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Estimates of soil erosion using cesium-137 tracer models

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Abstract The soil erosion was studied by ^{137}Cs technique in Yatagan basin in Western Turkey, where there exist intensive agricultural activities. This region is subject to serious soil loss problems and yet there is not any erosion data towards soil management and control guidelines. During the soil survey studies, the soil profiles were examined carefully to select the reference points. The soil samples were collected from the slope facets in three different study areas (Kırtas, Peynirli and Kayısalan Hills). Three different models were applied for erosion rate calculations in undisturbed and cultivated sites. The profile distribution model (PDM) was used for undisturbed soils, while proportional model (PM) and simplified mass balance model (SMBM) were used for cultivated soils. The mean annual erosion rates found using PDM in undisturbed soils were 15 t ha^{-1} year^{-1} at the Peynirli Hill and 27 t ha^{-1} year^{-1} at the Kırtas Hill. With the PM and SMBM in cultivated soils at Kayışalan, the mean annual erosion rates were obtained to be 65 and 116 t ha^{-1} year^{-1}, respectively. The results of ^{137}Cs technique were compared with the results of the Universal Soil Loss Equation (USLE).

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Introduction

Several quantitative and qualitative techniques have been developed and used to estimate soil erosion and deposition throughout the world. However, most of them do not produce the spatial patterns of soil movements and redeposition of eroded particles within the fields to understand soil loss. Use of nuclear techniques in erosion monitoring and especially for qualification of soil loss has offered a fast and economical tool to estimate erosion rate starting with ^{137}Cs in 1970s (Ritchie and McHenry 1990).

^{137}Cs techniques have been used extensively to quantify erosion-induced soil losses over the 35–40 years (McIntyre 1987; Walling et al. 1995; Walling and He 1999; Ritchie and Rasmussen 2000; Theocharoploulos et al. 2002; Ugur et al. 2003a,b, 2004; Sac 2003). Fallout of this artificial radionuclide from the atmospheric testing of nuclear weapons began in 1954 and reached a peak in 1963, the year of international test ban treaty, after which it declined sharply. Since the late 1970s, rates of ^{137}Cs deposition have been very low, although in some parts of Europe and adjacent regions, an additional short-term input of ^{137}Cs was received in 1986 as a result of the

Chernobyl nuclear accident (He and Walling 1997). The northern soils of Turkey have been highly effected by this accident. According to reports of TAEK (Turkish Atomic Energy Agency) (2006), the ^{137}Cs levels in soils of Karadeniz, Marmara and Ege-Akdeniz regions were determined to be 16–2225 Bq kg^{-1} , 4–200 Bq kg^{-1} and 3–40 Bq kg^{-1}, respectively. ^{137}Cs (half-life of 30.2 years) deposited on land became tightly sorbed to soil particles and was concentrated in the surface layer of undisturbed soils. At the field level deposition of ^{137}Cs appears to have been relatively uniform (Oztas 1993).

Several studies have compared erosion rates estimated using ^{137}Cs measurements and the conventional method USLE (Universal Soil Loss Equation). Ritchie et al. found a strong logarithmic relationship between ^{137}Cs loss and predicted soil loss for many different land uses based on the USLE. Fredericks and Perrens found that soil loss predictions using the nuclear technique were substantially greater than the ones found by USLE (Oztas 1993).

The advantages of using the ^{137}Cs technique to study soil erosion are that it (a) requires a single sampling trip to the field; (b) provides results quickly; (c) allows retrospective assessment of soil erosion rates (average losses for 35–40 year period thus is less influenced by extreme events); (d) provides estimates of soil erosion rates, deposition rates, and export rates and (e) allows a sampling strategy to provide any spatial resolution required (Nouira et al. 2003).

The choice of a suitable reference site is one of the most important aspects of the technique. The reference site should have received the same annual precipitation and have the same geomorphological parameters as the field studied.

Application of nuclear techniques in erosion studies in Turkey has started by Ugur et al. (2003a) in Gokova region in Western Anatolia. They investigated the availability of Cs-137 and Pb-210 techniques for estimation of soil loss in Yatagan basin in the region. The erosion rates for two hills, one cultivated and other uncultivated, in the basin were determined using Cs-137 technique with proportional model (PM) and profile distribution model (PDM), respectively (Ugur et al. 2004).

In the present study the soil erosion was studied for the other three hills located in the basin using SMBM in addition to PM and PDM models.

The study sites

The studied catchment is a basin located in the northern part of Mugla in Western Turkey. Two hills, Yatagan at the north and Urnez at the south-east of the basin were already studied in the previous work. To obtain a complete set of erosion data for the region the three other hills in the basin were chosen as study sites. Two of them, the Peynirli Hill at the west and the Kırtas Hill at the south of the basin, are not suitable for cultivation. The other one, the Kayısalan Hill at the east, is of cultivated soils. The shoulder slopes of the hills with typical range 4–27% were selected for sampling (Fig. 1).

The climate is typically Mediterranean with a mean annual rainfall of 630 mm, most of which is concentrated during the period extending from December to April.

Soil sampling for ^{137}Cs analysis

The sampling grid in the different fields was adjusted to accommodate the different sizes of the fields. In general, several transects were established along the contour with the spacings of sample points ranging from 24 to 64 m. Typically, between 11 and 22 bulk samples were obtained at each site. Depending on the soil properties, different soil corers were used. Larger core (diameter: 15.5 cm) was used on stony soils and small one (diameter: 8.5 cm) on cultivated areas

Fig. 1 Map of Yatagan Basin showing the location of the study

Table 1 Topographic data of sampling sites

Sampling sites	Elevation (m)	Coordinate	Diameter of sampling corer (cm)	Depth of sampling corer (cm)	Grid cells (m^2)
Peynirli Hill	407	37°18′N, 28°06′E	15.5	15	10×40
Kırtaş Hill	396	37°17′N, 28°08′E	15.5	15	10×35
Kayısalan Hill	460	37°20′N, 28°10′E	8.5	30	10×28

(Table 1). Soil samples from different depths were collected in order to obtain information on local reference inventory and the depth distribution of ^{137}Cs in the soil profiles. Reference cores were sampled at 5 cm increments to a depth of 40 cm.

To estimate the ^{137}Cs reference inventory, reference sites were chosen near each study field on a flat area with a minimal intervention, located at some altitude with respect to the study field and also not affected by soil erosion or sedimentation and exhibiting a full grass and shrub cover during the whole year.

All samples were oven dried at 105°C for 48 h, disaggregated and sieved to separate the <2 mm fraction. They were packed into a 1,200 ml (1.5 kg) plastic Marinelli beaker for measurement of ^{137}Cs activity. The samples were analysed for ^{137}Cs by direct gamma assay, using Tennelec/Nucleus HPGe (184 cc) planar type coaxial intrinsic germanium detector (FWHM: 850 eV at 122 keV, FWHM: 1.85 keV at 1.33 MeV, relative efficiency %25 and peak/compton=57/1). Detector is situated in a chamber with 54×34×29 cm^3 dimensions and surrounded by 11 cm lead shielding. The ^{137}Cs activities were determined from the net area under the full-energy peak in the spectrum at 662 keV. The ^{137}Cs standard of Amersham (Certificate no. 317776-3 of sealed radioactive sources) was used to calibrate the efficiency of the detection system. Counting times were 30,000 s, providing a precision of ±10% at the 95% level of confidence.

Models used for erosion rates from ^{137}Cs measurements

Erosion rates for undisturbed soils (Peynirli, Kırtas) were estimated using the profile distribution model (PDM) since an exponential reduction was observed in undisturbed soil profiles (Fig. 2). This model is a simple exponential function derived from the vertical distribution of the ^{137}Cs inventory within reference profile (Sac 2003).

Assuming, as a simplification that the total ^{137}Cs fallout occurred in 1963, the year of maximum bomb fallout and that the depth distribution of ^{137}Cs in the soil profile is independent of time, the erosion rate Y can be estimated as: (Porto et al. 2001).It has been made corrections for ^{137}Cs fallout due to Chernobyl accident in collected soil samples.

$$Y = \frac{10}{t - 1963} h_0 \, ln\left(1 - \frac{X}{100}\right) \quad (1)$$

Where Y is the annual soil loss (t ha^{-1} year^{-1}) (negative value), t the year of sample collection

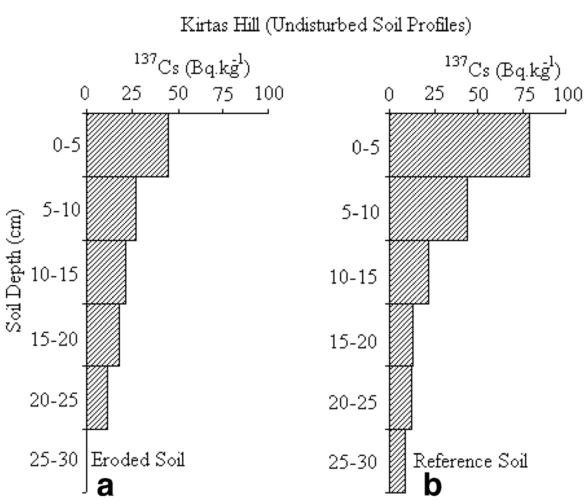

Fig. 2 Representative examples of the vertical distribution of ^{137}Cs at undisturbed soils (**a**) and reference soils (**b**) in the study field at the Kırtas Hill

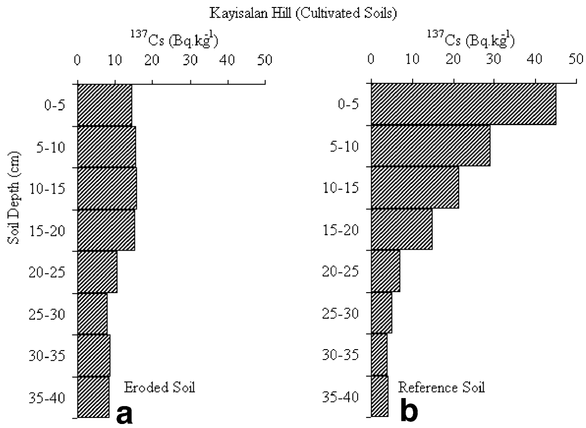

Fig. 3 Representative examples of the vertical distribution of ^{137}Cs at cultivated soils (**a**) and reference soils (**b**) in study field at the Kayısalan Hill

(year), h_0 the relaxation depth describing the profile shape (kg m^{-2}), X the percentage reduction in the ^{137}Cs inventory in relation to the local ^{137}Cs reference value defined as [(A_{ref}–A_u)/A_{ref})100] where A_{ref} and A_u are the measured total ^{137}Cs (Bq m^{-2}) inventories at the reference and sampling points, respectively.

Erosion rates for cultivated site (Kayısalan) were estimated using two models, namely the PM and SMBM. The PM assumes that ^{137}Cs is uniformly distributed throughout the tillage layer and ^{137}Cs loss with eroded soil is directly proportional to the depth of soil removed by erosion processes. Figure 3a shows a representative example of the vertical distribution ^{137}Cs concentrations at a cultivated point.

The annual erosion rate predicted by the proportional method is: (Walling and He 1999).

$$Y = 10\frac{BdX}{100T} \tag{2}$$

where d is the depth of the plough or cultivation layer (m), B the bulk density of the soil (kg m^{-3}), T the time elapsed since the initation of ^{137}Cs accumulation (year).

The cultivation depth was estimated to be 25 cm because that was the depth that a hoe or oxen-drawn plough was observed to penetrate. Bulk density for each sample was calculated from the dry mass of the sample and the core volume.

Due to the fact that the proportional model does not take into account the dilution of ^{137}Cs concentrations in the plough layer after surface lowering by soil erosion, the results obtained may underestimate the actual rates of soil loss (Nouira et al. 2003).

According to SMBM, the mean annual soil loss rate (t ha^{-1}year^{-1}), Y is expressed as follows: (Nouira et al. 2003).

$$Y = 10Bd\left[1 - \left(1 - \frac{X}{100}\right)^{\frac{1}{t-1963}}\right] \tag{3}$$

Where t is the ellapsed time since 1963.

Contrary to PM this model takes into account the dilution of ^{137}Cs concentration due to surface effect in the plough layer.

Results

Undisturbed soils

The mean ^{137}Cs inventories in undisturbed soils of Peynirli and Kırtas Hills were obtained to be 28.16± 2.23 kBq m^{-2} and 10.96±0.82 kBq m^{-2}, respectively.

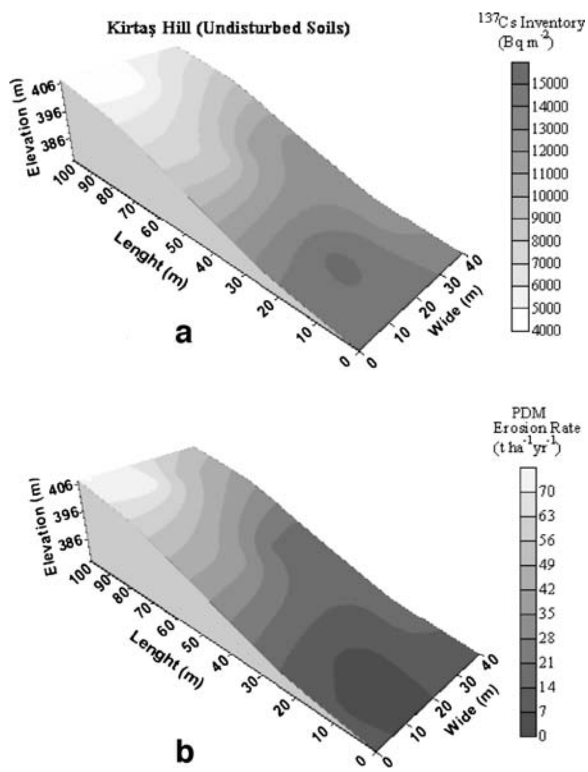

Fig. 4 Distributions of ^{137}Cs inventories and erosion rates at the Kırtas Hill

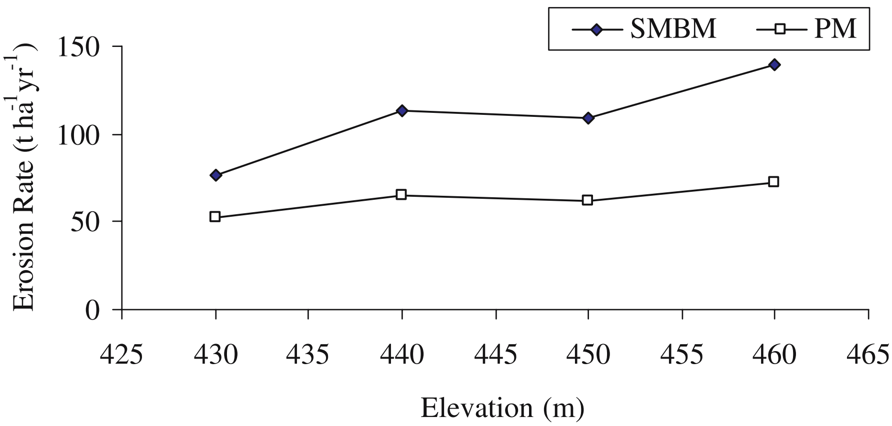

Fig. 5 The erosion rates estimated using simplified mass balance (SMBM) and proportional model (PM) at the Kayısalan Hill

Since all sampling points present ^{137}Cs activities lower than reference activity, no deposition areas are observed down slope the fields. The longitudinal variation in ^{137}Cs inventory with distance from upslope to down slope along transects is presented in Fig. 4 for the Kırtas Hill. Usually the longitudinal variation in ^{137}Cs inventory related to the soil loss depends on the variations of the topography and the position of the sampling point from hilltop. The average erosion rates estimated by profile distribution method in undisturbed soils for the Peynirli and the Kırtas Hills were found to be 15 and 27 t ha^{-1} year^{-1}, respectively.

Higher erosion rates are found along the Kırtas Hill slopes where its soils are stony whereas the lower values are observed along the Peynirli Hill slopes on which vegetation cover is more uniform.

Cultivated soils

The mean ^{137}Cs inventory measured in cultivated soils of Kayısalan was calculated to be 6.66± 0.58 kBq m^{-2}. The mean erosion rate in the Kayısalan Hill is estimated to be 65 t ha^{-1} year^{-1} by applying the proportional model whereas by using the simplified mass balance model it was as 116 t ha^{-1} year^{-1}. In general the difference between the two models becomes more important for the high soil erosion rates as it is in Kayısalan case. This fact can be observed in Fig. 5 which illustrates the erosion rate redistribution along one of the transects. The erosion rates derived from the proportional model remain always lower than those predicted with the simplified mass balance model. It is because, in contrary with PM, SMBM takes into account the effect of surfaced

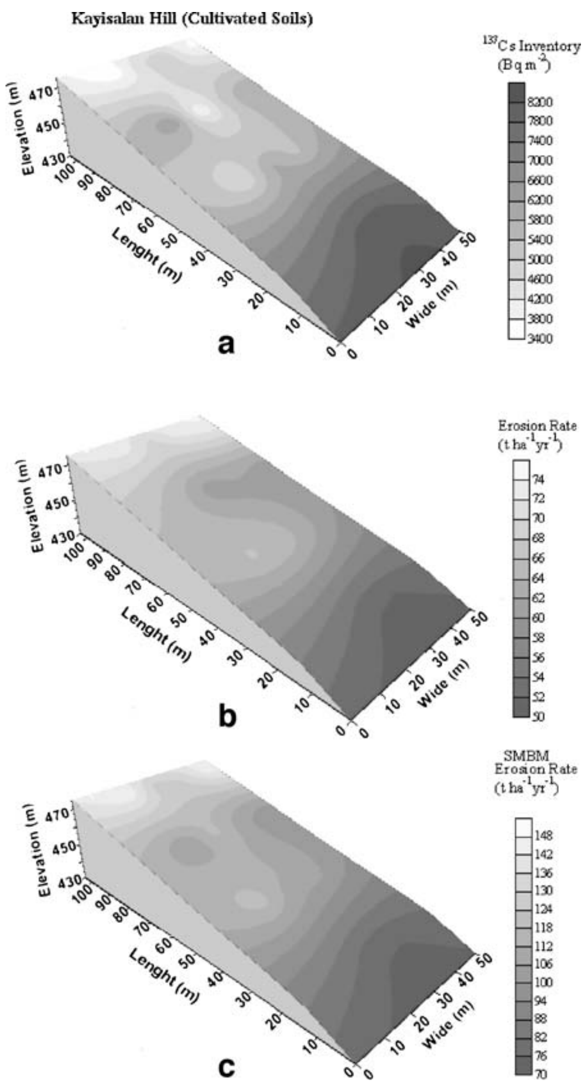

Fig. 6 Distributions of ^{137}Cs inventories and erosion rates at the Kayısalan Hill

Table 2 The average annual erosion rates derived using different models in study sites

Sampling sites	USLE (t ha^{-1} year^{-1})	PDM (t ha^{-1} year^{-1})	PM (t ha^{-1} year^{-1})	SMBM (t ha^{-1} year^{-1})
Yatagan (uncultivated)*	29	36	–	–
Peynirli (uncultivated)	16	15	–	–
Kırtas (uncultivated)	28	27	–	–
Ürnez (cultivated)[a]	46	–	47	70
Kayısalan (cultivated)	74	–	65	116

[a] Ugur et al. 2004

^{137}Cs loss by erosion on change in the ^{137}Cs distribution in time along the plough depth.

Increase in soil loss in these sites could be attributed to the fact that these hills have bare landscape without any natural plant cover and also downhill cultivation processes are applied.

Figure 6 shows distribution of ^{137}Cs inventories and soil losses for shoulder slope of Kayısalan Hill.

Annual erosion rates estimated by ^{137}Cs techniques were compared with the USLE results (Table 2). Figure 7 gives the comparison realized including also the results obtained for two other hills in the same region, namely the Urnez and the Yatagan Hills studied previously (Ugur et al. 2004). Results indicated that the estimated average annual erosion rates by PDM and PM methods were similar with the ones obtained by USLE (R=0.97, p<0.01).

Conclusion

The following points were deduced in the present study from the comparison of the results of three models of ^{137}Cs technique and USLE estimates.

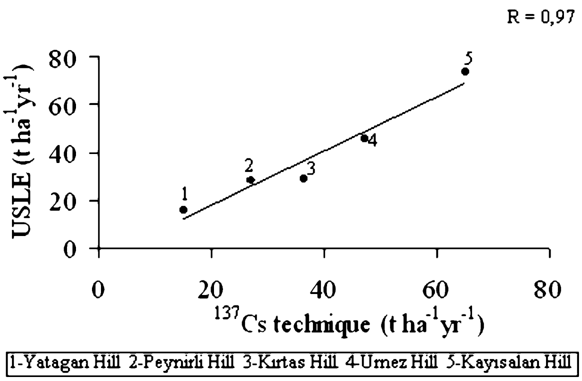

Fig. 7 Comparison of average soil loss estimates derived from USLE and ^{137}Cs techniques (PDM, PM)

A good agreement (R=0.97) was observed between soil losses predicted by two 137Cs and USLE techniques (Fig. 7). This indicates that in the all the regions studied the soil loss by wind is not much effective since USLE technique does not include the wind erosion whereas ^{137}Cs technique does.

The high erosion rates obtained in the cultivated sites in both techniques have pointed out a significant tillage contribution to soil loss and yet the water erosion seems to be the major component among several factors. That is why SMBM approach would be more suitable for water affected erosion studies in cultivated sites.

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