Arch. Biol. Sci., Belgrade, 63 (4), 1117-1125, 2011 DOI:10.2298/ABS1104117C

MOSSES AS BIOMONITORS FOR RADIOACTIVITY FOLLOWING THE CHERNOBYL ACCIDENT

ANA ČUČULOVIĆ[1], R. ČUČULOVIĆ[2], TIJANA CVETIĆ ANTIĆ[3] and D. VESELINOVIĆ[4]

INEP- Institute for the Application of Nuclear Energy, 11080 Zemun, Serbia
[2]*The Faculty for the Applied Ecology Futura, Singidunum University,* 11000 Belgrade, Serbia
[3]*Faculty of Biology, University of Belgrade,* 11000 Belgrade, Serbia
[4]*Faculty of Physical Chemistry, University of Belgrade,* 11001 Belgrade, Serbia

Abstract - In this work ^{137}Cs and ^{40}K radionuclide concentrations in moss collected at NP Djerdap in the period from 1996 to 2009 are presented. Values of the substrate-moss transfer factor for ^{137}Cs and ^{40}K were calculated. The effective and biological half-life of ^{137}Cs in *Homalothecium sericeum* moss collected in the period from 1996 to 2008 on the archeological locality of Lepenski Vir was also calculated.

Key words: NP Djerdap, mosses, ^{137}Cs, ^{40}K

UDC 574:504.5(497.11)

INTRODUCTION

Biomonitoring is the use of properties of an organism - a bioindicator - or part of it to obtain information about certain characteristics of the biosphere. The term bioindicator generally refers to all organisms that provide information on the environment or the quality of environmental changes, and biomonitors are organisms that provide quantitative information on the quality of the environment. Biomonitoring is a passive method and provides a measure of integrated exposure over a period of time (for review see Walterbeek, 2002; Szczepaniak and Biziuk, 2003).

To be suitable for application as a monitor for air particulate matter, specific requirements have to be met by a biological tissue or monitor (Market and Weckert, 1989; Chakrabortty and Paratkar, 2006). Biomonitoring species for radionuclides, trace elements and other air pollution are selected on the basis of specificity so that accumulation is considered to occur from the atmosphere only (Rühling, 1994). There are many other selection criteria, such as general occurrence, a well-defined representation of sampling site (Wolterbeek and Bode, 1995), and the accumulation ratio (Sloof, 1993). Generally, a biomonitor should concentrate the elements of interest, and it should quantitatively reflect its ambient elemental conditions, without any significant impact on the monitor behavior (Wolterbeek, 2002).

The mosses essentially meet most of the requirements for an organism to be used in biomonitoring. One-cell thick leaves, thick cell walls and the absence of cuticles provide effective adsorption of trace elements from air and deposited material by ion exchange (Brown and Brown, 1990; Wolterbeek, 2002). The large surface to weight ratio in mosses (Mishev et al., 1996, Zechmeister et al., 2006) improves trace element adsorption. The absence of roots ensures absorption mainly from air deposition, and it has been shown that mosses concentrate particulates and dissolve chemical species from dry and wet deposition (Stainnes, 1995). The deposition and removal of radioactive elements in mosses is also related to rainfall (Taylor and Witherspoon, 1972; Krmar et al., 2009). It seems that adsorbed elements are transported into the protoplasts (Tyler, 1990; Wells and Brown, 1990), and from older to younger parts of moss (Brown and Brown, 1990). This process probably prevents further rainfall-related loss. According to Dragović et al. (2004), most of the ^{137}Cs seems to be distributed in membrane and cell wall fractions.

However, care should be taken regarding the species used in investigations, since it has been shown that for heavy metal deposition pleurocarpous mosses reflect short-term, and acrocarpous mosses long-term deposition (Sabovljević et al., 2005).

Together with lichens, mosses have been the most commonly applied biomonitors for atmospheric pollution (Tyler, 1990; Wolterbeek, 2002; Szczepaniak and Biziuk, 2003). Both mosses and lichens are thought to absorb trace elements passively. The advantage of mosses is that their age can be easily determined, in contrast to certain lichen species (Sawidis et al., 2009). Also, moss biomonitoring has been more popular because it causes fewer technical and analytical problems than lichens (Szczepaniak and Biziuk, 2003).

Pollution with anthropogenic radionuclides is mainly regional in character, but it can be wider in the case of strong nuclear explosions. Radiocesium (^{137}Cs) is one of the most important artificial radionuclides produced by nuclear fission. It has been introduced into the terrestrial environmental by nuclear weapons testing, authorized discharge of nuclear waste and accidental release from nuclear facilities. Isotopes of potassium are chemical analogues of cesium and consequently they are included in the nutrient cycle and cause long-term irradiation to biota and man (Ciuffo et al., 2002). A long half-life together with its chemical and ecophysiological similarity with potassium makes ^{137}Cs one of the most important and harmful radionuclides released into the environment by the nuclear industry (Sawidis et al., 2009).

The accident in the Chernobyl nuclear power plant has marked the XX century (26.04.1986, Ukraine). The most significant and dangerous radionuclides released into the atmosphere were ^{131}I, ^{134}Cs and ^{137}Cs. Soon after the Chernobyl accident, extensive research started on radionuclide concentrations in mosses, lichens and other bioindicators (Elstner et al., 1987; Papastefanou et al. 1989; Marović et al. 2008, and many more). In moss in Finland in 1986 (Ilus et al., 1987) ^{137}Cs radionuclide concentrations were 28000 Bq/kg, while in Bavaria and Munich they were 12370 Bq/kg, i.e. 30000 Bq/kg (Elstner et al., 1987; Heinzl et al., 1988).

While monitoring of pollution of the environment by radionuclides in moss was expanding in the world, in ex-Yugoslavia research in this field was neglected. According to Saračević et al. (1989), ^{137}Cs radionuclide concentrations in moss in 1985 (before the Chernobyl accident) in hunting ground in Bosnia and Herzegovina were from 267 Bq/kg to 508 Bq/kg (mean value 429 Bq/kg), while in 1987 (after the accident) they were from 858 Bq/kg to 4604 Bq/kg (mean value 2645 Bq/kg).

^{137}Cs radionuclide concentrations in moss samples from areas in ex-Yugoslavia after the Chernobyl accident were different. In *Plagiothecium sp*. moss collected on the territory of the National Park Durmitor (Montenegro) in 1993 ^{137}Cs radionuclide concentrations were 5181 Bq/kg. (Stanković et al., 1999), while in 1996, in *Isothecium myurum* Brid. moss from the territory of NP Kopaonik they were 2183 Bq/kg, and 873 Bq/kg in *Amblystegium serpens* (Hedw) Br. Evr. moss from southern Serbia (Grdelica) (Stanković et al., 1997).

Radionuclides released in the Chernobyl accident are still present in ecosystems. It has been shown that in Belgrade and its surroundings, 24 years after the accident both soil and moss samples still contain relatively high concentrations of ^{137}Cs (Grdović et al., 2010). The aim of this study was to establish radionuclide concentrations, soil-to-moss transfer, and the biological half-life for ^{137}Cs and ^{40}K, over a period of 13 years (1996-2009) in mosses collected from the Djerdap National Park.

MATERIALS AND METHODS

The samples of mosses and substrates were collected from 1996 to 2009 on the territory of the National Park Djerdap. The samples were air-dried and then homogenized, and the activities were measured gamma-spectrometrically. The specific activity of radionuclides was measured using an HPGe gamma-ray spectrometer (ORTEC-AMETEK, with 8192 channels, resolution of 1.65 keV and relative efficiency of 34% at 1.33 MeV for ^{60}Co). Samples were measured in Marinelli vessels. Sample weight was about 0.1 kg. The counting time for each sample was 60000s. The relative error for sample preparation and measurement was 10%. Gamma Vision 32 MCA emulation software, was used to analyze gamma-ray spectra. The specific activity of the artificially produced radionuclide ^{137}Cs was measured via the γ-line at the energy of 661.6 keV. The specific activity of the ^{40}K radionuclide was determined from its 1460.8 keV gamma-ray line. Nuclides were identified using a library-driven search routine, and quantitative analyses were carried out using the appropriate detector calibration. Radionuclide results were reported in Bq/kg on a dry weight basis.

RESULTS

Table 1 shows the radionuclide concentrations (Bq kg^{-1} dry weight) of ^{137}Cs and ^{40}K in moss samples collected in 2003 in NP Djerdap (Ploče, Veliki kazan, Duboki potok, Šomrda, Alibegov potok, PRC) (Čučulović et al., 2005). Radionuclide contamination due to the Chernobyl accident was not homogenous on the territory of NP Djerdap which resulted in great differences in moss contamination. Maximal radionuclide concentrations of ^{137}Cs were measured in samples from the Veliki kazan locality (4923 Bq/kg), while minimal levels were measured in samples collected after a fire on the Šomrda locality (76 Bq/kg). Concentrations of the natural radionuclide ^{40}K in moss samples from the NP Djerdap territory are from 95 Bq/kg (sample 6) to 992 Bq/kg (sample 5).

Table 2 shows ^{137}Cs radionuclide concentrations in moss samples collected in 2006 on the territory of NP Djerdap. Analysis of the obtained results shows that in all samples in 2006 ^{137}Cs was still present and the ^{137}Cs radionuclide concentrations in the moss samples were not uniform. In moss samples from 2006, ^{137}Cs radionuclide concentrations were from 72 Bq/kg (*Ctenidium molluscum,* from the Čezava locality) to 3463 Bq/kg (*Brachythecium mildeanum,* from the Crni vrh locality) (Čučulović and Veselinović, 2008). The activity concentrations of analyzed radionuclides varied with moss species. The mean ^{137}Cs radionuclide concentrations in moss

Table 1. Radionuclide concentrations (Bq/kg d.w.) in moss samples from the NP Djerdap collected in 2003.

No.	Site	^{137}Cs	^{40}K
1	Asphalt road, turning for Ploče	4756	184
2	Veliki kazan, Ploče	511	110
3	Duboki potok	1671	226
4	Veliki kazan, viewpoint	4923	217
5	Šomrda	2721	992
6	Šomrda	192	95
7	Šomrda, relay	1239	143
8	Šomrda, fire	76	389
9	Alibeg's stream	2365	261
10	Alibeg's stream	592	733
11	PRC, hotel	438	145

Table 2. Radionuclide concentrations (Bq/kg d.w) in moss and substrate samples in the NP Djerdap territory collected in 2006.

No.	Site	Sample	^{137}Cs	^{40}K	TF ^{137}Cs	TF ^{40}K
1	Djerdap, 8a, Monastery wood	*Isothecium myurum*	83	154		
2	Djerdap, 25a, Prapazešće	*Brachythecium mildeanum*	1410	153		
2a	Djerdap, 25a, Prapazešće	substrate	1539	199	0.92	0.77
3	Djerdap, 41a, Brzujka	*Bryum argenteum*	508	191		
3a	Djerdap, 41a, Brzujka	substrate	660	231	0.77	0.83
4	Djerdap, 48b, Faca Tekija	*Hypnum cupressiforme*	365	172		
5	Djerdap, 67i	*Hypnum cupressiforme*	186	471		
6	Djerdap, 75b	*Homalothecium lutescens*	131	284		
7	Djerdap, 78f, Popovac	*Dicranum scoparium*	124	108		
8	Crni vrh, 21c	*Brachythecium mildeanum*	3463	481		
8a	Crni vrh, 21c	substrate	3892	521	0.89	0.92
9	Čezava, 36	*Ctenidium molluscum*	72	386		
10	Čezva, 37	*Brachythecium mildeanum*	208	442		
10a	Čezva, 37	substrate	770	546	0.27	0.81
11	Štrbac stream bed, 65a, Alibeg's stream	*Hypnum cupressiforme*	2737	58		
11a	Štrbac stream bed, 65a, Alibeg's stream	substrate	3220	192	0.85	0.30
12	River on the right, 37	*Brachythecium mildeanum*	205	133		
13	River on the right, 46	*Homalothecium sp.*	174	106		
14	River on the right, 47	*Hypnum cupressiforme*	190	174		
15	River on the left, 27	*Pseudoleskeella nervosa*	463	304		
15a	River on the left, 27	substrate	552	367	0.84	0.83
16	River on the left, 29	*Sphagnum fuscum*	166	233		
16a	River on the left, 29	substrate	422	378	0.39	0.62
17	Private wood, 18f, Tekija	*Dicranum scoparium*	1029	526		
17a	Private wood, 18f, Tekija	*substrate*	1132	551	0.91	0.95
18	Private wood, 22a, Tekija	*Ctenidium molluscum*	405	493		
19	Private wood, 30a, Tekija	*Isothecium myurum*	1040	202		
19a	Private wood, 30a, Tekija	substrate	1233	307	0.84	0.66
20	Private wood, KO Tekija, Kosovica	*Hypnum cupressiforme*	116	79		

collected in 2006 from the territory of NP Djerdap was 1225 Bq/kg. ^{40}K radionuclide concentrations in moss collected in 2006 was from 58 Bq/kg (*Hypnum cupressiforme,* Štrbac stream bed, Alibeg's stream) to 526 Bq/kg (*Dicranum scoparium*, private woods, Tekija). The mean ^{40}K radionuclide concentrations in moss collected in 2006 from the NP Djerdap territory was 258 Bq/kg.

Table 2 also shows ^{137}Cs radionuclide concentrations in moss substrate collected in 2006 on the NP Djerdap territory. ^{137}Cs radionuclide concentrations in the substrate samples are not uniform (from 422 Bq/kg, Čezava, to 3892 Bq/kg, Crni vrh). The different radiocesium activity concentrations in the substrates are the consequence of non-uniform contamination of locations after the Chernobyl accident. The mean ^{137}Cs activity concentrations in the substrates were 1491 Bq/kg. ^{40}K activity concentrations in the substrates were from 152 Bq/kg (Štrbac stream bed, Alibeg's stream) to 551 Bq/kg (private woods, 18f). The mean ^{40}K activity concentrations in substrates from the NP Djerdap territory was 366 Bq/kg.

Knowing the ^{137}Cs and ^{40}K radionuclide concentrations in mosses and their substrates enabled calculation of transfer factors given in Table 2. Transfer factors (TF) were calculated as the ratio of the radionuclide concentration in plants (Bq/kg plant) to its concentration in soil (substrate) (Bq/kg soil):

Table 3. Radionuclide activity concentrations (Bq/kg d.w.) in moss and substrate samples from the NP Djerdap territory collected in 2008 and 2009.

No.	Site	Sample	^{137}Cs	^{40}K
		2008		
1	Djurakovo	*Hypnum cupressiforme*	11.8	260
2	Golubac	*Hypnum cupressiforme*	120	242
3	Golubac	*Homalothecium lutescens*	76	228
4	Brnjica	*Brachythecium rutabulum*	21	364
5	Brnjica	*Homalothecium sericeum*	7.14	168
6	Lepenski vir	*Brachythecium salebrosum*	14.0	192
7	Lepenski vir	*Isothecium myosuroides*	146	484
8	Lepenski vir	*Leucodon sciuroides*	417	322
		2009		
1	Golubac city	*Hypnum cupressiforme*	7.95	184
2	Golubac city	*Homalothecium lutescens*	5.43	142
3	Golubac city	*Homalothecium lutescens*	14.5	189
3a	Golubac city	substrate	16.4	148
4	Golubac city	*Hypnum cupressiforme*	19.2	192
5	Golubac city	*Hypnum cupressiforme*	15.7	190
6	Brnjica	*Brachythecium rutabulum*	27	227
6a	Brnjica	substrate	38	243
7	Lepenski vir	*Brachythecium salebrosum*	12.7	140
8	Lepenski vir	*Isothecium myosuroides*	111	346
8a	Lepenski vir	substrate	105	356
9	Lepenski vir	*Isothecium myosuroides*	104	471

TF=Bq/kg plant (dry weight)/ Bq/kg soil (dry weight) [1]

The soil-to-moss transfer factor for the ^{137}Cs studied was from 0.27 to 0.92 (mean value for ^{137}Cs was 0.74). Potassium remains in homeostatic equilibrium in the plants and is readily assimilated by the plants and generally shows a TF smaller than 1. Potassium-40 TF values ranged from 0.30 to 0.95 (mean value for ^{40}K was 0.74).

The ^{137}Cs and ^{40}K activity concentrations in the mosses did not exhibit any competitive relationship, probably because mosses act as atmospheric filters and accumulate both radioisotopes in a directly related manner).

Analysis of the ^{137}Cs and ^{40}K activity concentrations is mosses and their substrata (Table 2) leads to the conclusion that there is a linear dependence between ^{137}Cs (^{40}K) activity concentrations is mosses and ^{137}Cs (^{40}K) activity levels in the substrate.

Table 3 shows ^{137}Cs activity levels in moss and substrate samples collected in 2008 and 2009 on the NP Djerdap territory. ^{137}Cs activity concentrations (Bq/kg) in mosses collected in 2008 on the NP Djerdap territory range from 7.14 (*Homalothecium sericeum*, Brnjica) to 417 Bq/kg (*Leucodon sciuroides*, Lepenski vir). The mean activity concentration of ^{137}Cs in moss collected in 2008 on the NP Djerdap territory was 102 Bq/kg. The results of ^{137}Cs activity concentrations in mosses show that there were no new contaminations of the NP Djerdap territory with this radionuclide. ^{40}K activity concentrations (Bq/kg) in mosses collected in 2008 were from 168 (*Homalothecium sericeum*, Brnjica) to 484 Bq/kg (*Isothecium myosuroides*, Lepenski vir). The mean activity concentration of ^{40}K in mosses collected in 2006 on the NP Djerdap territory was 283 Bq/kg.

Table 4. ^{137}Cs (Bq/kg) and ^{40}K (Bq/kg) activity concentrations in *Homalothecium sericeum* moss and its substrate collected on a rock close to the Lepenski vir archeological site in the period from 1996 to 2008.

Sample year	^{137}Cs (Bq/kg)	^{40}K (Bq/kg)
1996. moss	724	287
substrate	1413	---
1997. moss	1417	437
1999. moss	1055	---
substrate	1491	---
2000. moss	1352	---
2001. moss	855	405
2003. moss	745	397
2004. moss	377	253
2008. moss	234	332

These results indicate that there was no new ^{40}K pollution of the NP Djerdap territory.

^{137}Cs activity concentrations (Bq/kg) in mosses collected in 2009 on the NP Djerdap territory were from 5.43 (*Homalothecium lutescens,* Golubac city) to 111 Bq/kg (*Isothecium myosuroides,* Lepenski vir). The mean activity concentration of ^{137}Cs in mosses collected in 2009 NP Djerdap territory was 35 Bq/kg. ^{40}K activity concentrations (Bq/kg) in mosses collected in 2009 were from 140 (*Brachythecium salebrosum,* Lepenski vir) to 471 Bq/kg (*Isothecium myosuroides*, Lepenski vir). The mean activity concentration of ^{40}K in moss collected in 2008 on the NP Djerdap territory was 231 Bq/kg.

Table 3 shows ^{137}Cs activity concentrations in moss substrate samples collected in 2009 on the NP Djerdap territory (Čučulović and Veselinović, 2009). ^{137}Cs activity concentrations in the substrate samples were from 16.4 Bq/kg (substrate 3a, Golubac city) to 105 Bq/kg (substrate 8a, Lepenski vir). ^{40}K activity concentrations in the substrates were from 148 Bq/kg (substrate 3a, Golubac city) to 356 Bq/kg (substrate 8a, Lepenski vir). The different radionuclide concentrations in the substrate are the consequence of non-uniform contamination of locations by the Chernobyl accident.

Confirmation that there were no new contaminations with radiocesium on the NP Djerdap territory is found in the results presented in Table 4. It gives the results of activity concentrations (Bq/kg) of ^{137}Cs and ^{40}K in *Homalothecium sericeum* moss growing on a rock near the entrance to the Lepenski vir archeological site. *H. sericeum* moss was collected from the same spot in the summer period from 1996 to 2008. It is obvious that the radiocesium activity concentration decreases with time which shows that there were no new contaminations with this radionuclide on this area and wider.

The results presented in Table 4 indicate that in a certain time period the activity concentrations of ^{137}Cs decrease faster in moss than the physical half-life period (30.2 years). This reduction in radionuclide concentrations in the moss gametophyte is explained as the consequence of an increase in biomass while the radionuclide amount remains unchanged.

Using the data on ^{137}Cs activity concentration in moss from Lepenski vir in the period from 1997 to 2008 given in Table 2 we can calculate the biological and effective half-life period of ^{137}Cs in *Homalothecium sericeum* moss. The biological and effective half-life period depends on the chemical form of the radionuclide, surrounding pH, temperature, moss type and some external parameters.

Knowing that

$$A_t=A_0 \exp-(\lambda+\lambda_b)t \qquad [2]$$

where: A_t is the activity per unit moss dry weight at any time

A_0 is the activity per unit moss dry weight at t=0

λ is the constant = $\ln2/T_f$ = 0,023 year^{-1}, T_f is the physical half-life of ^{137}Cs of 30.2 years

$\lambda_b = \ln2/T_b$ (year^{-1}), T_b is the biological half-life, and

t is the time period of 9 years if we use data from 1999 to 2008.

Exchanging values for A_t, A_0, λ and t, values for λ_b of 0. 1408 year^{-1} and T_b (biological half-life of ^{137}Cs) of 4.9 years are obtained.

Knowing that

$$T_{eff} = T_f T_b / T_f + T_b \quad [3]$$

where: T_{eff} is the effective half-life of ^{137}Cs in moss

T_f is the physical half-life of ^{137}Cs

T_b is the biological half-life of ^{137}Cs in moss,

then the effective half-life of ^{137}Cs can be then calculated in *Homalothecium sericeum* moss (Sloof, 1993). In our case the effective half-life was 4.2 years. The calculated values for T_b and T_{eff} are lower than the values obtained for *Evernia prunastri* lichen collected in southern Serbia in the period from 1989 to 1993 where T_b was from 8.3 to 10.1 years and T_{eff} was from 6.5 to 7.5 years (Stanković, 1994).

DISCUSSION

In this work the presence of ^{137}Cs was noted in all investigated samples. Activity concentrations of the analyzed radionuclides varied with moss species, as well as among samples of the same species collected from different localities. Different activity concentrations of radiocesium in the same moss species from different locations are mostly due to non-uniform contamination of locations after the Chernobyl accident. While intraspecific variation in radioactivity is due to different deposition and washout rates, interspecific variation of activity concentration is due to different morphology and anatomy (Sabovljević et al., 2005; Sawidis et al., 2009; Cevik and Celik, 2009), leading to different accumulation of radioactivity from dry and wet deposition.

A decreasing trend of activity concentrations has been observed in all samples. Since activity already accumulated in mosses will make some decreasing trend of activity deposition less prominent (Krmar et al., 2009), this decreasing trend is even more certain, and confirms what is usually stated: that after the Chernobyl accident there was no significant ^{137}Cs emission. The temporal variations in ^{137}Cs activity shown in *Hypnum cupressiforme* (Krmar et al., 2009) are not significant, since in our study the accumulated activity is much higher than this variation level.

The biological half-life of ^{137}Cs for *Homalothecium sericeum* moss was 4.9 years, while the effective half-life of ^{137}Cs for moss was 4.2 years. The calculated values for T_b and T_{eff} are lower than the values obtained for *Evernia prunastri* lichen collected in southern Serbia in the period from 1989 to 1993 where T_b was from 8.3 to 10.1 years and T_{eff} was from 6.5 to 7.5 years (Stanković, 1994). This value is comparable to the mean ecological half-life for ^{137}Cs in mosses, which was calculated to be 4.4 years by Cevik and Celik (2009). However, for the same species in their study, the ecological half-life was much longer (10.4 years). Since ecological half-life depends on many factors (including different morphoanatomic and microclimatic differences), this introduces some uncertainty to the estimation.

There was no correlation in accumulation between ^{137}Cs and ^{40}K. The absence of any correlation between activity concentrations of these radionuclides in mosses was also demonstrated in other radioecological studies (Korobova et al. 2007), but contrary to the findings of Cevik and Celik (2009). A linear dependence of ^{137}Cs (^{40}K) activity concentrations in moss on the ^{137}Cs (^{40}K) activity concentrations in the substrate was observed. This indicates that differences between localities are mainly the consequence of different rates of deposition after the Chernobyl accident, and not different washout rates. Substrate-moss transfer factors were calculated for ^{137}Cs and ^{40}K, and for both radionuclides the values were less than 1. This means that no significant transfer of radionuclides from substrates occurred, and that the radioactivity in the moss is mainly from atmospheric deposition.

In this work, mosses have again been shown to be good biomonitors for atmospheric radionuclide deposition. Although substantially decreased, ^{137}Cs is still present in moss tissue. This radioactivity is thought to originate mainly from the Chernobyl accident. Monitoring of ^{137}Cs activity in mosses thus provides a very sensitive method for detection of this radionuclide and should be performed as a means of continuous evaluation of environment pollution.

Acknowledgements -This work was supported by the Ministry of Education and Science of the Republic of Serbia, project codes III 43009 and 173040

References

Brown, D.H., and *R.M. Brown* (1990). Reproducibility of sampling for element analysis using bryophytes. In: *Element Concentration Cadasters in Ecosystems* (Eds. H. Lieth and B. Markert), 55–62., VCH Publishers, Weinheim.

Cevik, U., and *N. Celik* (2009). Ecological half-life of ^{137}Cs in mosses and lichens in the Ordu province, Turkey. *J. Environ. Radioact.*, **100**, 23-28.

Chakrabortty, S., and *G.T. Paratkar* (2006). Biomonitoring of Trace Element Air Pollution Using Mosses. *Aerosol, Air Quality Res.*, **6,** 247-258.

Ciuffo, L.E.C., Belli, M., Pasquale, A., Menegon, S., and *H.R. Velasco* (2002). ^{137}Cs and ^{40}K soil-to-plant relationship in a seminatural grassland of the Giulia Alps, Italy. *Sci. Total Environ.*, **295**, 69-80.

Čučulović, A., and *D. Veselinović* (2008). Nivoi aktivnosti ^{137}Cs u uzorcima mahovina sa područja NP Djerdap, Zbornik radova, EkoIst 08, Ekološka istina, Sokobanja, 43-46.

Čučulović, A., and *D. Veselinović* (2009). Nivoi aktivnosti ^{137}Cs i ^{40}K u mahovinama Istočne Srbije, Zbornik radova, EkoIst 09, Ekološka istina, Kladovo, 37-40.

Čučulović, A., Veselinović, D., and Š. Miljanić (2005). Akumulacija radionuklida u bioindikatorima NP Djerdap, Zbornik radova, EkoIst 05, Ekološka istina, Bor, 105-108.

Delfanti, C., Papucci, C., and *C. Benco* (1999). Mosses as indicators of radioactivity deposition around a coal-fired power station. *Sci. Total Environ.*, **227**, 49-56.

Dragović, S., Nedić, O., Stanković, S., and *G. Bačić* (2004). Radiocesium accumulation in mosses from highlands of Serbia and Montenegro: chemical and physiological aspects. *J. Environ. Radioact.*, **77,** 381–388.

Elstner, E.F., Fink, R., Höll, W., Lengfelder, E., and *H. Ziegler* (1987). Natural and Chernobyl-caused radioactivity in mushrooms, mosses and soil-samples of defined biotops in SW Bavaria. *Oecologia,* **73,** 553-558.

Grdović, S., Vitorović, G., Mitrović, B., Andrić, V., Petrujkić, B., and *M. Obradović* (2010). Natural and anthropogenic radioactivity of feedstuffs, mosses and soil in the Belgrade environment, Serbia. *Arch. Biol. Sci*. **62,** 301-307.

Heinzl, J., Korscinek G., and *E. Nolte* (1988). Some measurement on Chernobyl, *Phys. Scr*., **37**, 314-316.

Ilus, E., Sjöblom, K.L., Aaltonen, H., Klemola S., and *H. Arvela* (1987). Monitoring of radioactivity in the environs of Finnish Nuclear power stations in 1986: Supplement 12 to annual report STUK-A55. Report No. STUK-A67.

Korobova, E.M., Brown, JB., Ukraintseva, N.G., and *V.V. Surkov* (2007). ^{137}Cs and ^{40}K in the terrestrial vegetation of the Yenisey Estuary: Landscape, soil and plant relationships. *J. Environ. Radioact*. **96**, 144-156.

Krmar, M., Radnović, D., Mihailović, D.T., Lalić, B., Slivka, J., and *A. Bikit* (2009). Temporal variations of ^{7}Be, ^{210}Pb and ^{137}Cs in moss samples over 14 month period. *Appl. Radiat. Isot.*, **67**, 1139-1147.

Market, B., and *V. Weckert* (1989). Time and Site Integrated Long-term Biomonitoring of Chemicals by Means of Mosses. *Toxicol. Environ. Chem*. **40**, 177-189.

Marović, G., Franić, Z., Sencar, J., Bituh, T., and *O. Vugrinec* (2008). Mosses and some mushroom species as bioindicators of radiocaesium contamination and risk assessment. *Coll Antropol*. **32,** 109-14.

Mishev, P., Damyanova, A., and *L. Yurukova* (1996). Mosses as biomonitors of airborne pollution in the northern part of Rila mountain. *Observatoire de montagne de Moussala OM2*, 137–141.

Papastefanou, C., Manolopoulou, M., and *T. Sawidis* (1989). Lichens and mosses: Biological monitors of radioactive fallout from the Chernobyl reactor accident. *J. Environ. Radioact.*, **9,** 199-207.

Rühling, Ǻ (1994). Atmospheric Heavy Metal Deposition in Europe—Estimations based on Moss Analysis. NORD 9, Nordic Counsil of Ministers. AKA-Print, A/S, Arhus.

Sabovljević, M., Vukojević, V., Mihajlović, N., Dražić, G., and Ž. Vučinić (2005). Determination of heavy metal deposition in the county of Obrenovac (Serbia) using mosses as bio-indicators. I: Aluminum (Al), arsenic (As) and boron (B). *Arch. Biol. Sci.* **57,** 205-212.

Saračević, L., Kljajić, R., Mihajl, A., and *Z. Milošević* (1989). Komparativni prikaz nivoa radioaktivnosti lišaja i mahovine u lovištima BiH prije i poslije havarije u Černobilju. XV Jugoslovenski simpozijum za zaštitu od zračenja, Priština, 3-6.

Sawidis, T., Tsikritzis, L., and *K. Tsigaridas* (2009). Cesium-137 monitoring using mosses from W. Macedonia, N. Greece. *J. Environ. Manag.,* **90,** 2620–2627.

Sloof, J. (1993). Environmental lichenology: Biomonitoring trace-element air pollution, Interfacultair Reactor Instituut, Delft University of Technology, Thesis.

Stainnes, E. (1995). A critical evaluation of the use of naturally growing moss to monitor the deposition of atmospheric metals. *Sci. Total Environ. 160*, 243–249.

Stanković, A. (1994). Nivo aktivnosti Cs-134 i Cs-137 u lišajima u postčernobiljskom periodu, magistarski rad, Univerzitet u Beogradu, Fakultet za fizičku hemiju, Beograd.

Stanković, A., Stanković, S., and *G. Pantelić* (1999). Levels of activity of natural radionuclides in samples of mosses and lichens from the National Park Durmitor, *Ekologija,* **34,** 49-54.

Stanković, S., Stanković, A., and *G. Pantelić* (1997). Prirodni i veštački radionuklidi u mahovinama sa različitih lokaliteta Srbije. Zbornik radova Naša ekološka istina V naučno stučni skup o prirodnim vrednostima i zaštiti životne sredine X stručni sastanak preventivne medicine Timočke Krajine, Donji Milanovac, 190-193.

Szczepaniak, K., and *M. Biziuk* (2003). Aspects of the biomonitoring studies using mosses and lichens as indicators of metal pollution. *Environ. Res.,* **93,** 221-230.

Taylor, F.G., and *J.P. Whitherspoon* (1972). Retention of simulated fall out particles by lichens and mosses. *Health Physics*, **23**, 867–869.

Tyler, G. (1990). Bryophytes and heavy metals: a literature review. *Bot. J. Linn. Soc.,* **104**, 231–253.

Wells, J.M., and *D.H. Brown* (1990). Ionic control of intracellular and extracellular Cd uptake by the moss *Rhytidiadelphus squarrosus* (Hedw.) Warnst. *New Phytol.,* **116,** 541–553.

Wolterbeek, B. (2002). Biomonitoring of trace element air pollution: principles, possibilities and perspectives. *Environ. Pollut.,* **120,** 11–21.

Wolterbeek, H.T. and *P. Bode* (1995). Strategies in sampling and sample handling in the context of large-scale plant biomonitoring surveys of trace element air pollution. *Sci. Total Environ.,* **176**, 33–43.

Zechmeister, H.G., Hagendorfer, H., Hohenwallner, D., Hanus-Illnar, A., and *A. Riss* (2006). Analyses of platinum group elements in mosses as indicators of road traffic emissions in Austria. *Atmos. Environ*. **40,** 7720–7732.