The enrichment of $^{137}$Cs in the soil loss from small agricultural watersheds

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Summary — Zusammenfassung

Enrichment ratios (ER) are widely used to predict loss of sorbed nutrients or pesticides with runoff sediment, while ER is frequently neglected in studies which quantify past erosion from global fallout $^{137}$Cs losses. The ER of $^{137}$Cs (ER,$^{137}$Cs) in the soil loss and the subsequent depletion of $^{137}$Cs at the soil surface were determined for eight small watersheds (1.6–16.8 ha) with different soils and land use. Due to preferential loss of the clay fraction, the upper 5 mm of the soil surface was significantly depleted of $^{137}$Cs after a heavy storm. A total of 31 watershed-events were investigated with soil losses ranging between 1.2 and 480 kg ha$^{-1}$ and sediment concentrations between 1.98 and 54.1 g L$^{-1}$. The concentration range (ER $^{137}$Cs: mean, 1.72, range, 0.40–4.95) was positively correlated to the ER of clay, organic carbon, total nitrogen and calcium-acetate-extractable phosphorus (P$_{\text{CAL}}$). A close correlation between ER,$^{137}$Cs and ER,P$_{\text{CAL}}$ was also found for sediment samples of detention ponds, where most of the ER values were less than 1.0 due to depletion. Therefore, ER,P$_{\text{CAL}}$ seems to be a suitable estimate of ER,$^{137}$Cs for both ponds, erosion and deposition processes. Our findings strongly support the need for considering ER,$^{137}$Cs, when $^{137}$Cs data are used to assess rates and pattern of soil redistribution. Otherwise, soil loss will be overestimated in a range of about factor 2 in many cases.

Key words: enrichment / cesium-137 / phosphorus / soil loss / tracer / watershed / agroecosystem

1 Introduction

The concept of enrichment ratios (ER) to predict the loss of sorbed nutrients or pesticides has been integrated into most soil erosion and water quality models, such as CREAMS (Knisel, 1980) or AGNPS (Young et al., 1987). By definition, the ER of a specific constituent is the ratio of its concentration in the eroded sediment to that in the original soil and was empirically obtained by many studies (cf. Palis et al., 1990). Due to selectivity of erosion processes, through shearing action of raindrop impact (Ghadiri and Rose, 1991), preferential transport of fine or low-density particles and preferential deposition of coarse particles (Palis et al., 1990), the fraction of clay and organic matter in the eroded sediment increases. This physical enrichment is associated with a chemical enrichment, because (1) clay and organic matter are the main sorbents for nutrients or pesticides and (2) the outer part of aggregates are typically high in chemical concentrations (Ghadiri and Rose, 1991). Therefore values of ER are generally greater than 1.0, with range and upper level depending on site-specific conditions (land use, soil texture and aggregation) and dominant type of erosion, with interrill erosion being selective and concentrated flow erosion proved to be non-selective (Proffitt and Rose, 1991).

Cesium-137 ($^{137}$Cs), deposited on the soil with the global fallout of nuclear weapon tests and with the Chernobyl fallout, is predominantly sorbed by the clay fraction (cf. Ritchie and McHenry, 1990). This is of particular significance as $^{137}$Cs is widely used as a tracer for assessment of rates and pattern of erosion and deposition, commonly

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Table 1: Selected characteristics of the experimental watersheds.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Land (%)</th>
<th>Crops in 1993</th>
<th>Dominant soil type</th>
<th>Topsoil properties&lt;sup&gt;1)&lt;/sup&gt;</th>
<th>137Cs Bq kg&lt;sup&gt;-1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>E01</td>
<td>1.60</td>
<td>7.4</td>
<td>53&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>winter wheat</td>
<td>Dystric Eutrochrept</td>
<td>0.13 0.39 0.33 0.15 14.4 0.079 82.5</td>
<td></td>
</tr>
<tr>
<td>E02</td>
<td>3.57</td>
<td>6.9</td>
<td>95</td>
<td>potatoes</td>
<td>Oxyaqual UdiCflux</td>
<td>0.05 0.29 0.46 0.21 12.0 0.081 79.4</td>
<td></td>
</tr>
<tr>
<td>E03</td>
<td>4.23</td>
<td>7.3</td>
<td>93</td>
<td>winter wheat</td>
<td>Dystric Eutrochrept</td>
<td>0.02 0.21 0.57 0.20 15.1 0.136 82.1</td>
<td></td>
</tr>
<tr>
<td>E05</td>
<td>16.78</td>
<td>9.0</td>
<td>82</td>
<td>corn/potatoes/winter wheat</td>
<td>Dystric Eutrochrept</td>
<td>0.06 0.31 0.45 0.18 12.3 0.065 88.2</td>
<td></td>
</tr>
<tr>
<td>E06</td>
<td>11.07</td>
<td>9.3</td>
<td>81</td>
<td>corn/winter wheat</td>
<td>Typic EpiAqual</td>
<td>0.07 0.34 0.42 0.18 12.4 0.067 94.4</td>
<td></td>
</tr>
<tr>
<td>E08</td>
<td>3.44</td>
<td>6.1</td>
<td>87</td>
<td>lupines</td>
<td>Typic Udorthent</td>
<td>0.22 0.48 0.21 0.10 11.2 0.078 95.3</td>
<td></td>
</tr>
<tr>
<td>E14</td>
<td>1.56</td>
<td>8.2</td>
<td>58&lt;sup&gt;2)&lt;/sup&gt;</td>
<td>potatoes</td>
<td>Dystric Eutrochrept</td>
<td>0.08 0.35 0.40 0.18 14.0 0.082 89.0</td>
<td></td>
</tr>
<tr>
<td>E16</td>
<td>2.02</td>
<td>7.4</td>
<td>88</td>
<td>potatoes</td>
<td>Dystric Eutrochrept</td>
<td>0.04 0.36 0.43 0.17 14.9 0.109 98.3</td>
<td></td>
</tr>
</tbody>
</table>

1) average of all inventory samples within a watershed (n = 5–65), concentrations are related to bulk soil (depth: 0.15–0.31 m)
2) according to Soil Survey Staff (1992)
3) remainder is fallow and hedges
4) remainder is pasture

referred to as 137Cs technique (Ritchie and McHenry, 1990; Walling and Quine, 1991). Most uncertainties concerning interpretation of 137Cs data arise from the lack of knowledge of the relationship between 137Cs loss and soil loss, which is fundamental for accurate estimates of both rates and pattern of soil redistribution (Quine et al., 1996). Among others, enrichment of 137Cs in the eroded sediment (ER-137Cs) is of particular interest. Most studies simply assumed a direct proportionality between soil loss and 137Cs loss, i.e. an ER-137Cs of 1.0 (cf. Quine et al., 1996). As a consequence, soil loss was substantially underestimated, because preferential 137Cs loss is most likely to occur, except under conditions where unselective rill erosion or translocation of soil by tillage operation is the dominant process of soil redistribution (Govers et al., 1996; Quine et al., 1996). Only few studies investigated the movement of 137Cs with surface runoff. Most were using rainfall simulation with bare, homogeneous soils, either on a laboratory (Dalgleish and Foster, 1996) or a small plot scale (Bernard et al., 1992), whereas studies under field conditions are missing.

Therefore, the objective of this paper was to determine ER-137Cs under field conditions in eight small watersheds by runoff sampling and measuring 137Cs in soils and sediments. Correlation analysis of ER-137Cs and the phycoschemical properties of the sediments were performed in order to find general transfer functions, which could be used to estimate ER-137Cs in the soil loss for an improved interpretation of 137Cs data used for assessment of soil redistribution within agroecosystems.

2 Materials and methods

2.1 Experimental watersheds and runoff sampling

The investigations were carried out at the 143 ha Scheyern Experimental Farm, which is located about 40 km north of Munich (long. 09°11′E, lat. 48°30′N) in the Tertiary hills of southern Germany. Soils derived from a wide range of parent materials, comprising unconsolidated gravely, sandy sediments with embedded clay lenses, partly covered by loess deposits on shallow slopes. Main soil types and other selected characteristics of the eight experimental watersheds are summarized in Tab. 1. Each watershed area (1.6–18.8 ha) is typically composed of one agricultural field, except E06 and E05 with 2 and 4 contributing fields, respectively. Five to 47% of the watershed areas consist of pasture, fallow, hedges or non-paved roads. Slope is 8.4% on average, exceeding 16% in one fourth of the total area. Since 1990 farming practice is characterized by reduced tillage (cultivator, rotary harrow) and the use of cover crops and crop residues as mulch.

At the downslope end of most watersheds runoff is routed through small runoff detention ponds (50–490 m²), equipped with an inlet riser and an underground tile outlet, constructed to prevent gullying of downslope fields and retain sediments. Through PVC pipes (150–300 mm dia.) runoff is channeled on a Coshocton-type sampling wheel (ISRI, Salching, Germany), passing a constant aliquot to a collecting tank (800–3500 l). For each watershed event, runoff volumes are calculated from aliquot volume and split-factor of the wheel. Accuracy of the sampling wheel is within ±15% (Bernard, 1988) for flow rates below wheel capacity (20 l sec<sup>-1</sup>), which is achieved by the restricting inlet riser. After homogenization in the collecting tanks, runoff samples were drawn. Results reported here were obtained from 20 rain events, which generated runoff at least on one of the experimental watersheds between March 1993 and March 1994. A central tipping bucket rain gauge measured and recorded rainfall in a 10 min-time resolution. Kinetic energy of rain was calculated according to Brown and Foster (1987).

2.2 Sampling and analysis of soils and sediment

The soils of the study area were sampled in 1991 at the 471 nodes of a rectangular 50 x 50 m grid to a 1.2 m depth. Five horizons were sampled on average. Bulk analysis of the Ap-horizon is used here (average depth: 0.24 m). Sampling strategies and soil analysis of the soil inventory are described in detail by Schiernitz et al. (1997).

After a heavy storm in May 1993 the uppermost 10 mm of soil were collected at 20 locations within two watersheds (E02 and E08). A handhold auger (45 mm dia.) equipped with an internal plastic tube allowed cutting at increments of 5 mm thickness (0–5 mm, 5–10 mm) by carefully extruding the soil core. A total of 30 cores were combined for each layer and sampling location.

For the same event, sediment which had settled in the detention ponds was sampled at 8 representative locations within each pond area. Sediment was separated from the runoff samples by settling and decantation and sediment concentration measured by weighting after
evaporation (50°C) to dryness. Air dried soil or sediment samples were sieved at 2 mm. After dispersion for 16 h with 0.0125 M Na₂P₂O₇, particle size distribution was measured using a combination of wet sieving and laser diffraction technique for the inventory samples (Scheinert et al., 1997) and wet sieving and pipette analysis (Kohn, 1928) for the surface and sediment samples. Total carbon (Cₜ) and nitrogen (N) were determined by dry combustion (CN-analyzer 1500, Carlo-Erba), organic C (Cₜ or Corg) after correction for carbonate C by repeated measurement after heating (500°C, 5 h). Calcium-acetate-factate-extractable phosphorus (P₁₆) was analyzed after Schüller (1969). ¹³⁷Cs activity was determined by direct gamma spectrometry using a coaxial HPGe-detector or a HPGe well detector (near 4 n geometry), both linked to a multichannel analyzer. Counting times were 24–48 h for 15–500 ml sample beakers and 4–7 d for 4 ml samples. Counting errors were typically around ± 2%. All activities have been corrected for radioactive decay to reference date 01.06.1991. For the particle sizes and chemical properties the enrichment ratio (ER) was calculated as:

$$\text{ER} = \frac{C_{\text{sed}}}{C_{\text{soil}}} \quad (1)$$

where $C_{\text{sed}}$ is the concentration of the constituent concerned in the sediment and $C_{\text{soil}}$ the corresponding concentration in the Ap-horizon. All topsoil properties were averaged over all inventory samples within a watershed. Concentrations were always expressed on a stone containing basis as the stone content of both, sediments and soils, was measured.

3 Results

3.1 Preferential depletion of ¹³⁷ Cs at the soil surface

A 5 year-storm on May, 27th 1993, with 25 mm of rain within 30 min, induced considerable erosion on the watersheds E02 and E08. Differences in particle size distribution, Corg and ¹³⁷Cs-activity between the uppermost soil layers indicated preferential removal of fine soil particles from the top 5 mm of soil (Fig. 1). Higher stone and sand content of the upper layer coincided with significant lower content of clay in this layer for both watersheds, while silt did not change significantly. Corg decreased for the loess-derived soils of watershed E02, whereas no superproportional loss was detected for E08.

Predominant sorption of ¹³⁷ Cs to the clay fraction depleted significantly the ¹³⁷Cs activity with the same ranking like clay content for both watersheds. Fairly constant ¹³⁷Cs-to-clay-ratios, 0.43 and 0.45 Bq g⁻¹ clay for E02 and 1.06 and 1.07 Bq g⁻¹ clay for E08, for the first and second layer respectively, proved the equivalence between the loss of clay fraction and ¹³⁷Cs activity. Ritchie and McHenry (1990) recommended to express ¹³⁷Cs activity per unit clay for interpretation of different textured sediment profiles. The soil properties shown in Fig. 1 were related to fine earth, which was selectively lost. If related to bulk soil, the exceptional high enrichment of stones for E08 would result in net loss of all other fractions, whereas for E02 the general pattern of loss and gain would not change. This stone enrichment probably was not only caused by the erosion event, but was already preformed by previous tillage operation or a wash-in of fines during earlier rains (Poesen and Lavee, 1994) as 16.6 mm of rain fell since last tillage on E08, but only 2.0 mm on E02.

Figure 1: Differences in particle size distribution, Corg and ¹³⁷Cs-activity between soil layer 1 (0–5 mm) and soil layer 2 (5–10 mm) in two watersheds after a 25 mm-storm; average of 6–10 samples for each watershed; data except for stones were related to fine earth; shown are differences to layer 2; * and ** indicate significant differences between layer 1 and layer 2 at the 0.05 and 0.01 probability level, respectively, all others were not significant (paired t-test).

Abbildung 1: Unterschiede in Korngrößenverteilung, Corg und ¹³⁷Cs-Aktivität zwischen Bodenschicht 1 (0–5 mm) und 2 (5–10 mm) nach einem 25 mm-Gewitter in zwei Einzugsgebieten; Mittelwerte von 6–10 Probenahmen je Einzugsgebiet; alle Werte, außer Steingehalt, sind auf Feinboden bezogen, die Unterschiede auf Schicht 2; *, ** bedeuten signifikante Unterschiede zwischen Schicht 1 und 2 bei einer Irrtumswahrscheinlichkeit von 0.05 bzw. 0.01, alle anderen sind nicht signifikant (paarweiser t-Test).

No corresponding data of sediment discharge was available for this event, because the runoff samplers had not yet been in operation. However, the event caused significant sediment deposition in the detention ponds and amount and concentrations of this sediment were used for calculation. Using a mass balance approach with the assumptions that (1) pre-event particle size distribution of the topsoil was homogeneous and equalled that of the 5–10 mm layer, (2) half of the enrichment of stones in E08 was already preformed and (3) all stones transported with soil loss had been deposited in the detention ponds, total soil loss and related ER were calculated. With post-event differences between the two layers (Fig. 1) and amount of stones in the detention ponds (0.41 t ha⁻¹ for E02 and 0.32 t ha⁻¹ for E08), resulting soil loss was 11.3 t ha⁻¹ for E02 and 5.7 t ha⁻¹ for E08. Corresponding ER of stones, sand, silt and clay were 0.8, 0.8, 1.0, and 1.4 for E02 and 0.2, 1.3, 1.9, and 2.1 for E08 respectively. With help of the ¹³⁷Cs-to-clay-ratio, loss of the tracer was estimated as 125 Bq m⁻² for E02 and 95 Bq m⁻² for E08, representing 0.45% and
Table 2: Mean, range and coefficient of variation (CV) of runoff volume, soil loss, sediment concentration and ER of various sediment fractions (n = 31 runoff events between March 1993 and March 1994).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff</td>
<td>mm</td>
<td>0.43</td>
<td>0.02</td>
<td>6.1</td>
</tr>
<tr>
<td>Soil loss</td>
<td>kg ha⁻¹</td>
<td>30.4</td>
<td>1.2</td>
<td>480</td>
</tr>
<tr>
<td>Soil lossprev²</td>
<td>kg ha⁻¹</td>
<td>480</td>
<td>0.8</td>
<td>2950</td>
</tr>
<tr>
<td>Sediment conc.</td>
<td>g L⁻¹</td>
<td>7.13</td>
<td>1.98</td>
<td>54.1</td>
</tr>
<tr>
<td>ER-sand</td>
<td></td>
<td>0.04</td>
<td>0.001</td>
<td>1.75</td>
</tr>
<tr>
<td>ER-silt</td>
<td></td>
<td>1.19</td>
<td>0.72</td>
<td>2.66</td>
</tr>
<tr>
<td>ER-clay</td>
<td></td>
<td>2.45</td>
<td>0.73</td>
<td>4.57</td>
</tr>
<tr>
<td>ER-Corg</td>
<td></td>
<td>1.87</td>
<td>0.52</td>
<td>4.58</td>
</tr>
<tr>
<td>ER-N</td>
<td></td>
<td>2.42</td>
<td>0.50</td>
<td>5.85</td>
</tr>
<tr>
<td>ER-Pcal</td>
<td></td>
<td>1.89</td>
<td>0.62</td>
<td>3.50</td>
</tr>
<tr>
<td>ER-¹³⁷Cs</td>
<td></td>
<td>1.72</td>
<td>0.40</td>
<td>4.95</td>
</tr>
</tbody>
</table>

1) runoff, soil loss, sediment conc. and ER-sand were log-transformed, soil lossprev was square-root-transformed to approach normal distribution
2) coefficient of variation (%)
3) cumulative soil loss since last tillage operation previous to the event

Table 3: Correlation matrix of sediment-ER and selected properties of the related erosion events (|r| > 0.36, |r| > 0.46, or |r| > 0.57 indicates significance at the 0.05, 0.01, or 0.001 probability level, respectively; n = 31; runoff, soil loss, sediment conc. and ER-sand were log-transformed, soil lossprev was square-root-transformed).

<table>
<thead>
<tr>
<th>ER-silt</th>
<th>ER-clay</th>
<th>ER-Corg</th>
<th>ER-N</th>
<th>ER-Pcal</th>
<th>ER-¹³⁷Cs</th>
<th>Runoff</th>
<th>Soil loss</th>
<th>Soil lossprev</th>
<th>Sediment conc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.03</td>
<td>-0.70</td>
<td>-0.40</td>
<td>-0.48</td>
<td>-0.40</td>
<td>-0.51</td>
<td>0.04</td>
<td>0.25</td>
<td>0.23</td>
<td>0.42</td>
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<tr>
<td>0.20</td>
<td>0.61</td>
<td>0.53</td>
<td>0.38</td>
<td>0.49</td>
<td>0.04</td>
<td>0.19</td>
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<tr>
<td>0.79</td>
<td>0.84</td>
<td>0.81</td>
<td>0.87</td>
<td>0.87</td>
<td>-0.30</td>
<td>-0.48</td>
<td>-0.43</td>
<td>-0.41</td>
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</tr>
<tr>
<td>0.97</td>
<td>0.83</td>
<td>0.83</td>
<td>0.90</td>
<td>-0.16</td>
<td>-0.48</td>
<td>-0.43</td>
<td>-0.43</td>
<td>-0.41</td>
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<tr>
<td>0.82</td>
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<td>0.87</td>
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<td>-0.26</td>
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<td>0.84</td>
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<td>-0.44</td>
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<tr>
<td></td>
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<td></td>
<td>0.85</td>
<td>0.27</td>
<td>-0.05</td>
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<tr>
<td></td>
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<td>0.30</td>
<td>0.47</td>
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</tbody>
</table>

3.2 ER-¹³⁷Cs in runoff sediments

1993 was a wet year with a total amount of precipitation of 940 mm, as compared to the long-term average of 797 mm yr⁻¹ (1961—1990). On average single rainfall depth of the 20 runoff generating rains was 14.4 mm (range: 4.0—57 mm), highest 30 min-intensity 11.3 mm h⁻¹ (1.6—50.4 mm h⁻¹) and kinetic energy of rain 230 J m⁻² (40—1160 J m⁻²). Due to different topography, soils and land use, frequency and amount of runoff and soil loss varied widely among the experimental watersheds. All 31 watershed-events thus cover a wide range of runoff depth, soil loss and sediment concentration (Tab. 2).

All ER were significantly correlated among each other, except ER-silt to ER-sand and to ER-clay (Tab. 3). Clay, Corg, N, Pcal and ¹³⁷Cs representing fine particles or fine particles sorbates, all the ERs had positive mutual correlation and negative correlation to runoff, soil loss, cumulative previous soil loss or sediment concentration. Sand fraction, with a 30-fold lower concentration in sediment than in topsoil on average, showed opposite correlations. Silt was enriched or depleted for different events and watersheds. This resulted in an average ER of about 1 (Tab. 2) and only a weak or non-significant correlation to the other ER and event parameters (Tab. 3).

ER of clay, Corg, N, and Pcal each could explain between 70 and 80% of variation of ER-¹³⁷Cs, but the regressions exhibited some differences. The high correlation between ER-¹³⁷Cs and ER-Corg was caused by a few low and high values, while most of the data were clustered (not shown). 80% of the runoff sediments had ER-Corg between 1.6 and 2.2 while correspondent range of ER-¹³⁷Cs was larger (1.1—2.6) and a correlation for this range was not significant. The same was observed for ER-N. Both indicated, that, in spite of large coefficients of correlation, organic matter was not the carrier for sorbed ¹³⁷Cs.

Because of the selective sorption of ¹³⁷Cs by clay minerals, ER-clay should be a close estimate for ER-¹³⁷Cs. But in the present study ER-clay was about 40% higher than ER-¹³⁷Cs on average (Tab. 2) and regression deviated considerably from unity (ER-¹³⁷Cs = −0.41 + 0.87 ER-clay, r² = 0.76 (2)). This may be explained by the soil loss processes from watersheds with potato fields (52% of the runoff sam-
amples were taken from potato watersheds). Construction of potato ridges and rilling in the furrows favors a substantial soil loss from the subsoil. This in turn increases the calculated ER-clay because subsoils had a significantly higher clay content (0.163 kg·kg⁻¹ for the Ap-horizon and 0.193 kg·kg⁻¹ for the next 0.1 m below; p < 0.001, paired t-test of all inventory samples), but did not increase ER-¹³⁷Cs, because the subsoils were almost free of ¹³⁷Cs (87.6 Bq·kg⁻¹ vs. 3.1 Bq·kg⁻¹, p<0.001). Mapping of rills was available. Rills covered only small parts of some watersheds and it was difficult to estimate how much they contributed to the soil loss of succeeding events. No correction of ER for rills was hence carried out.

The different concentration of topsoils and subsoils and the effect of erosion events cutting into the subsoil, can probably be best described by ER-PCAL, because, similar to ¹³⁷Cs, the Ap-horizon contains more P_CAL (0.081 g·kg⁻¹ on average) than the subsoil (0.046 g·kg⁻¹). ER-PCAL should therefore be the best predictor of ER-¹³⁷Cs. The regression between ER-¹³⁷Cs and ER-PCAL was:

\[ \text{ER-¹³⁷Cs} = -0.31 + 1.07 \cdot \text{ER-PCAL} \]

\[ r^2 = 0.71, n = 31 \]

(3)

This regression is close to unity, but some data were clustered around ER-PCAL of 2.5 (Fig. 2). One highly enriched sediment deviated considerably from the 1:1 line of perfect agreement. The small negative intercept could be due to the smaller proportion of ¹³⁷Cs in the subsoil (ratio between Ap-horizon and subsoil: 28) than of P_CAL (ratio: 1:8).

The regression was also valid for sediments, which had been deposited in the detention ponds. The regression for the pond sediments did not differ significantly from eq. 3 and the regression including both sediment types was:

\[ \text{ER-¹³⁷Cs} = -0.24 + 1.04 \cdot \text{ER-PCAL} \]

\[ r^2 = 0.83, n = 55 \]

(4)

In comparison to ER-PCAL, the other ER of the pond samples deviated more from regressions derived from runoff samples. Therefore, eq. 3 seems to cover a wide range of erosion processes, from selective erosion to unselective soil loss, like rill or tillage erosion, and also subsoil erosion and colluvial deposition.

4 Discussion and conclusion

It is evident that both, ER-¹³⁷Cs in the soil loss and corresponding depletion of ¹³⁷Cs at the soil surface have to be considered, when using ¹³⁷Cs data to assess soil redistribution. ER-¹³⁷Cs was less than 1 for rill incision below plow layer and for sediments deposited in detention ponds, but was up to 5 for preferential erosion on coarse textured soils, hence reflecting a high variability of erosion processes in watersheds. Even on a plot scale, Bernard et al. (1992) found ER-¹³⁴Cs ranging from 1.8 to 10.8, with highest values for coarse textured soils like in the present investigation. Hence, estimates from ¹³⁷Cs loss will overpredict soil loss from sheet erosion by a factor of 2 or more, if the effect of particle size selectivity on ¹³⁷Cs loss is not accounted for. Furthermore, preferential adsorption to the clay fraction causes significant losses of ¹³⁷Cs even from large watersheds, in which a large portion of eroded soil is deposited again. This in turn affects all kinds of sediment budgets. Therefore, it is essential to include a reliable estimate of ER-¹³⁷Cs. This is quite more important than corrections for tillage dilution (Kachanoski and Delong, 1984), which was typically less than 1% (Quine et al., 1996), or a 5% reduction of ¹²⁷Cs due to snow drift or harvest loss (Delong et al., 1982). A better assessment would be achieved from a relation of ER-¹³⁷Cs to more general measured or predictable parameters, like sediment discharge or sediment concentration, commonly used to estimate ER of nutrients in most soil erosion and water quality models (Knisel, 1980, Young et al. 1987). This approach should also be applicable to ¹³⁷Cs as indicated by the close correlation between ER-¹³⁷Cs and ER-PCAL over a wide range of soil loss and deposition rates (Fig. 2). There are, however, some general limitations of this prediction concept. For the same soil loss different ER-¹³⁷Cs for the various watersheds were obtained, i.e. a soil loss of 60 kg·ha⁻¹ resulted in ER-¹³⁷Cs between 0.51 and 2.46. Menzel (1980) suggested, that site-specific differences should be responsible for typically less significant correlation between ER and sediment discharge under field conditions, whereas close correlations generally were obtained for rainfall simulation experiments, using intensive rains on homogeneous and bare soils (Sharpley, 1980, 1985).
Another source of variability is inherent to the concept of ER-calculation (eq. 1) with the average topsoil concentration as the fixed base. Temporal changes in compound concentration of the uppermost, hence contributing soil layer or incision into the subsoil can cause mispredictions. Even for high erosive, and therefore less selective events, such changes should not be neglected, as demonstrated for the upper 5 mm of the soil after a 5-year-storm (Fig. 1). The depleted soil surface exposed to the following rains diminished ER for succeeding events, until a high-erosive event or soil disturbance by tillage removed this depleted layer and reexposed the original soil. The presence of this process is indicated by the negative correlation between ER and cumulative previous soil loss (Tab. 3). The same was found by Auerswald and Haider (1992) for P and Cu.

Beside these general constraints, the close correlation between ER-$^{137}$Cs and ER-$^{137}$Cs in the soil loss and sediment deposits is of particular importance concerning the estimation of ER-$^{137}$Cs. This relationship is probably not site-specific, but also valid for other agricultural landscapes because the distribution in the soil and the selection processes are similar for both, $^{137}$Cs and $^{137}$Cs. The extensive literature on ER-P (total or extractable) can thus probably also be applied to ER-$^{137}$Cs, as the ER of various forms of extractable P are not significantly different from total P (Sharpley, 1985). This should allow further improvements of the $^{137}$Cs technique.

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References


