelo bajo CLSQ respecto a las obtenidas en LT (0.14±0.2 kg m^{-2} a^{-1} y 1.1±0.2 kg m^{-2} a^{-1} respectivamente), siendo éstos representativos de un área expuesta a procesos de erosión previo al cambio en el sistema de labranza. Estos resultados señalan los importantes beneficios del sistema cero labranza en términos de permitir un manejo sustentable del recuso suelo manteniendo su productividad y una disminución de los impactos asociados a la degradación de cursos de agua adyacentes. Relacionado a lo anterior, la exportación de sedimento fuera del sitio de estudio -sean zonas de uso agrícola en que la acumulación de material se genera por una posición cóncava de la pendiente o secciones de cierre de la microcuenca con posterior salida hacia cursos de agua- se redujo de un 100% bajo LT a un 19% bajo CLSQ. Esta disminución en el porcentaje de sedimento exportado bajo el sistema de CLSQ, tiene gran relevancia en la mitigación de los impactos ambientales generados por el depósito de sedimentos fuera del sitio, tales como cambio en las propiedades físico-químicas del suelo (acumulación de materia orgánica, modificación de la estructura, cambio en la velocidad de infiltración de agua en el perfil del suelo, etc.), disminución del cauce efectivo y capacidad de carga en cuerpos de agua, desbordes de ríos y esteros y eutrofización de recursos hídricos.

En general, mediante la implementación del método simplificado en un predio agrícola de la Región de la Araucanía, se amplió el área en estudio y se cuantificó el impacto de la cero labranza sobre la reducción de la erosión del suelo, obteniendo información relevante (tasas medias de erosión y/o sedimentación, fracción de la superficie afecta a cada uno de estos procesos, erosión y/o sedimentación neta del área estudiada y razón de pérdida de sedimentos desde el área) permitiendo evaluar la efectividad de la técnica de CLSQ como práctica de conservación del recurso suelo por sobre el sistema de LT.

De acuerdo a lo reportado en la literatura (Bachhuber et al., 1982) y al trabajo realizado en esta tesis, la distribución inicial de ^{137}Cs en el suelo y la profundidad de penetración de este radionucleido dependería de propiedades del suelo que determinan la infiltración de agua y la adsorción de ^{137}Cs a las partículas del suelo. Schuller y Ellies (1994), analizaron la influencia de la textura del suelo y de la precipitación media anual sobre la distribución vertical del ^{137}Cs en suelos no disturbados, derivados de ceniza volcánica del centro-sur de Chile. La profundidad de penetración del ^{137}Cs y el inventario de éste crecen al aumentar la precipitación media anual del sitio estudiado. El volumen del espacio poroso de los suelos derivados de ceniza volcánica contribuye a la penetración del ^{137}Cs en el perfil del suelo. Sin embargo, la alta capacidad de adsorción de estos suelos contribuye a la retención de ^{137}Cs en las estratas superficiales y, por consiguiente, a reducir la migración vertical. La migración del ^{137}Cs en profundidad es mayor en suelos arenosos, seguido de suelos limosos, siendo menor en suelos arcillosos. Según lo descrito anteriormente, la relación $A(t) = A_b(t) + C(t)$ necesaria para aplicar el método simplificado (Schuller et al., 2007), debe determinarse bajo las condiciones edafoclimáticas del sitio a ser estudiado. La constante C, kg m^{-2}, que refleja el inventario de ^{137}Cs que ha migrado bajo la profundidad de homogenización de este radionucleido en el suelo, dependerá principalmente de la mineralogía de las arcillas, textura, estructura, densidad aparente, estado hídrico, actividad biológica, contenido de materia orgánica del suelo y de la precipitación del lugar. Adicionalmente, el estado o calidad del recurso asociado a la intensidad de uso de éste, influirá en la distribución en profundidad del ^{137}Cs a través del cambio en las propiedades del suelo anteriormente señaladas. La alta migración de ^{137}Cs en suelos arenosos puede constituir una limitante en la aplicabilidad de la técnica del ^{137}Cs.

Dada la sensibilidad que el parámetro profundidad másica de relajación de ^{137}Cs en el corto plazo (h_o, kg m^{-2}) presenta para la estimación de tasas de redistribución de suelo (parámetro utilizado en los modelos de conversión de inventarios de ^{137}Cs en tasas de redistribución de suelo propuestos por Walling y He, 1999), se determinó el valor de h_o para las condiciones edáfoclimáticas específicas del sitio de estudio (suelo Ultisol, serie Araucano, Typic Hapludult; Región de la Araucanía). De este modo, se confiere mayor precisión a las tasas de redistribución de suelo obtenidas utilizando la técnica del ^{137}Cs en el período de LT, constituyendo un avance importante en la adaptación de esta metodología a las condiciones particulares de la zona en la cual se emplazó el estudio.

El método del ^{7}Be permite estimar montos de redistribución del suelo asociados a un evento erosivo particular, constituyendo una herramienta complementaria a la técnica del ^{137}Cs (Blake et al., 1999; Wallbring and Murray, 1993; Wilson et al., 2003). En particular, la implementación de la técnica del ^{7}Be en un suelo de uso agrícola en la zona centro-sur de Chile, abordada en esta tesis, representa la primera aproximación al uso de ^{7}Be para estimar montos de redistribución de suelo asociados a un periodo de precipitación intensa sobre suelo de uso agrícola sin cobertura vegetal sujeto a cero labranza con quema de residuos de cosecha (CLCQ).

La técnica del ^{7}Be fue aplicada en el mismo sitio de estudio que el utilizado para la determinación de tasas medias de redistribución de suelo asociadas al cambio en el sistema de labranza, utilizando mediciones de ^{137}Cs en el suelo. El uso de ^{7}Be como trazador de desplazamiento de suelo se realizó una vez ocurrido el cambio en el sistema de cero labranza, desde CLSQ a CLCQ, dos años después de finalizada la investigación previa utilizando ^{137}Cs. Así, el suelo a la fecha de muestreo (Mayo 2005) estaba sujeto a quema de residuos de cosecha, práctica realizada al término del periodo estival 2005 (Marzo), permaneciendo el suelo desnudo sin cobertura vegetal durante el periodo de precipitación intensa registrado en el mes de Mayo de 2005 (400.5 mm de agua caída en 27 d). Respaldado por el registro pluviométrico del sitio de estudio, durante los cuatro meses previos al inicio del periodo de precipitación intensa, el monto y la distribución temporal de la precipitación junto con el estado hídrico insaturado del suelo, permiten inferir la no ocurrencia de escorrentía superficial y por tanto considerar una distribución espacial uniforme de ^{7}Be en el área de estudio al inicio del periodo de precipitación intensa.

Los resultados de redistribución de suelo obtenidos utilizando ^{7}Be revelan un aumento en los montos netos de erosión y razón de pérdida de sedimentos bajo CLCQ (1.2±0.2 kg m^{-2} y 88% respectivamente) respecto a lo obtenido previamente utilizando la técnica del ^{137}Cs en sistema de CLSQ (0.14±0.2 kg m^{-2} a^{-1} y 19% respectivamente). El incremento de la erosión neta y razón de pérdida de sedimentos durante CLCQ están asociados al evento de precipitación extrema registrado durante el periodo analizado y a la quema de residuos de cosecha. Además, en el sistema de cero labranza estudiado, el impacto de la quema de residuos respecto al periodo anterior sin esta práctica evidenció un aumento en la densidad aparente superficial del suelo y disminución de la conductividad hidráulica de éste. Esto, junto al aumento en los montos netos de erosión y exportación de sedimentos, confirma el impacto negativo de la quema de residuos sobre la calidad del suelo. Los resultados obtenidos sugieren que la quema de residuos en el periodo estival incrementa la erosión del suelo durante la siguiente estación lluviosa, especialmente si ocurren eventos erosivos intensos. Por lo tanto, la quema de residuos de cosecha puede constituir una práctica no recomendable en el contexto de un sistema de cero labranza.

Sin embargo, en virtud de la sensibilidad del método del ^{7}Be en la determinación de montos de redistribución de suelo asociado a un evento de precipitación intensa y quema de residuos en un sistema de cero labranza, se sugiere analizar a futuro la contribución aislada de cada uno de estos factores en los montos netos de erosión y sedimentación de suelo. Para ello se sugiere determinar:

- la adsorción de ^{7}Be asociada a diversos tamaños de partícula y la posible introducción de un factor de corrección que de cuenta, por ejemplo, de la redistribución preferencial de la fracción fina y del ^{7}Be adsorbido a ésta, dado un evento erosivo para distintos tipos de suelo,
- el impacto de eventos de precipitación de diversa intensidad en los montos de redistribución de suelo en sistemas de cero labranza sin y con quema de residuos,
- el impacto de eventos de precipitación en la redistribución de residuos orgánicos quemados y el ^{7}Be adsorbido en ellos.

A través de la utilización de la técnica del ^{7}Be se implementó una herramienta adicional a la técnica del ^{137}Cs, que permite determinar montos y distribución espacial de la redistribución del suelo (montos medios y netos de erosión/sedimentación, fracción del área afectada por estos procesos, razón de exportación de sedimentos) asociada a un periodo de precipitación intensa bajo las condiciones edafoclimáticas del sitio estudiado. Así, la información obtenida mediante esta técnica contribuye al seguimiento y monitoreo del efecto de la cero labranza sobre la redistribución de suelo asociada a eventos erosivos intensos.

La utilización de técnicas isotópicas, particularmente ^{137}Cs y ^{7}Be, para la cuantificación de la erosión y sedimentación del suelo, permiten estimar retrospectivamente la redistribución del suelo (mediano plazo utilizando ^{137}Cs (años o décadas) y corto plazo utilizando ^{7}Be (días o meses)) basado en sólo un evento de recolección de muestras en el sitio de estudio, obviando la necesidad de mantener anualmente ensayos experimentales en el sitio y con ello evitar alterar el desarrollo normal de las labores agrícolas sobre el mismo. Junto a ello, dada la característica de retrospectividad temporal y amplitud de los periodos estudiados, la representatividad de los resultados obtenidos a través de la técnica del ^{137}Cs para un sistema de labranza agrícola determinado, no se ve influenciada por condiciones climáticas excepcionales. Además, los montos de redistribución de suelo estimados mediante las técnicas isotópicas descritas representan la sumatoria de los efectos producidos por todos los agentes erosivos presentes en el área estudiada.

En general, una de las mayores contribuciones de las técnicas isotópicas ha sido una mejor comprensión de la relación entre topografía y erosión (Pennock, 2003), al entregar información respecto a la distribución espacial de la redistribución del suelo. Dado que el material transportado por el agua hacia zonas de sedimentación está constituido por partículas pequeñas de baja densidad a las que se encuentran asociados tanto nutrientes (Avnimelech y McHenry, 1984) como materia orgánica activa (Gregorich et al., 1998), se genera en esas posiciones una mayor formación de agregados (Ritchie, 2001), aumentando la protección física a la materia orgánica del suelo, retrasando su reciclaje y permitiendo de este modo secuestrar carbono (Van Veen y Paul, 1981; Elliott, 1986; Kimble et al., 2001; VandenBygaart, 2001). Desde esta perspectiva y en consideración a que zonas de depósito o sedimentación de suelo se postulan como importantes reservorios de carbono orgánico del suelo (COS), una mejor estimación de la redistribución del suelo puede mejorar el conocimiento sobre los procesos de redistribución del COS. Esto permitiría estimar la contribución relativa de la erosión y sedimentación del suelo sobre la redistribución del COS junto con los efectos netos de la contribución del COS en los niveles de CO_2 atmosféricos (VandenBygaart, 2001; Ritchie y McCarty, 2003). De este modo, utilizar los radionucleidos ambientales ^{137}Cs y ^{7}Be como herramienta para contribuir a la comprensión del efecto de la erosión y sedimentación del suelo sobre la redistribución del COS y su impacto sobre la calidad del suelo tiene un gran potencial e interesantes proyecciones.

5.2. BIBIBLIOGRAFÍA

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