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Modern parameters of caesium-137 root uptake in natural and agricultural grass ecosystems of contaminated post-Chernobyl landscape, Russia

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Abstract

The estimation of modern parameters of ^{137}Cs root uptake was conducted in natural meadow and agricultural ecosystems of post-Chernobyl landscapes of Tula region. The agrosystems with main crops of field rotation (barley, potatoes, rape, maize) occupying watersheds and slopes with arable chernozems are contaminated at a level 460-670 Bq/kg (4.7-6.0 Ci/km^2); natural meadow ecosystems occupying lower parts of slopes and floodplains are contaminated at a level 620-710 Bq/kg (5.8-7.6 Ci/km^2). In the arable soils ^{137}Cs uniformly distributed to a depth of A_p horizon (20-30 cm of thickness), while in meadow soils 70-80% of the radionuclide is concentrated within the top A_d horizon (9-13 cm of thickness). These topsoil layer accords with rhizosphere zone, where >80-90% of plant roots are concentrated, and from which ^{137}Cs is mostly consumed by vegetation. Total amount of ^{137}Cs root uptake depends on the level of soil radioactive contamination (correlation coefficient 0.61). So ^{137}Cs activity in meadow vegetation (103-160 Bq/kg) is generally more than one in agricultural vegetation (9-92 Bq/kg). The values of ^{137}Cs transfer factor in the studied ecosystems vary from 0.01 (rape) to 0.20 (wet meadow), that confirms the discrimination of the radionuclide's root uptake. The larger are the volume of roots and their absorbing surface, the higher are the values of transfer factor from soil to plant (correlation coefficients 0.71 and 0.64 respectively). ^{137}Cs translocation from roots to shoots is also determined by biological features of plants. At the same level of soil contamination above-ground parts of meadow herbs accumulate more ^{137}Cs than *Gramineae* species, and in agrosystems above-ground parts of weeds concentrate more ^{137}Cs than cultivated cereals. Thus, the level of soil radioactive pollution and biological features of plants are determinants in the process of ^{137}Cs root uptake and translocation and should be considered in land use policy.

Keywords: radioactive contamination, caesium-137, root uptake, transfer factor, Chernobyl accident

Introduction

It has been known that after the Chernobyl accident the combined area of radioactively contaminated agricultural lands in Russia with excess of national standards of radiation safety for ^{137}Cs in soil ≤1 Ci/km^2 (Rodin and Bazilevich, 1965) comprised about 2.3 million ha and more than 1 million ha of which were contaminated at a level 5-80 Ci/km^2, so the Chernobyl accident can be said with assurance as an accident in agriculture (Alexakhin and Korneev, 1991). Nowadays due to extremely long-term consequences of radioactive accidents a significant part of Russian soils still contains ^{137}Cs at a level 5-10 and more Ci/km^2

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and is assumed will be polluted until the end of the century (Anonymous, 2006; Frissel et al., 2002; Yablokov et al., 2007).

At the same time a high portion of lands contaminated by ^{137}Cs after Chernobyl accident belongs to fertile chernozems, so ones widely continued to be used as croplands in spite of radioactive pollution. Root uptake and translocation of ^{137}Cs from soil into cultural crops or meadow grasses is the key for understanding of general ecological situation and for elaboration of land use policy on such territories.

There are numerous investigations concerning dependence of ^{137}Cs root uptake by different plant species on the level of ^{137}Cs presence in soil, soil properties, climatic conditions, seasonal features. But literature reviews indicate that mostly edible or above-ground parts of plants are taken into account in these studies (Ehlken and Kirchner, 2002; Fujiwara, 2013; Hampton et al., 2005; Staunton et al., 2003; Tamponnet et al., 2008). Even the specialized IAEA's Programme EMRAS (Environmental Modeling for radiation Safety) takes a similar approach to the assessment of ^{137}Cs behaviour in a "soil-plant" system (Fesenko et al., 2007). It is reasonable for practical measures of the control of plant production and soil remediation, but does not provide accurate information of ^{137}Cs root uptake by vegetation in radioactively contaminated terrestrial ecosystems. The more so as hydroponics or soil culture's model experiments demonstrate that ^{137}Cs distribution between roots and shoots is frequently non-uniqueness, and in many case roots accumulate more radionuclide then green parts of plants (Aktar et al., 2009; Brambilla et al., 2002; Golosov et al., 1999; Izrael, 1998; Anonymous, 2009; Smolders and Tsukada, 2011; Takeda et al., 2008; Tamponnet et al., 2008; Walling and Quine, 1990). The detailed studies of the radionuclide behaviour in a "soil-plant" system in the natural conditions of the quasi-equilibrium biogeochemical radionuclide cycle of ^{137}Cs in post-Chernobyl landscapes are fascinating in this connection.

Material and Methods

Study Area

With the object to evaluate overall parameters of ^{137}Cs root uptake by grass vegetation on radioactively contaminated lands the study in agricultural and natural meadow ecosystems of post-Chernobyl forest-steppe landscape was conducted. The investigated territory is situated in the central part of Plavsk radioactive hot spot (Figure 1) – the area of pronounced Chernobyl fallout in European Russia (Tula region) where initial level of ^{137}Cs in soils after accident ranged from 5 to 15 Ci/km^2 and averaged ≈8 Ci/km^2 (Greger, 2004). Bomb-derived ^{137}Cs fallout in this region during 1949-1963 was negligibly small, so pool of the radionuclide inventory in soils may by completely attribute with Chernobyl accident.

Landscape Characteristics

The investigated area represents a typical agricultural landscape with arable soils dominating on the watersheds and slopes (altitudes 210-250 m) and natural grassland ecosystems occupying lower parts of slopes and floodplains (altitudes 190-210 m) which are used as pastures and hayfields. The agrosystems with main crops of field rotation (spring barley, potatoes, summer rape, maize) as well as natural ecosystems of dry and wet meadows were selected for the detailed study (Table 1). Total biological productivity of agricultural crops varies between 1 and 4 kg/m^2, the biomass of natural grass ecosystems is about 2 g/m^2, ash content in above- and below-ground parts of vegetation constitutes 5-8%; all is typical for Russian agricultural and natural ecosystems of forest-steppe zone (Rodin and Bazilevich, 1965).

According to the World Reference Base of soil classification, soil cover of the area is presented mainly by haplic chernozems of watersheds and slopes derived from loess calcareous loams and alluvial meadow soils of floodplains derived from calcareous alluvial loams. They have similar properties – heavy loam texture, bulk density 0.9-1.2 g/cm^3, sum of A+AB horizons ~60-80 cm with C_{org} to 5-7%, neutral pH_w.

Soil and Vegetation Sampling

On each plot vegetation was collected from a fixed space taking into account above- and below-ground biomass (50^{x}50 cm^2 and 10^{x}10^{x}30 cm^3 correspondently). The quantitative characteristics of vegetation below-ground fraction were estimated after washing from soil particles with a control of adhesion process by visual method and following laboratory analysis of ash content.

Soil samples were collected from the same fixed volume 10^{x}10^{x}30 cm^3 by step 10 cm. The sampled soil profile up to 30 cm was assumed both as rhizosphere space and current depth of 90% ^{137}Cs penetration [3, 11]. Replication on each soil and vegetation site was threefold.

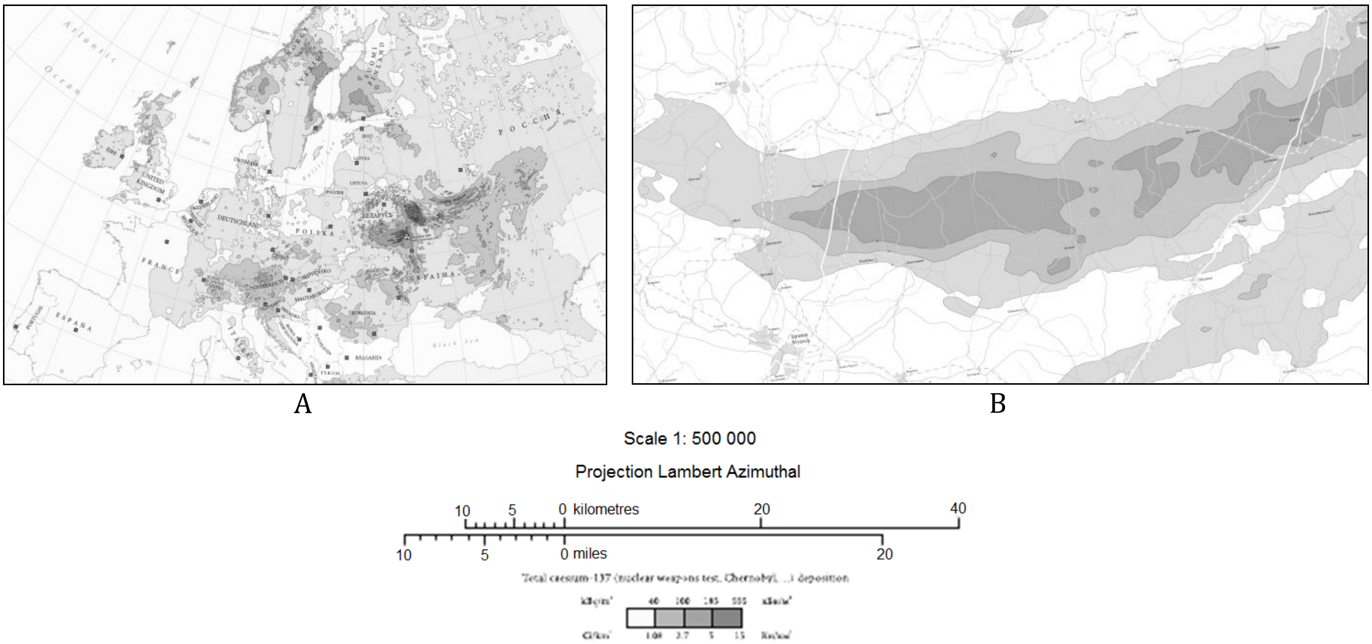


Figure 1. Location of the area under study: A - general location of Plavsk radioactive hot spot and B – location of the investigated area on a map of Europe initial pollution by ^{137}Cs after Chernobyl accident (Izrael, 1998)

Table 1. General characteristic of grass ecosystems under study

Charachteristic	Agrosystems				Natural ecosystems	
	barley	maize	rape	potatoes	dry meadow	wet meadow
Altitude, m	248	248	245	213	208	194
Relief	watershed			middle part of slope, 3-5°	lower part of slope, 7-10°	floodplain
Landscape	eluvial			trans-accumulative		accumulative
Parents rocks	loess calcareous loams					alluvial loams
Land use	arable lands				pasture	hayfield
Soil	arable haplic chernozem				haplic chernozem	calcareous alluvial
- humus, %	6.5	6.8	6.7	6.3	5.2	5.8
- pH_w	6.6	6.5	6.5	6.9	7.1	6.9
- bulk density, g/cm^3	1.05	0.98	1.21	0.92	1.16	1.16
Vegetation	cultural crops with admixed weeds				grass-herb meadow	herb-grass meadow
- total biomass, kg/m^2	2,2	3,9	1,0	1,9	1.9	2.2
- above-ground biomass, kg/m^2	1,5	1,4	0,4	1,1	0.2	0.3
- below-ground biomass, kg/m^2	0,7	2,5	0,6	0,8	1.7	1.9
- above-ground / below-ground biomass ratio, %	67 / 33	35 / 65	41 / 59	56 / 44	8 / 92	13 / 87
- ash content in total biomass, %	5.4	7.3	5.3	5.2	8.4	7.0
- ash content in above-ground biomass, %	5.4	7.6	8.1	4.9	7.9	8.4
- ash content in below-ground biomass, %	5.4	7.5	3.3	5.5	8.5	6.8

Laboratory Analysis

Subsequent laboratory treatment of soil and vegetation samples involved oven-drying at 105°C, grinding, sieving to particles <2 mm and homogenization of samples for gamma spectrometric and other analysis. The ^{137}Cs activity was measured with counting time 0.5 hour at 661.66 keV, using a scintilla gamma-ray NaI detector. Maximum relative error of ^{137}Cs activity determination reached 10–20%.

Vegetation biomass, ash content and bulk density of soils were estimated by weight method. Root volume and absorbing surface of roots were deduced by displacing of water and quantitative absorption of methylene blue. Soil chemical analysis (C_{org}, pH_w) were conducted by standard methods.

Results and Discussion

^{137}Cs Activity in Soil and Vegetation

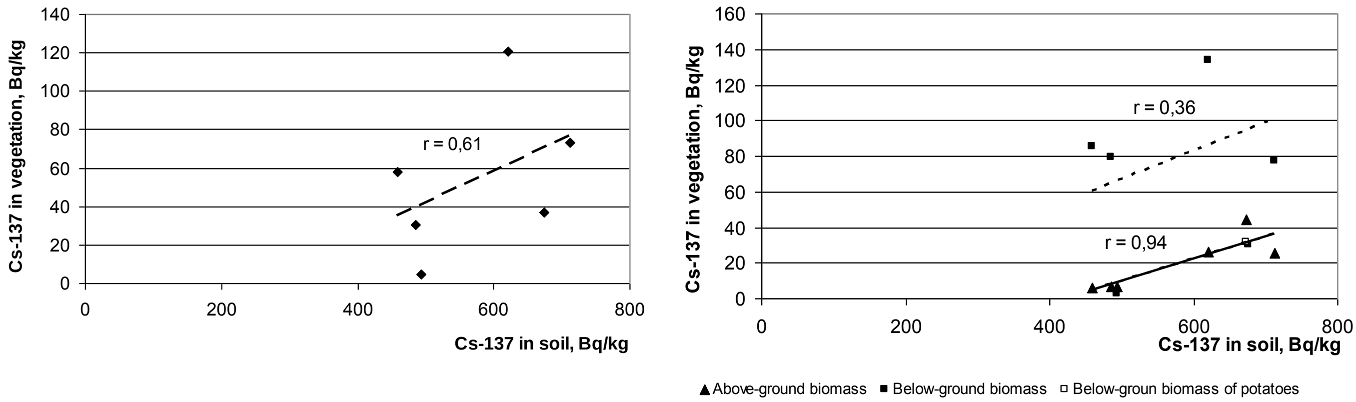
Current values of ^{137}Cs activity in the upper 30-cm layer of the investigated soils of Plavsk radioactive hot spot exceed 450 Bq/kg (Table 2), that confirms the long-term consequences of ^{137}Cs contamination in terrestrial ecosystems. Parameters of the radionuclide's accumulation in soils of meadow ecosystems are significantly higher than ones in arable chernozems. This indicates a pronounced redistribution of the radionuclide within the river catchments of forest-steppe zone, leading to an increase in the density of radioactive contamination in geochemically subordinate positions. A such data is mainly associated with water and tillage erosion transport of ^{137}Cs developing on cultivated hill slopes (Belyaev et al., 2013; Greger, 2004; Yablokov et al., 2007), but advanced surface of meadow herbs and grasses in comparison with rare vegetation of agrosystems in the course of April-May Chernobyl fallout in 1986 probably fulfilled a role of additional biological barrier for ^{137}Cs assertion in "soil-plant" system of natural grass ecosystems.

Table 2. Mean ^{137}Cs activity in soil and vegetation of investigated grass ecosystems and TF values

Charachteristic	Agrosystems				Natural ecosystems	
	barley	maize	rape	potatoes	dry meadow	wet meadow
	^{137}Cs activity, Bq/kg					
Soil	486	459	494	674	712	621
Total biomass	30,7	58,0	4,8	37,0	73,0	120,4
Above-ground biomass	6,6	6,0	6,6	44,7	25,4	26,0
Below-ground biomass	79,2	85,7	2,4	31,8	77,5	134,1
	Transfer factor					
TF_{tot}*	0.06	0.13	0.01	0.05	0.10	0.19
TF_{ag}**	0.01	0.01	0.01	0.07	0.04	0.04
TF_{bg}***	0.16	0.19	0.01	0.05	0.11	0.22

* TF_{tot} – transfer factor of ^{137}Cs for total biomass, ** TF_{ag} – transfer factor of ^{137}Cs for above-ground biomass, *** TF_{bg} – transfer factor of ^{137}Cs for below-ground biomass

The values of ^{137}Cs activity in vegetation is an order less than in soils. Meadow plants, especially vegetation of wet meadow, growing on more polluted soils are characterized by relatively higher ^{137}Cs activities, and maize as a whole is slightly enriched by ^{137}Cs among other investigated cultural crops. Generally total accumulation of ^{137}Cs in vegetation somewhat depends on the level of soil radioactive contamination (Figure 2A). But this correlation is more distinctly pronounced in a pair "^{137}Cs in soil – ^{137}Cs in above-ground biomass" and appears rather slightly in a pair "^{137}Cs in soil – ^{137}Cs in below-ground biomass" (Figure 2B).



(A) (B)

Figure 2. Relationship between averaged ^{137}Cs activity (Bq/kg) in vegetation and soil of investigated grass ecosystems: A – total biomass, B – above-ground and below-ground biomass

The other reason of the relatively increased ^{137}Cs activity in natural meadow vegetation may be the predominance of perennial herbs and grasses which may gradually accumulate ^{137}Cs during lifetime whereas agrosystems consist of annual crops with a short biogeochemical cycle of nutrients.

But the most striking feature of ^{137}Cs accumulation in vegetation is a significant difference in the radionuclide's content between above-ground and below-ground fractions of plants. The values of ^{137}Cs specific activity in below-ground biomass (mainly roots) are 2-5 times greater than ones in green parts of plants except rape having stem root system and potatoes where the distribution of ^{137}Cs over total biomass is relatively uniform (but below-ground fraction of potatoes mainly is represented by modified shoots, but no roots).

The depositing role of the below-ground vegetation fractions regarding ^{137}Cs is even more pronounced in the event of biomass inventories scan. Since 33-65% of total biomass in barley and maize agrosystems and 87-92% of total biomass in meadows is concentrated underground, then more than 86-98% of ^{137}Cs inventories are confined to the below-ground biomass.

Biological Features of ^{137}Cs Root Uptake and Translocation into Shoots

The absence of direct proportion between ^{137}Cs activity in soil and in below-ground biomass demonstrates barrier function of roots in ^{137}Cs penetration into plant tissues and the importance of revealing the biological features of different species and families of plants influenced on this process.

To estimate the biological features of ^{137}Cs root uptake unaffected by the level of soil radioactive contamination transfer factor values (TF, the ratio of the specific ^{137}Cs activity in the plant tissue and in soil) were calculated (Table 2). Total values of ^{137}Cs TF_{tot} in the studied grass ecosystems vary from 0.01 (rape) to 0.20 (wet meadow), that confirms the common discrimination of the radionuclide root uptake resulted from ^{137}Cs xenobiotic nature.

At the same time there is a noticeable difference in ^{137}Cs TF_{tot} as well as in TF_{bg} for plant tissues of various ecosystems. The highest TF_{bg} values in below-ground fraction are typical for vegetation with dominant *Gramineae* family species (barley, maize, herb-grass meadows) having fibrous root system. And such amounts are typical for cereals whether cultural or wild, annual or perennial. The lowest TF_{bg} value in below-ground fraction is characterized for rape agrosystem having stem root system.

There is no doubt that accumulation of ^{137}Cs in vegetation is connected with the intensity of the radionuclide root uptake. A comparison of modern soil profile distribution of ^{137}Cs, root volume and root absorbing surface values shows very similar characteristics (Figure 3) with correlation coefficients 0.71 and 0.64 respectively. So root systems of grass vegetation not only develop within the most radioactively contaminated soil layers, but also can serve as disseminators of ^{137}Cs penetration in a soil profile. In the arable chernozems ^{137}Cs uniformly distributed to a depth of A_p horizon (20-30 cm of thickness), while in meadow soils 70-80% of the radionuclide is concentrated within the top A_d horizon (9-13 cm of thickness).

Process of ^{137}Cs translocation from roots to shoots is also determined by biological features of plants. But whereas root uptake of ^{137}Cs for the most parts increases with increasing in below-ground biomass (correlation coefficient 0.68), ^{137}Cs activities in above-ground parts of vegetation are nearly invariant from above-ground biomass or from the ratio between above-ground biomass and below-ground biomass. So transfer of ^{137}Cs from roots to shoots still further depends on biological depends on the biological properties of plant species, and not merely on the rate of the above-ground biomass growth. The most significant discrimination of ^{137}Cs translocation into green parts is expressed in cultural cereals agrosystems where TF_{ag} in above-ground fraction are 12-14 times less then ones in below-ground fraction. In herb-grass meadow plant associations the ratio of TF_{bg} and TF_{ag} values is 3-5. So there is additional biological barrier for ^{137}Cs between roots and shoots in the majority of plant species. On the other hand, in rape and potatoes agrosystems TF values for ^{137}Cs in above- and below-ground parts are little different, that may be depend on stem root system of *Brassicaceae* family in the first case, whereas in potatoes agrosystem similarity of TF_{ag} and TF_{bg} values may be determined by the peculiarity of tubers tissues having analogy to shoot tissues.

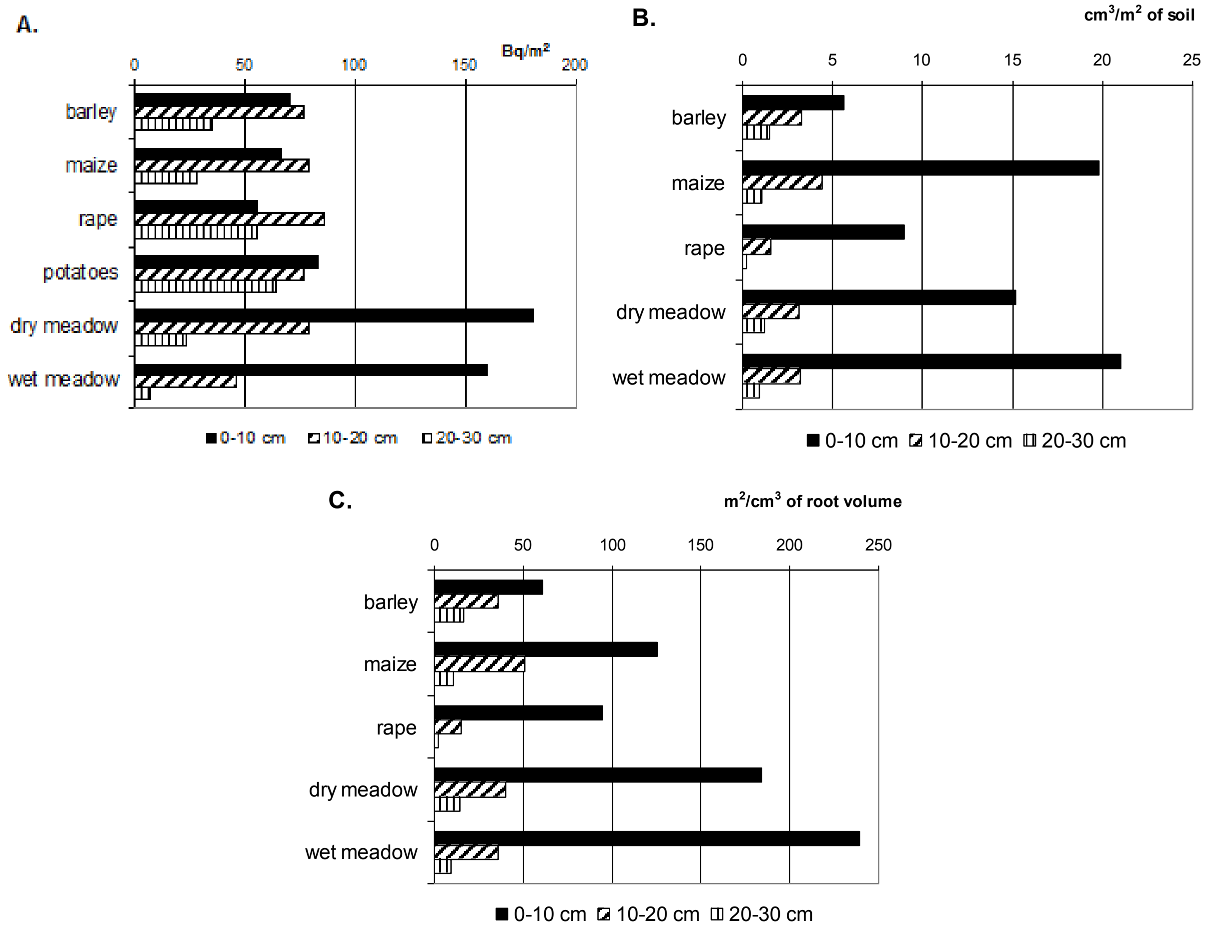


Figure 3. Soil profile distribution. A – inventories of ^{137}Cs in soil (Bq/m^2);
B – root volume (m^3/m^2 of soil); C - root absorbing surface (m^2/cm^3 of root volume)

The importance of plant species features in the process of ^{137}Cs translocation over below- and above-ground parts may also be noticed under comparison of TF_{ag} values for different biological groups of plants growing at the same level of soil radioactive contamination (Figure 4). Above-ground parts of meadow herbs universally accumulate more ^{137}Cs than *Gramineae* species, and above-ground parts of weeds (bindweed, *Convolvulaceae* family, in barley agrosystem and quinoa, *Chenopodiaceae* family, in maize agrosystem) concentrate more ^{137}Cs than corresponding cultivated cereals.

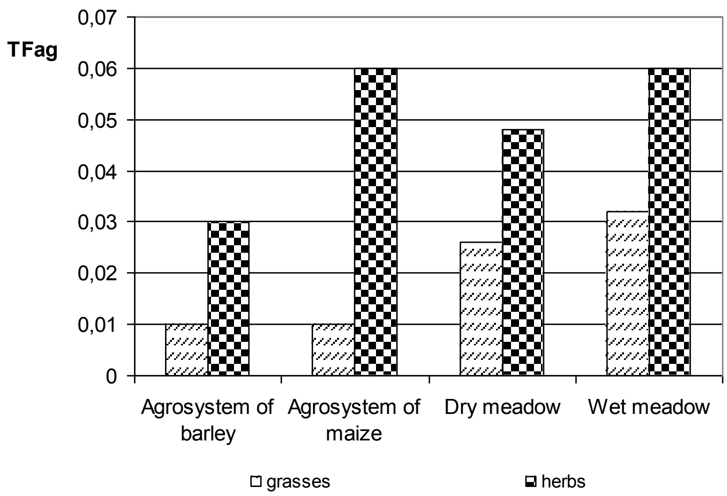


Figure 4. Transfer factor of ^{137}Cs for above-ground biomass of plant species from different biological groups

Inventories of ^{137}Cs in Grass Ecosystems of Plavsk Hot Spot Post-Chernobyl Landscape

The final assessment of the ^{137}Cs distribution of in the “soil-plant” system of grass ecosystems of Plavsk hot spot has revealed that 99.9% and more of total ^{137}Cs inventory is localized in soil (Table 3). Annual inventory of ^{137}Cs in vegetation is very small; especially the ^{137}Cs yield alienation in agrosystems is minor. In such conditions of strong ^{137}Cs fixation by soils and insignificant radionuclid’s root uptake by plants there is a possibility to obtain ecologically acceptable agricultural production on contaminated post-Chernobyl lands in the remote period after the accident.

Table 3. Inventories of ^{137}Cs in “soil-plant” system of investigated grass ecosystems

Grass ecosystem	Total inventories of ^{137}Cs in “soil-plant” system, Ci/km^2	Inventories of ^{137}Cs in soil		Inventories of ^{137}Cs in vegetation	
		Ci/km^2	%	Ci/km^2	%
Agrosystems					
barley	4,908	4,906	99,96	0,002	0,04
maize	4,700	4,694	99,87	0,006	0,13
rape	5,303	5,302	99,99	0,001	0,01
potatoes	6,012	6,011	99,98	0,001	0,02
Natural ecosystems					
dry meadow	7,631	7,627	99,95	0,004	0,05
wet meadow	5,766	5,759	99,87	0,007	0,03

Conclusion

- Soil contamination by ^{137}Cs in natural and agricultural grass ecosystems of the post-Chernobyl Plavsk hot spot area is currently being evaluated as 5-8 Ci/km^2. Soils of geochemically subordinate natural meadow landscapes accumulate ~ 25% more the radionuclide than arable soils of eluvial landscapes.
- Modern parameters of ^{137}Cs root uptake are characterized by low intensity that reveals the discrimination in ^{137}Cs transfer from contaminated soil into grass vegetation. 99.9% and more of total ^{137}Cs inventory is strongly fixed in soil. So there is a possibility to obtain ecologically acceptable agricultural production on contaminated post-Chernobyl lands in the remote period after the accident.
- ^{137}Cs activity in below-ground biomass in so doing may be 2-5 times greater than in the above-ground biomass, which requires quantitative account of ^{137}Cs accumulation not only in eatable, as a rule green parts, but also in below-ground parts especially for the plant species from *Gramineae* family.
- There is a close connection between distribution of ^{137}Cs, root volume and root absorbing surface values in soil profile. So roots of grass vegetation not only develop within the most radioactively contaminated soil layers, but also can serve as disseminators of ^{137}Cs penetration into the depth. In the arable chernozems ^{137}Cs uniformly distributed to a depth of A_p horizon (20-30 cm of thickness), while in meadow soils 70-80% of the radionuclide is concentrated within the top A_d horizon (9-13 cm of thickness).
- The major differences in the ^{137}Cs root uptake and further translocation into above-ground biomass are closely related to the level of soil radioactive pollution and biological features of plant species and families that should be considered in land use policy.

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