Application of Chernobyl-derived ^{137}Cs for assessment of soil redistribution in agricultural catchments of central Russia

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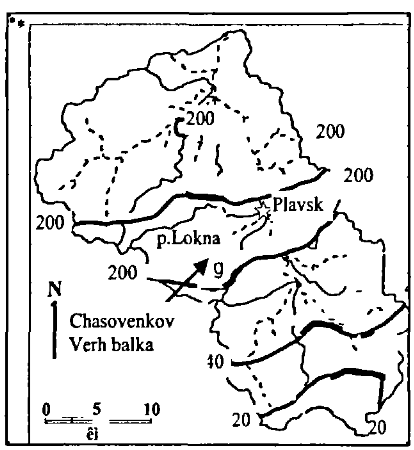
Introduction

Problems of soil degradation and water pollution are very significant for agricultural zone of Russia, because of two reasons: relatively high soil erosion rates and Chernobyl contamination of vast areas within Russian Plain. The northern part of Srednerusskaya upland is one of the hot plots, where combination both high intensity of soil erosion and extremely high level of radionuclide contamination are observed. This area 200-300 km south of Moscow is characterized by very contrast relief with deep river and balka valley and the high erosion index of rain-storms. The cultivated area varies from 60% to 75% from total area of the small river basin. The most part of the land is cultivating during 300-350 years and as far as 120-130 years ago the area of arable lands reached the maximum up to 80%. Even extremely steep valley slopes were ploughed in this period. As a result the increase the sheet, rill and gully erosion was observed. About 40-50% of small creek and some of the small rivers were completely filled and they transformed into dry valley with relatively flat bottom without permanent flow, which are named locally balka. Now the balka basin is the main area of sediment and sediment-associated pollutant redistribution. This contribution aims to study the contemporary soil redistribution rates based on ^{137}Cs redistribution within typical slope catchments located within the Lokna river basin 250 km south of Moscow in the center of Plavsk ^{137}Cs plot.

Study site

Three slope catchments with different configuration were chosen for detail study in the Chasovenkov Verh balka basin, which is the right tributary of the Lokna River, 2 km west of Plavsk in the Tula region of Central Russia (Figure 1). This area was contaminated by Chernobyl fallout with maximum inventories in excess of 400 kBq.m^{-2} along the Lokna river valley. Pre-existing bomb-derived ^{137}Cs inventories were in 100 times lower. So it is not necessary to take bomb-derived ^{137}Cs into consideration for study spatial redistribution of ^{137}Cs within the study area. The Chasovenkov Verh

Figure 1
Location of the Chasovenkov Verh balka basin within Plavsk Chernobyl contamination plot.



200～200 - ^{137}Cs inventory, kBq.m^{-2}.
■ - location of the Chasovenkov Verh balka within the Lokna river basin.

balka is the former river (according of the map produced in the middle of XIX century) which were completely filled by sediment due to intensive gully and rill erosion in the end of XIX century. Recently gullies stop their growth and most part of sediment delivered to the balka bottom from cultivated slope as a product of rill and sheet erosion. The underlying geology of the both catchments is limestone with clay layers overlying Holocene loess. Mean annual precipitation is 650 mm with about half of them during cold period as snow.

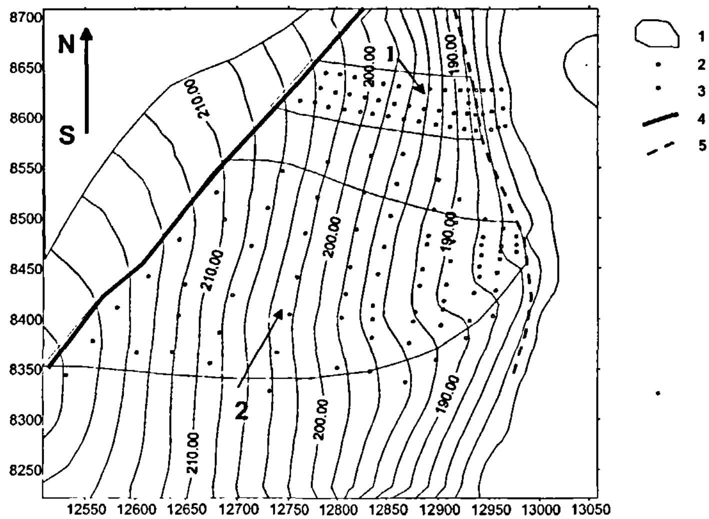
The soils are primarily typical and leaching chernozem, with a loamy texture. The most part of cultivated soil lost about half of their initial humus content in the upper 10 cm layer during the period of cultivation. The upper parts of cultivated slopes are occupied by typical chernozem and the lower relatively steep parts of cultivated slopes are occupied by leaching chernozem.

Three slope catchments of different configuration were chosen for detail study of erosion rates within the Chasovenkov Verh balka basin (Table 1). The first catchment has complex longitudinal form

	Area ha	Slope length, m	Slope gradient, %	Configuration	Soil	Humus content, %
Site 1	0.92	200-250	6-15	convex slope	leaching chernozem	2.4-3.8
Site 2	6.6	200-400	4-8	hollow catchment	leaching+ typical chernozem	2.4-3.8 4.6-5.5
Site 3	7.7	450-550	5-10	straight slope	leaching chernozem	2.4-3.8

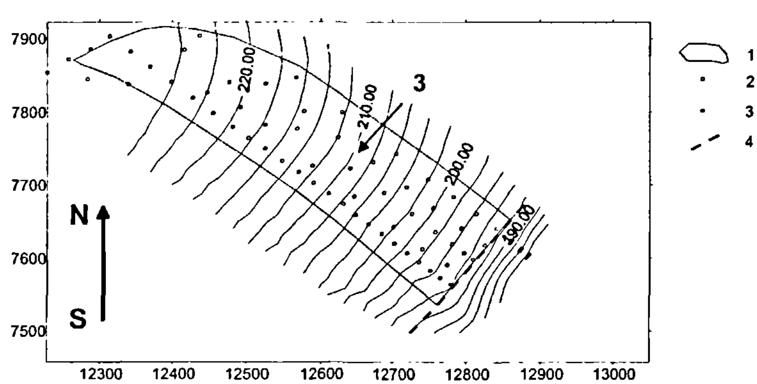
Table 1
Catchments characteristics.

with maximum angle in the bottom of cultivated part (Figure 2). The small hollow watershed is the second site. This catchment has asymmetrical form with relatively steep short south slopes and more gentle north slopes (Figure 2). The catchment located on the lower part of slope and part of surface runoff and sediments from the upper slopes cross the ground road, located upper border of this



Key: 1- border of watershed, 2 – point of sampling and in situ measurements, 3 – points in situ measurements, 4 – ground road, 5 – lower border of cultivated slope.

I Figure 2
Topographical plan of slope catchments 1 and 2.



Key: 1- border of watershed, 2 – point of sampling and in situ measurements, 3 – points in situ measurements, 4 –lower border of cultivated slope.

I Figure 3
Topographical plan of slope catchment 3.

catchment (Figure 2), in few places and flow through it. In the result the part of sediment, which delivered from upper slopes to the ground road, redeposit in the upper part of catchment 2. It is typical situation for sediment redistribution within cultivated fields of Sredne-Russkaya upland. The third catchment has relatively straight longitudinal profile with small increase of angle in the lower half of slope (Figure 3).

It should be noted that direction of tillage as well as tractor wheel tracks usually change direction of flow. In the result the catchment areas can vary from year to year.

Methods

The main task of sampling program was to evaluate the ^{137}Cs redistribution for different parts of key slope catchments using both laboratory measurements of ^{137}Cs inventory and *in situ* measurements of ^{137}Cs inventory. Sampling was undertaken during the periods May-June 1998. Particular attention was given to the identification of reference locations where the measured ^{137}Cs inventories should be representative of the total fallout input. The relatively flat cultivated field and adjacent forest-shelter belt were chosen for detail study of reference inventory 27 in situ measurements of ^{137}Cs inventory were done. In addition 9 samples for laboratory analisys were taken in the same points. Also the other reference points were selected on the alka sides within areas without deposition. The most of samples were bulk. Two cores (0-30 and 30-40 cm) were taken from few points within cultivated part of flat interfluve field to determine of vertical migration rate of ^{137}Cs. Bulk core samples were collected from each of the study watersheds, using a 36.2 cm^2 core tube inserted to a depth of 30 cm. Simultaneously with the collection of the depth incremental samples and the soil cores, *in situ* measurements of ^{137}Cs inventory were made adjacent to each sampling point and at additional sites using a Corad field-portable collimated spectrum sensitive NaI detector (Govorun *et al.*, 1994; Chesnokov *et al.*, 1997). Based on field experiments undertaken by the designers of the Corad equipment, the detector is capable of measuring ^{137}Cs inventories in the range 0.37 - $5.55 x 10^2$ $kBq.m^{-2}$ to depths of up to 40 cm with a precision better than ±20%. Because of the high levels of ^{137}Cs present in the soil of the study area, problems associated with interference by other radionuclide are minimised and the *in situ* measurements required count times of only a few minutes. The possibilities of use *in situ* ^{137}Cs inventory measurements for analysis of ^{137}Cs redistribution were discussed elsewhere (Golosov *et al.*, 2000).

A detailed topographic survey of the each key watershed, the sampling and measurements points was made using a differential GPS system, which provided measurements of height and position with a maximum error of ±2cm. The resulting data were used to produce 1:2000 plans of the study catchment (Figure 2, 3).

All soil samples were dried and sieved to <2mm prior to laboratory measurement of their ^{137}Cs content by gamma spectrometry using an HPGe coaxial detector calibrated with Standard Reference Materials and laboratory standards made using standard solutions. Count times were sufficient to provide a typical analytical precision of ±4-5%.

The information about crop rotation and peculiarities of soil cultivation was collected for period 1986-1998 for each watershed from local farmers. Also additional meteorological information for period 1986-1998 were received from meteorological station, which is located in 1.5 km east of key catchments. Data about soil characteristics were taken from Agricultural Institute of the Central Region, which are located near the Lokna river basin.

The proportional and standard mass-balance models were used for calculation of erosion and deposition rates for each key catchment, using software elaborated by D.E. Walling and Q. He. The proportional model can be represented as follows:

$$Y = 10 \frac{BdX}{100\,TP} \qquad (1)$$

where: Y – mean annual soil loss ($tons.ha^{-1}.yr^{-1}$); d – depth of plough or cultivation layer (m); B– bulk density of soil ($kg.m^{-3}$); X – percentage reduction in total ^{137}Cs inventory; T – time elapsed since initiation ^{137}Cs accumulation (yr); P – particle size correction factor.

Percentage reduction in total ^{137}Cs inventory defined as:

$$X = \frac{A_{ref} - A}{A_{ref}} \times 100 \qquad (2)$$

where:

A_{ref} – local ^{137}Cs reference inventory ($Bq.m^{-2}$);
A – measured total ^{137}Cs inventory at the sampling point ($Bq.m^{-2}$).
Standard Mass Balance Model (MBM-1) was used for calculation erosion-deposition rates within each sites. For calculation of erosion rates the following equation was applied:

$$Y = \frac{10\,dB}{P}\left[1 - \left(1 - \frac{X}{100}\right)^{1/(t-1986)}\right] \qquad (3)$$

where:

Y – mean annual soil loss ($tons.ha^{-1}.yr^{-1}$); d – depth of plough or cultivation layer (m); B – bulk density of soil ($kg\ m^{-3}$); X – percentage reduction in total ^{137}Cs inventory defined as $(A_{ref}-A)/A_{ref} \times 100$); t – time (yr); P – particle size correction factor .
Deposition rate was estimated from the ^{137}Cs concentration of the deposited sediment according to:

$$R = \frac{A_{ex}(t)}{\int_{1986}^{t} C_d(t')e^{\lambda(t-t')}dt'} = \frac{A(t) - A_{ref}}{\int_{1986}^{t} C_d(t')e^{\lambda(t-t')}dt'} \qquad (4)$$

where:

$A_{ex}(t)$ – excess ^{137}Cs inventory of the sampling point over reference inventory at year t' ($Bq.m^{-2}$); $C_d(t')$ – ^{137}Cs concentration of deposited sediment at year t' ($Bq.kg^{-1}$); λ – decay constant for ^{137}Cs (yr^{-1}), P' – particle size correction factor.

Calculation of soil erosion rate using modified version of USLE (for assessment of rain erosion) and model of State Hydrological Institute (for assessment of erosion during snow-melting period) (Larionov, 1993) was made for each key catchment. In the result the soil erosion maps for each site were produced.

Results

The comparison results of calculations with actual soil losses from different cultivated slope of Russian Plain demonstrate that in the cases erosion models (modified version of USLE and State Hydrological Institute model) results overestimated annual sediment output from slope catchments mostly on 20-40%, but sometimes even in two times (Golosov, 1998). However it probably can be explain the absent of correct information about crop rotation for the entire period of calculation. In our study we have the detail information about crop rotation from 1986. Soil erosion map with annual soil losses for the period 1986-1998 were produced for each key catchment. Using USLE, the mean annual erosion rates for all catchments are in one range: 11.5; 11.8 and 13.8 $Mg.ha^{-1}$ from catchment 1, 2 and 3 respectively.

Because *in situ* and laboratory measurement of ^{137}Cs inventory were made, it is necessary to compare both sets of data. First it should be noted that the measurements provided by the Corad equipment relate to a surface area of 2.1 m^2, which represents the field of view below the detector collimator, whereas those for the cores relate to an area of only 36.2 cm^2. In view of the microscale spatial variability of ^{137}Cs inventories, which has been widely reported in the literature (Sutherland, 1991, 1994; Owens and Walling *et al.*, 1996), the larger surface area sampled by the *in situ* detector could be expected to reduce the effects of this variability and should therefore result in lower values of standard deviation, coefficient of variation and range for the *in situ* measurements.

As our previous study demonstrate (Golosov *et al.*, 2000), in the case of the cultivated areas difference between *in situ* and laboratory measurement is not high. This reflects the mixing caused by ploughing and cultivation, which reduce the microscale variability of ^{137}Cs inventories and thus the potential contrast between the two sets of measurements. The enough good correlation between two data sets was received for two catchments of the Chasovenkov balka basin (Figure 4). The each sampling point represent the mean value between rill and interrill surfaces. *In situ* measurement char-

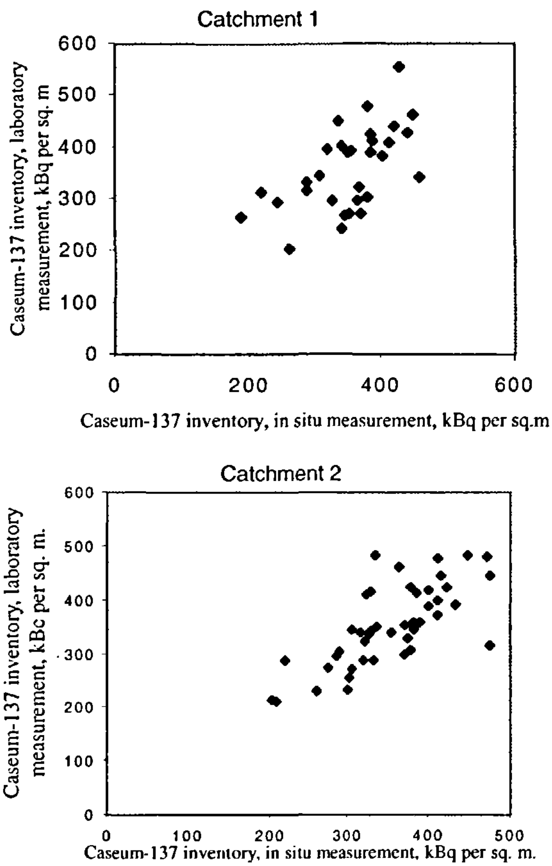


Figure 4 Relationship between *in situ* and laboratory measurements of ^{137}Cs inventory in catchments 1 and 2.

acterise the 2.1 m^2 area with accidental relationship between rill and interrill surfaces. So it is possible to use *in situ* measurement for the study of ^{137}Cs inventory within cultivated slope of the Chasovenkov balka basin. *In situ* measurements are used for analysis of sediment redistribution. ^{137}Cs reference inventories in undisturbed soil profiles around the key sites average ca 354 $kBq.m^{-2}$ with standart deviation 37.9 and coeffient variation 0.11.

Walling and He (1999) summarised the existence approaches to transform the ^{137}Cs distribution patterns to the soil distribution patterns. Also they suggested some improved models, which are able to take into consideration some peculiarities of interaction between fresh bomb-derived ^{137}Cs fallout, grain size and tillage. However the proportional model (Mitchell *et al.*,1980; Walling and Quine *et al.*, 1990) and standard mass balance model (Kachanoski and de Jong, 1984; Quine, 1989; Walling and Quine,1990; Ostrova *et al.*, 1990) is enough correct for area with Chernobyl-derived ^{137}Cs, because Chernobyl radionuclide fallout accumulation was occurred during very short period of time (27 April- 15 May 1986) and the all bare slopes were cultivated shortly after the fallout input. Uncertainties associated with the fate of freshly deposited ^{137}Cs prior to its incorporation into the plough layer by cultivation are substantially reduced. This is also true for fields under winter corn and perennial grass, because according of observation erosion rate is very low under these crops during summer period. According of results of comparison of grain size distribution of suspended sediment, which were taken from flow near lower border of cultivated field, and samples of surface soil from cultivated field from Chasovenkov Verh balka basin demonstrates, that they are very similar (Walling *et al.*, in press). Tillage effect is not significant yet for cultivated slope of the Lokna river basin, because only twelve years pass from 1986 with only maximum two tillalage operations per year. However the tillage operation influence on the soil redistribution within shoulders of the local catchments. The proportional and standard mass-balance models were used for calculation of erosion and deposition rates for each key catchment, using software elaborated by D.E. Walling and Q. He.

The results of calculation the erosion and sedimentation rates are presented in Tables 2 and 3. If it is compare the patterns of soil redistribution, which were received used proportional and standard mass-balance models, there are no essential differences (Figure 5). However some disparity can be found between values of gross and net erosion rates and deposition rates. Mass-balance model give more contrast results (Table 3, 4). It is interesting that area of eroding sites decrease with complication of relief pattern from relatively simple catchment 3 to hollow catchment 2 (Table 3, 4). However area of aggrading sites is enough vast within the all sites. The soil aggradation in the upper part connects with transport of soil particle with runoff from the fields located upper the road and their redeposition within the top part of catchment 2. As we observed during rain storm, stream formed along road overflows through the road edge during extreme erosion events.

Measure	Catchment 1	Catchment 2	Catchment 3
Gross erosion rate (tons.h^{-1}.year^{-1})	11.0	4.7	10.2
Eroding sites			
Mean erosion rate (tons.h^{-1}.year^{-1})	18.0	11.5	14.0
% total area	62	41	73
Aggrading sites			
Mean deposition rate (tons.h^{-1}.year^{-1})	13.3	12.6	12.2
% total area	38	59	27
Net erosion rate (tons.h^{-1}.year^{-1})	6.1	-2.88	6.9
Sediment delivery ratio	55	0	68

I Table 2
Integrated field data for the slope catchments at the Chasovenkov Verh balka basin (proportional model, *in situ* measurement of ^{137}Cs inventory).

Measure	Catchment 1	Catchment 2	Catchment 3
Gross erosion rate (tons.h^{-1}.year^{-1})	13.1	5.2	11.0
Eroding sites			
Mean erosion rate (tons.h^{-1}.year^{-1})	21.6	13.3	15.1
% total area	61	39	72
Aggrading sites			
Mean deposition rate (tons.h^{-1}.year^{-1})	16.1	15.0	13.3
% total area	39	61	28
Net erosion rate (tons.h^{-1}.year^{-1})	6.8	-3.9	7.4
Sediment delivery ratio	52	0	67

I Table 3
Integrated field data for the slope catchments at the Chasovenkov Verh balka basin (mass-balance model-1, *in situ* measurement of ^{137}Cs inventory).

It is obviously, that only part of soil mobilised by erosion was exported from the field towards the balka valley bottom depending from relief. So the sediment delivery ratio is very different for slope catchments of different configuration (Table 2, 3). 67% of the soil mobilised by erosion was transported from the field. The maximum sediment accumulation rate in the bottom part of slope is

Method of assessment	Mean annual rates, tons.ha^{-1}.year^{-1} Site 1	Site 2	Site 3
Modified version of USLE	11.5	11.8	13.8
^{137}Cs technique			
Corad measurement			
Proportional model			
Net erosion	6.1	- 2.9	6.9
Cross erosion	11.0	4.7	10.2
Mass balance model			
Net erosion	6.8	-3.9	7.4
Cross erosion	13.1	5.1	11.0

Table 4
Mean annual soil losses from cultivated catchments for period 1986-1997 established by different methods.

40-45 tons.ha^{-1}.yr^{-1}. The sediment accumulation in the bottom part of cultivated slope connects with dam effect of lower tillage edge. The other zone of sediment storage is in the upper part of slope, where gradient of slope is relatively lower. The combination effect of soil and tillage erosion is responsible for some deposition in this area. Deposition on the flat slope usually occur if direction of tillage operation cross the flow path along slope gradient.

The sediment delivery ratio for the slope catchment 1 is about 52-55% (Table 2, 3). The maximum deposition rate is observed within two storage zones. One of them is located near the slope bottom. The origin of this plot underpins the suggestion about wave nature of erosion/deposition processes. The storage zone in the upper part of slope is consequence of sediment transport from ground road, which is located upslope catchment. The sediments redeposit within this relatively flat upper part of catchment.

The catchment 2 is transit type field. The artificial runoff, which concentrated along the ground road upslope of hollow catchment 2, overflows the road edge and move toward of hollow bottom. Most part of sediment is stored in the upper part of catchment, because the flow transformed from concentrated to dispersal. In the result the sediment input exceed sediment output (Table 2, 3). Areas with maximum erosion rates are located along the hollow bottom, because of flow concentrations, (*answer on question* L). Typically even direction of tillage can influence on the increase or decrease of erosion/deposition rates within gentle slopes. From the other hand probably the density of measurement points was not enough within upper part of this catchment (Figure 2-II). It is obviously, that twelve years passed from 1986 is not enough time for forming the pattern of rill net within gentle slopes. At least it is possible to suggest that some ^{137}Cs input was delivered to the upper parts of catchments 1 and 2 during spring-summer 1986, because of dust transfer from ground road.

Discussion and conclusion

Attempt to use Chernobyl-derived ^{137}Cs for assessment sediment redistribution demonstrates that only 12 years after Chernobyl accident it is possible to identify the areas with high erosion and deposition rates. However some areas within slope catchments, which are named stable (Figure 5), can not be defined as loss/gain sites, because the changes of ^{137}Cs do not exceed the initial variability of Chernobyl-derived ^{137}Cs fallout.

Soil losses, which were received by calculation of erosion rates using modified version of USLE and SGI model, are much more close to gross erosion rates, which were received using ^{137}Cs technique (Table 4). Erosion models were validated for Russian conditions previously (Golosov, 1998). These erosion models do not take in account intra-field deposition. However deposition is actually observed within cultivated fields. Also it should be noted, that ^{137}Cs technique allow to determine soil deposition for transit catchments. Probably ^{137}Cs technique is unique opportunity to determine the actual pattern of soil loss/gain areas within cultivated field, because traditional soil-morphological method demand much more field work and so more expensive.

It should be noted that 15 years after Chernobyl accident ^{137}Cs technique can be apply for assessment of erosion and deposition rates

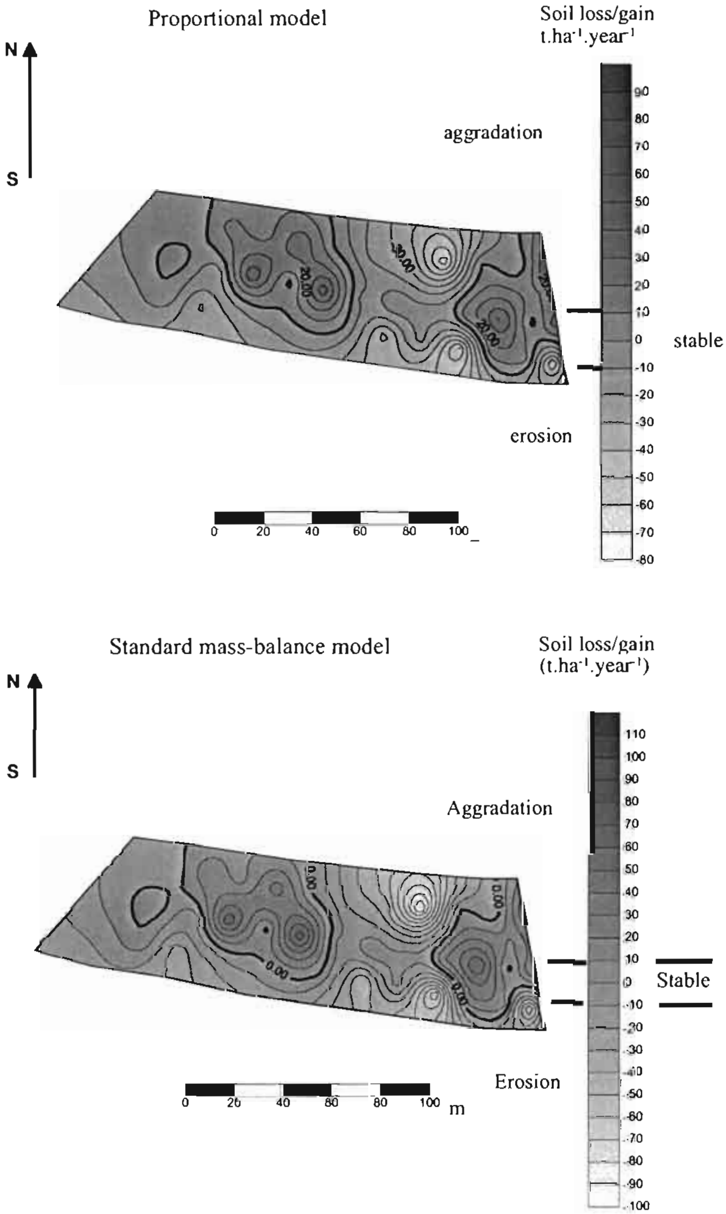


Figure 5
Maps of soil intra-field redistribution for period 1986-1997, catchment 1.

for sites with mean annual erosion rates exceed 10 tons.ha^{-1}. The absolutely correct results can be received for areas within part of fields with annual soil losses 20 tons.ha^{-1} (Litvin *et al.*, 1994). There are no essential differences between using *in situ* and laboratory measurements of ^{137}Cs inventory for calculation erosion/deposition rates. However *in situ* measurements allow defining more correct pattern of soil redistribution because the larger surface area sampled by the *in situ* detector could be expected to reduce the effects of random variability of ^{137}Cs inventory.

Application of ^{137}Cs technique for assessment of erosion/deposition rate allows to receive pattern of soil redistribution within study area, including influence sheet, rill and tillage erosion, as well as some possible input of soil because of sediment transit from topographically upper located fields or local wind erosion. Maps of intra-field erosion demonstrate that maximum soil losses are observed within lower half of midslopes. Usually few strips with high soil losses usually alternate with strips where erosion rates are lower. It is consequences of wave nature of erosion/deposition processes. The upper boundary of the area of high soil losses depends from configuration of slope profile and as a rule it is very close to shoulder between relatively gentle and relatively steep part of slope. Bottom of cultivated hollows is the other area of extreme erosion rates. However some compensation of soil losses in hollow bottoms happen in period between erosion events because of redistribution of soil by tillage erosion processes. So the actual soil losses from hollow bottom can be identified by ^{137}Cs technique only if monitoring of ^{137}Cs redistribution is organised for hollow site.

The values of sediment delivery ratio (SDR) change in very wide range for key catchments. The SDR coefficient increases proportionally to gradient of slope. However it is necessary to take into consideration the type of slope catchment and 3-dimension model of slope.

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